Space based gravitational wave detectors: LISA mission, constellation, measurement, and sensitivity

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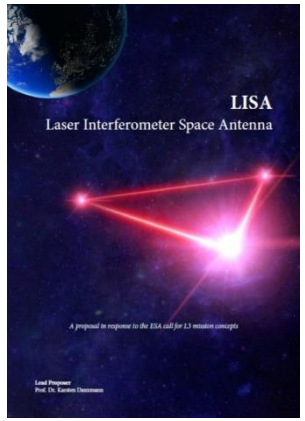
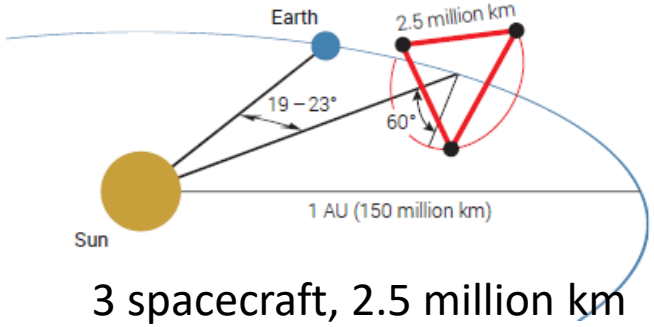
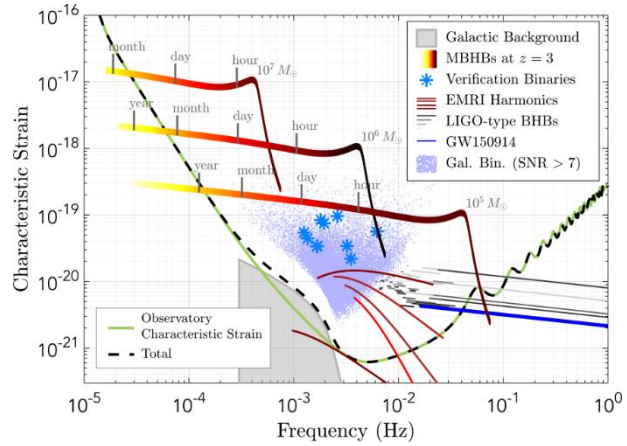


Adopted 2024
Launch 2035



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



0.1 mHz to 1 Hz (required)
(LPF demo at 0.02 mHz)

International School in Gravitational Wave Detection Technology
Erice, 21 May 2026

Rough outline

LISA experimental challenge: measurement and science, why space

Measurement concept (one arm)

Mission and constellation

Three experimental pillars and three main noise sources:

- laser interferometry metrology
- time-delay interferometry
- free-falling test masses and drag-free control

see Gudrun Wanner!

see Lorenzo Sala!

Why do we think it will work (experimental heritage)

LISA data (1 slide)

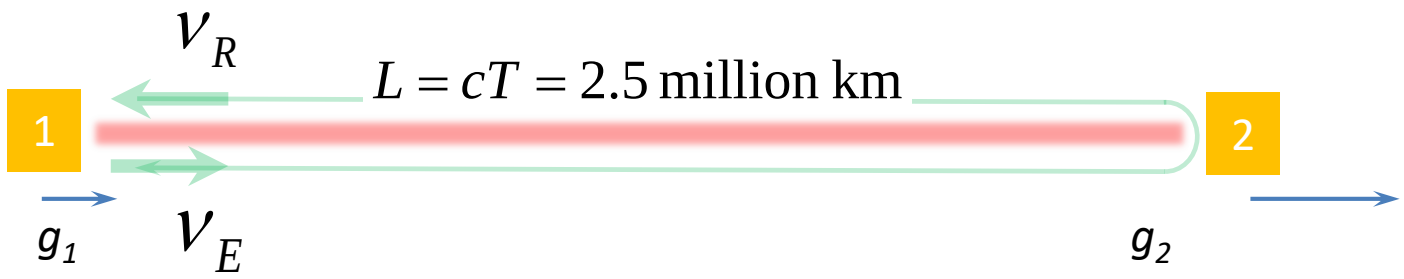
see Riccardo Buscicchio!

After LISA ...

GW observation as time-delayed Doppler gravity gradiometer

- Exchange of light beam between free-falling observers (light travel time ***T=L/c≈8.5 s***)
- 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

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

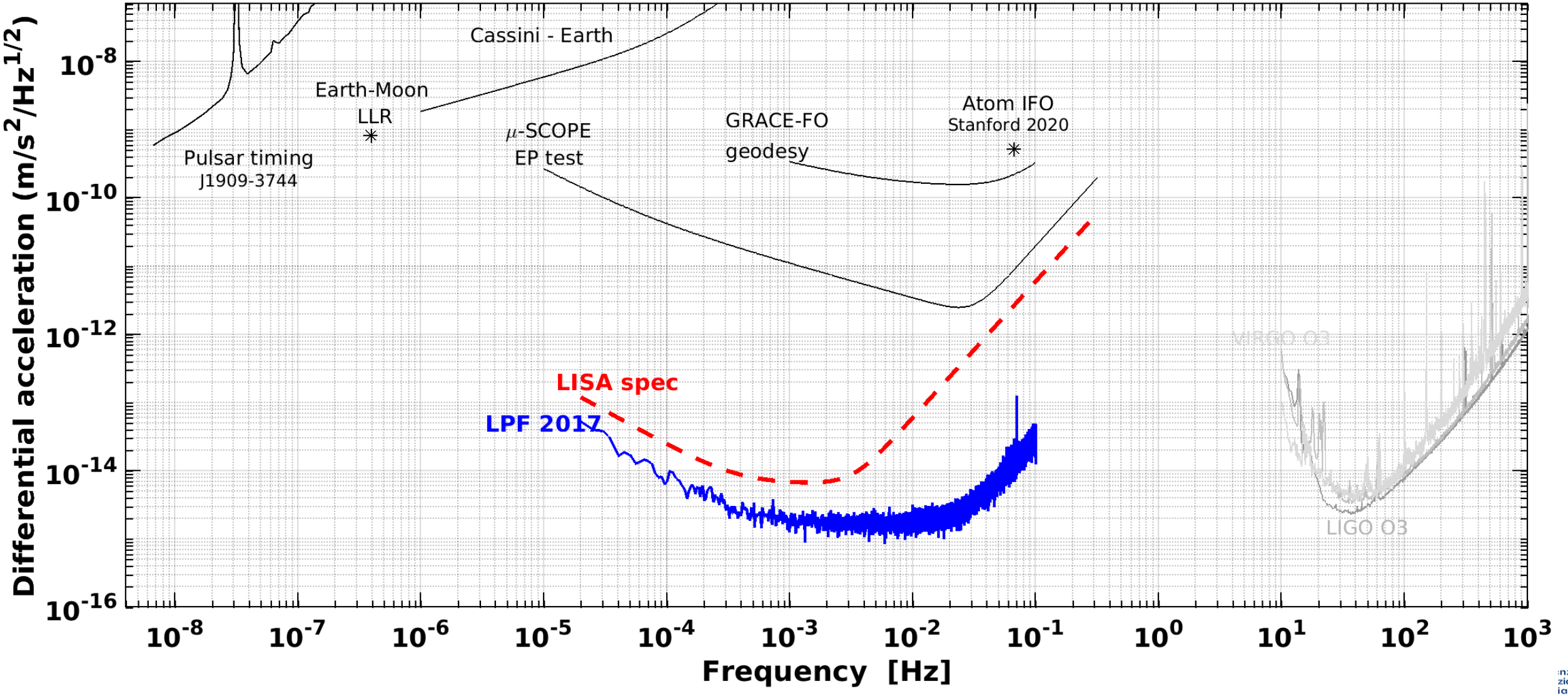
Phase/frequency measurement noise

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

laser freq noise

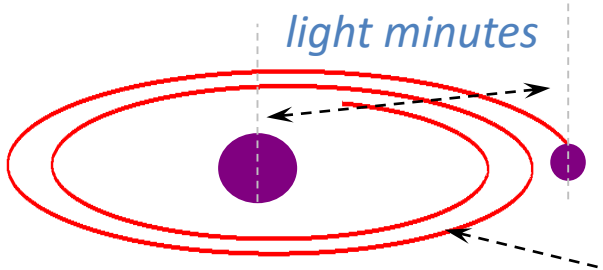
- LISA is made of three such single-arm measurements
- laser frequency noise removed with 2 arms + TDI

Differential accelerometer sensitivity in experimental gravitation

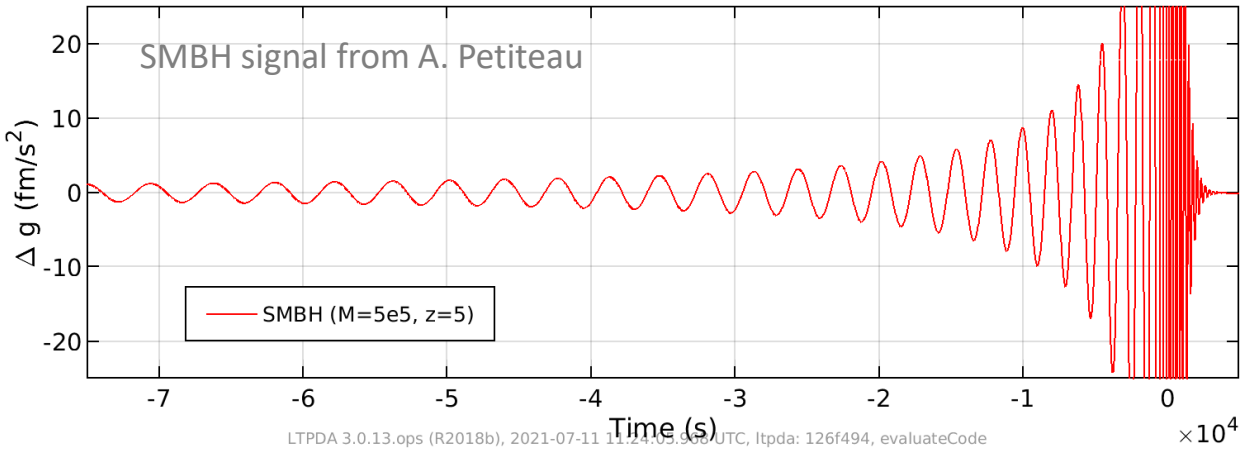


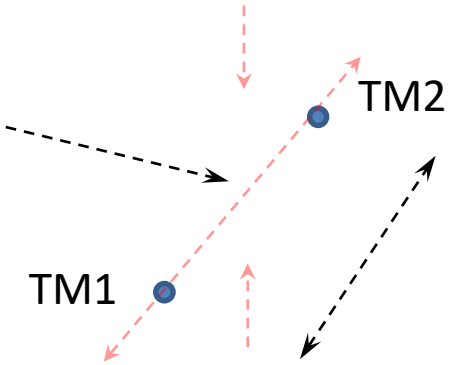
LISA experimental challenge:

- detect sub-fm/s^2 tidal accelerations from distant super massive black hole merger (in this case 500000 solar masses)
  - constellation of free-falling test masses as «antenna»
  - laser interferometer as Doppler gravity-gradiometer



$D_L \approx 10^{11}$ light year





2.5 million km
8.3 light seconds

LISA experimental challenge:

- detect sub-fm/s^2 tidal accelerations from distant super massive black hole merger (in this case 500000 solar masses)
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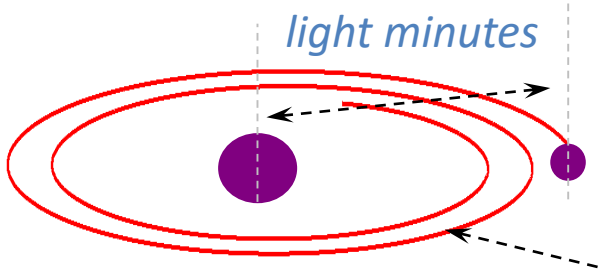
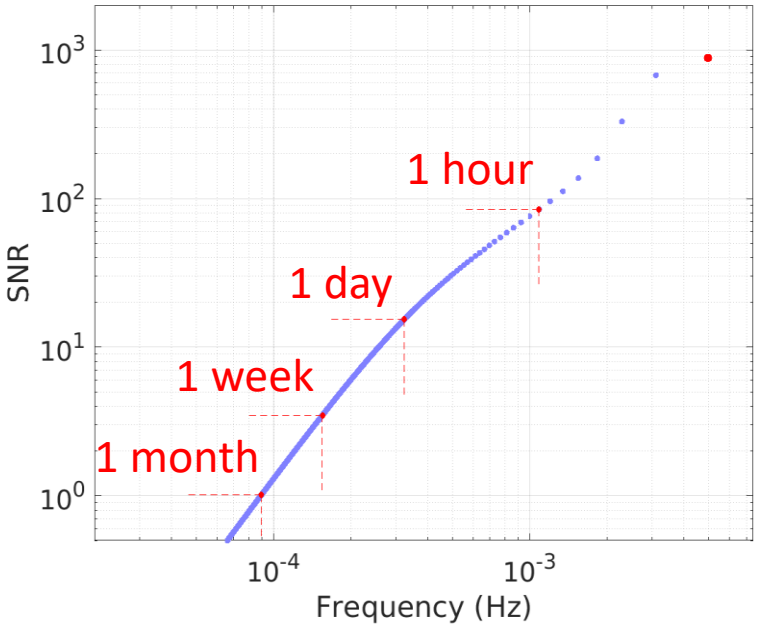
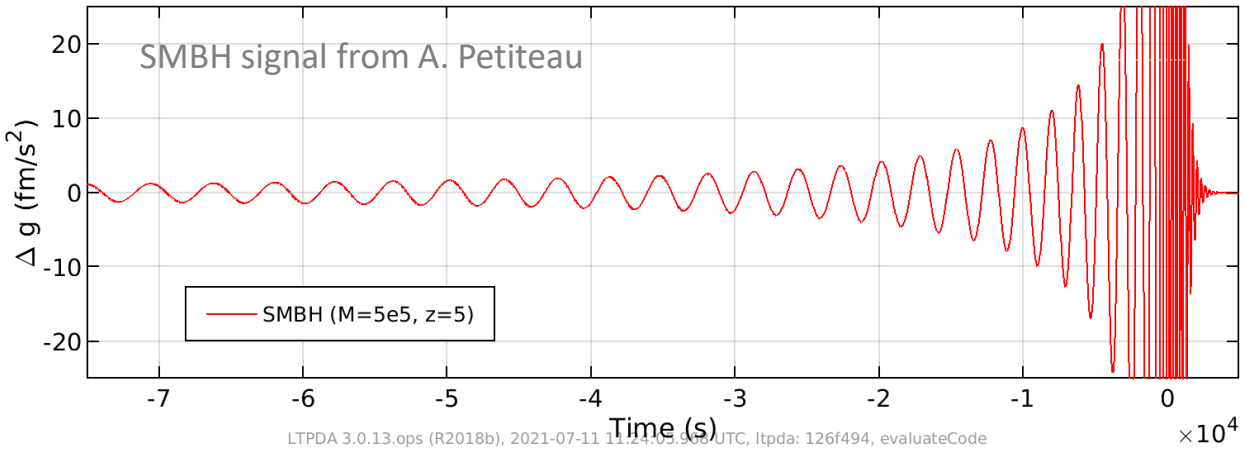
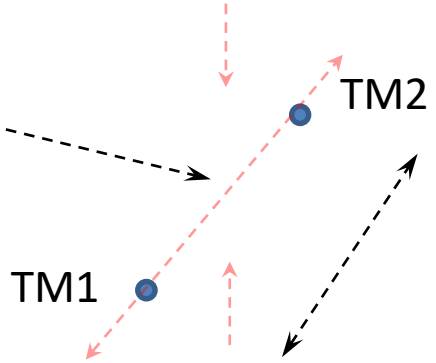




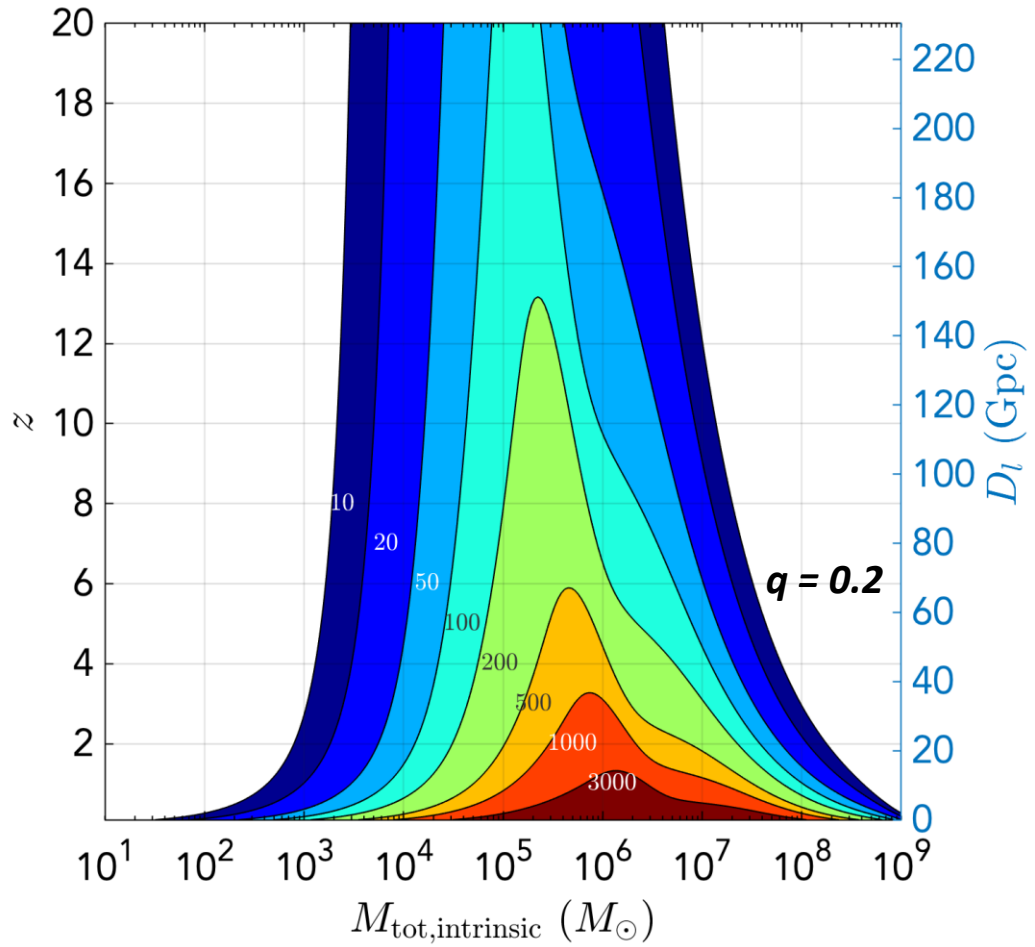
$D_L \approx 10^{11}$ light year





2.5 million km
8.3 light seconds

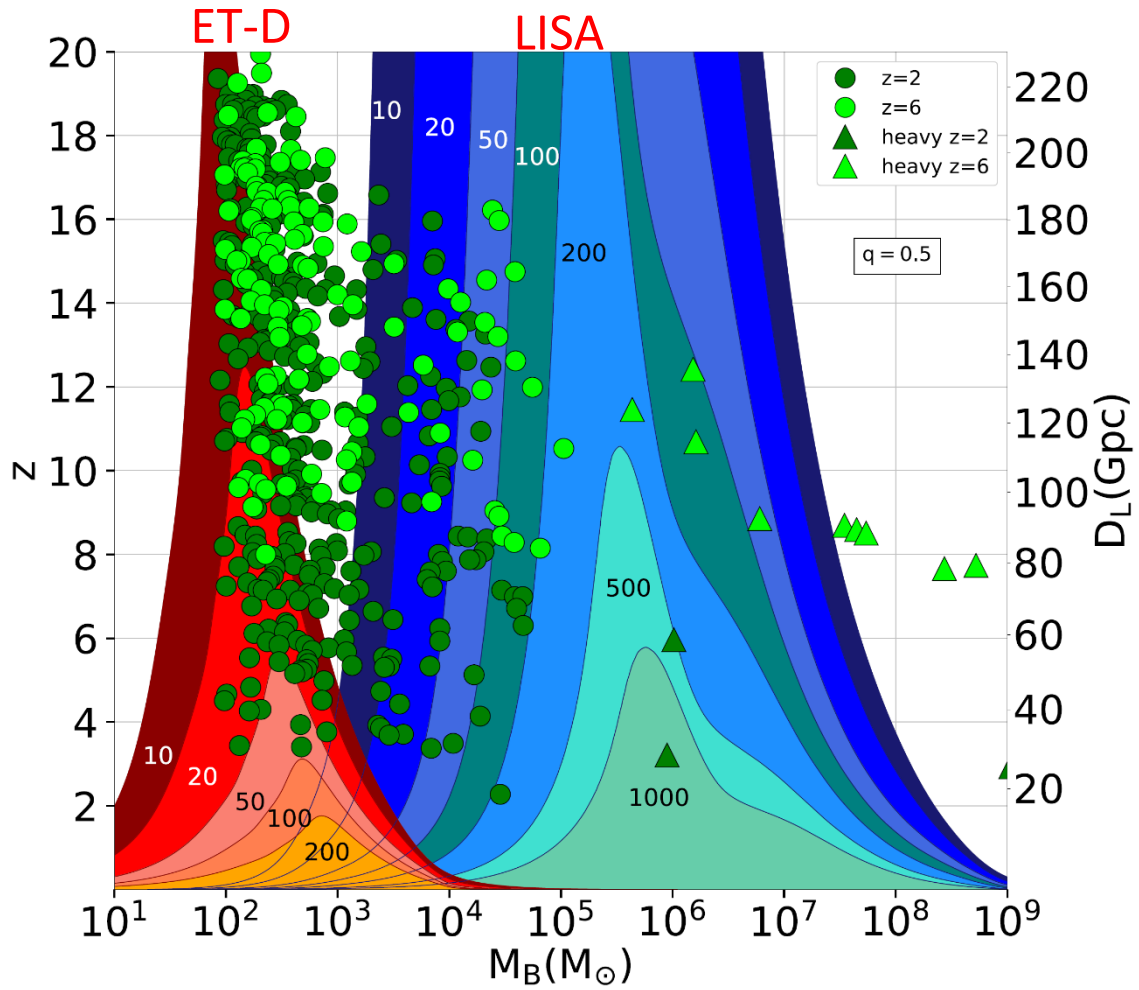
LISA black hole merger reach and resolution



- 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 – ET SMBH survey



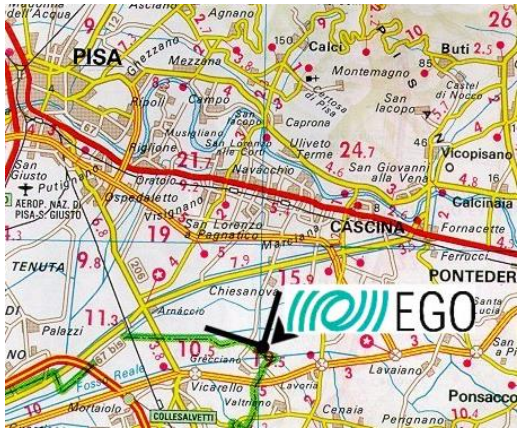
Between LISA and ET cover entire merger range of «seed» black hole scenarios out to z = 10-20

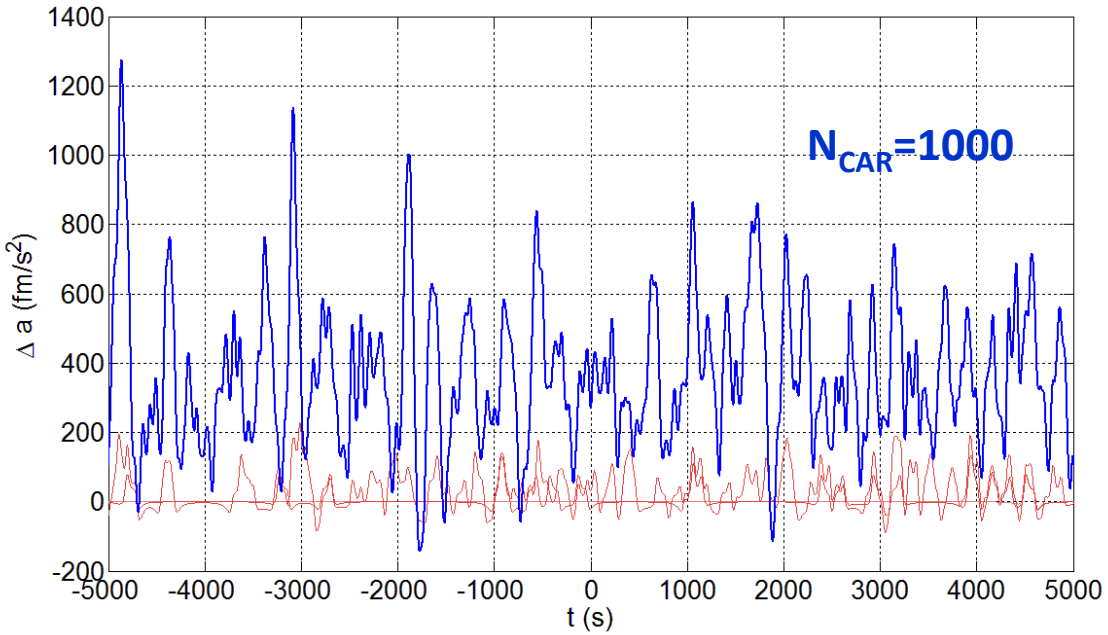
[Colpi + Valiante, in preparazione]

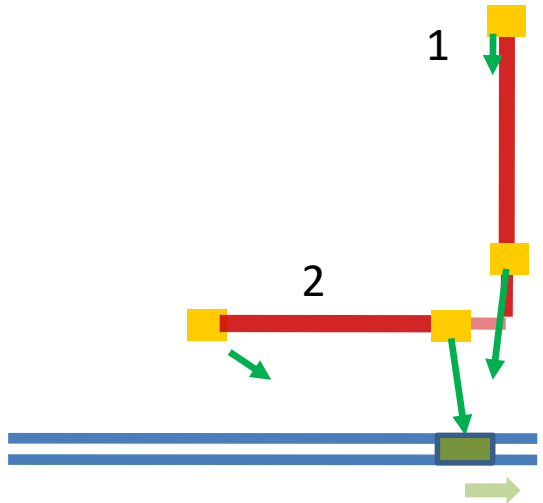
Going to low frequencies requires space:

«Newtonian noise» gravity gradients overwhelm astrophysical strain below 1 Hz

Example:
VIRGO and cars on the Fi-Pi-Li







NB: NS – NS centro galassia

Crea Δa = 5 10^{-3} fm/s^2 a 0.1 Hz

Δa = 2 10^{-5} fm/s^2 a 0.01 Hz

→ Newtonian noise climbing steeply below 1 Hz
→ cars aren't the real problem: moving mass of oceans, air, and Earth crust are

→ **gravitational observation below 1 Hz requires an observatory far from the Earth**

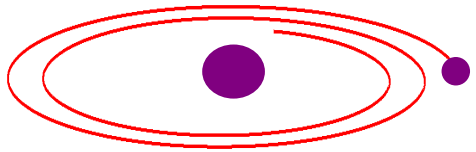
Why space? → Why low frequencies?

- **sources «dwell in band» much longer at low frequencies**
  → many more sources at low frequencies

$$\tau \equiv \frac{1}{\frac{1}{f_{GW}}\frac{df_{GW}}{dt}} \propto f_{GW}^{-8/3}$$

NS-NS

1 mHz → 3 mHz in 1 million years
10 mHz → 30 mHz in 3000 years
1 Hz → 3 Hz in 5 days
100 Hz → 300 Hz in 2 s



order 100 NS-NS in Milky Way mHz band

- **Massive sources merge before entering 1 Hz band**

→ compact objects “touch" for $f_{GW} < 1$ Hz

Ex: 2 black holes with mass M_{BH}

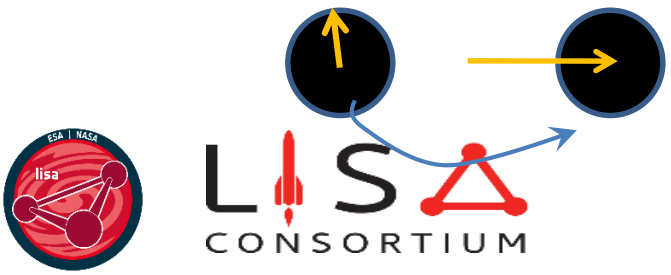
$$R_{BH} = \frac{2GM_{BH}}{c^2} \qquad R_{ORB} = \left(\frac{G(2M_{BH})}{\omega_{ORB}^2}\right)^{1/3}$$

«Touch» for $R_{ORB} = 2\,R_{BH}$

$$f_{GW} = \frac{\omega_{ORB}}{\pi} < \frac{c^3}{8\pi G M_{BH}}$$

1 solar mass f_{MAX} = 8 kHz
10^6 solar mass f_{MAX} = 8 mHz

10^6 solar masses requires mHz band (and thus space)



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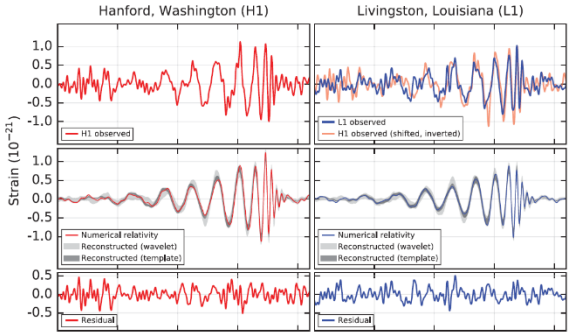
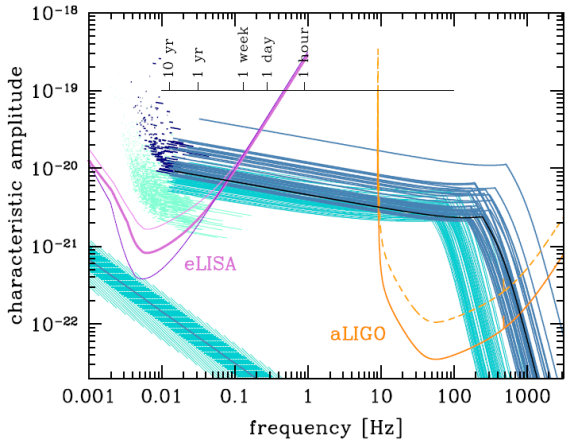
LIGO 30 $M_\odot$ binaries – observable by LISA (5-15 years pre-merger)



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 could have detected this (with low SNR)

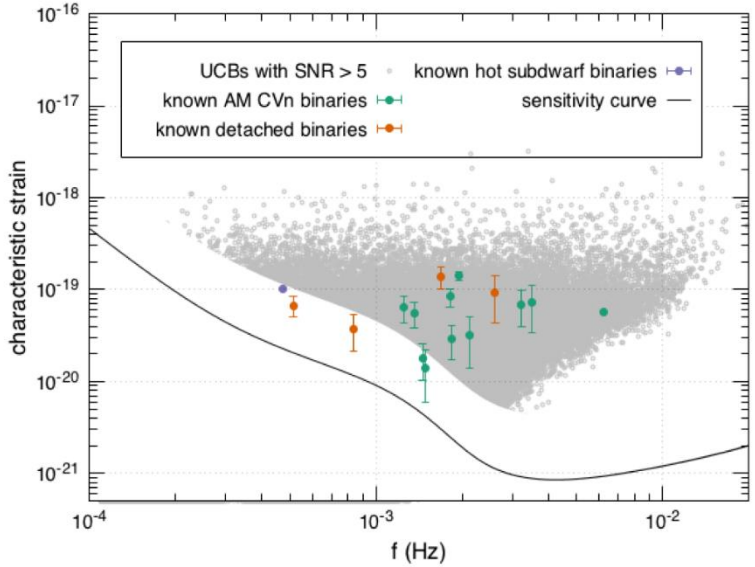
- 5-10 years pre-merger, 10-20 mHz

[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 galactic «Ultra Compact Binaries» survey



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

[SNR for 4 year mission]

Survey with > 10000 resolvable galactic binary signals

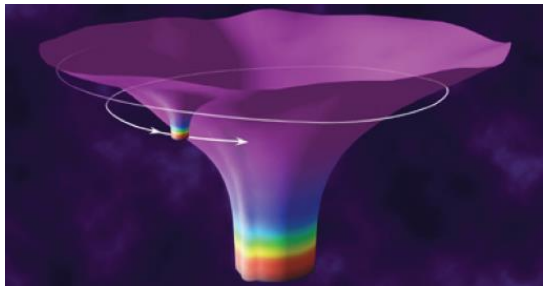
- Includes ***all*** galactic UCB with f > 5 mHz
- Resolvable in first weeks of mission, some to within 1 degree on sky
- Many chirping – **ΔP/P > 1 ppm** – some non-GR
- > 100 expected to be observable optically
- > 11 known «calibration» binaries with SNR > 20 in 4 years (GAIA distances 5-10%)

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

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

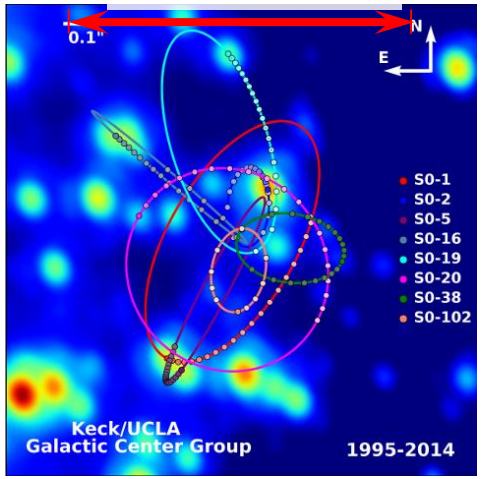
→ 10^6 “frequency bins” below 10 mHz

A test particle orbiting a massive black hole



Stars around Milky Way center

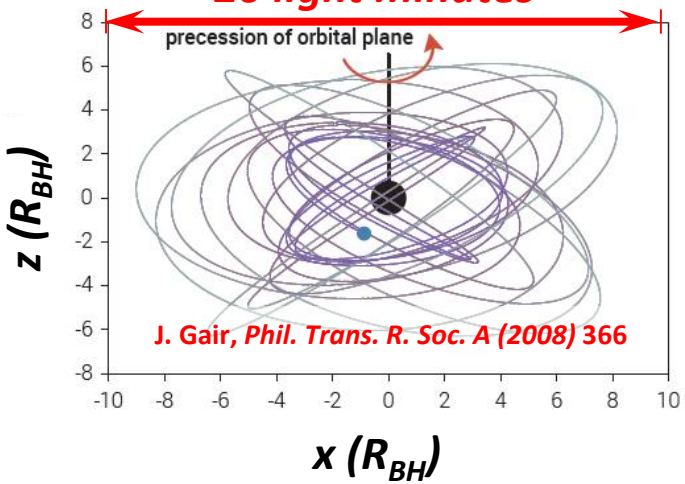
50 light days



- periods ~ 10 year
- R_{ORB}~ light days
- Observe Milky Way

Stellar mass black hole around massive black hole

20 light minutes

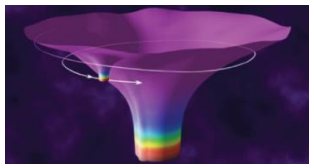


- Orbital period 10s of minutes
- R_{ORB} ~ light minutes
- ***Beyond Milky Way***

Extreme mass ratio inspiral (EMRI)

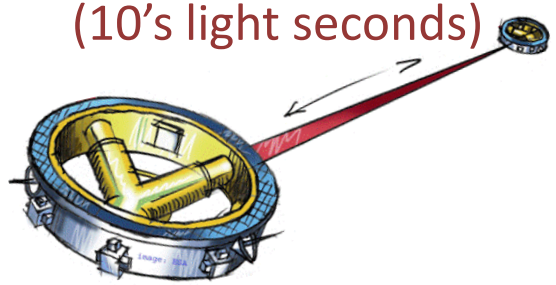
Experimental challenge:

Measure the gravity gradient produced by black hole binary 10^9 light years away



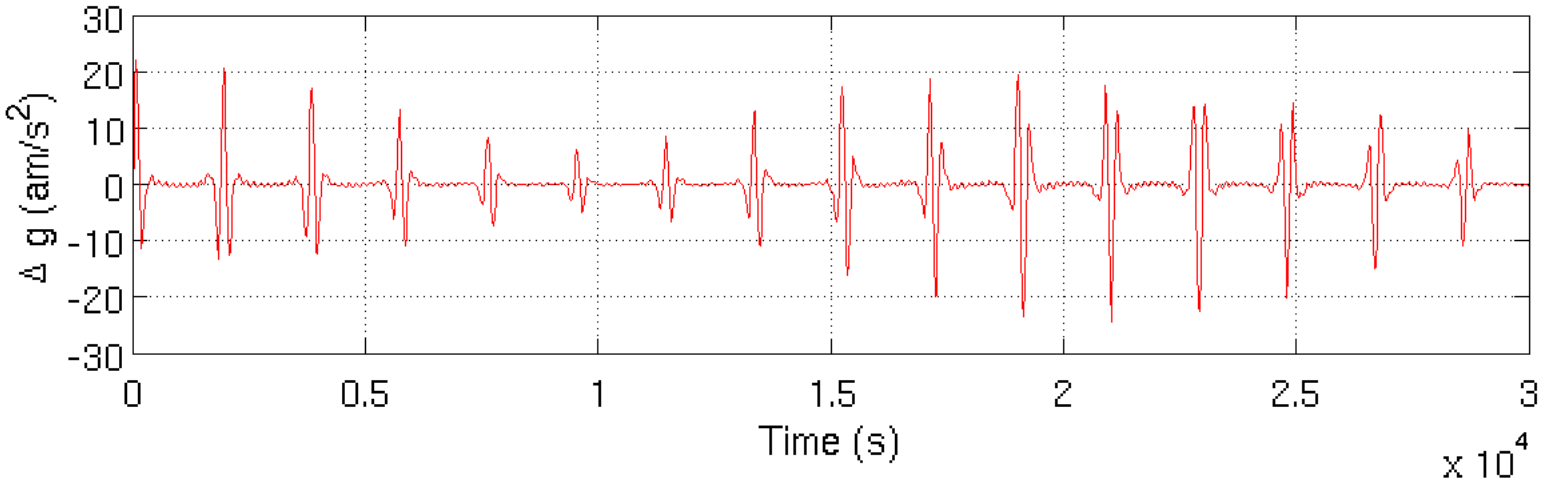
10^9 light years

Several 10^9 m
(10's light seconds)



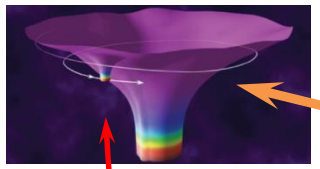
Our signal:

Gravitational tidal acceleration ~10^{-16} m/s^2 at mHz
between 2 test particles separated by millions km



Experimental challenge:

Measure the gravity gradient produced by black hole binary 10^9 light years away



$$h \approx \frac{R_{BH1} \times R_{BH2}}{r \times R_{ORB}}$$

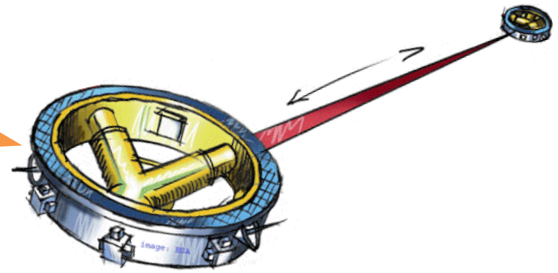
"little" BH2 at event horizon of BH1

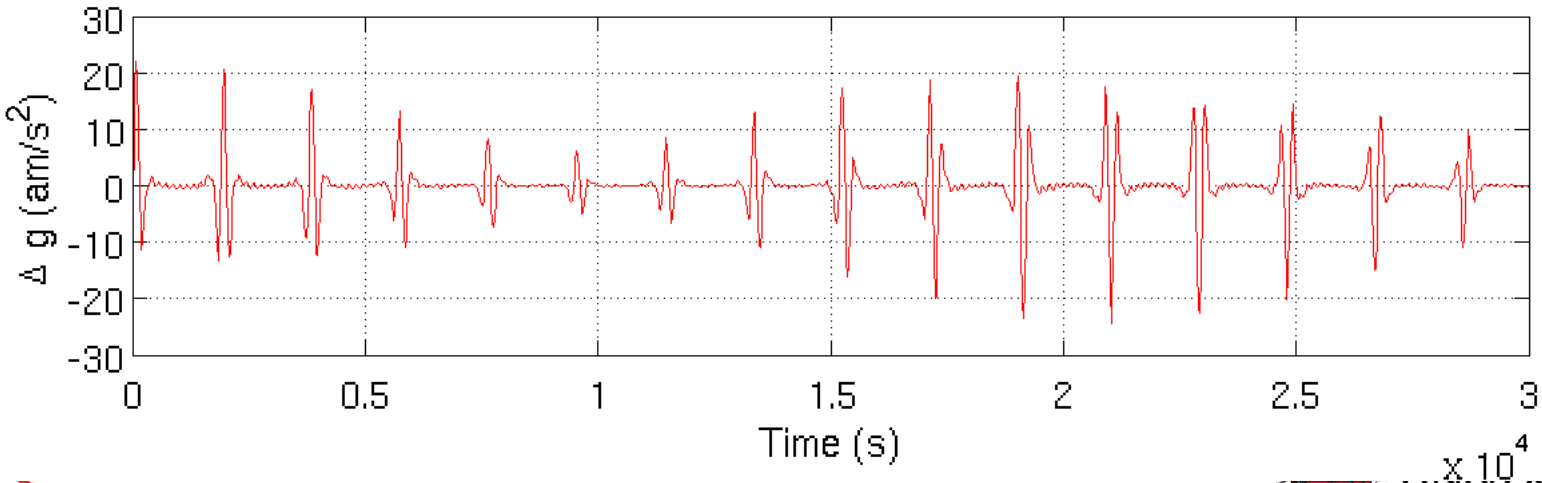
$$R_{ORB} \approx R_{BH1}$$

$$h \approx \frac{R_{BH2}}{r}$$

r

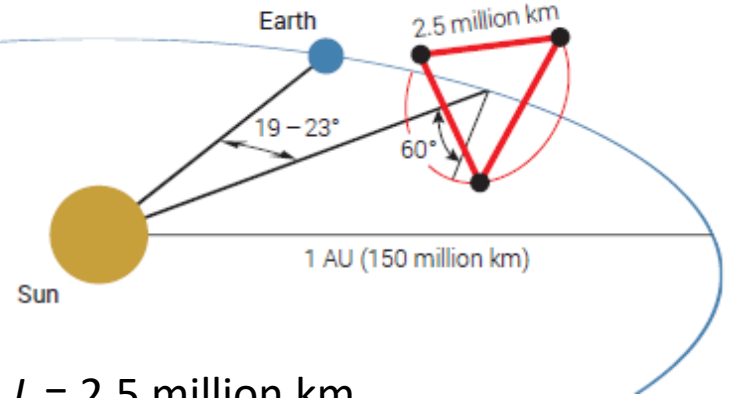
$$R_{BH2} = \frac{2GM_{BH2}}{c^2}$$



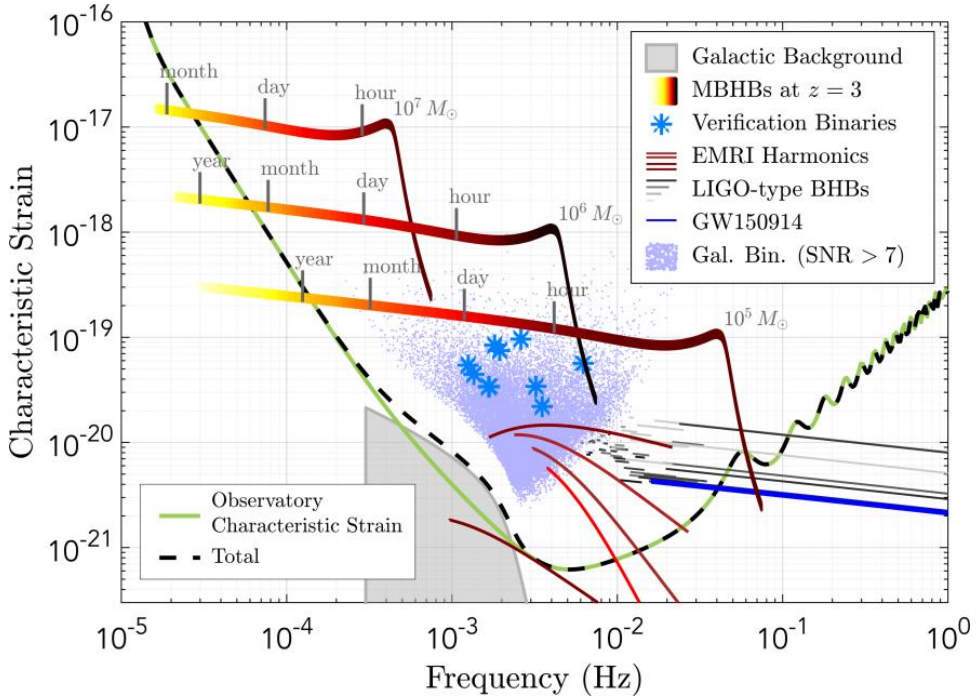


LISA: Laser Interferometer Space Antenna

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$^{1/2}$**



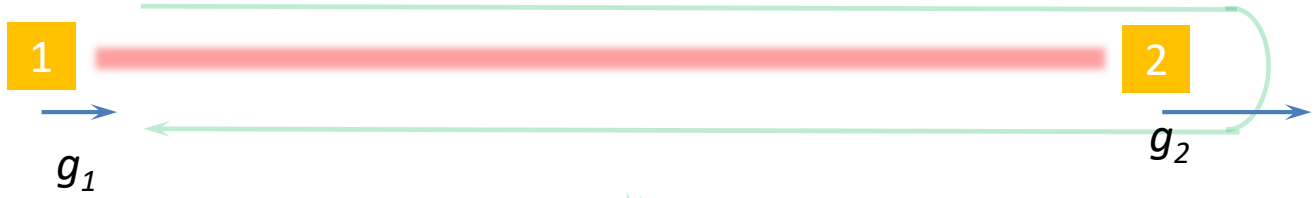
- 3 arms (6 one-way links), *L* = 2.5 million km
  - 2 Michelson combinations and a «null channel»
- free-falling TM, no suspension
  - orbital tidal accelerations μm/s², GW fm/s²
  - spacecraft drag-free control
- «open-loop» laser interferometry
  - Δv 10 m/s → 10 MHz fringe rates (GW μHz modulation)
- 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

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, amplifies (phase coherent) and sends back
- O1 interferes incoming light with local beam, measures «beat frequency» between received and emitted beams:

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

- NB LISA is made of three such arm measurements



Laser frequency is noisy (variation in ν_{1E})

Measurements of beat frequency noisy (ν_{n1}, ν_{n2})

GW strain **stray acceleration**

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

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

Time derivative of beat frequency

laser freq noise

Phase/frequency measurement noise

GW observation as time-delayed Doppler gravity gradiometer

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

Ignoring laser frequency noise:

- "intrinsic" limit from phase noise and TM acceleration noise (cannot be subtracted)

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

Fourier transform

$$\frac{j\omega}{\nu}\Delta\tilde{\nu} = \omega \sin\omega T\, \tilde{h} \exp - j\omega T + \frac{2}{c}\left[\tilde{g}_1 \cos\omega T - \tilde{g}_2\right]\exp - j\omega T + \frac{j\omega}{\nu}\left[\tilde{\nu}_{1n} + \tilde{\nu}_{2n} \exp - j\omega T\right]$$

GW observation as time-delayed Doppler gravity gradiometer

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

Fourier transform

$$\frac{j\omega}{\nu}\Delta\tilde{\nu} = \omega \sin\omega T\, \tilde{h} \exp -j\omega T + \frac{2}{c}[\tilde{g}_1 \cos\omega T - \tilde{g}_2]\exp -j\omega T + \frac{j\omega}{\nu}[\tilde{\nu}_{1n} + \tilde{\nu}_{2n} \exp -j\omega T]$$

Resulting noise for gravitational waves:

- assumes 2 equal noise TM
- equal noise phase measurements (converted into displacement)

$$\frac{j\omega\tilde{\nu}_{1n}}{\nu} = -\frac{\omega^2}{c}\tilde{x}_{IFO}$$

$$S_h = \frac{S_{\Delta\nu}}{\left|\frac{d\Delta\nu}{dh}\right|^2}$$

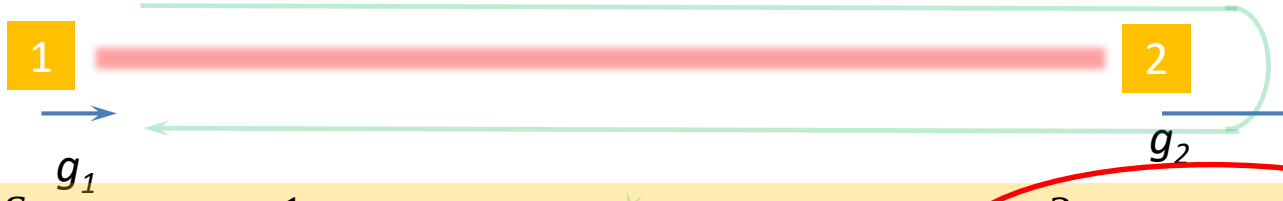
$$\approx \frac{1}{\left(\omega^2 L \frac{\sin\omega T}{\omega T}\right)^2}\left[4S_g\left(1+\cos^2\omega T\right)+2\omega^4 S_{IFO}\right]$$

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

Low frequency

$$\omega T << 1$$

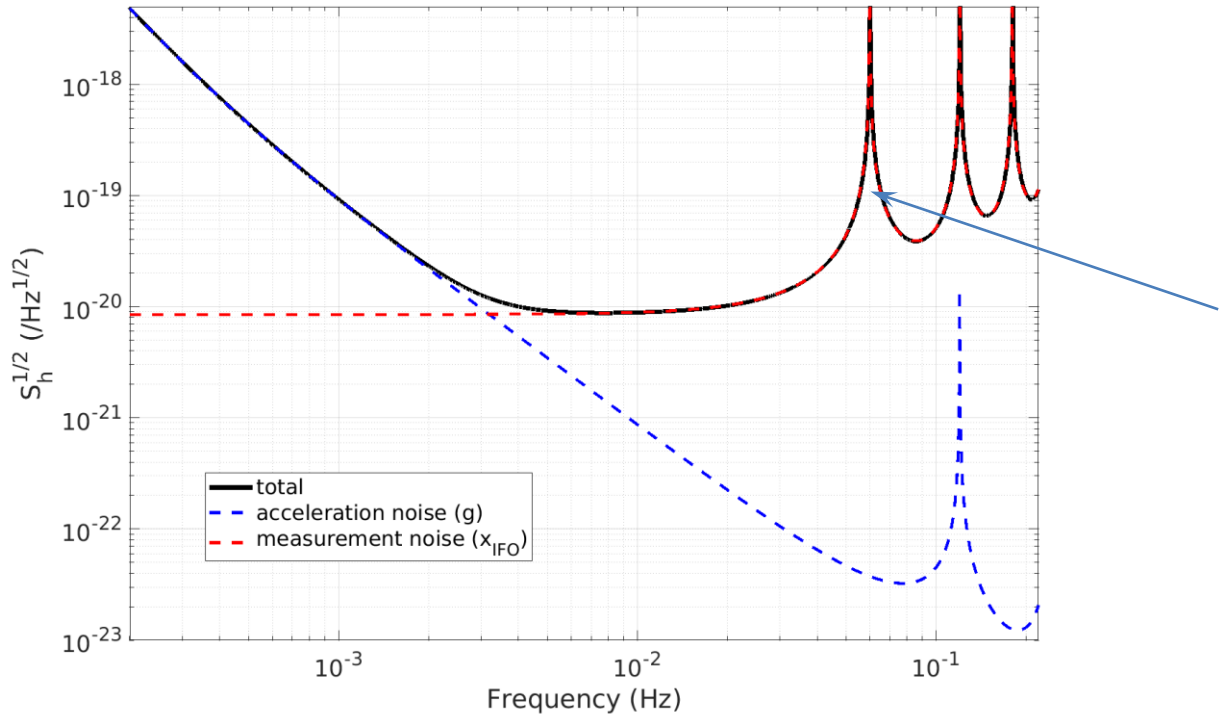
GW observation as time-delayed Doppler gravity gradiometer



$$S_h = \frac{S_{\Delta\nu}}{\left|\frac{d\Delta\nu}{dh}\right|^2} \approx \frac{1}{\left(\omega^2 L \frac{\sin\omega T}{\omega T}\right)^2}\left[4S_g\left(1+\cos^2\omega T\right)+2\omega^4 S_{IFO}\right] \approx \frac{2}{\omega^4 L^2}\left[4S_g+\omega^4 S_{IFO}\right]$$

Low frequency approx

$$\omega T << 1$$

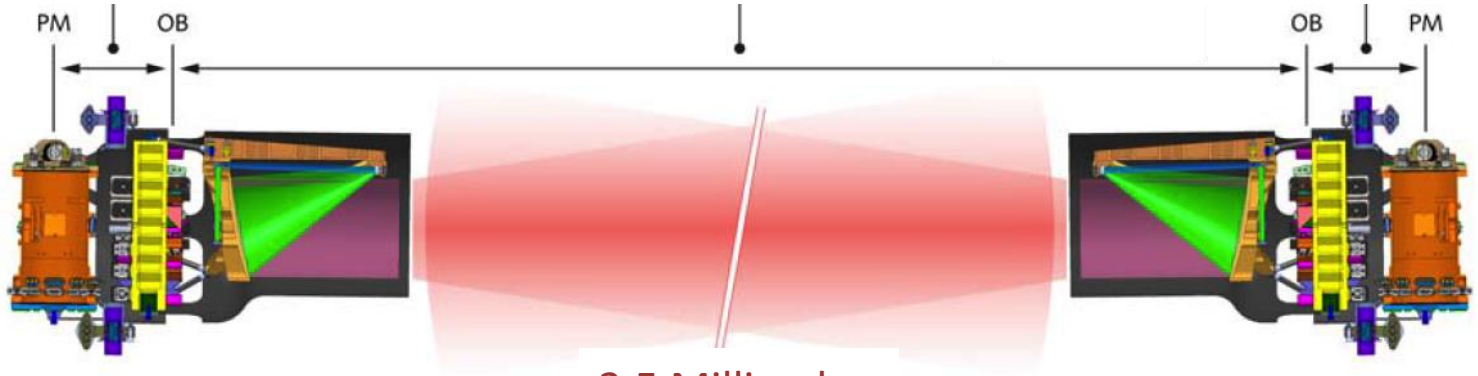


Lose sensitivity at

$$2fT = n$$

Strain sensitivity cancels out in outgoing/return photon trip
[60 mHz = 1/(17 s)]

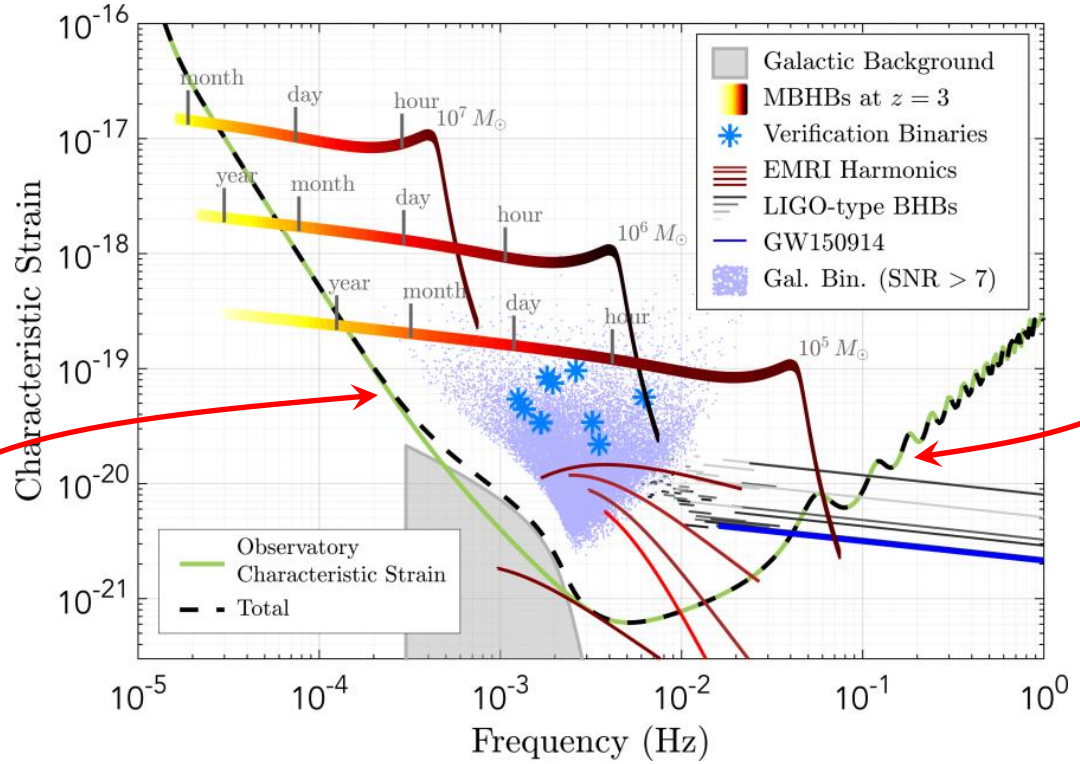
LISA measurement concept and sensitivity



2.5 Million km

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

- 3 parts: TM-SC, SC-SC, SC-TM
- Time delay interferometry
- Drag-free SC



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

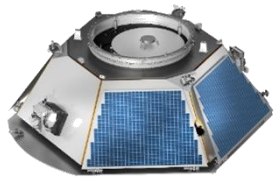
High freq limit:
Interferometer readout noise, 15 pm/Hz$^{1/2}$

Weber- Erice-20260521

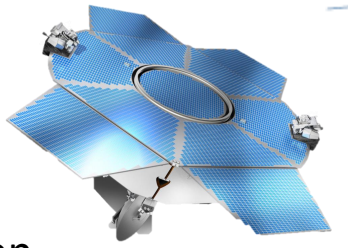
LISA: 2nd ESA Cosmic Vision Large Mission

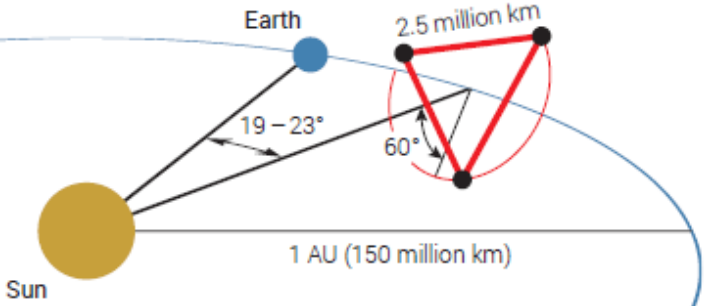
Ariane 6.4

Launch into Earth orbit



separation
18 mo. xfer phase (x3)
solar electric propulsion





ESA: mission lead and system prime

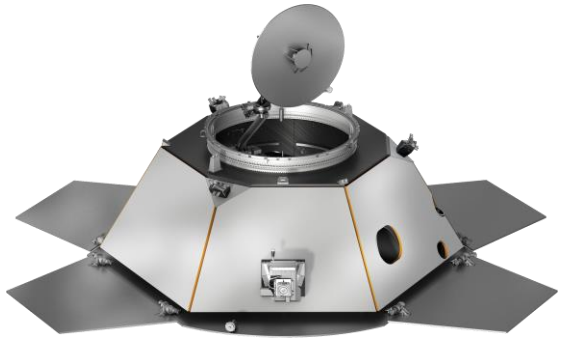
- spacecraft (x3) + payload items
- launch, transfer, communications, propulsion, SC control ...
- mission and science operations
- guarantees mission performance

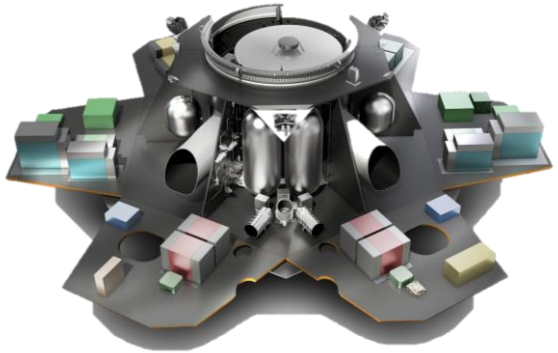
6 months commissioning + calibration

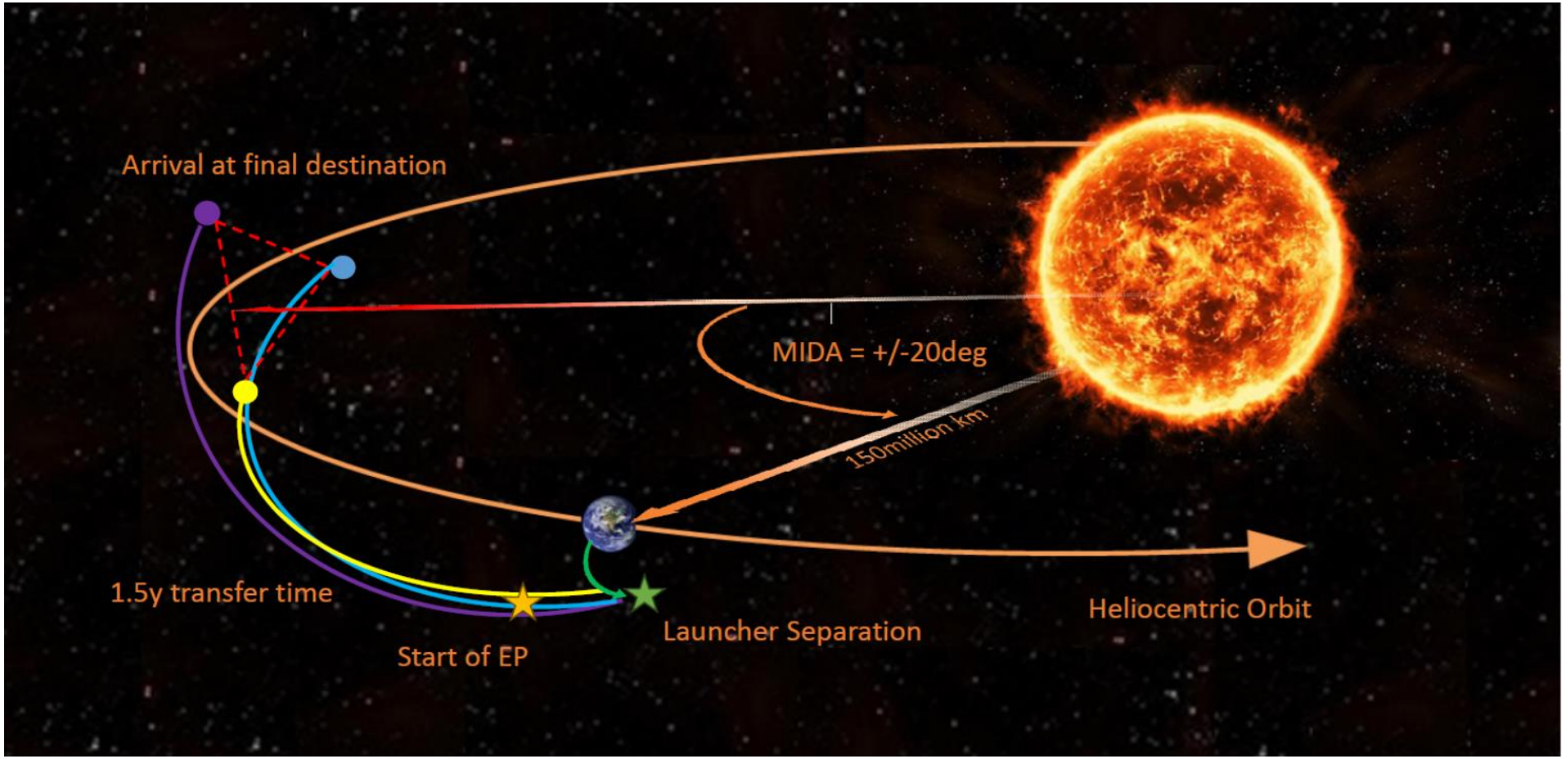
Orbits, fuel tanks for 11 years on orbit

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

4 Hz science data // 150 kbit/s



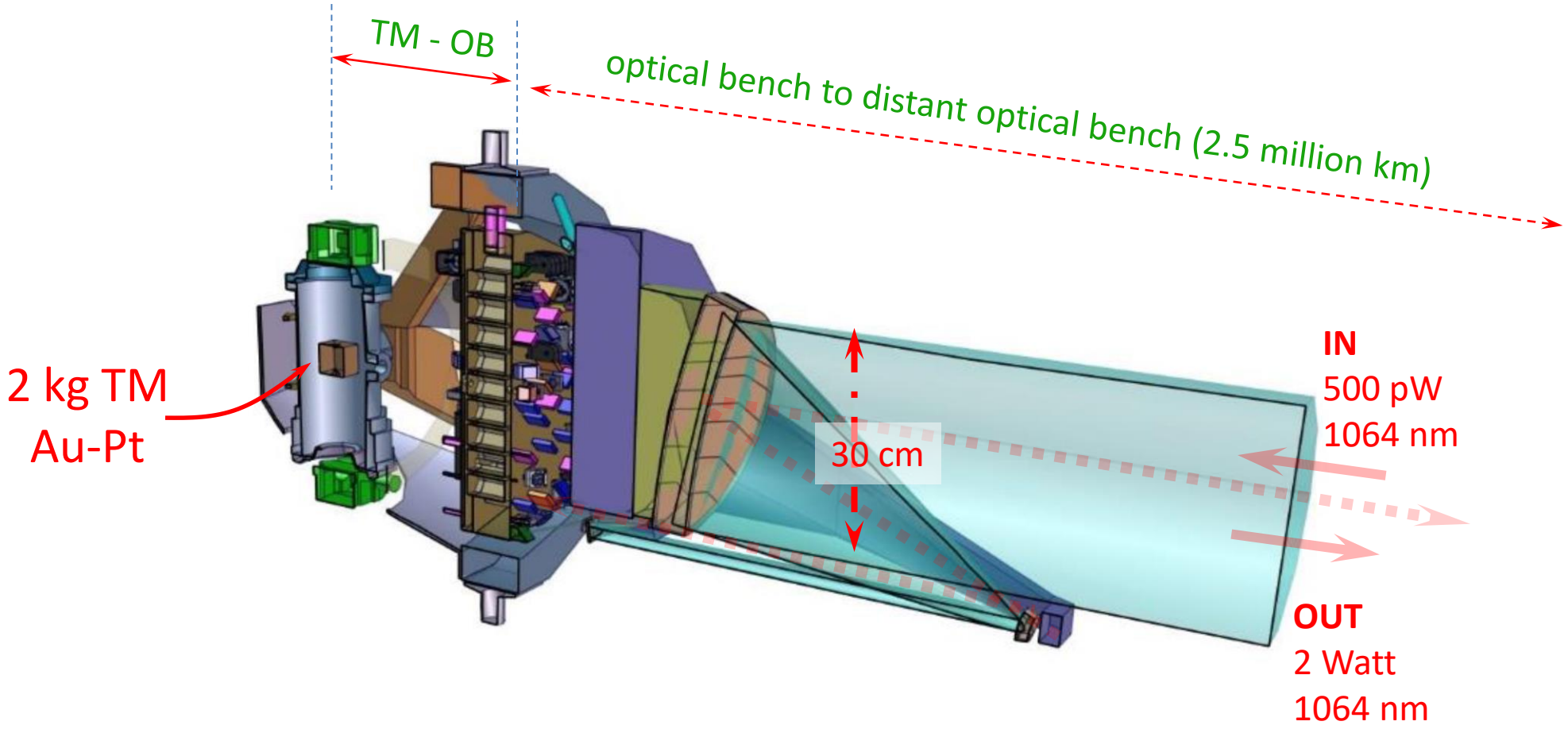



Arrival at final destination
MIDA = +/-20deg
150million km
1.5y transfer time
Start of EP
Launcher Separation
Heliocentric Orbit

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 «interferometer end-station»

Optical metrology esa

Optical bench

+ phasemeter

+ laser

Telescope

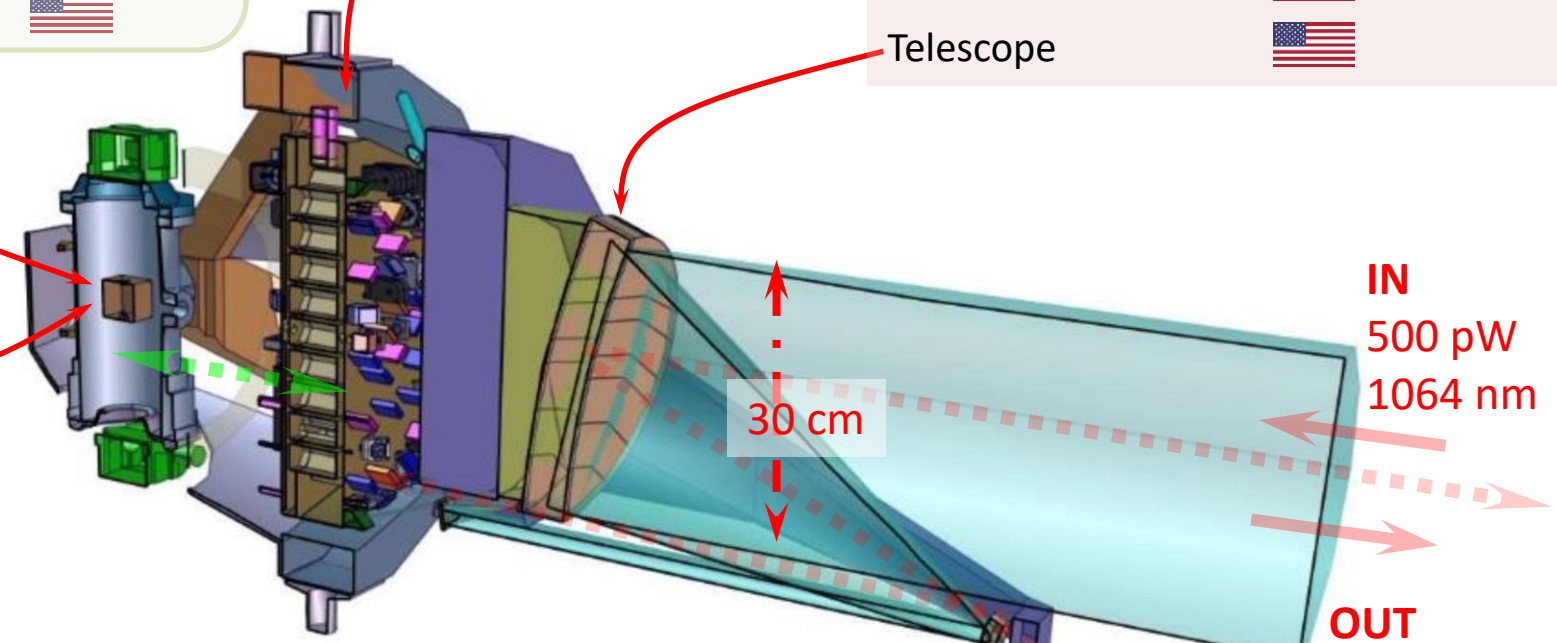
Signal Detection & Processing

Gravitational reference system

GRS head

+ electronics

+ UV light source



2 kg TM
Au-Pt

IN
500 pW
1064 nm

OUT
2 Watt
1064 nm

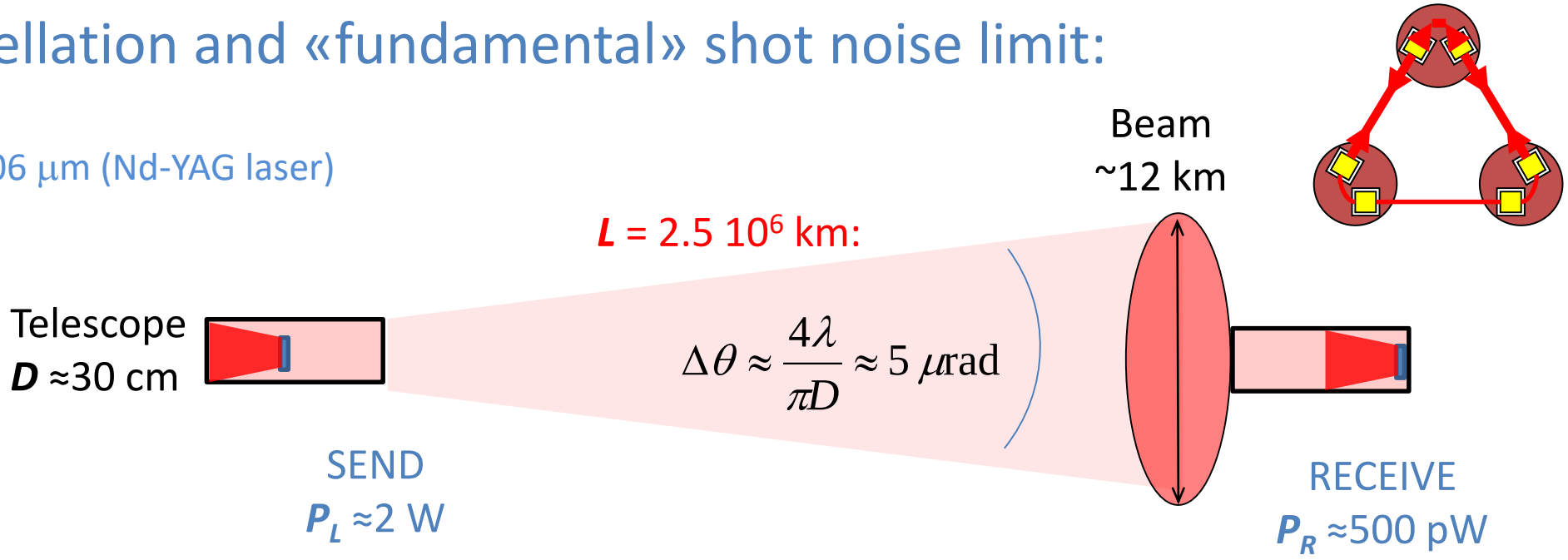
Diagnostics

Optical testing

2 MOSA per each SC

LISA constellation and «fundamental» shot noise limit:

λ = 1.06 μm (Nd-YAG laser)



shot noise: $S_x^{SHOT} \approx \left(\frac{\lambda}{2\pi}\right)^2 \left(\frac{hc}{\lambda P_R}\right)$

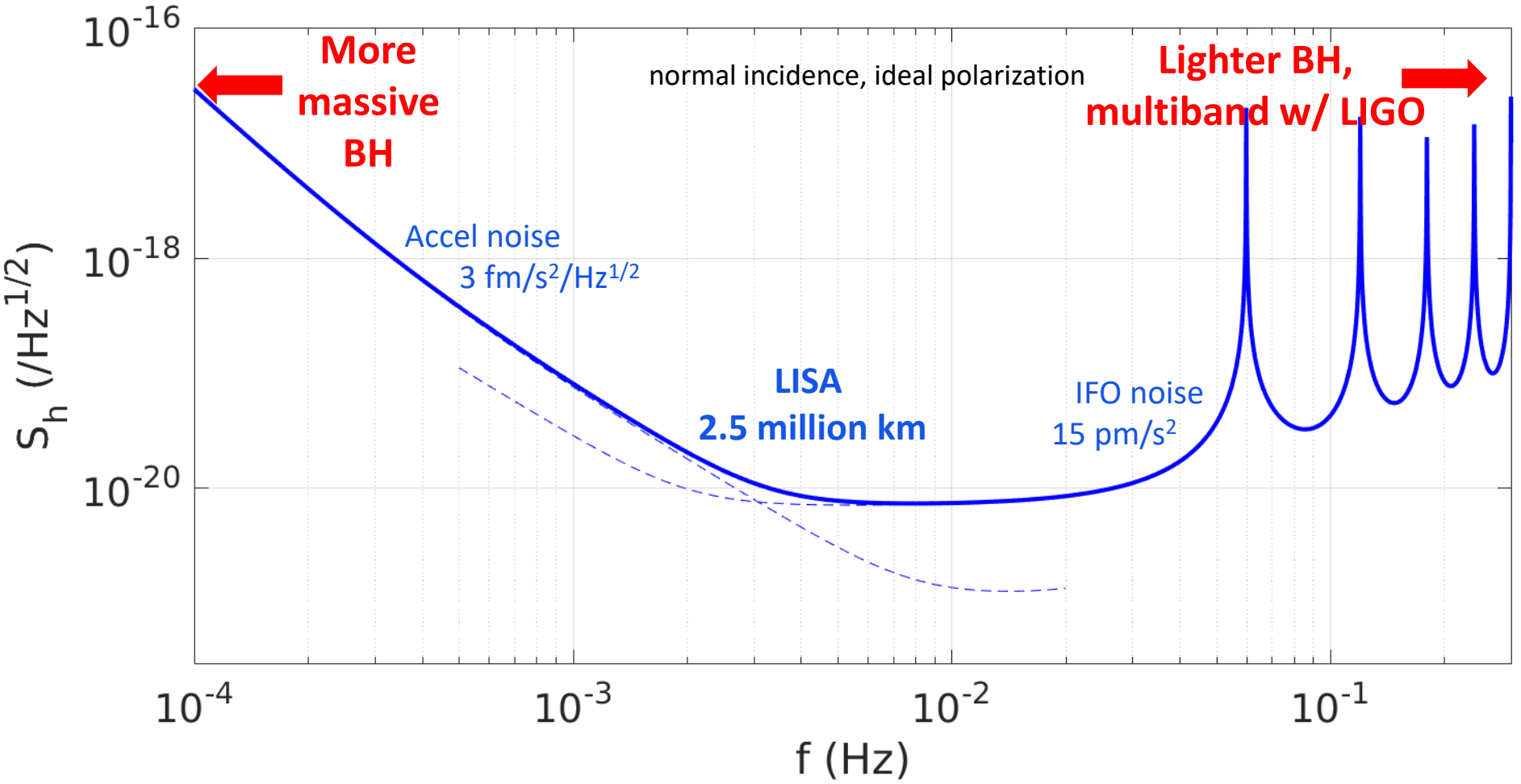
2 W
λ = 1.06 μm YAG
→ 5 pm/Hz$^{1/2}$

- received power ~ D^4 (1 way attenuation 10^{10})
  - gain quickly with a larger aperture telescope

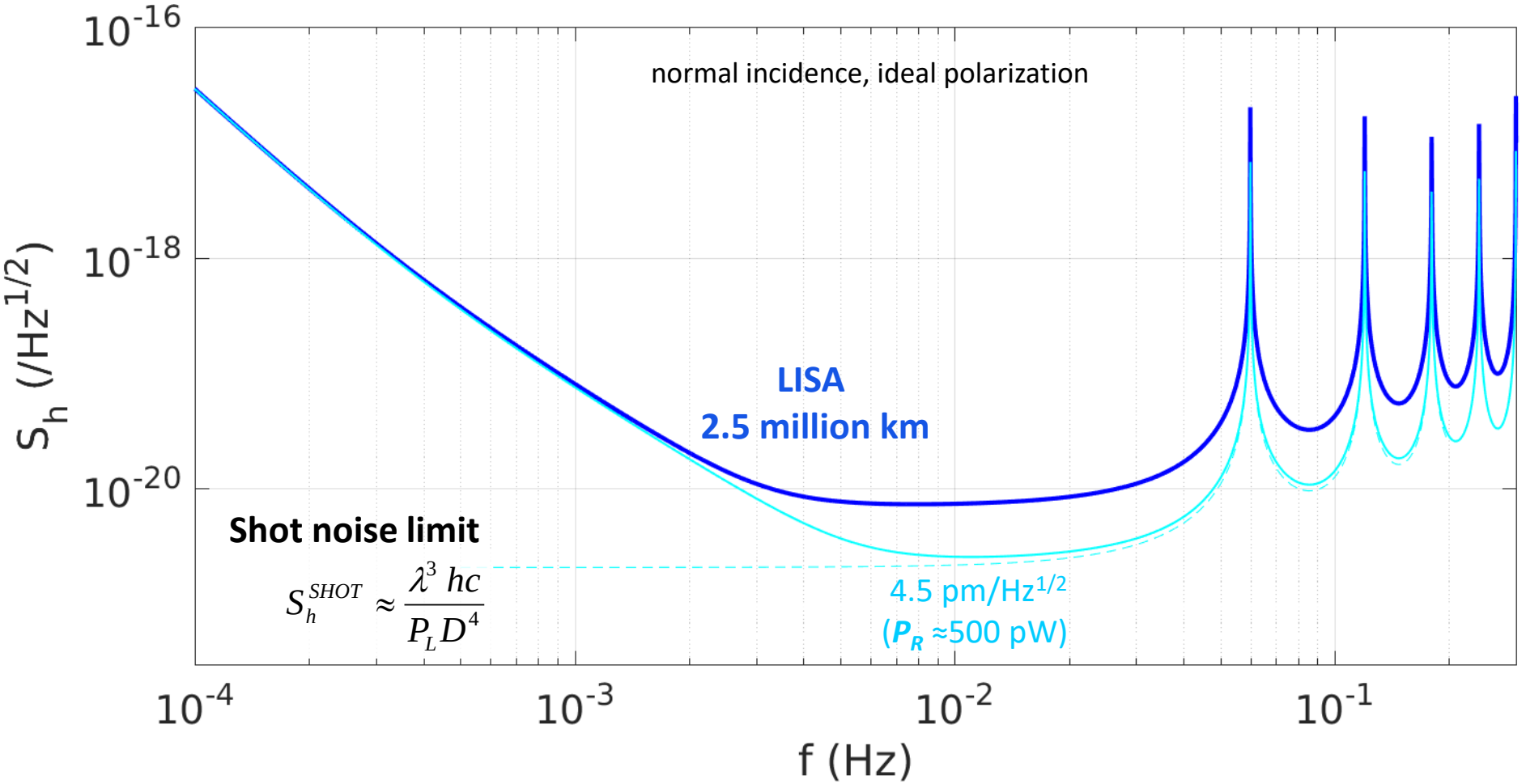
$$P_R \approx P_L \frac{D^4}{\lambda^2 L^2}$$

- reflected beam would be <1 photon / s → need transponder system
  → phase coherent lock / amplification for return beam

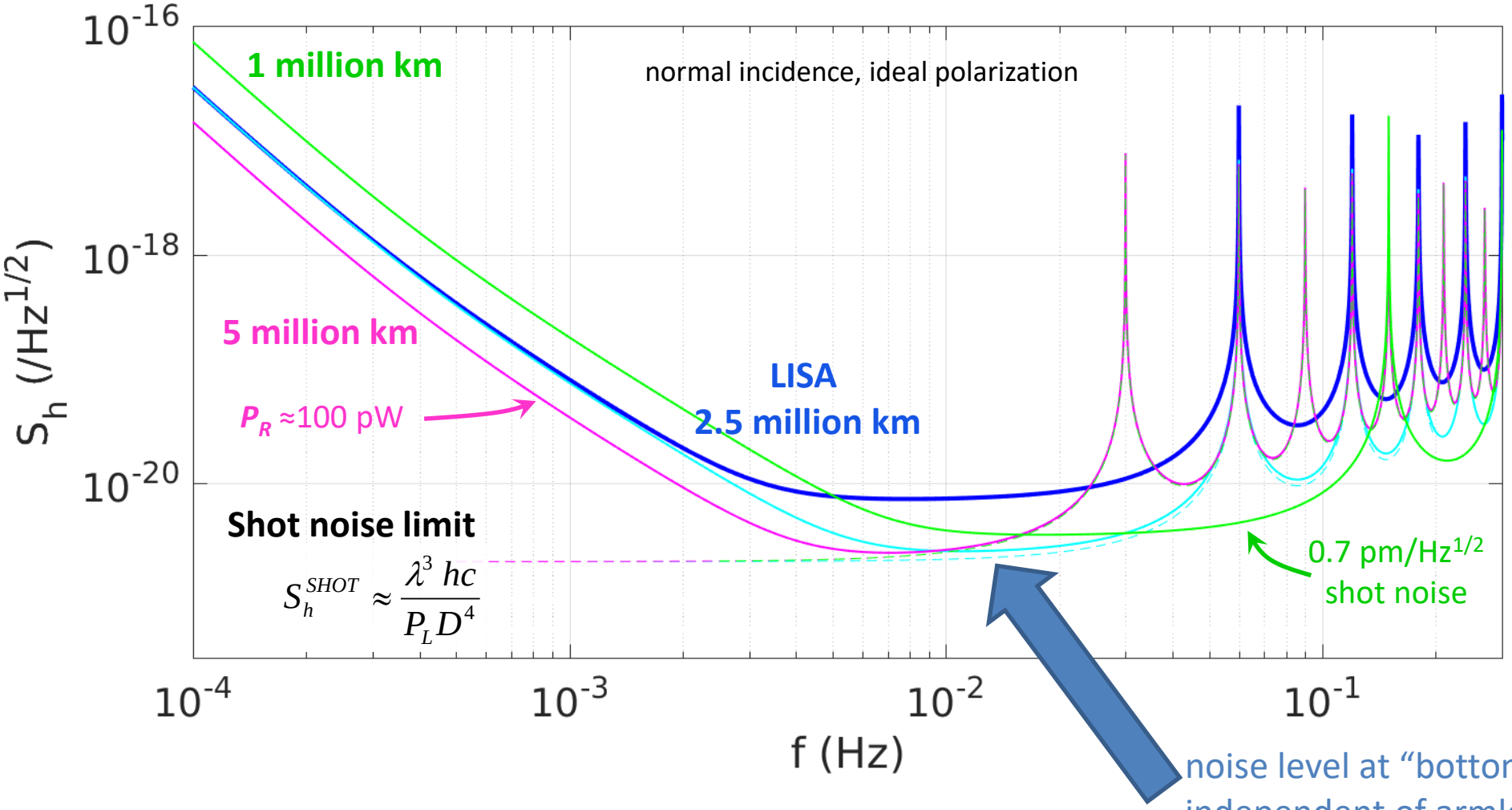
The right size for LISA: why ***L*** = 2.5 million km?



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



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



noise level at “bottom of bucket” independent of armlength

- gain in tidal acceleration signal, but lose in light power

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

- "shot noise limit" noise minimum: independent of length L
  - increased length increases tidal deformation, but we lose light power
  - armlength sets frequency of noise minimum

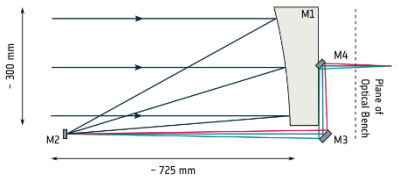
$$S_h^{SHOT} \approx \frac{\lambda^3 hc}{P_L D^4}$$

- 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)

$$S_h^{IFO} \approx \frac{2S_{IFO}}{L^2}$$

one way IFO measurement noise ($m/Hz^{1/2}$)

- improving at high frequencies (shorter ***L***) requires limiting all other IFO noise
  - need to go sub-$pm/Hz^{1/2}$ (10 $pm/Hz^{1/2}$ LISA)
  - coupling to SC motion ($nm/Hz^{1/2}$), mechanical deformation



$$S_{IFO}^{SHOT} \approx \left(\frac{\lambda}{2\pi}\right)^2 \left(\frac{hc}{\lambda P_R}\right)$$

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

- improving at lower frequencies (longer ***L***)
  - longer ***L*** means locking laser with sub-100 pW (order 300 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 ...)

The LISA constellation: a quasi-rigidly rotating quasi-equilateral triangle with Keplerian breathing

Classical orbital dynamics – mostly 2 body Keplerian dynamics – do not produce fully "rigid rotation" of equilateral triangle

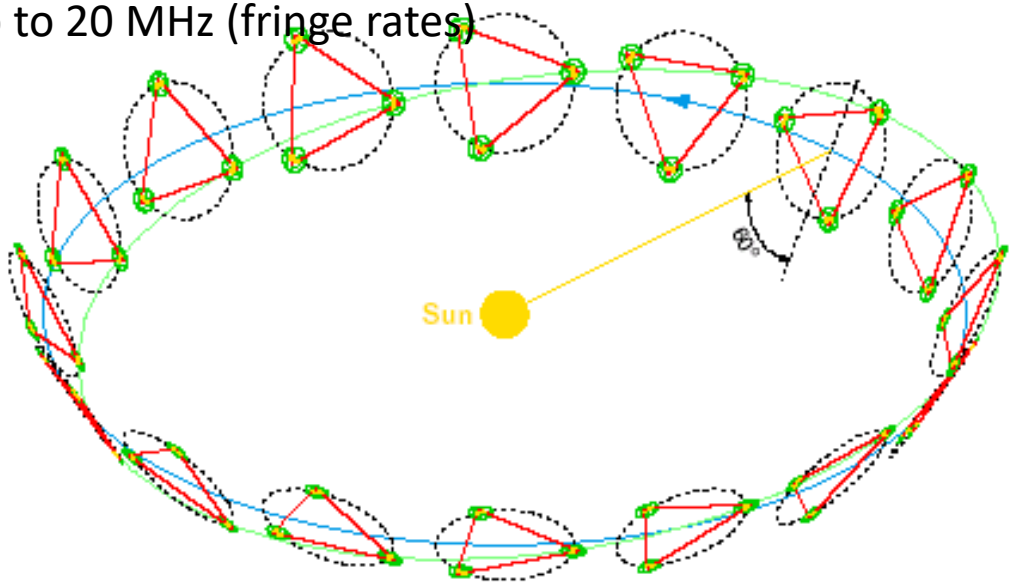
- worsened over time by secular pull of Earth

$\Delta\phi$ ~ +/-1.5 ° → telescope angle must breathe

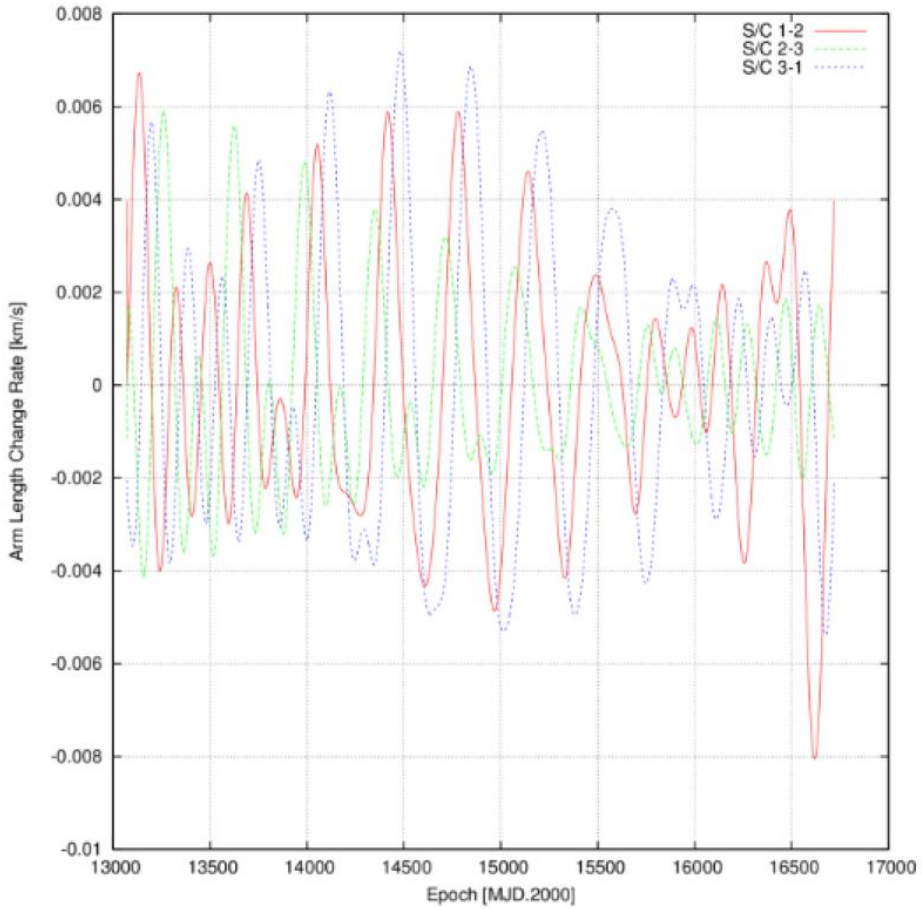
ΔL ~ 30000 km → unequal arm interferometer

Δv ~ 10 m/s → relative velocity causes Doppler shift up to 20 MHz (fringe rates)

interferometer signals are RF beat notes
science signal is a μHz phase modulation



LISA: annual orbital variations (inter-SC relative velocity)

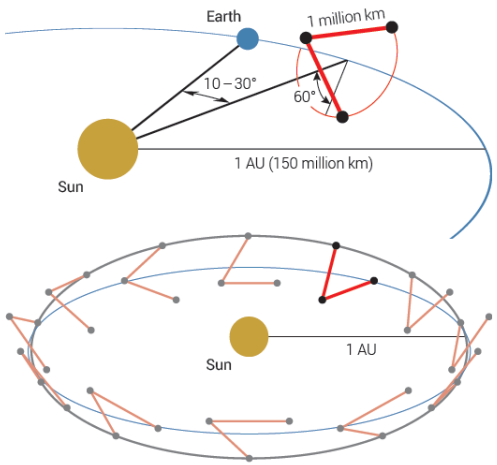


Relative velocities of SC along IFO arms up to 8 m/s

Related Doppler shift:

$$\frac{\Delta\nu}{\nu} \approx \frac{\Delta v}{c}$$

$$\Delta\nu \approx \frac{\Delta v}{\lambda}$$



Doppler shifts up to 8 MHz – phasemeter dynamic range

NB: relative accelerations during year: up to 2 μm/s²

→ Cannot achieve fm/s²/Hz$^{1/2}$ residual acceleration noise while applying 2 μm/s² accelerations

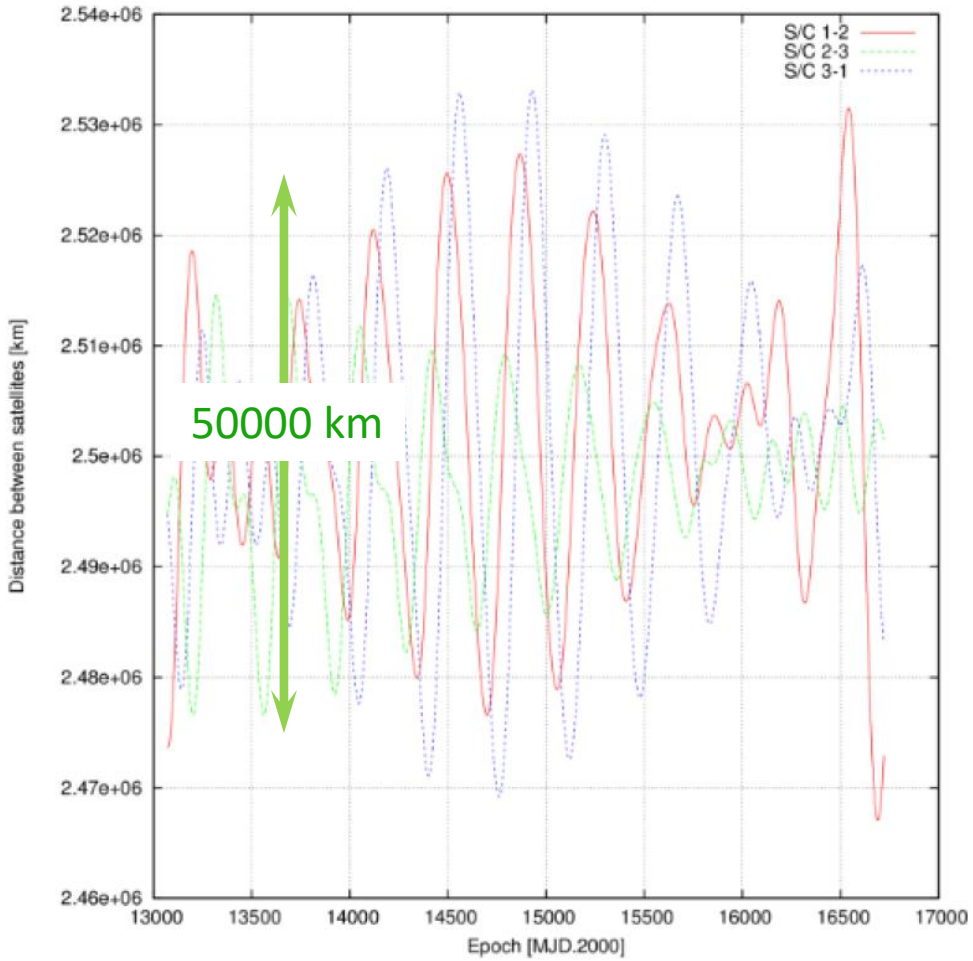
→ would require «part-per-billion» actuators

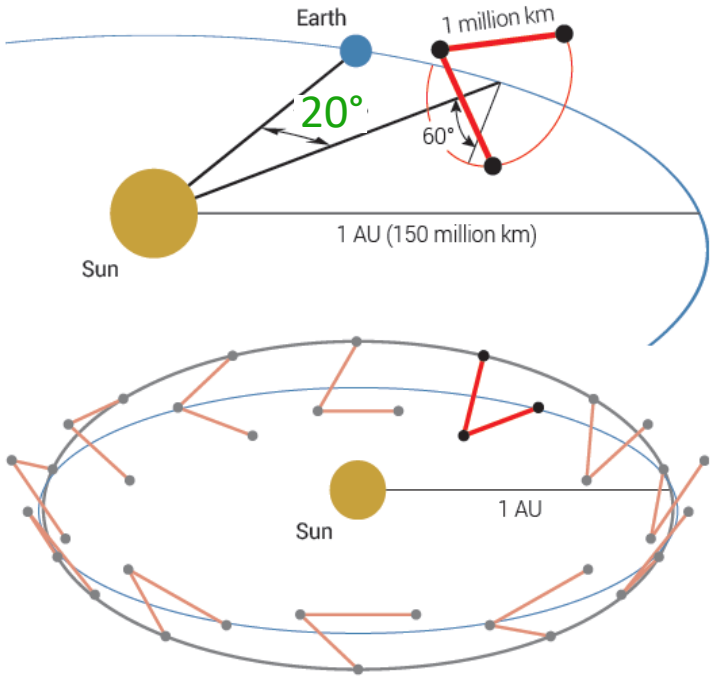
→ LISA is «open loop», reference TM (mirrors) freely orbiting along IFO axis (actively aligned but not locked «on fringe»)

LISA: annual orbital variations (distance between SC)

Due to Keplerian effects – orbital eccentricity and inclinations

- Differences of 20000-30000 km between different arms
  – a very unequal arm interferometer (TDI)





over time, secular effect of (eccentrically orbiting) Earth pulls the constellation apart

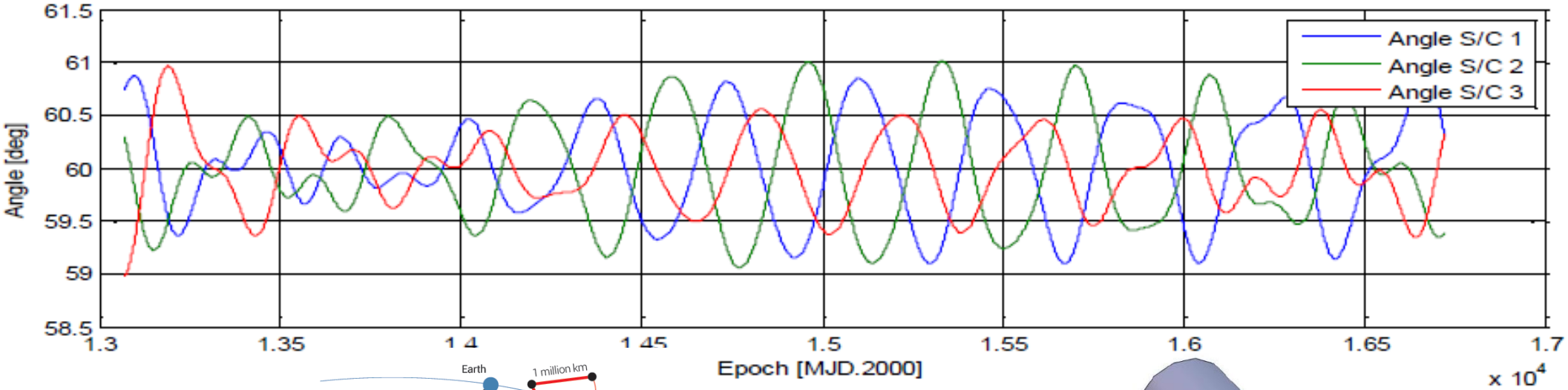
- larger ΔL, larger Δv ($\Delta \nu$), larger $\Delta \phi$
- 20° Earth trailing angle = 60 million km to Earth = 3 minutes light time

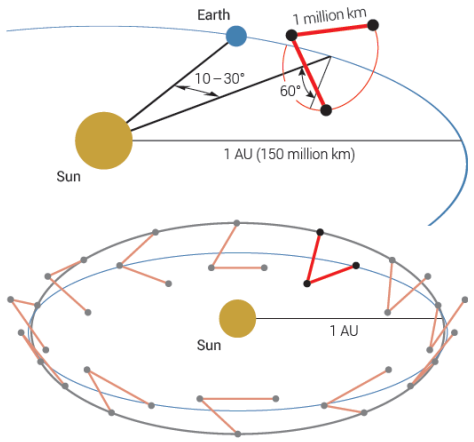
→ tradeoff between long life (farther) and data rate (closer)

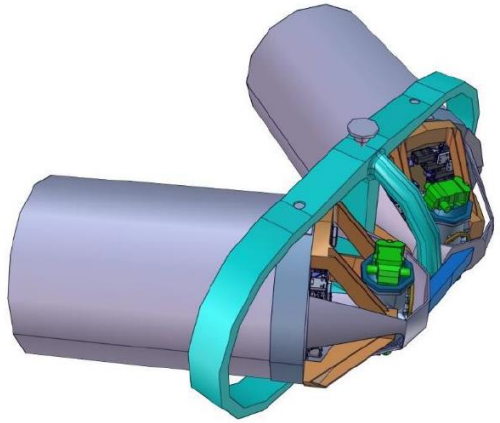
LISA: annual orbital variations (angle between IFO arms)

Triangle «corner angle» annual breathing +/- 1 degree – telescope angle must be adjustable

- continuous actuation (5 nrad/s) to «hit» distant spacecraft with laser beams

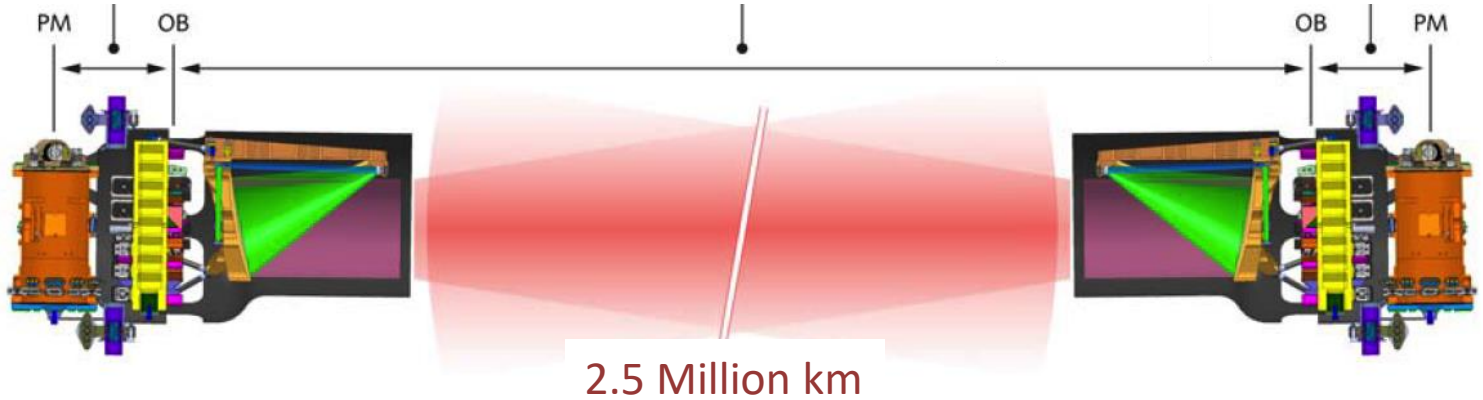






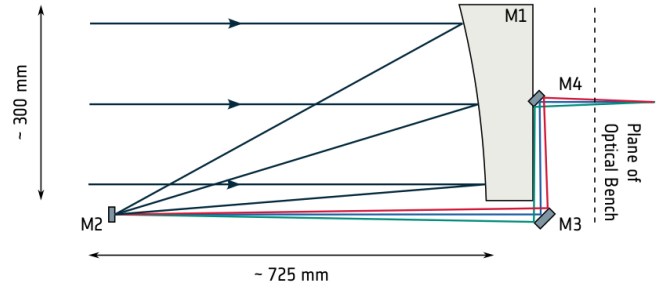
Test mass to test mass with 15 pm/Hz$^{1/2}$

3 parts: TM to SC + SC to SC + SC to TM



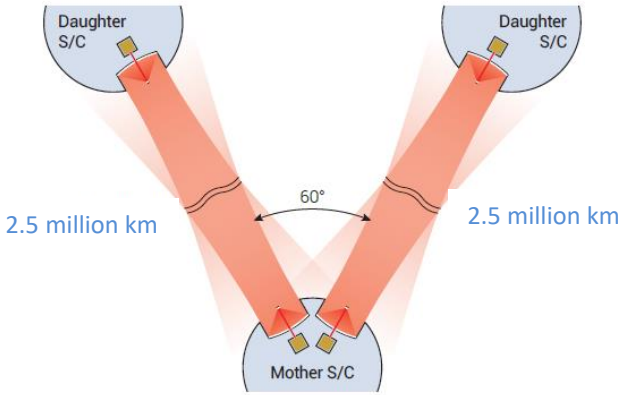
LISA telescope

- 130x beam expander
- sub-pm deformation
- avoid backscatter



Long arm interferometer (SC-SC 2.5 million km)

- 2 W 1064 nm light from ϕ 30 cm telescope
- 500 pW received light, shot noise 5 pm/Hz$^{1/2}$
- order 10 MHz doppler beat frequencies
- unequal arm IFO: ΔL 30000 km

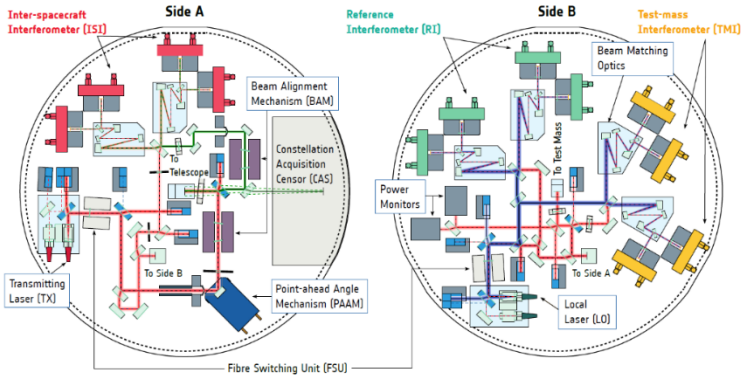


Short arm interferometer (TM-SC)

Reference interferometer

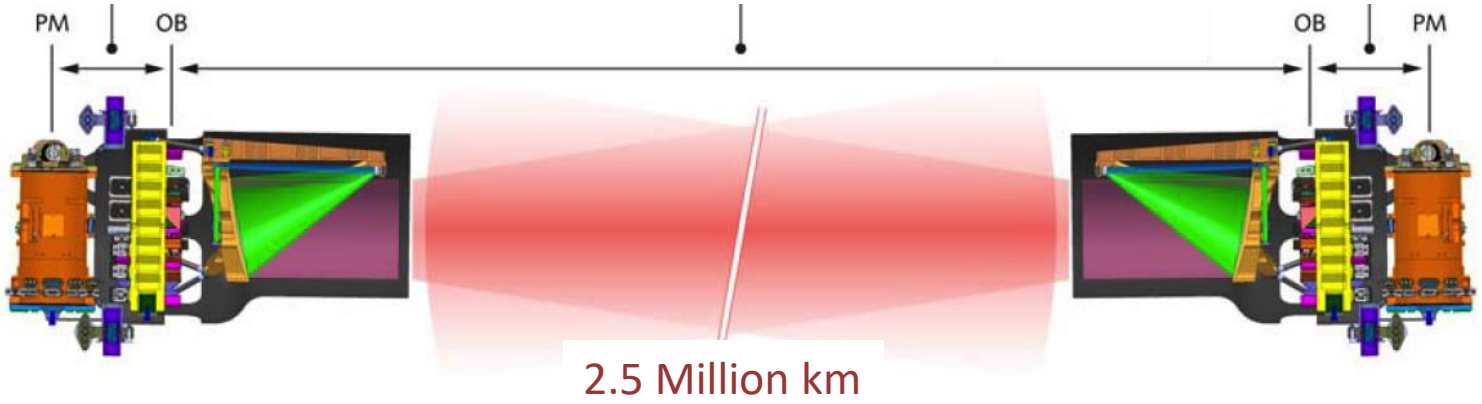
- phase reference between phase measurements on optical benches of adjacent arms in same SC

LISA optical bench



Test mass to test mass with √2 * 3 fm/s²/Hz^1/2

3 parts: TM to SC + SC to SC + SC to TM

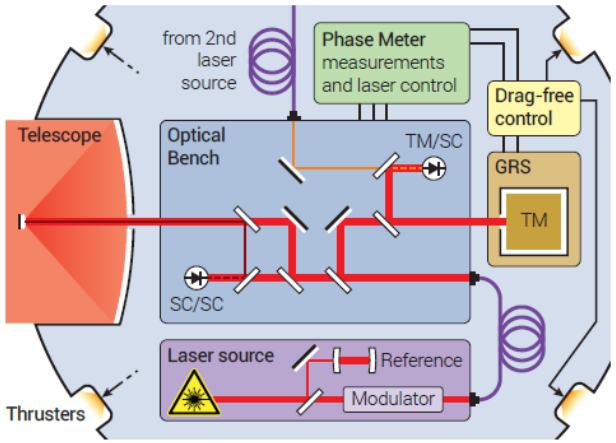


- **TM force noise per unit mass (acceleration relative to inertial frame):**

3 fm/s²/Hz^1/2

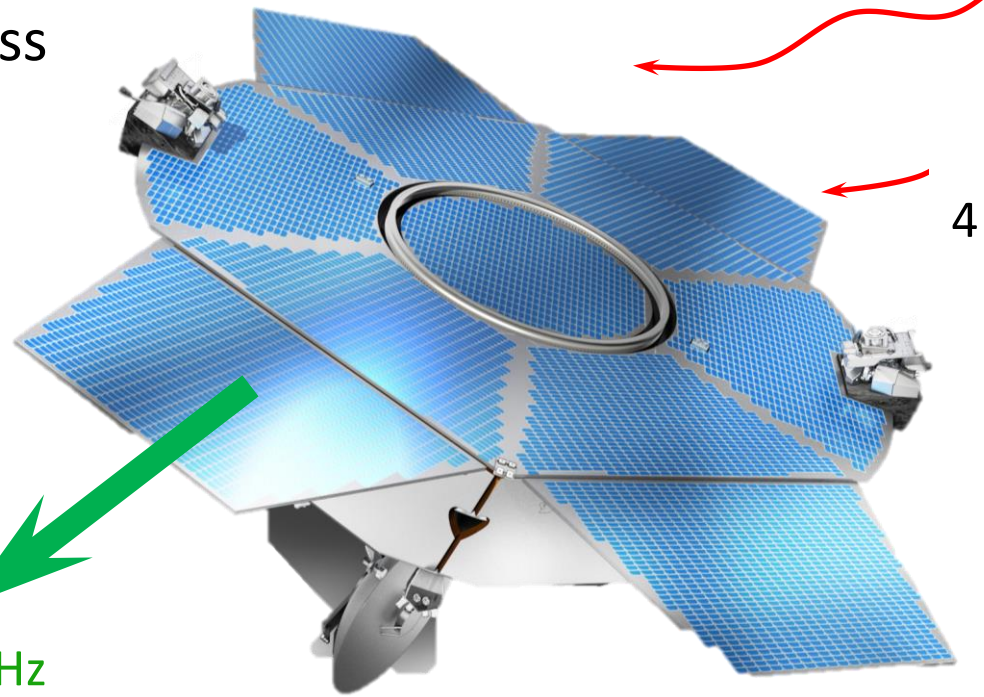
- Drag-free control of SC at 3 nm/Hz^1/2
- but need to measure TM-TM – moving in 6 DOF – at 10 pm/Hz^1/2

Local SC – TM measurement



Spacecraft as free-falling geodesic reference test mass?

≈20 m^2 area
≈2000 kg mass



≈1300 W/m^2

4 $W/m^2/Hz^{1/2}$ at 0.1 mHz

≈100 μN
≈50 nm/s^2

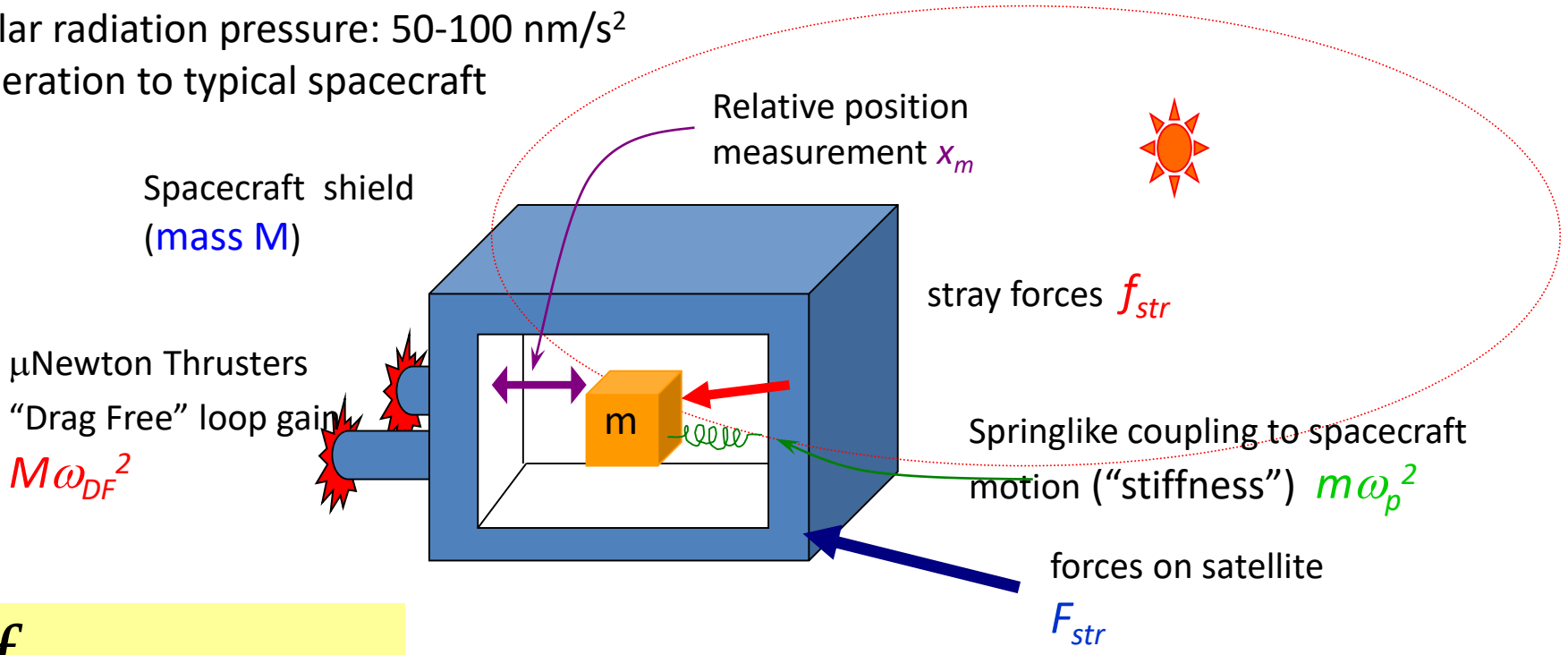
150 $pm/s^2/Hz^{1/2}$ at 0.1 mHz

- solar radiation pressure “DC” acceleration too large (destroys triangular constellation over time)
- in-band radiation pressure fluctuations 4 orders of magnitude too large

→ need a much better ($fm/s^2/Hz^{1/2}$), shielded free-falling test mass geodesic reference

Drag-free control and free-falling reference test masses

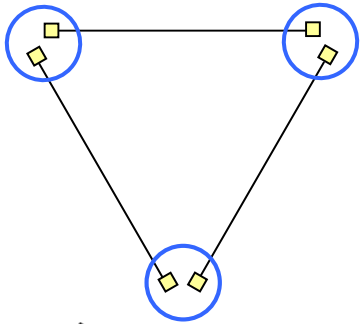
- Solar radiation pressure: 50-100 nm/s^2 acceleration to typical spacecraft



$$g = \frac{f_{str}}{m} + \omega_p^2(\Delta x)$$

Δx is SC-TM relative motion ("control jitter")

LISA needs $S_g^{1/2} < 3$ fm/s^2/Hz$^{1/2}$ at mHz frequencies acceleration relative to inertial frame



LISA drag-free control on 2 non-orthogonal axes

drag-free:

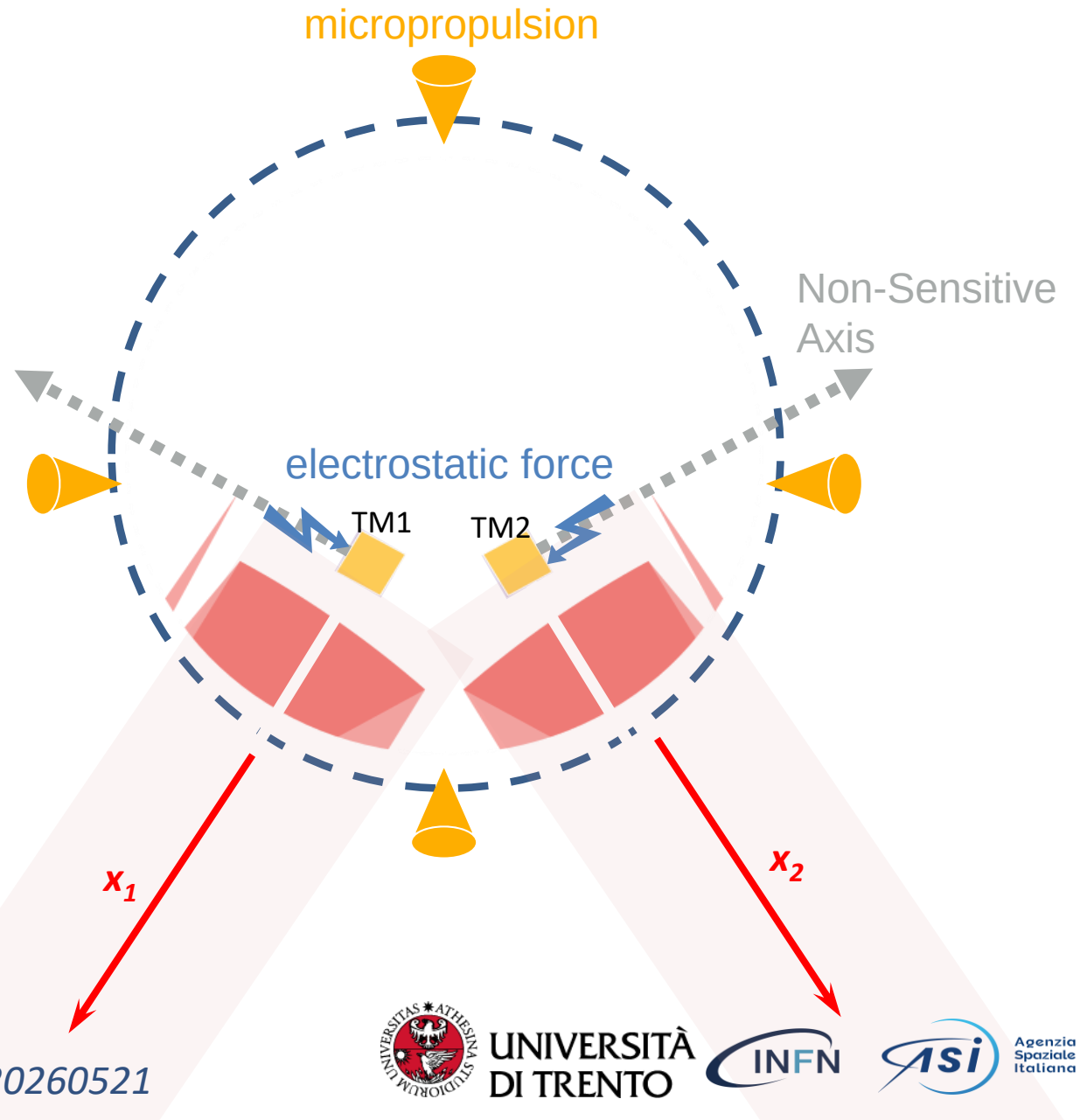
- SC thrusted to follow TM1 along long arm IFO axis 1
- SC thrusted to follow TM1 along long arm IFO axis 1
- **no forces applied to TM along sensitive axes**

electrostatic suspension:

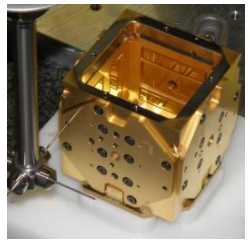
- force TM1 and TM2 to follow SC along non-sensitive axes orthogonal to IFO axes
- at DC, have to balance any differential force per unit mass on the two TM
  - mostly spacecraft “self-gravity” (< nm/s^2)
  - otherwise they bump into SC

SC rotation

- control (thrust) SC to incoming laser wavefronts
- electrostatic torque on TM to align to local laser

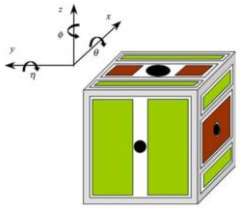


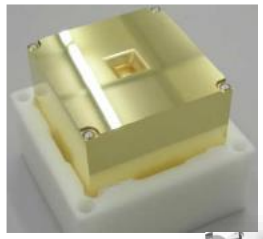
Designing GRS for fm/s^2 free-fall ... (starting from nm/s^2-level)

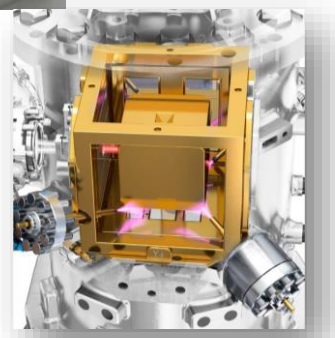


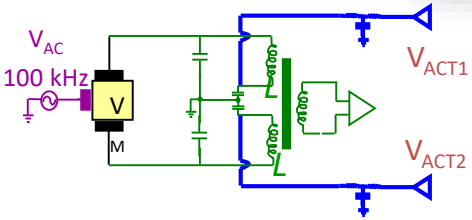
Gravitational Reference System

- 6DOF nm capacitive sensing
- nN electrostatic force actuation
- fm/s^2 free-fall reference
- pm «end mirror»









- heavy TM, 2 kg / 46 mm Au-Pt cube (Au coated)
- large 3-4 mm gaps
- high conductivity metal electrode housing
- no contacts (no discharge wire)
- AC-carrier electrostatic actuation
- vent to space (< 2 μPa)

Engineering costs ...

- TM hard to cage
- need UV TM discharge
- **need IFO sensing**

fN force noise sources:

- simple physics mechanisms, but impossible to calculate
  - stray E fields, outgassing, dissipation ...
  - at 10^{-4} Hz "datasheet value" does not exist

- ***B, dB/dt, T*** & ***ΔT, g***, electrical noise ...

HW images: ESA, OHB-I, C. Zanoni

Frequency noise: first a «single arm» LISA

Round trip light time = ***2 T = 2 L / c***

Beat frequency time derivative

GW strain

laser freq noise

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

- Essentially comparing laser frequency now with that emitted a time ***2T*** before!

in Fourier domain:

$$\frac{\Delta\dot{\nu}(\omega)}{\nu_L} = \omega \exp j\omega T \times \sin \omega T \times \left[h(\omega) + 2\frac{\delta\nu_L(\omega)}{\nu_L} \right]$$

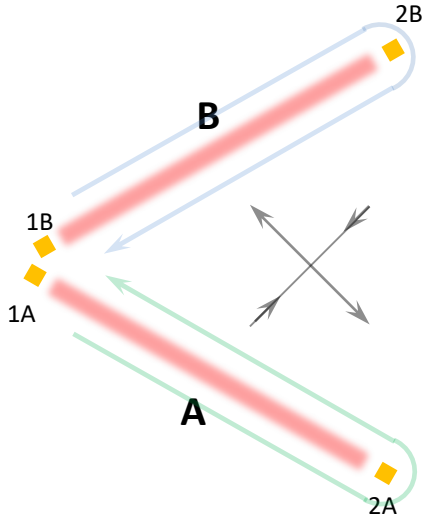
Goal strain sensitivity
PSD: <10^{-20} /Hz$^{1/2}$

Cavity stabilized laser
PSD: 10^{-13} /Hz$^{1/2}$

More than 7 orders of magnitude!

GW observation as time-delayed Doppler gravity gradiometer:

Michelson combination to reject laser noise (almost)



Compare beat notes in two non-parallel arms

$$\Delta\nu_{MICH} \equiv \Delta\nu_A(t) - \Delta\nu_B(t)$$

NB: distant observers phase lock to light from SC1 – a single laser source with frequency noise ν_L

$$\frac{\Delta\dot{\nu}_{MICH}}{\nu} = \frac{1}{2}\cos\frac{\pi}{6}\left[2\dot{h}_\times(t) - \dot{h}_\times(t-2T_A) - \dot{h}_\times(t-2T_B)\right]$$

GW strain (arms at 60°)

$$+\frac{1}{c}\left[g_{1A}(t-2T_A) + g_{1A}(t) - 2g_{2A}(t-T_A) - g_{1B}(t-2T_B) - g_{1B}(t) + 2g_{2B}(t-T_B)\right]$$

Stray accelerations (4 TM)

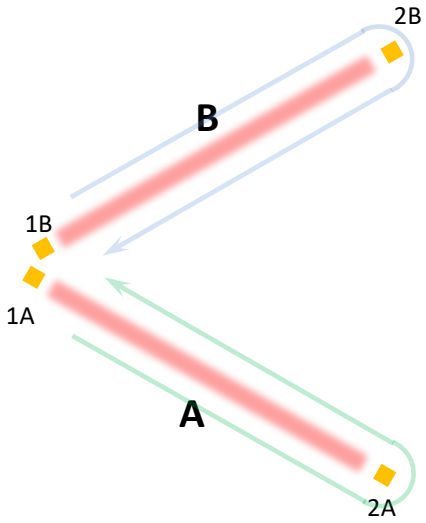
$$+\frac{1}{\nu}\left[\dot{\nu}_{n1A}(t) - \dot{\nu}_{n2A}(t-T_A) - \dot{\nu}_{n1B}(t) + \dot{\nu}_{n2B}(t-T_B)\right]$$

4 frequency measurements

$$+\frac{1}{\nu}\left[\dot{\nu}_L(t-2T_A) - \dot{\nu}_L(t-2T_B)\right]$$

1 laser frequency noise
armlength imbalance ($T_A - T_B$)

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}

$$\frac{\delta\nu_L}{\nu_L}$$

Laser relative frequency noise

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

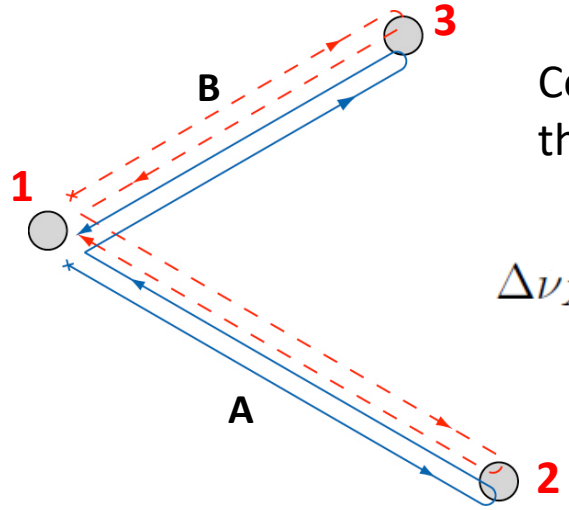
$$S_{h_\times} \approx \frac{4}{3}\frac{1}{\left(L\omega^2\frac{\sin\omega T}{\omega T}\right)^2} \times \left\{4S_g + \omega^4\left[S_{IFO} + S_{\delta\nu/\nu}\,(\Delta L)^2\right]\right\}$$

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

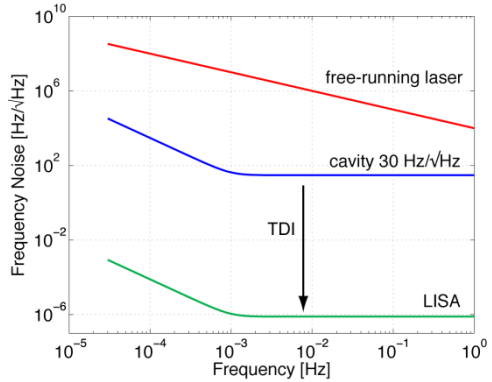
Time-delay interferometry:

«Synthesize» an equal arm (to within 1 m) interferometer in post-processing

- Requires knowledge of travel times T_A, T_B → ranging tone (like GPS) superimposed modulated on laser beam

- synthesize equal arm (< 1m – several ns) in post-processing
  - NB: need to interpolate 10 Hz data with ns precision

- Achieving 30 Hz/Hz$^{1/2}$ laser noise requires cavity



- Cancellation «perfect» only for fixed arms – change of arm during light travel time

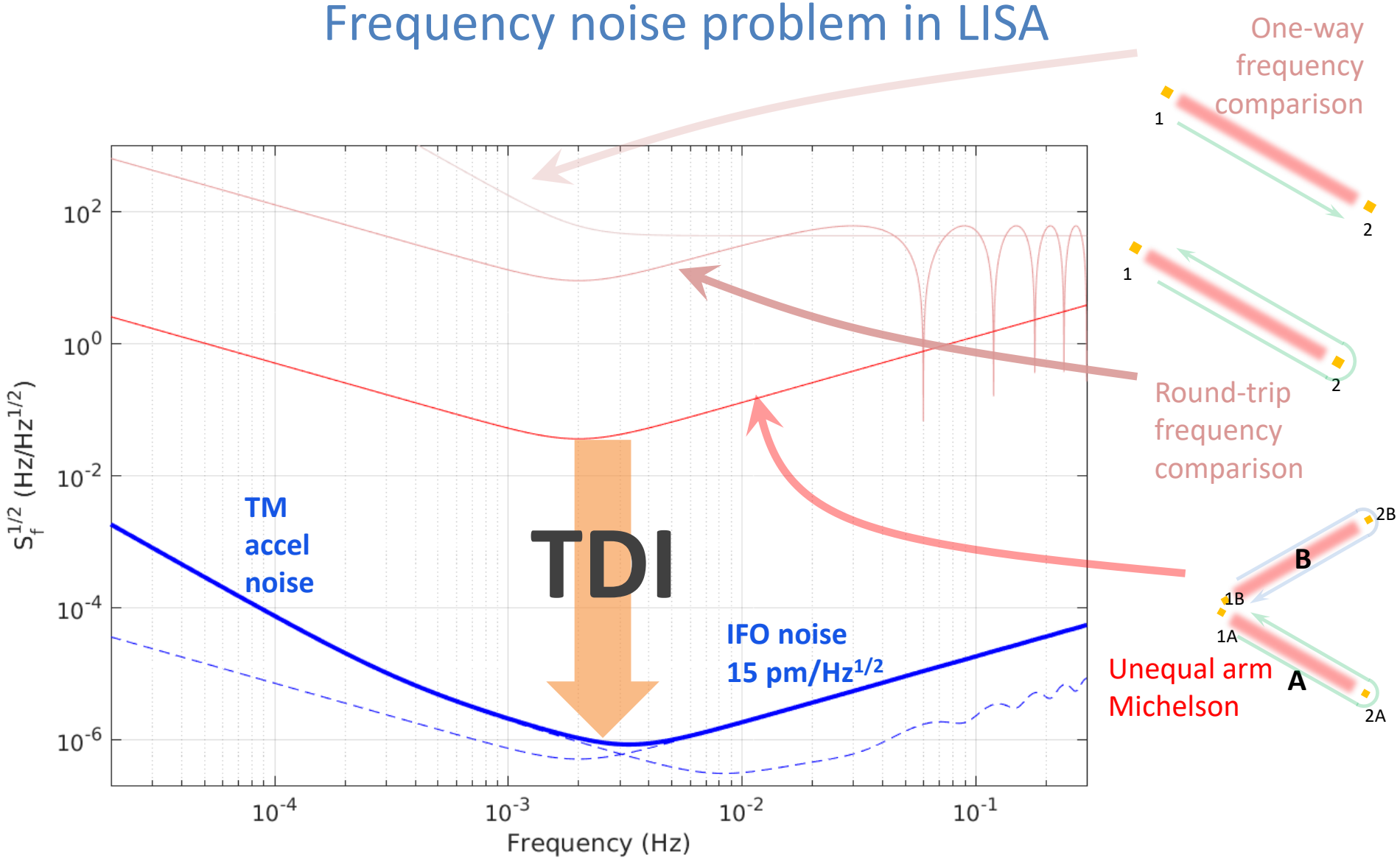
  8 m/s * 17 s round trip travel time → arms change by 150 m

  Relevant error at high frequencies

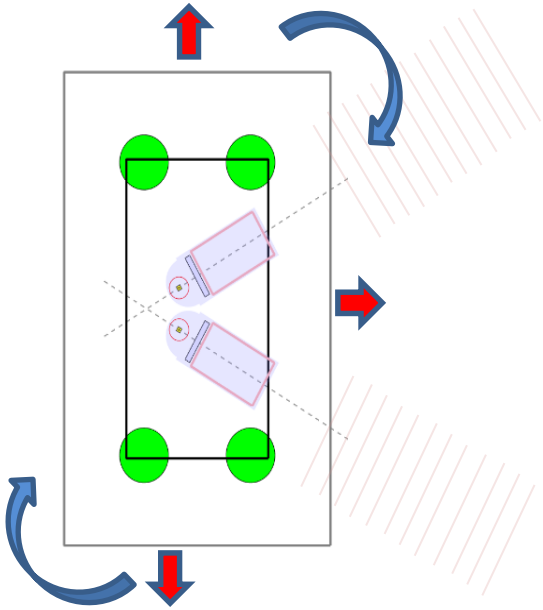
  Requires 2nd generation TDI – 8 pulses (compare 2 trips down each arm)

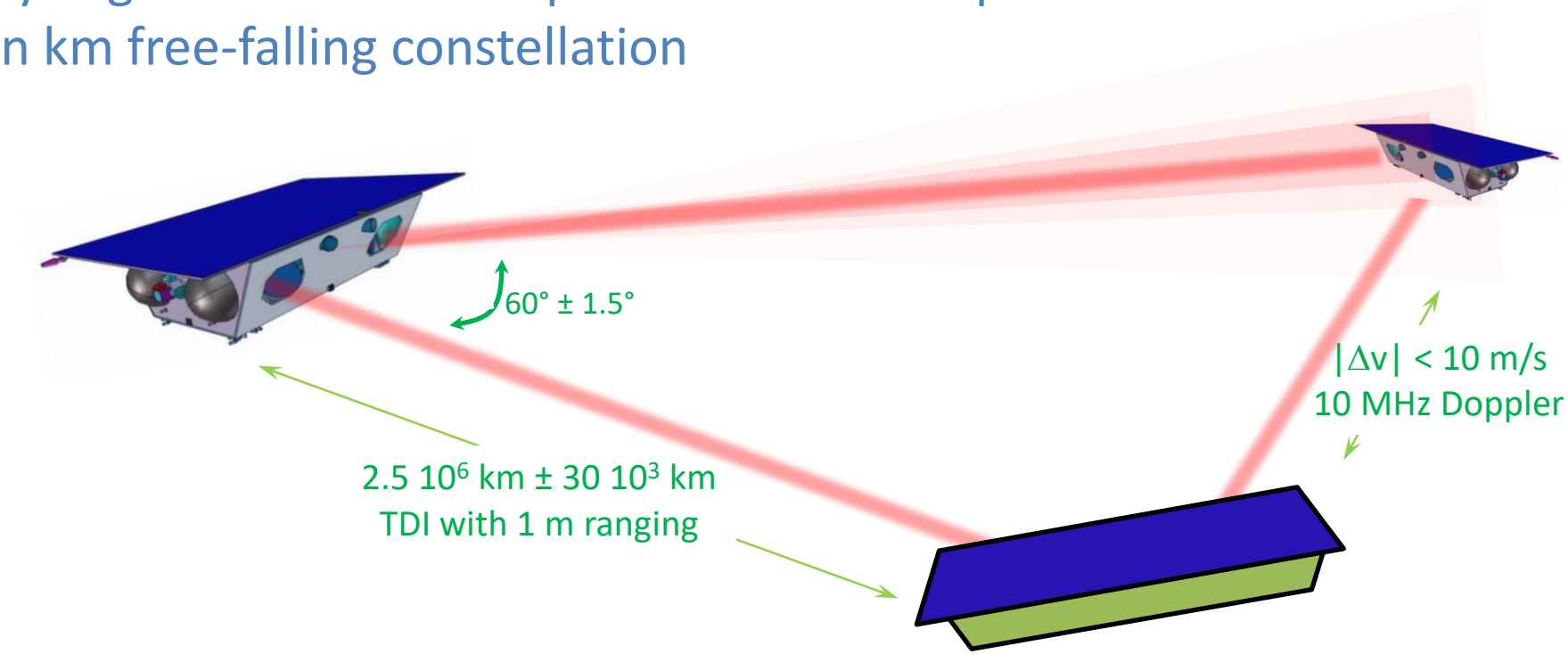
Additional complications: clock noise and «sample jitter» (high inter-SC velocity)
Cured by effective clock synchronization (modulate clock signal onto laser beam)

Frequency noise problem in LISA

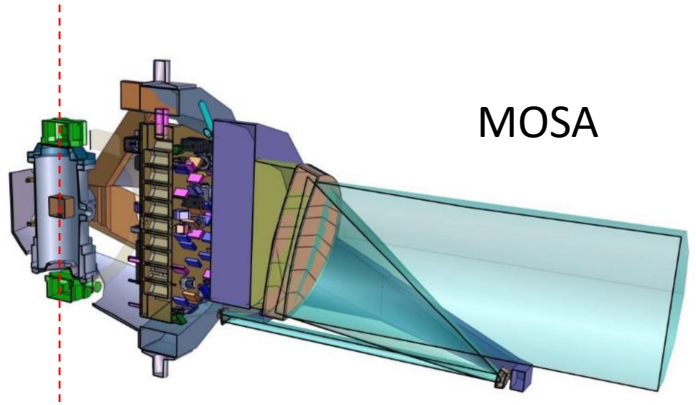


LISA: a finely aligned mechanical-optical instrument spread across a 2.5 million km free-falling constellation

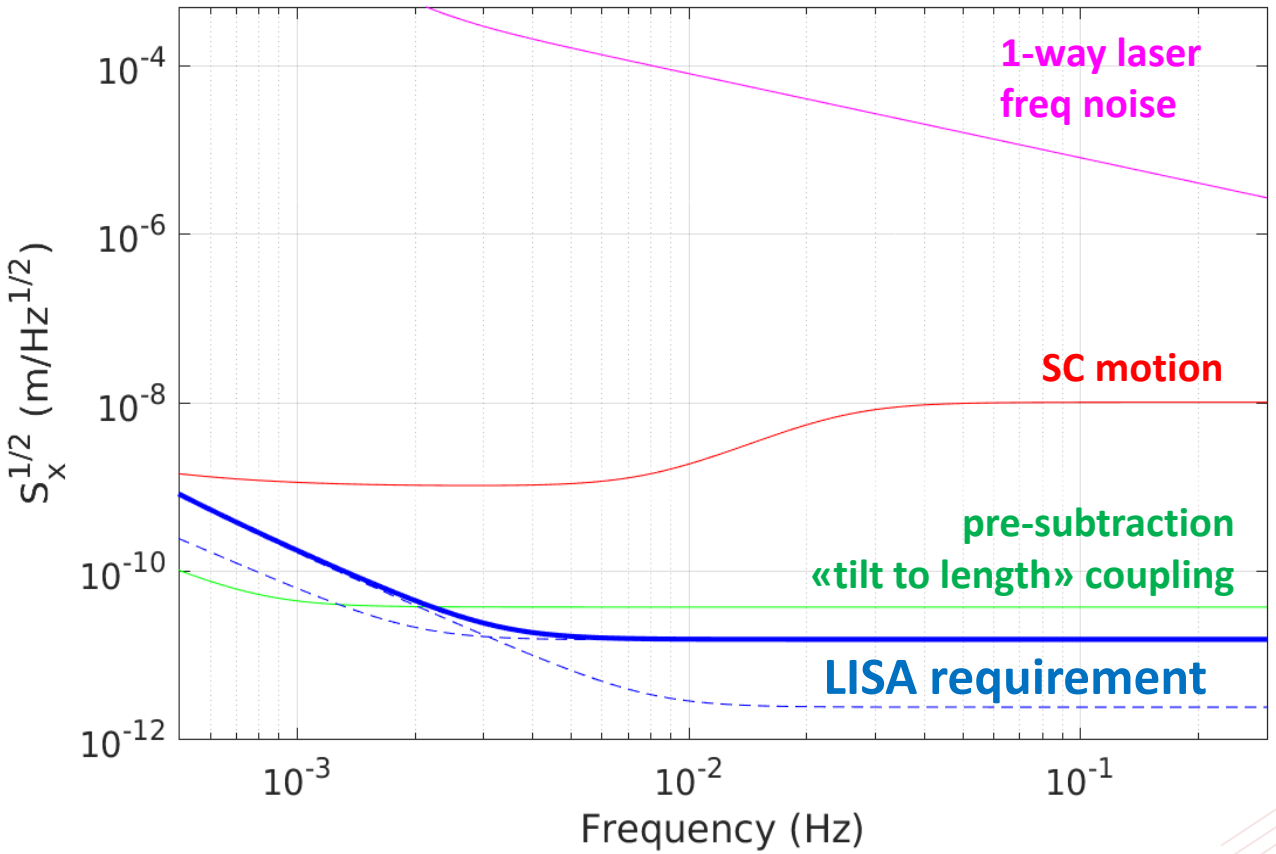




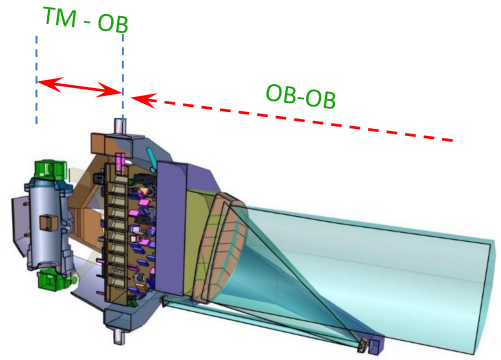
- payload moves – telescope pointing
- new SC gravitational balancing (and role of DC forces)
- spacecraft + TM control both local and global



key «common mode rejections» in LISA

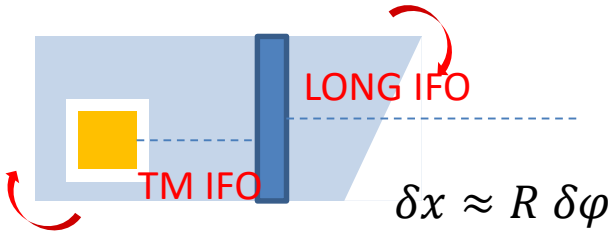


10^7 suppression with TDI

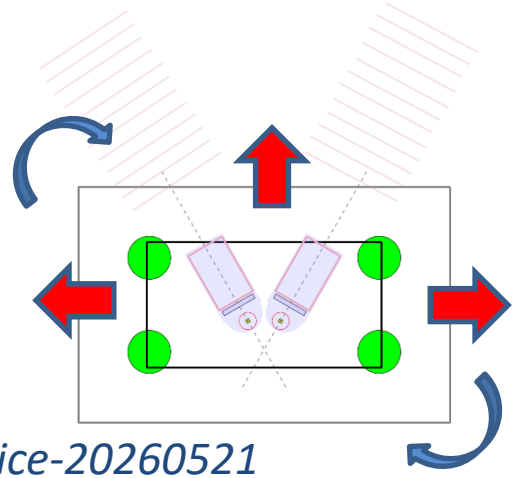


10^3 rejection of SC motion (local/long IFO)

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

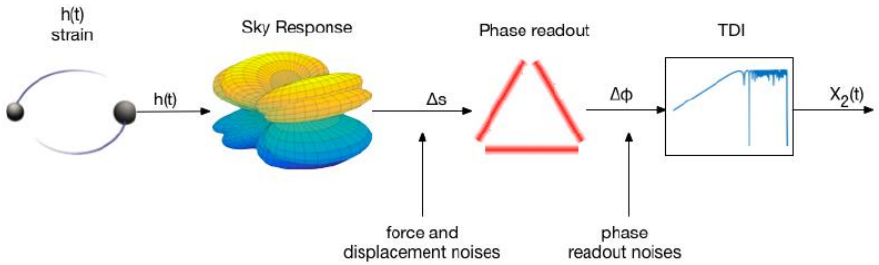


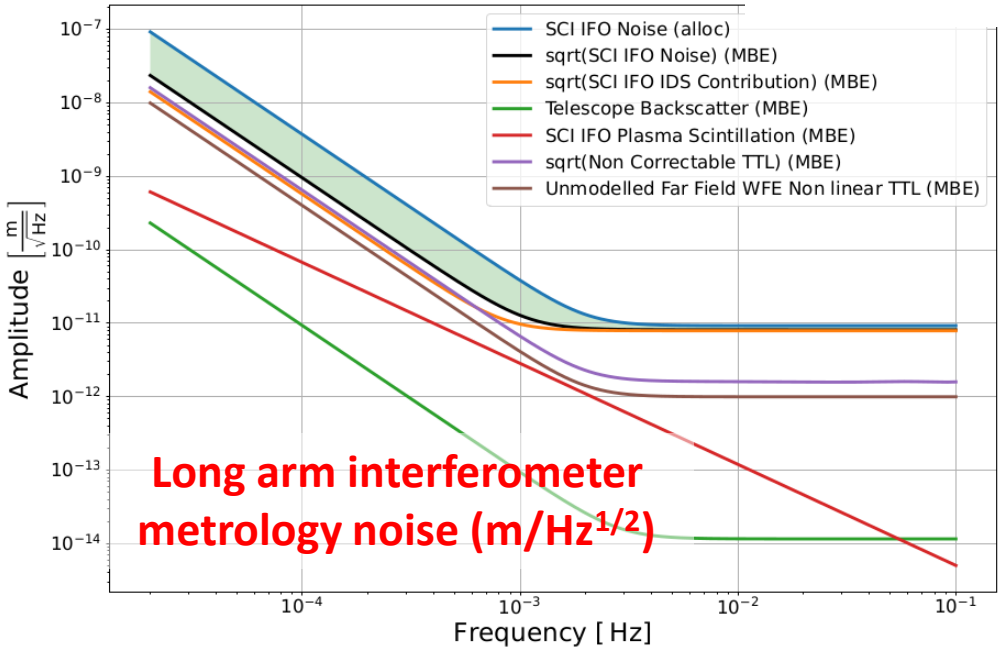
$\delta x \approx R\,\delta\varphi$

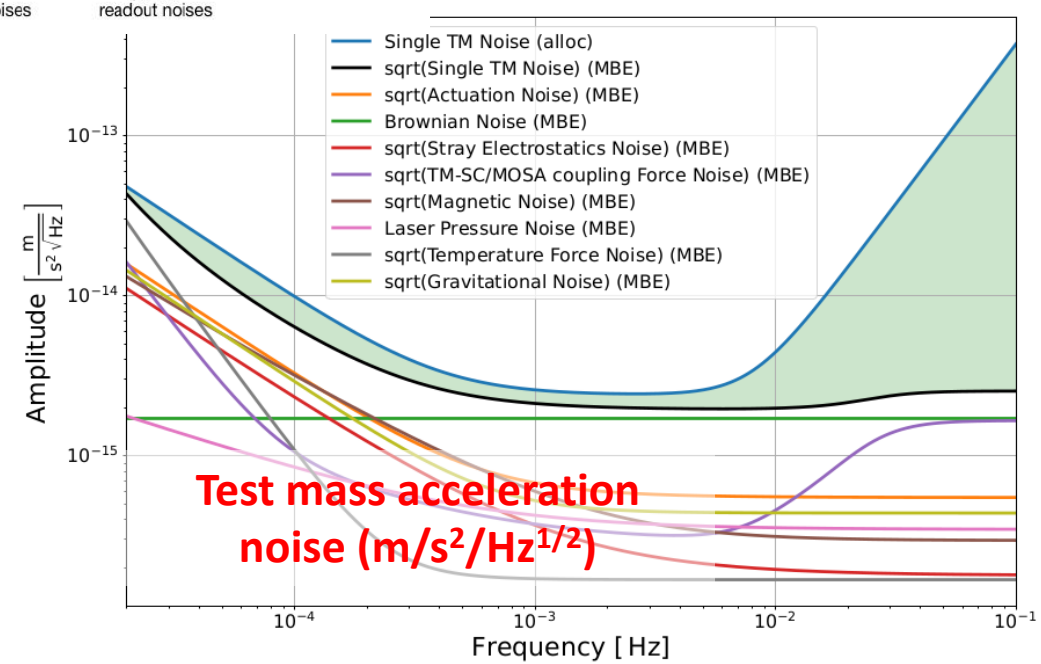


Sub-femto-g and picometers ... why do we think this will work?

Lots of analysis and models of noise sources ...







ESA / LISA Consortium Performance Model

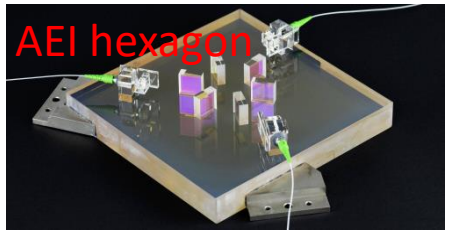
Sub-femto-g and picometers ... why do we think this will work?

... mostly, lots of experimental evidence

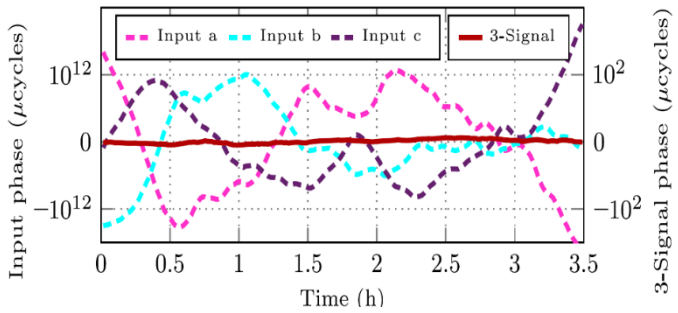
Optical metrology

Lab test high dynamic range phasemeter

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

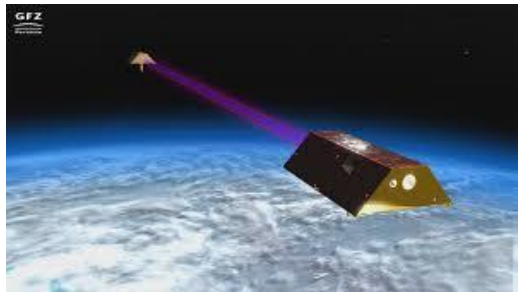


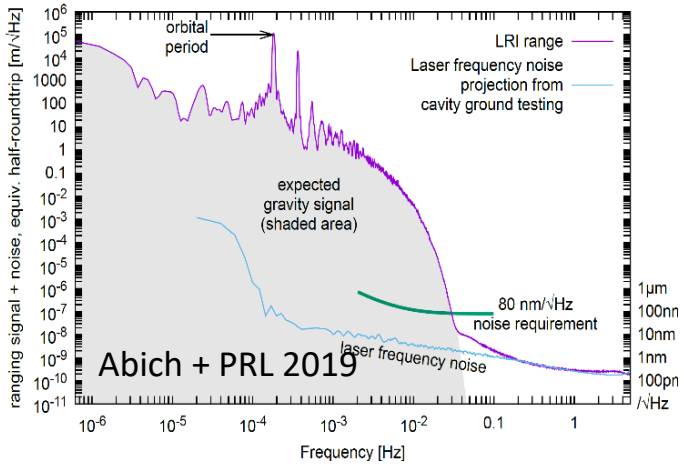
Schwarze+ PRL 2019



Demonstrate 10^{11} dynamic range phasemeter

GRACE-FO inter-spacecraft IFO

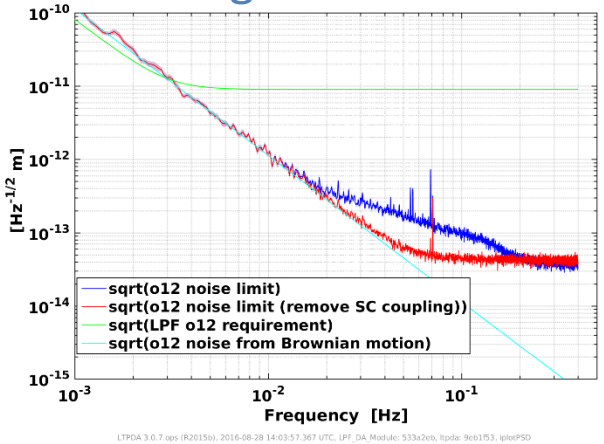


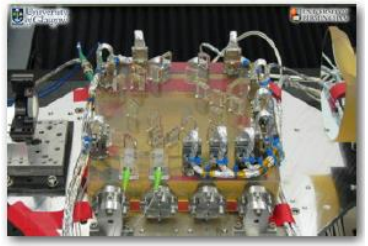


200 pm/Hz$^{1/2}$ inter-spacecraft laser IFO

- low power, MHz, cavity-stable laser

LPF interferometric tracking of free-falling TM





- 35 fm/Hz$^{1/2}$ noise floor
- high stability optical bench

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

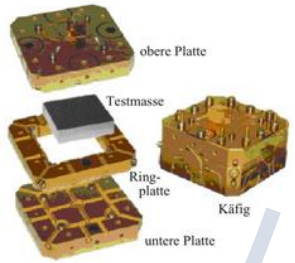
... mostly, lots of experimental evidence

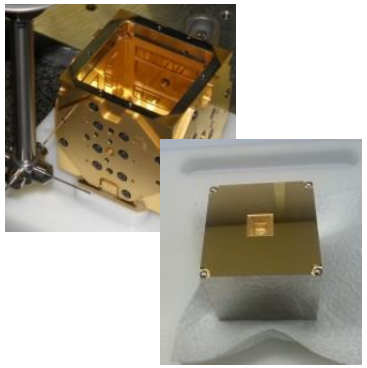
Free-falling TM

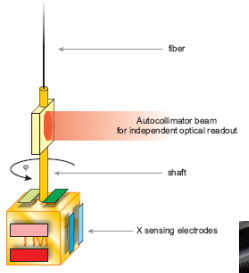
Free-falling test masses at 3 fm/s^2/Hz$^{1/2}$

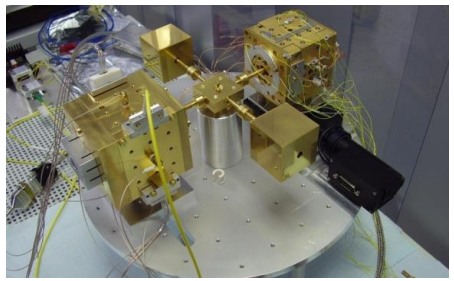
- geodesy (GRACE, GOCE) 10-100 pm/s^2/Hz$^{1/2}$
- design changes ...
- torsion pendulum– simplified test at 30 fm/s^2/Hz$^{1/2}$

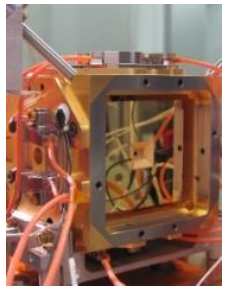
bigger TM
bigger gaps
no wires!

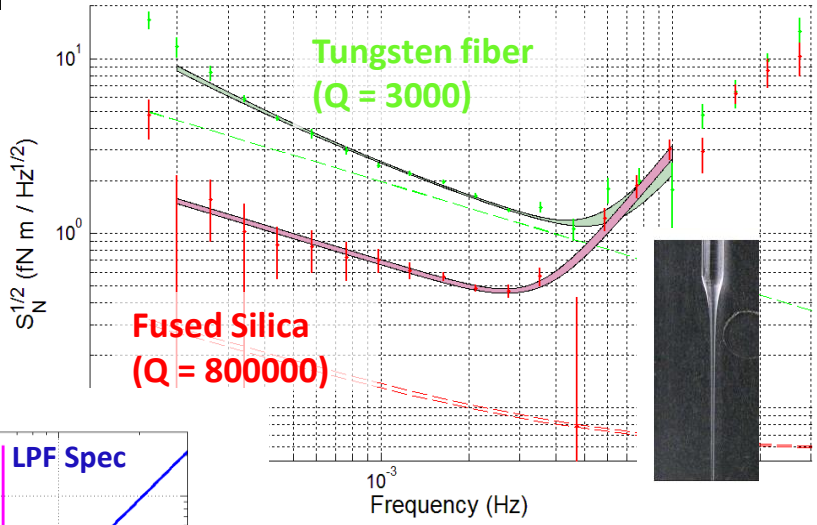


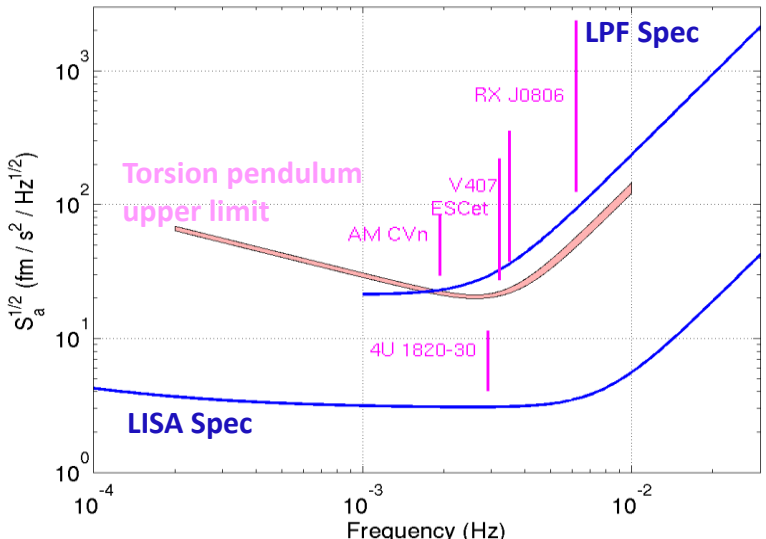












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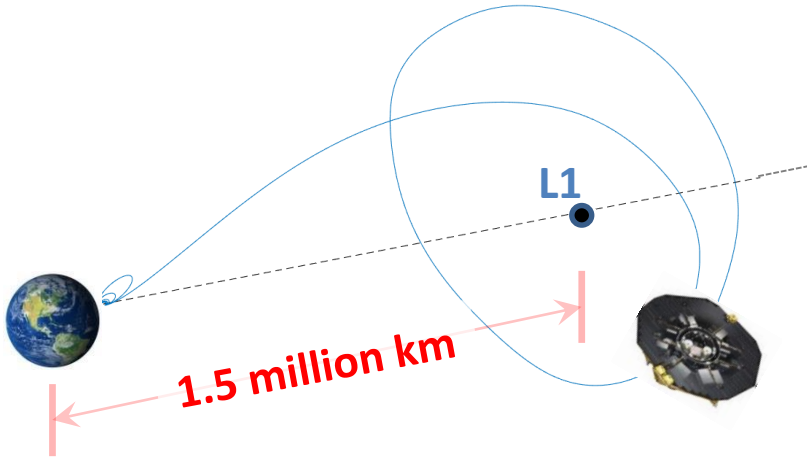
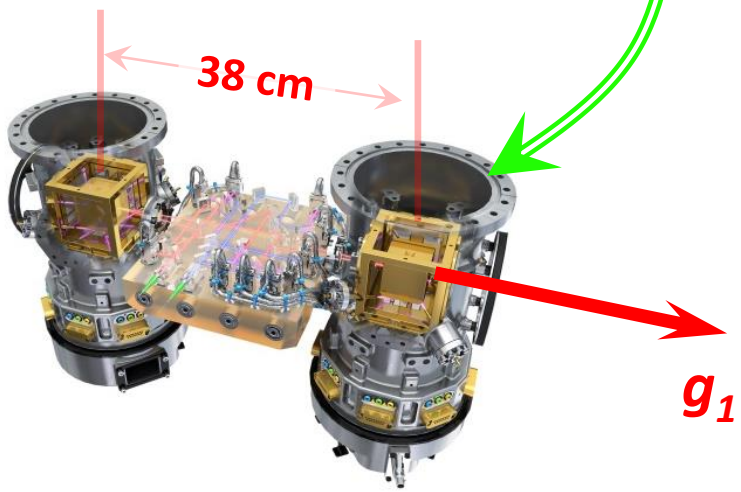
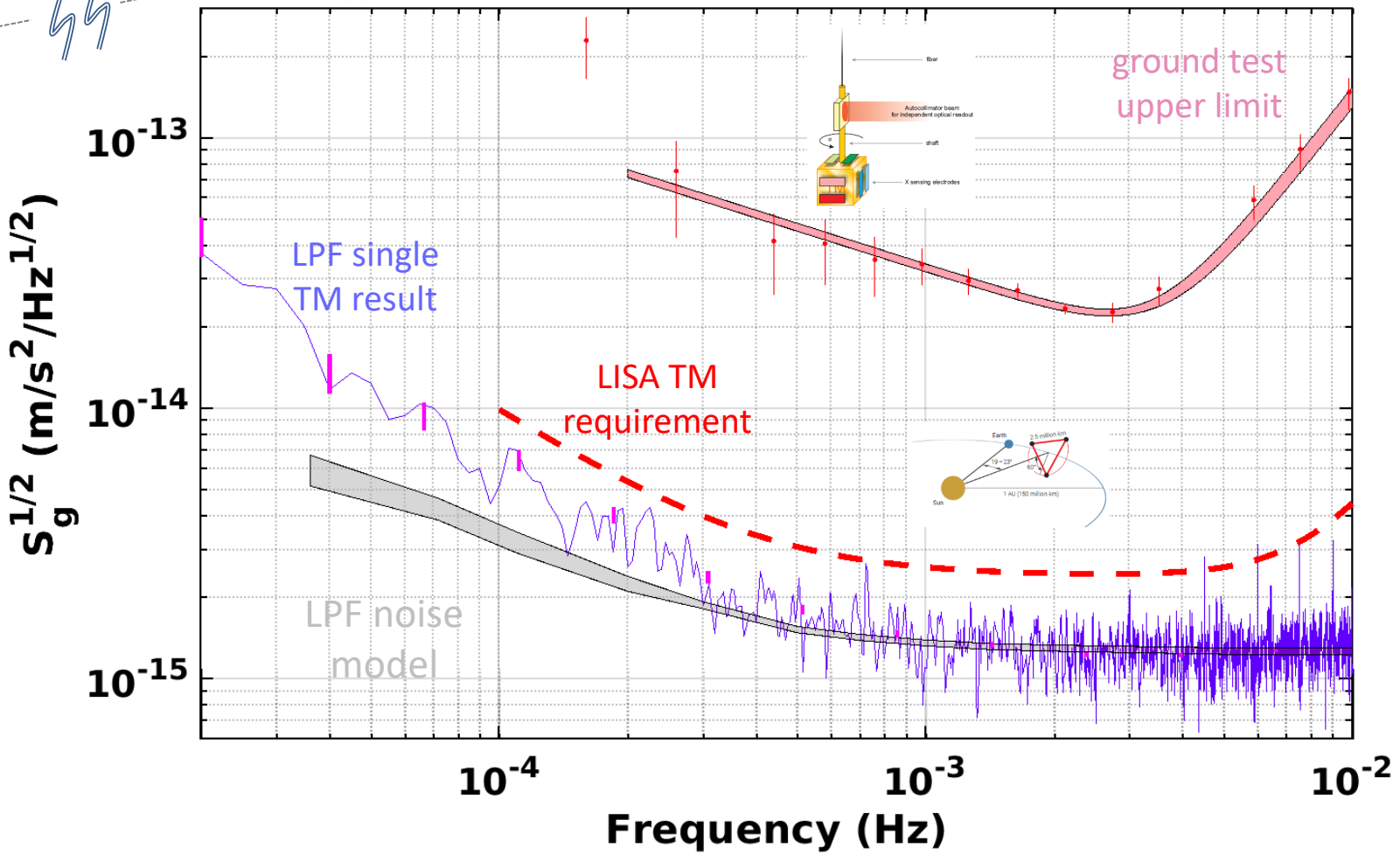
Sub-femto-g and picometers … why do we think this will work?

… mostly, lots of experimental evidence

Free-falling TM







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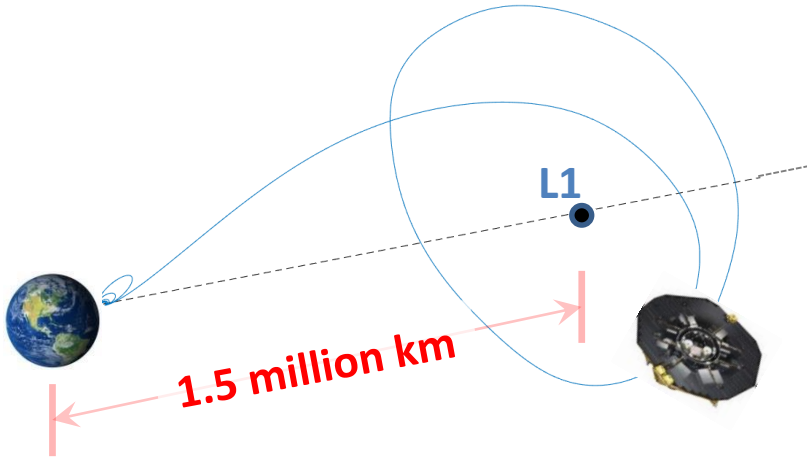
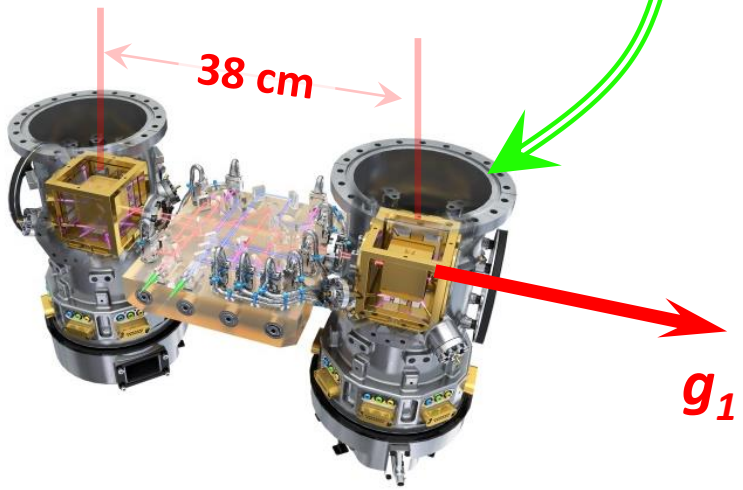
Free-falling TM





LPF tested:

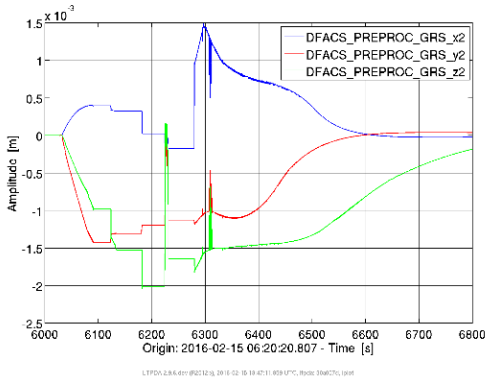
- LISA free-falling test mass «gravitational reference system»
- local TM interfermetric readout
- drag-free control with cold gas and colloidal thrusters

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

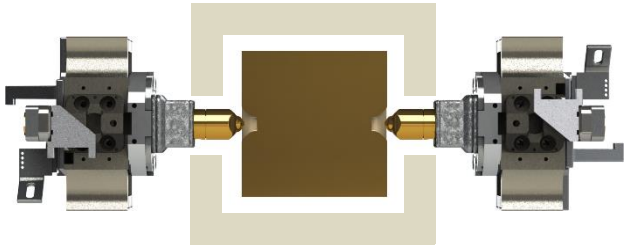
Selected «little engineering details» en route to LISA science

Test mass release

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

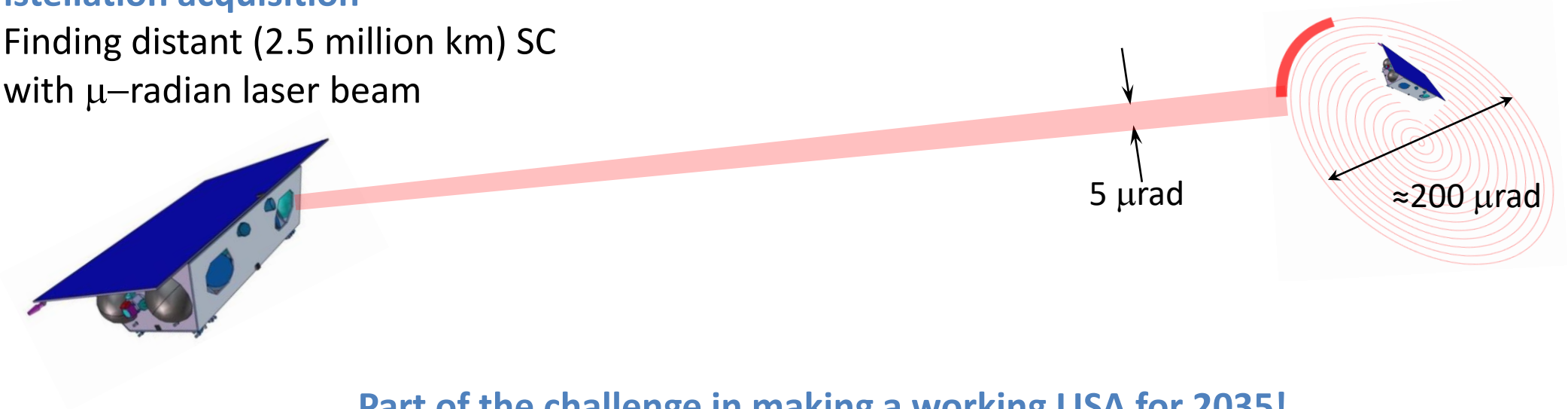


LPF first release ... 30 μm/s
Much better in later tests!



Constellation acquisition

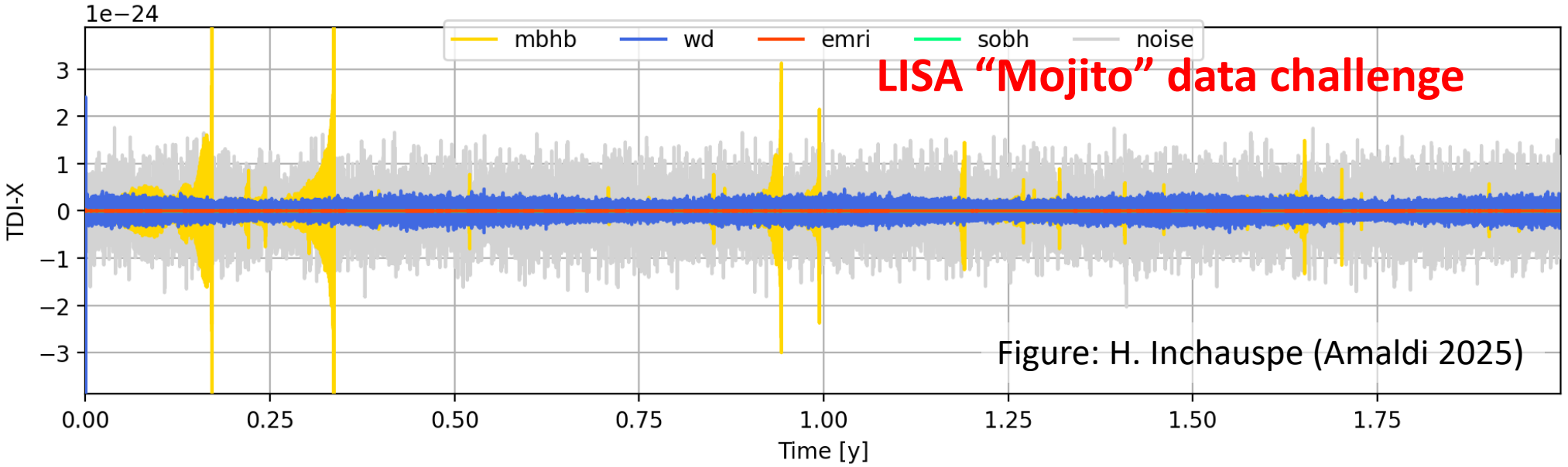
- Finding distant (2.5 million km) SC with μ–radian laser beam



Part of the challenge in making a working LISA for 2035!

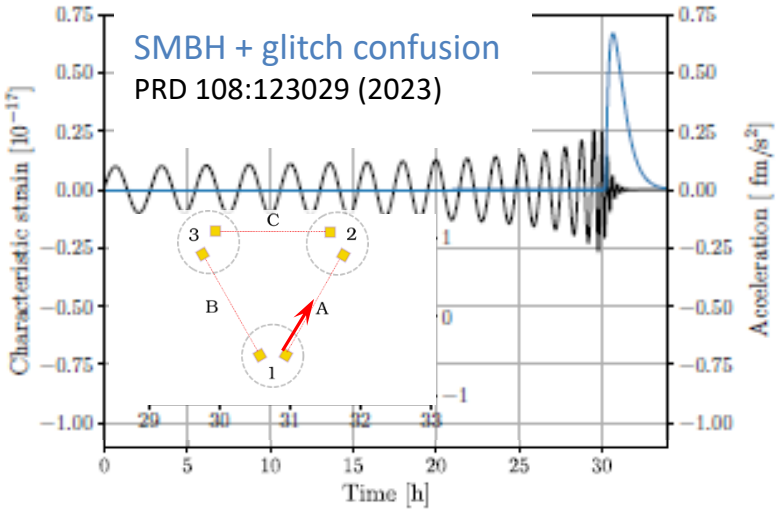
LISA Data Analysis: Getting the LISA science out of the data

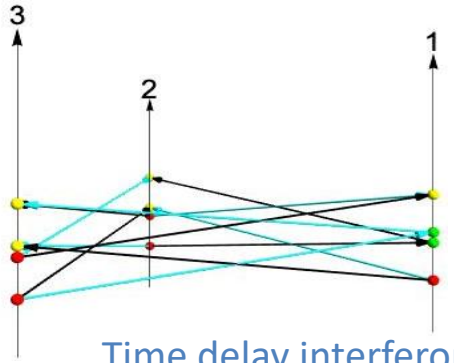
Cocktail party problem: no “dark sky” but trying to hear thousands of “resolvable” overlapping signals always



mHz noise dominated by Milky Way WD-WD!

Challenge for astrophysical data analysts AND instrument scientists

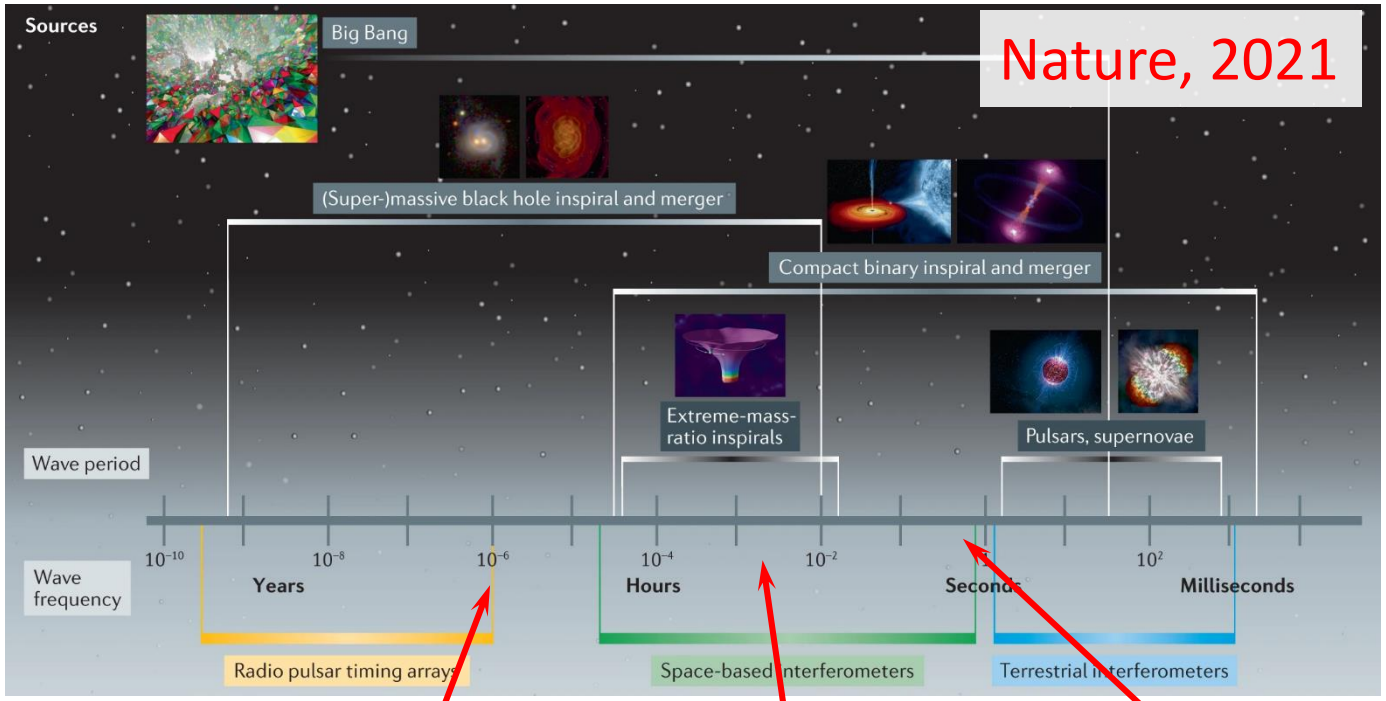




Time delay interferometry
“null channel”
PRD 107:082004 (2023)

- a super massive black hole?
  - or a burst of gas hitting the test mass?
- is that a stochastic GW from Big Bang?
  - or instrument noise?

There will be a space gravitational wave observatory after LISA ...



ESA Voyage 2050

- "New Physical Probes of Early Universe"

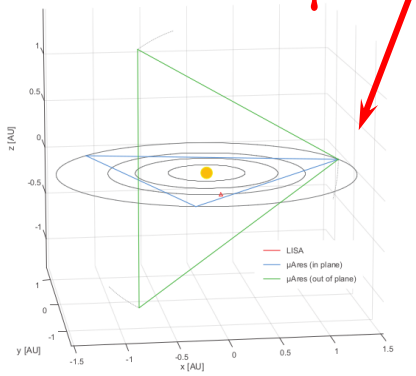
selected as Large Mission theme (2035-2050)

- "Adding colour and depth to GW sky"

white papers: cosmos.esa.int/voyage-2050

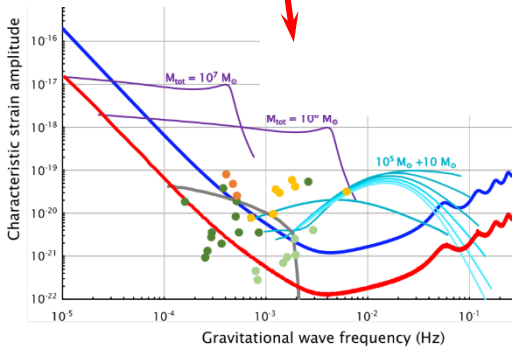
... and it will likely look a lot like LISA

μHz



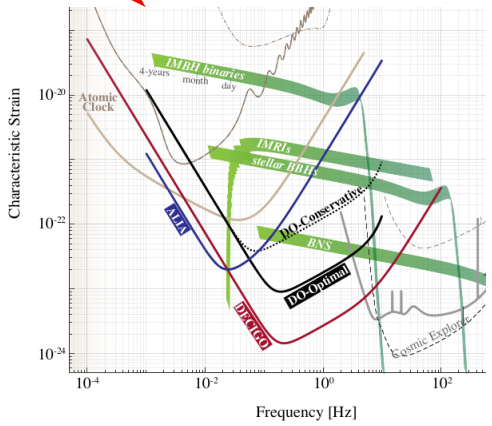
μARES ... $L = \sqrt{3} \times \mathrm{AU}$

mHz



AMIGO = LISA *10

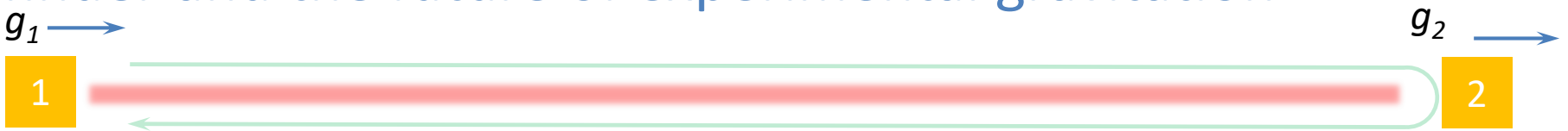
deciHz

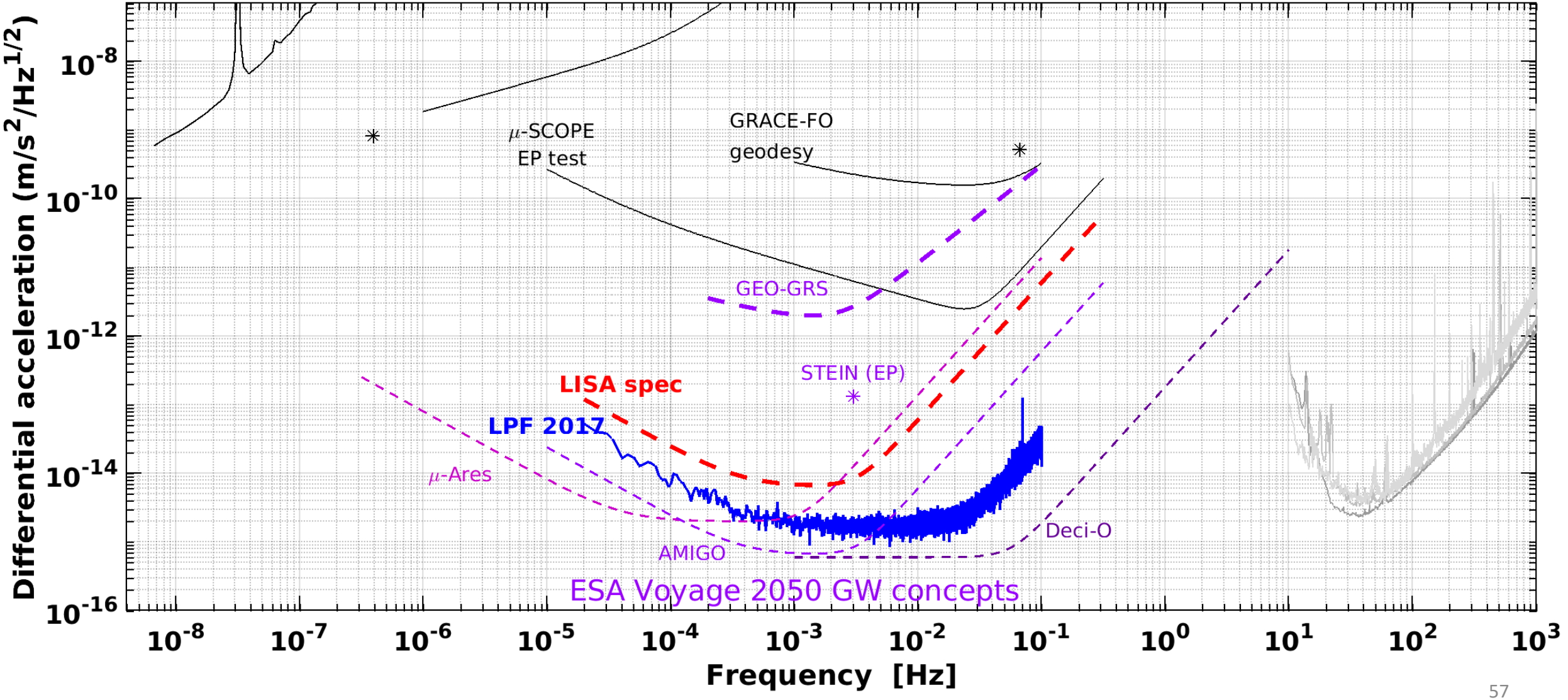


DO ... 10^5 km /10 W/D=2 m

- interferometry between macroscopic free-falling test masses in drag-free SC
  - a better test mass?
- vast science scope to be narrowed
- LISA will lead in defining "feasible" AND in defining scientific landscape

LISA, LISA Pathfinder and the future of experimental gravitation





LTPDA 3.0.14.dev (R2022b), 2026-04-19 13:34:07.345 UTC, ltpda: 0eece92, accel_noise_mission_comparison_20260412

Thank you!

Trento LISA team

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