Observing GW from space : The LISA mission

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LISA CONSORTIUM

LISA FRANCE

Outline

- Introduction
- LISA Science Objectives
- From LISA Pathfinder to LISA
- Mission description
- Conclusion

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- **Introduction**
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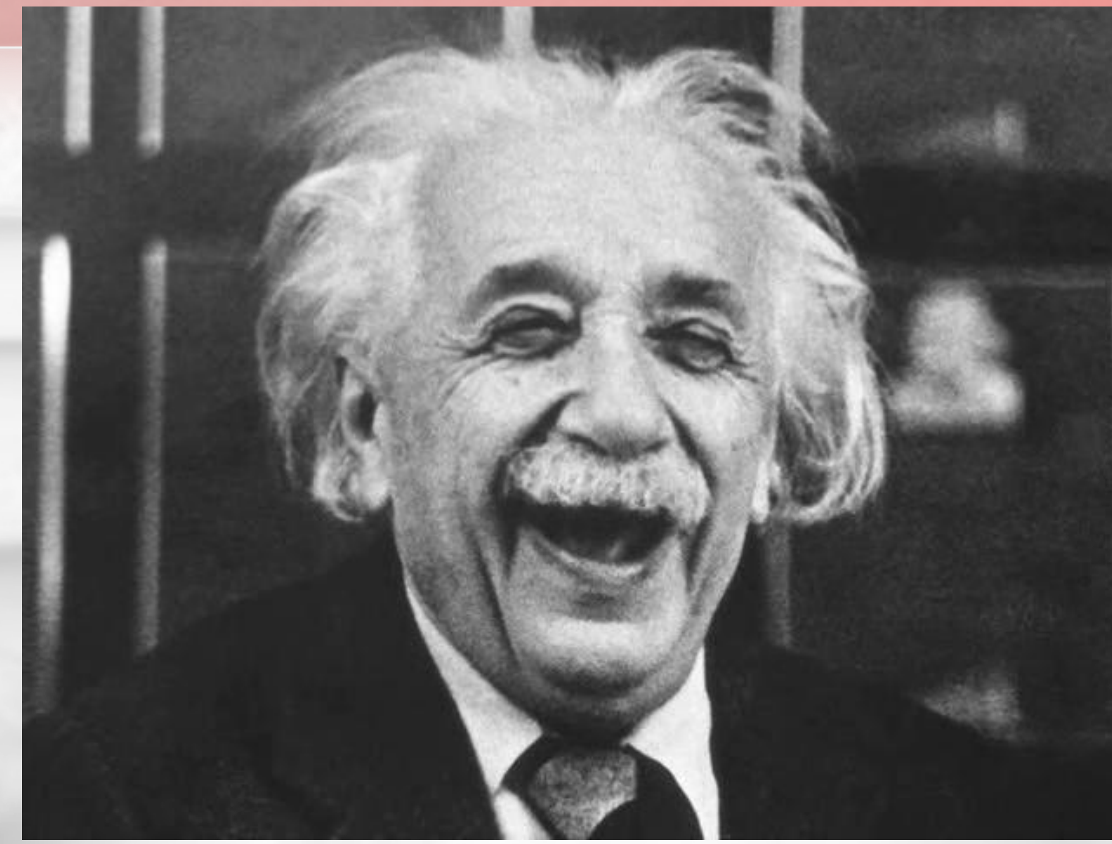
Reminder …

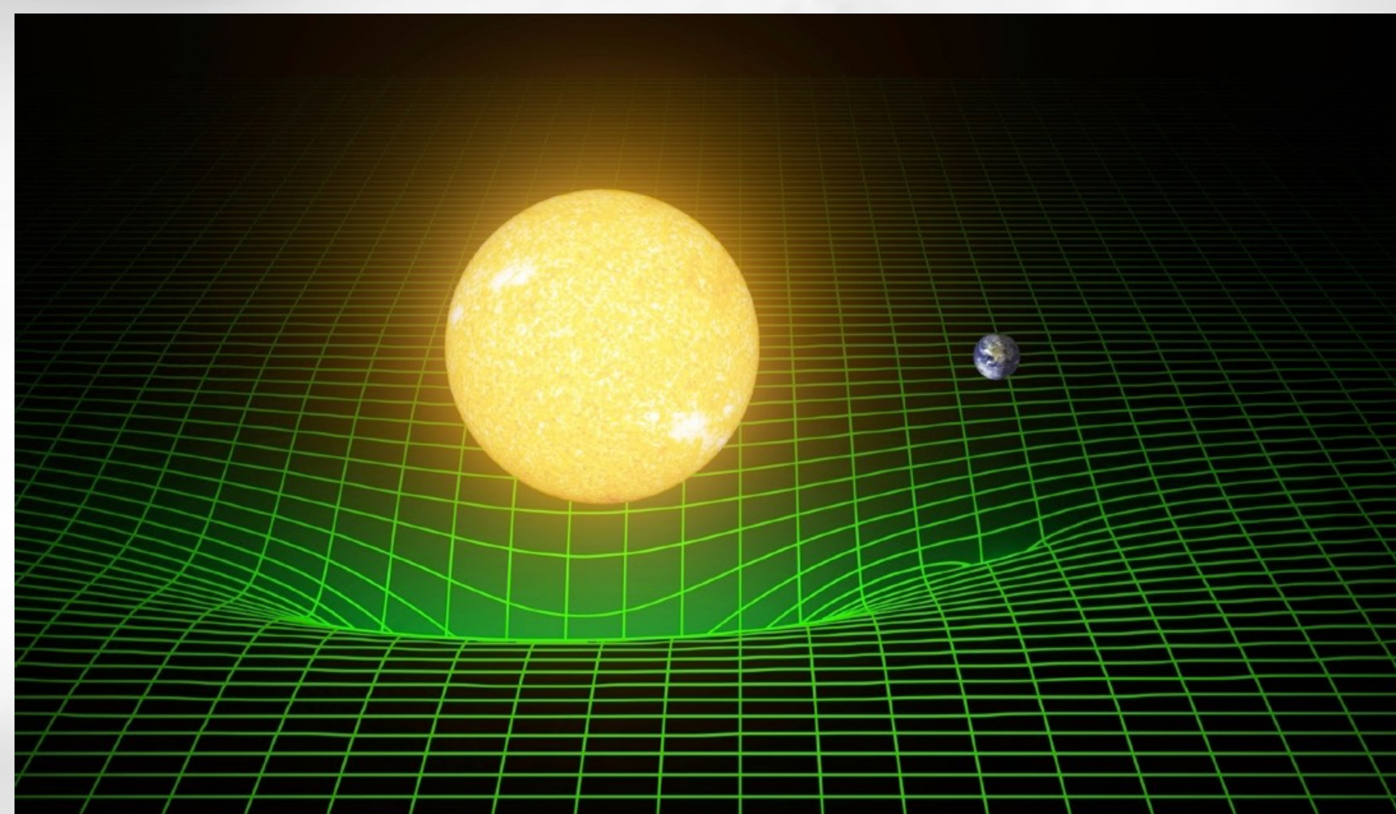
- Albert Einstein (1915) : Gravity is not a force …
  - Mass deforms geometry of space-time.
  - Bodies are moving in a curved space.
  - Gravitational information propagates at the speed of light.
  - Dissipation of energy through deformation of space-time ==> gravitational waves



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometry of space-time

Energy distribution



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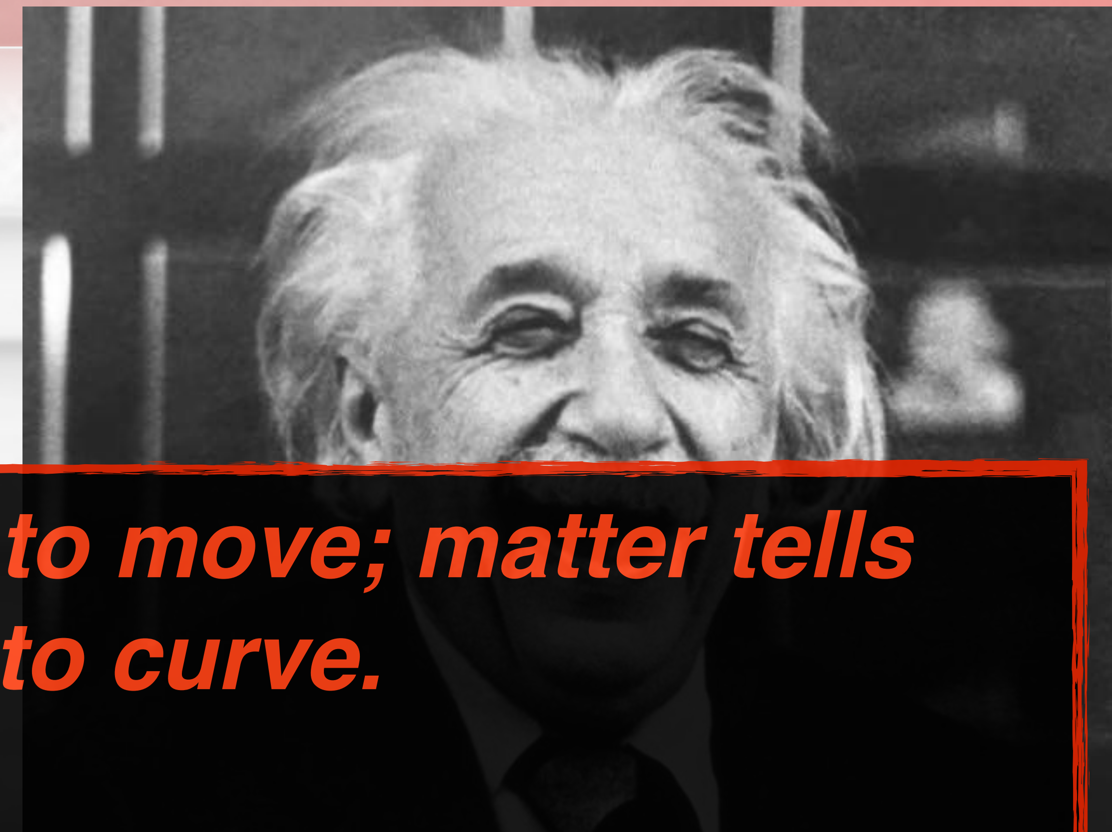

Spacetime tells matter how to move; matter tells spacetime how to curve.

John Archibald Wheeler, "Geons, Black Holes, and Quantum Foam: A Life in Physics", 1990

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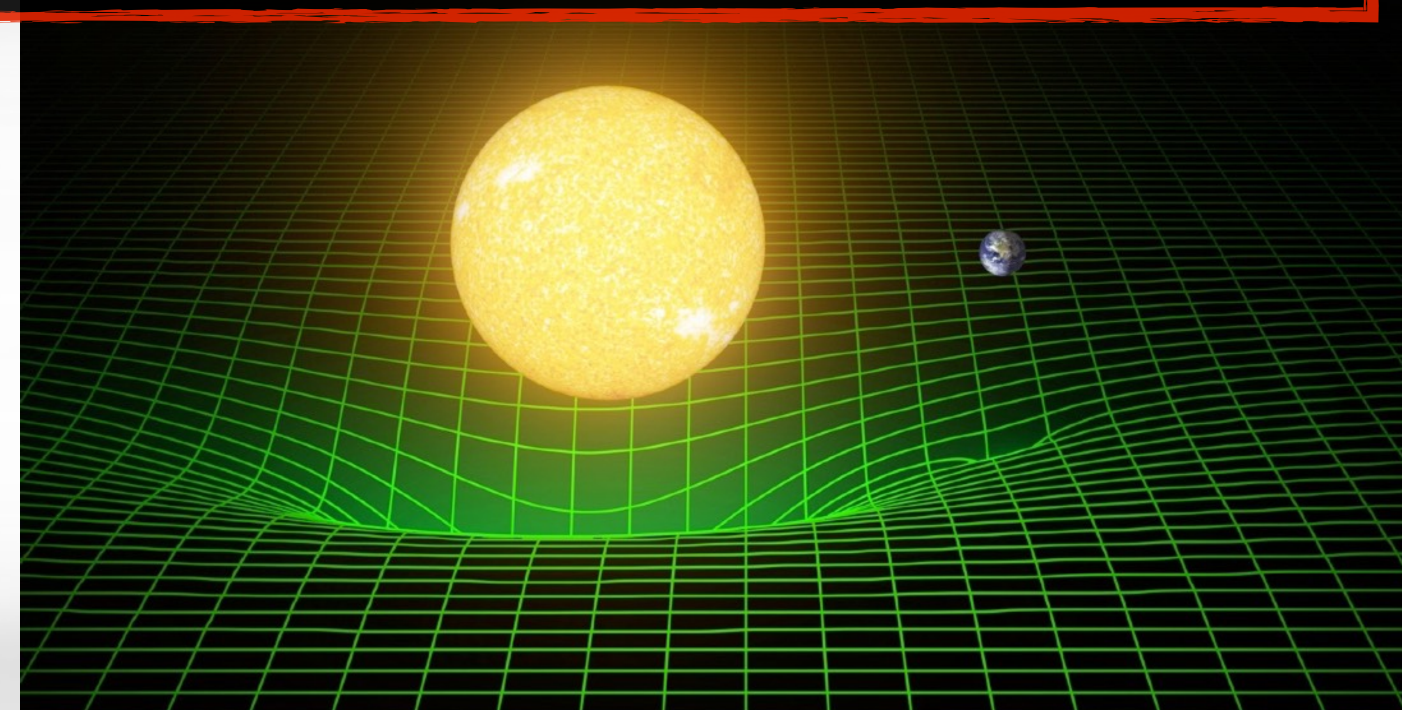
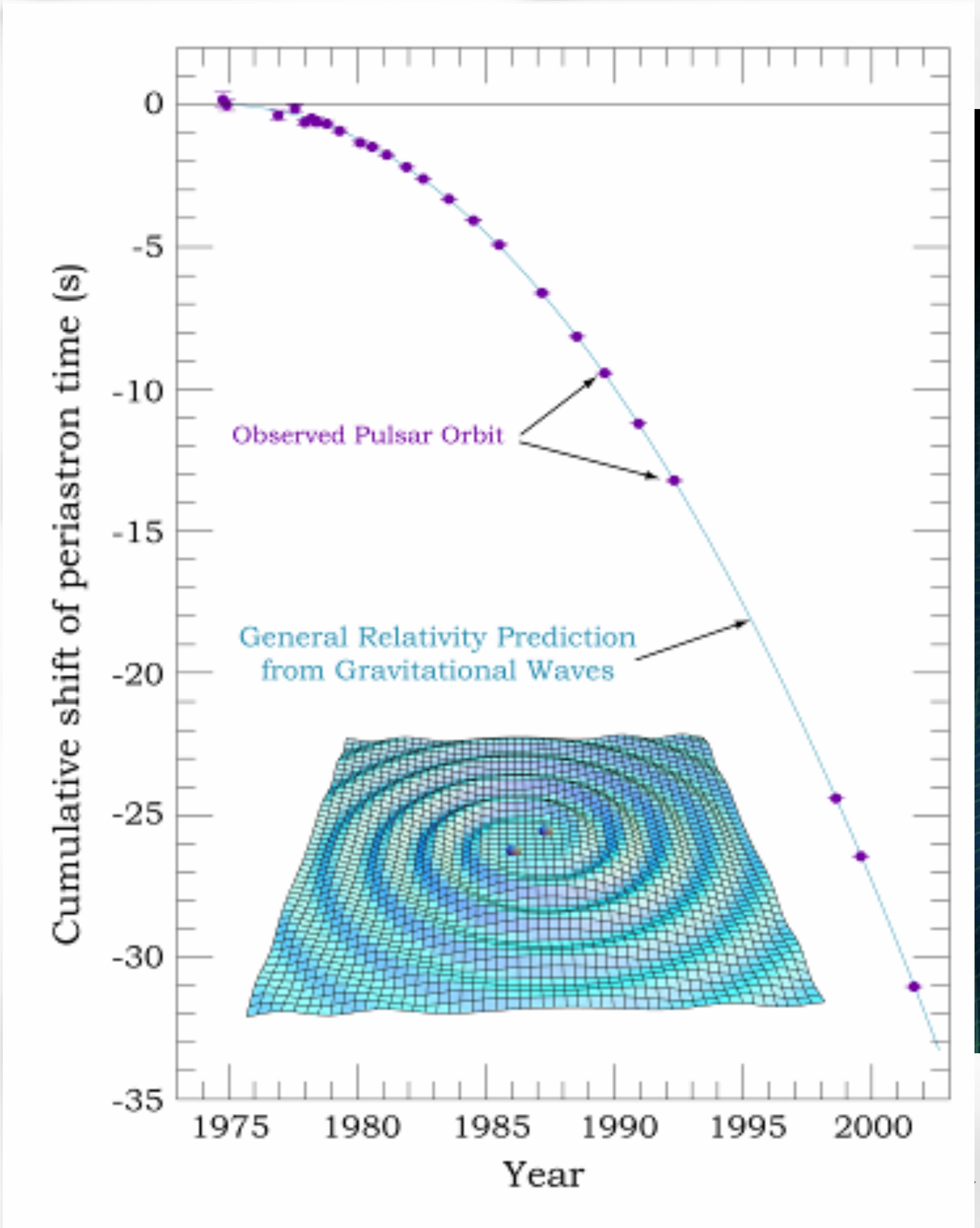
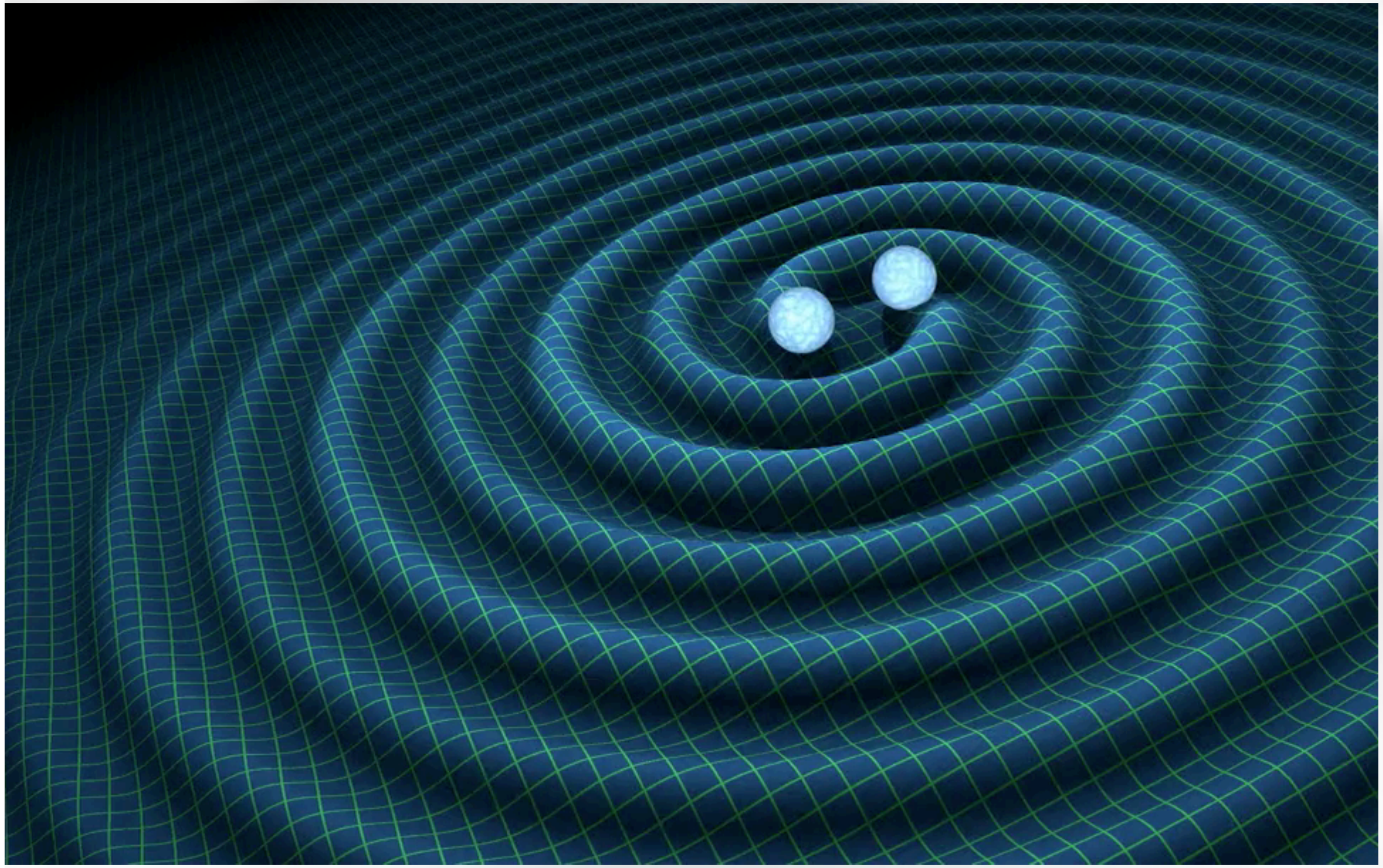


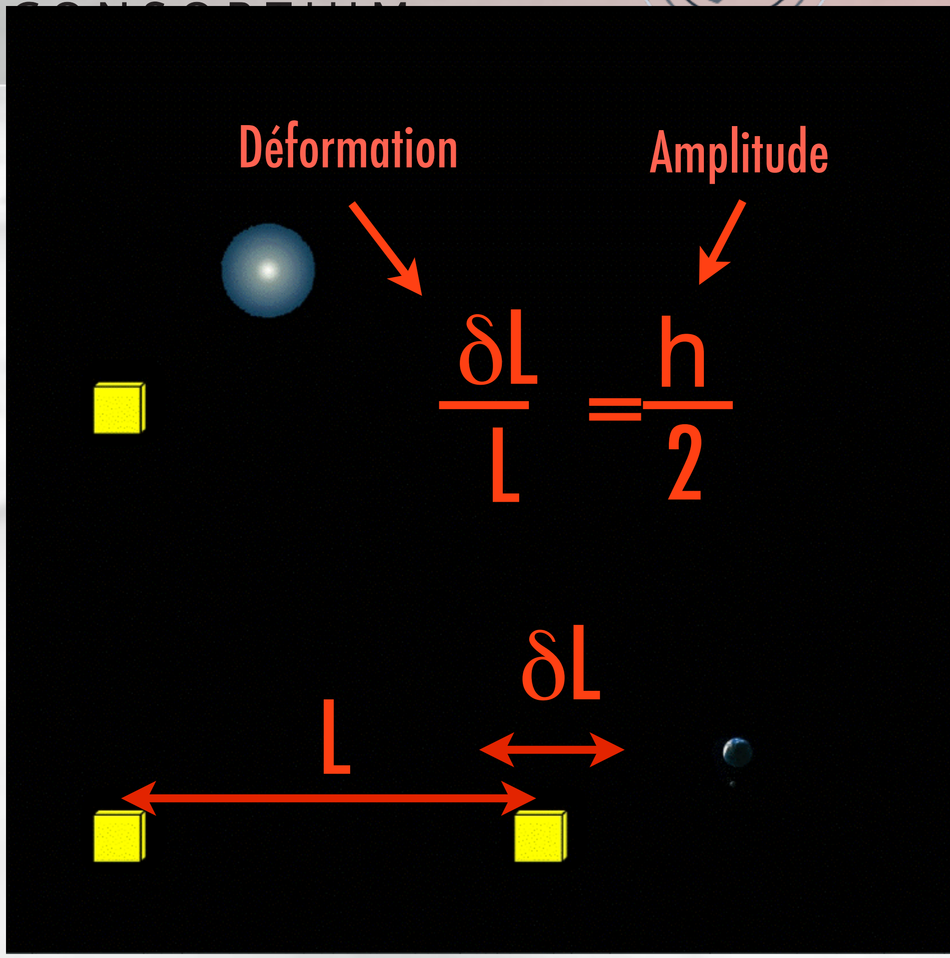
Gravitational waves ?

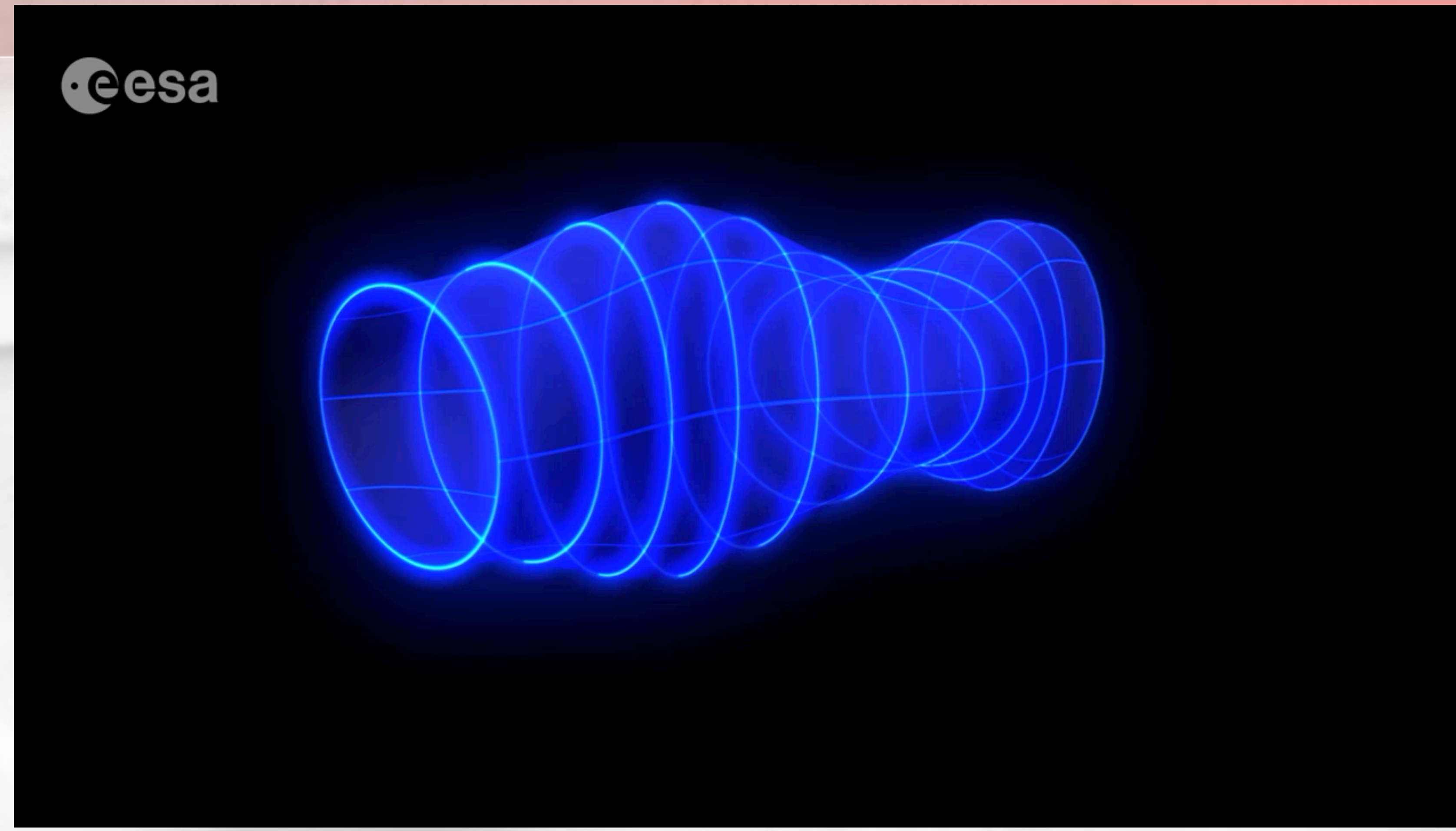
- What are GW ?
  - The GW are elastic deformations of the space-time metric
  - Transverse, quadrupole waves, 2 polarisations

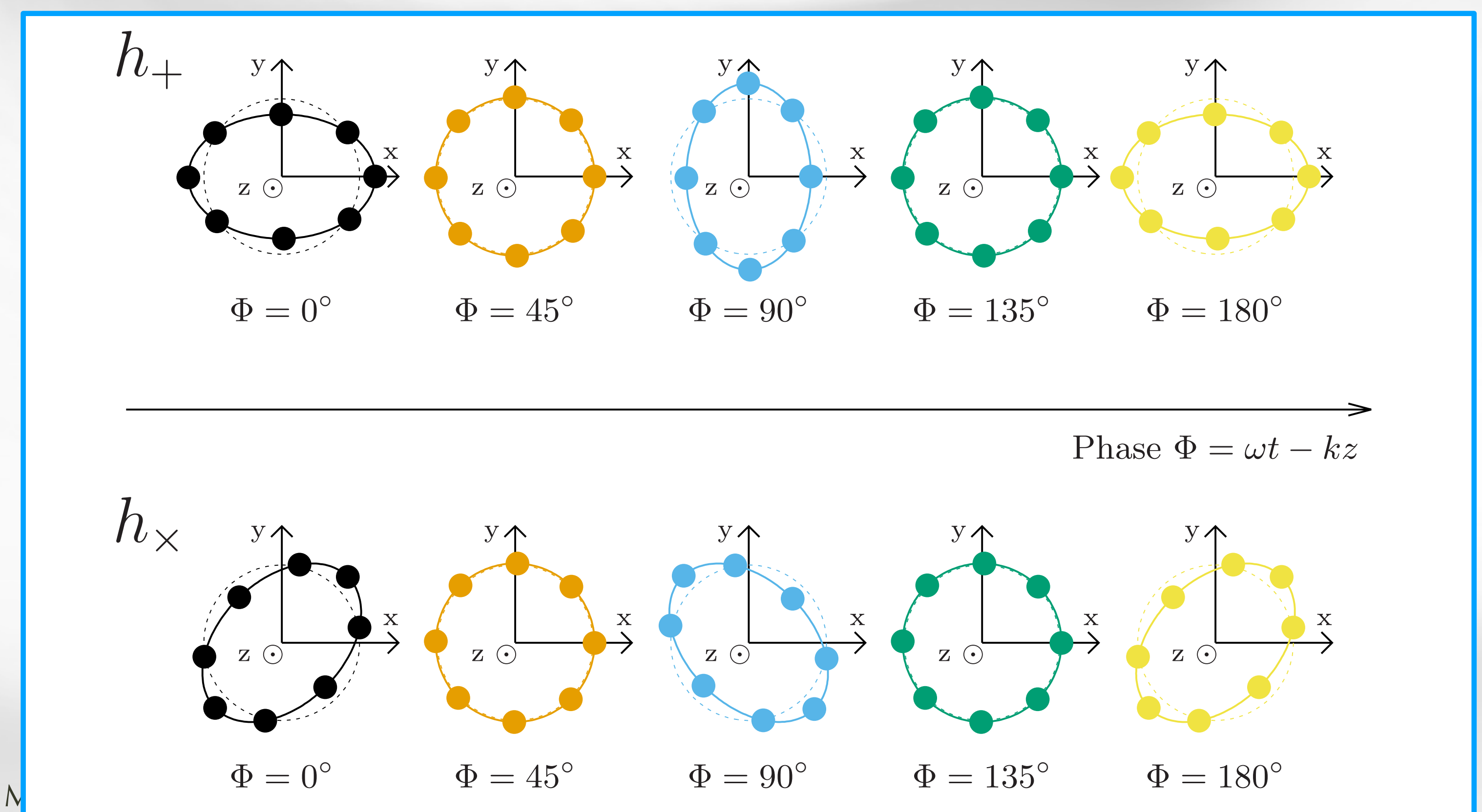


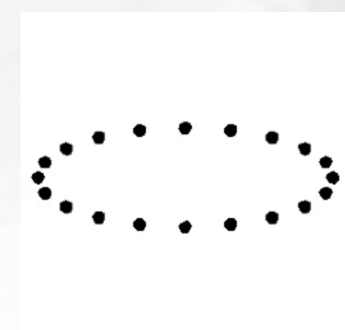


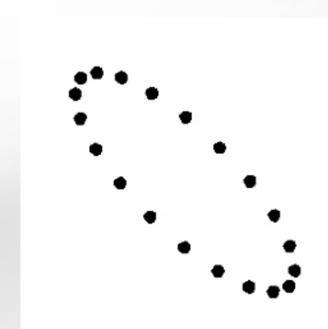
GW = space-time deformation









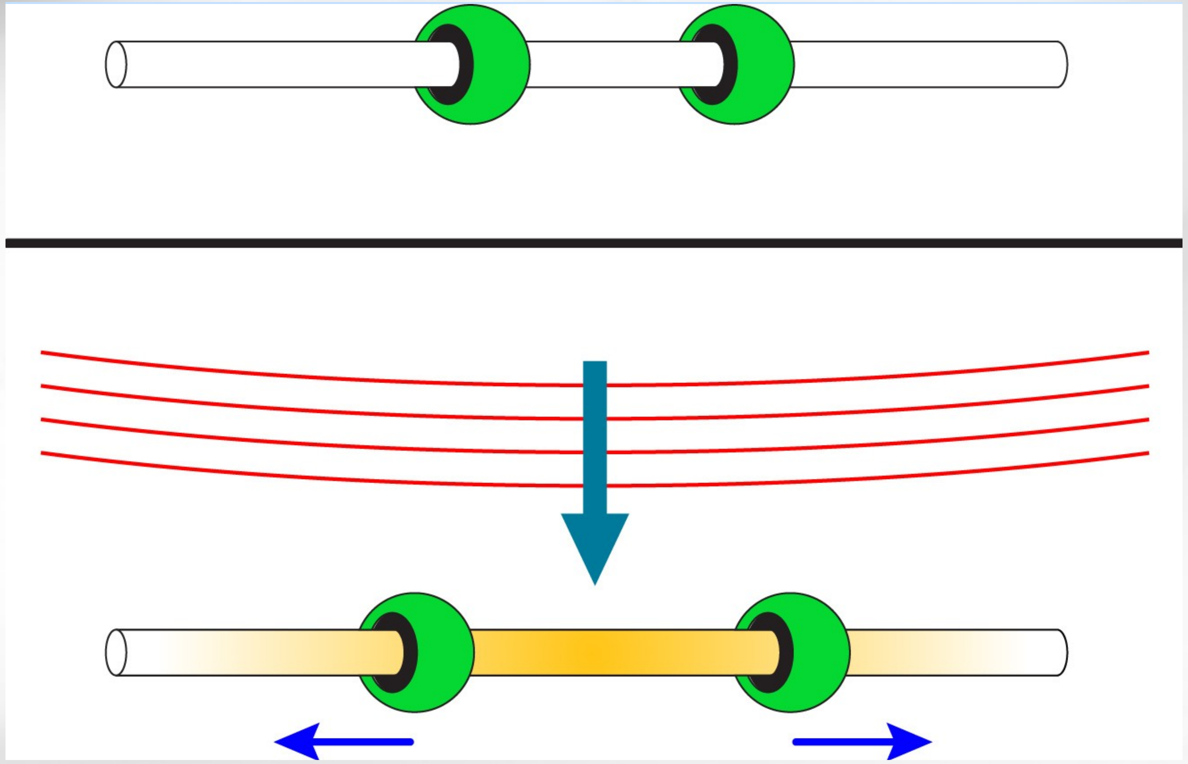


Are they detectable ?

- Until 1950's the approximations used to compute the GW induced doubts in their 'real' physical effects.
  - Linear perturbations of a flat space-time
    - —> What is the influence of the strong curvature zone close to the source ?
  - Traceless, transverse gauge
    - —> Could GW be an artefact of this particular choice of coordinate system ?

- Do GWs have an actual physical effect ?
  - Pirani [1956] : Yes, space-time curvature changes induce fluctuations in the proper distance between inertial objects

- Do GWs carry energy ?
  - Yes : the 'Sticky bead' argument [Feynman & Bondi, Chapel Hill Conference, 1957]



Astrophysical GW sources

- Orders of magnitude
  - Compacité of a gravitational system

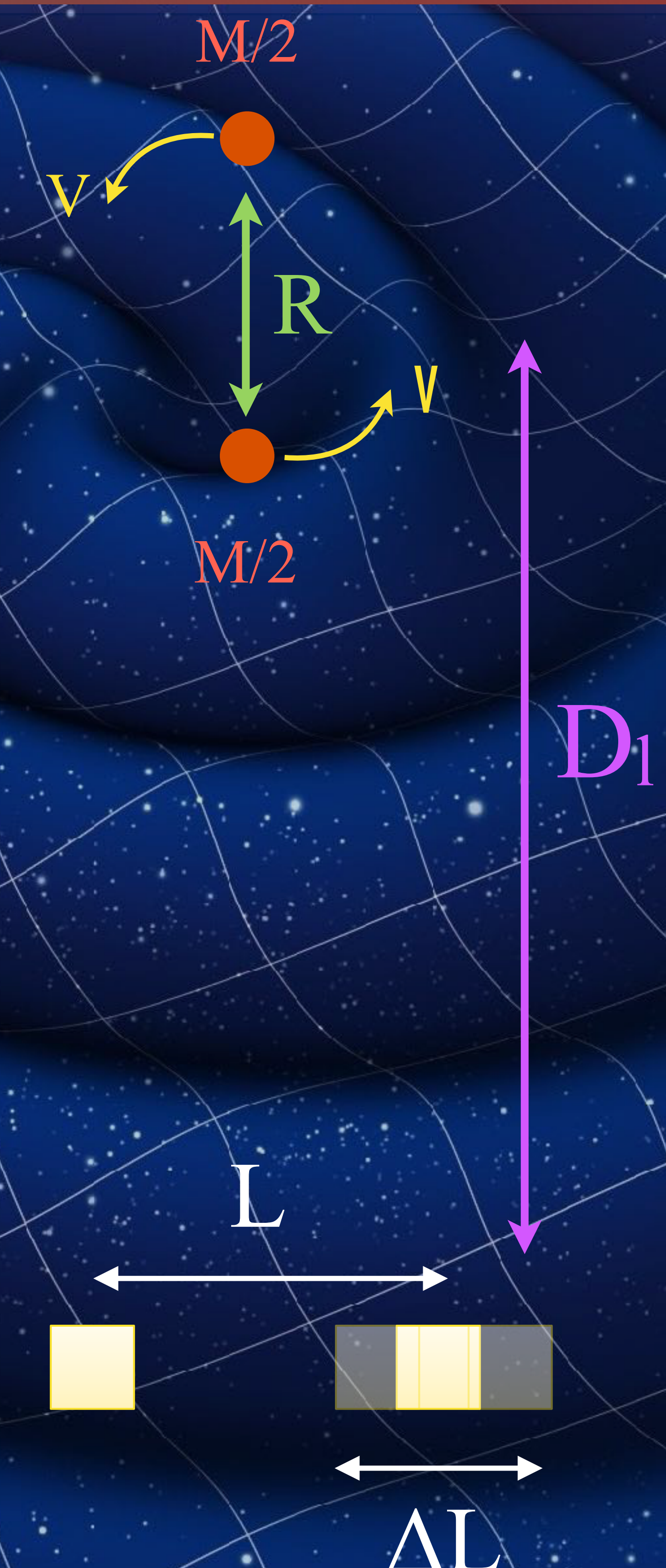
$$\frac{v^2}{c^2} \approx \frac{GM}{Rc^2} = \Xi < 1$$

  - Wave amplitude

$$h = 2\frac{\Delta L}{L} \lesssim \frac{\Xi}{10^{-1}} \cdot \frac{M}{10^6 M_\odot} \cdot \frac{10\ \mathrm{Gpc}}{D_l} \quad \mathrm{nm/Mkm}$$

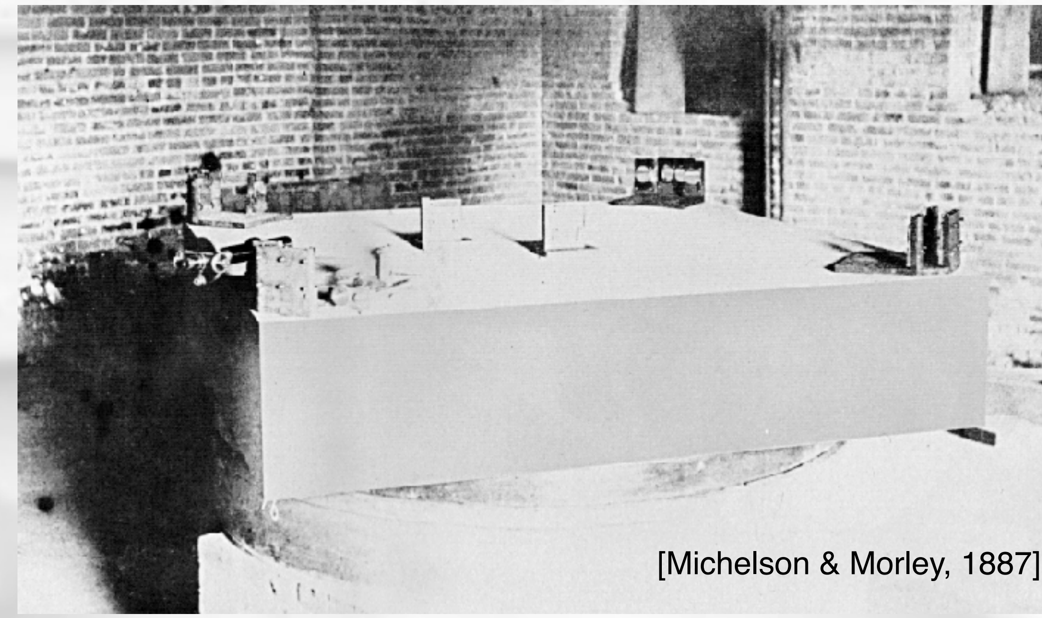
  - Wave frequency

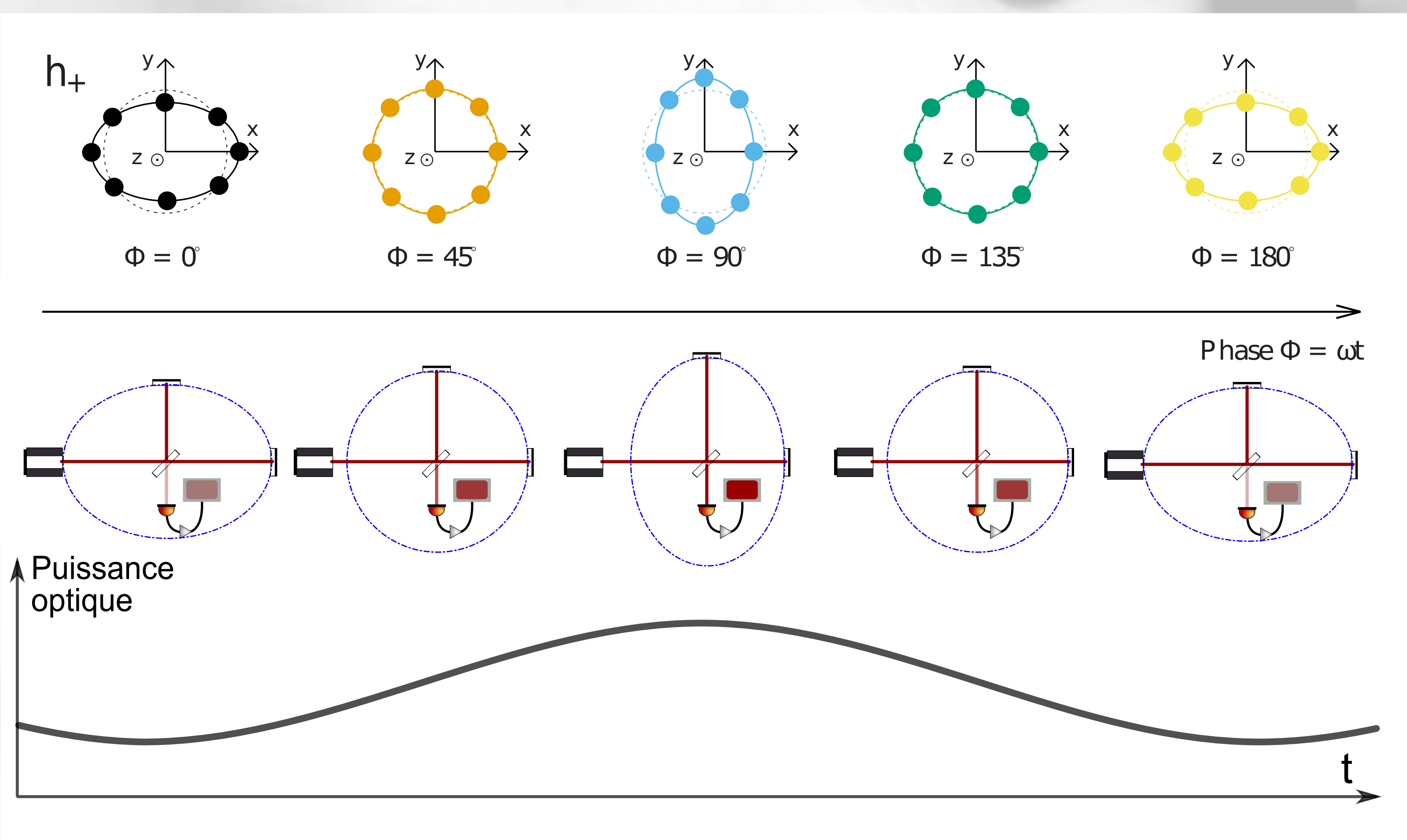
$$f \approx 14 \times \left(\frac{\Xi}{10^{-1}}\right)^{3/2} \cdot \frac{10^6 M_\odot}{M} \quad \mathrm{mHz}$$



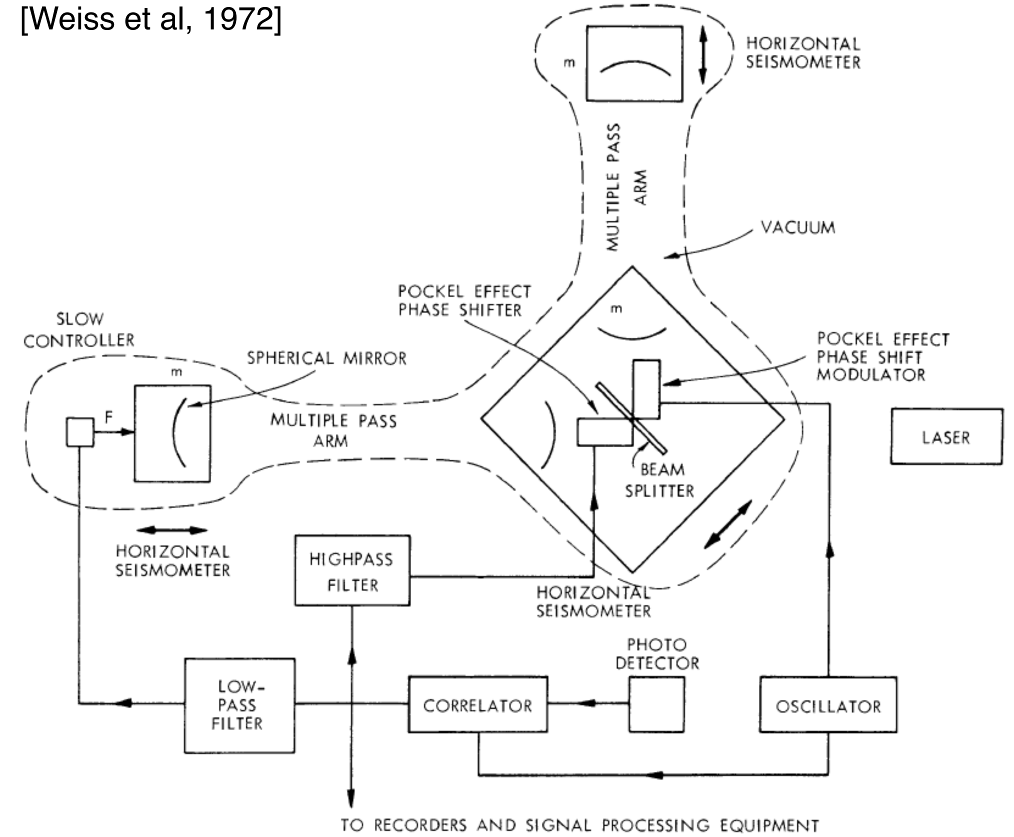
Interferometric detectors

- The geometry and sensitivity of the Michelson interferometer particularly well suited for detecting Gas
  - Require mirrors 'free falling' along the line of sight
- First concepts in the 60's in USSR [Gertsenshtein et Pustovoit, 1963] an in the USA [Moss et al, 1971]
  - R. Weiss, 1972 : identification and computation of the most important sources of noise

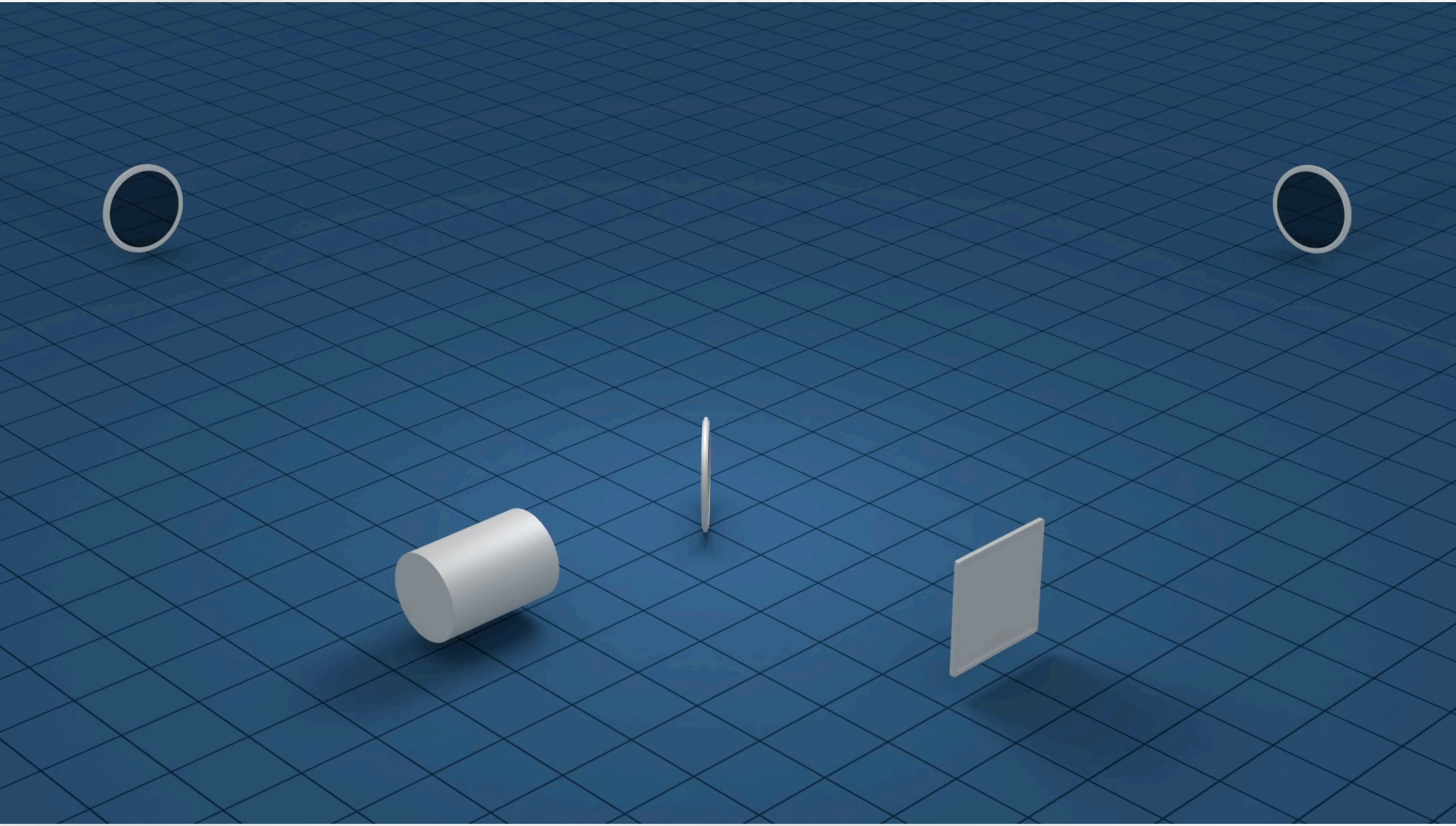

[Michelson & Morley, 1887]



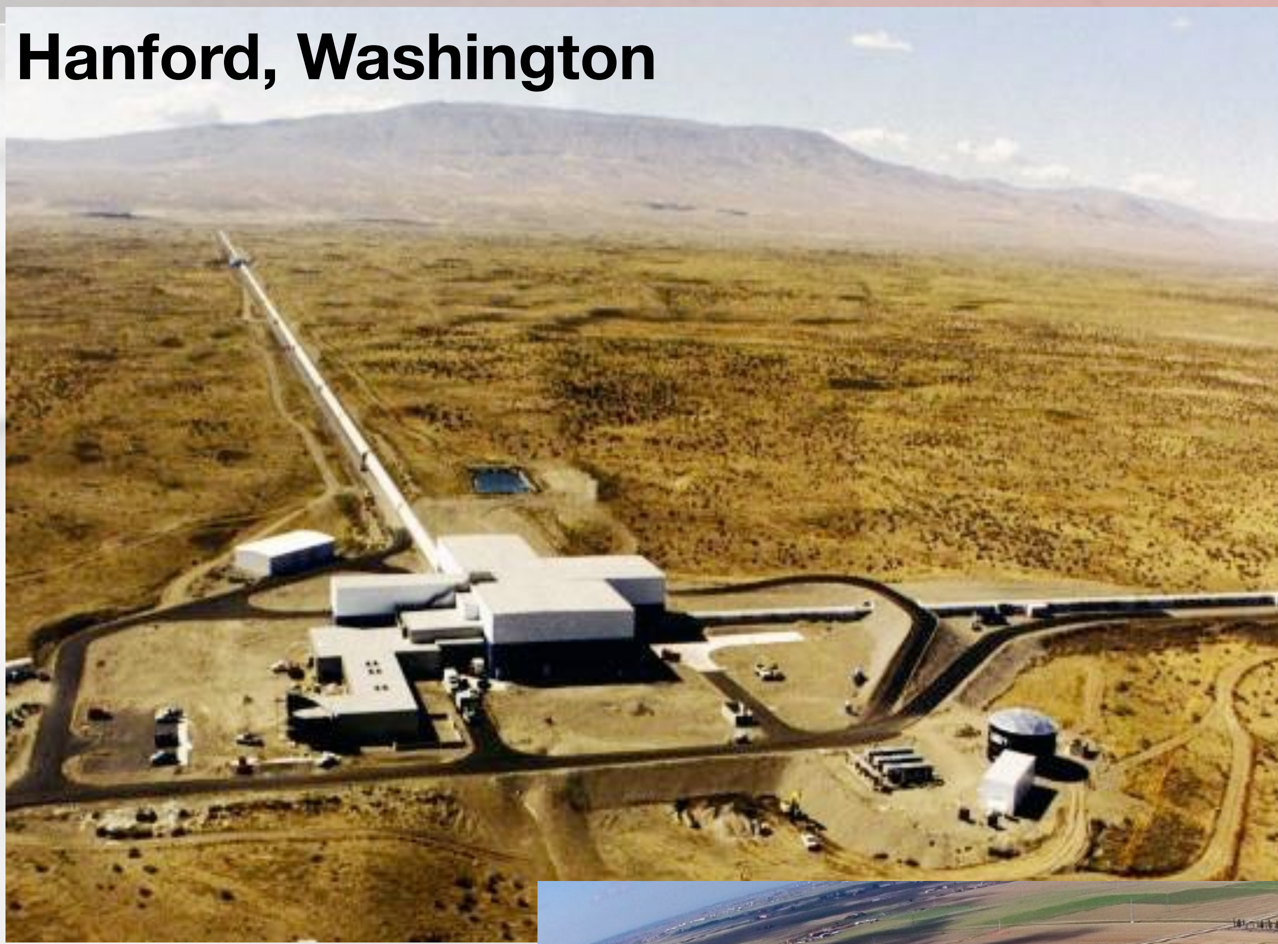
[Weiss et al, 1972]



Interferometric detectors



Ground based interferometers



VIRGO
3 km
armlength

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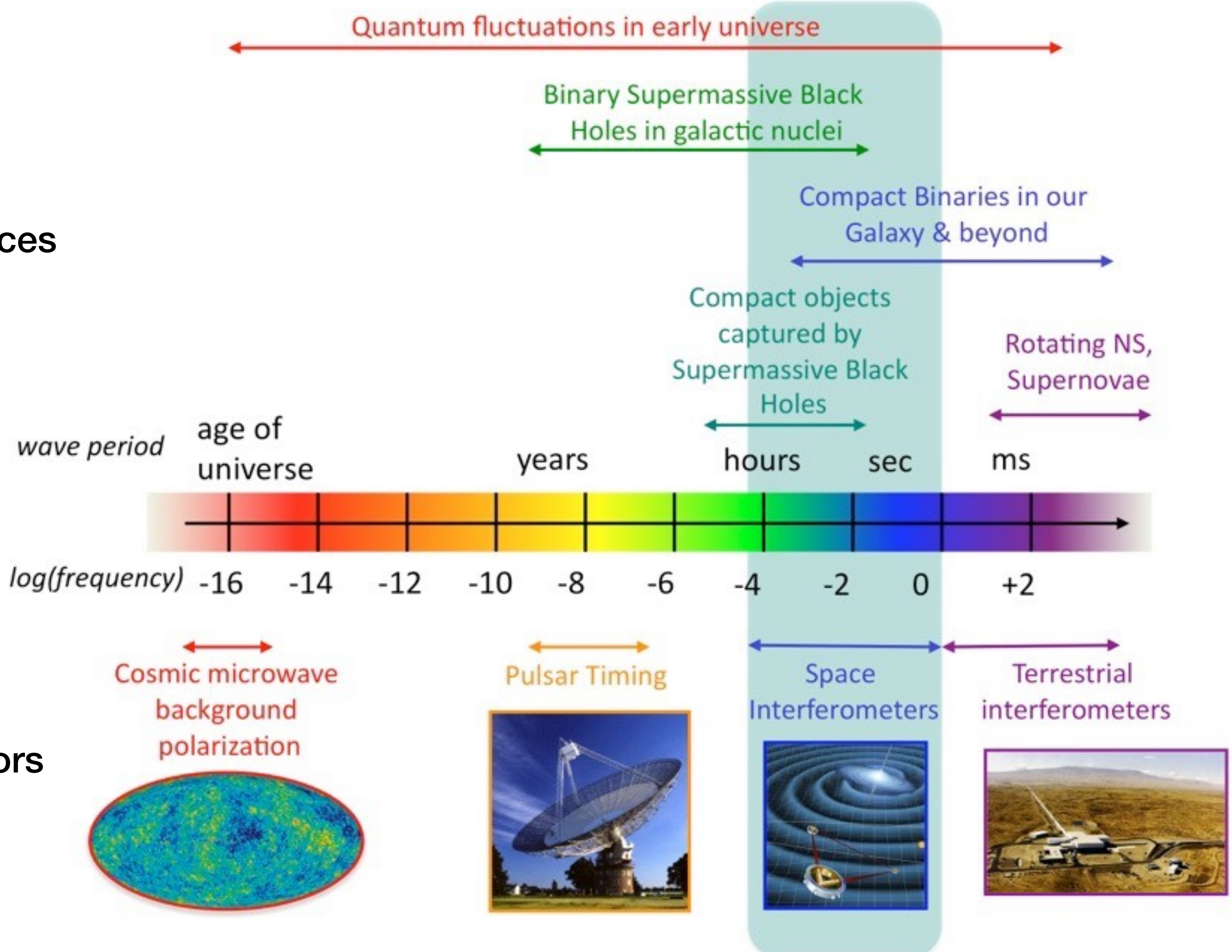
The GW spectrum

Sources



Detectors

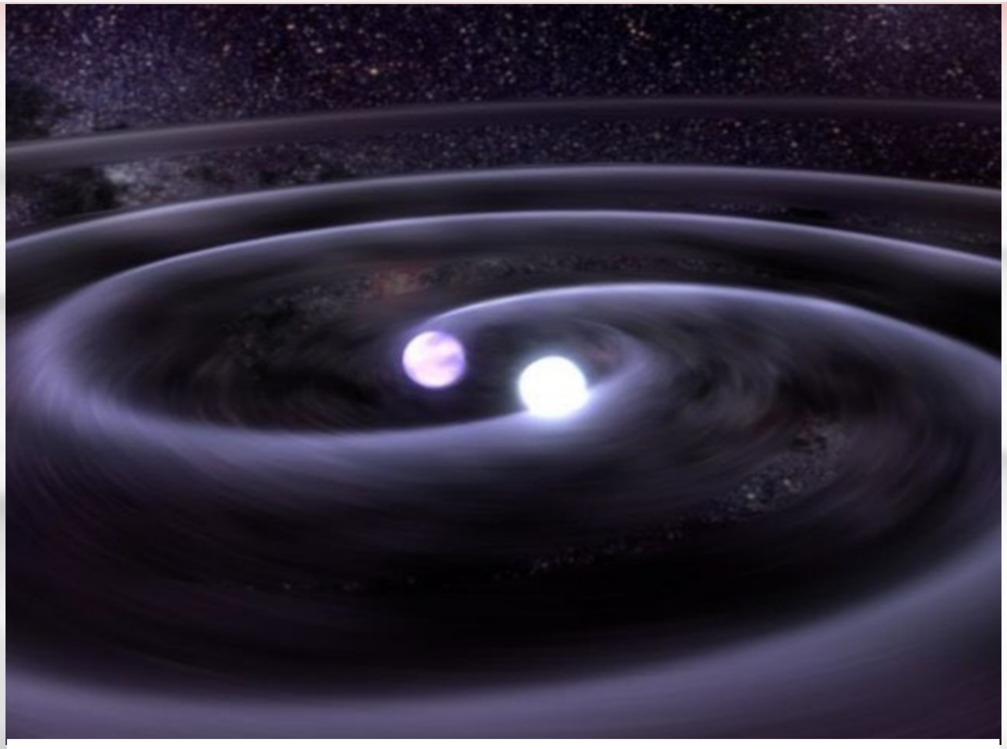
Study the formation and evolution of compact binary stars in the Milky Way Galaxy.

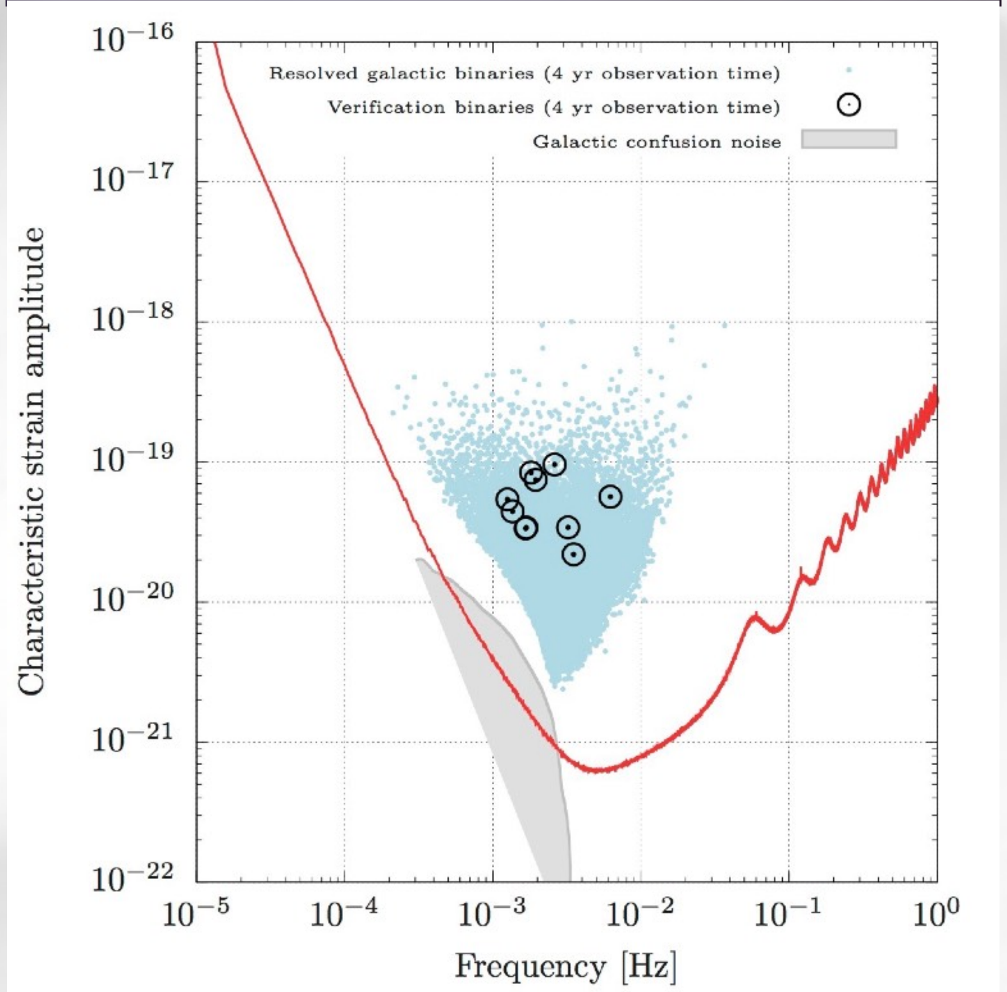
- Large number of stars are in binary systems

- Evolution in white dwarf (WD) and neutron stars (NS).
  - Existence of WD-WD NS-WD and NS-NS binaries
  - Estimated population for the Galaxy : ~10^7.

- Monochromatic sources for LISA (far from coalescence)

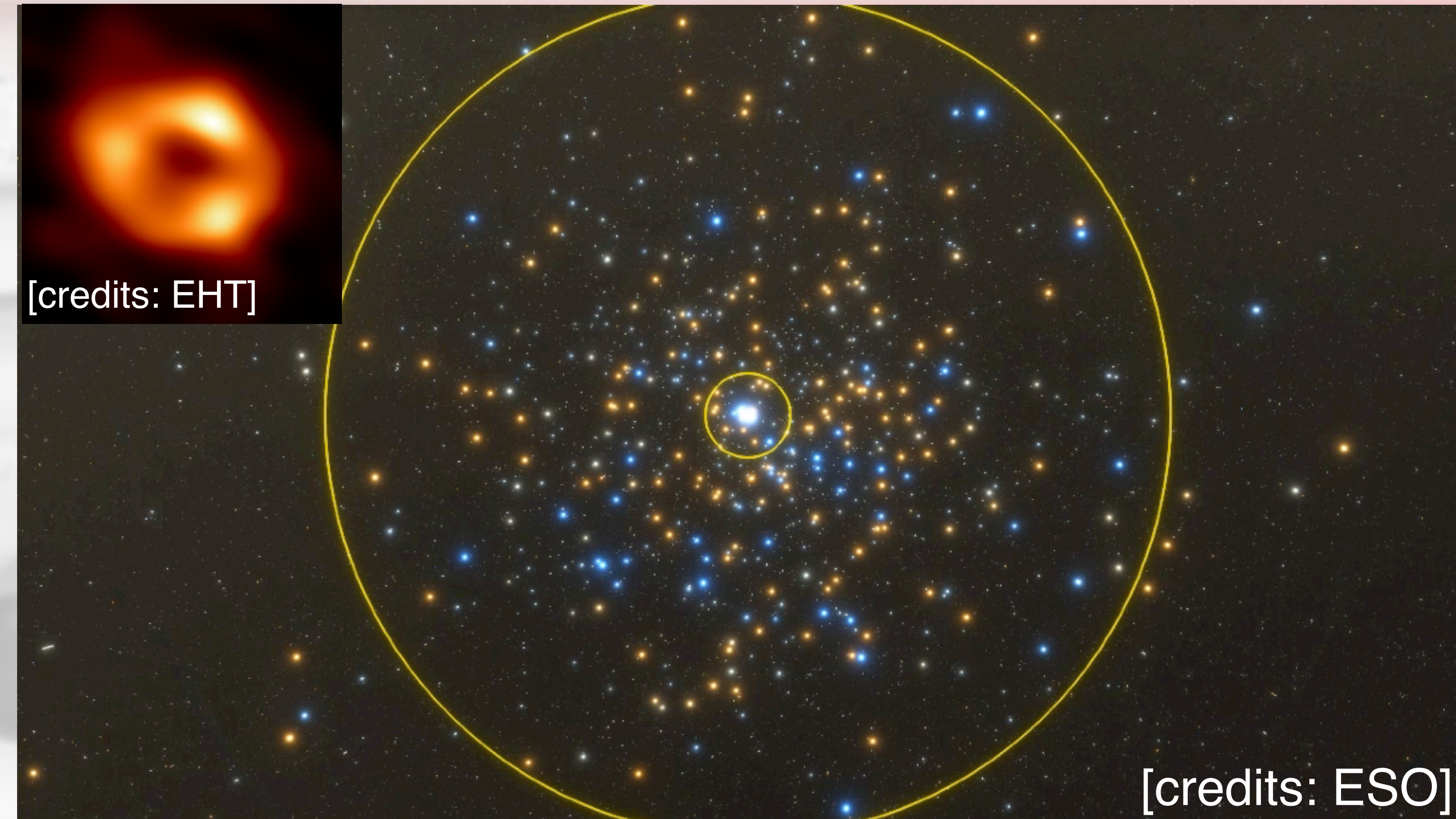
- Three categories
  - Joint EM - GW sources (Gaia, LSST)
    - Already ~10 known verification binaries in the LISA band
  - Individually detected : ~10^4
  - Stochastic GW signal
    - foreground 'noise'





Massive BH binaries

- Massive BHs in the nucleus of every Galaxy
  - 4 10^6 M_{sun} at the center of the Milky Way
- MBHs accumulate mass
  - gas accretion
  - merging with other BHs
- Galaxies merge
  - observed…
  - may result in a MBH binary which could merge in a reasonable time
    - Stars and/or gas required to dissipate orbital momentum and bring it in GW driven regime

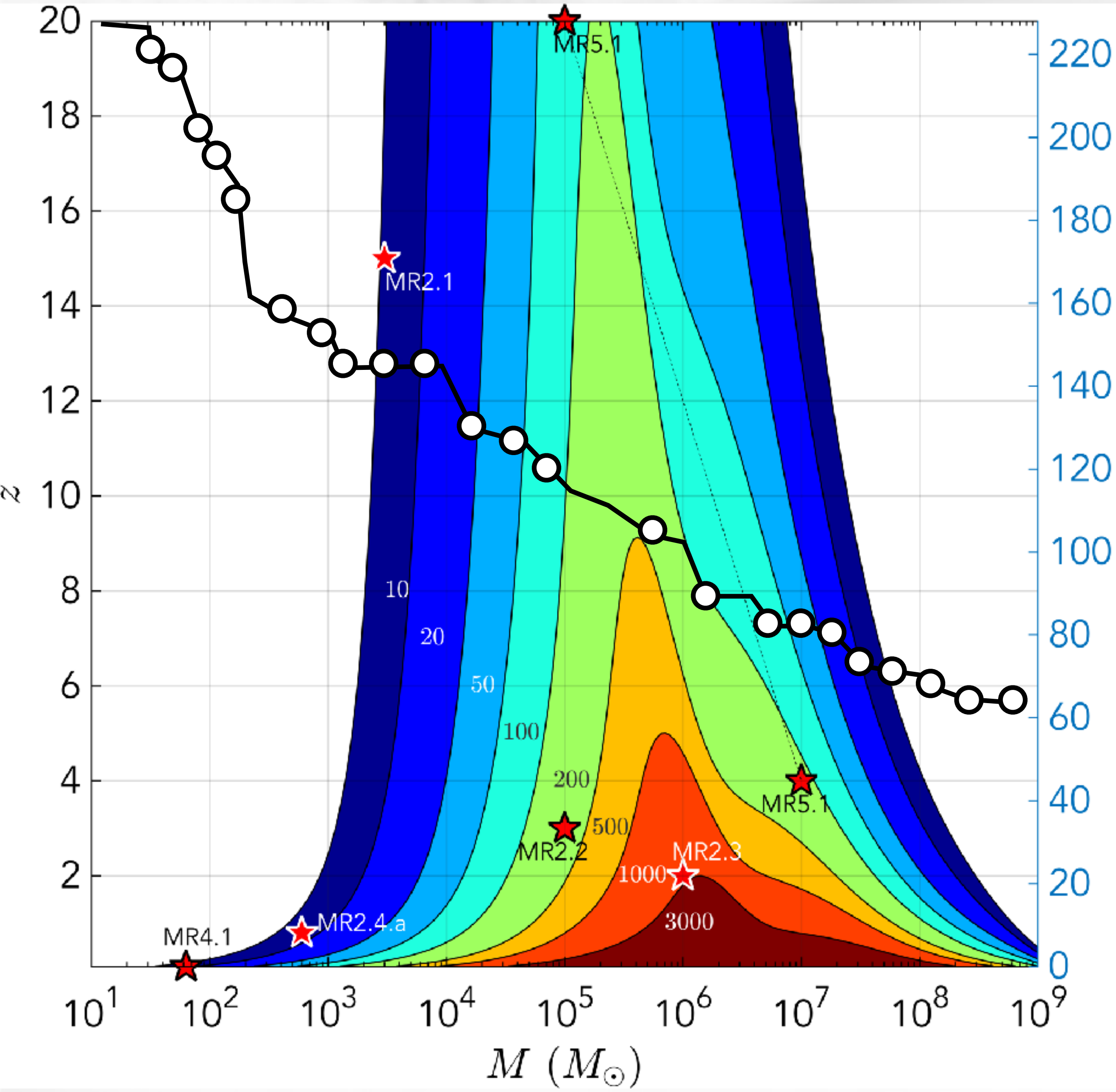


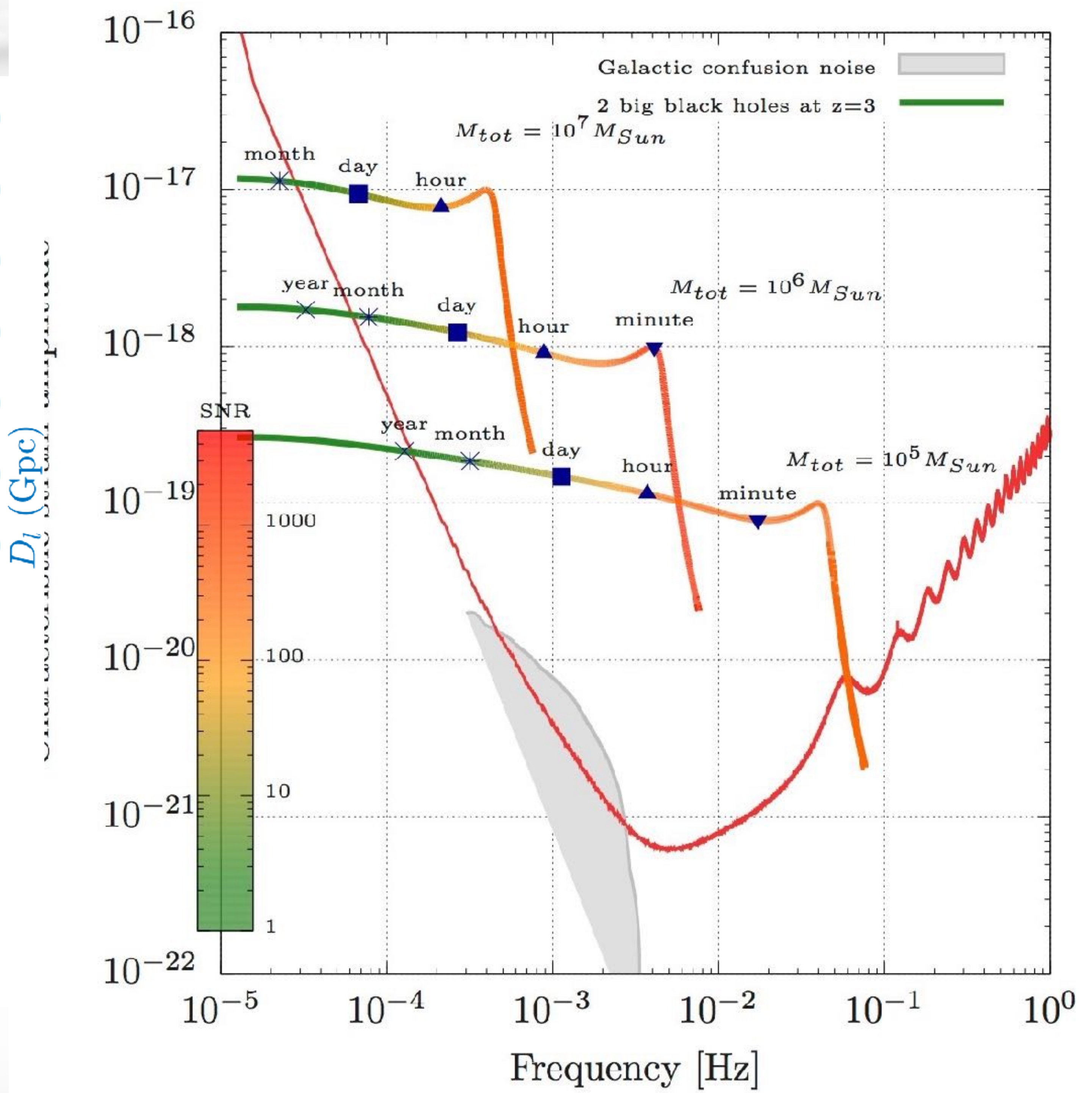
[credits: EHT]

[credits: ESO]

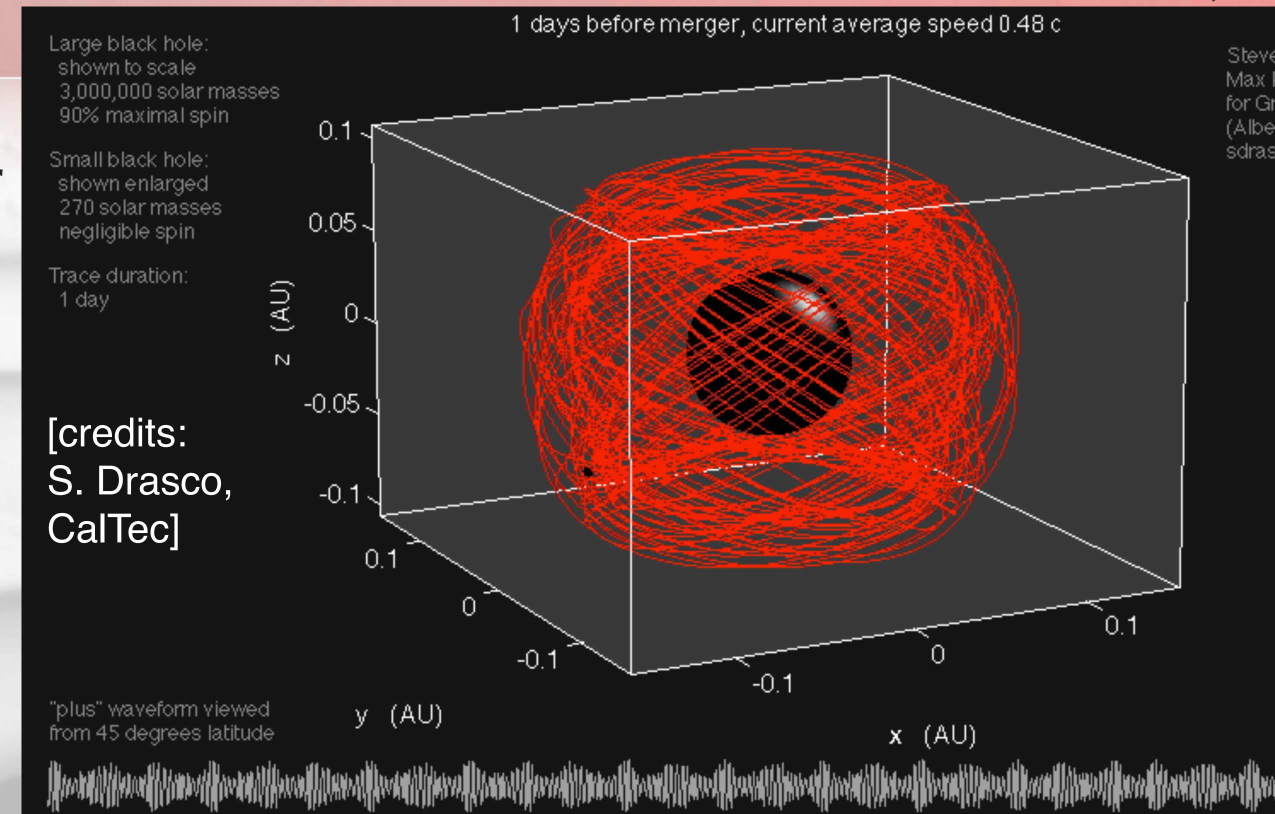
[credits: HST]

Origin, growth and merger history of massive black holes across cosmic ages

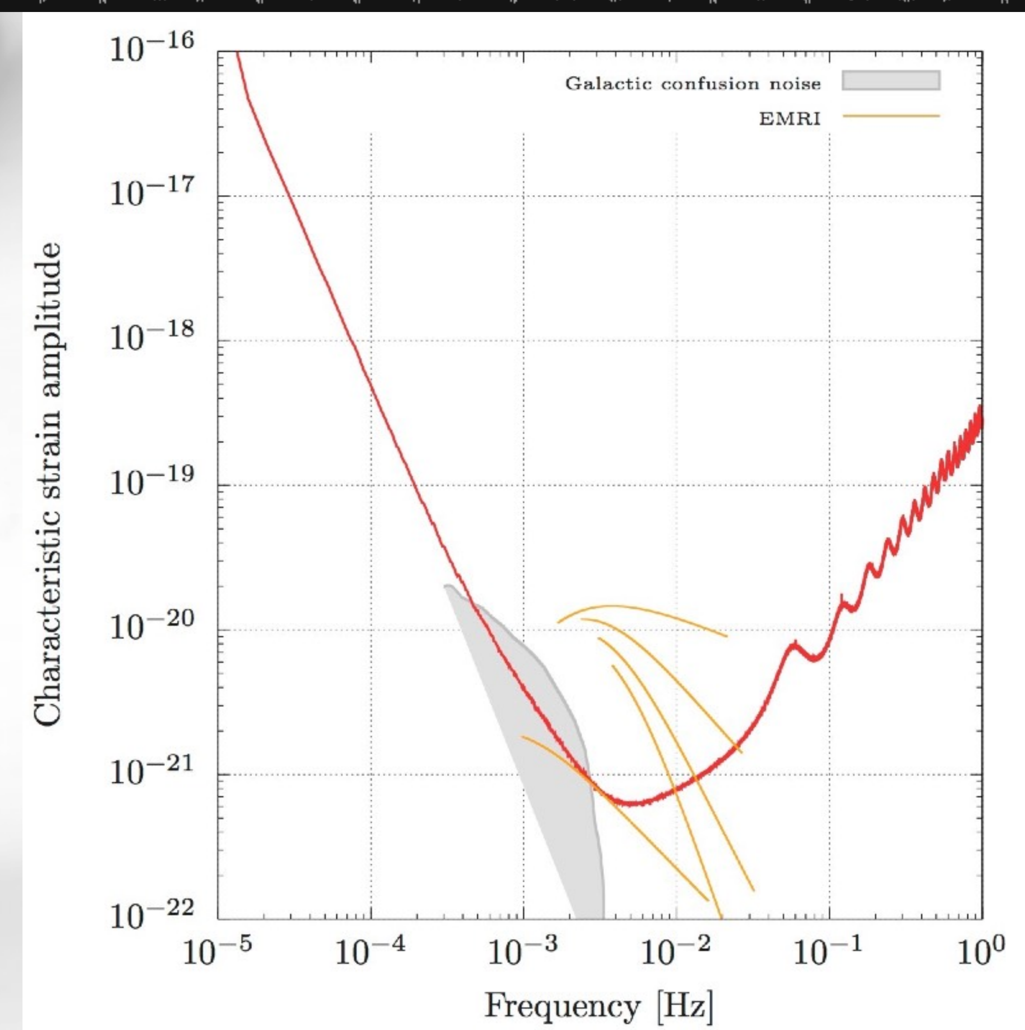




EMRIs (extreme mass ratio inspirals)

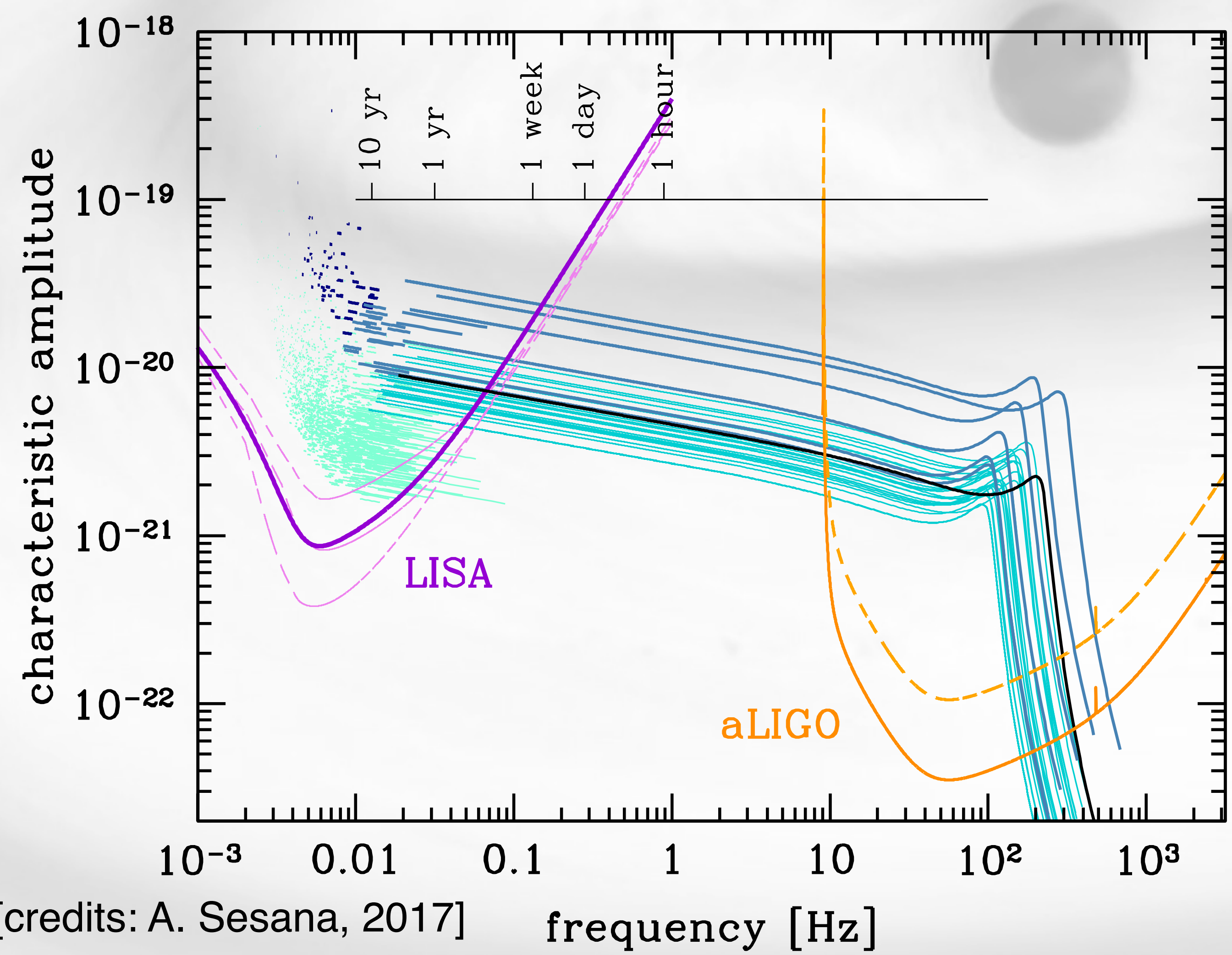


- Massive BHs could be embedded in stellar cusps
  - high density stellar environment
- Massive BH could capture a compact object
  - companion : NS, stellar mass BH
  - very eccentric orbit shrinking under GW radiation
- EMRI: Binary system with an extreme mass ratio: 10^{-7} - 10^{-5}
  - ~10^6 orbits of the compact object close to the MBH before the plunge
- Companion as 'test particle'
  - Strong relativistic effects
  - Complex (and very informative…) waveforms

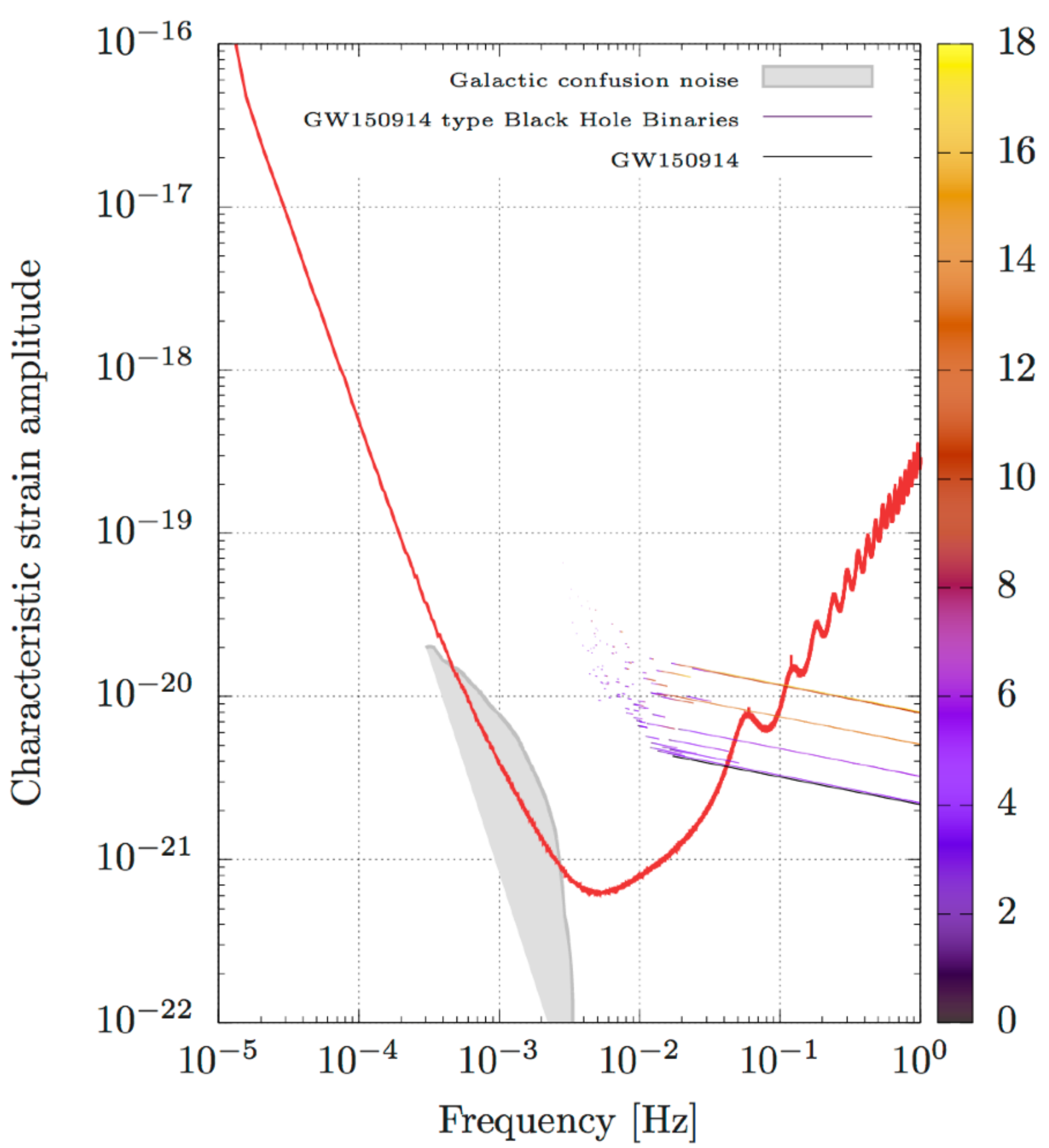


Multiband GW astronomy

- Stellar BH may be detectable by LISA prior coalescing in the ground based detectors band
  - Observed for ~years in LISA until ~days before merger
- Possible pre-warning
  - Time of coalescence at ~10s accuracy
  - Sky localisation : 0.1 - 1 deg^2

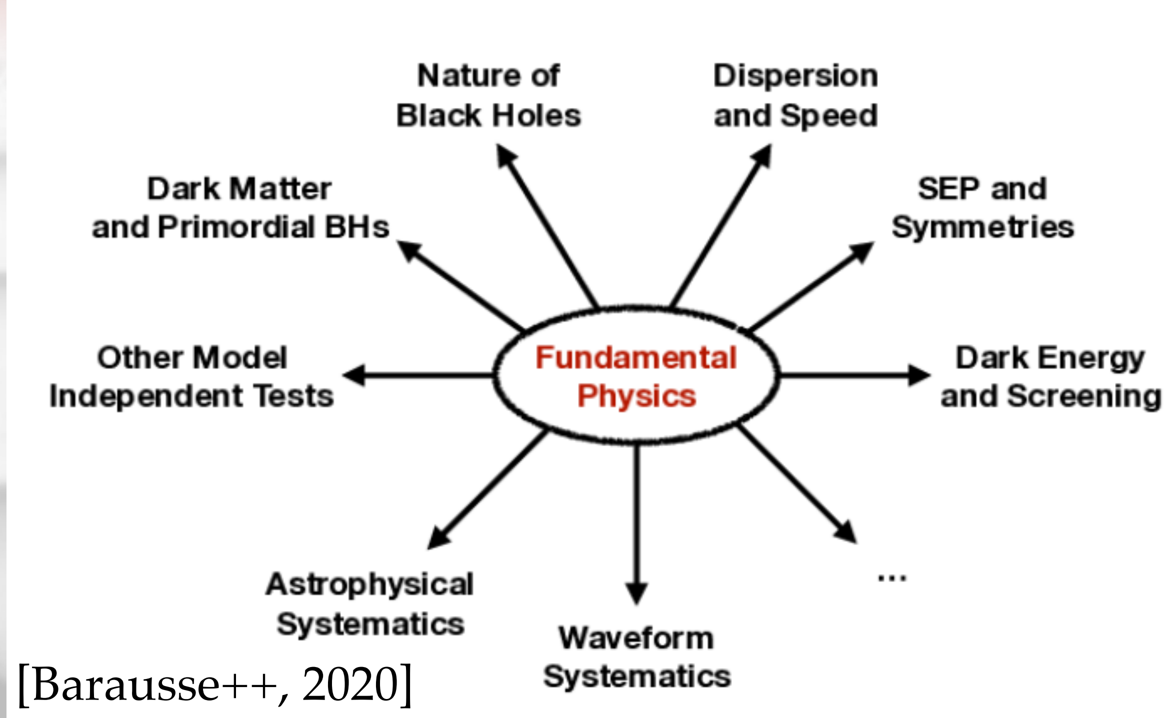


[credits: A. Sesana, 2017]



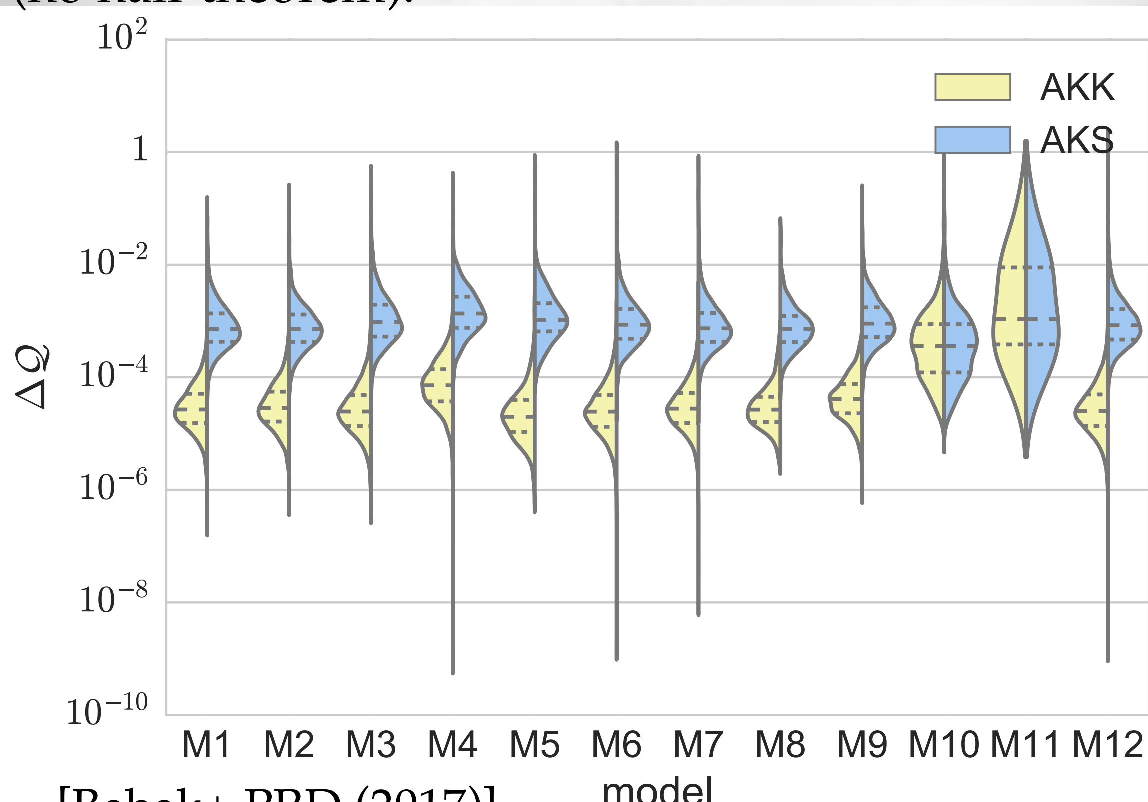
Fundamental physics with LISA

- Using emitted GW to map the spacetime structure
- Tests of GR
  - Fundamental principles and symmetries of GR
  - Testing GR with compact objects
- Tests of the Nature of Black Holes
- Dark matter and Primordial Black Holes
- Model-independent tests
  - Consistency of GR vs constraining Modified Gravity
  - Parametrized tests
  - Other tests including: Polarisation, GW propagation, Stochastic GW Background
- Astrophysical and Waveform systematics



[Barausse++, 2020]

Deviation in quadrupole moment from Kerr value (no hair theorem):



[Babak+ PRD (2017)]

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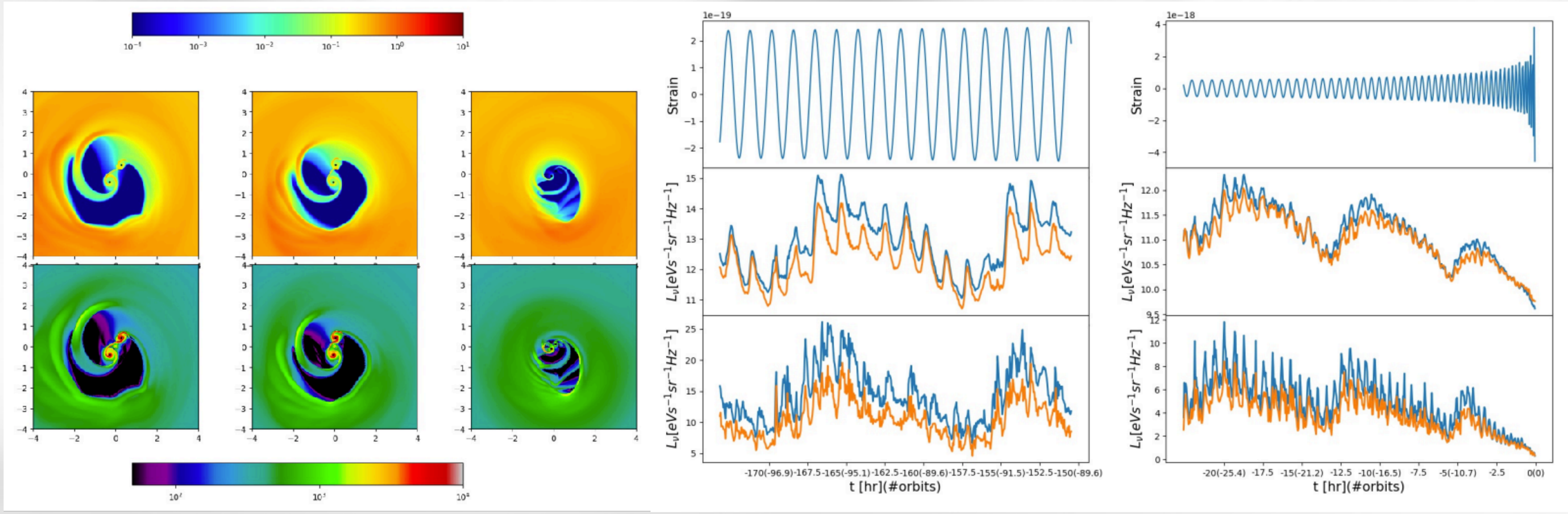
Possible e/m counterparts

- Possible X-ray emission during the late stages of the SMBH inspiral (days to hours before final merger) comes from:
  - Circumbinary disc:
    - X-ray emission in soft x-rays (≤1keV)
  - Mini-discs around black holes
    - Hard x-ray emission (≥10keV) from accretion of minidiscs individually onto each black hole
  - Interaction of circumbinary and mini discs:
    - Accretion of circumbinary disc onto mini-discs via optically thick streams
    - Thermal radiation dominated by the inner edge of the circumbinary disc, producing soft x-rays (~2keV)
  - X-ray emission shows clear modulation on timescales as short as a few hours

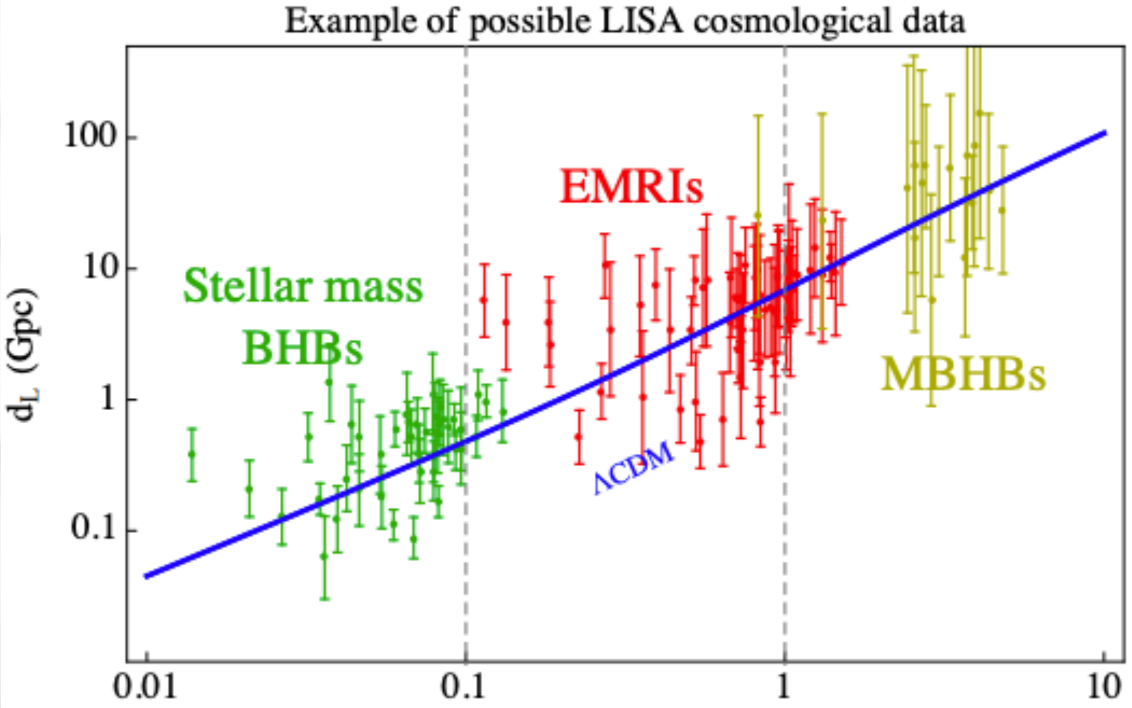


Y. Tang+, MNRAS 2018

Cosmography with LISA

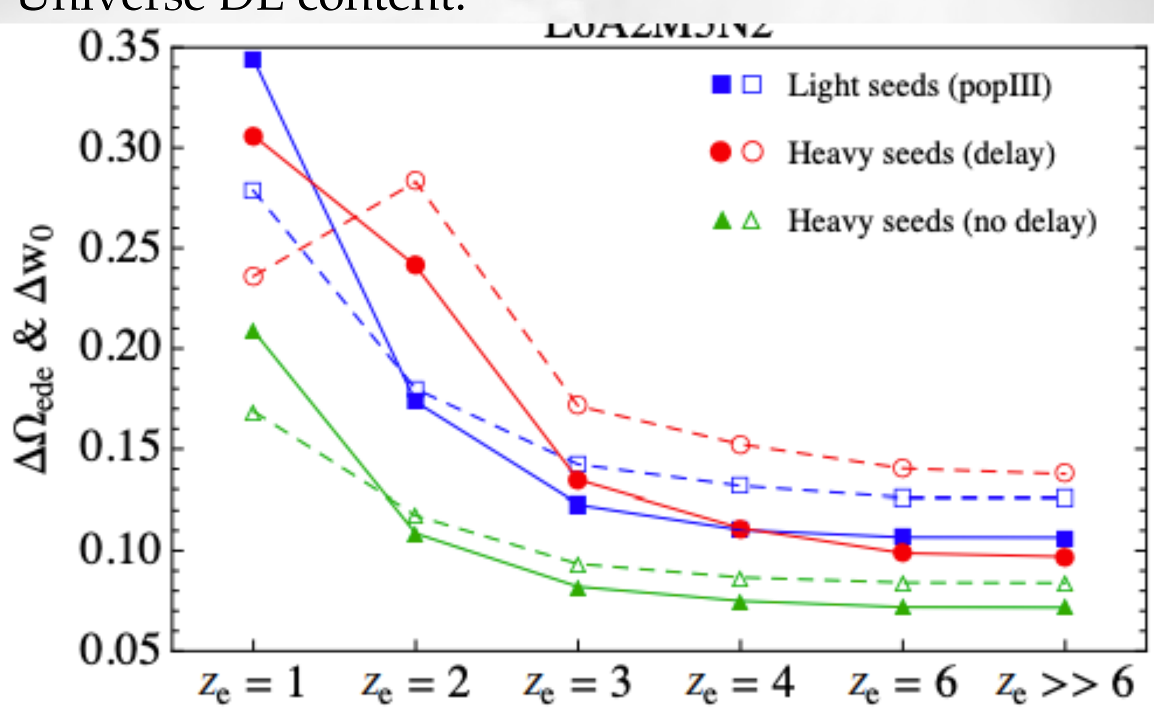
- LISA may help on many cosmological problems
  - Expansion rate of the Universe : late acceleration ?
    - CMB : $H_0 = 66.93 \pm 0.62$ km.s^{-1}.Mpc^{-1}
    - SN Ia : $H_0 = 73.5 \pm 1.4$ km.s^{-1}.Mpc^{-1}
  - Dark energy
    - Cosmological constant ?
    - Early dark energy: DE evolves with redshift and contributes to rate of expansion at z>1
  - Modification of GR on large scale
- LISA can probe the Universe at different scales
  - Use BHBs merger events as standard sirens
  - Requires the knowledge of the redshift
    - from e/m counterpart of the host galaxy
    - or from statistical inference

Universe expansion rate from GW events :



N. Tamanini J. Phys. CF 2016

Universe DE content:

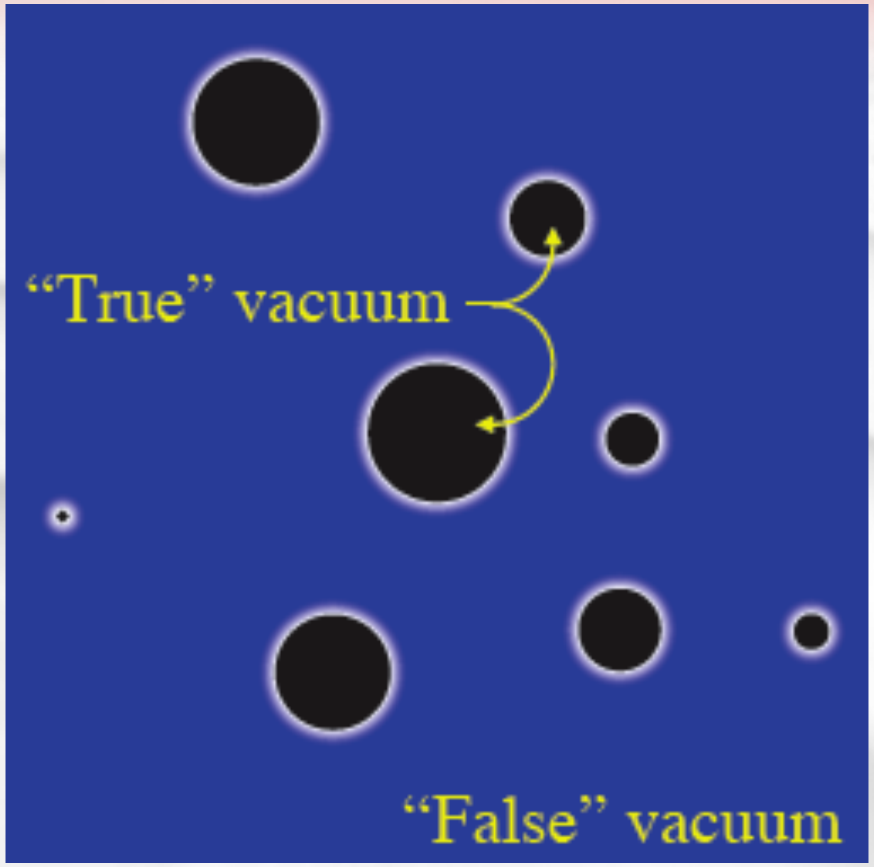


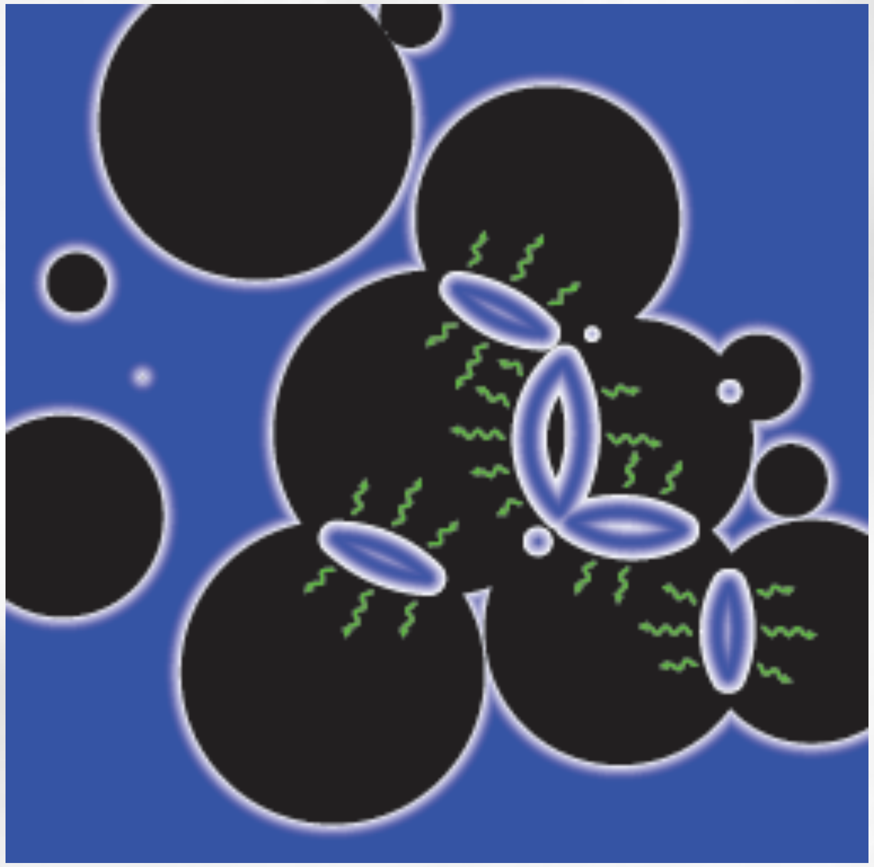
Ch. Caprini, N. Tamanini JCAP 2016

Early Universe in GWs

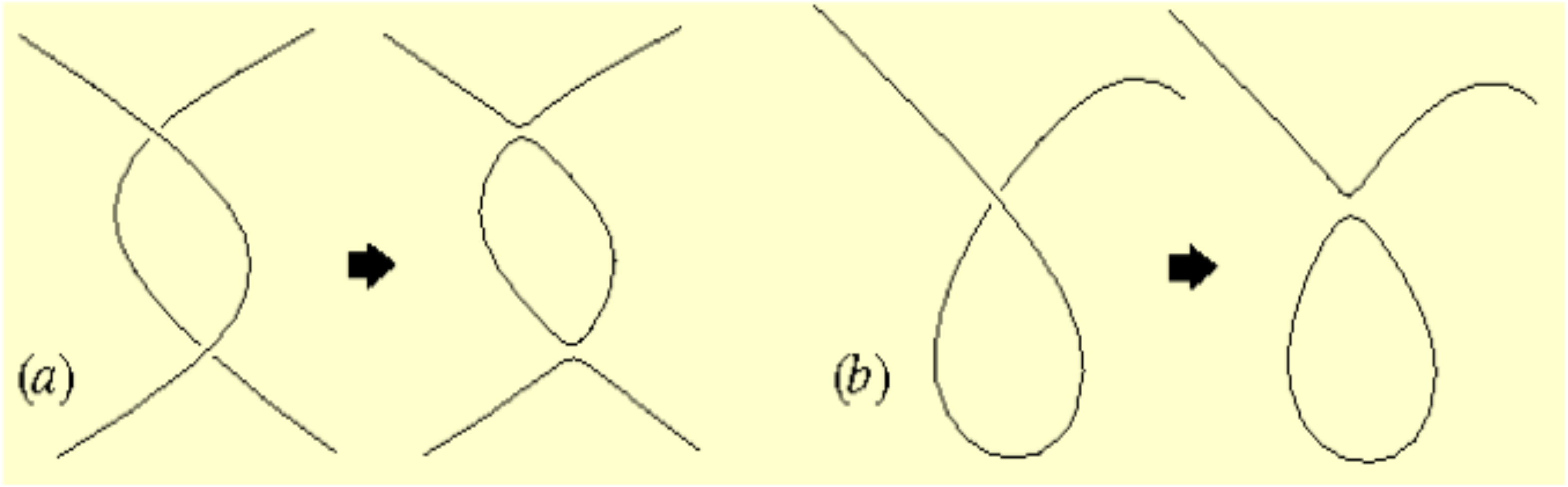
- Violent processes in the early Universe may produce stochastic GW background (SGWB)

- First order phase transition
  - Collision of true vacuum bubbles and conversion to the symmetry-broken phase accompanied with anisotropic stresses.
  - The LISA band (10^{-4} - 0.1 Hz) corresponds to the energy scale of the EW (electroweak) phase transition (up to 10^{4} TeV).
  - Formation of sound wave, shocks and turbulence in the plasma





- Cosmic strings:
  - A network of strings formed in the early Universe generates SGWB (as superposition of many uncorrelated sources) and (possibly) individual bursts

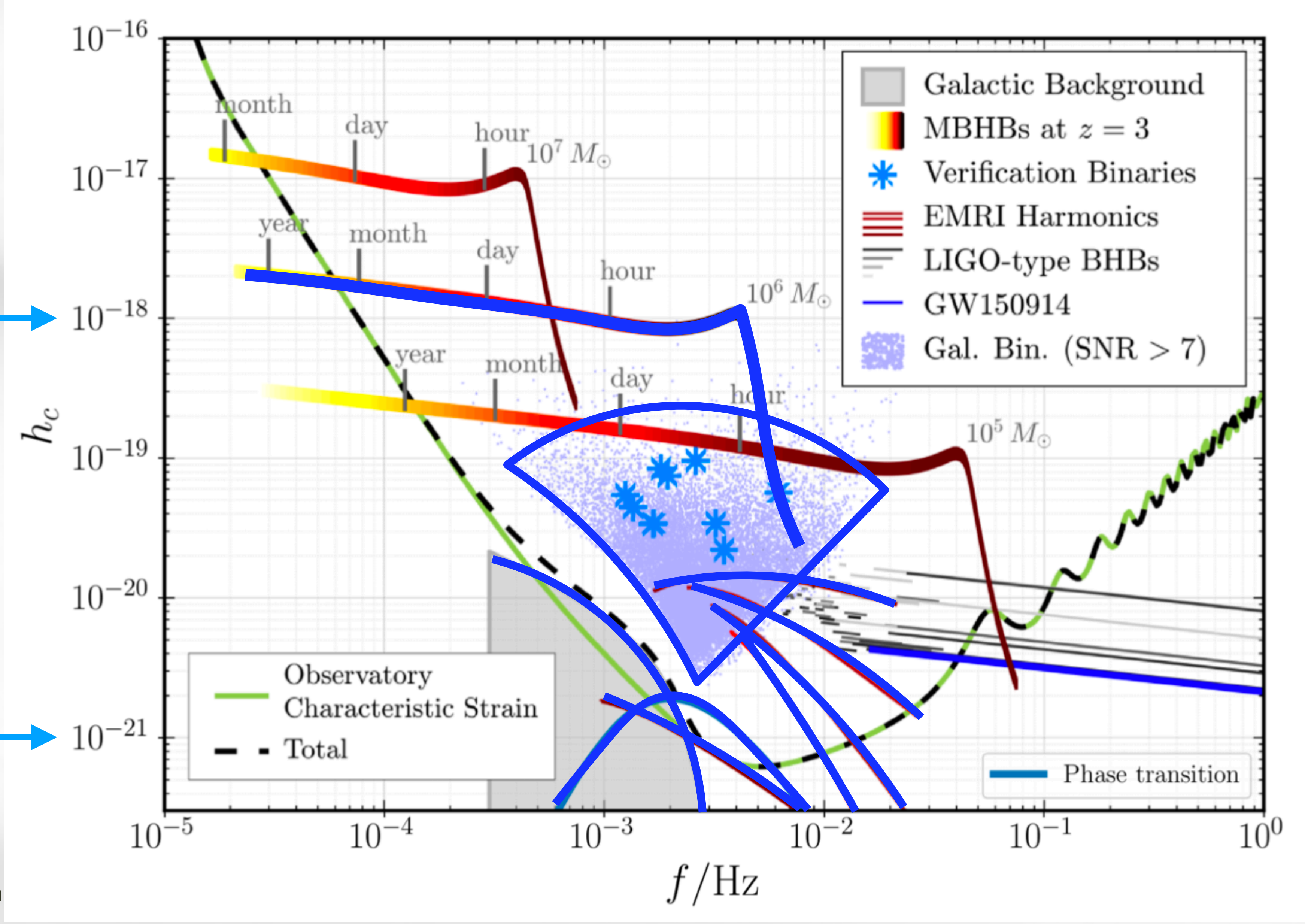


mHz GW science

- Many sources …
  - Compact galactic binaries
  - Coalescence of SMBH
  - Extrem mass inspirals
  - Stochastic background from the early Universe
  - ….
- … to answer important scientific questions
  - Formation and evolution of compact binaries
  - Origin and evolution of BH since the early ages
  - Strong field tests of GR
  - Estimation of cosmological parameters
  - …

1 nm/Mkm → 10^{-18}

1 pm/Mkm → 10^{-21}



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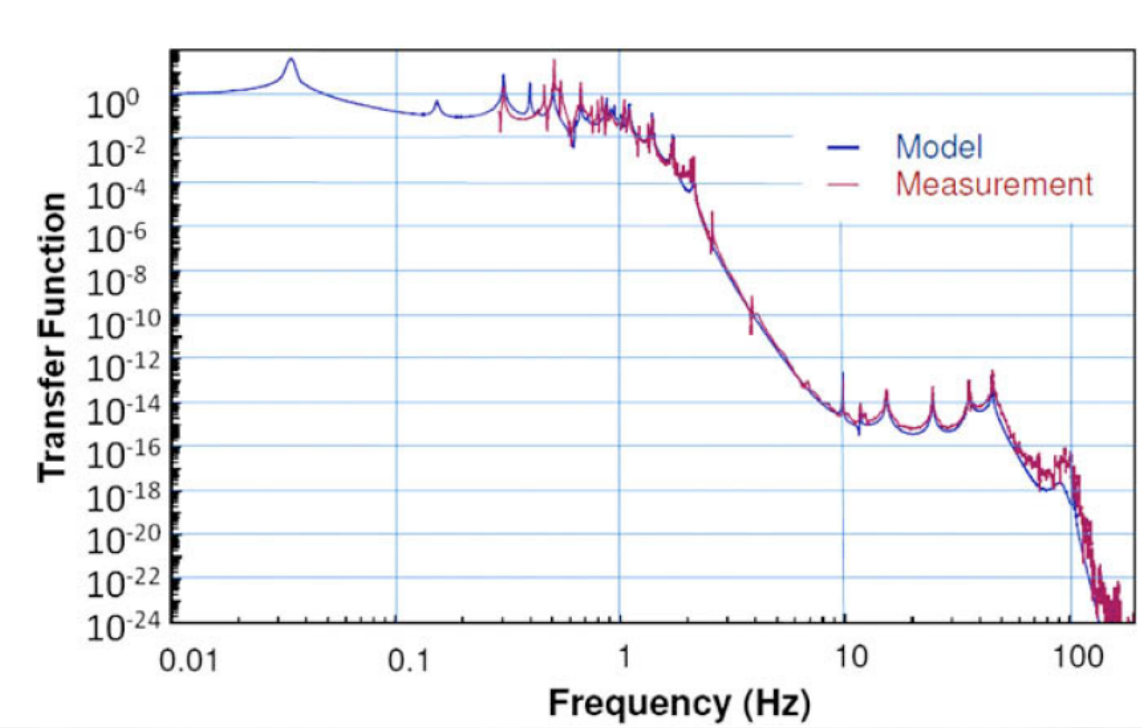
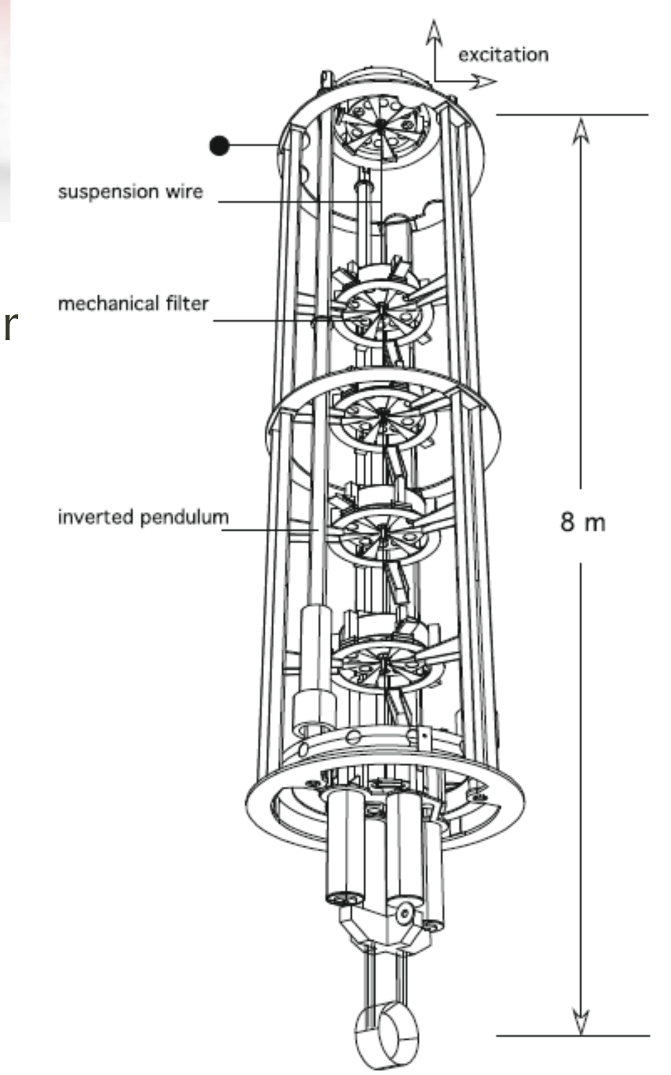
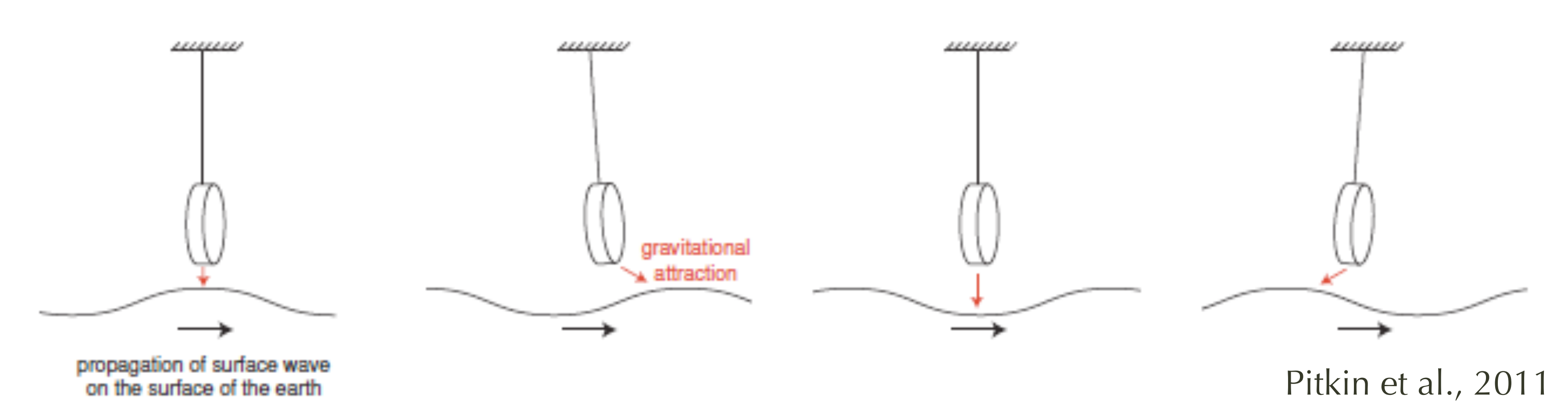
Why going to space ?

- Ground-based interferometers are limited by seismic and Newtonian noises
  - Detection bandwidth ≳ 10's Hz
- (very) long armlength are possible
  - On ground : a few km max (eq. to 100's km using cavities and folding mirrors)
- —> mHz GW observations only possible from space

VIRGO superattenuator

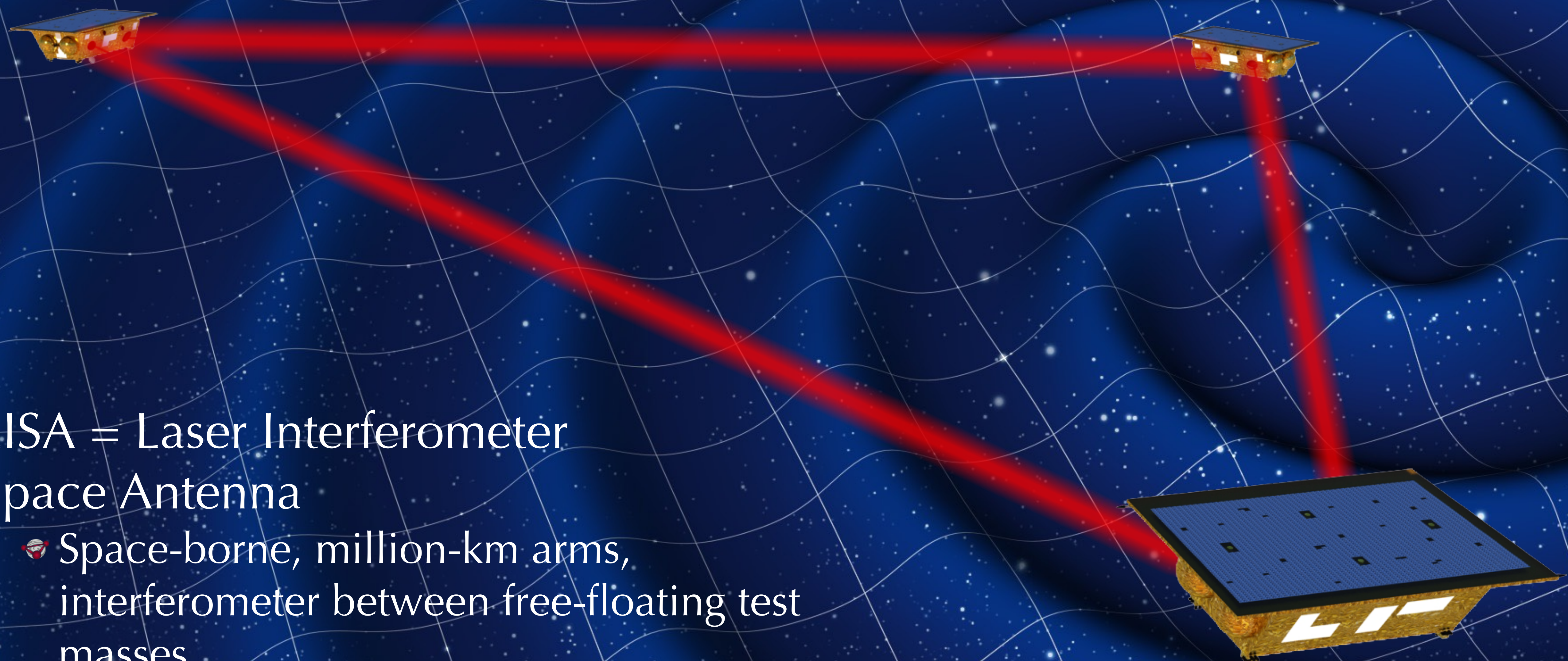






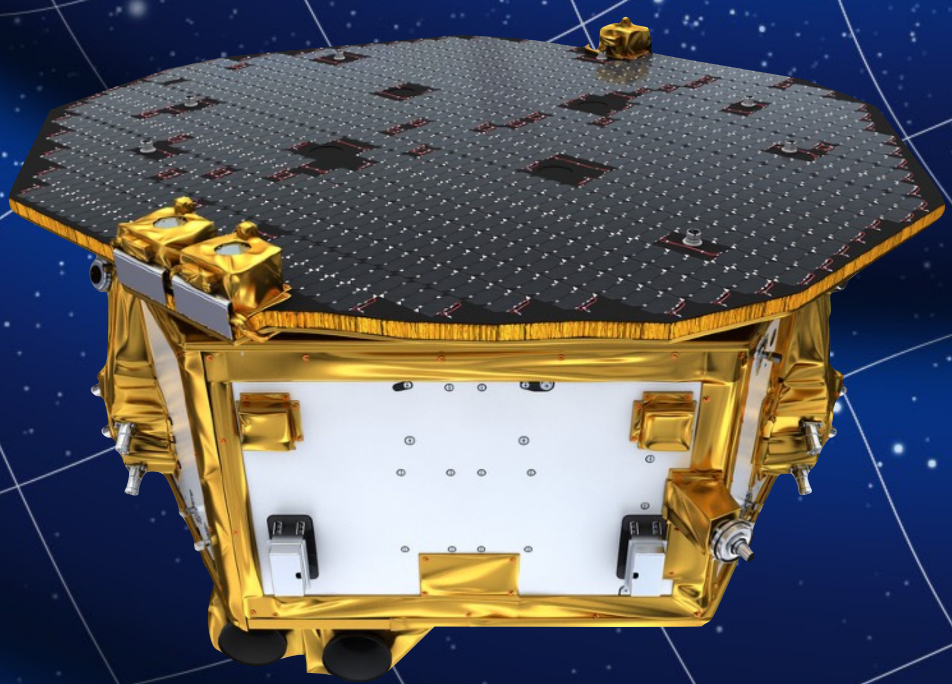
Pitkin et al., 2011

Acernese et al., 2010



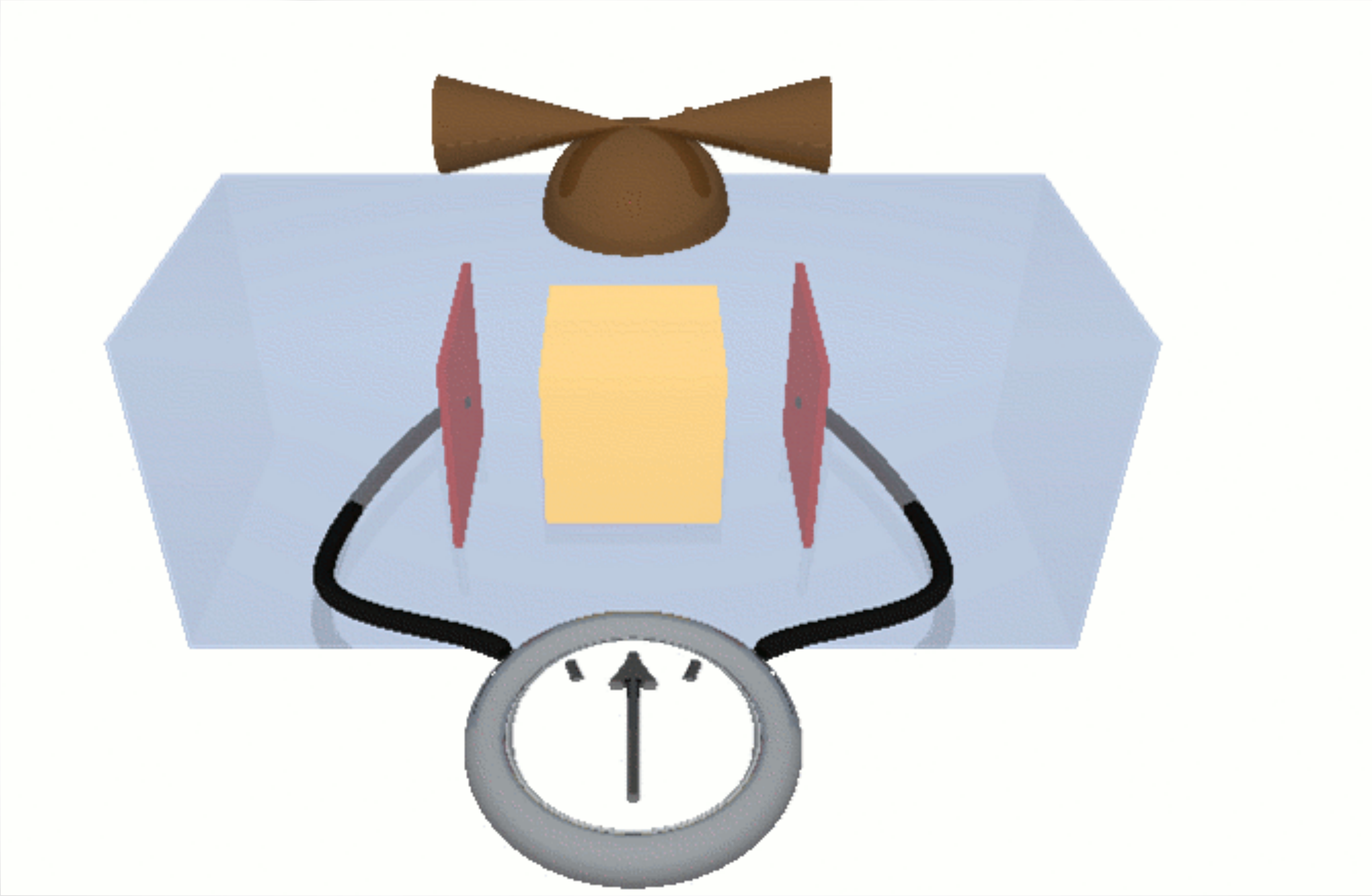
- LISA = Laser Interferometer Space Antenna
  - Space-borne, million-km arms, interferometer between free-floating test masses
  - Response bandwidth : ~0.1 mHz - 1 Hz
  - ‘Large’ ESA mission (Phase B), launch expected in ~2035

- LISA Pathfinder = technology demonstrator for LISA
  - Launched in December 2015
  - End of mission in July 2017



Drag-free flying ?

- Test masses must be protected from external perturbations (mainly solar wind)
- Technology demonstrator : LISA Pathfinder

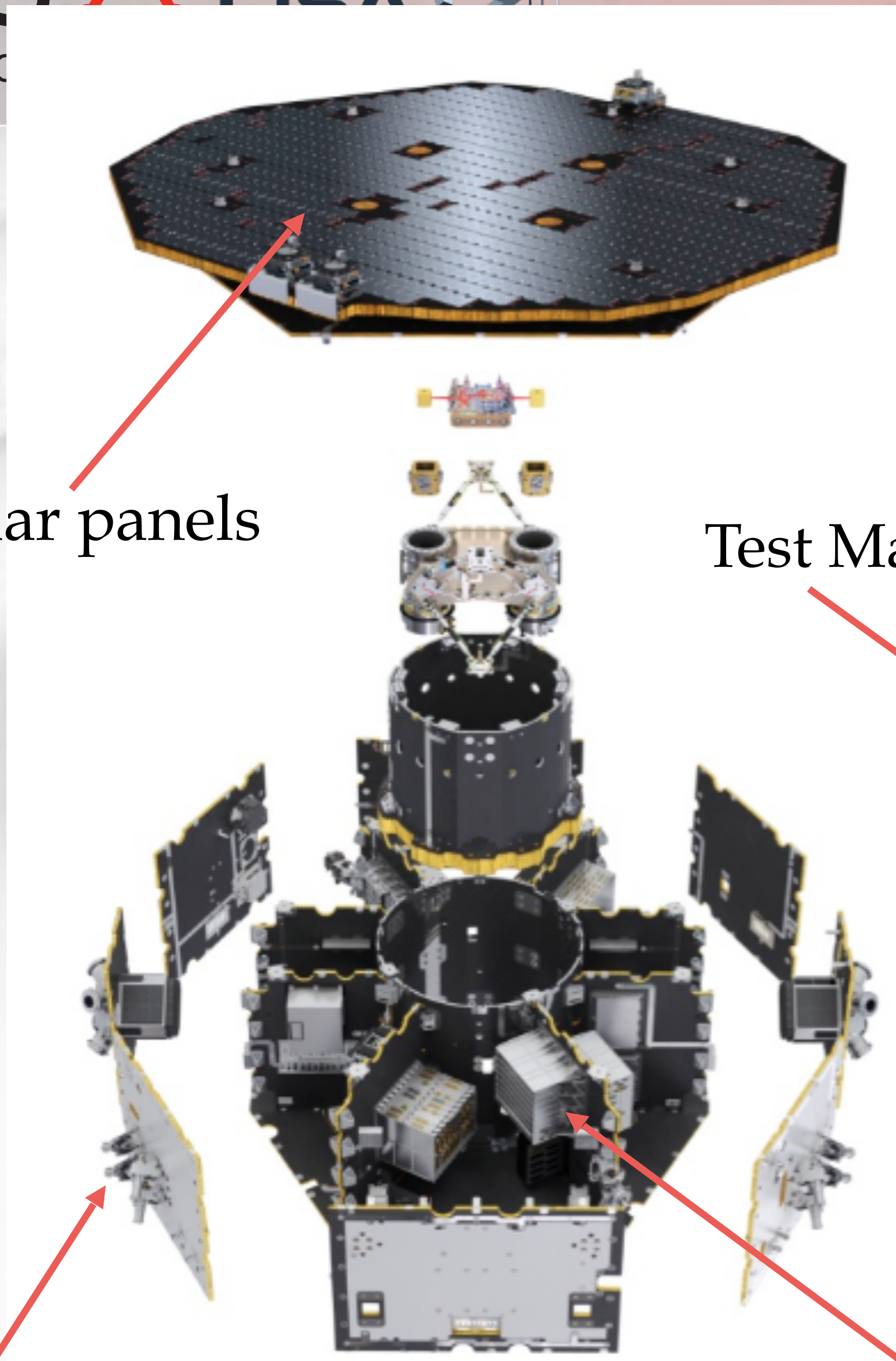


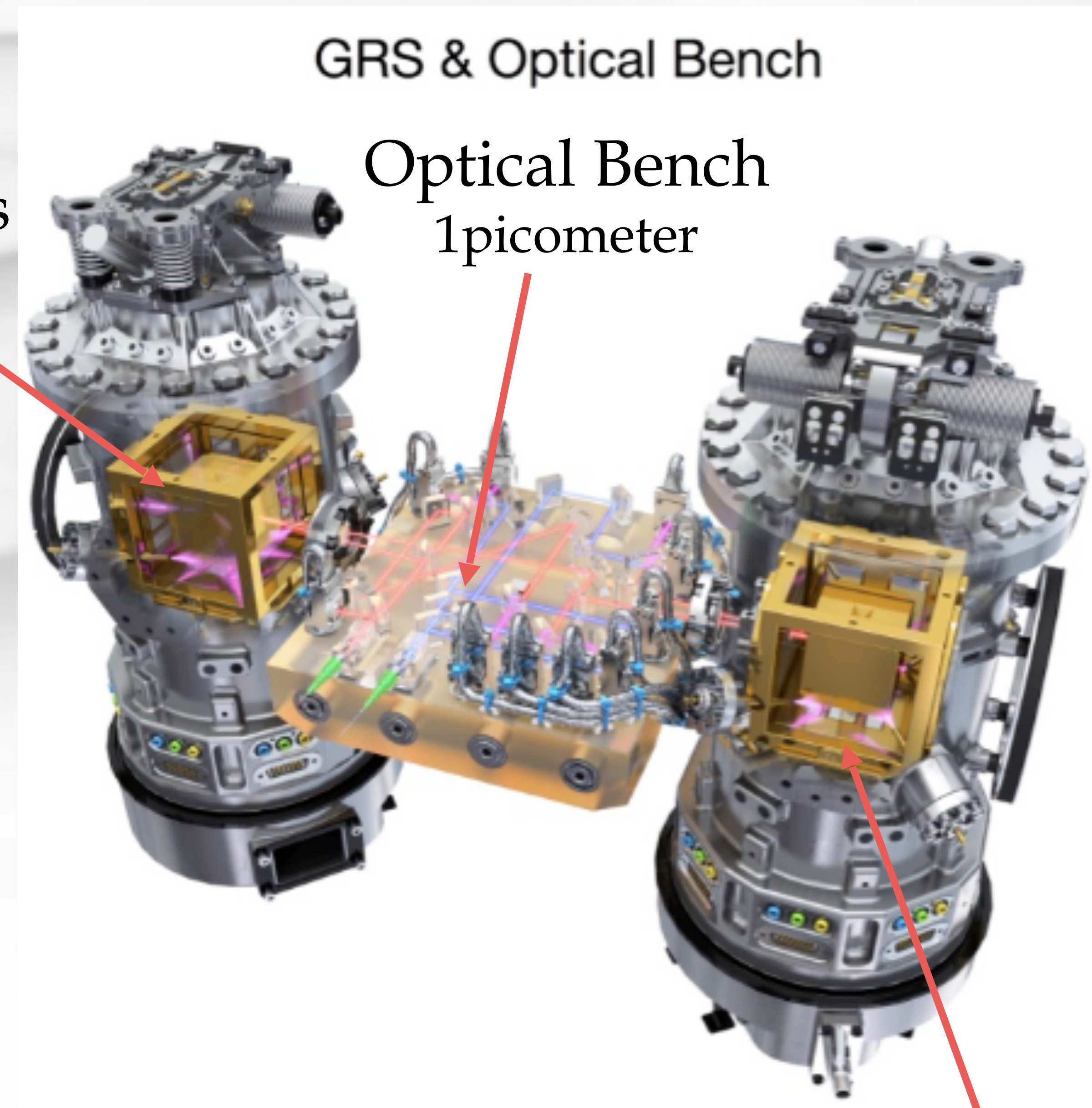
LISA Pathfinder

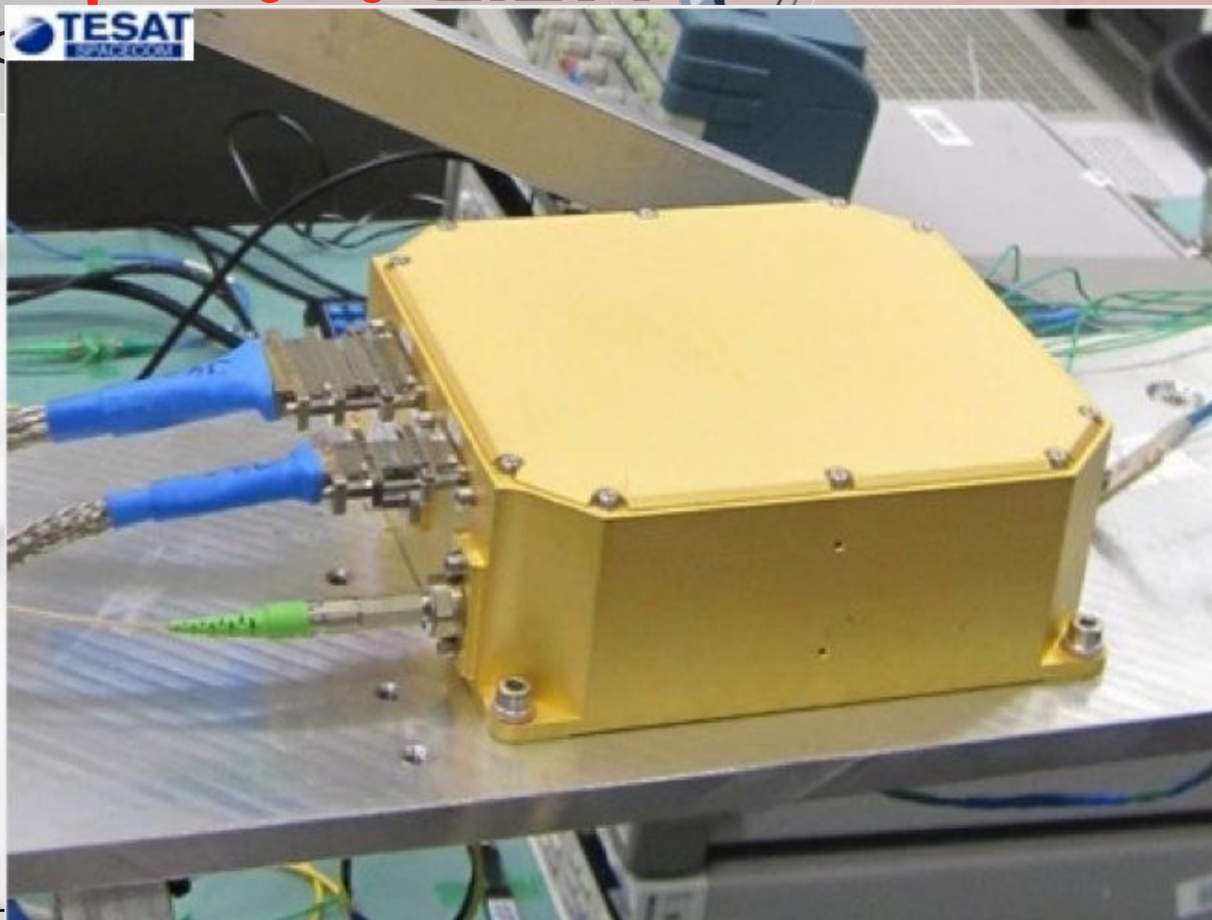
- Main goal: demonstrate the possibility of "Free Fall" in space at the level of $\approx 10^{-14}$ m.s$^{-2}/\sqrt{\text{Hz}}$, around 1 mHz

- A number of effects had to be minimized:
  - The static gravitational potential between the TMs and the SC,
  - Residual links of the TMs w.r.t the SC via the residual vacuum,
  - Cross talk between various electrostatic actuators,
  - TM charging by cosmic rays that is eliminated by UV illumination,
  - Temperature fluctuations,
  - Magnetic field fluctuations,
  - …

LisaPathfinder : A technology demonstrator



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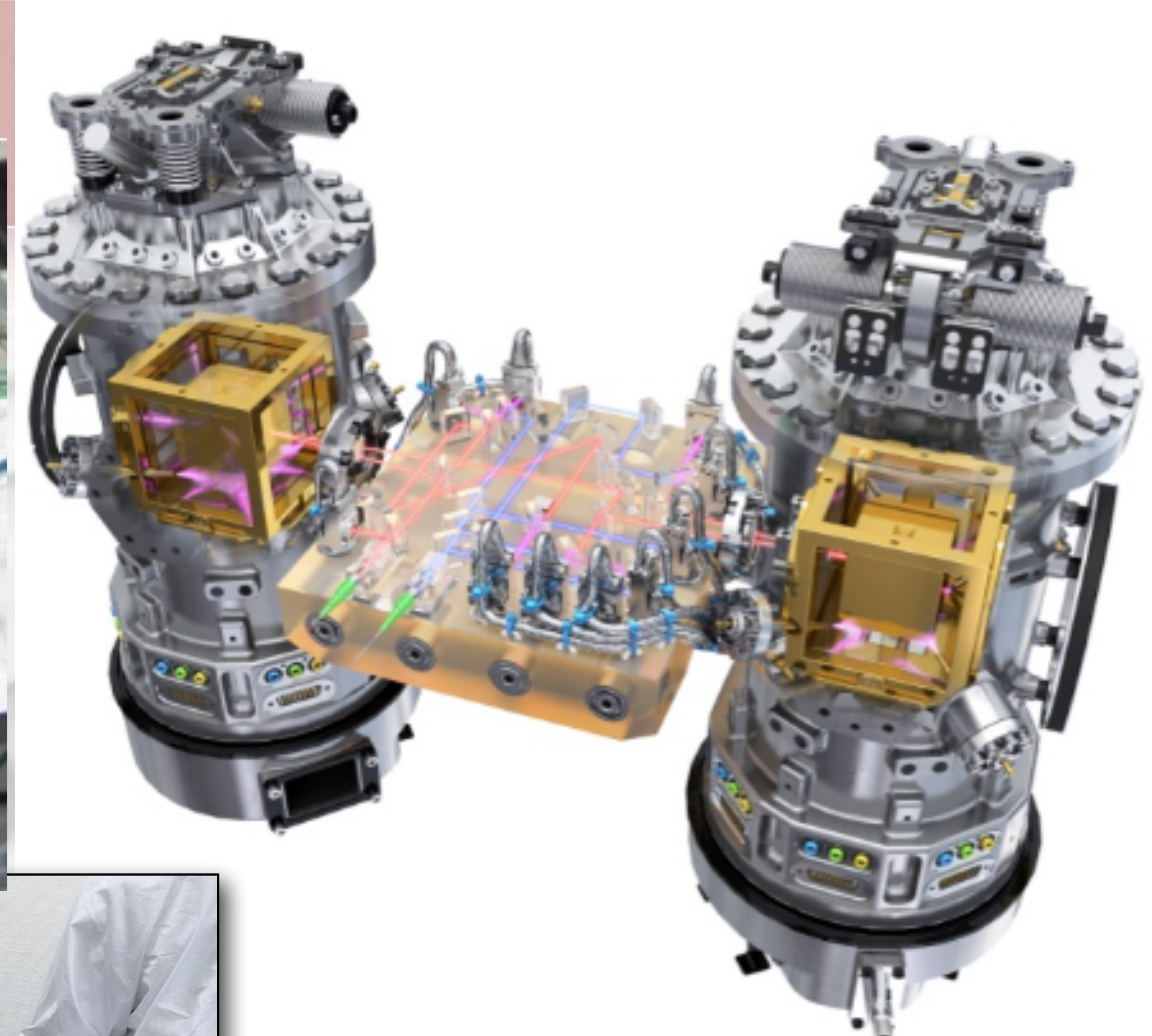
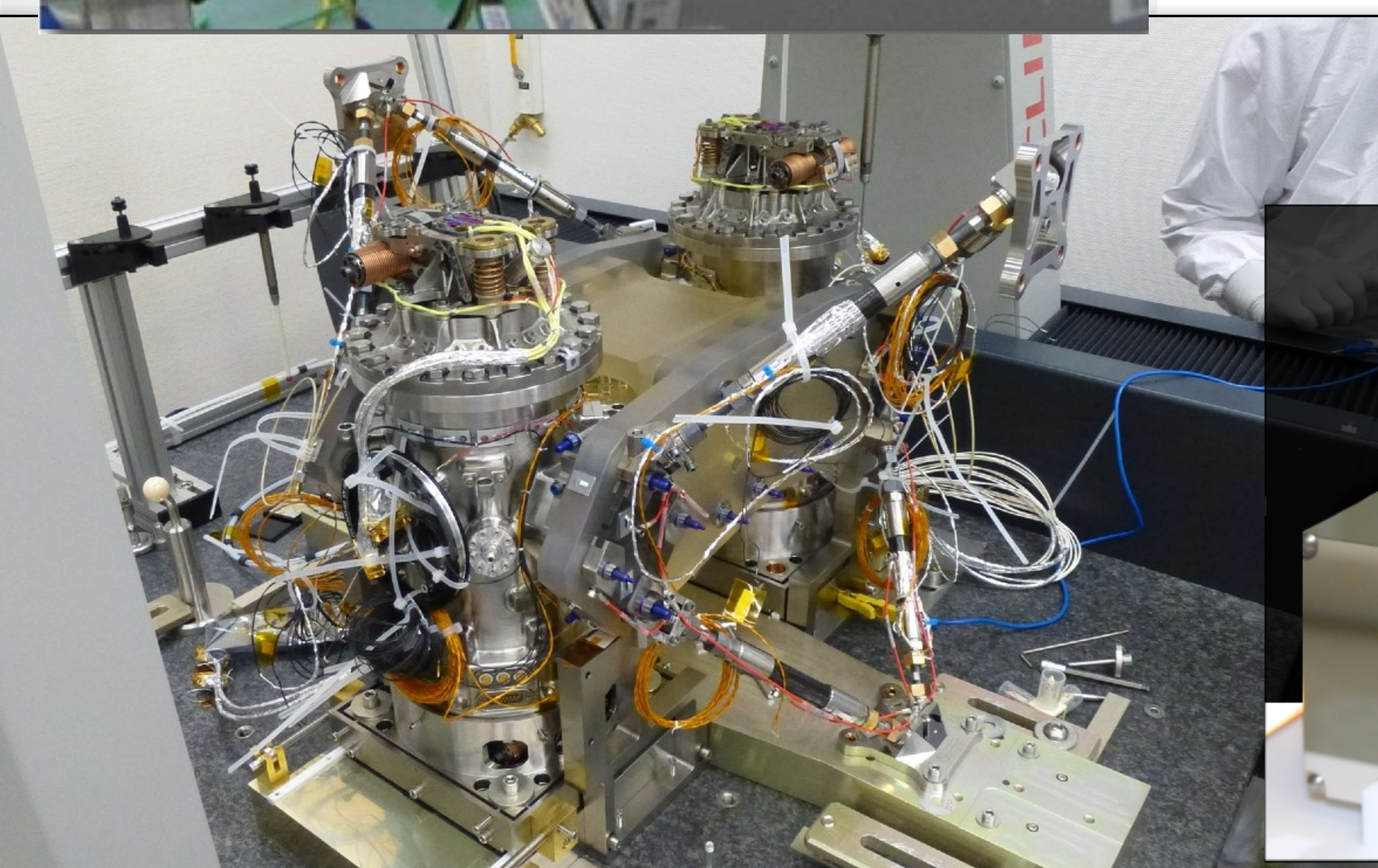
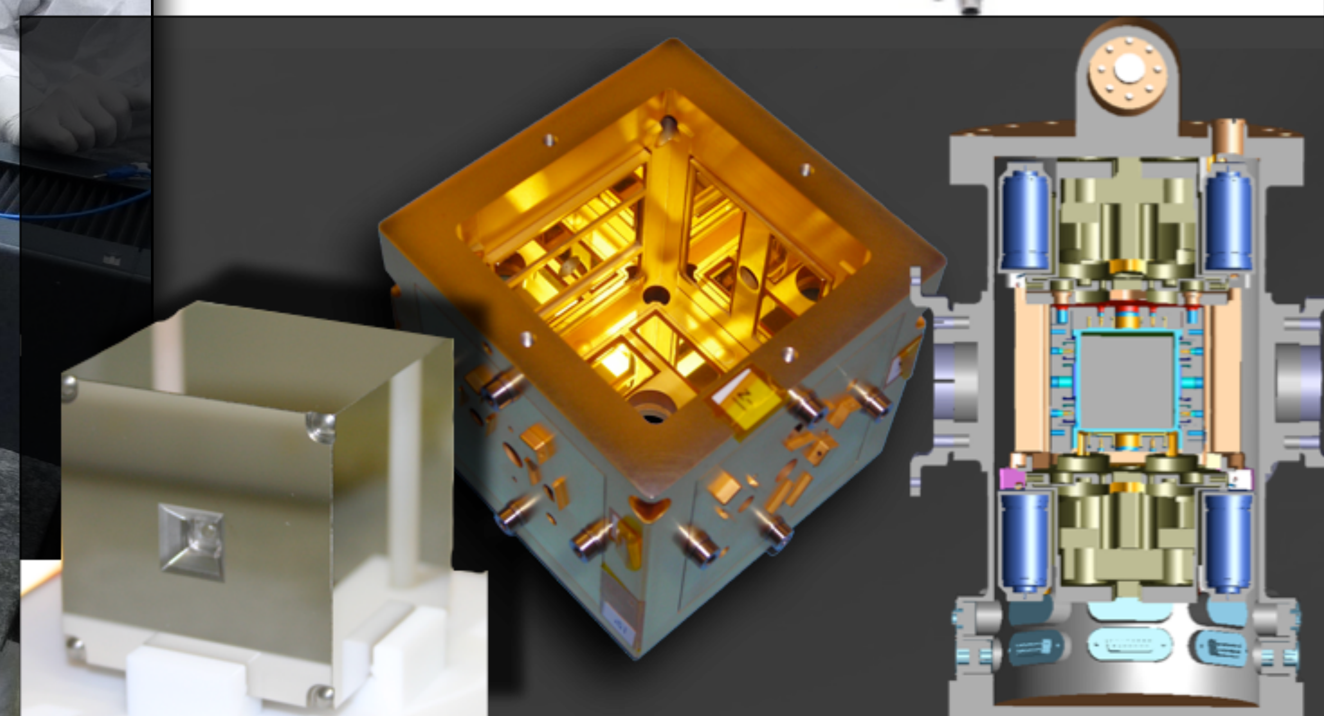
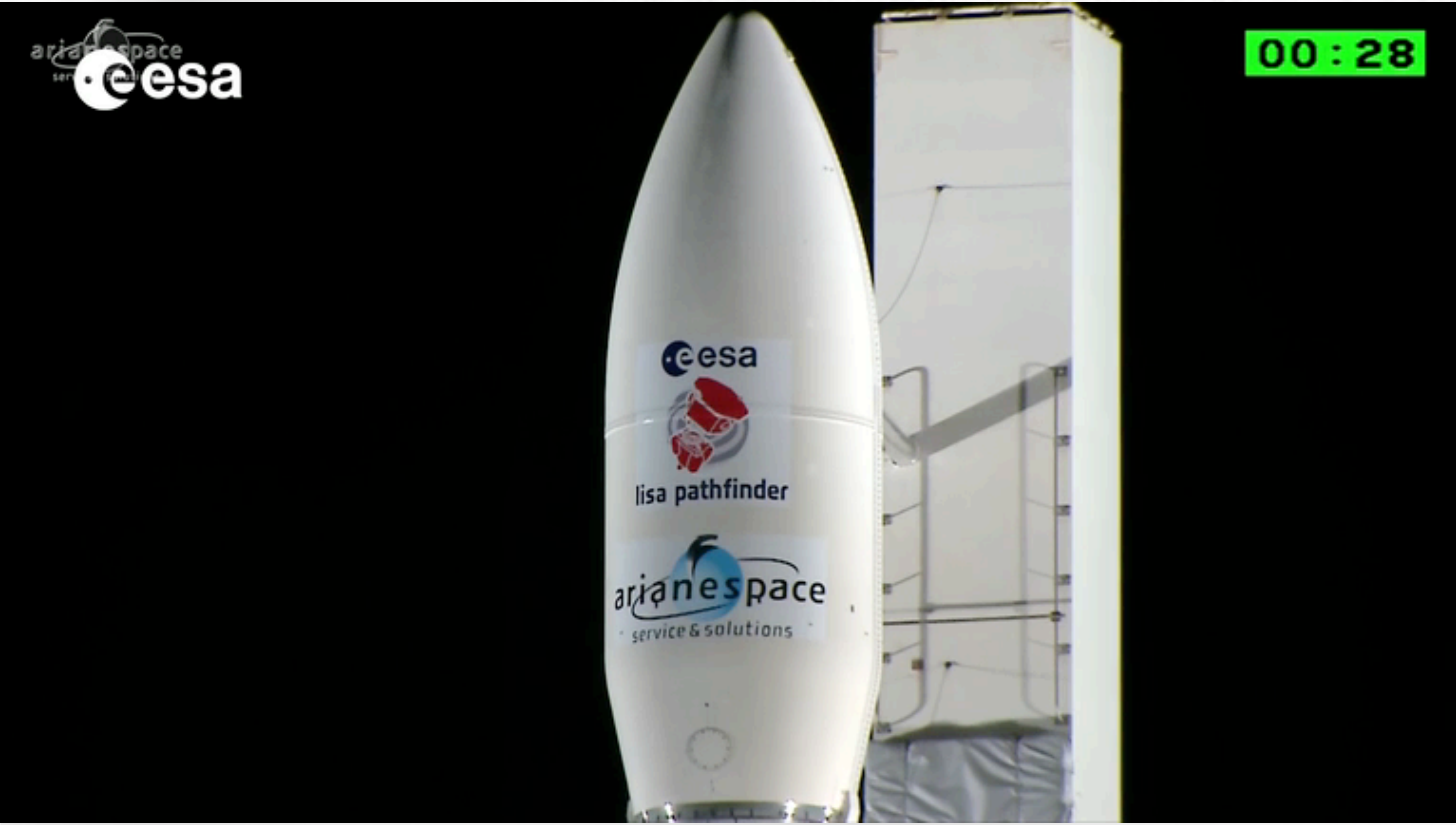




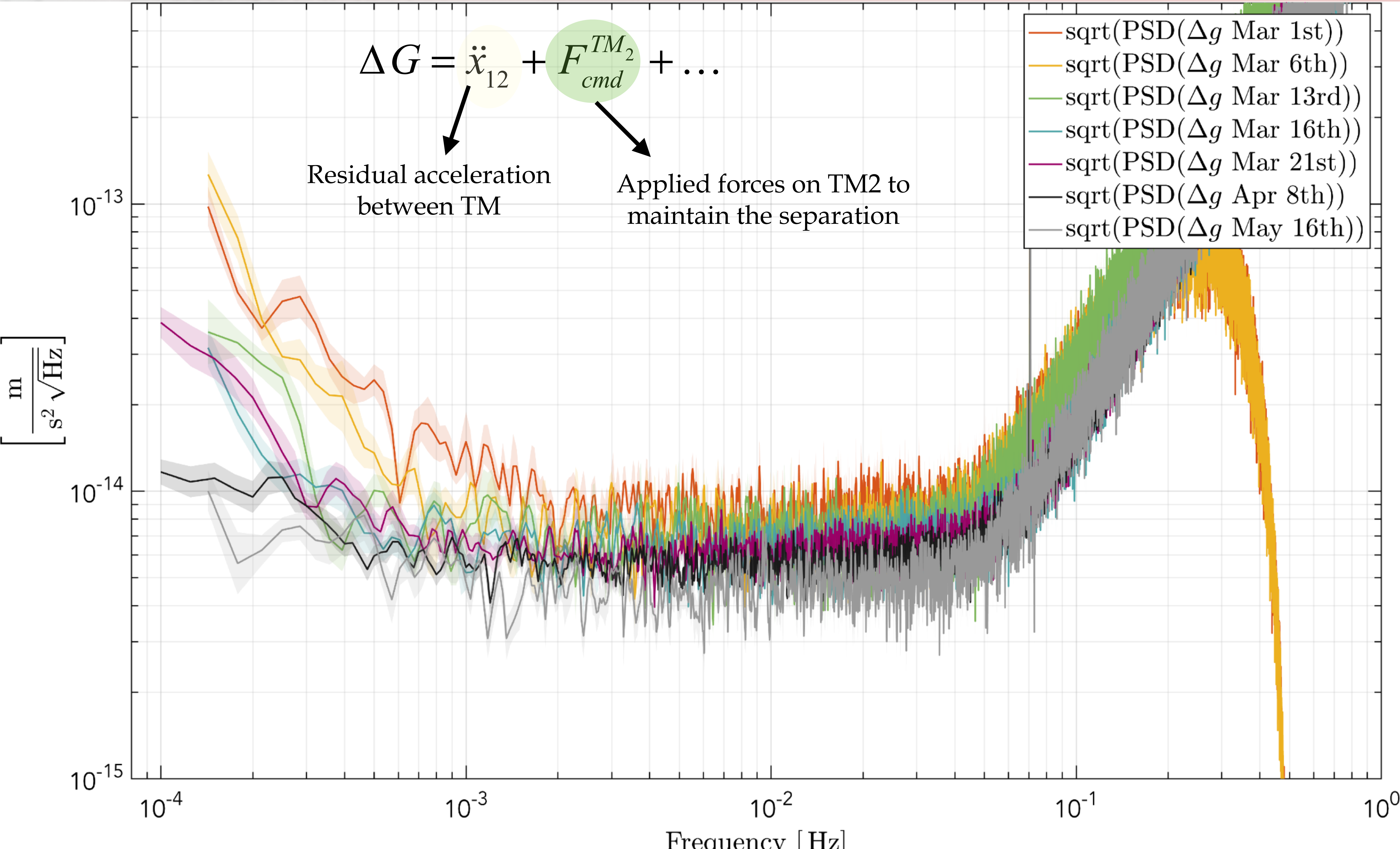
Testing inertial flight with LISA Pathfinder


IABG

LISA Pathfinder - 03/12/15



In-flight performance evolution

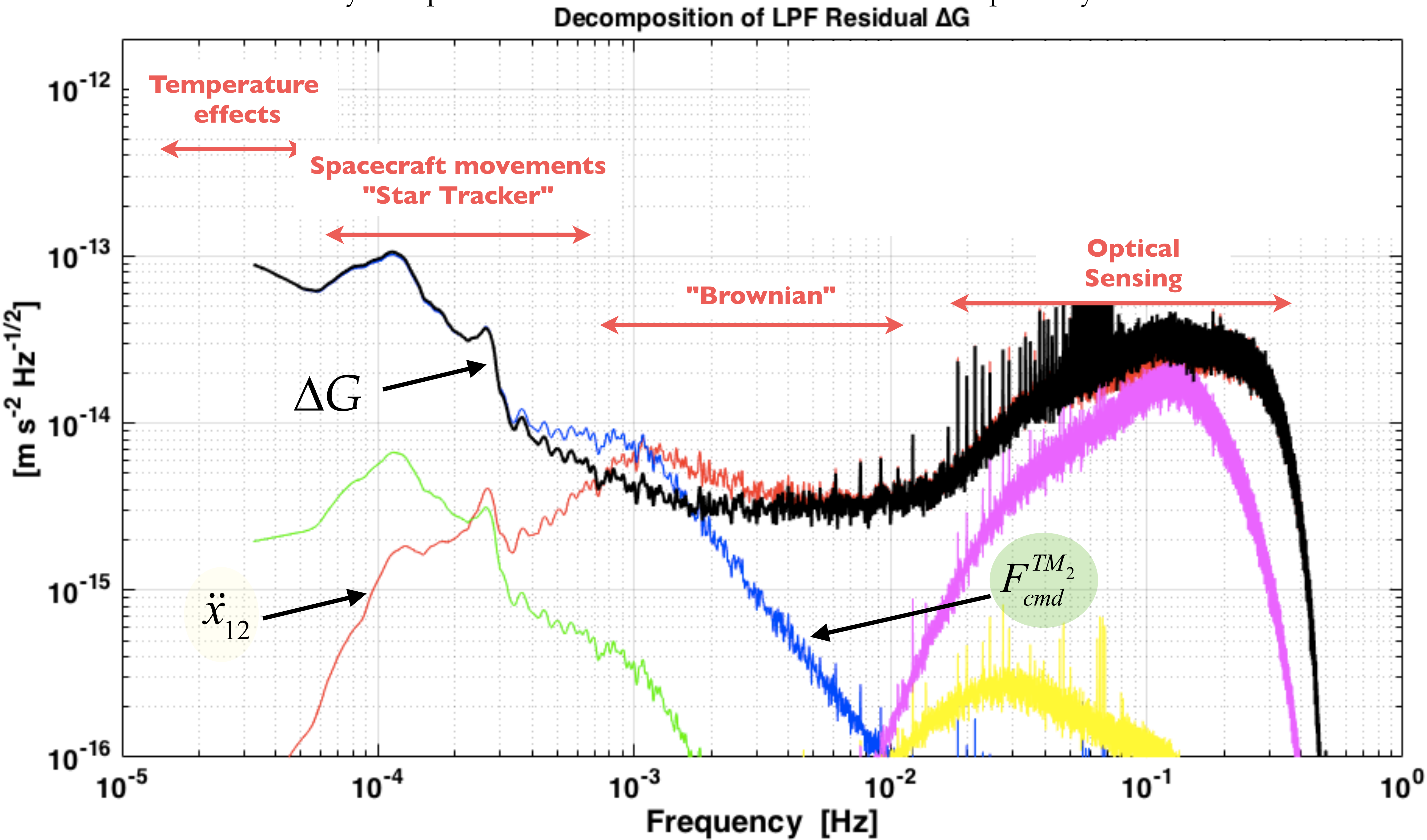


The Different Frequency Ranges

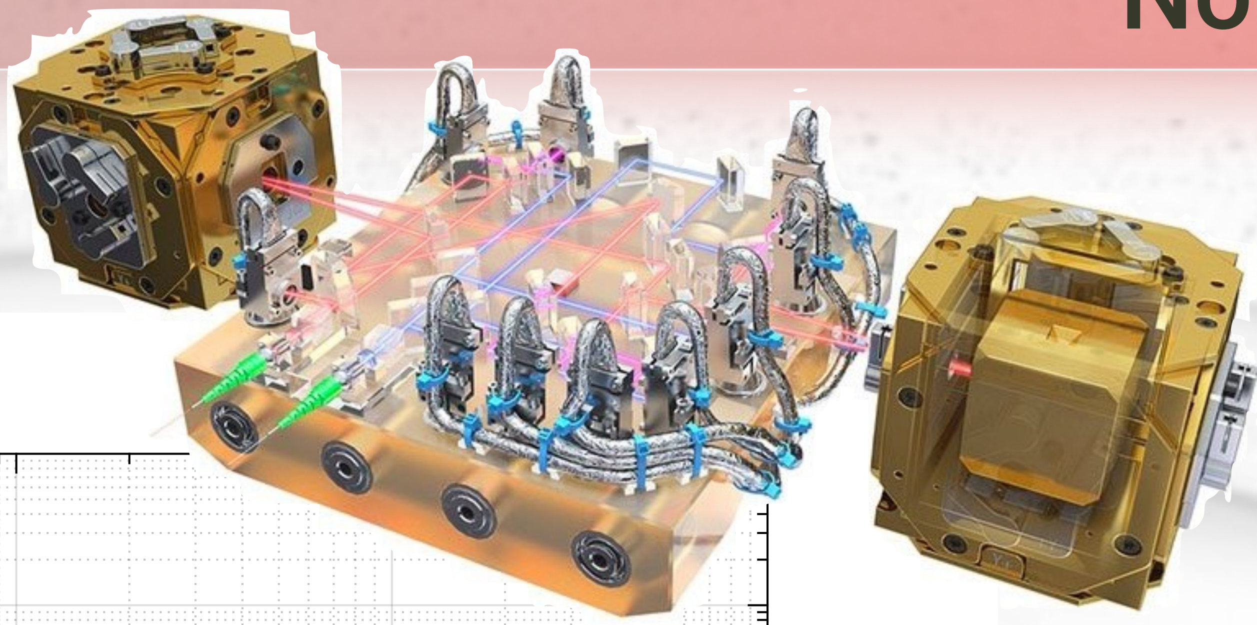
$$\Delta G = \ddot{x}_{12} + F_{cmd}^{TM_2} + \ldots$$

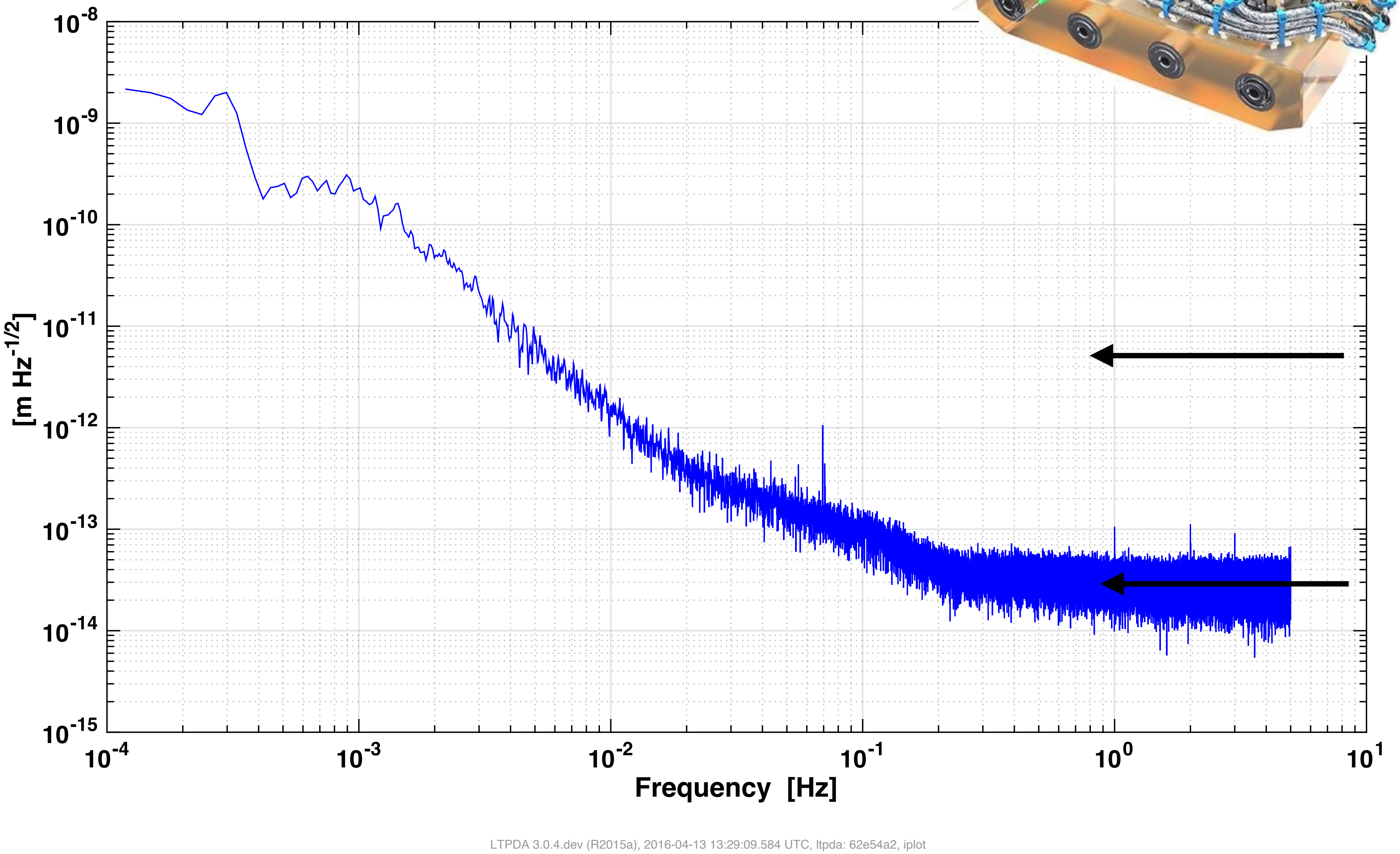
x_{12} is measured by the optical bench

Obtained by "on board" telemetry and precisely calibrated.



Looking in depth: Optical Sensing Noise



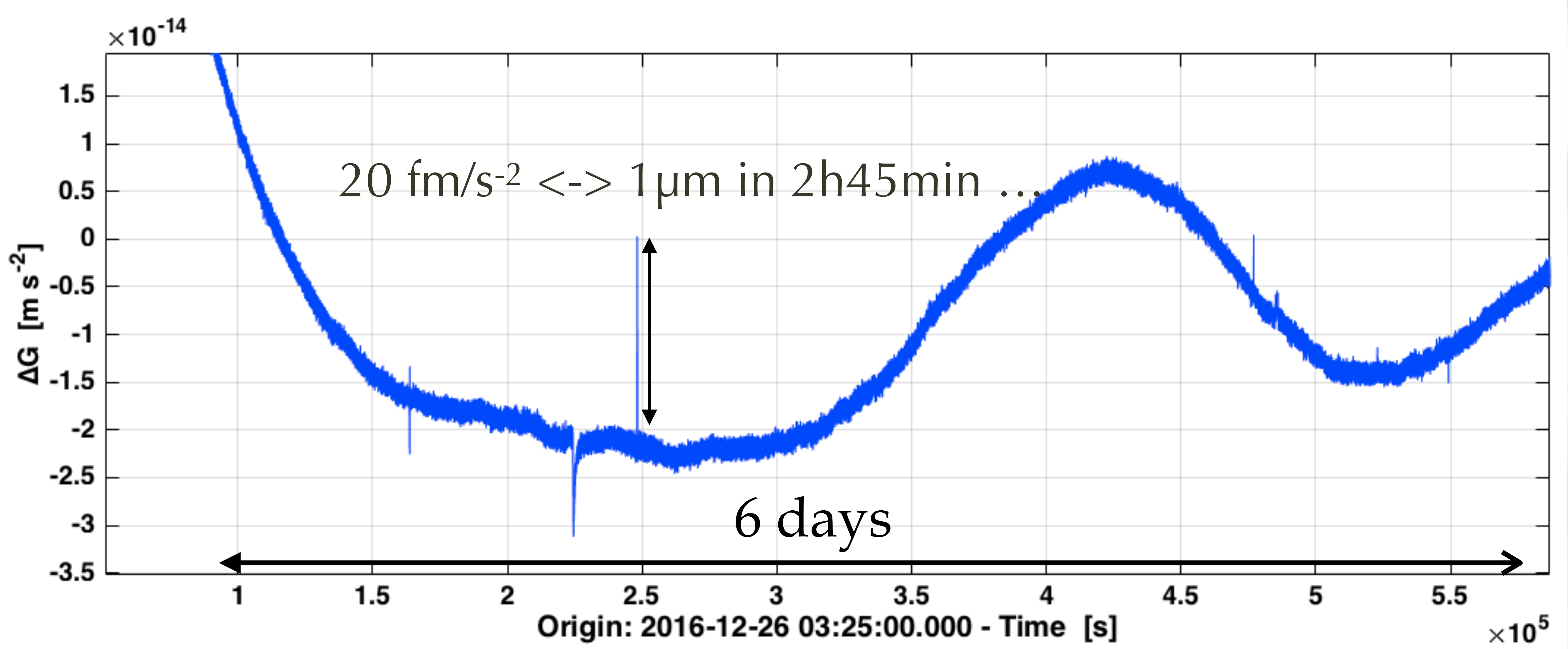


in the lab
6 pm/√Hz

in space
30 fm/√Hz

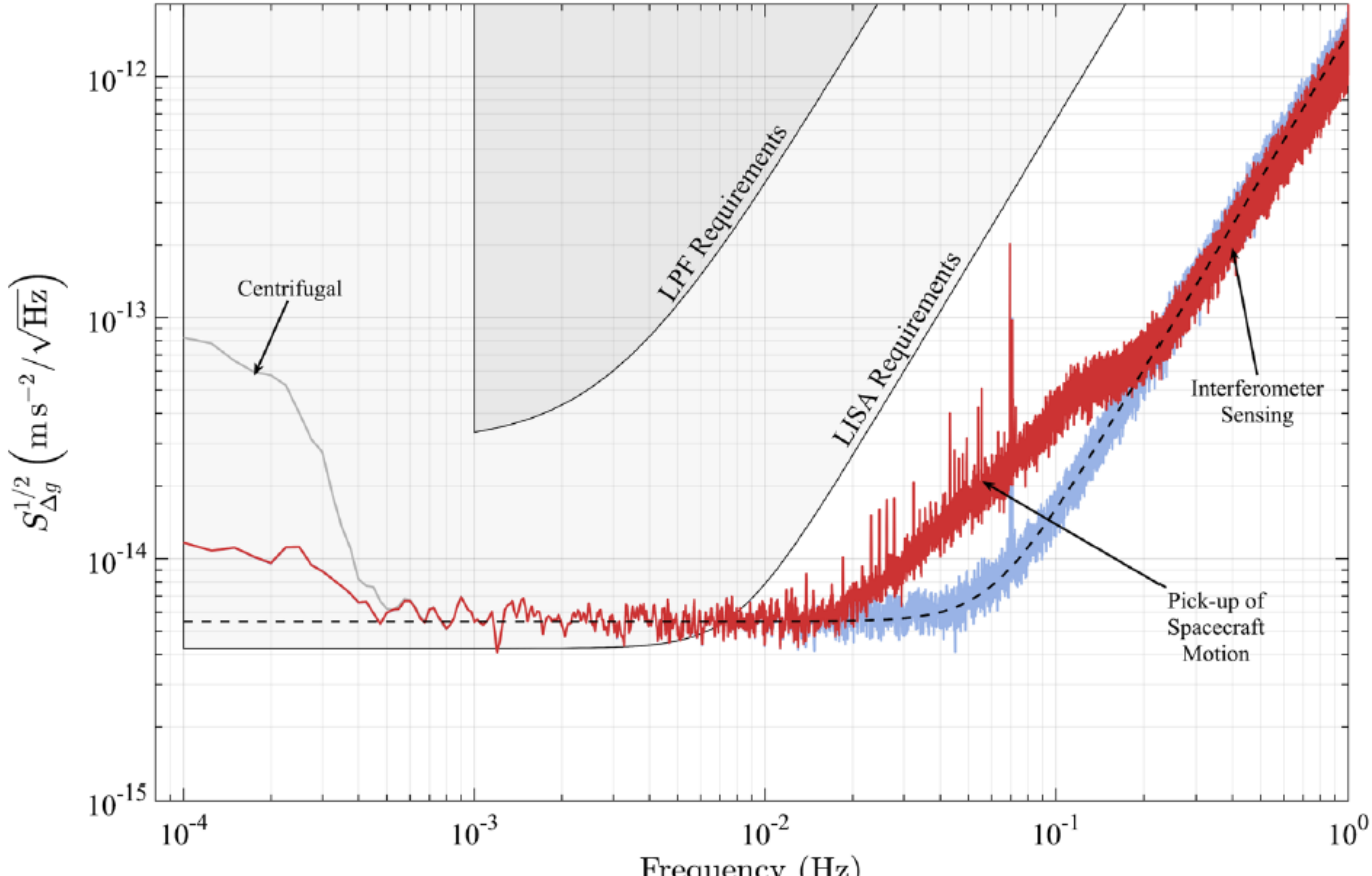
« Glitches »

- Occurred every ~1.5 days
- Caused by micro-meteorites and other unknown causes
- Modeled and subtracted from the data



Selected for a Viewpoint in *Physics*
PRL 116, 231101 (2016) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2016

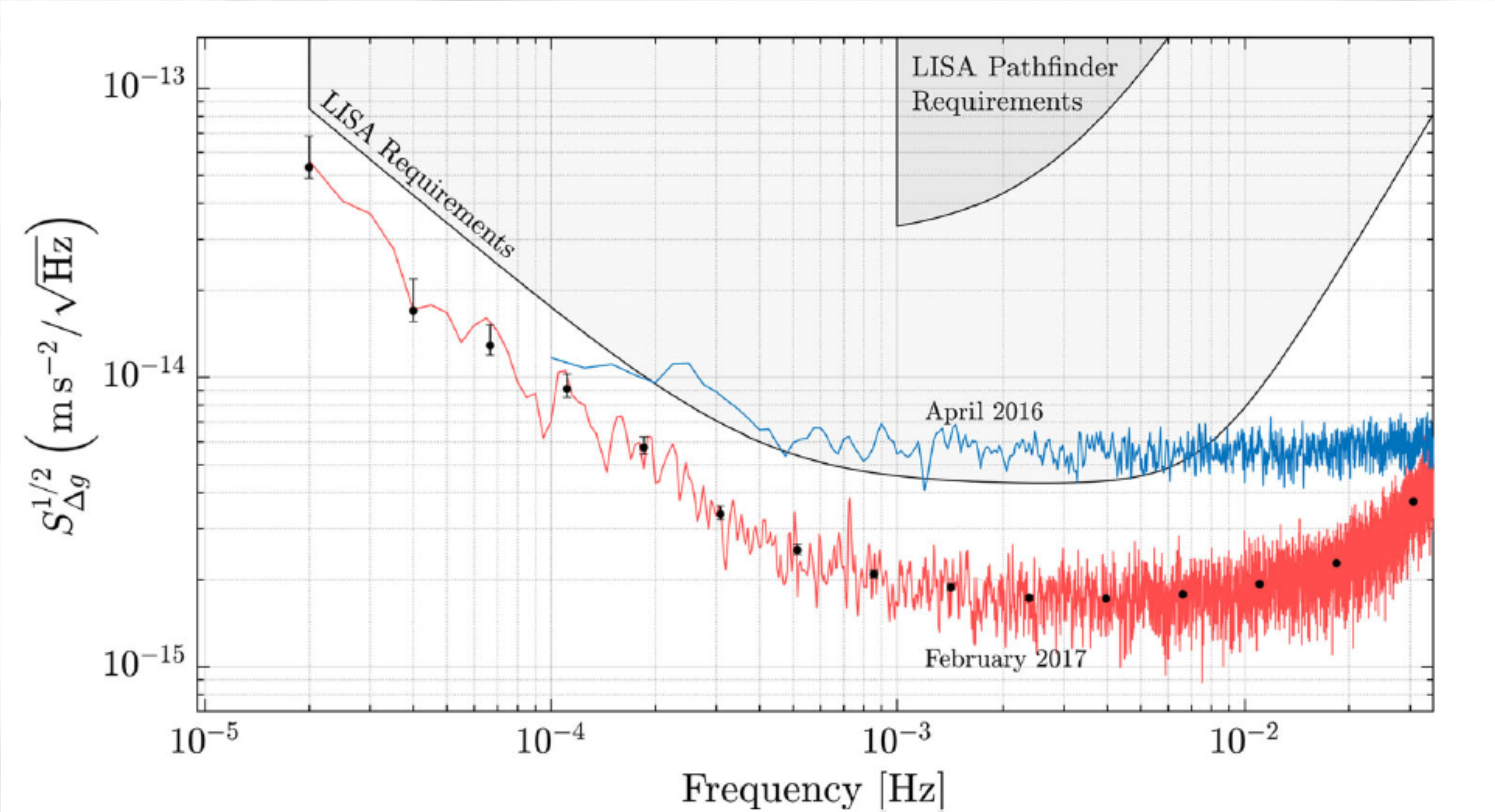
Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results



PHYSICAL REVIEW LETTERS 120, 061101 (2018)

Editors' Suggestion | Featured in Physics

Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 μHz

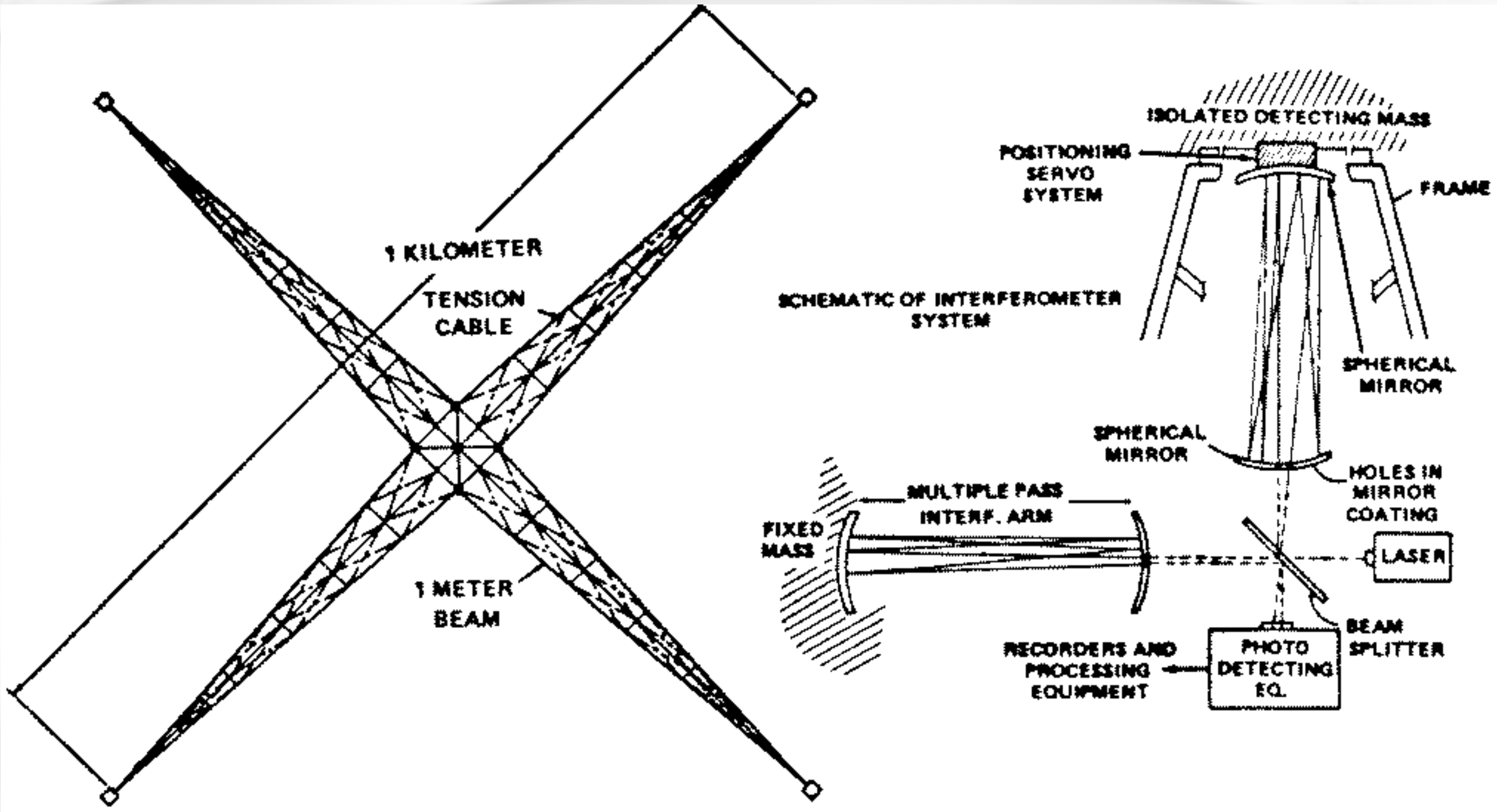


Outline

- *Introduction*
- *LISA Science Objectives*
- *From LISA Pathfinder to LISA*
- **Mission description**
- Conclusion

A long awaited mission

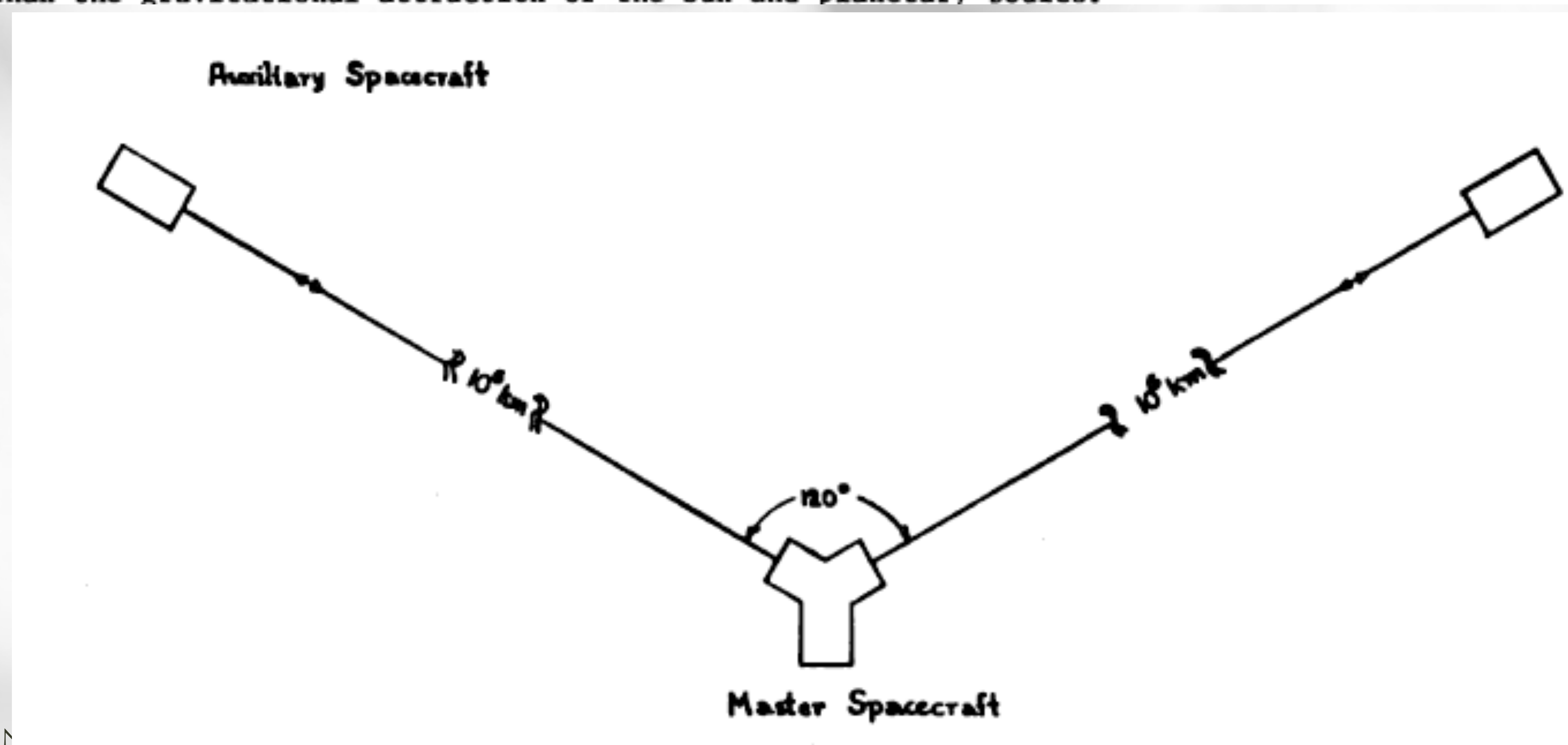
- First NASA studies in 1978
  - Deployable rigid structure 1x1 km



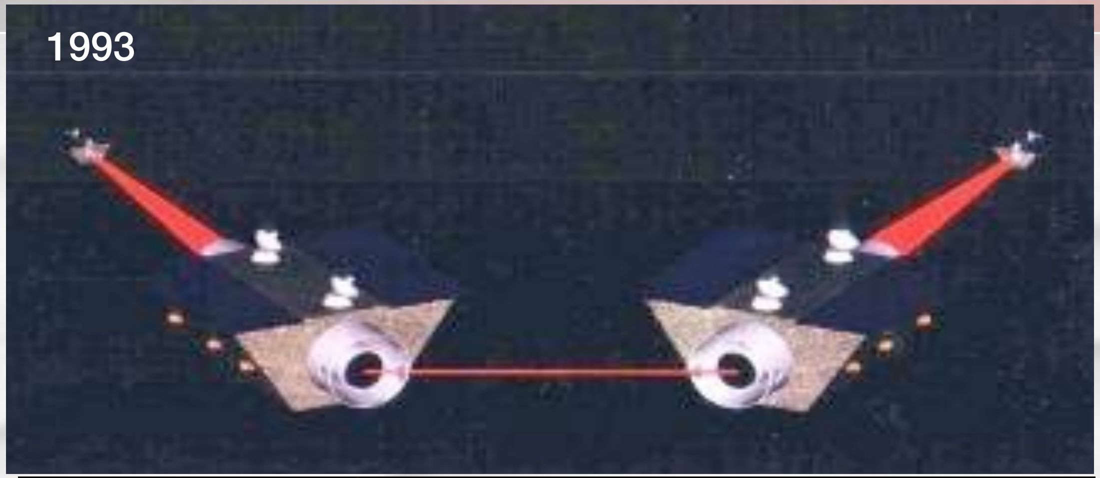
(Almost) final configuration in 1984

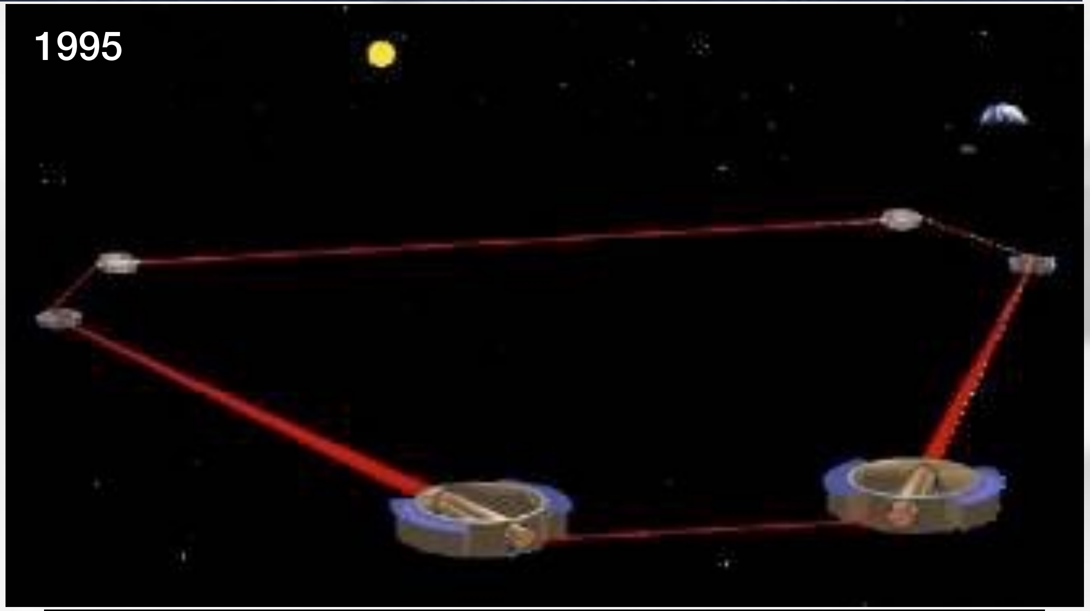
- J.E. Faller, P.L. Bender, J.L. Hall, D. Hills and M.A. Vincent, *Proc. Colloquium «Kilometric Optical Arrays in Space»*, Cargèse (Corsica), **23-25 October 1984**

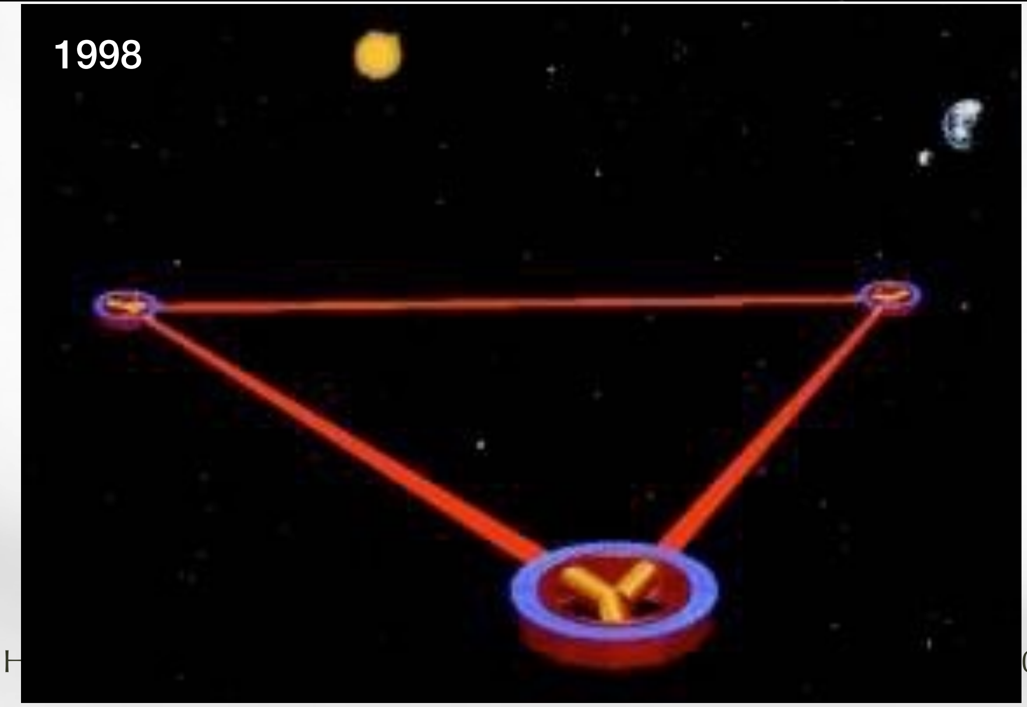
We are investigating possible designs for a laser gravitational wave antenna in space using free test masses and heterodyne (interferometric) detection. One possibility is to use baselines about 10^6 km long between three spacecraft in nearly circular one-year orbits about the sun. If the orbit elements are chosen properly, the distances between the spacecraft can be kept constant to roughly 1 part in 10^3 without orbit corrections. With milliwatt-transmitted laser power levels and 50 cm diameter optics, a strain sensitivity of $10^{-19}/\sqrt{Hz}$ over at least the period range from 10 to 10^4 seconds appears feasible. The primary goal of the measurements is to observe gravitational radiation associated with present or past interactions of super-massive objects. A number of binary sources can, however, also be studied. For periods shorter than 10 seconds, the sensitivity for a baseline length of 10^6 km would degrade as a result of multiple gravitational wavelengths being contained in the arm lengths. For longer periods, the main limitation is likely to come from spurious accelerations due to forces other than the gravitational attraction of the sun and planetary bodies.



The hazards of a space mission

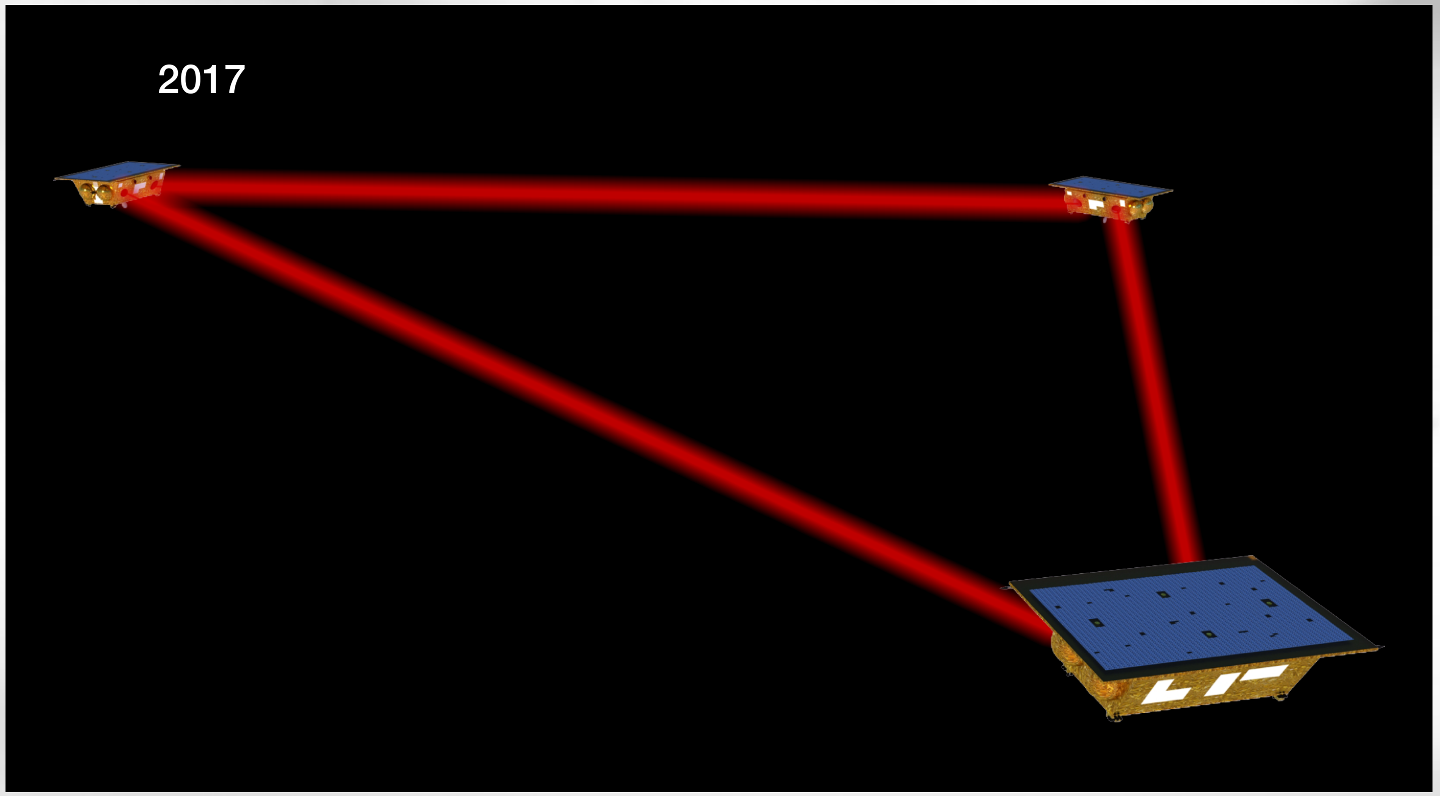






- Joint ESA-NASA mission in 1993
  - 4 (1993) → 6 (1994) → 3 (1997) satellites
  - LISA name appeared (Laser Interferometer Space Antenna) in 1993
  - ESA 'Cornerstone' mission, launch before 2010
- 2011: NASA out of the project
  - Recommandation : « NASA cannot participate to any large mission for the next decade because of the JWST cost »
  - ESA decide to go alone, on a 'optimized' (cheaper) design : the eLISA mission concept (only 2, shorter, arms)

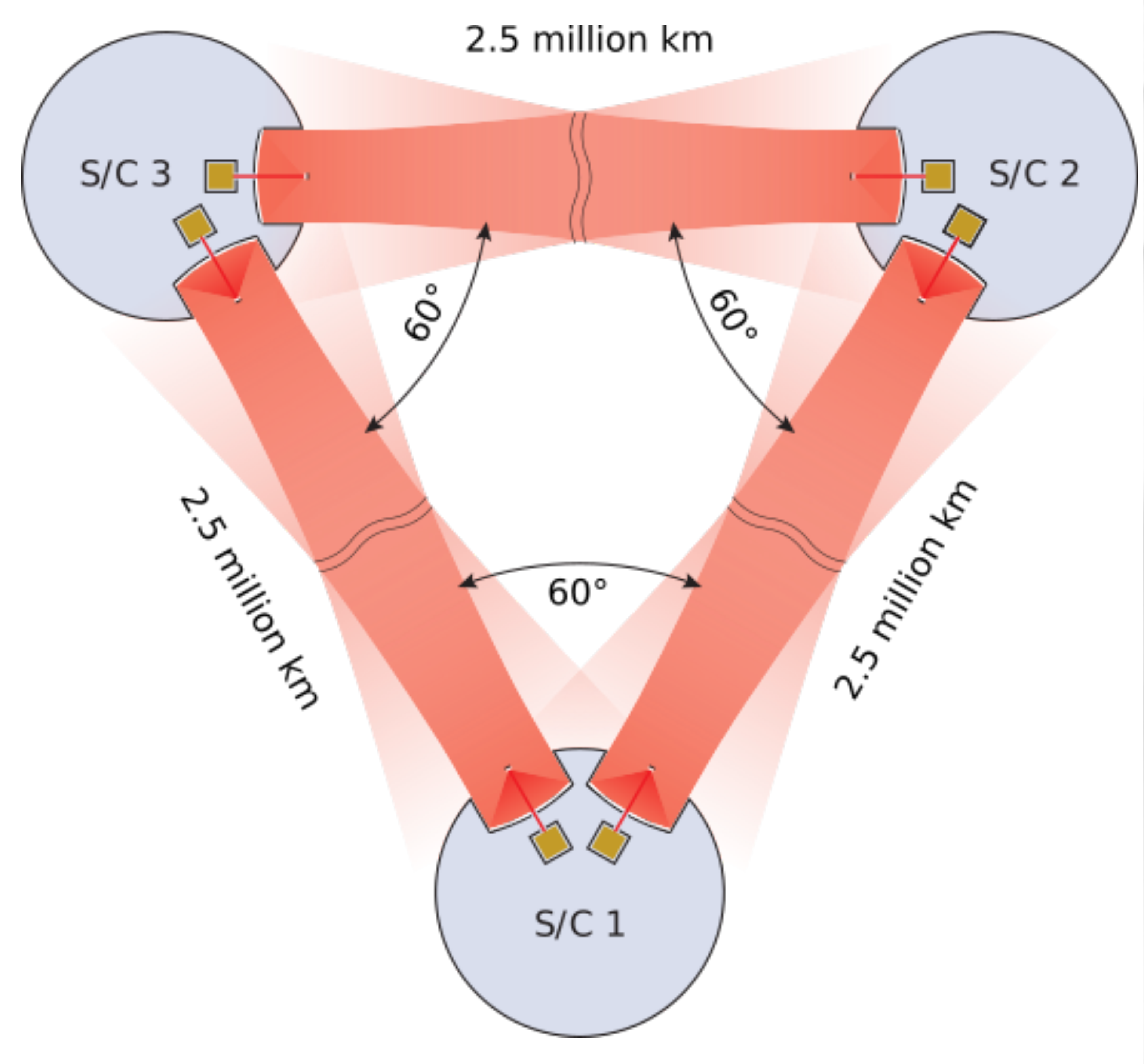
And finally ...



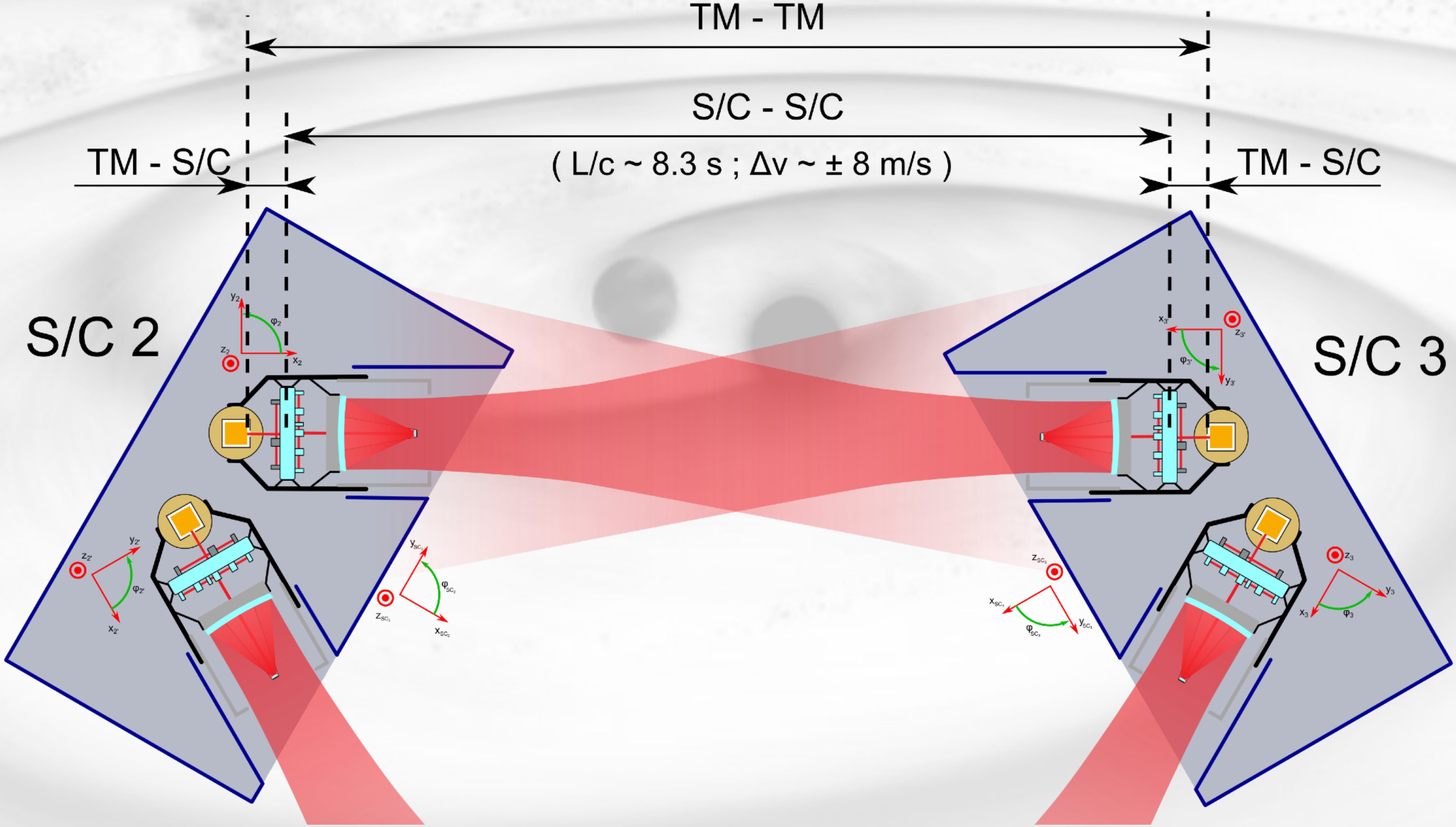
- 2013 : selection of the ‘Gravitational Universe’ as the science theme of the ‘L3’ mission
  - eLISA as strawman mission concept
  - Launch in 2034
- Déc. 2015 - July 2017 : LISA Pathfinder flight
  - Achieved performance far beyond expectations…
- 2017 : selection of LISA as the ‘L3’ mission candidate
  - NASA back into LISA as ‘Junior’ partner
  - 3 interferometric arms, 2.5 Mkm long
- Since then LISA follows mission development phases
  - Phase A (feasibility studies) : 2017 - 2021
  - Phase B (preliminary design) : 2022 - …
  - Adoption : expected end 2023
  - Launch : ~2035

LISA Interferometer

- Equilateral configuration
  - 3 arms / 6 links ; 2.5 Mkm
- Test masses
  - Direct heritage from LPF
  - 2 TM / satellite
  - 2 steerable optical benches / satellite
- Typical metrology requirement : **~10 pm/√Hz @ 1 mHz**

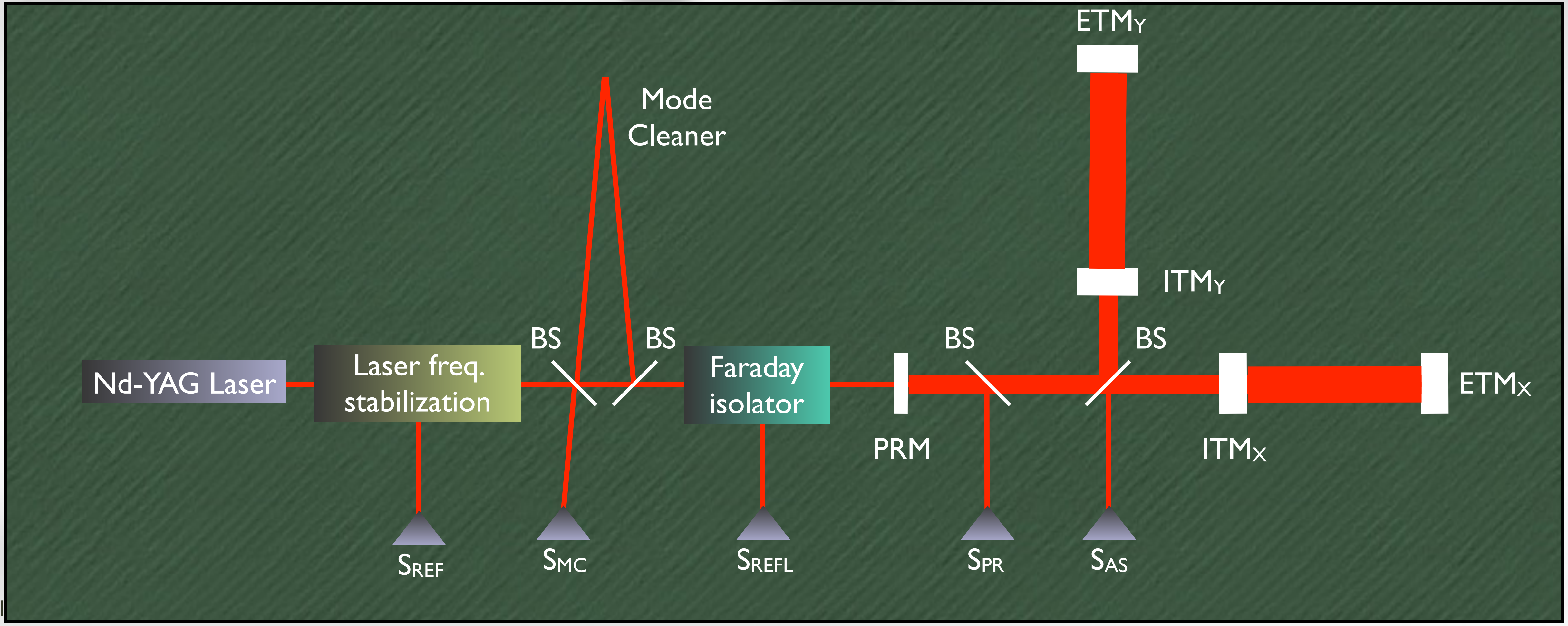


Measurement principle



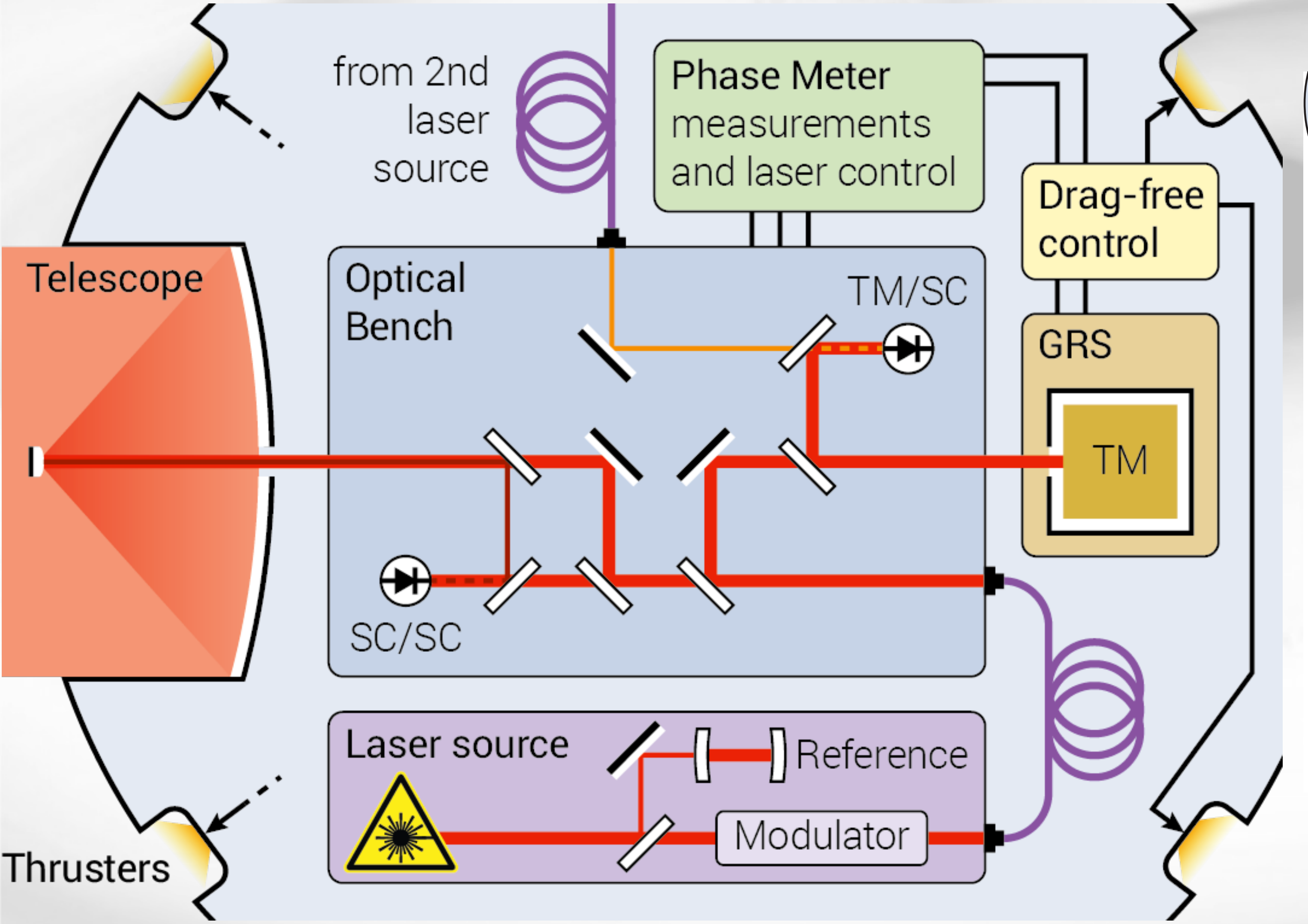
Ground vs. space designs

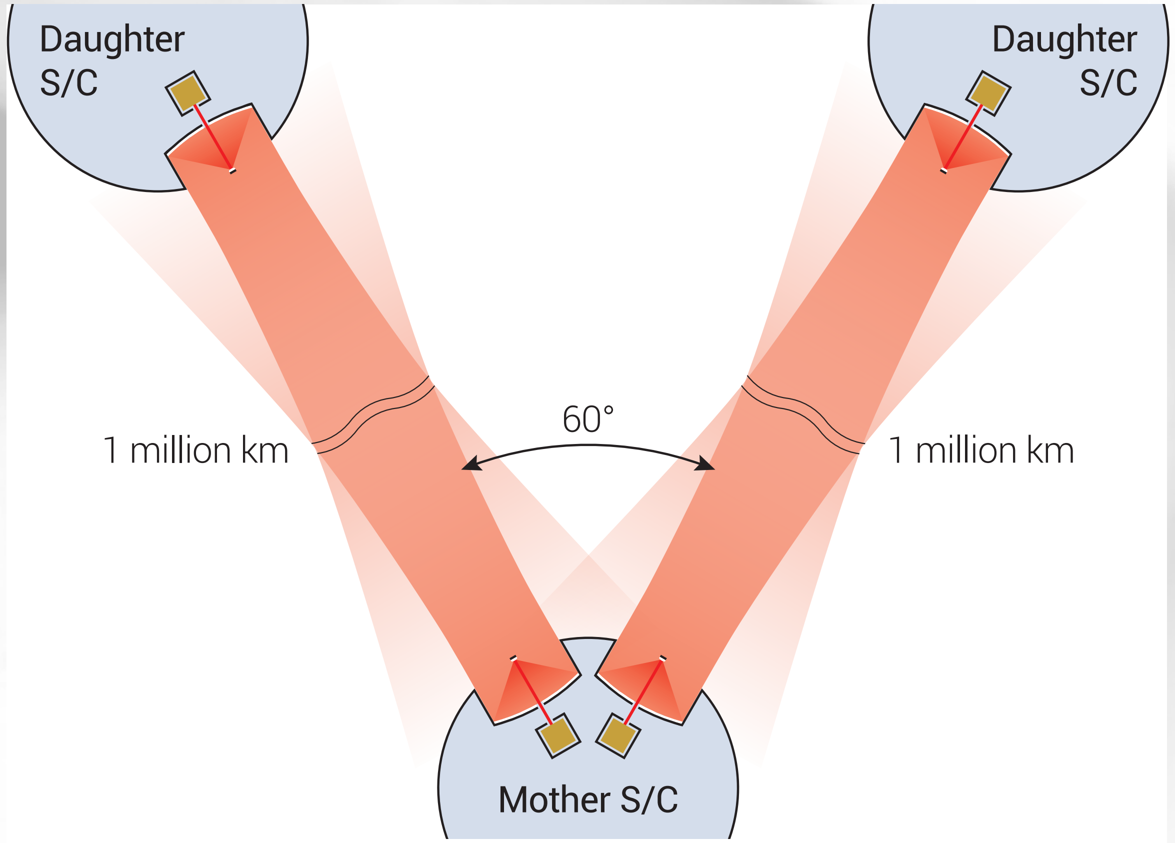
- Ground based interferometers
  - Test masses = suspended mirrors
  - Increase of arm-length using Fabry Perot cavities
  - Power recycling mirror
  - —> High optical power in the arms !
  - —> Linear response only close to resonance : electronic feedback loops to lock the cavities



Ground vs. space designs

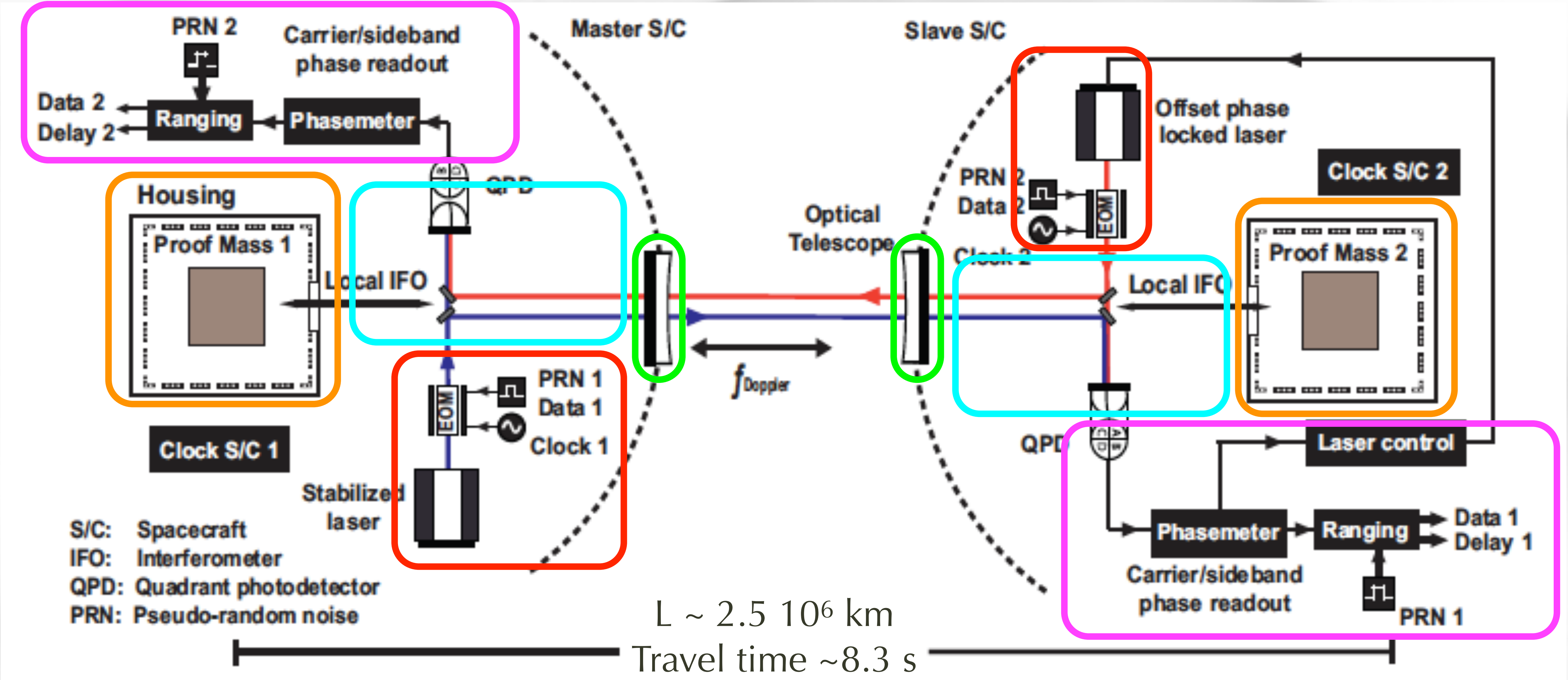
- Space-based interferometers
  - Test masses : free floating mirrors, long arms
  - —> in LISA : 1.1 W emitted, 650 pW received
  - Keplerian orbits : variable armlength. and Doppler shifts
  - —> requires heterodyne interferometry : distance measured as phase stability of a RF signal
  - Independent S/C
  - —> phase-locked lasers (transponder mode) + clocks synchronisation signals





LISA Payload Elements

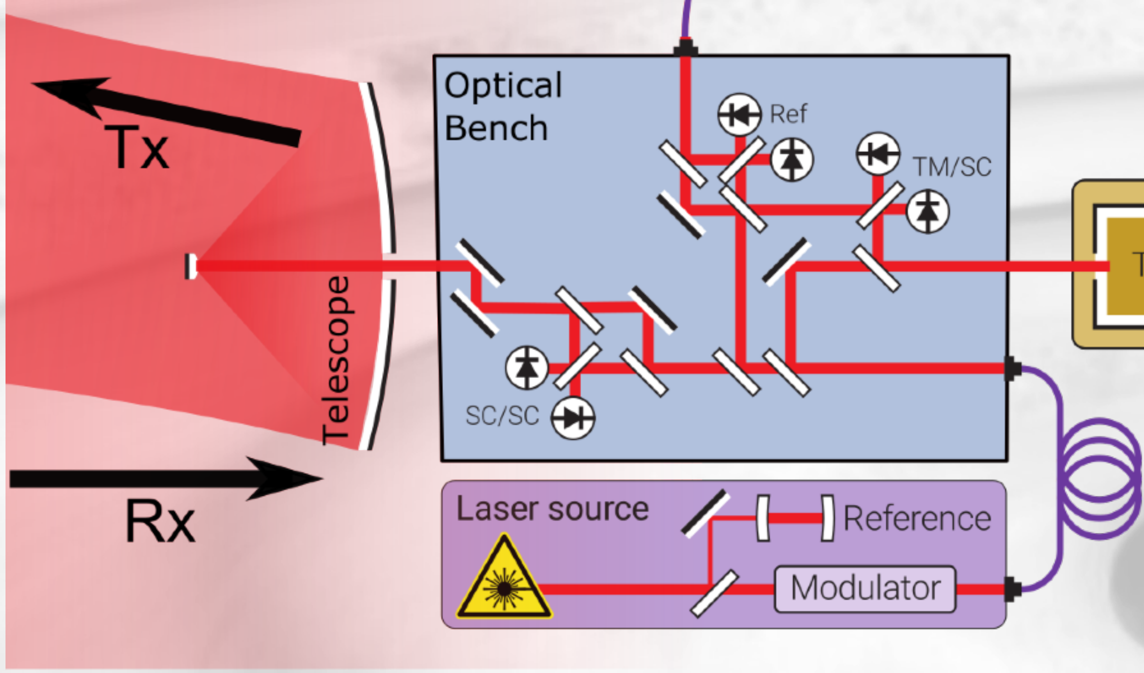
- Main payload elements
  - Gravitational Reference System (GRS)
  - Zerodur Optical Bench
  - Phase & frequency extraction (Phasemeter)
  - Telescope

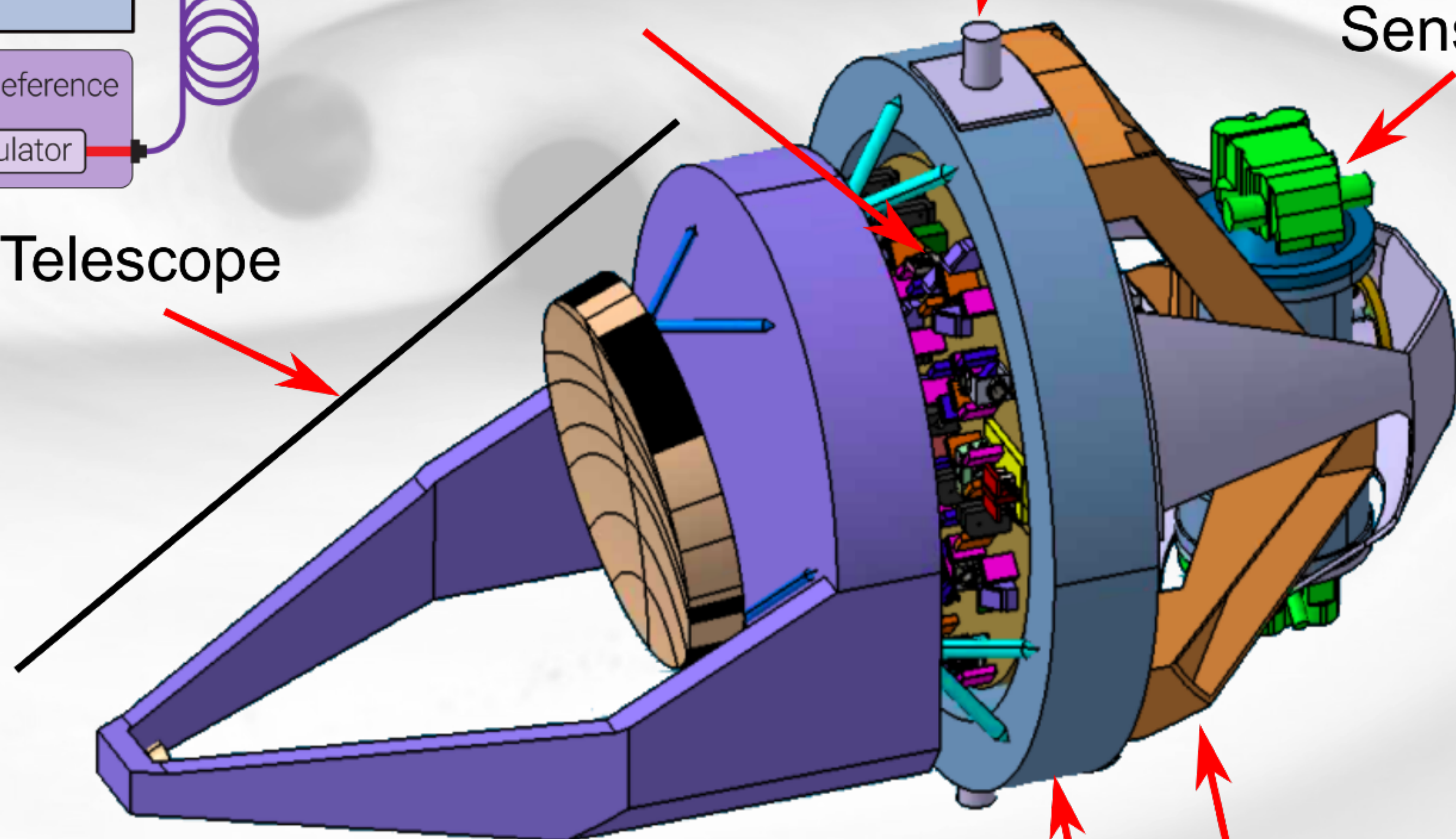


Esteban et al., «Experimental demonstration of weak-light laser ranging and data communication for LISA.», *Optics Express*, **2011**, vol. 19 p. 15937

Scheme of a instrument

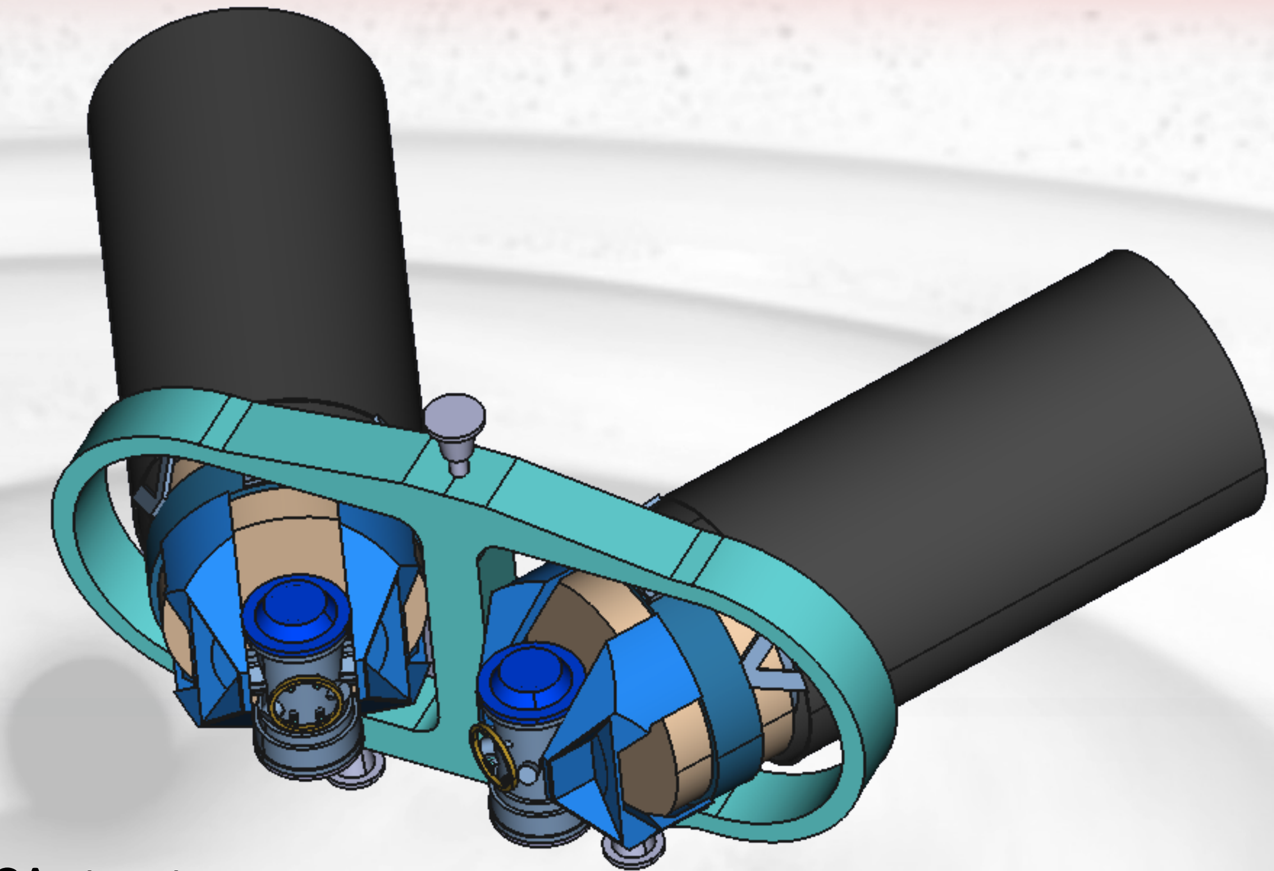
- MOSA = Movable Sub-assembly

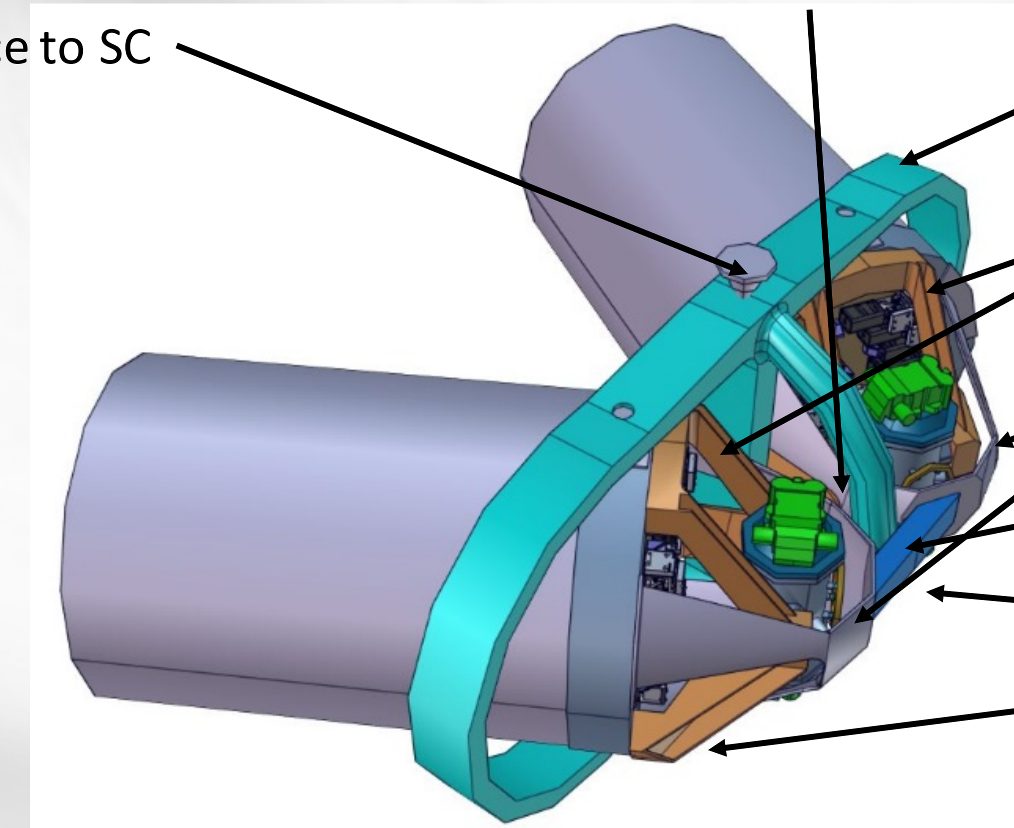




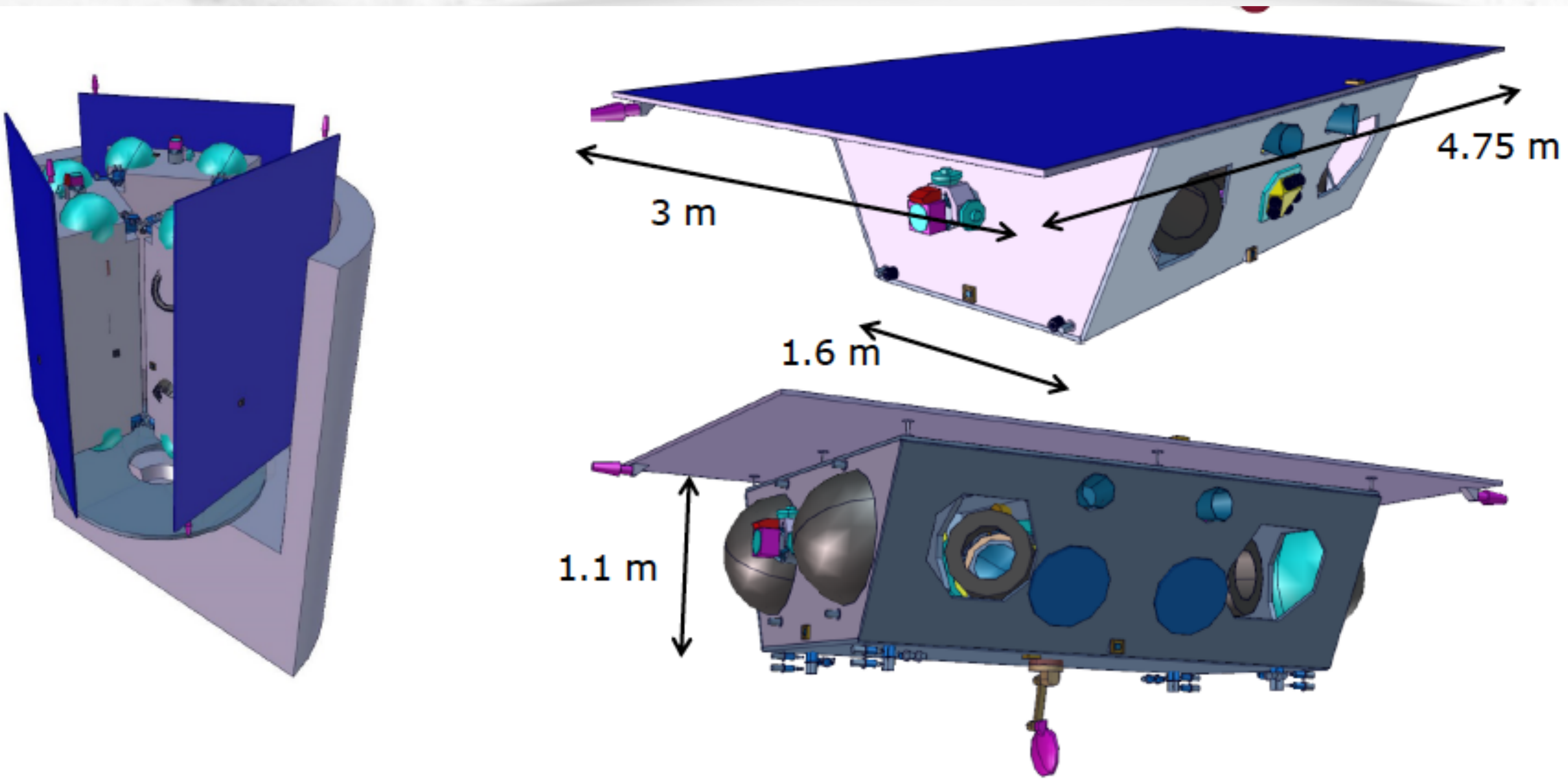
Two MOSAs form an LCA …

- LCA = LISA Core Assembly



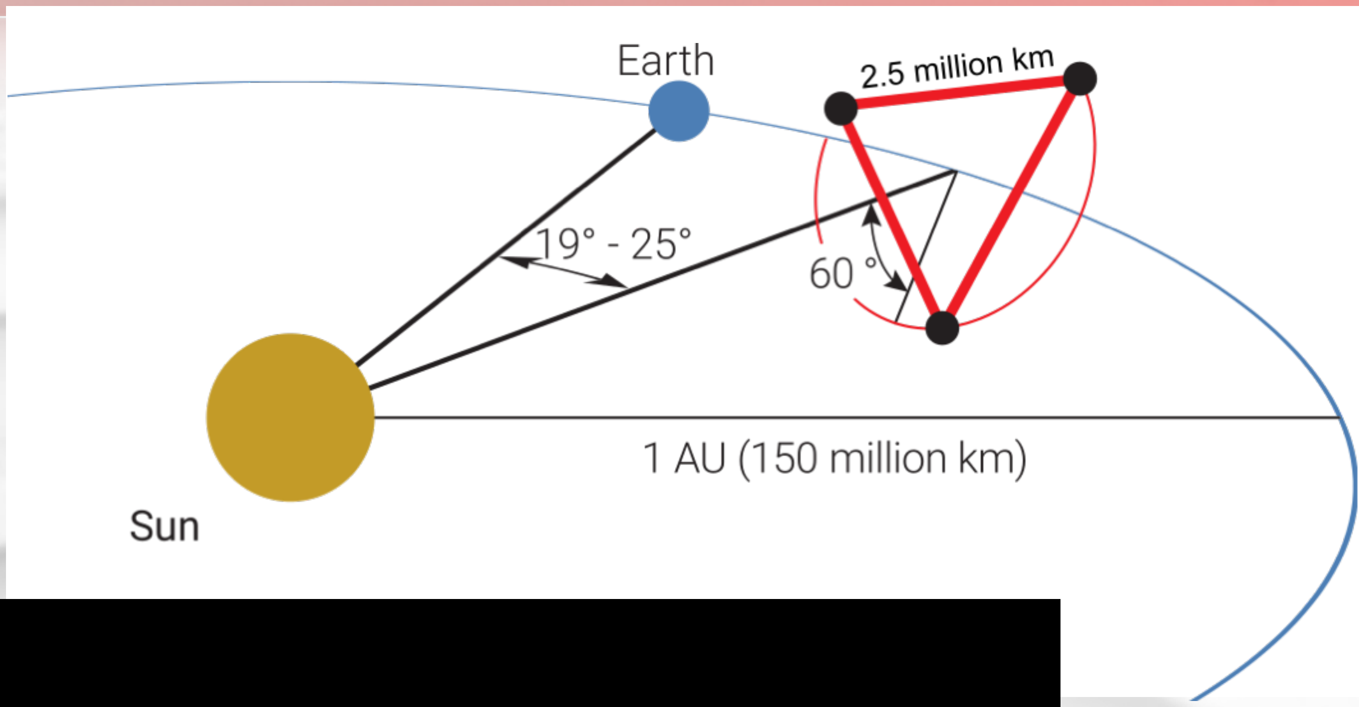


Three S/C fit into an Ariane 6.4



LISA mission profile

- Heliocentric orbits
  - 19° to 25° trailing the Earth



Interferometer response function

- The effect of a GW on a laser link is a Doppler shift of the laser frequency

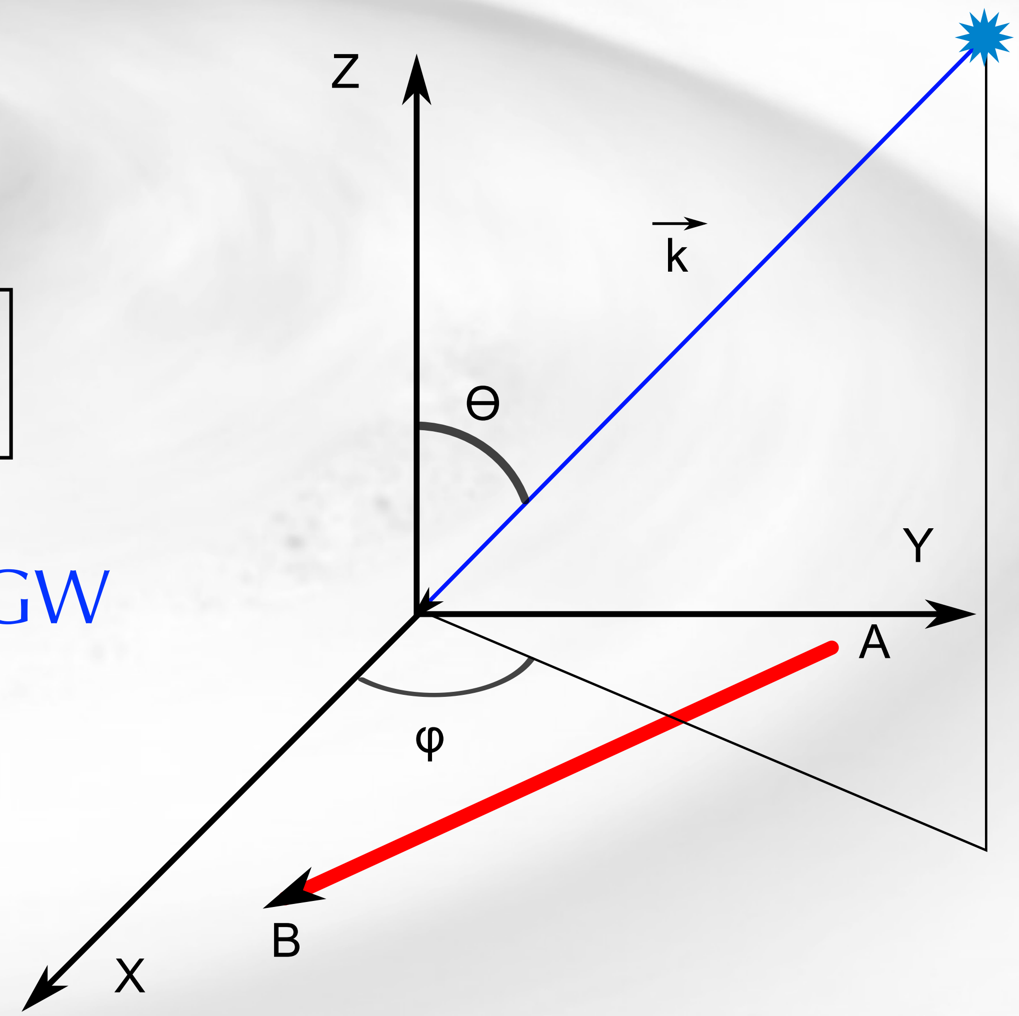
$$\vec{k} = \begin{pmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi \\ \cos\theta \end{pmatrix} ; \vec{\theta} = \frac{\partial \vec{k}}{\partial \theta} = \begin{pmatrix} \cos\theta\cos\phi \\ \cos\theta\sin\phi \\ -\sin\theta \end{pmatrix} ; \vec{\phi} = \frac{1}{\sin\theta}\frac{\partial \vec{k}}{\partial \phi} = \begin{pmatrix} -\sin\phi \\ \cos\phi \\ 0 \end{pmatrix}$$

$$\vec{n} = \vec{r}_B - \vec{r}_A$$

$$\xi_+ = (\vec{\theta}\cdot\vec{n})^2 - (\vec{\phi}\cdot\vec{n})^2 \ ; \ \xi_\times = 2(\vec{\theta}\cdot\vec{n})(\vec{\phi}\cdot\vec{n})$$

$$H(t) = \xi_+ \cdot h_+(t) + \xi_\times \cdot h_\times(t)$$

$$\frac{\delta\nu}{\nu_0}(t) = \frac{1}{2\left(1-\vec{k}\cdot\vec{n}\right)}\left[H\left(t - \frac{\vec{k}\cdot\vec{r}_B}{c}\right) - H\left(t - \frac{L}{c} - \frac{\vec{k}\cdot\vec{r}_A}{c}\right)\right]$$



- ξ+ and ξx define the angular response to GW
- For a bouncing laser link :

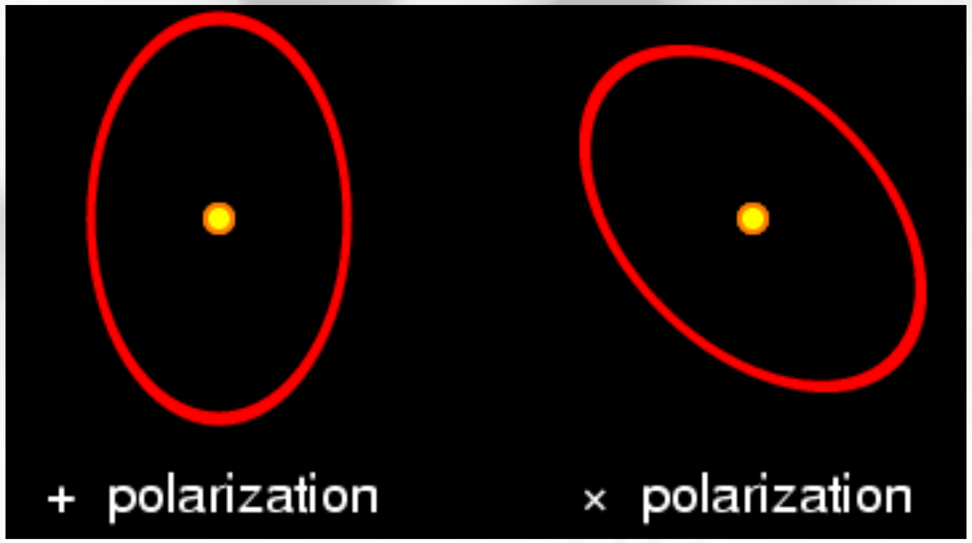
$$\left.\frac{\delta\nu}{\nu_0}\right|_{2ways}(t) = \frac{1}{2\left(1-\vec{k}\cdot\vec{n}\right)}\left[H\left(t - \frac{\vec{k}\cdot\vec{r}_B}{c}\right) - H\left(t - \frac{L}{c} - \frac{\vec{k}\cdot\vec{r}_A}{c}\right)\right] + \frac{1}{2\left(1+\vec{k}\cdot\vec{n}\right)}\left[H\left(t - \frac{L}{c} - \frac{\vec{k}\cdot\vec{r}_A}{c}\right) - H\left(t - \frac{2L}{c} - \frac{\vec{k}\cdot\vec{r}_B}{c}\right)\right]$$

Interferometer response function

- For n1=x, n2=y, k=-z, ϕ=0
  - i.e Michelson interferometer with the source direction perp. to arms plane.

$$\xi_{+,1} = +1; \xi_{\times,1} = 0\ ;\ \left.\frac{\delta\nu}{\nu_0}\right|_{2ways,1}(t) = \frac{1}{2}\left[h_+(t) - h_+\left(t - \frac{2L}{c}\right)\right]$$

$$\xi_{+,2} = -1; \xi_{\times,1} = 0\ ;\ \left.\frac{\delta\nu}{\nu_0}\right|_{2ways,2}(t) = -\frac{1}{2}\left[h_+(t) - h_+\left(t - \frac{2L}{c}\right)\right]$$



$$\left.\frac{\delta\nu}{\nu_0}\right|_{interf}(t) = \left.\frac{\delta\nu}{\nu_0}\right|_{2ways,1}(t) - \left.\frac{\delta\nu}{\nu_0}\right|_{2ways,2}(t) = h_+(t) - h_+\left(t - \frac{2L}{c}\right)$$

$$\Rightarrow \left.\frac{\delta\tilde{\nu}}{\nu_0}\right|_{interf}(f) = \tilde{h}_+(f)\left(1 - e^{-2i\pi f\frac{2L}{c}}\right) = \tilde{h}_+(f)\,2i\sin\frac{2\pi fL}{c}e^{-2i\pi f\frac{L}{c}}$$

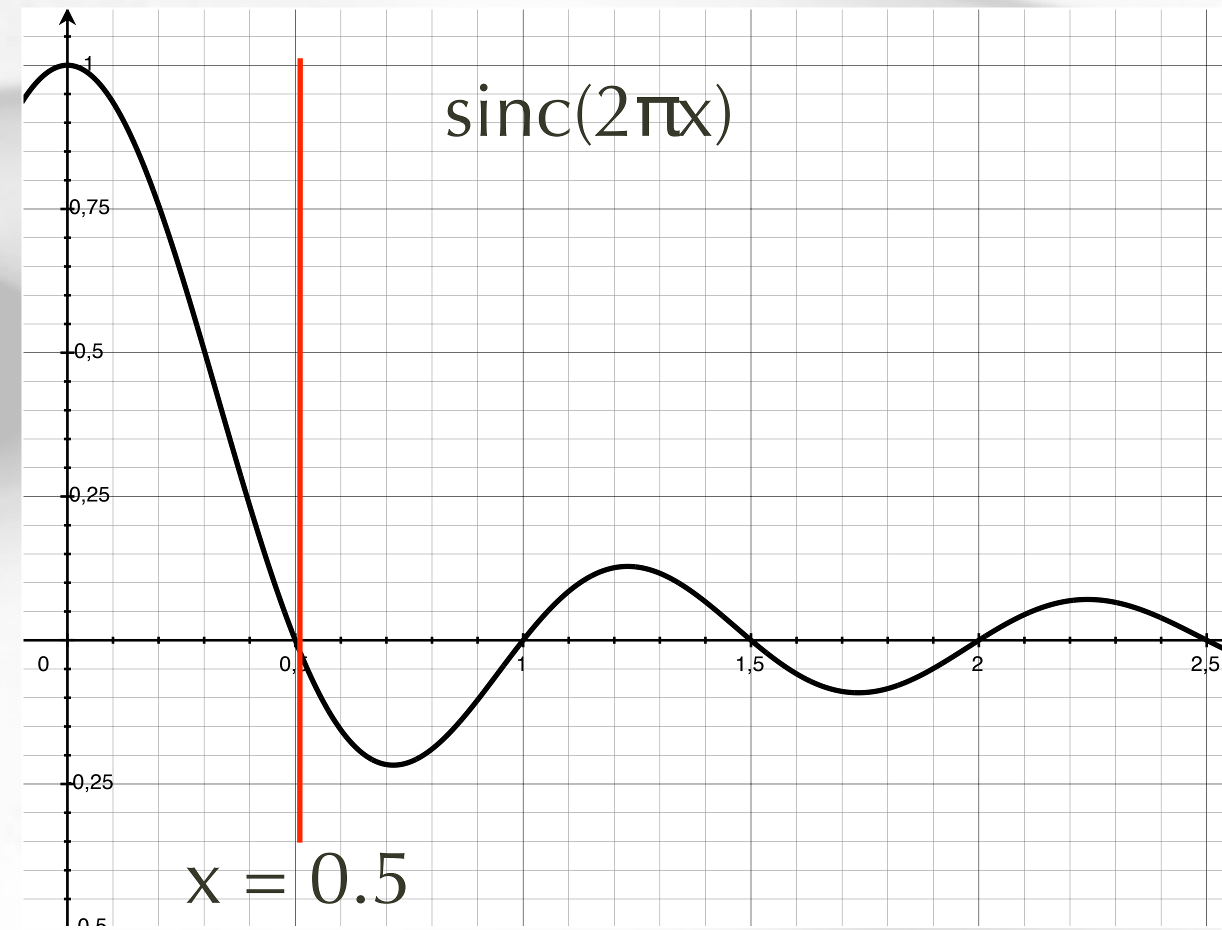
Interferometer response function

$$\Phi(t) = 2\pi \int \nu(t)dt \Rightarrow \delta\tilde{\Phi}\Big|_{interf}(f) = \nu_0 \frac{\delta\tilde{\nu}(f)}{i \cdot f} = 2\pi \times \tilde{h}_+(f)\,\frac{2L}{\lambda}\mathrm{sinc}\frac{2\pi f L}{c}e^{-2i\pi f \frac{L}{c}}$$

- Cut-off frequency at $f_c = c/2L$
  - Correspond to more than 1 oscillation in L
  - Space based (L=2.5 Mkm) => $f_c \sim 60$ mHz
- At low frequencies ($f \ll f_c$) :

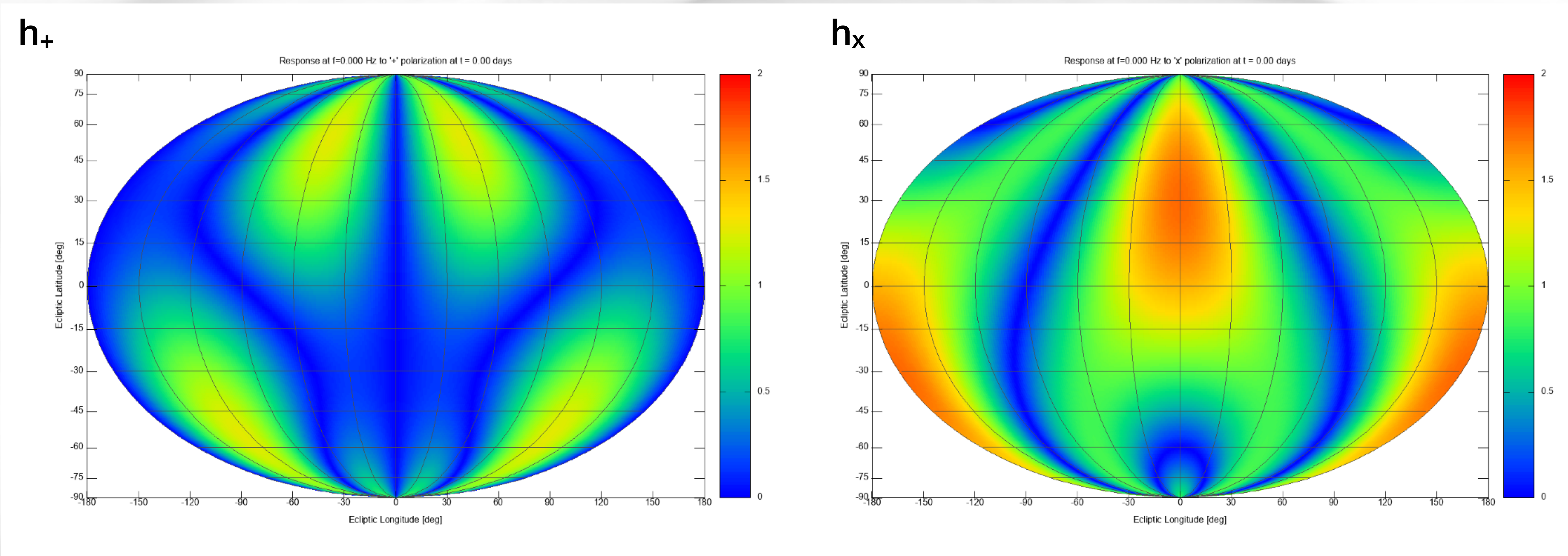
$$\delta\tilde{\Phi}\Big|_{interf}(f) \approx 2\pi \times \tilde{h}_+(f)\,\frac{2L}{\lambda}e^{-2i\pi f \frac{L}{c}}$$

$$\delta\Phi\big|_{interf}(t) \approx 2\pi \times h_+\left(t - \frac{L}{c}\right)\frac{2L}{\lambda}$$



LISA response to GWs

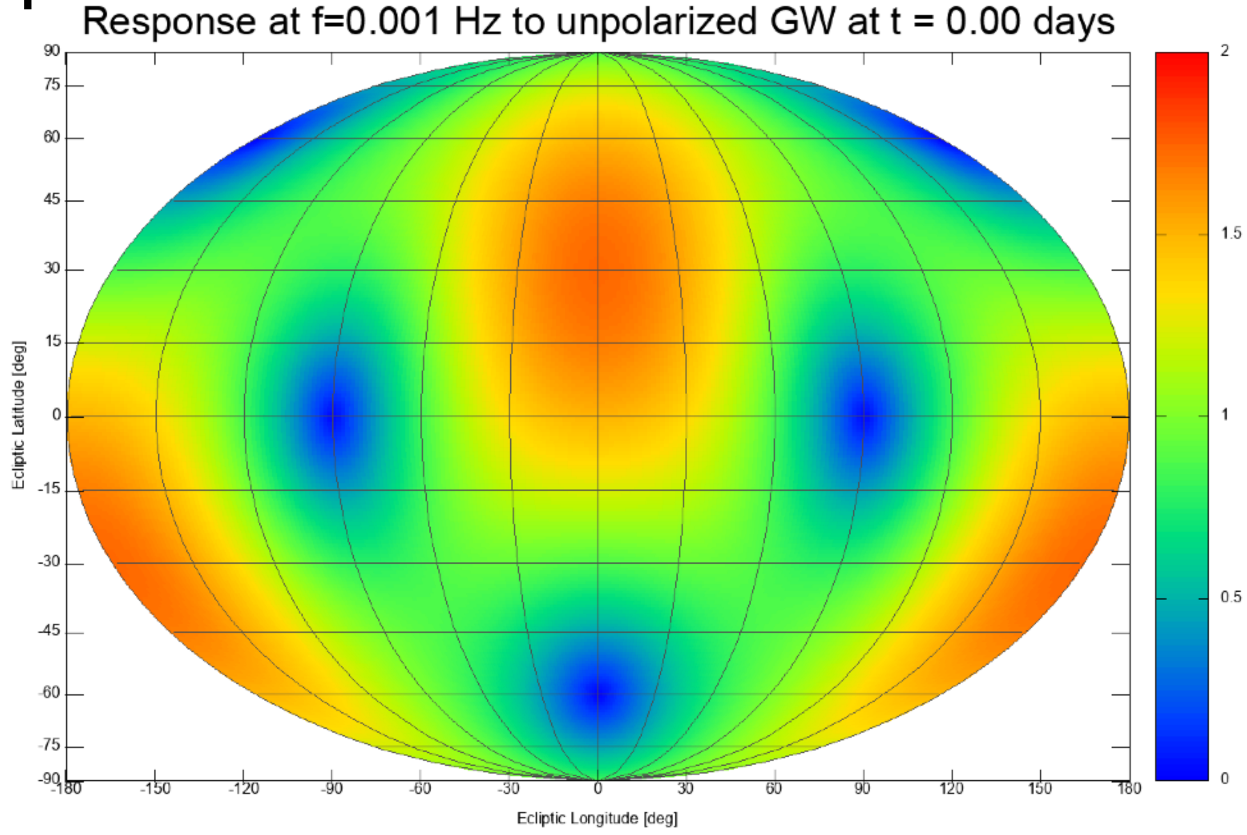
- LISA-type response in ecliptic coordinates
  - Neglecting Doppler effects (relative velocity w.r.t the source) and constellation deformations
  - Time modulation of the antenna pattern —> localization of the source
    - Also possible at a given time from Doppler shifts
  - The 3 links allow to disentangle polarizations

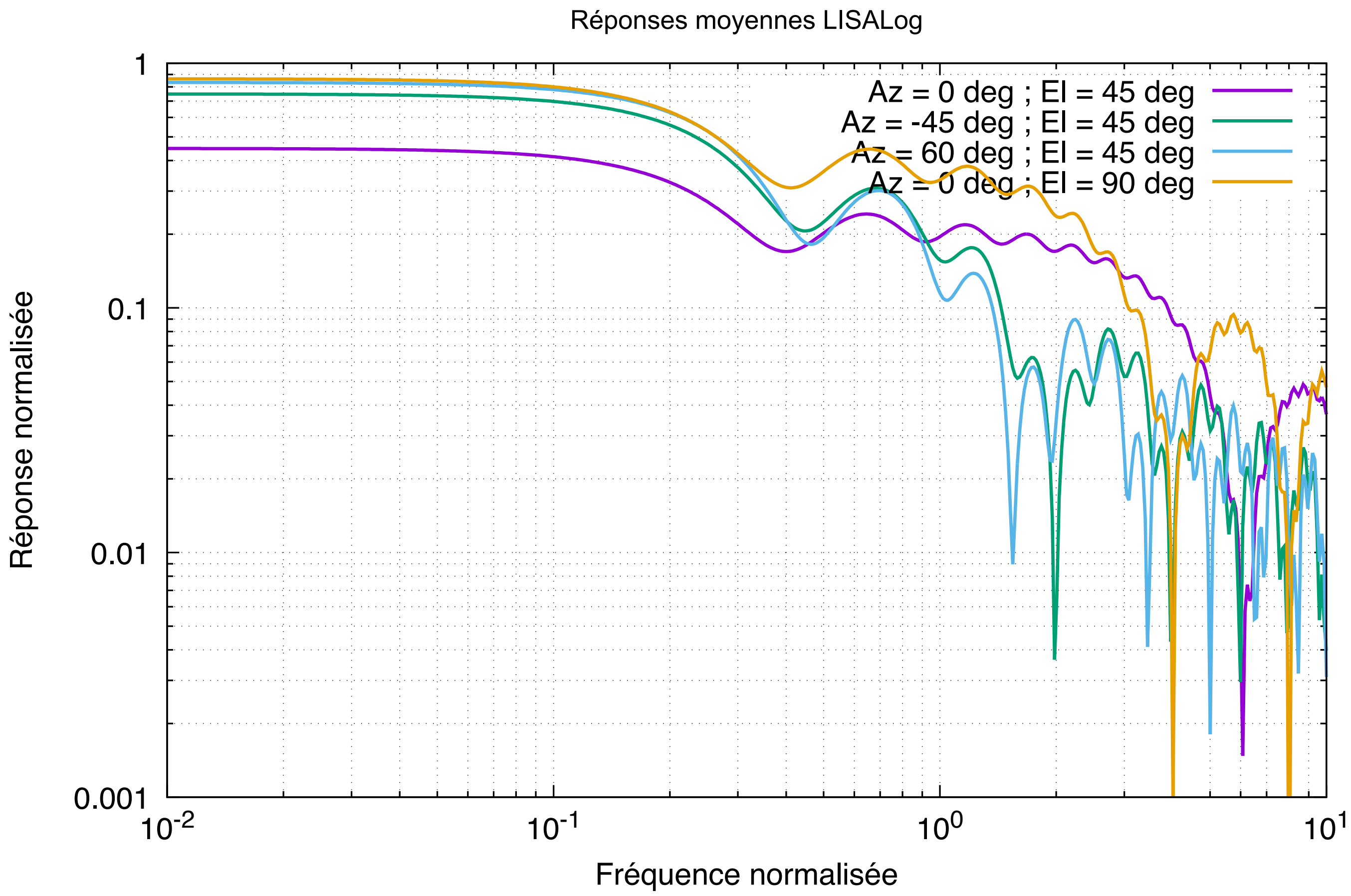


LISA response to GWs

- LISA response in ecliptic coordinates
  - Neglecting Doppler effects (relative velocity w.r.t the source) and constellation deformations
  - Attenuation of the response with wave frequency

Unpolarized





Orbital stability ?

- Mission constraints
  - Stable constellation over 12+ years
  - Constant inter-S/C distance : ~2.5 Mkm
  - Relative velocity between S/C : < ~20 m/s (20 MHz)
    - Set by the photoreceiver bandwidth
  - Distance to Earth <65 Mkm
    - Set by the required data rate with Earth
  - Pure inertial orbits
    - Solar pressure compensation, no orbit correction

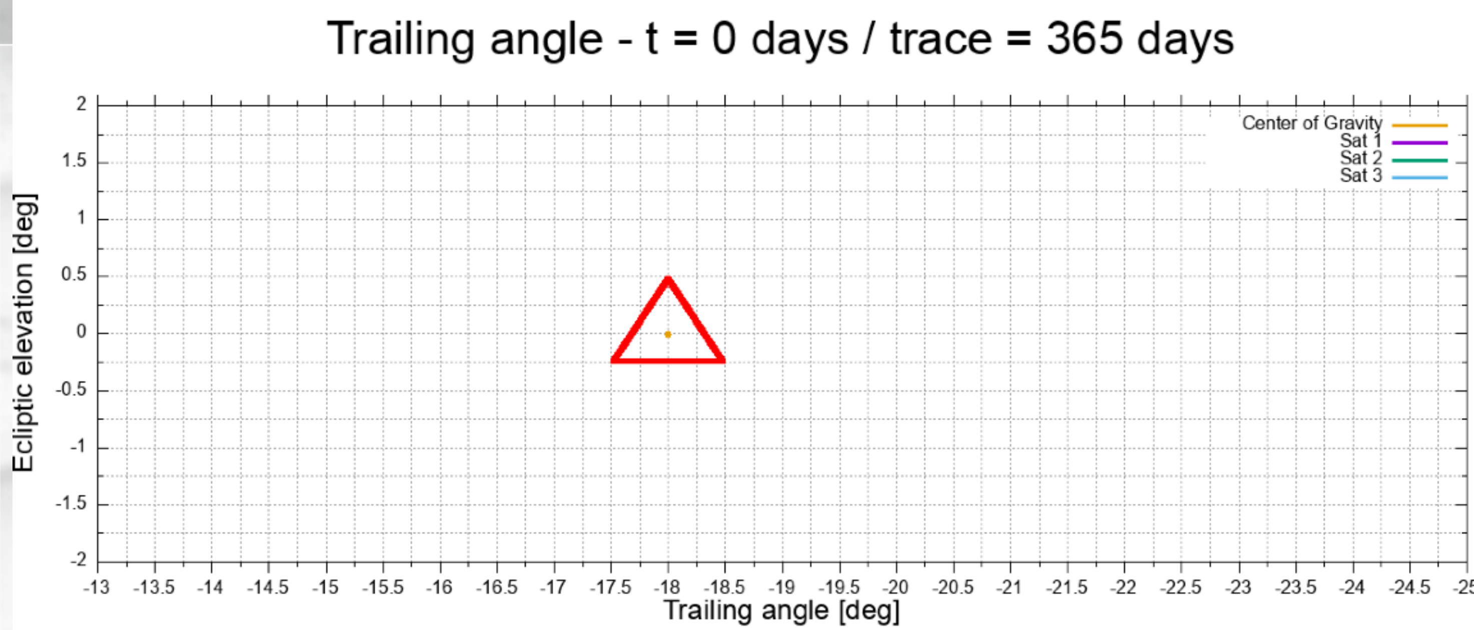
- —> Do such orbits exists ?

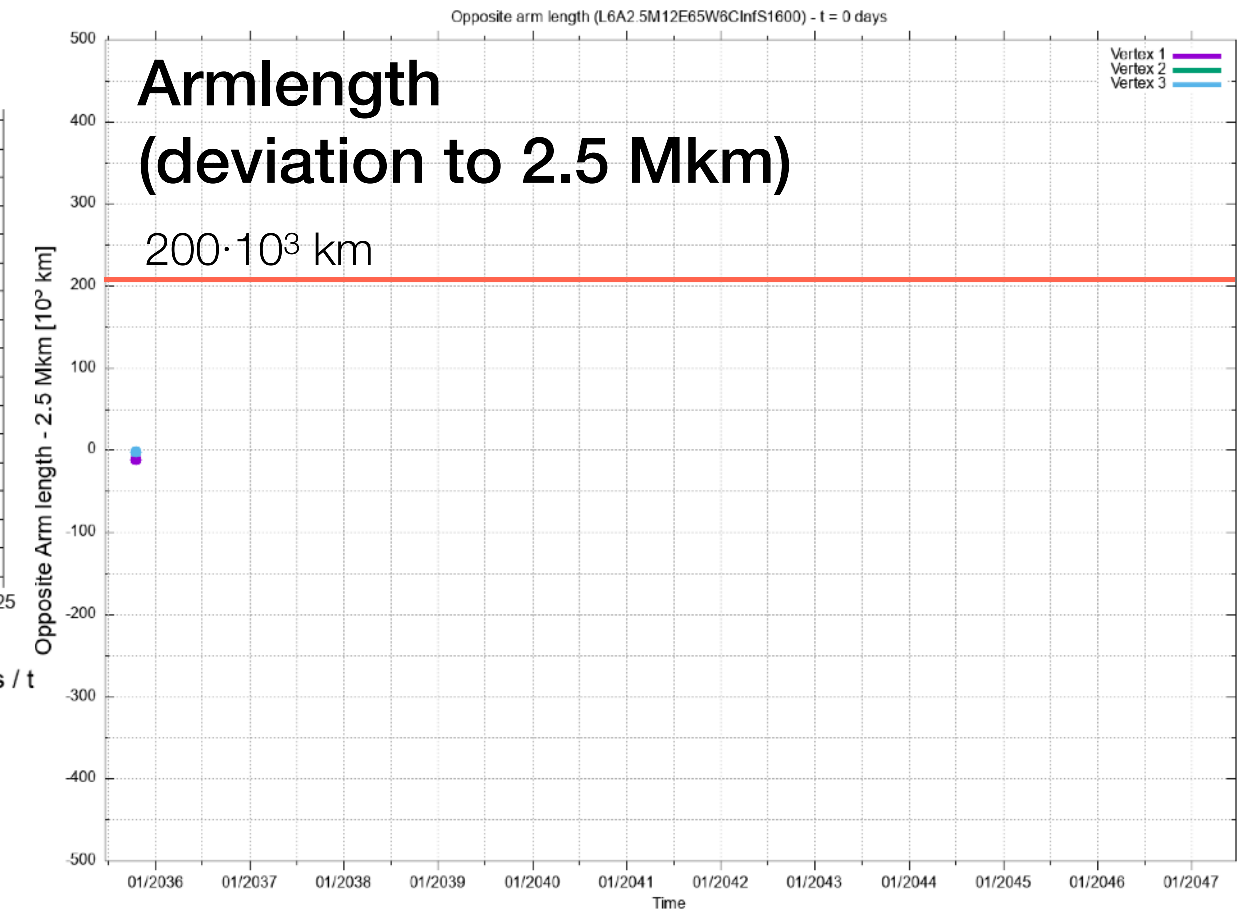
- Yes for a purely central force (i.e only Sun attraction)
  - Inclination of the constellation on the ecliptic : ~60.3°
  - Relative velocities : < 2 m/s (2 MHz)
  - Armlength : 2.5Mkm +/- 12 000 km

- However …
  - Gravitational perturbations from other celestial objects (mostly Earth+Moon)
  - —> Keplerian solution not suitable
  - —> Requires numerical optimisation

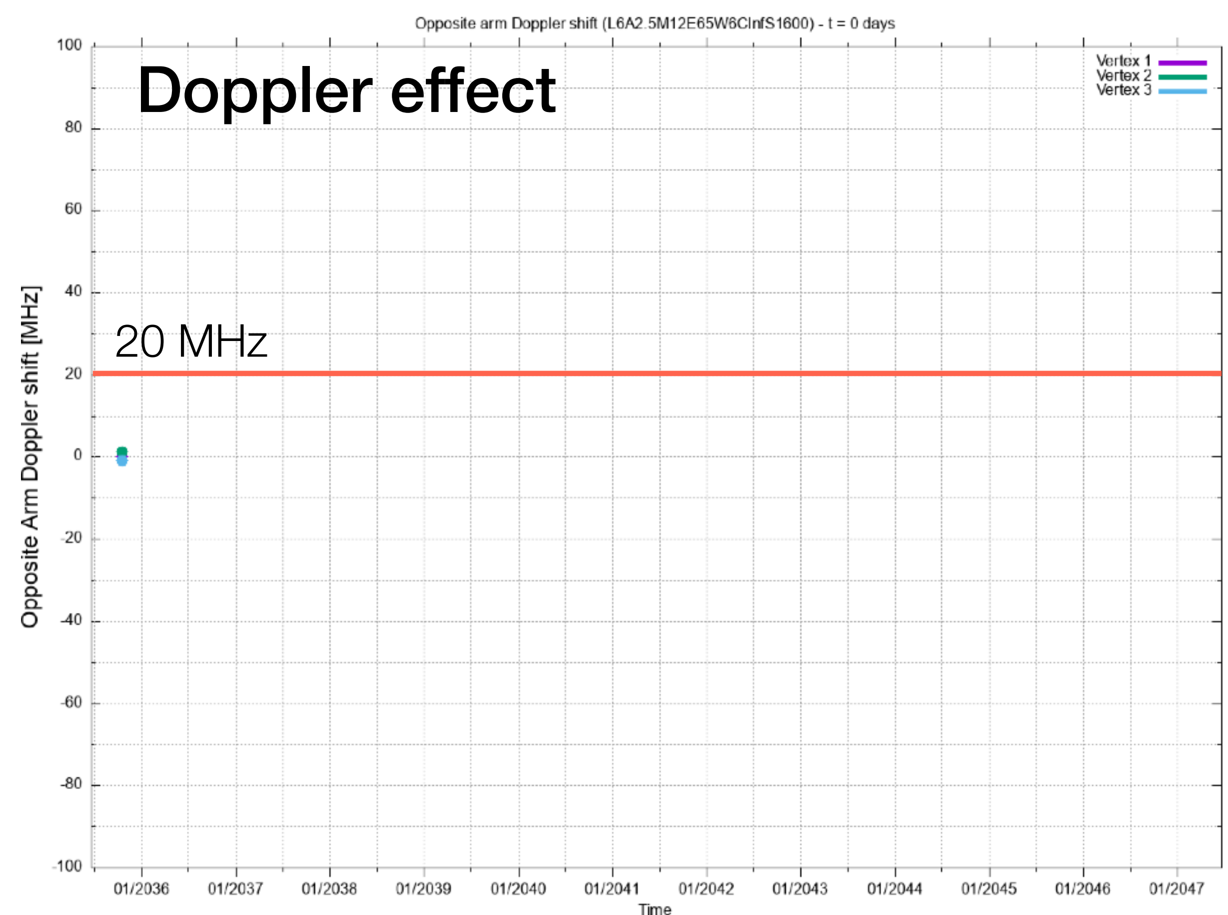
Orbital stability ?

Trailing angle of LISA





Constellation shape

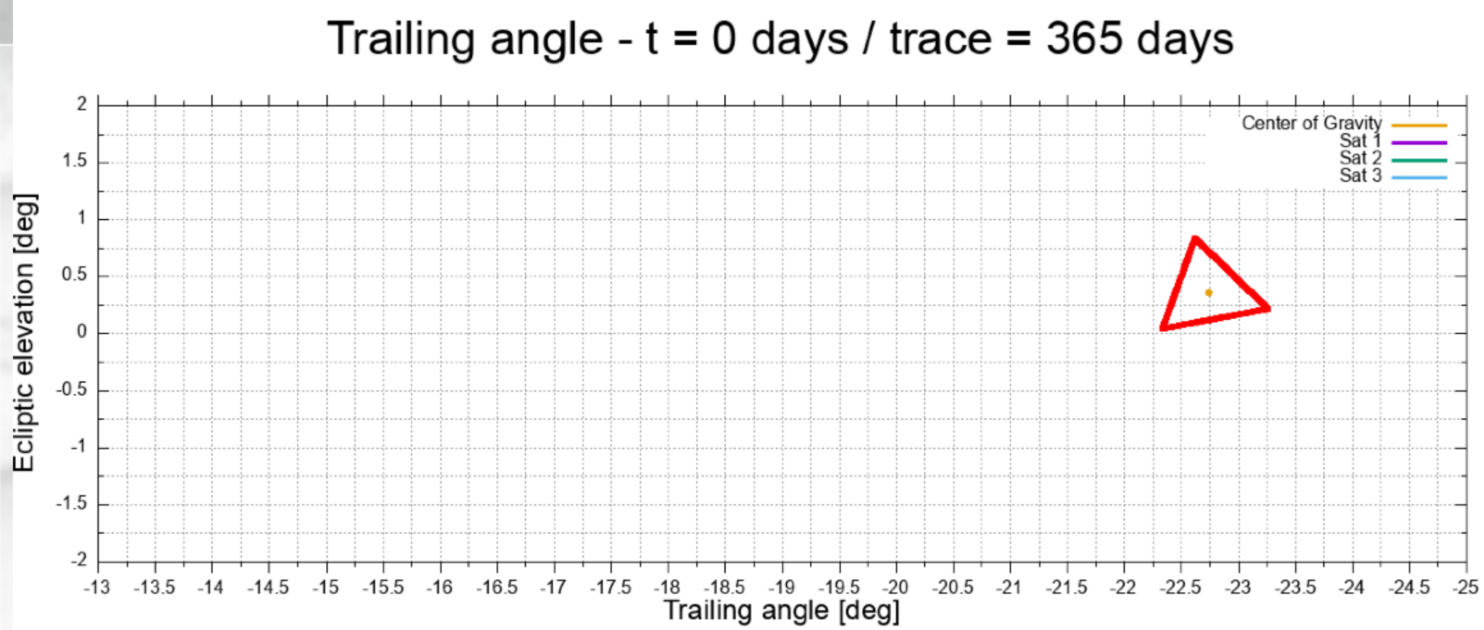


- Using ‘optimal’ keplerian parameters in presence of Earth gravitational perturbations

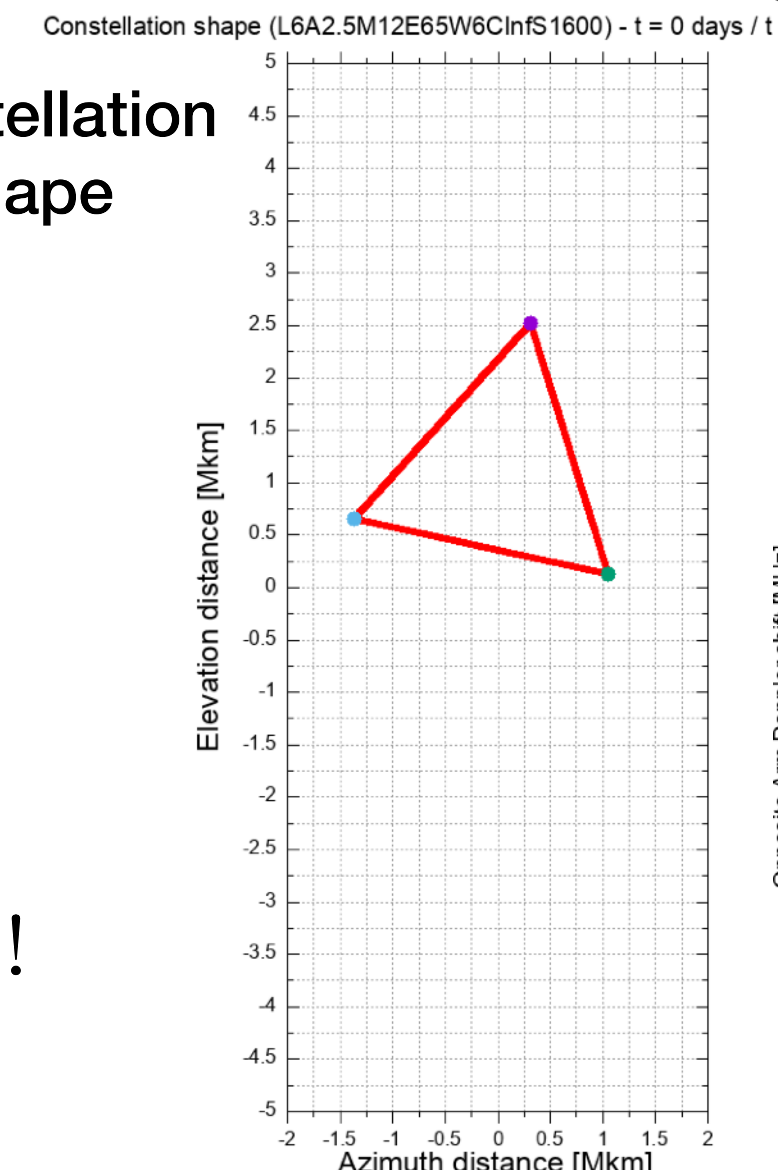
[Halloin, 2017]

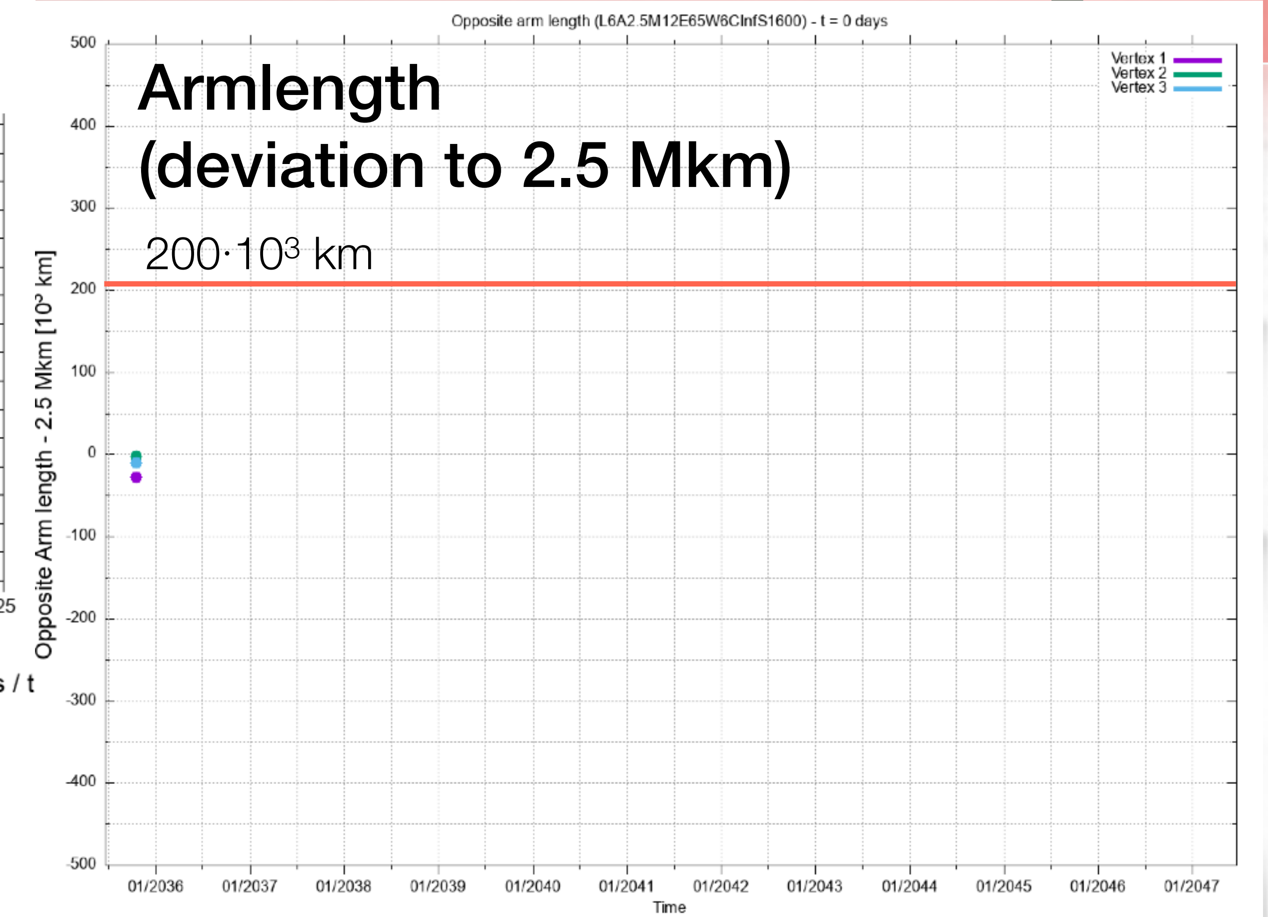
Orbital stability ?

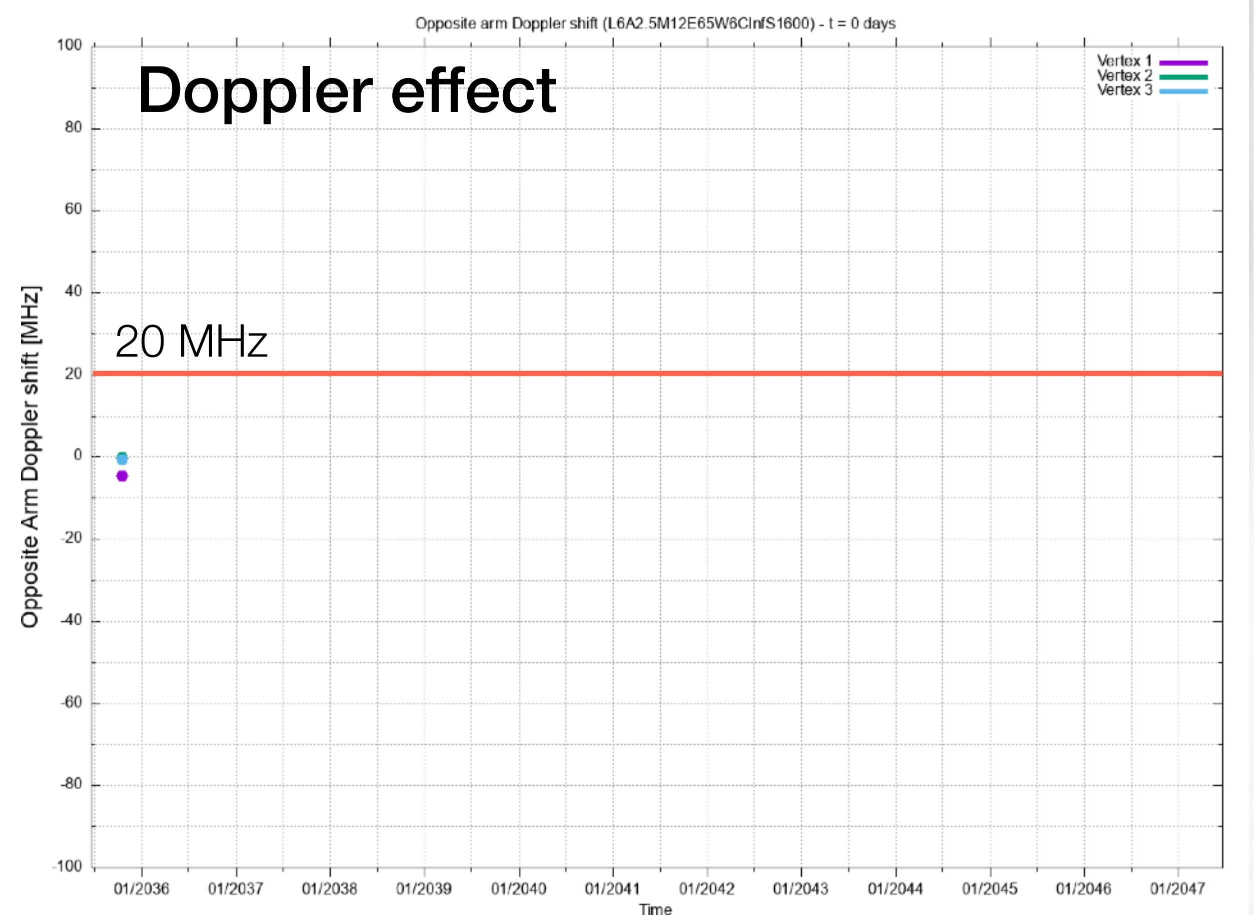
Trailing angle of LISA



Constellation shape



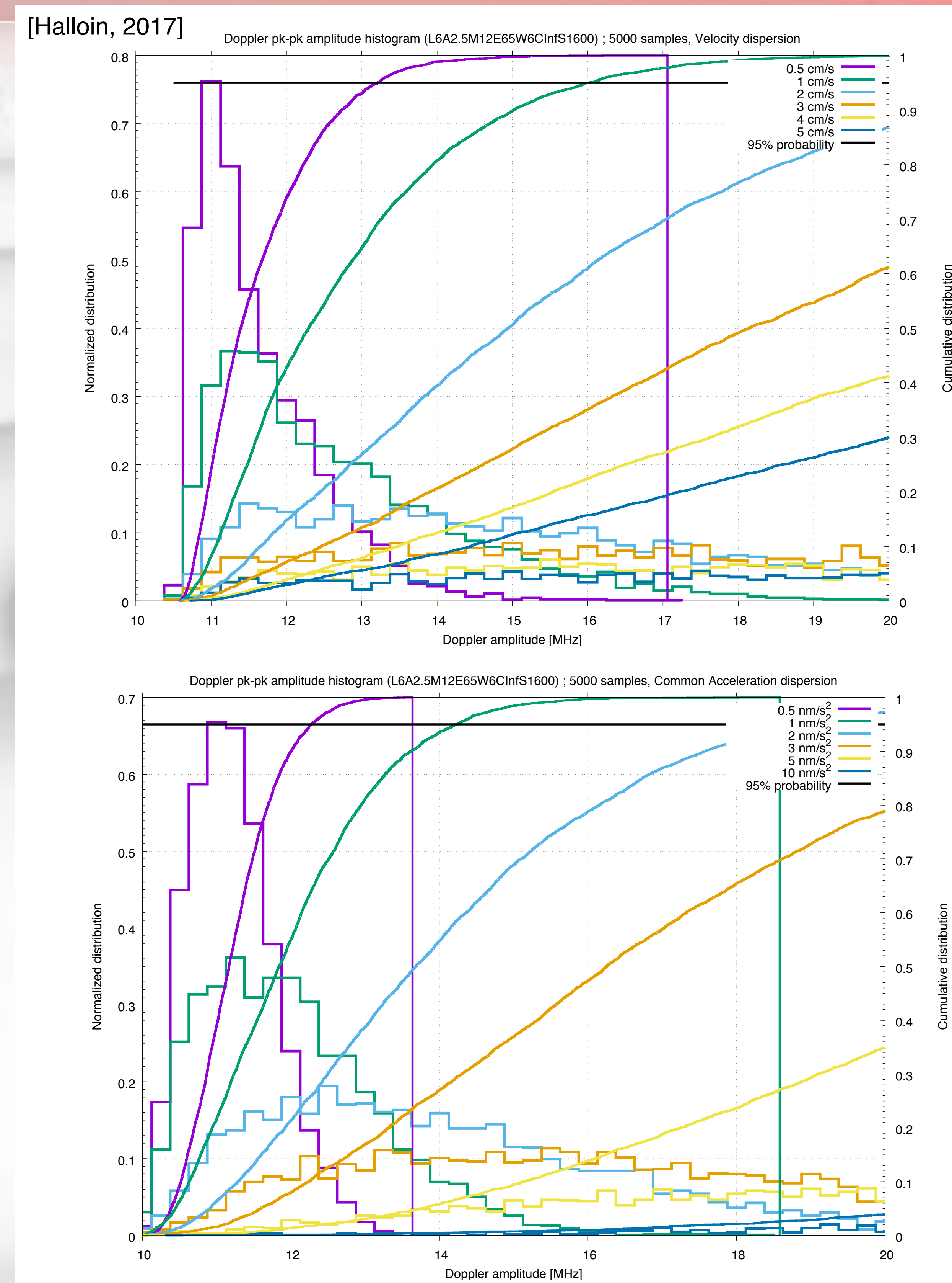


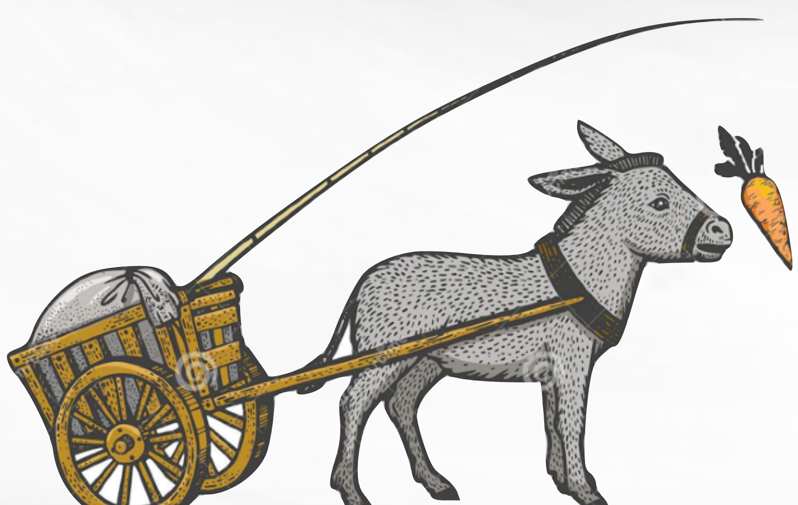


- After numerical optimization of the orbital parameters
- Yes, it works ;-) !

Orbital stability ?

- Sensitivity to local disturbances
  - Constraints on initial S/C positioning and velocity
    - ~50 km and 1 cm / s max
  - Constraint on residual gravitational field at test mass location
    - ~1,5 nm/s² max
    - Equivalent to 10 kg at 60 cm





Laser frequency noise

- Frequency instability of a laser beam couples to phase noise for unequal armlength

$$\delta\Phi = \Phi(t - 2L/c) - \Phi(t - 2(L - \Delta L)/c)$$
$$\approx \frac{2\Delta L}{c}\frac{\partial\Phi}{\partial t}(t - 2L/c) = \frac{2\Delta L}{c}2\pi\delta\nu$$
$$\Rightarrow \delta x = \lambda\frac{\delta\Phi}{2\pi} = 2\Delta L\frac{\delta\nu}{\nu}$$

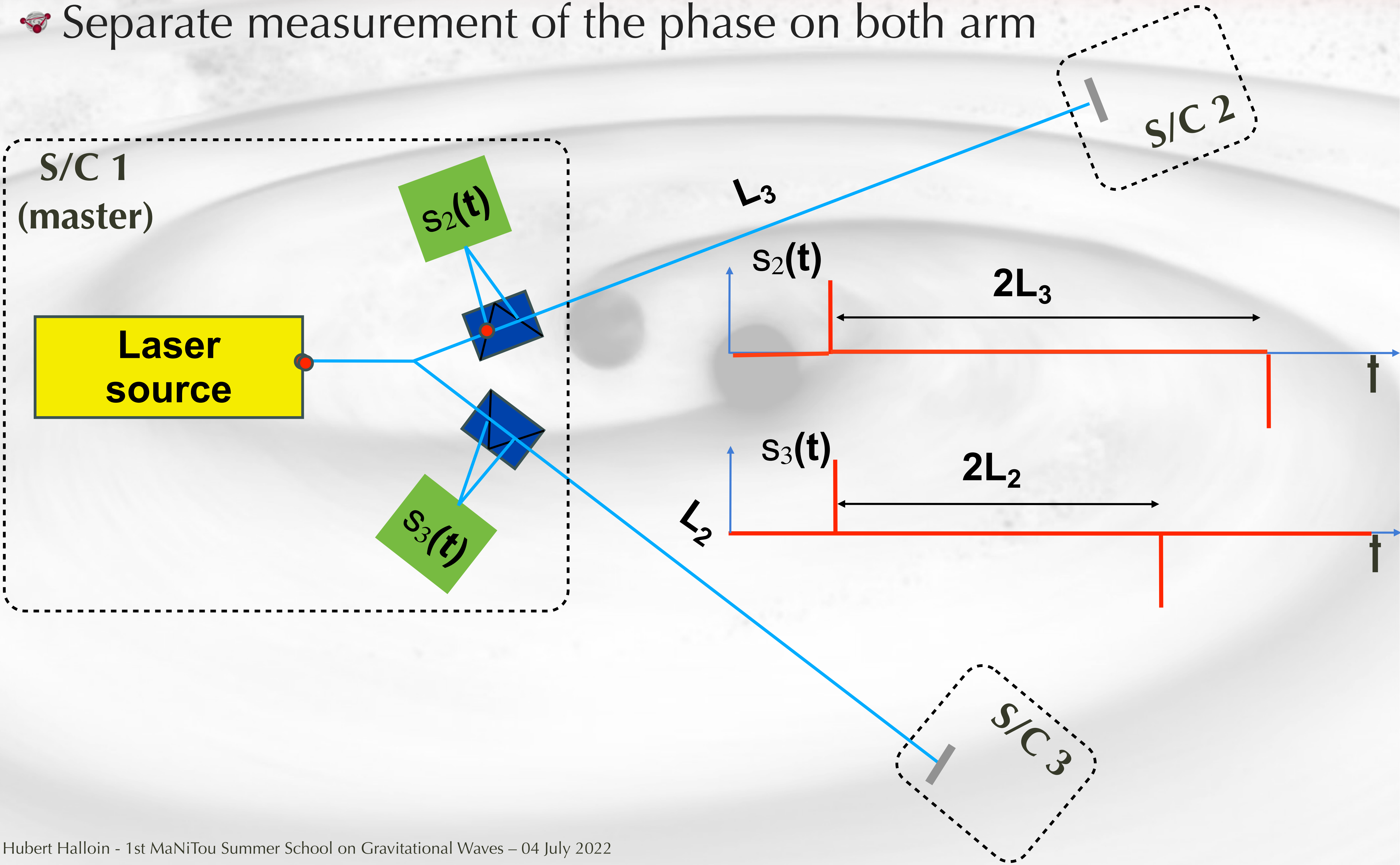
- For space-based detectors :
  - ΔL~10 000 km (inertial orbits)
  - ⇒ δν~10^{-6} Hz/√Hz in the range [0.1 mHz : 10 Hz]

- Best 'transportable' stable laser at ~10 Hz/√Hz …
  - In LISA : ultra-stable Fabry-Perot cavity

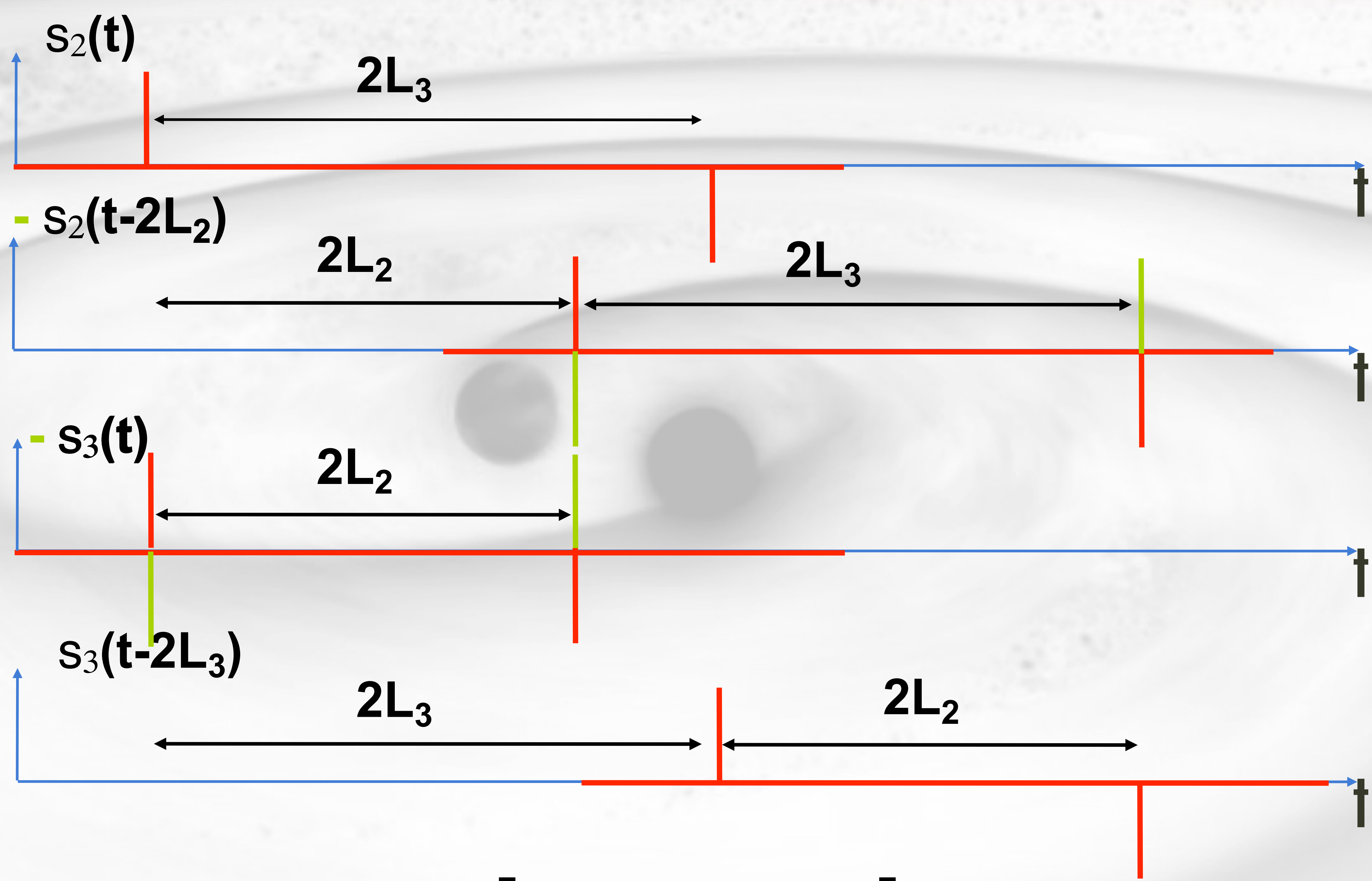
- —> How to reduce the frequency noise by 7 orders of magnitude ?
  - Time Delay Interferometry

Time Delay Interferometry

- Separate measurement of the phase on both arm



Time Delay Interferometry



$$s_2(t) + s_3(t-2L_3) - [\, s_3(t) + s_2(t-2L_2) \,] = 0 \ldots$$

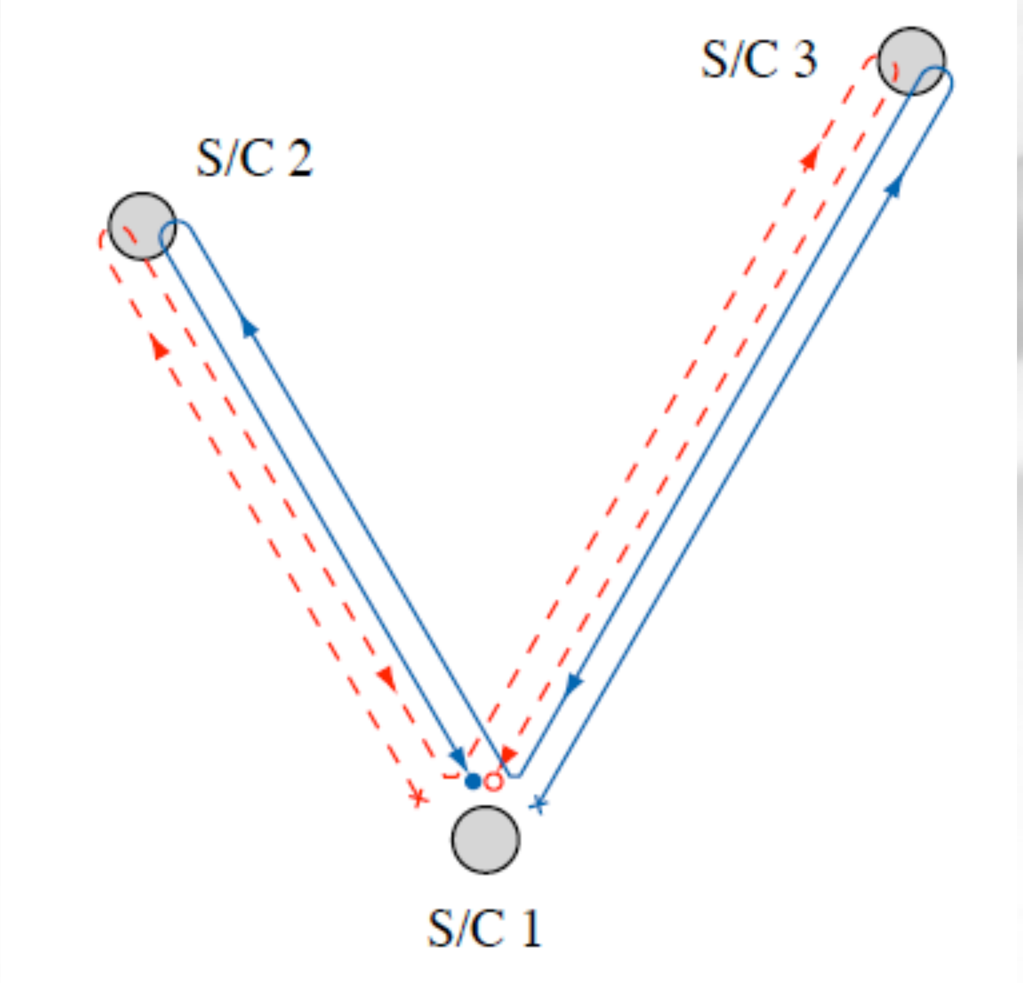
Time Delay Interferometry

$$s_2(t) + s_3(t-2L_3) - [\, s_3(t) + s_2(t-2L_2) \,] = 0 \ldots$$

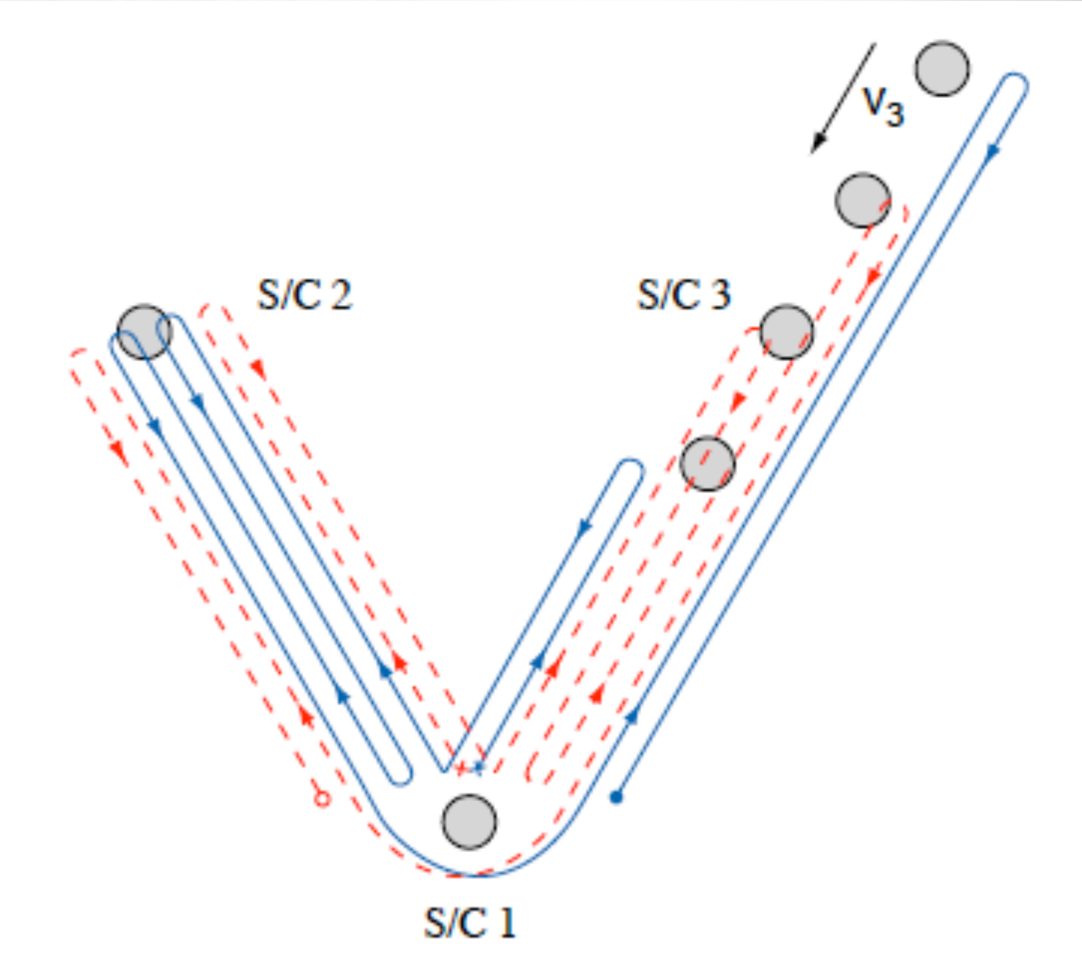
- The arm length difference is replaced by the uncertainty on the *knowledge* of the armlength
- Cancellation of propagated noises (mostly laser phase noise)
- Transfer function shaping (no signal at f multiple of 1/(2L) ~60 mHz)
- ⇒ Requires the knowledge of :
  - S/C distances with a few meters accuracy
  - Relative clock drifts at a few ns

Time Delay Interferometry

- More sophisticated combinations exist to account for the non-reciprocity of the delays (Sagnac effect) and the time-varying arm-length (S/C relative velocities)



Fixed, unequal, non-reciprocal propagation delays



Time-varying, unequal, non-reciprocal propagation delays

Key performance values

- 6 laser links, 2.5 Mkm
  - Measurement bandpass : [0.1 mHz : 1 Hz]
- Drag free performance : 3 $fm.s^{-2}/\sqrt{Hz}$
- Telescopes:
  - ~300 mm diameter,
  - Internal pathlength stability: ~ a few pms/√Hz
- Laser
  - Nd:YAG (1064 nm), 2 W emitted (received ~400 pW)
  - RIN : $<10^{-8}$ /√Hz above 5 MHz
  - ~30 Hz/√Hz
- Timing jitter in clock distribution: ~40 fs/√Hz
- Absolute ranging accuracy: ~1 m
- Thermal stability (optical bench): < 10 µK/√Hz at 1 mHz
- Laser beam pointing jitter: ~5 nrad/√Hz

Technology challenges for LISA

- Free flying test mass subject to very low parasitic forces:
  - Drag free control of spacecraft (non-contacting spacecraft)
  - Low noise microthruster to implement drag-free
  - Large gaps, heavy masses with caging mechanism
  - High stability electrical actuation on cross degrees of freedom
  - Non contacting discharging of test-masses
  - High thermo-mechanical stability of S/C
  - Gravitational field cancellation
- Precision interferometric, local ranging of test-mass and spacecraft:
  - pm resolution ranging, sub-mrad alignments
  - High stability monolithic optical assemblies
- Precision million km spacecraft to spacecraft precision ranging:
  - High stability telescopes
  - High accuracy phase-meter
  - High accuracy frequency stabilization
  - Constellation acquisition
  - Precision attitude control of S/C

Technology challenges for LISA

- **Free flying test mass subject to very low parasitic forces:**
  - **Drag free control of spacecraft (non-contacting spacecraft)**
  - **Low noise microthruster to implement drag-free**
  - **Large gaps, heavy masses with caging mechanism**
  - **High stability electrical actuation on cross degrees of freedom**
  - **Non contacting discharging of test-masses**
  - **High thermo-mechanical stability of S/C**
  - **Gravitational field cancellation**

Validated with LISA Pathfinder

- **Precision interferometric, local ranging of test-mass and spacecraft:**
  - **pm resolution ranging, sub-mrad alignments**
  - **High stability monolithic optical assemblies**
- Precision million km spacecraft to spacecraft precision ranging:
  - High stability telescopes
  - High accuracy phase-meter
  - High accuracy frequency stabilization
  - Constellation acquisition
  - **Precision attitude control of S/C**

Technology challenges for eLISA

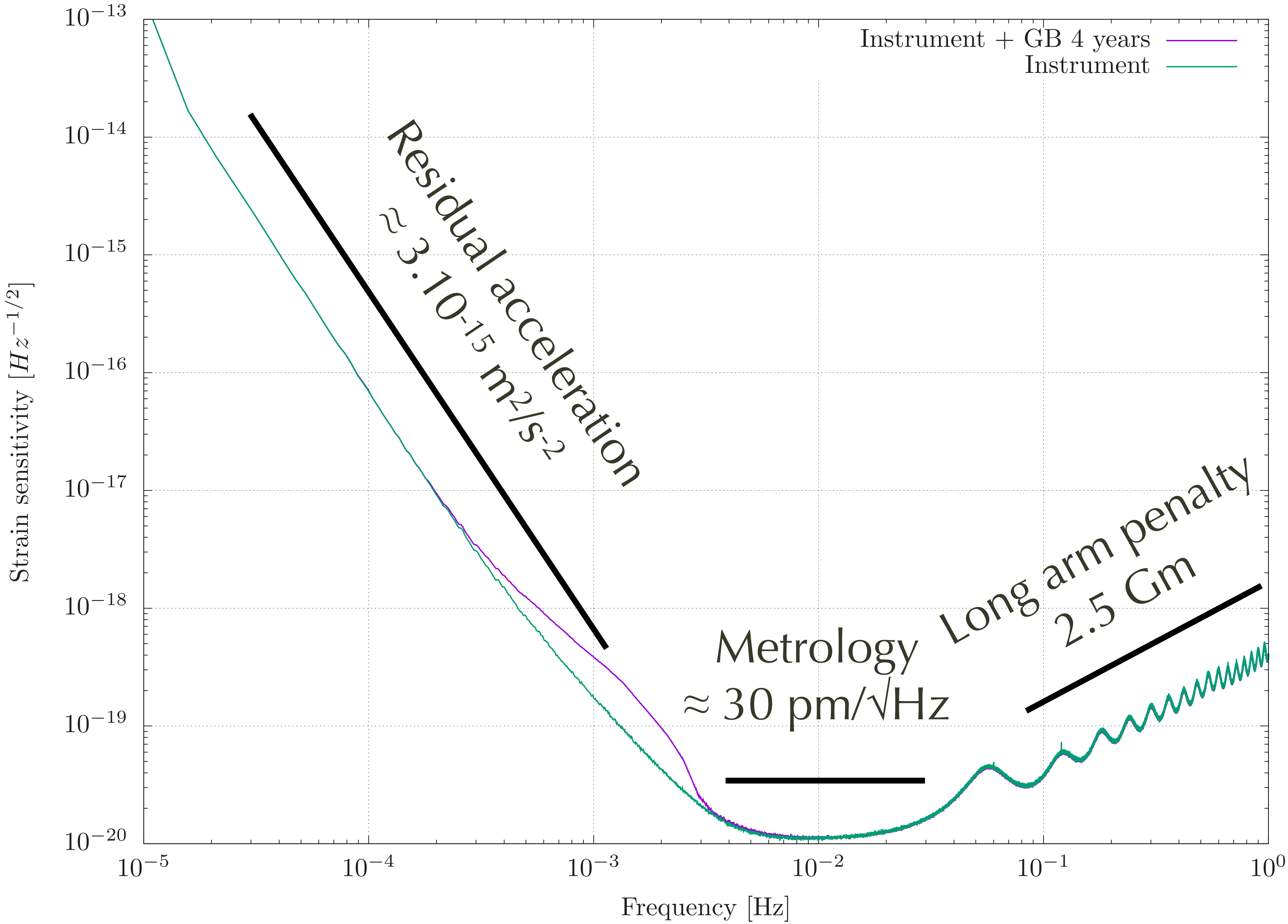
- Free flying test mass subject to very low parasitic forces:
  - Drag free control of spacecraft (non-contacting spacecraft)
  - Low noise microthruster to implement drag-free
  - Large gaps, heavy masses with caging mechanism
  - High stability electrical actuation on cross degrees of freedom
  - Non contacting discharging of test-masses
  - High thermo-mechanical stability of S/C
  - Gravitational field cancellation

Validated with LISA Pathfinder

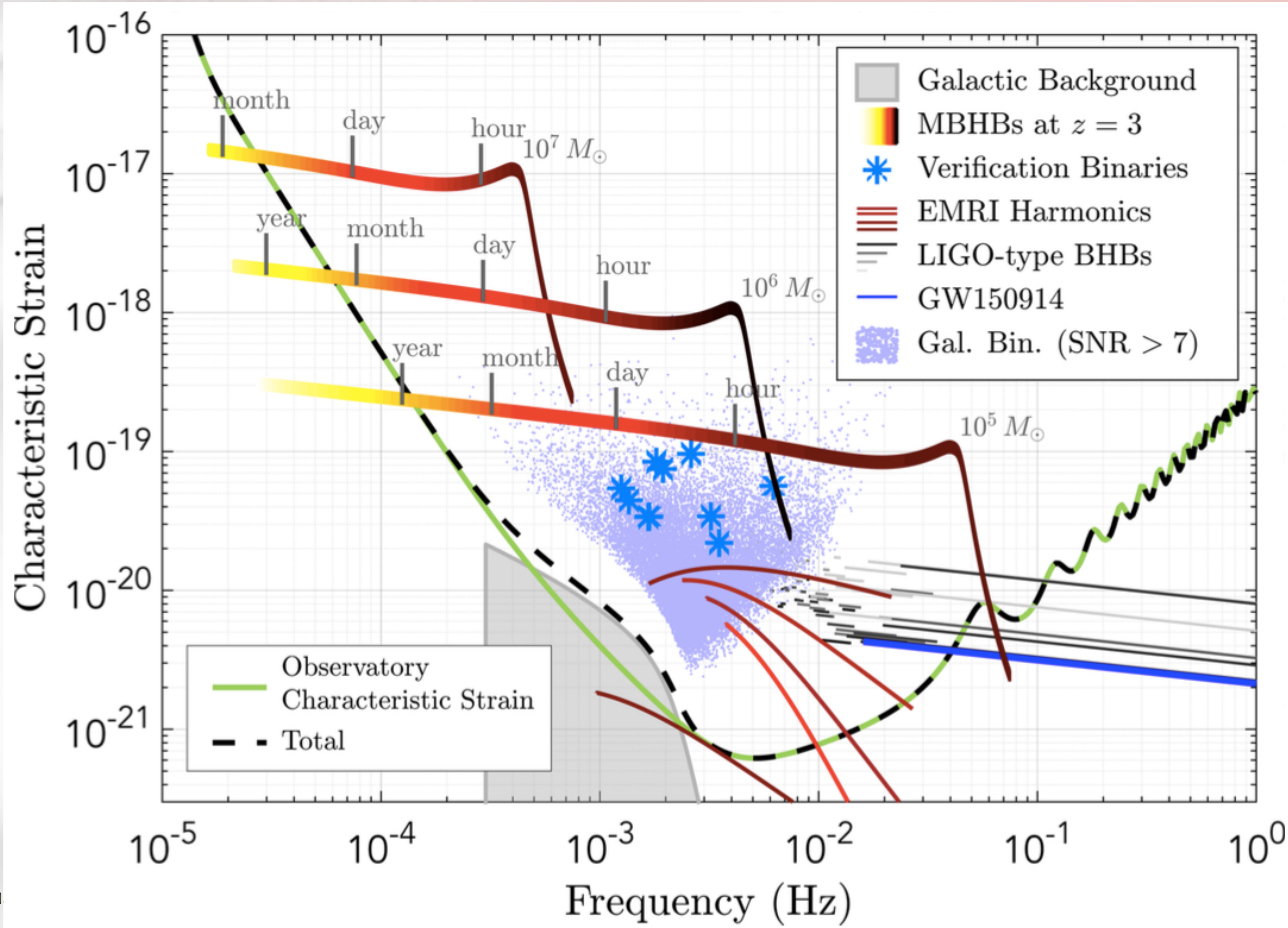
- Precision interferometric, local ranging of test-mass and spacecraft:
  - pm resolution ranging, sub-mrad alignments
  - High stability monolithic optical assemblies
- Precision million km spacecraft to spacecraft precision ranging:
  - High stability telescopes
  - High accuracy phase-meter and frequency distribution
  - High accuracy frequency stabilization (incl. TDI)
  - Constellation acquisition and low jitter laser pointing
  - Precision attitude control of S/C

Ground-based demonstrators

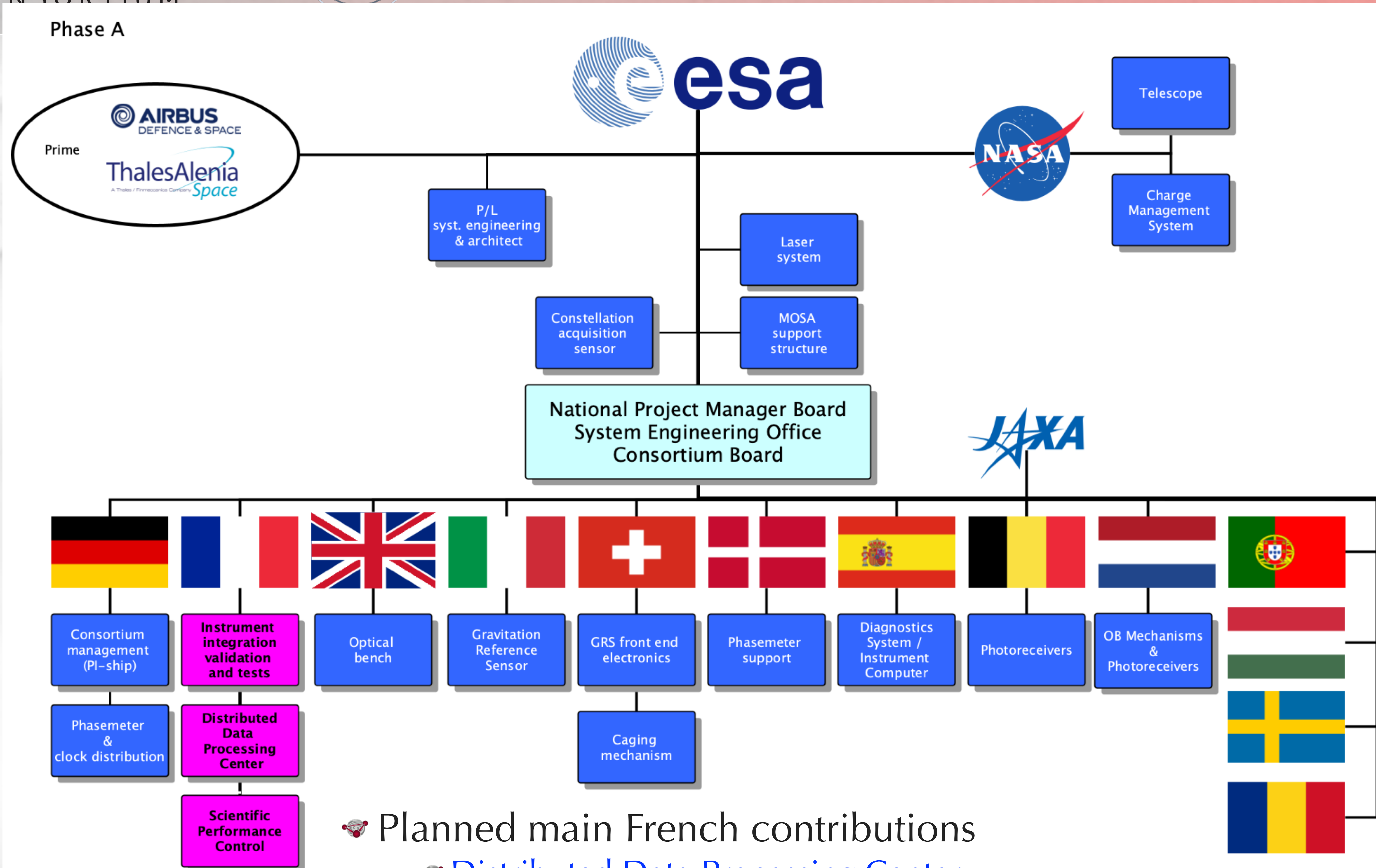
Global Performance



LISA Strain Sensitivity



French contribution to LISA ?



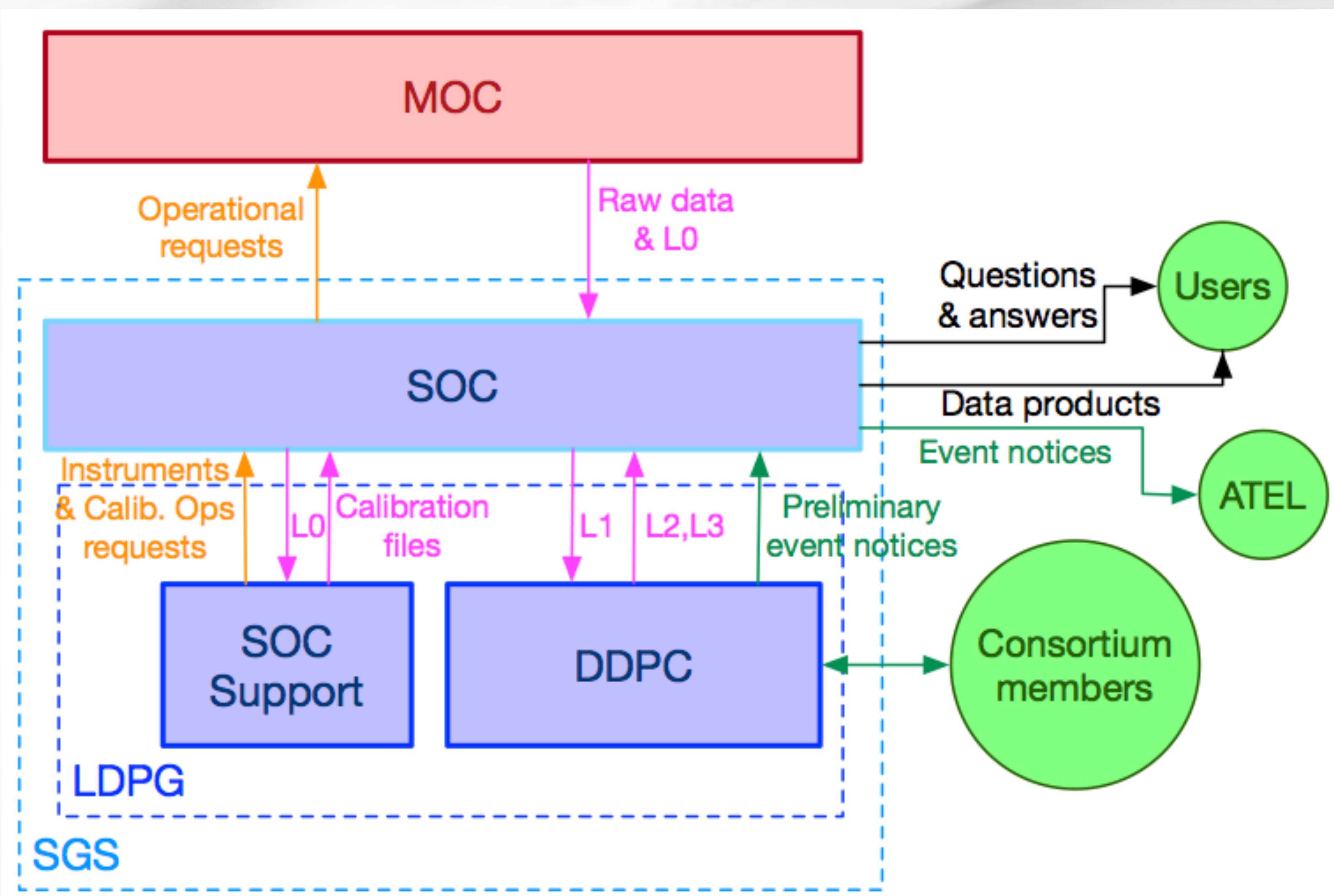
- Planned main French contributions
  - Distributed Data Processing Center
  - MOSA AIVT & Perf. Control

LISA France research institutes

- Presently 19 laboratories / research institutes participate to the LISA France collaboration
  - @IN2P3 : APC, CPPM, L2IT, LPCC, LMA/IP2I, CC-IN2P3
  - @INSU : LAM, IAP, LPC2E
  - @INSIS : Institut Fresnel
  - @Obs de Paris / INSU : SYRTE, LUTh
  - @Obs. de la Côte d'Azur / INSIS : ARTEMIS
  - @CEA : IRFU (DEDIP, DIS, DPhN, DPhP, DAP), IPhT
- CNES is managing and supporting the project activities with engineers and financial ressources (incl. short-term contracts).

Distributed Data Processing Center

- Development of a Distributed Data Processing Center for LISA
  - Produces scientific L2&L3 data and supports ESA on L0 to L1 software
  - Will implement, maintain and operate simulations and data analysis
  - Supports the LISA community for SW and collaborative tools
  - Prototype architecture based on virtualisation and continuous integration

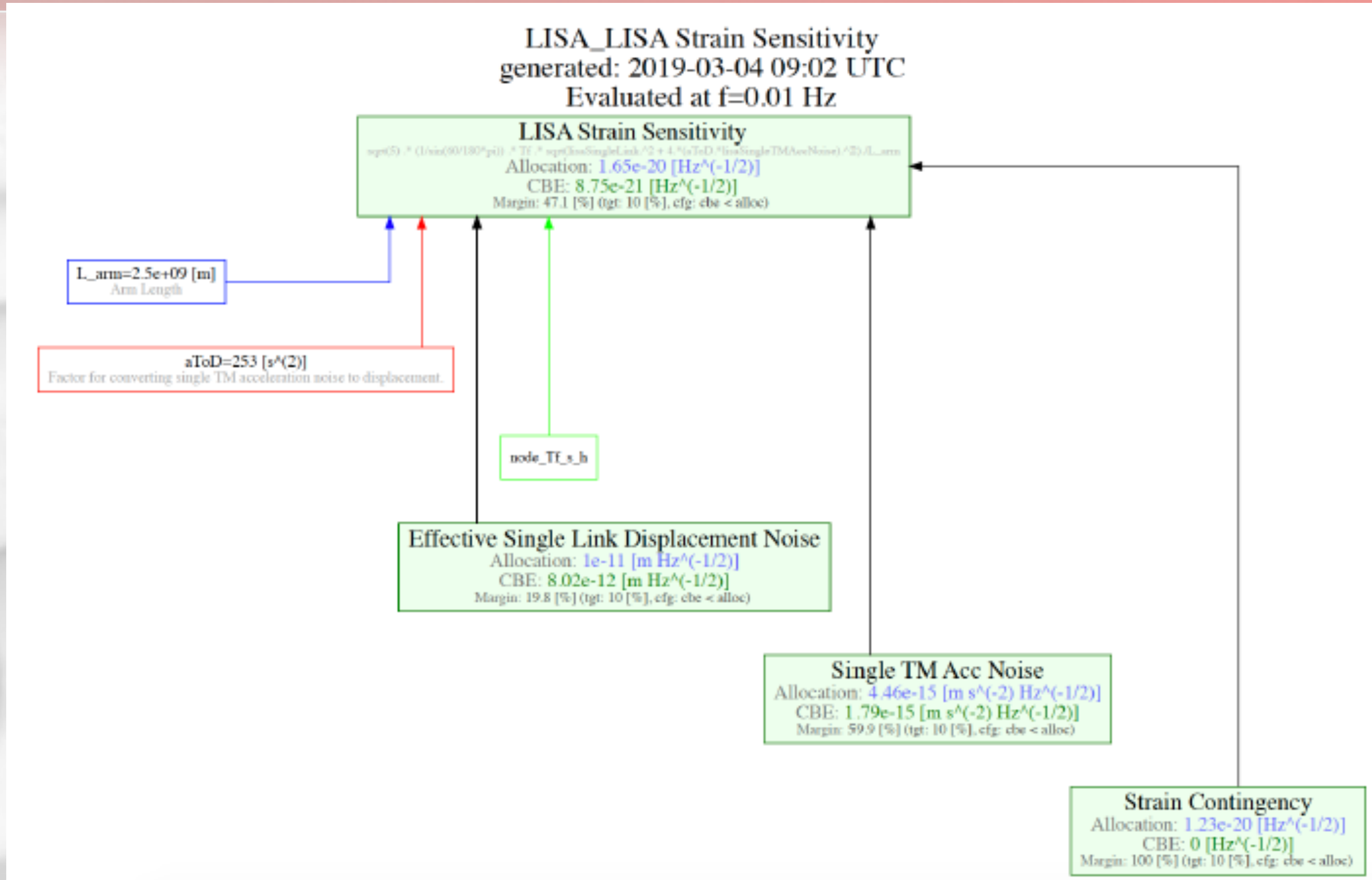


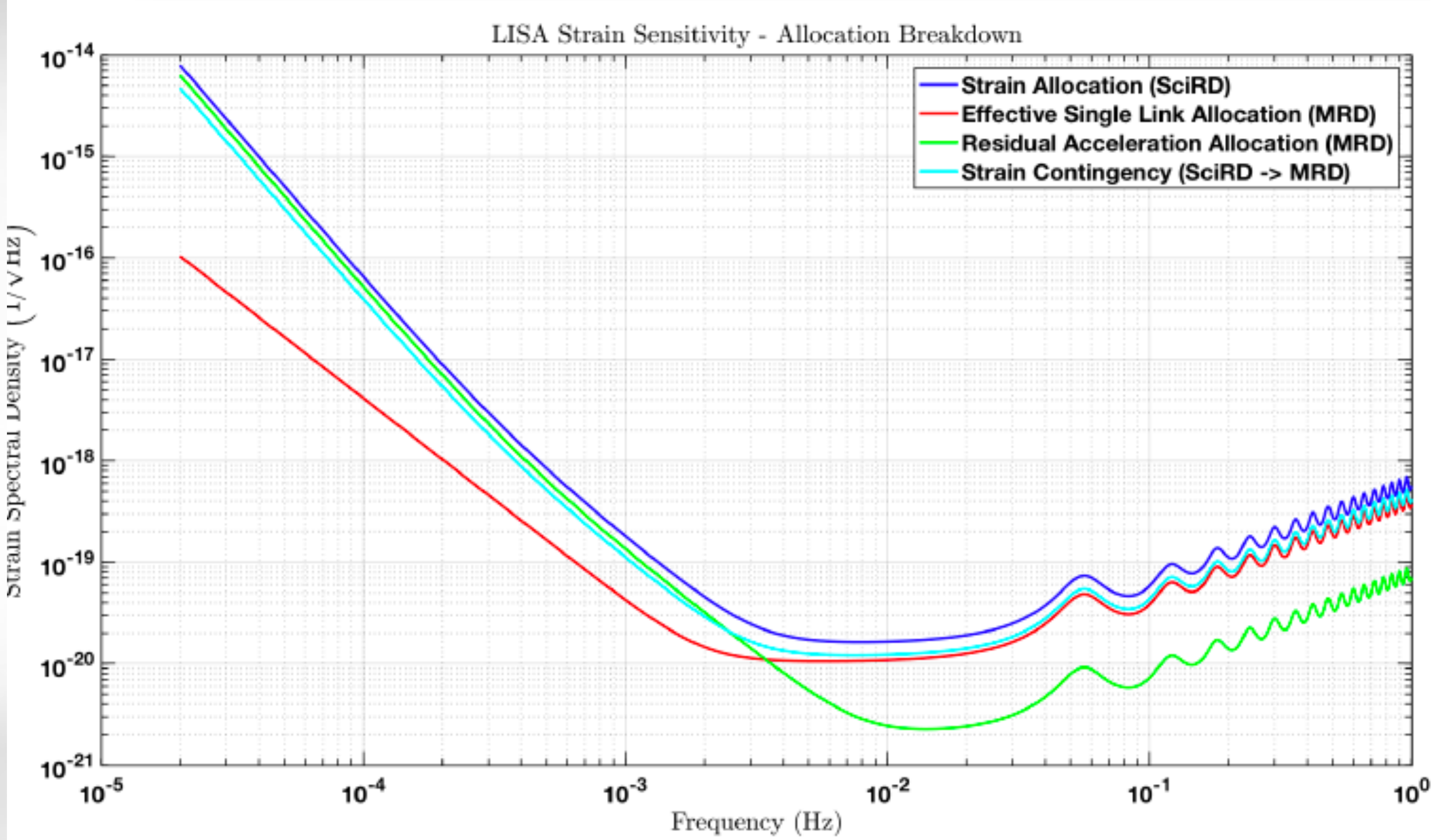
Scientific Performance Budget

- Objective : build a ‘simplified’, system-level, performance model
  - Identify critical items
  - Unified view of the system performance from science requirement to sub-systems level.
  - Support the allocation breakdown for each sub-system
  - Sensitivity analysis to support design trade-off

- Different sources of information
  - Specific or ‘end-to-end’ simulations
  - Mathematical & physical models
  - Lab experiments

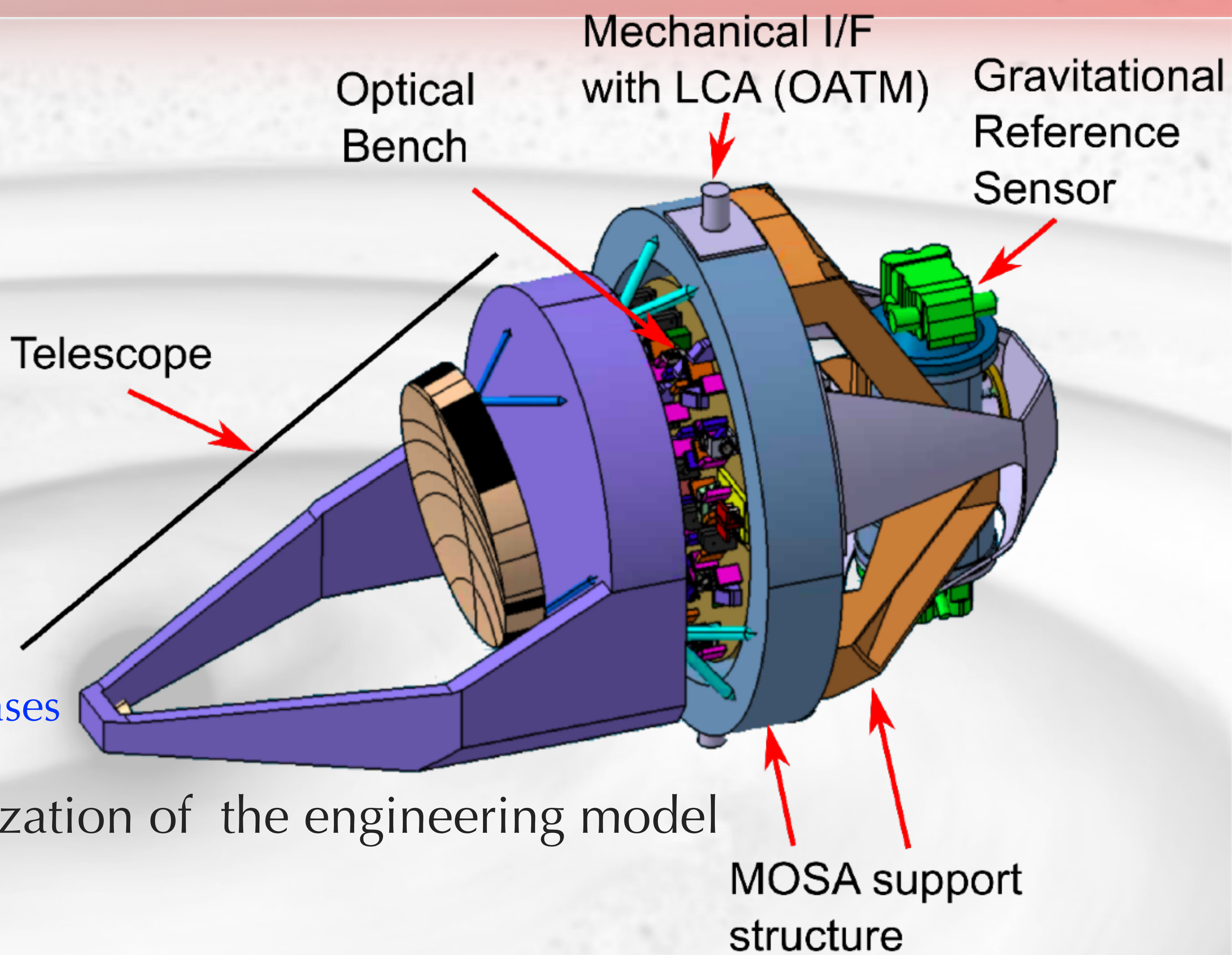
Interface with all stakeholders – Consortium, Agencies, Industry.





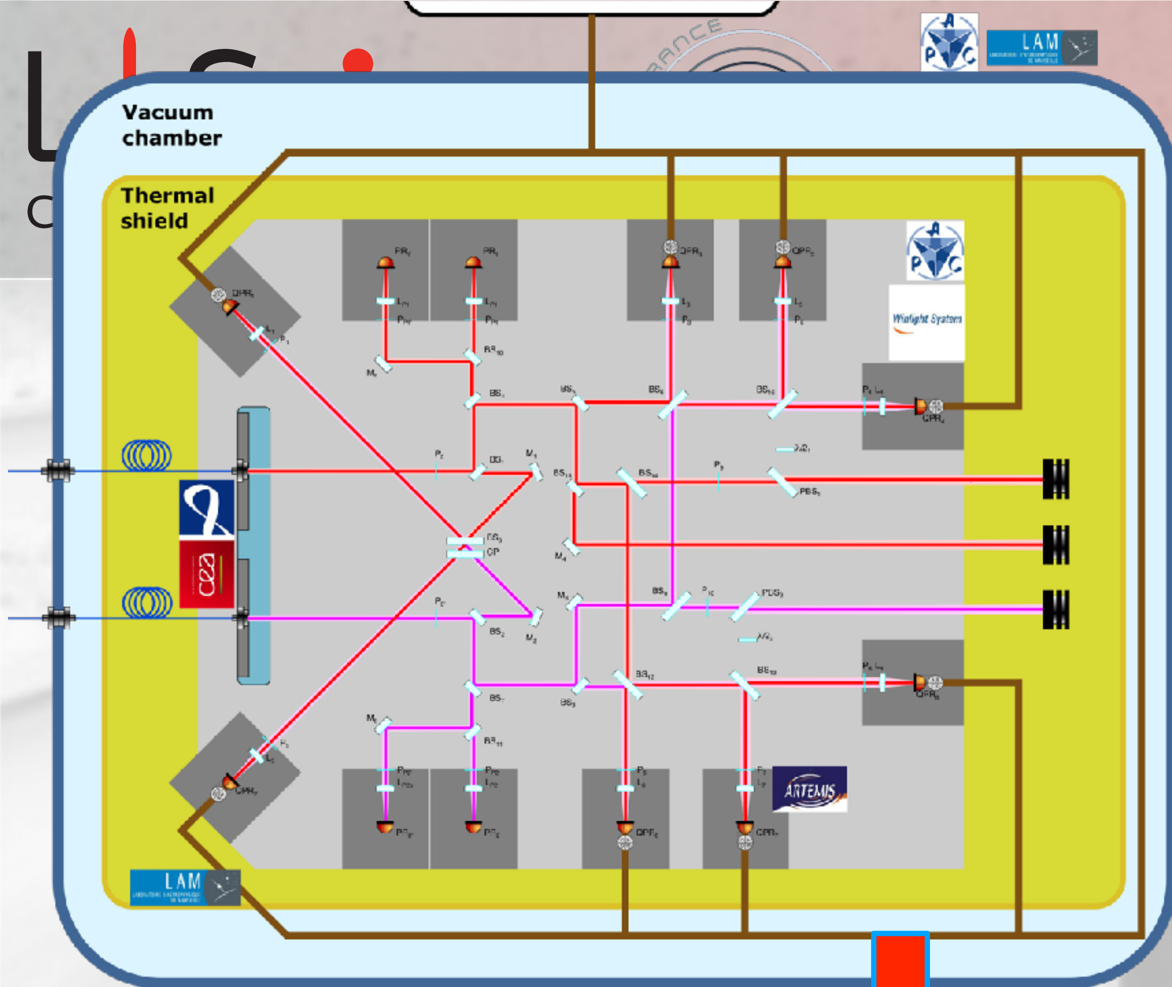
MOSA AIVT
Assembly, Integration, Validation and Tests

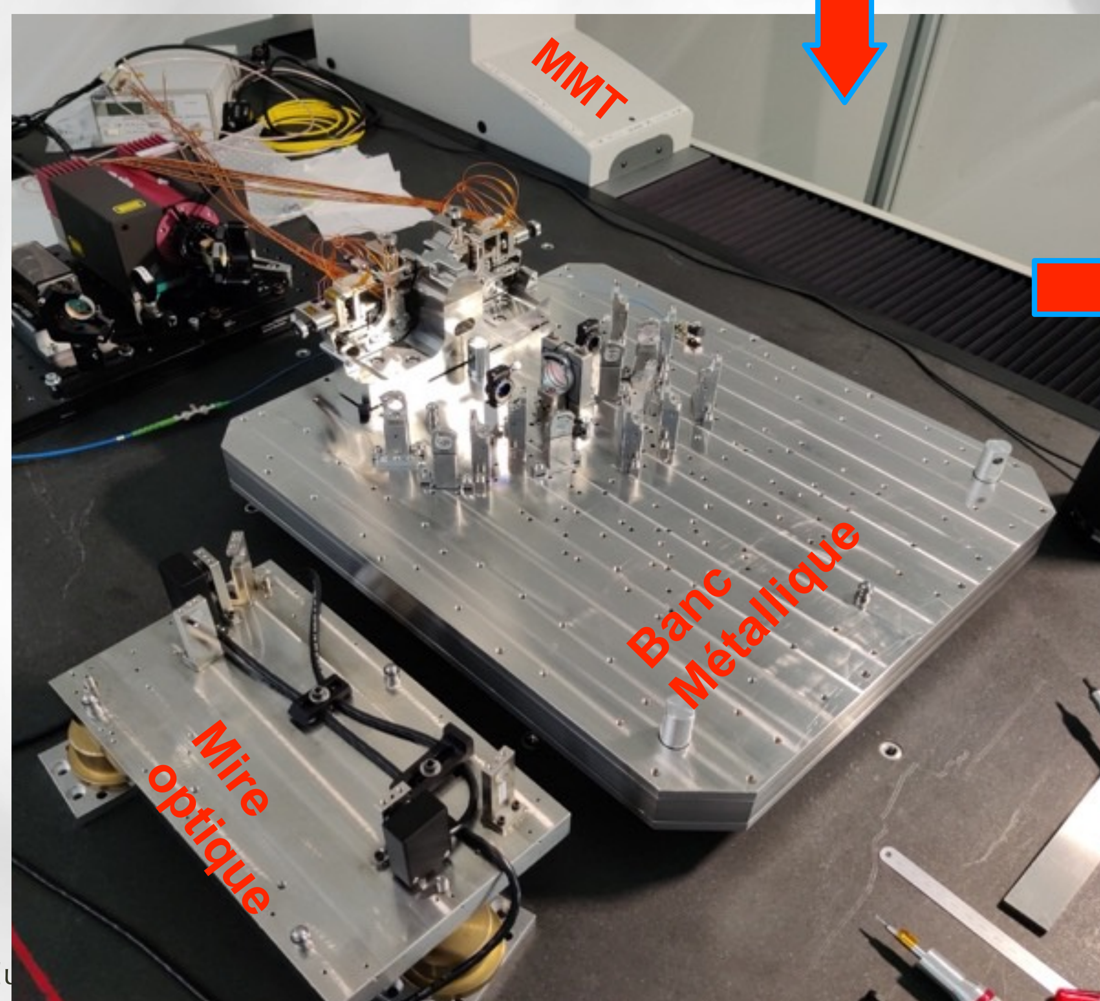
- LISA will be the first instrument of its kind
  - Not a collection of separate instruments
  - Combination of finely designed equipments, forming a Mkm-scale instrument
- LISA science return depends on the in-depth performance characterisation of the metrology core
  - Importance of the AIVT and scientific performance modelling
  - Crucial activity giving high visibility and involvement in early instrument development phases

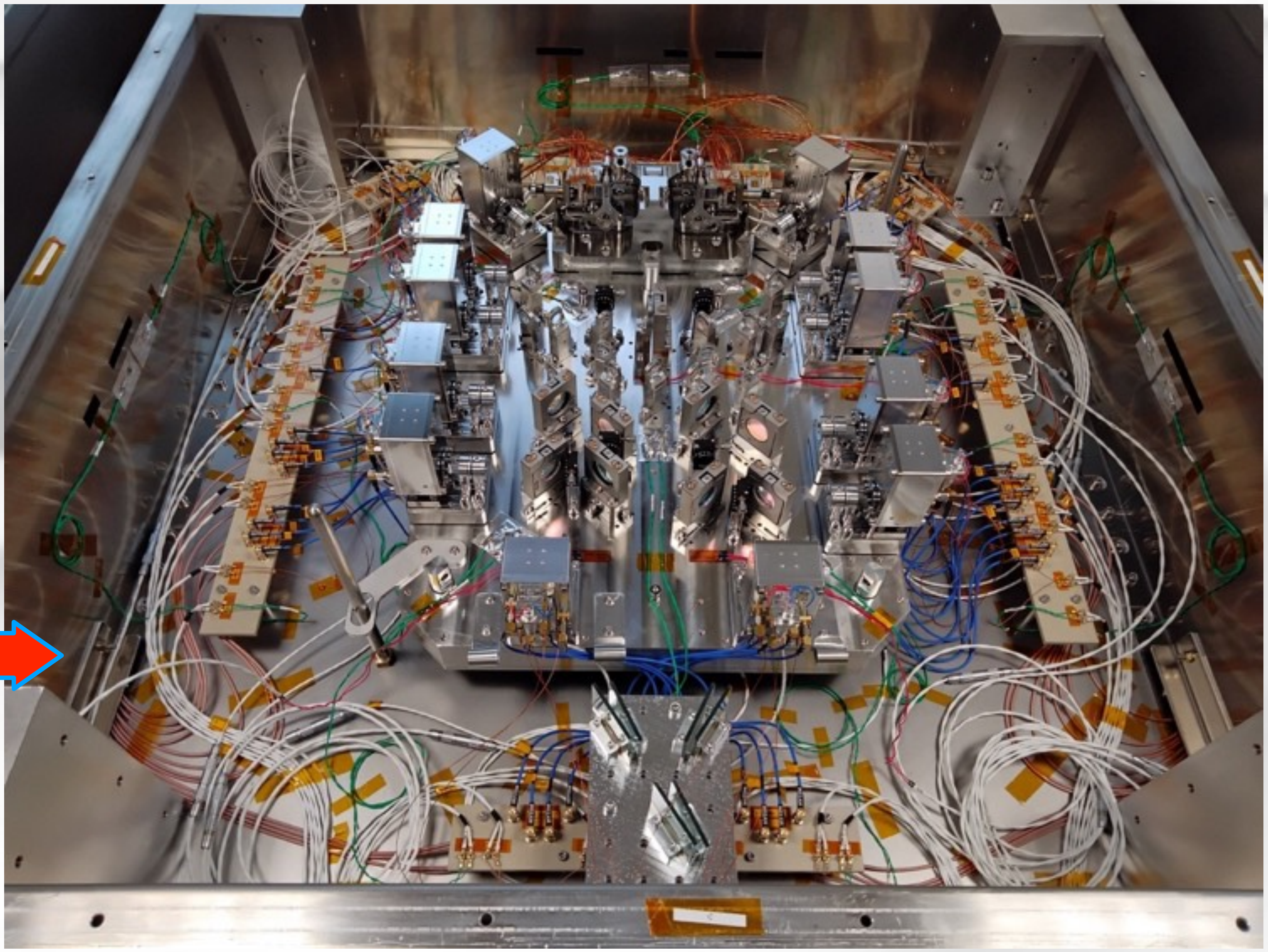


- Development of optical benches and characterization of the engineering model of the instrument 'core'
  - Optical bench + phasemeter + laser
- Integration and tests in close collaboration with industries
  - 10 MOSAs to integrate and validate (1 STM, 1 EQM, 1 PFM, 5 FMs, 2 spares)
  - Research institutes : development of optical metrology test benches and strong involvement in the QM characterisation
    - Experience on MOSA testing transferred to industry for the FMs
  - Industries : integration procedures and semi-serialisation of FMs & spares AIVT
    - The research institutes still follow the process and interpret the measurements

Optical bench prototype

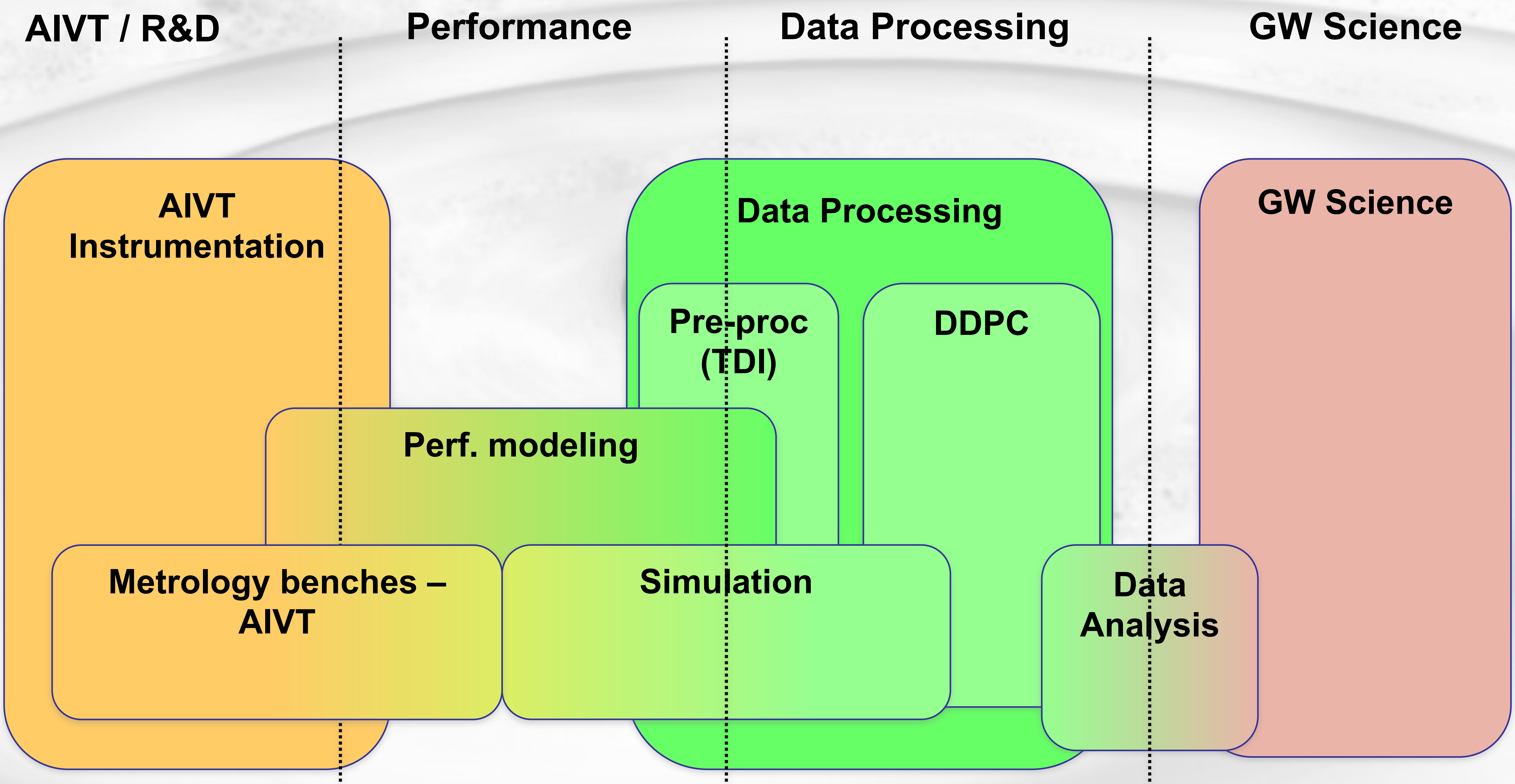






French LISA activities landscape

- Broad and continuous coverage, from instrument to GW science



Outline

- *Introduction*
- *LISA Science Objectives*
- *From LISA Pathfinder to LISA*
- *Mission description*
- **Conclusion**

Conclusion

- Laser interferometry is currently the most sensitive technique for detecting GWs
- LISA will observe mHz GWs around from space
  - Complementary to ground-based detectors
- Many technological challenges ahem been demonstrated with LISA Pathfinder
- The Preliminary Design Phase of LISA has started
  - Expected mission adoption end 2023
- Crucial contributions from French institutes
  - The hard work has now started …

Coming soon…