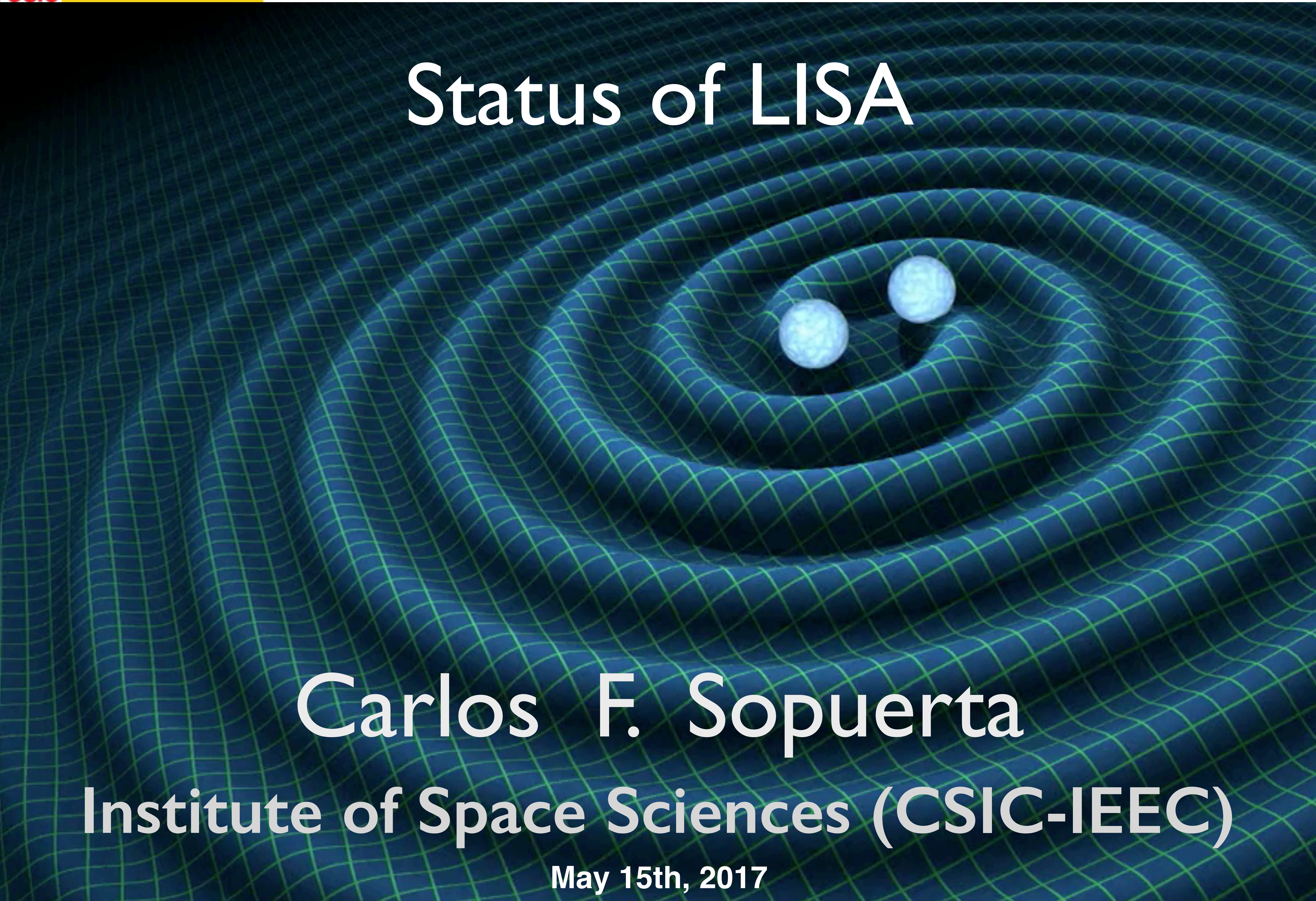
IGWM2017



Status of LISA

Carlos F. Sopuerta
Institute of Space Sciences (CSIC-IEEC)

May 15th, 2017

Key Documents about LISA

- White Paper for the selection of the scientific themes of the L2 and L3 ESA missions: *The Gravitational Universe* (arXiv:1305.5720)

THE GRAVITATIONAL UNIVERSE

A science theme addressed by the *eLISA* mission observing the entire Universe

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Detailed information at
http://elisascience.org/whitepaper

The last century has seen enormous progress in our understanding of the Universe. We know the life cycles of stars, the structure of galaxies, the remnants of the big bang, and have a general understanding of how the Universe evolved. We have come remarkably far using electromagnetic radiation as our tool for observing the Universe. However, gravity is the engine behind many of the processes in the Universe, and much of its action is dark. Opening a gravitational window on the Universe will let us go further than any alternative. Gravity has its own messenger: Gravitational waves, ripples in the fabric of spacetime. They travel essentially undisturbed and let us peer deep into the formation of the first seed black holes, exploring redshifts as large as $z \sim 20$, prior to the epoch of cosmic re-ionisation. Exquisite and unprecedented measurements of black hole masses and spins will make it possible to trace the history of black holes across all stages of galaxy evolution, and at the same time constrain any deviation from the Kerr metric of General Relativity. eLISA will be the first ever mission to study the entire Universe with gravitational waves. eLISA is an all-sky monitor and will offer a wide view of a dynamic cosmos using gravitational waves as new and unique messengers to unveil The Gravitational Universe. It provides the closest ever view of the early processes at TeV energies, has guaranteed sources in the form of verification binaries in the Milky Way, and can probe the entire Universe, from its smallest scales around singularities and black holes, all the way to cosmological dimensions.

- Final Report of the Gravitational Observatory Advisory Team (GOAT) set up by ESA (28/03/2016)

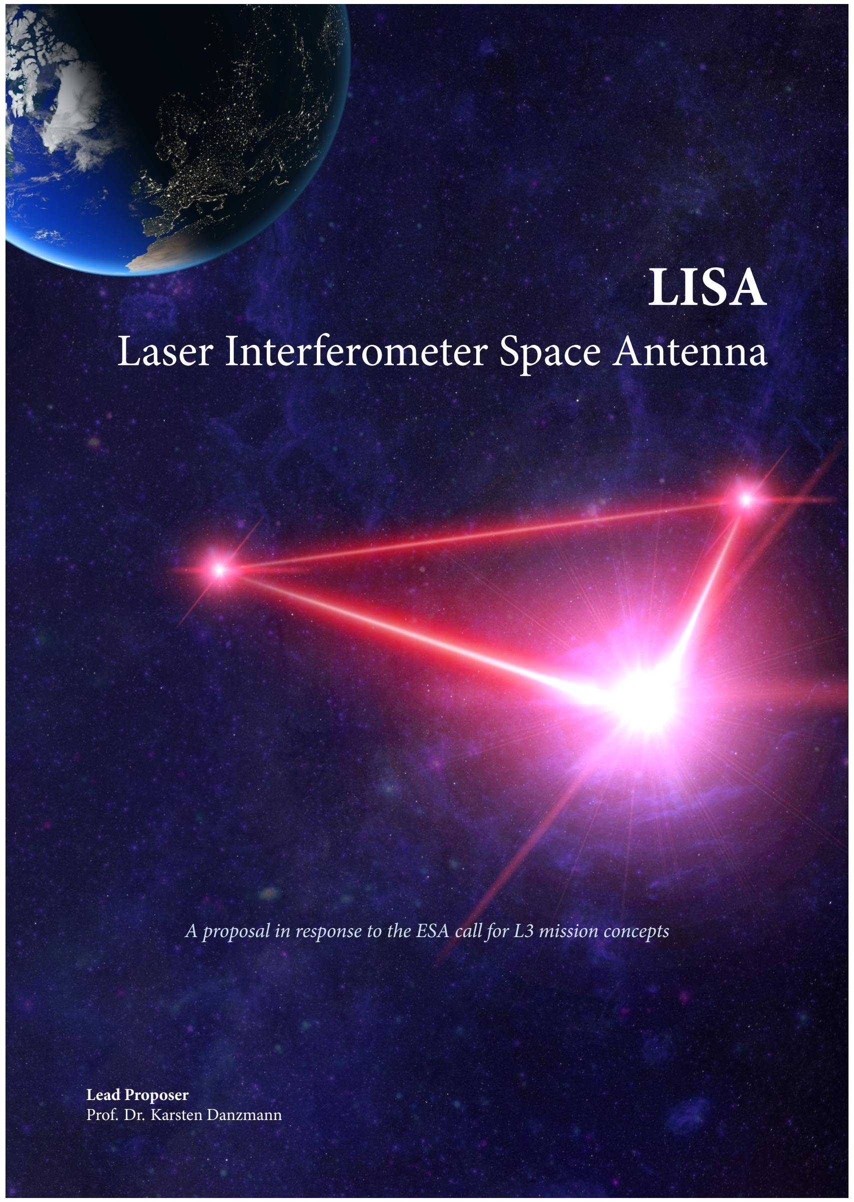
ESA website

The ESA–L3 Gravitational Wave Mission

Gravitational Observatory Advisory Team

Final Report

28 March 2016



- Proposal for the Call by the LISA Consortium for the L3 ESA mission call (25/10/2016) (arXiv:1702.00786)

OUTLINE

I. Gravitational Wave Detection from Space

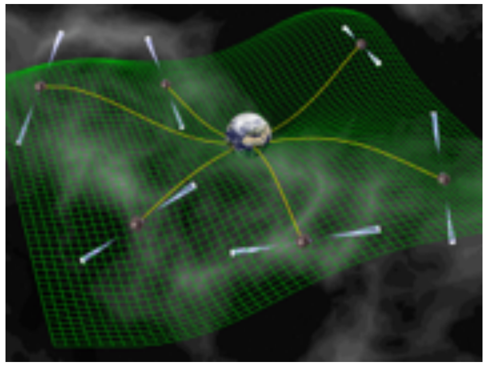
II. A bit of History

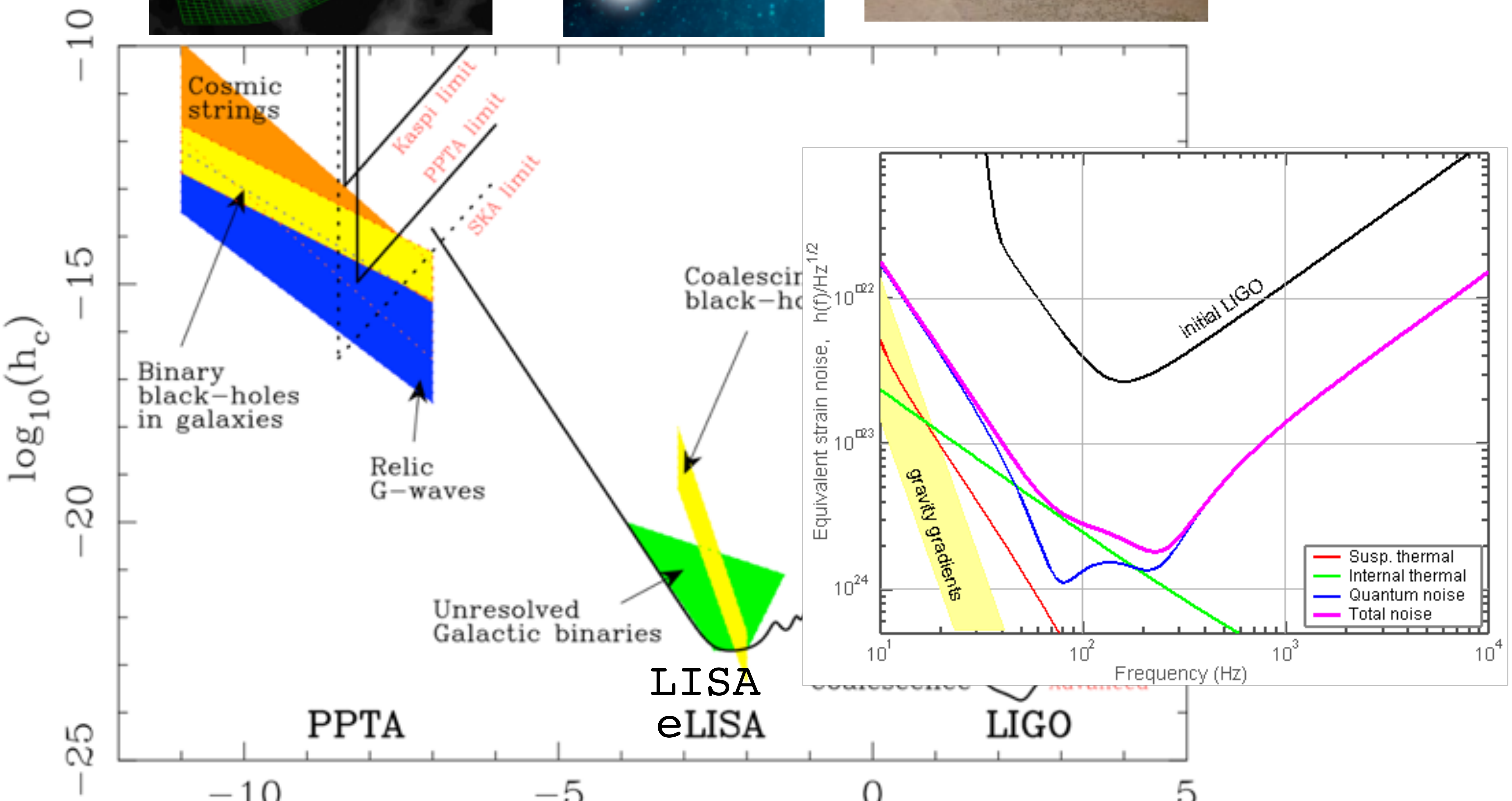
III.The ESA-L3 mission (LISA)

IV. Conclusions

Gravitational Wave Detection from Space

Gravitational Wave Spectrum (with Sources & Detectors)





Very Low-Frequency Band

Low-Frequency Band

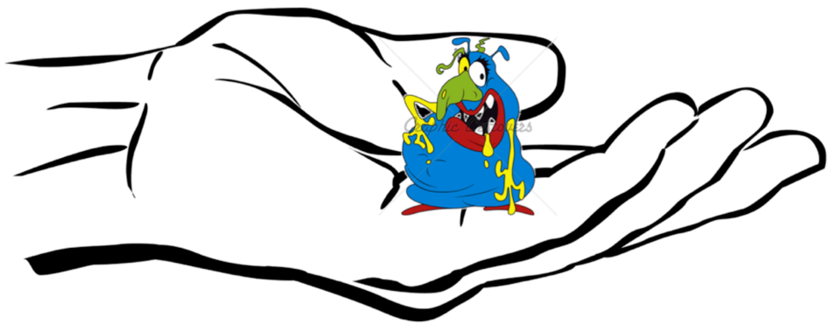
$\log_{10}(f/\mathrm{Hz})$

High-Frequency Band

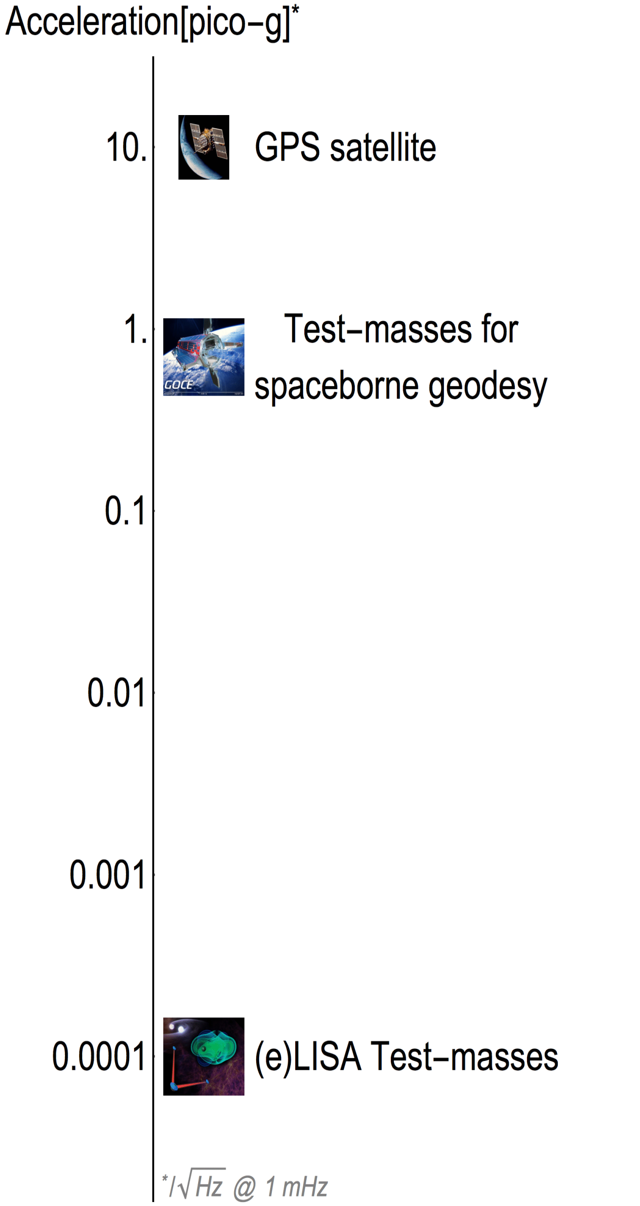
$$f_{\mathrm{GW}} \downarrow \;(\lambda_{\mathrm{GW}} \uparrow) \quad \Rightarrow \quad L_{\mathrm{arm}} \uparrow$$

Gravitational Wave Detection from Space

- ✳ We want to detect GWs via the slowly-oscillating (~1 hour), relative motion they impose onto far apart **free-falling** bodies.
- ✳ To achieve the low-frequency band [0.1 mHz, 1Hz] we need a very long baseline detector (L ~ 1 million km).
- ✳ Orders of magnitude better than in any other application:
- ✳ We need an instrument to detect tiny motion: ~ the size of an atom pick to pick
- ✳ No forces allowed above the weight of a bacteria..



1 pico = 10^{-12} = 0.000 000 000 001

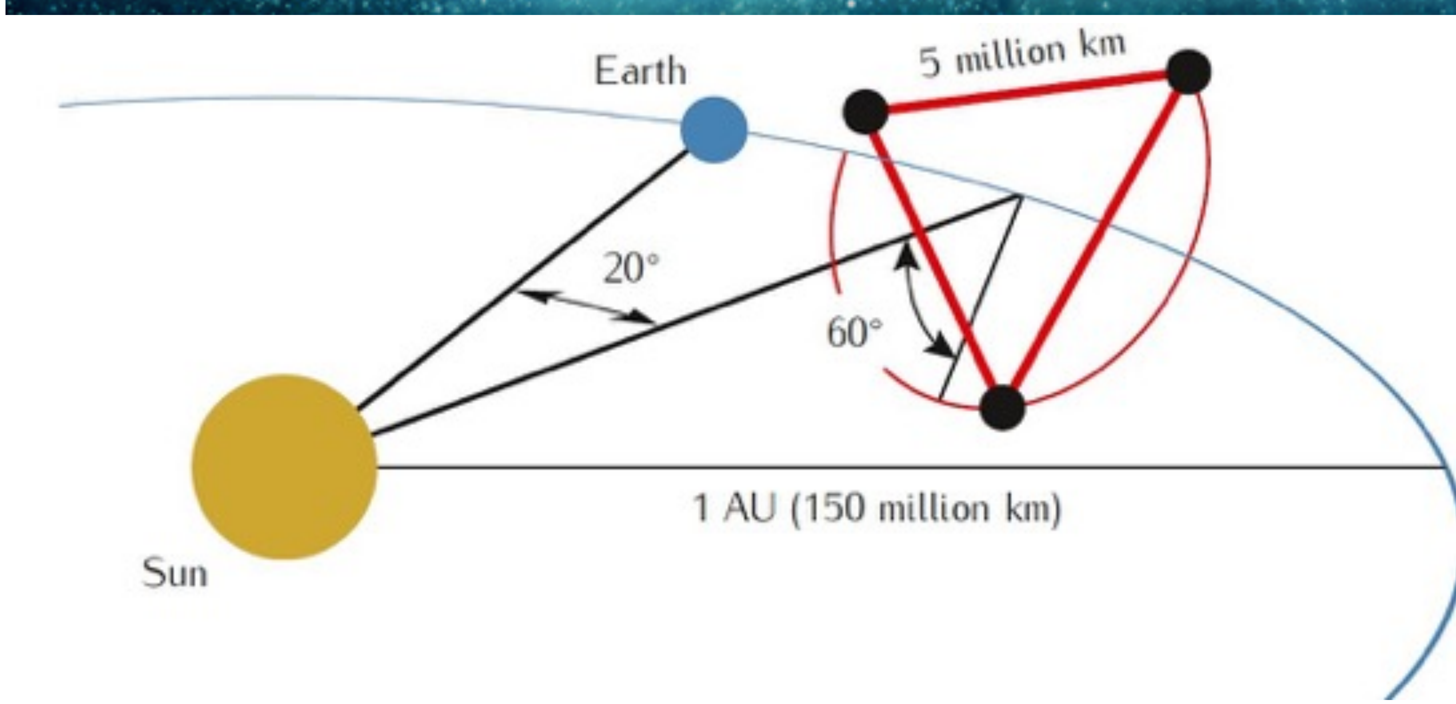


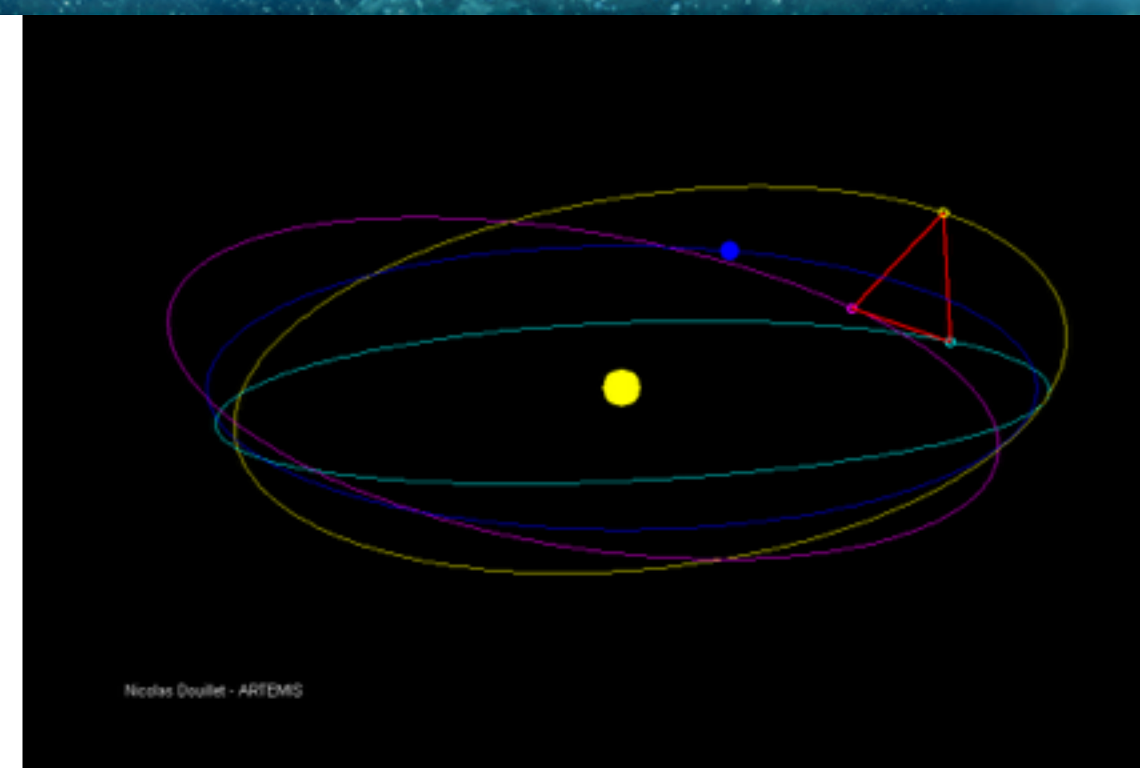
Gravitational Wave Detection from Space

Ground-Based are noise dominated detectors

$$0.1\ \mathrm{mHz} < f < 1\ \mathrm{Hz}$$

Space-Based are signal-dominated detectors

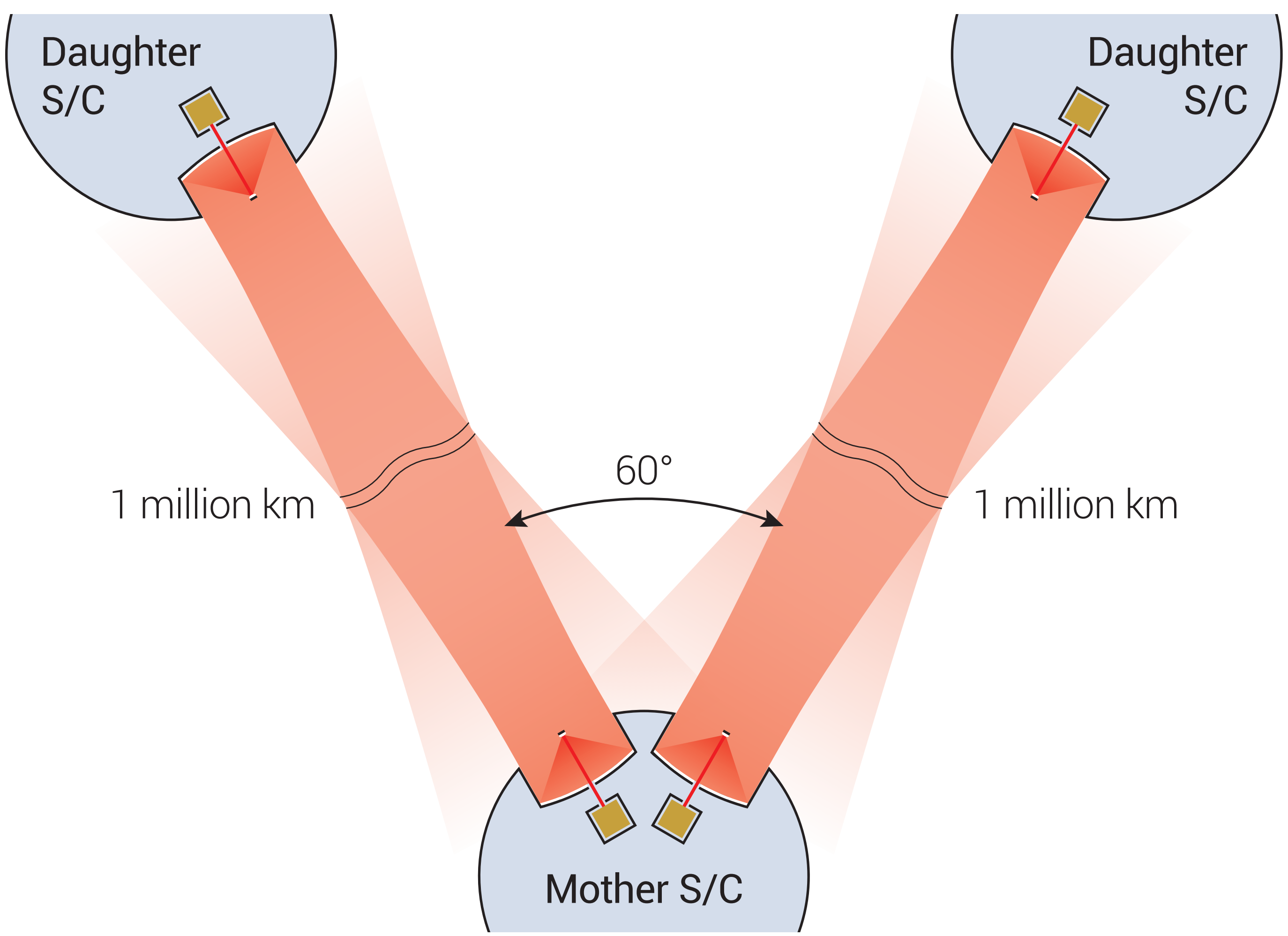


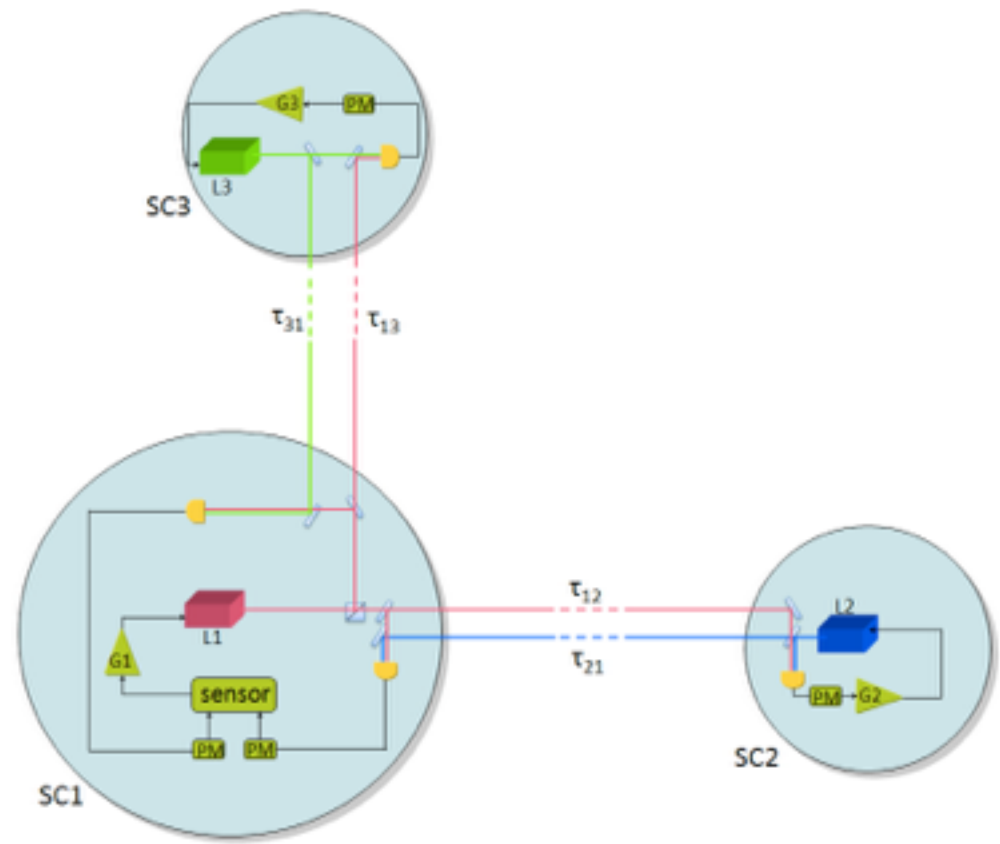


LISA = Laser Interferometer Space Antenna

Gravitational Wave Detection from Space

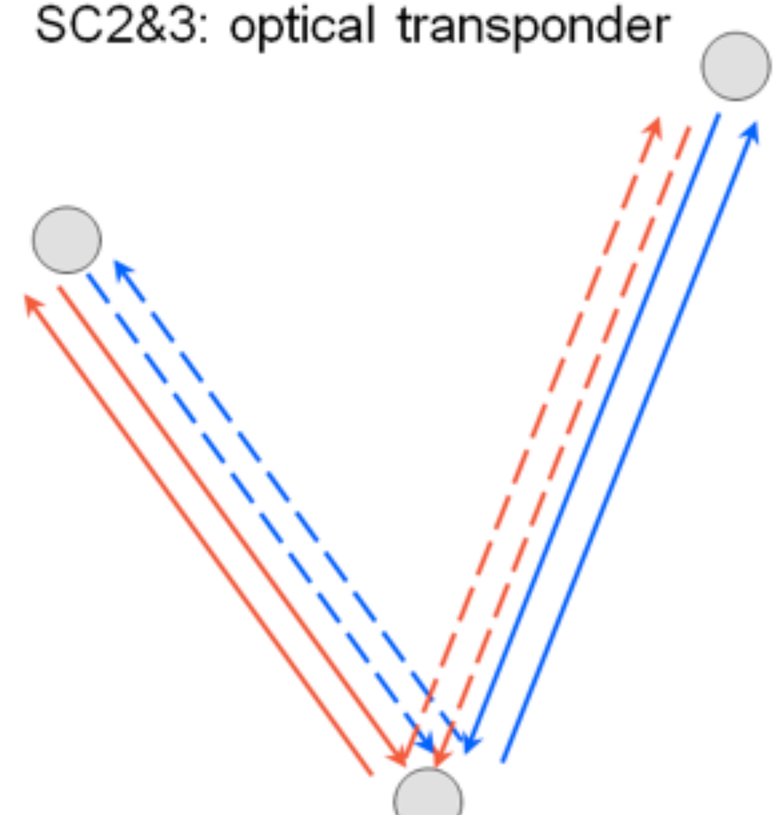
✳ With such baselines we cannot use mirrors for reflection (LISA ≠LIGO in Space). Instead, active mirrors with phase locked laser transponders on the spacecraft will be implemented.

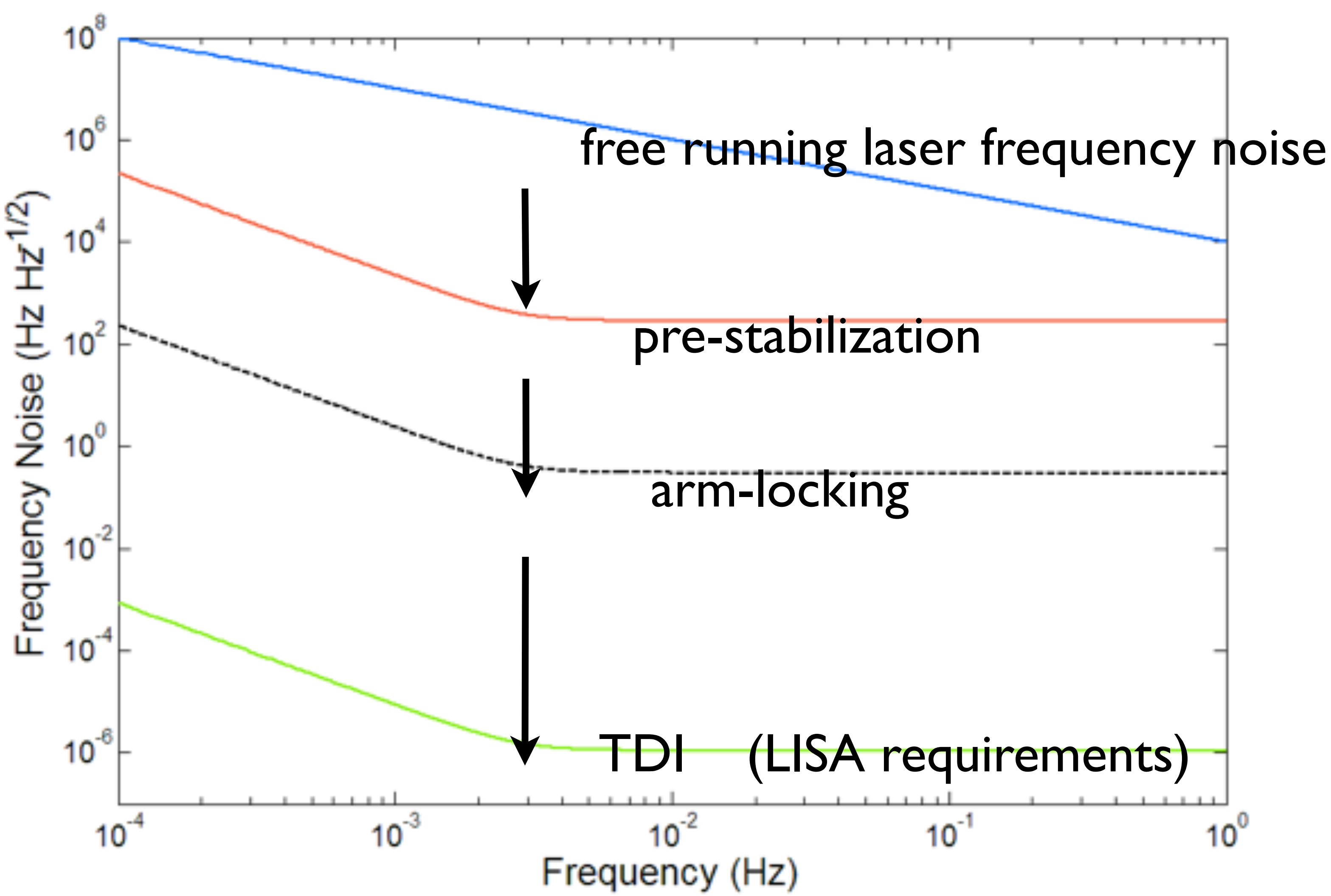


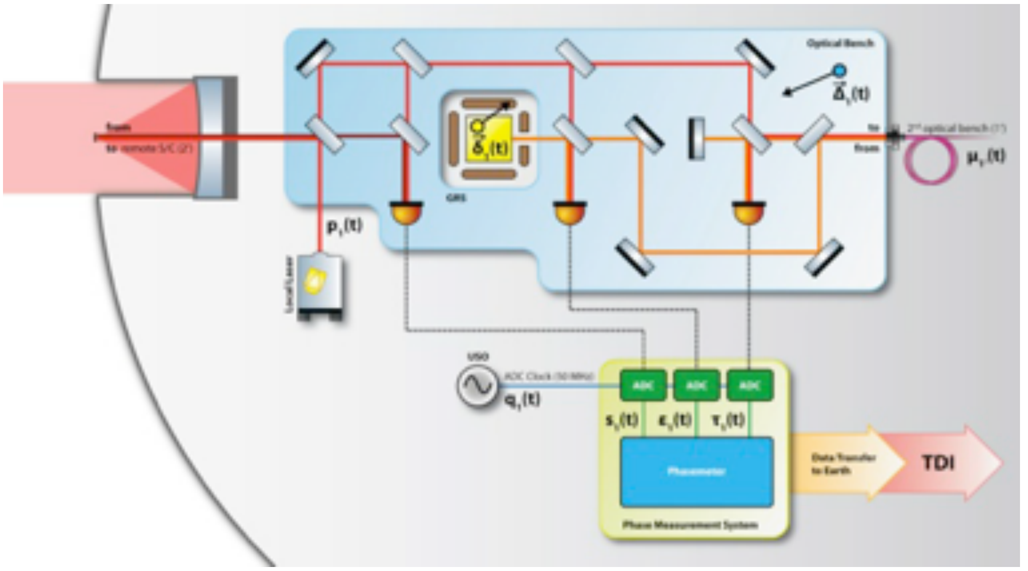


Gravitational Wave Detection from Space

✳Time-delay interferometry (TDI): Correlations in the frequency noise can be calculated and subtracted by algebraically combining phase measurements from different craft delayed by the multiples of the time delay between the spacecrafts.



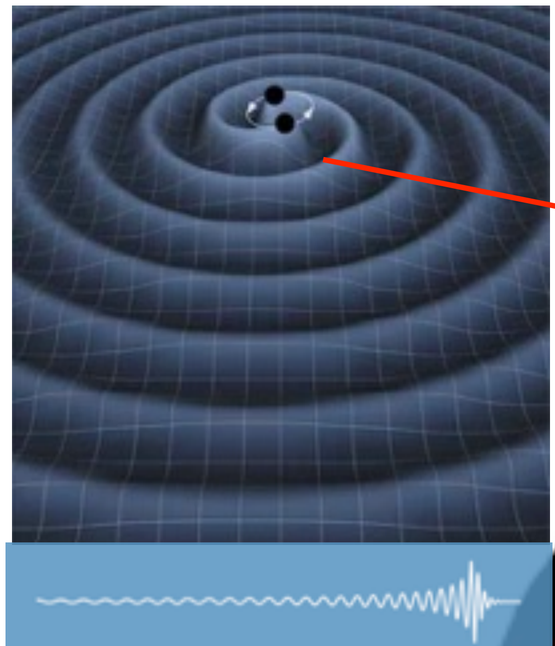




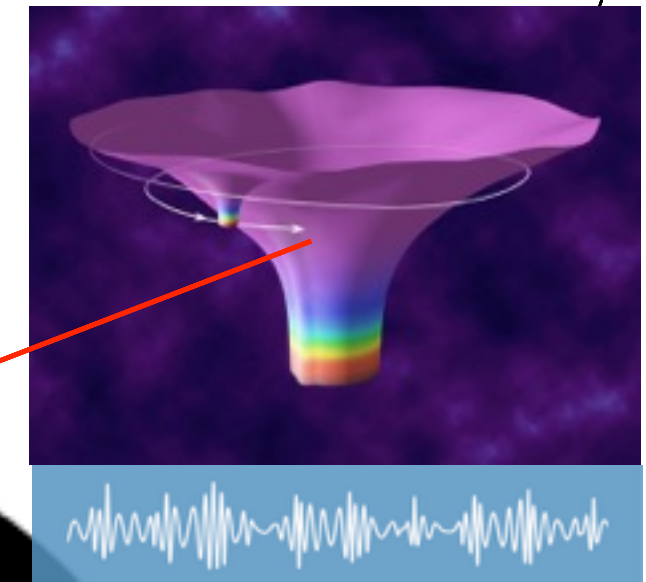
Gravitational Wave Detection from Space

✳ The Low-Frequency Band (0.1 mHz - 1 Hz):

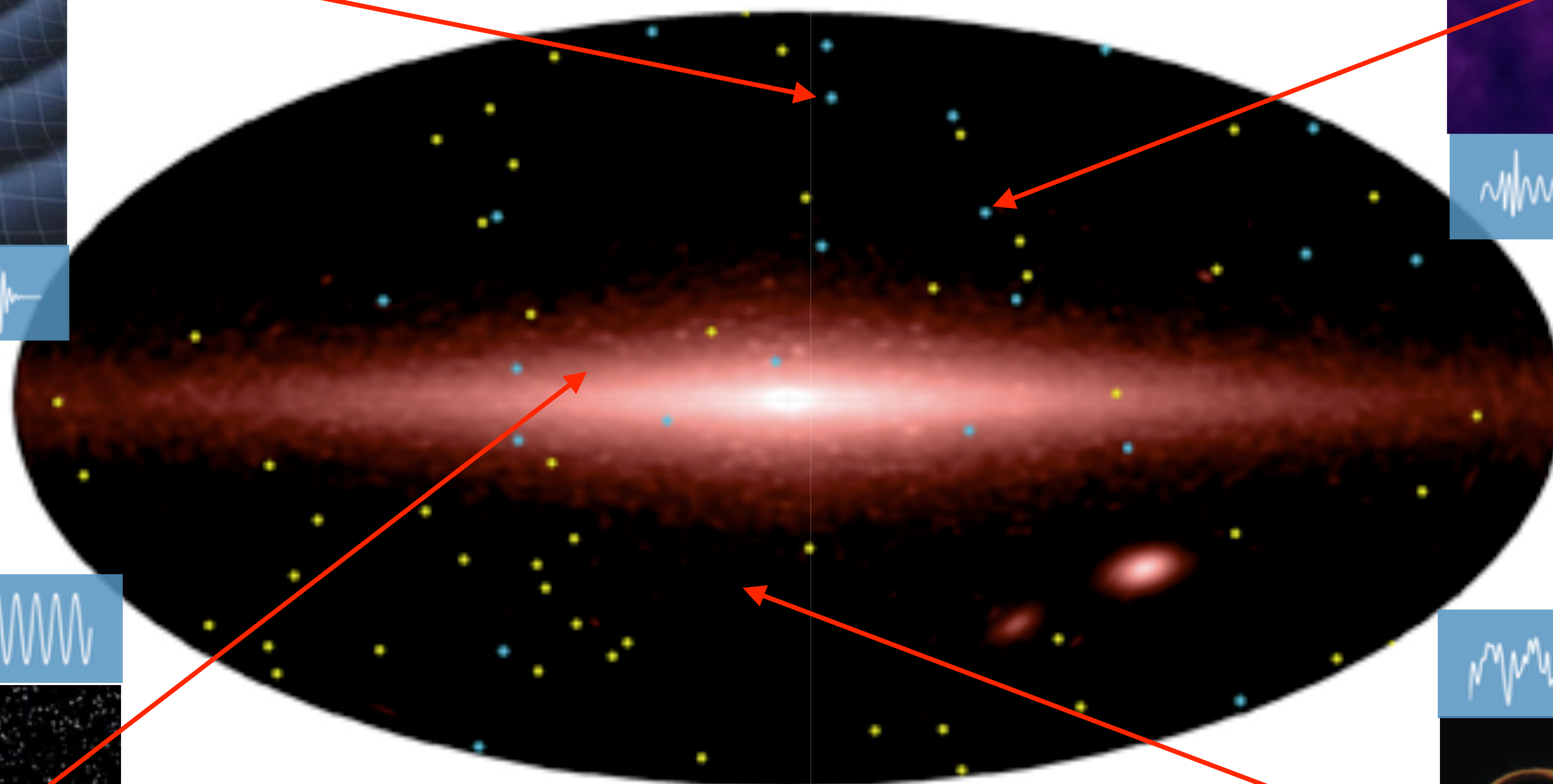
Massive Black Holes mergers (10^4 to 10^8 $M_\odot$)

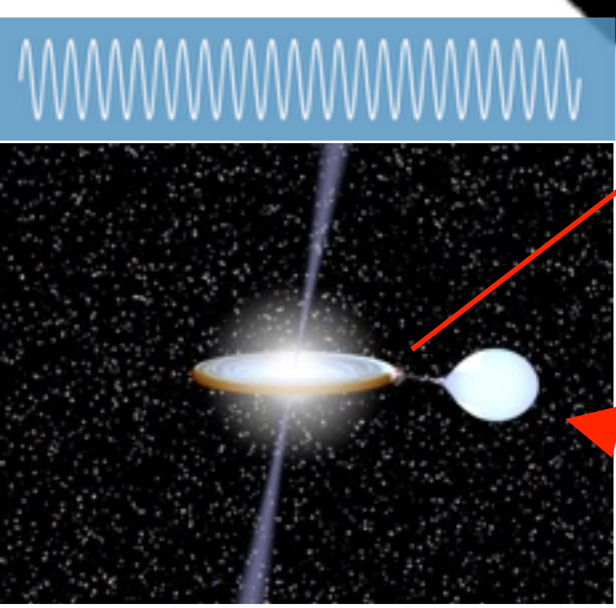


Extreme Mass Ratio Inspirals, EMRIs
(1 to 10 $M_\odot$ into 10^4 to 5×10^6 $M_\odot$)



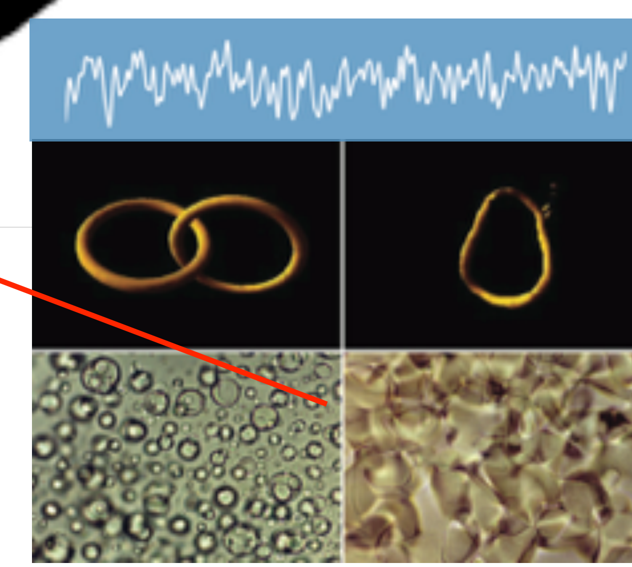
The GW Sky





Ultra-Compact Binaries in the Milky Way

Guaranteed Sources!



GW Stochastic Signals

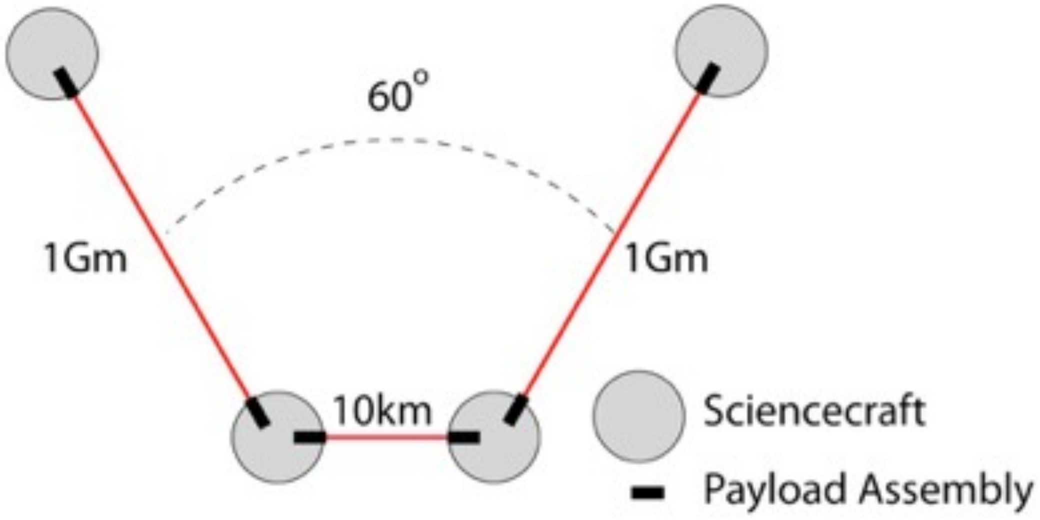
Carlos F. Sopuerta
Institute of Space Sciences (CSIC-IEEC)

A bit of History

A Bit of History

1974: First ideas about GW space-based detectors (Bender, Weiss, ...)

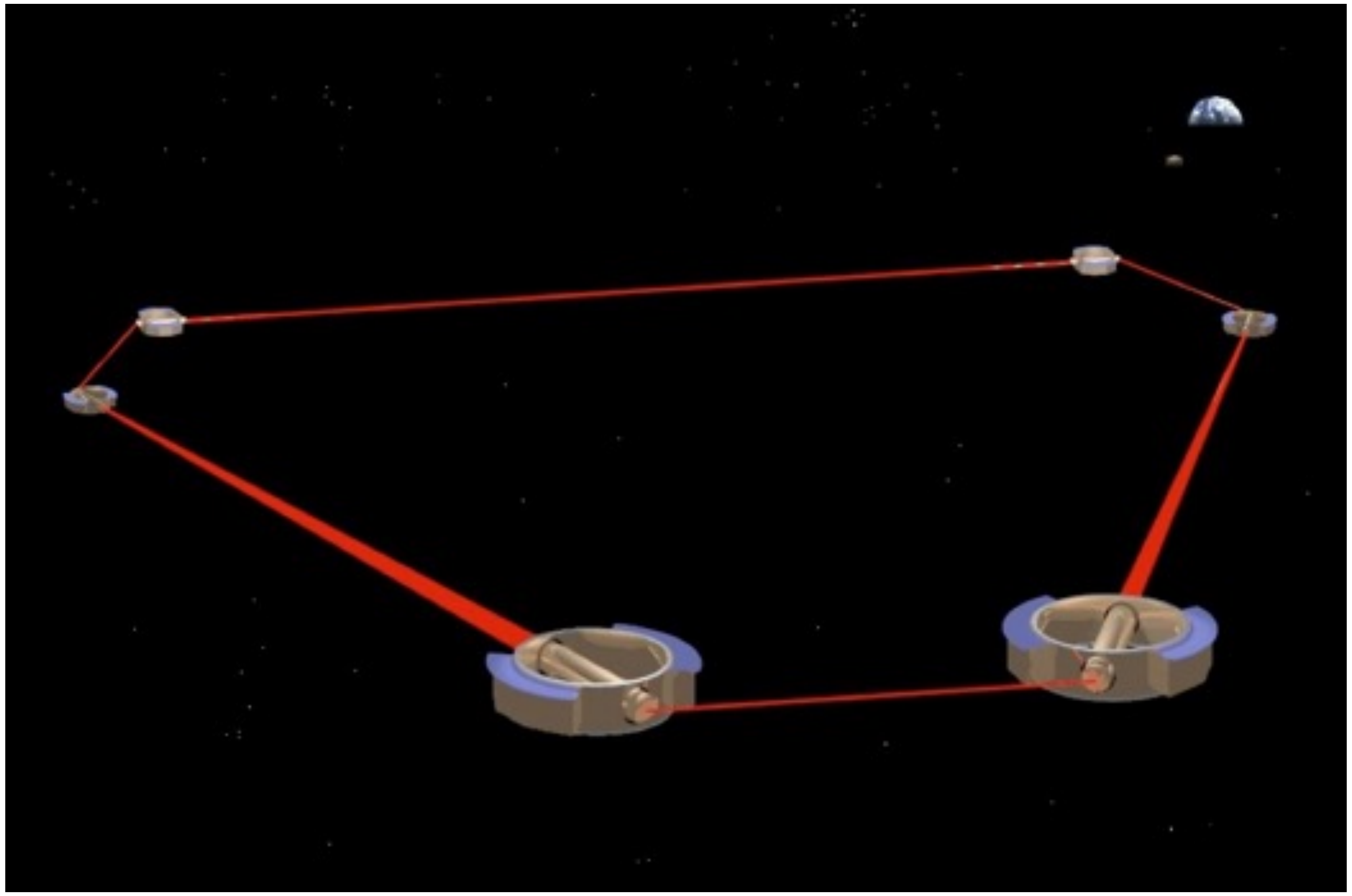
1984: **LAGOS**: **L**aser **A**ntenna for **GW** **O**bservations in **S**pace (Bender, Faller, Hall, Hils, Vincent)



1993: **LISA** (**L**aser **I**nterferometer **S**pace **A**ntenna; Danzmann) and Sagittarius (Hellings) are proposed to the Horizon 2000 program of ESA.

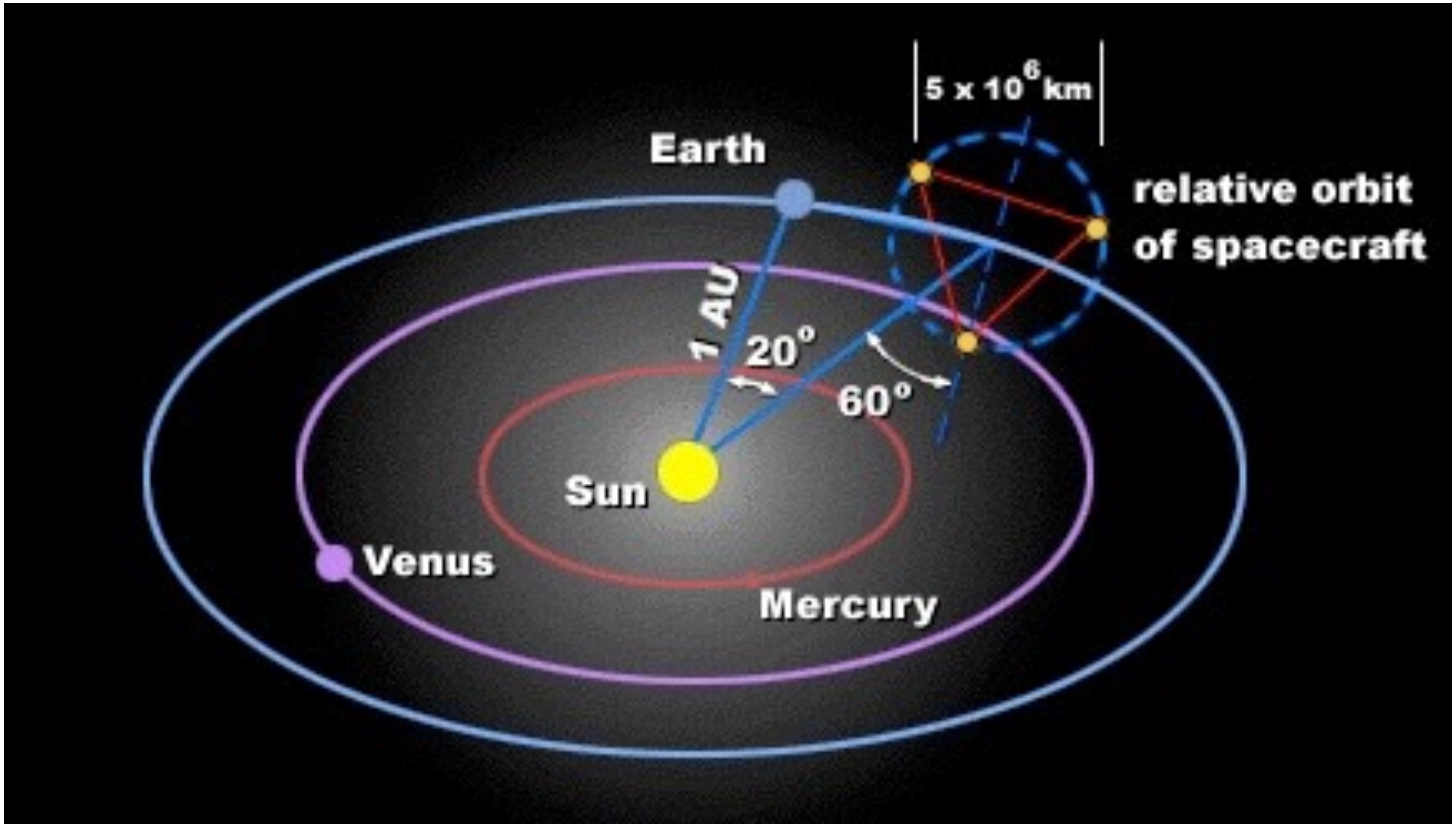
A Bit of History

1996: Design with 6 satellites and heliocentric orbit. It was chosen as a cornerstone mission for the program Horizon 2000+.
Launch Date proposed for the period 2017–2023



A Bit of History

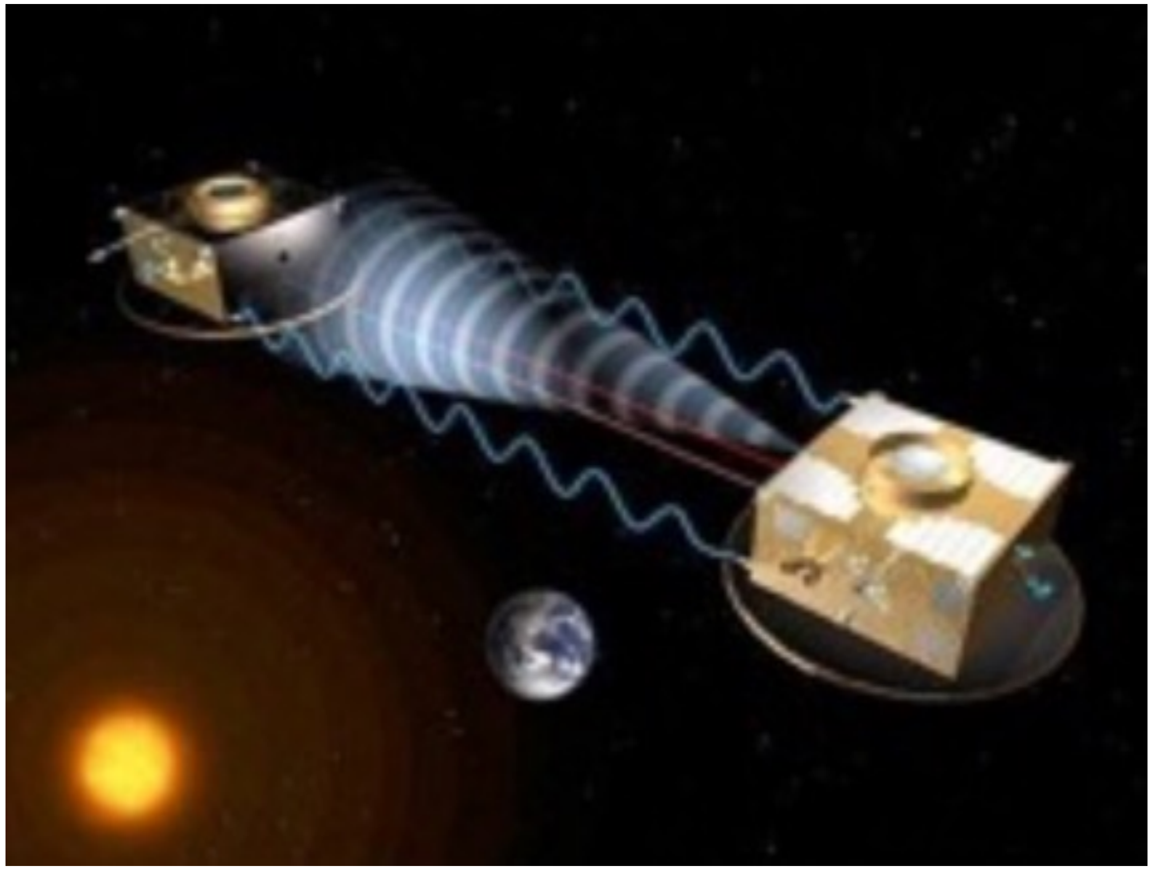
1997: Study by the Jet Propulsion Laboratory (Bender, Stebbins, Folkner): collaboration NASA–ESA, 3 satellites and heliocentric orbit.
Launch Date proposed for the period 2005–2010



A Bit of History

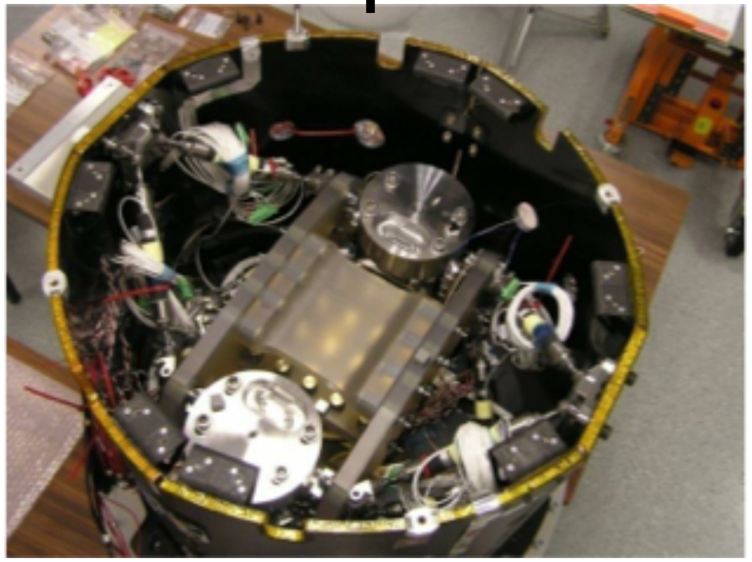
1998: **ELITE** (**E**uropean **LI**SA **TE**chnology) proposed:
Homodyne interferometer
Launch date 2002

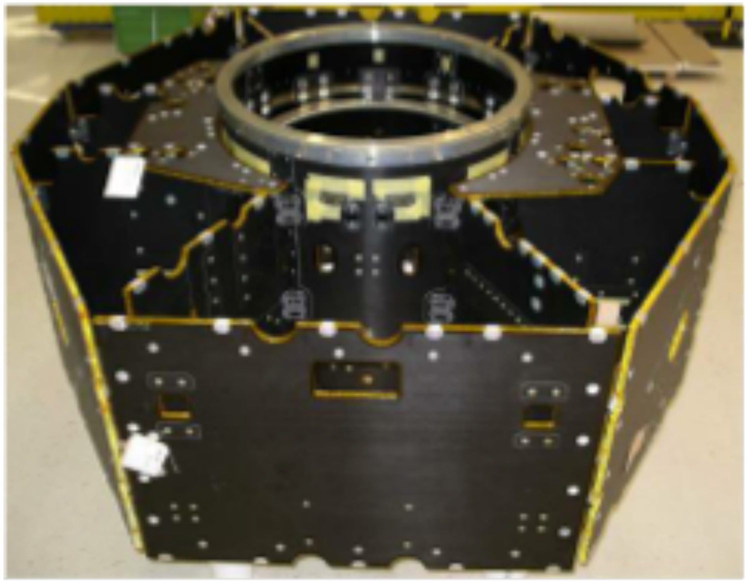
2000: **ELITE** proposed as **SMART**-2 (**S**mall **M**issions for **A**dvanced **R**esearch in **T**echnology):
Two spacescrafts, three payloads: **LISA** Pathfinder (ESA), Darwin Pathfinder (ESA), Disturbance Reduction System (NASA).



The LISA Pathfinder mission

- **LISA Pathfinder** is a Technology demonstrator for a laser interferometer space GW observatory like LISA (cannot be demonstrated on ground):
- Basic Idea: Take one eLISA link and squeeze it into one spacecraft





- The LISA Technology Package (LTP) will test:
  - Drag-free technology
  - Picometer interferometry
  - Other important subsystems and software

A Bit of History

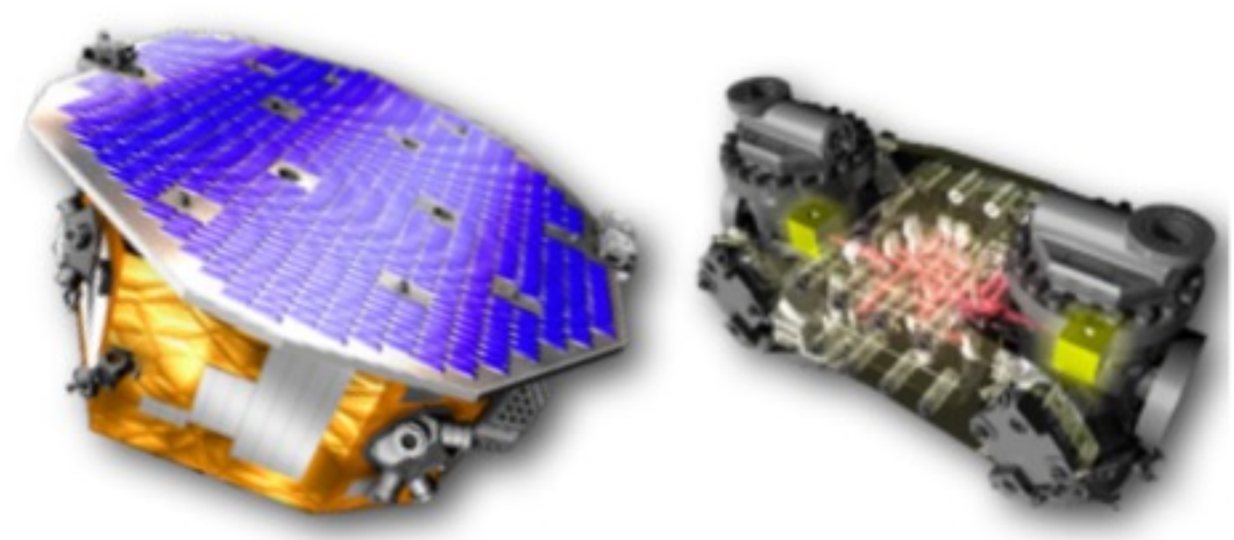
2000: U.S. decadal: **LISA** is second among the “moderate” projects.

2001: **SMART**-2 Descoped and renamed **LISA** Pathfinder:

Darwin Pathfinder cancelled

Single spacescraft, two payloads

LISA Technology Package (ESA) and **DRS** (NASA).



A Bit of History

2001: Starts the ESA **LISA** PathFinder, the technology demonstrator for **LISA**.

2004: Formal NASA–ESA agreement on **LISA**.
Launch Date proposed for the period 2012–2013.

2004: Alberto Lobo and the IEEC become part of the **LISA** Pathfinder Mission, leading the Spanish contribution.

2004: The **DRS** is descoped:
DRS interferometer and inertial sensor removed
DRS control laws and thrusters will use LTP sensors

A Bit of History

2007: Review of the NASA "Beyond Einstein" Program: **LISA** is second... but it is the first in science ("flagship")! Launch proposed for the period 2017-2020

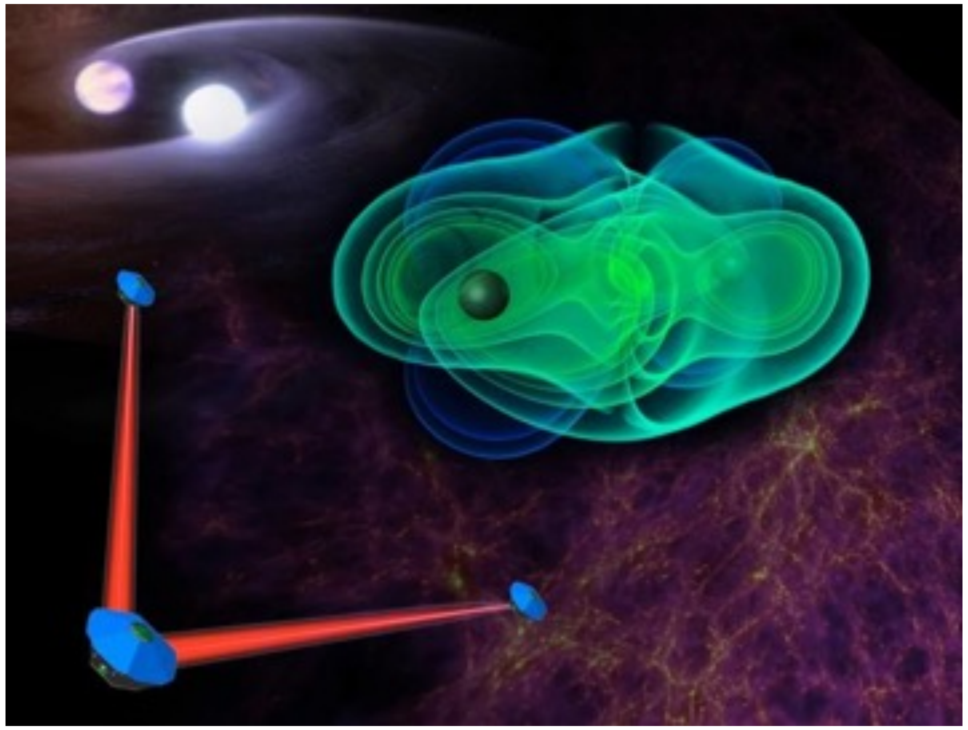
2010: Astro2010 decadal: **LISA**, "a gravitational-wave observatory that will open a completely new window to the exploration of the Universe" gets the third priority among the big space projects, after WFIRST and the Explorer program.

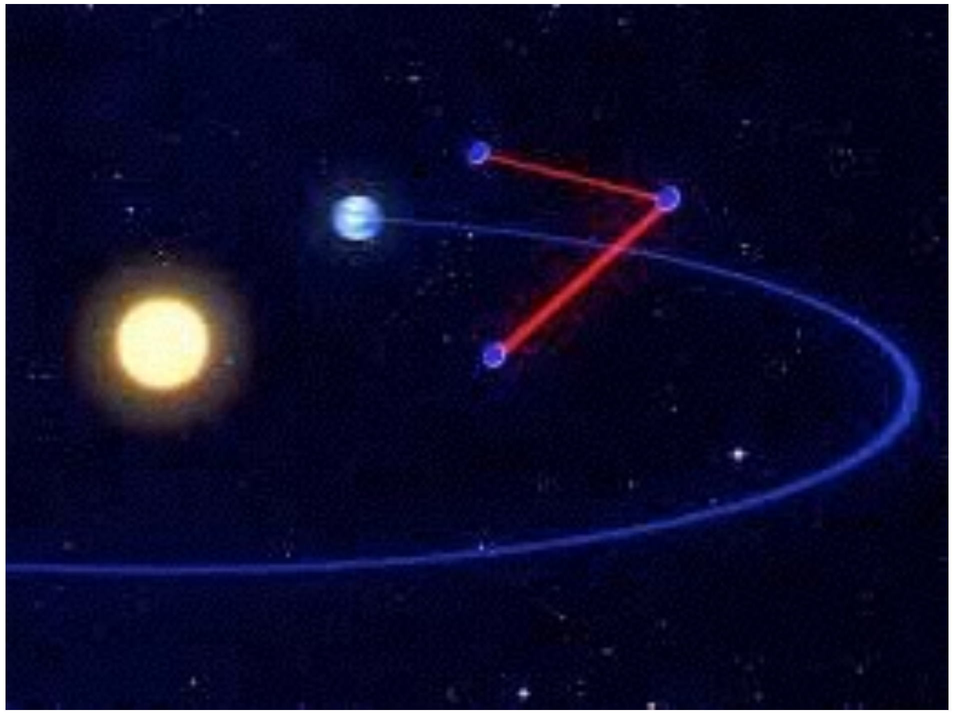
2011: NASA informs ESA that there is no budget to continue the collaboration according to the timeline of ESA's Cosmic Vision program: The collaboration in all the L-class missions is broken...

A Bit of History

2011: ESA decides to go ahead with the L-class missions (in particular **LISA**), but with new designs to fit a budget of (850 + ~300) MEuro!
One Slot for Launch in 2022

2011: The **LISA** community presents e**LISA/NGO**





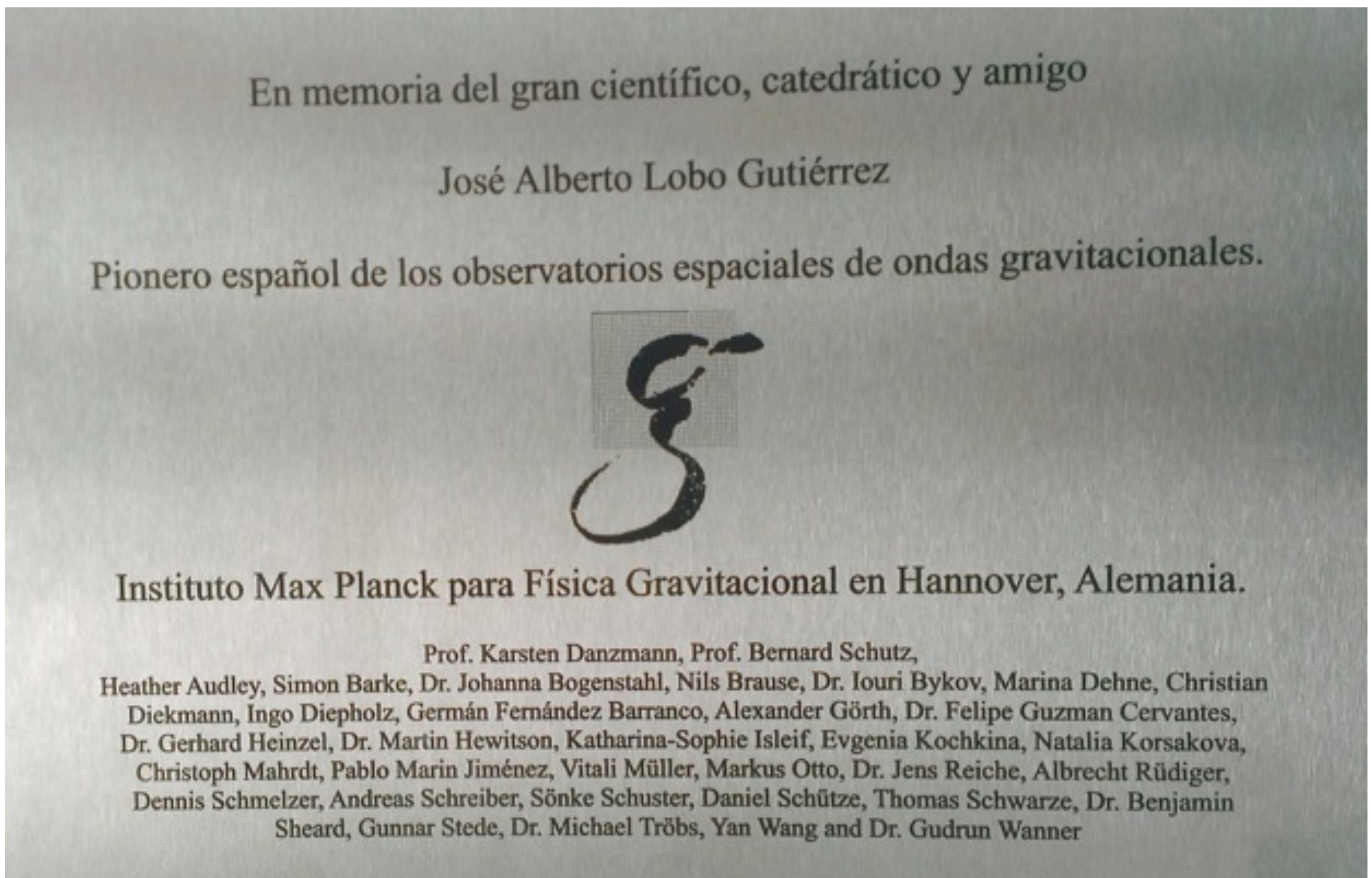
A Bit of History

2011: All the hardware assigned to IEEC for **LISA** Pathfinder is delivered and accepted by ESA:

A Bit of History

2012: ESA's SPC selects **JUICE** as the first L-class mission (L1) with Launch in the period 2020-22.
e**LISA/NGO** gets a good report = We are 2nd again!

2012: Alberto Lobo leaves us...



A Bit of History

esa

Call for White Papers for the definition of the L2 and L3 missions in the ESA Science Programme

5 March 2013

EXECUTIVE SUMMARY

The Director of Science and Robotic Exploration intends to define, in the course of 2013, the science themes and questions that will be addressed by the "L2" and "L3" missions. These are the two Large missions in the Cosmic Vision plan currently planned for a launch in 2028 and 2034, following the already selected L1 mission JUICE, to be launched in 2022. This process will start with a consultation of the broad scientific community, in the form of a "Call for White Papers", solicited through the present document. By means of the White Papers, the scientific community is invited to submit proposals for science themes and associated questions that should be addressed by the L2 and L3 missions.

A Bit of History

ESA/SPC(2013)29
Att.: Annex
ESA/SSAC(2013)7
Paris, 31 October 2013
(Original: English)

Selection of the science themes for the L2 and L3 missions

Summary:

Following the evaluation of the 32 White Papers proposing science themes for the L2 and L3 mission opportunities (currently foreseen in 2028 and 2034), which were received in response to the Call issued in March 2013, the Senior Survey Committee convened by the Director of Science and Robotic Exploration has issued its recommendations (in annex to the present document). Based on these recommendations the Director of Science and Robotic Exploration is herewith proposing to the SPC the selection of the science themes for the L2 and L3 mission opportunities.

Decision:

The SPC is invited

1) to approve the selection of the science theme "The hot and energetic Universe" for the L2 opportunity, to be pursued by implementing a large collecting area X-ray observatory with a planned launch date of 2028, and

2) to approve the selection of the science theme "The gravitational Universe", to be pursued by implementing a gravitational wave observatory with a planned launch date of 2034.

THE GRAVITATIONAL UNIVERSE

arXiv:1305.5720

The ESA-L3 mission will implement this science theme (selected in 2013 by ESA)

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A Bit of History

* The eLISA (NGO) Mission Design:

THE GRAVITATIONAL UNIVERSE

A science theme addressed by the *eLISA* mission observing the entire Universe

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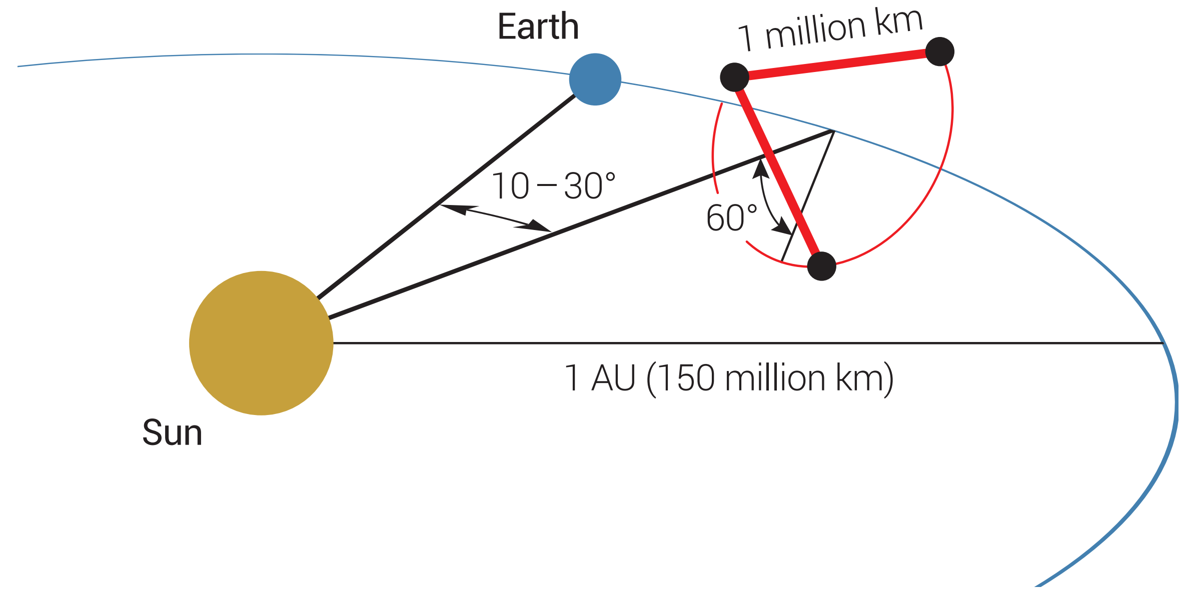
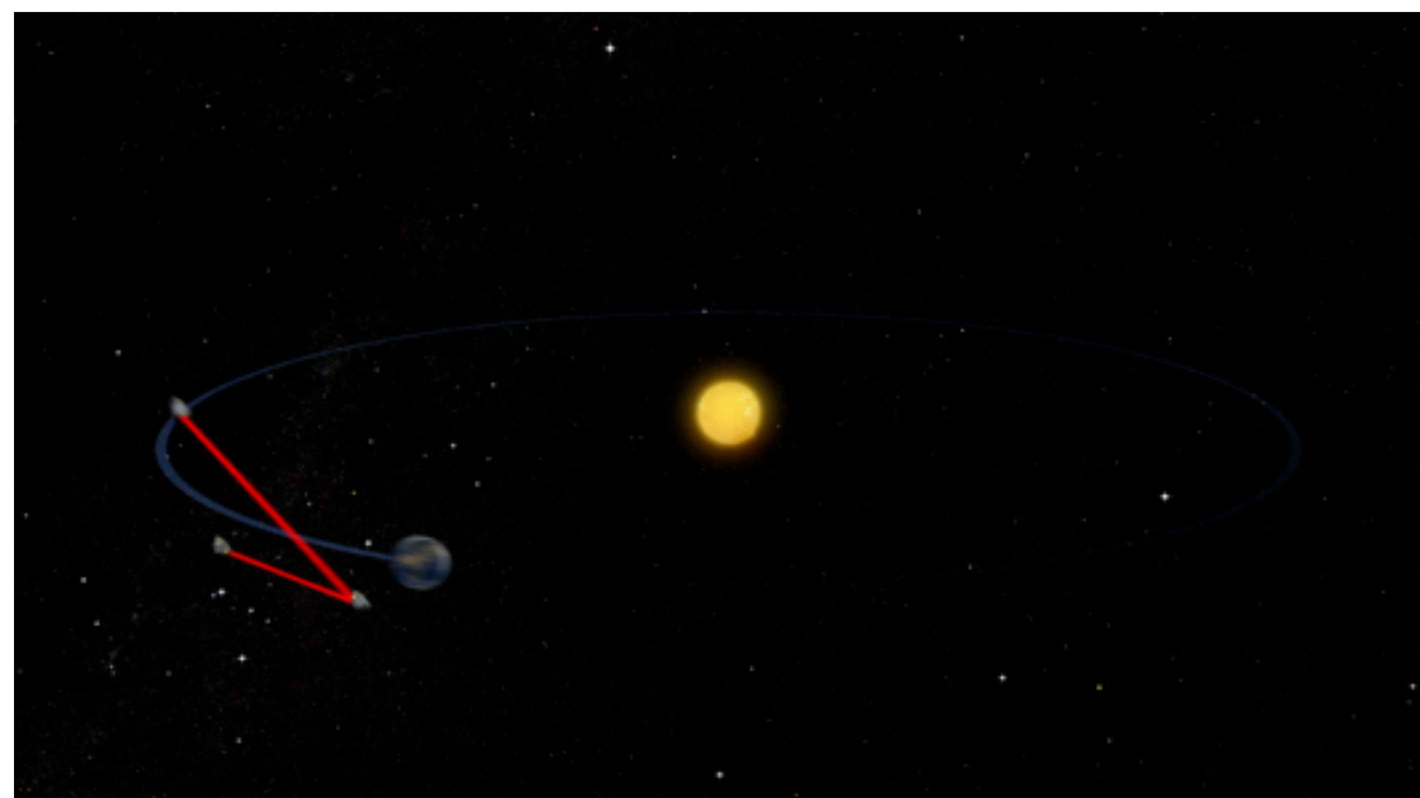
Detailed information at
http://elisascience.org/whitepaper

The last century has seen enormous progress in our understanding of the Universe. We know the life cycles of stars, the structure of galaxies, the remnants of the big bang, and have a general understanding of how the Universe evolved. We have come remarkably far using electromagnetic radiation as our tool for observing the Universe. However, gravity is the engine behind many of the processes in the Universe, and much of its action is dark. Opening a gravitational window on the Universe will let us go further than any alternative. Gravity has its own messenger: Gravitational waves, ripples in the fabric of spacetime. They travel essentially undisturbed and let us peer deep into the formation of the first seed black holes, exploring redshifts as large as z ~ 20, prior to the epoch of cosmic re-ionisation. Exquisite and unprecedented measurements of black hole masses and spins will make it possible to trace the history of black holes across all stages of galaxy evolution, and at the same time constrain any deviation from the Kerr metric of General Relativity. eLISA will be the first ever mission to study the entire Universe with gravitational waves. eLISA is an all-sky monitor and will offer a wide view of a dynamic cosmos using gravitational waves as new and unique messengers to unveil The Gravitational Universe. It provides the closest ever view of the early processes at TeV energies, has guaranteed sources in the form of verification binaries in the Milky Way, and can probe the entire Universe, from its smallest scales around singularities and black holes, all the way to cosmological dimensions.



eLISA Orbits



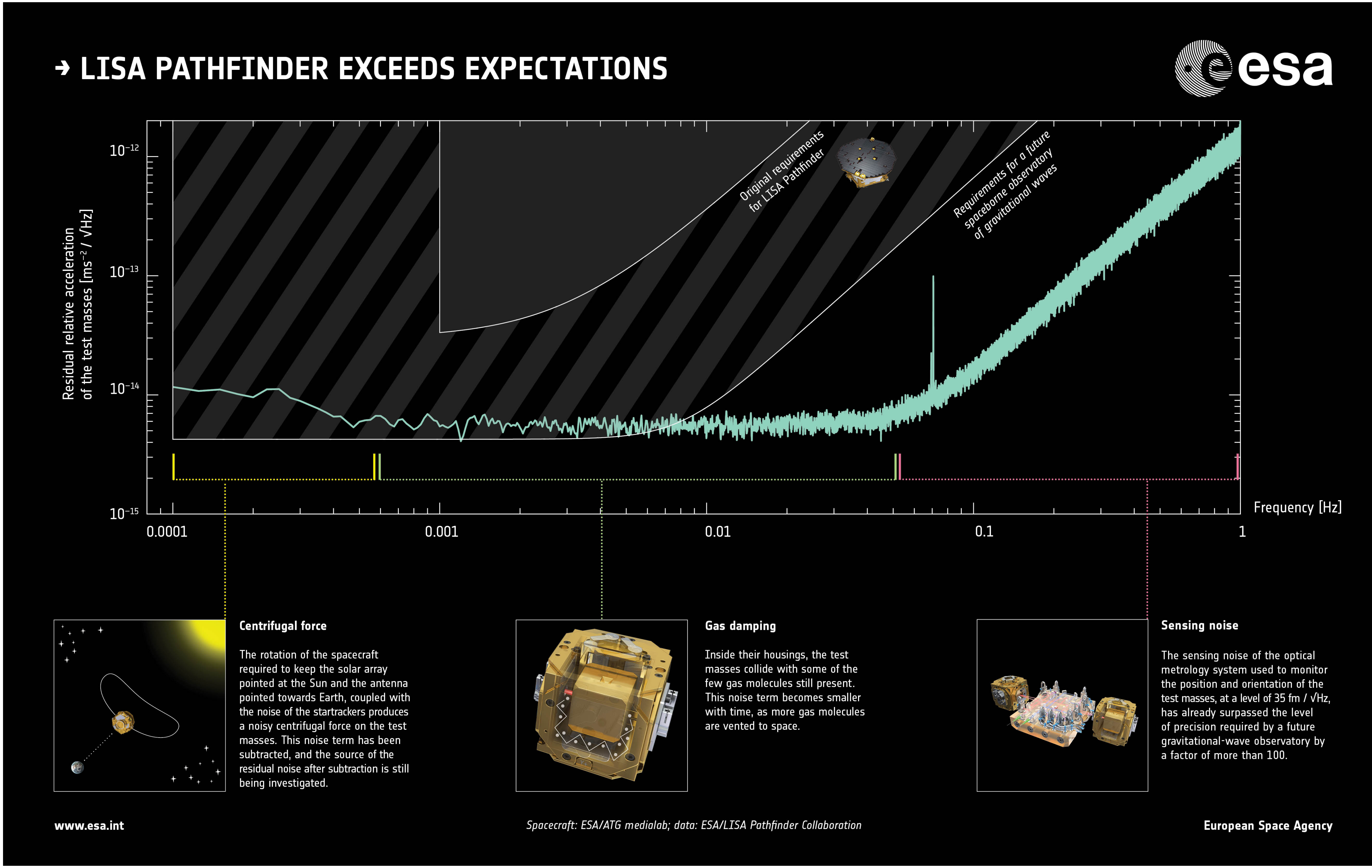
A Bit of History

2015: LIGO detects the first gravitational wave signals from binary black hole mergers (GW150914 and GW151226).

2015: LISA Pathfinder is launched from Kourou (French Guiana; December 3rd)

A Bit of History

2016: LISA Pathfinder first results (ESAC, June 7th)



A Bit of History

2016: LISA Pathfinder first results (ESAC, June 7th)

Physics

VIEWPOINT

Paving the Way to Space-Based Gravitational-Wave Detectors

The first results from the LISA Pathfinder mission demonstrate that two test masses can be put in free fall with a relative acceleration sufficiently free of noise to meet the requirements needed for space-based gravitational-wave detection.

by David Reitze*

The announcement in February 2016 that the Laser Interferometer Gravitational-wave Observatory (LIGO) had detected gravitational waves from the merger of two black holes stunned and electrified much of the physics and astronomy communities [1]. However, while all eyes were turned toward LIGO, the LISA Pathfinder (LPF)—a technology demonstration mission for the Laser Interferometer Space Antenna (LISA) gravitational-wave detector [2]—was quietly but convincingly paving the way toward the next revolution in gravitational-wave astronomy more than 1.5 million kilometers away from Earth. After a six-month program that began with the launch of the spacecraft in early December 2015, the team behind LPF has now announced the first results from the mission [3]. Following a 50-day journey to Lagrange Point 1 of the Sun-Earth system, LPF settled into orbit to begin a series of spacecraft acceptance tests and an observing campaign to measure the limits with which two test masses can achieve free fall.

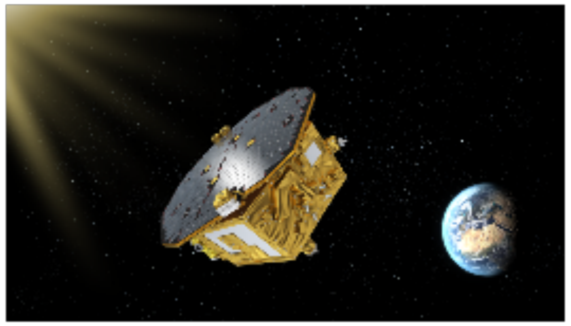


Figure 1: An artist's conception of the LISA Pathfinder spacecraft in orbit at Lagrange Point 1. Photovoltaic solar cells on the top of the spacecraft provide power. Micronewton thrusters can be seen on the sides of the spacecraft. The test masses and laser interferometer readout system are located inside the spacecraft. (European Space Agency/ C. Carreau)

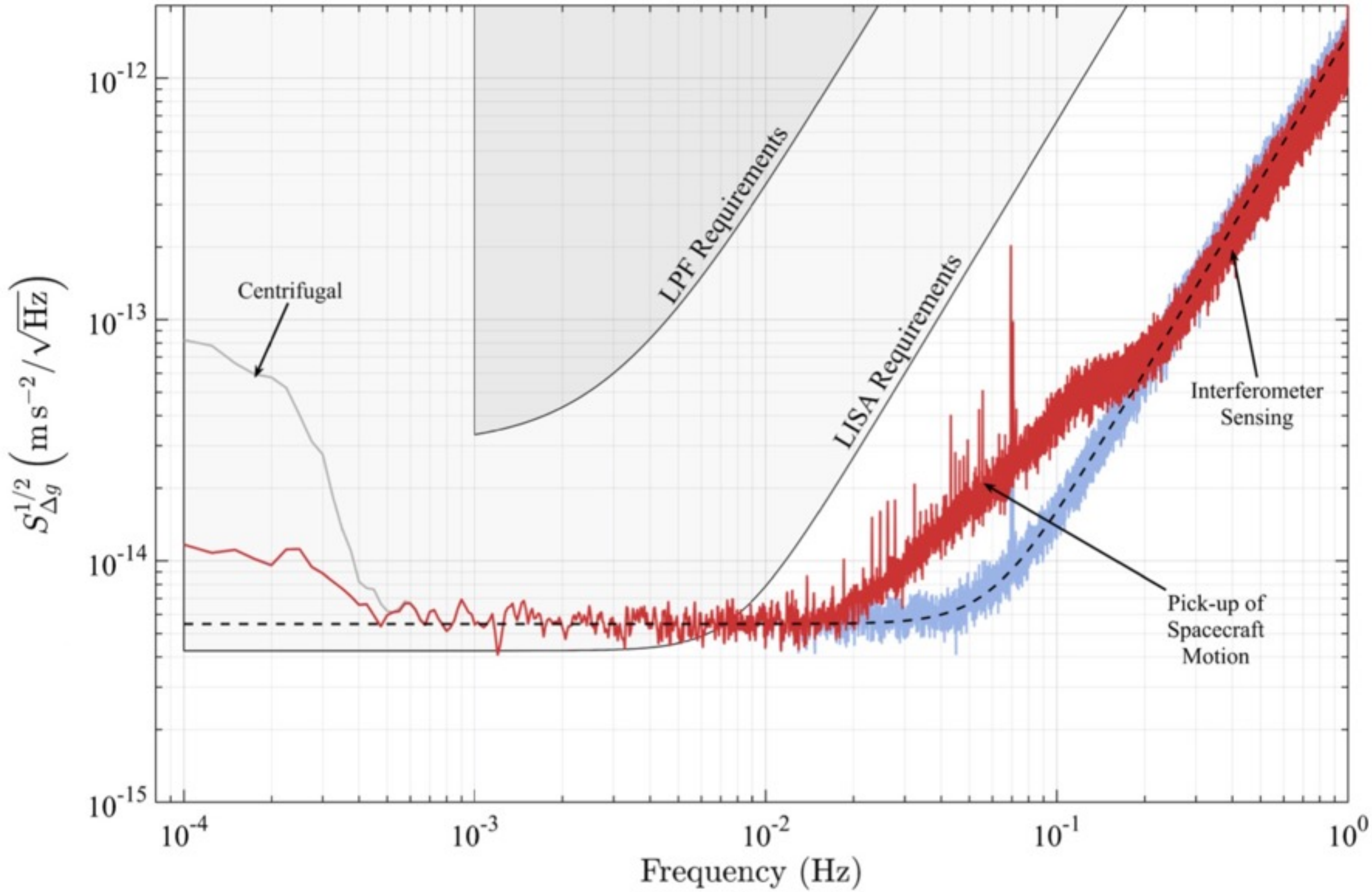
LPF was designed to test many of the key technologies needed by LISA. LISA will target a much lower gravitational-wave frequency band than LIGO, from about 100 mHz to 1 Hz. This regime is sensitive to gravitational waves from mergers of intermediate to massive black holes in the range of 10^4 to 10^7 solar masses, as well as from mergers of black holes that have an extreme mass ratio (in which one black hole is much more massive than the other). But it necessitates a space-based platform to avoid low-frequency noise sources arising on Earth, which easily overwhelm the signal from such waves. These mergers will provide the most stringent tests of General Relativity in the strong-gravity regime.

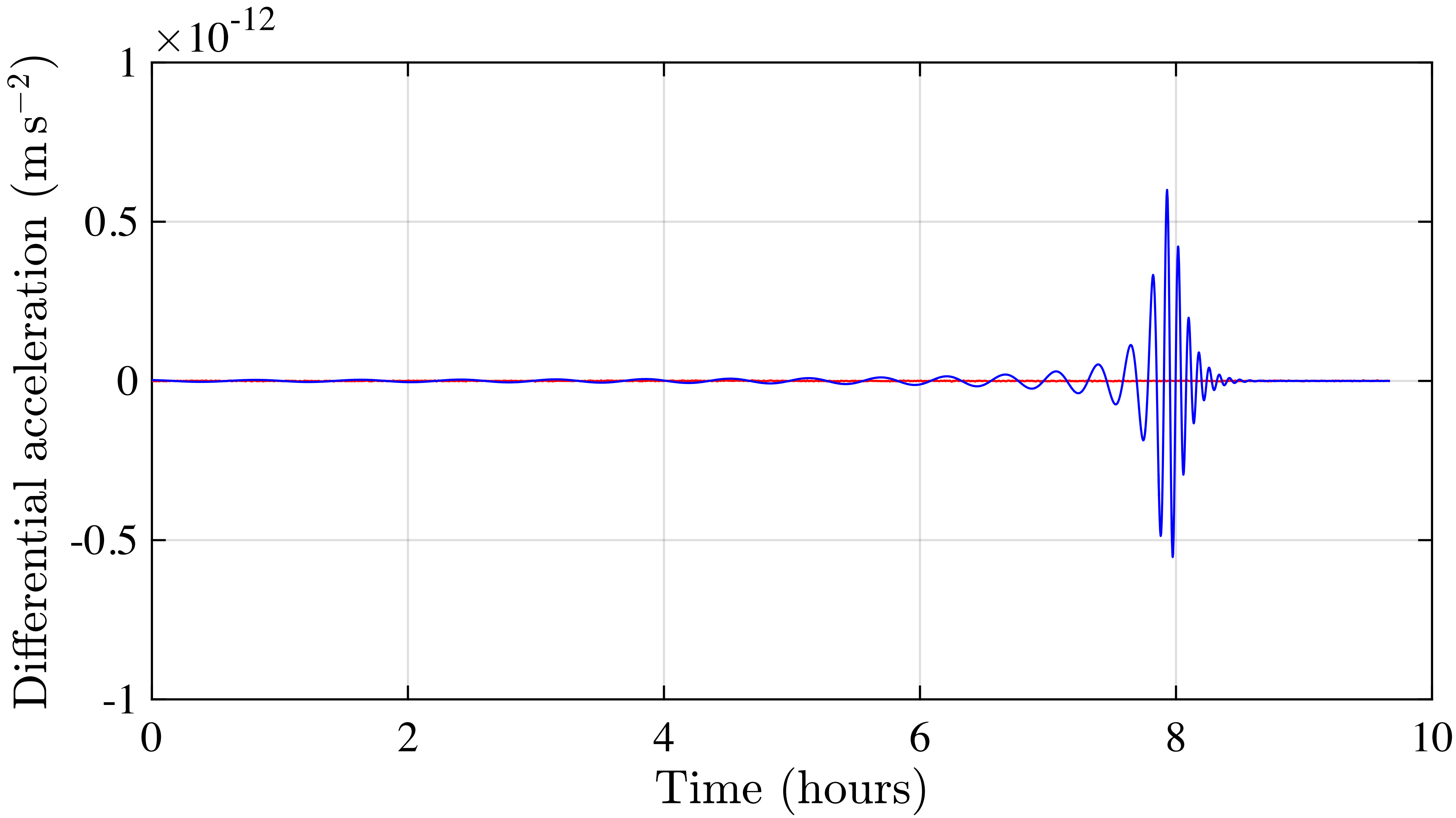
A gravitational wave physically manifests itself as a strain, $\Delta L/L$, on two separated, free-falling test masses: For masses separated by a distance L, a passing gravitational wave will dynamically stretch and compress, through one cycle of the wave, the distance between the masses along one direction perpendicular to the propagating wave, by an amount ΔL, while simultaneously compressing and stretching the distance by an equal amount in the other perpendicular direction. By measuring the time that light takes to travel between two sets of separated test masses, the time-dependent strain can be recorded. To meet its astrophysics goals, LISA demands a length L of 2 million kilometers and a sensitivity to a displacement ΔL of approximately 5×10^{-11} m at frequencies in a range near 100 mHz [2].

LPF is a single spacecraft whose test masses are separated by less than a meter. As such, it is completely insensitive to gravitational-wave strains, but it probes the limits of displacement sensitivity required by LISA, which will consist of three spacecraft configured in a triangle and located much further from Earth. The basic concept behind LPF is simple: place the two test masses in a spacecraft in free-fall and measure the residual time-dependent longitudinal displacement between the two masses over periods of days to weeks.

*LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

The LISA Pathfinder mission

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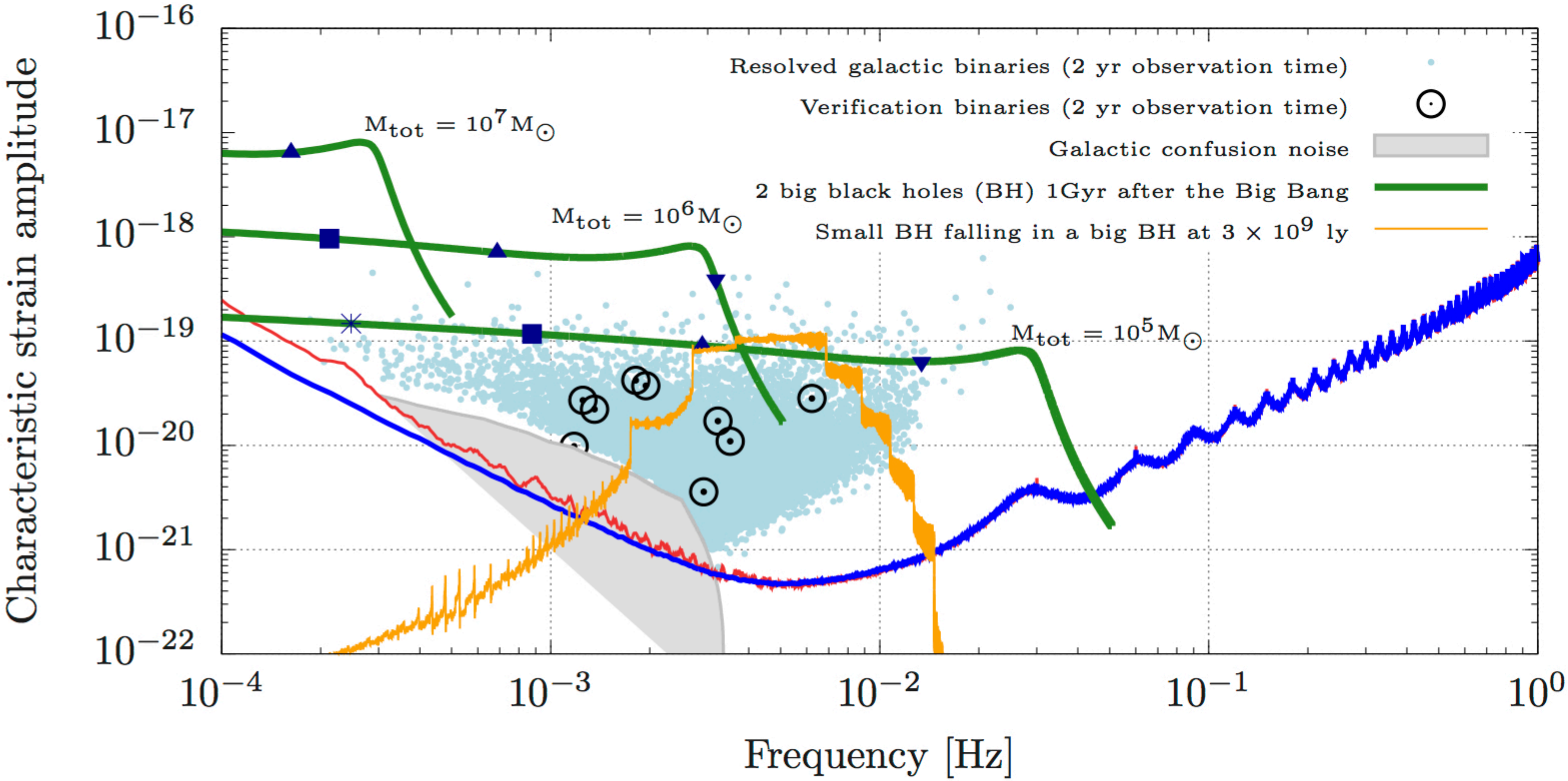
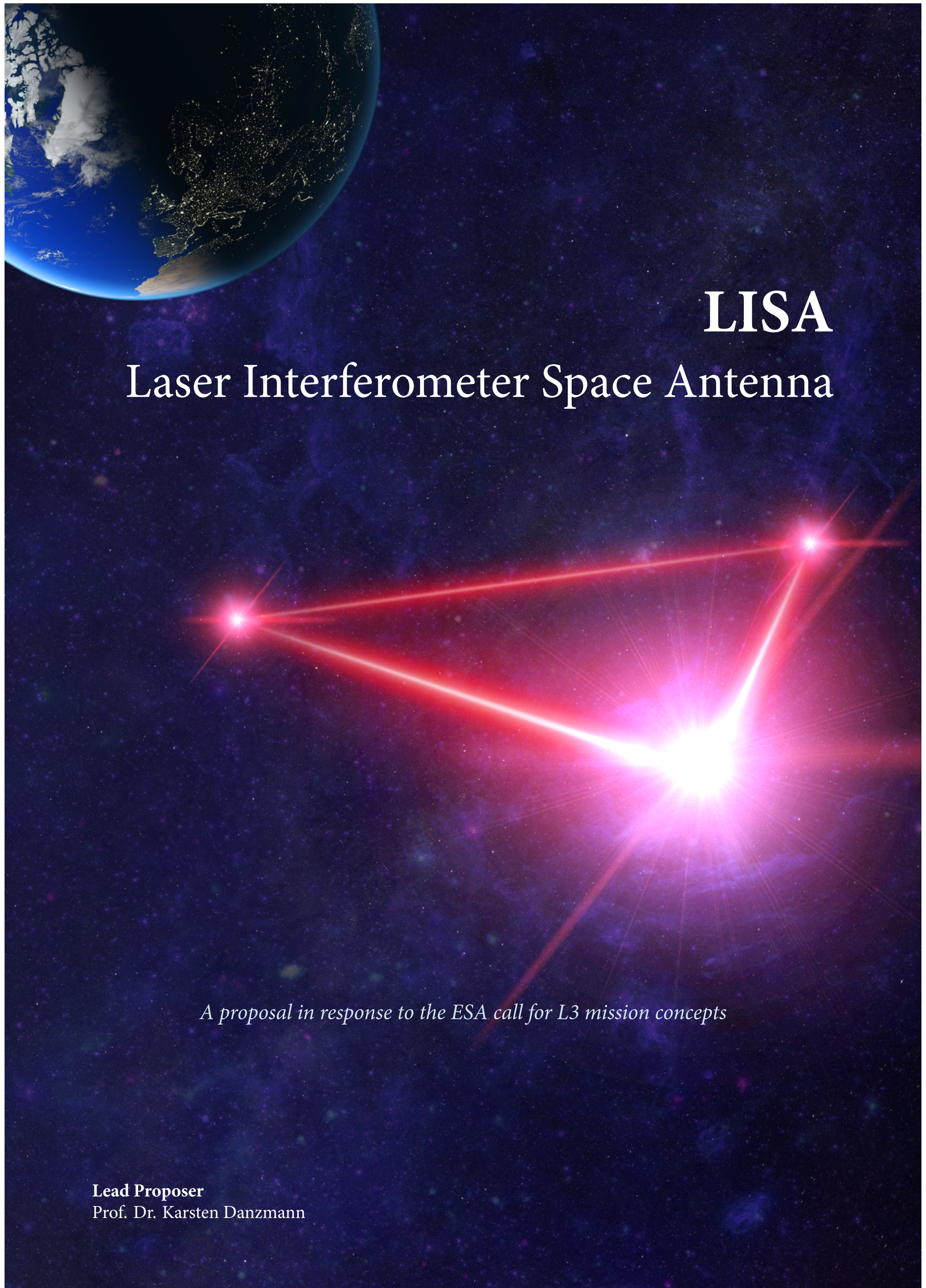
1
0.5
0
-0.5
-1
Differential acceleration (m s^−2)
0
2
4
6
8
10
Time (hours)

The LISA Pathfinder mission



A Bit of History

2017: The LISA Consortium submits the LISA proposal



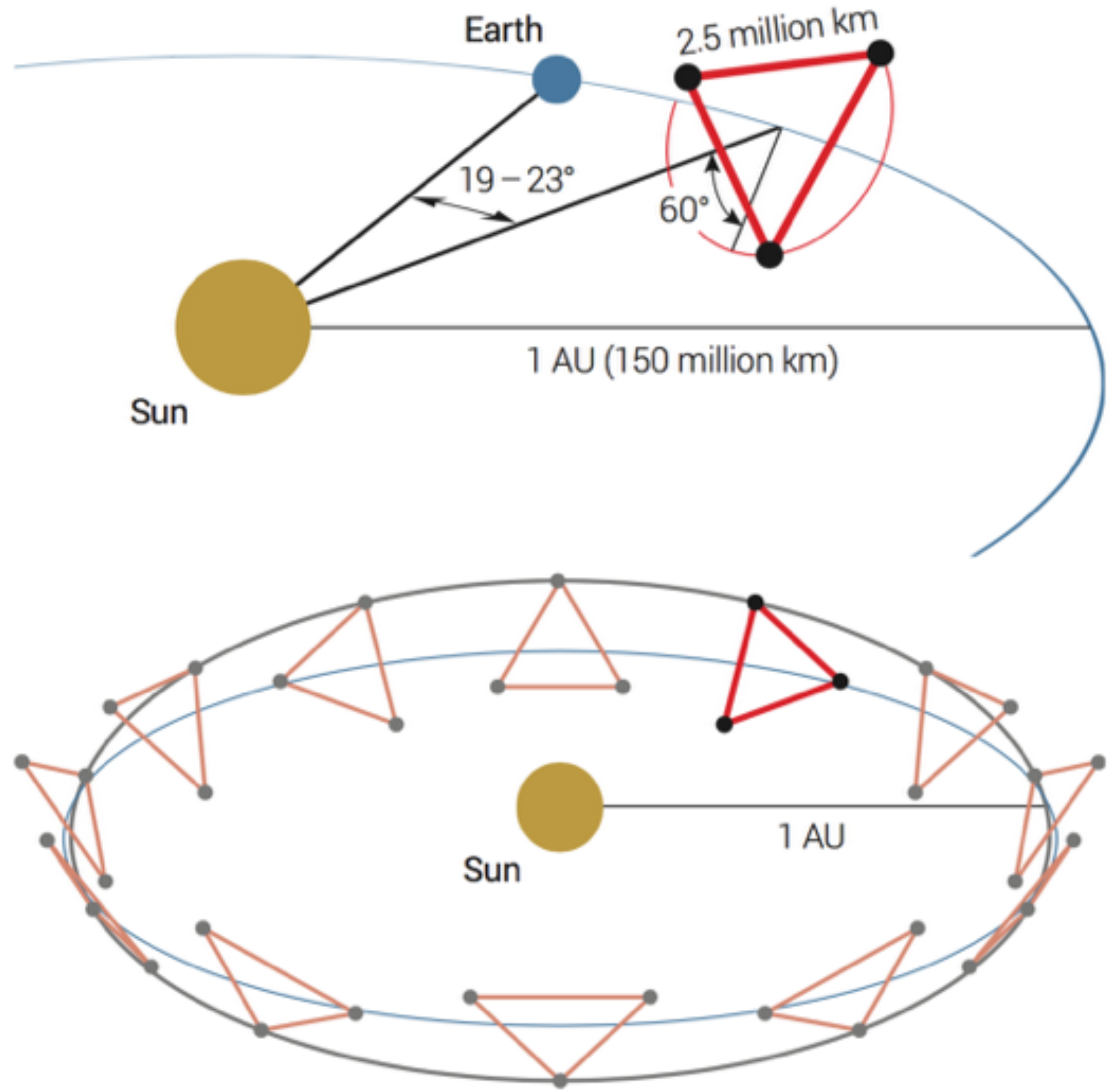
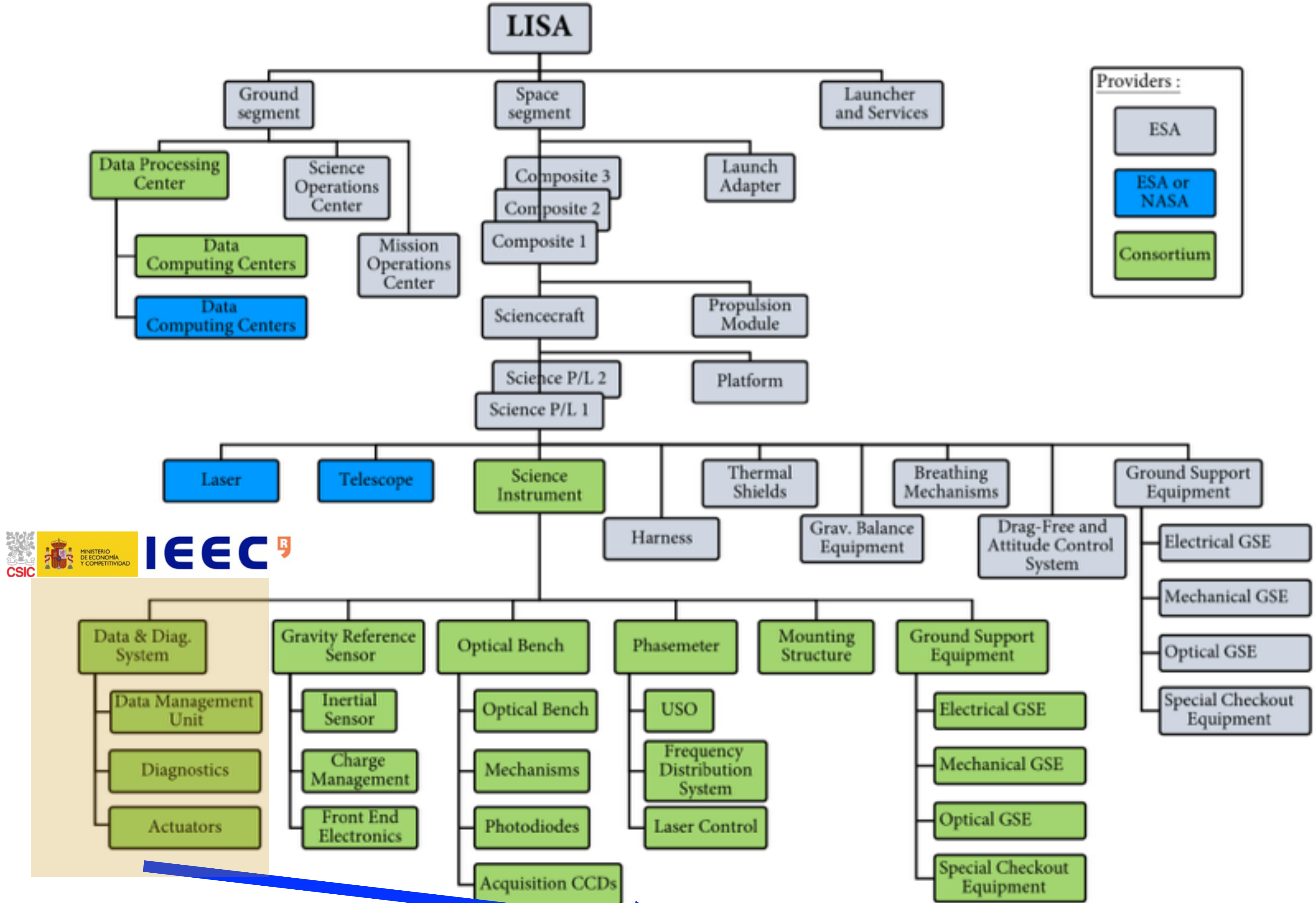


Figure 4: Depiction of the LISA Orbit.

Participation in LISA of the Gravitational Astronomy-LISA Group

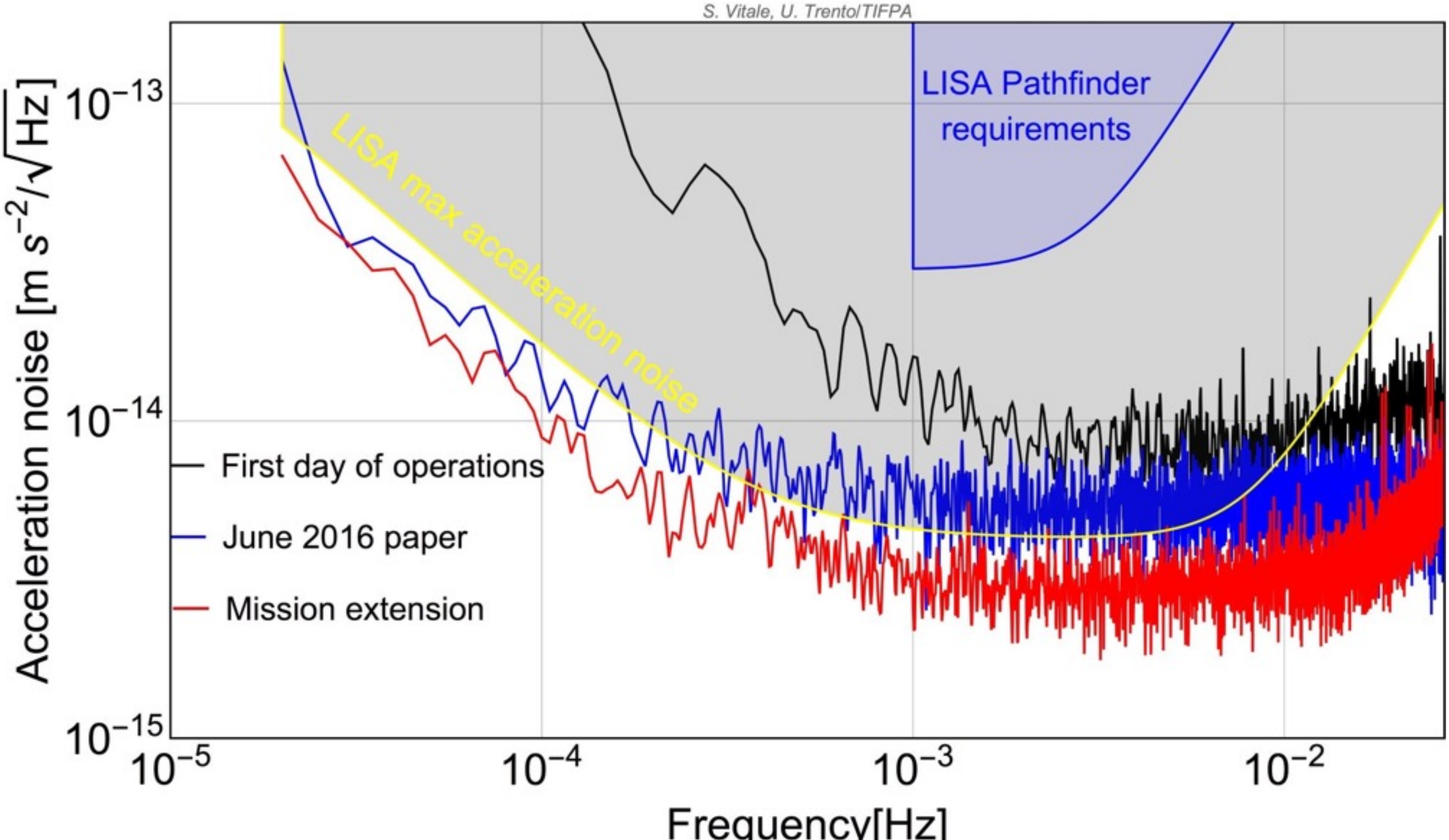


Diagnostics Technologies		
Diagnostic Items	LPF Heritage (TRL 9), LISA adaption for the temperature and magnetometer sensors to be done.	4

Table 8: Technology readiness levels of primary mission items.

Carlos F. Sopuerta
Institute of Space Sciences (CSIC-IEEC)

2017: LISA Pathfinder status during mission extension:

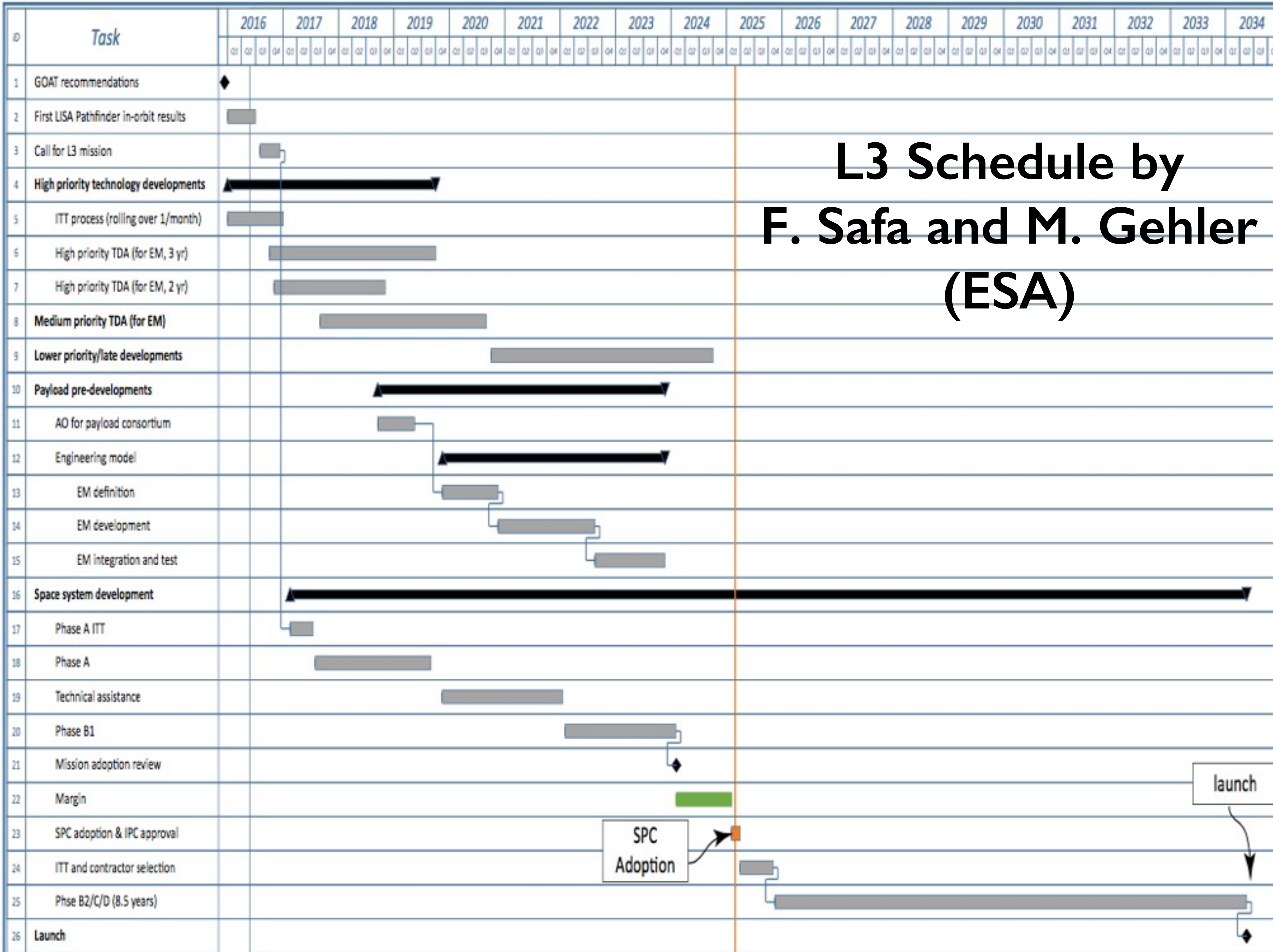


A Bit of History

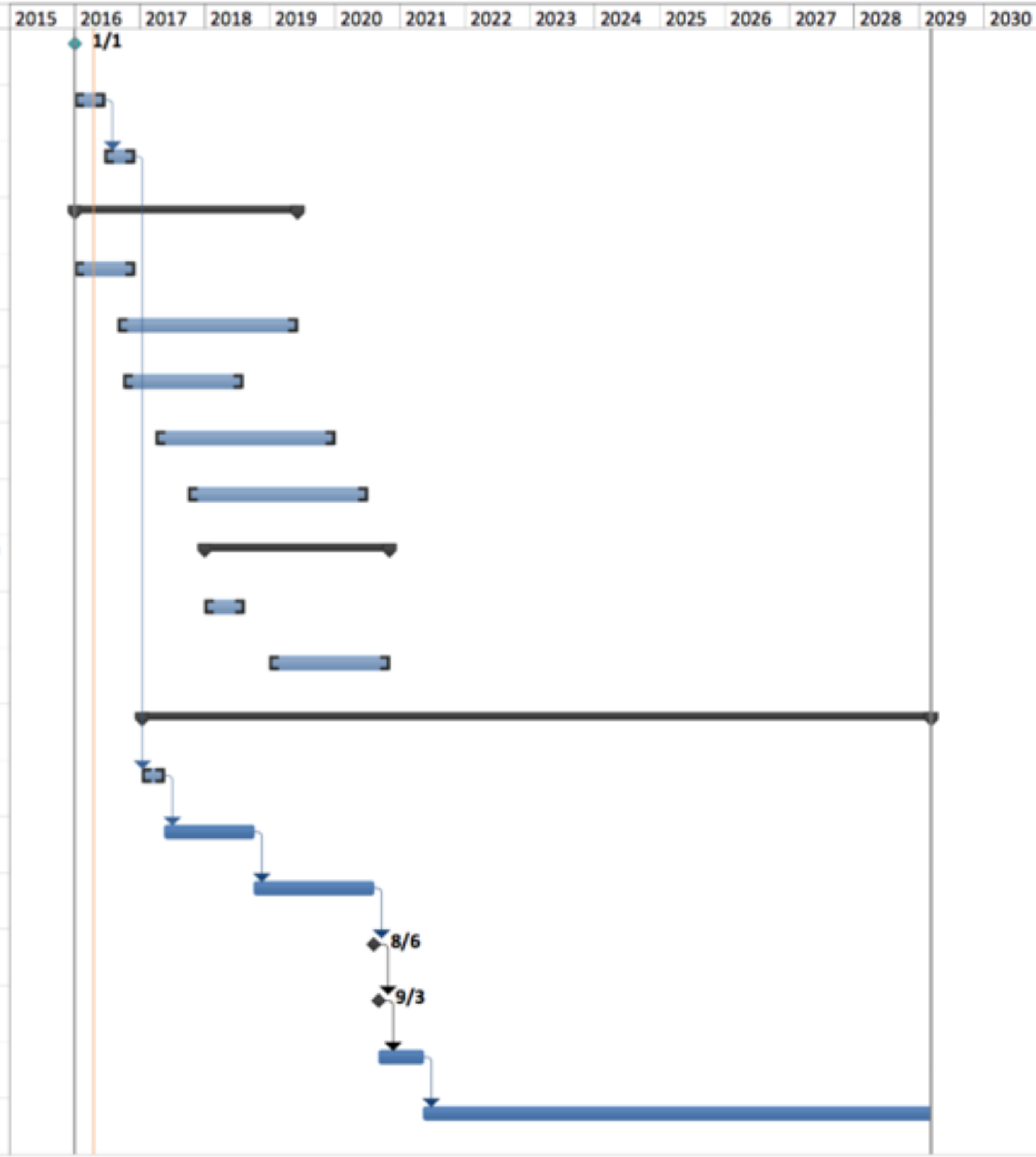
2017: CDF (ESA) presentation: May 5th

2017: Next step: SPC meeting June: LISA will be approved and become officially the ESA-L3 mission!!

L3 Schedule by F. Safa and M. Gehler (ESA)



ID		Task	Task Name	Duration	Start	Finish
1			GOAT recommendations	0 days	Fri 1/1/16	Fri 1/1/16
2			First LISA Pathfinder in-orbit results	6 mons	Fri 1/1/16	Thu 6/16/16
3			Call for L3 Mission	6 mons	Fri 6/17/16	Thu 12/1/16
4			**High priority Technology Developments**	**894 days**	**Fri 1/1/16**	**Wed 6/5/19**
5			ITT process (rolling over 1/month)	12 mons	Fri 1/1/16	Thu 12/1/16
6			High Priority (TDA (for EM, 3 yr)	36 mons	Thu 9/1/16	Wed 6/5/19
7			High prioirty TDA (for EM, 2 yr)	24 mons	Sat 10/1/16	Thu 8/2/18
8			Medium prioirty TDA (for EM)	36 mons	Sat 4/1/17	Thu 1/2/20
9			Lower priority/late developments	36 mons	Sun 10/1/17	Thu 7/2/20
10			**Payload pre-developments**	**741 days**	**Mon 1/1/18**	**Mon 11/2/20**
11			AO for Payload consortium	8 mons	Mon 1/1/18	Fri 8/10/18
12			System risk reduction	24 mons	Tue 1/1/19	Mon 11/2/20
13			**Space system development**	**3170 days**	**Fri 1/13/17**	**Thu 3/8/29**
14			phase A ITT	4.5 mons	Fri 1/13/17	Thu 5/18/17
15			Phase A	18 mons	Fri 5/19/17	Thu 10/4/18
16			Phase B1	24 mons	Fri 10/5/18	Thu 8/6/20
17			Mission adoption review	0 days	Thu 8/6/20	Thu 8/6/20
18			SPC adoption & IPC approval	0 days	Thu 9/3/20	Thu 9/3/20
19			ITT and contractor selection	9 mons	Fri 9/4/20	Thu 5/13/21
20			Phase B2/C/D (8.5 yrs)	102 mons	Fri 5/14/21	Thu 3/8/29



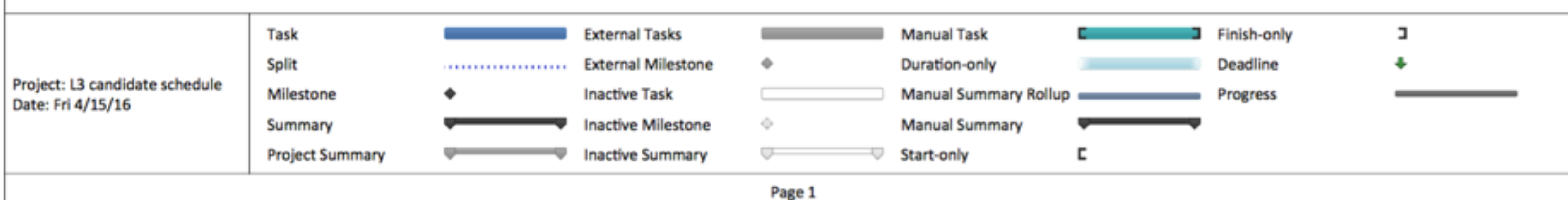
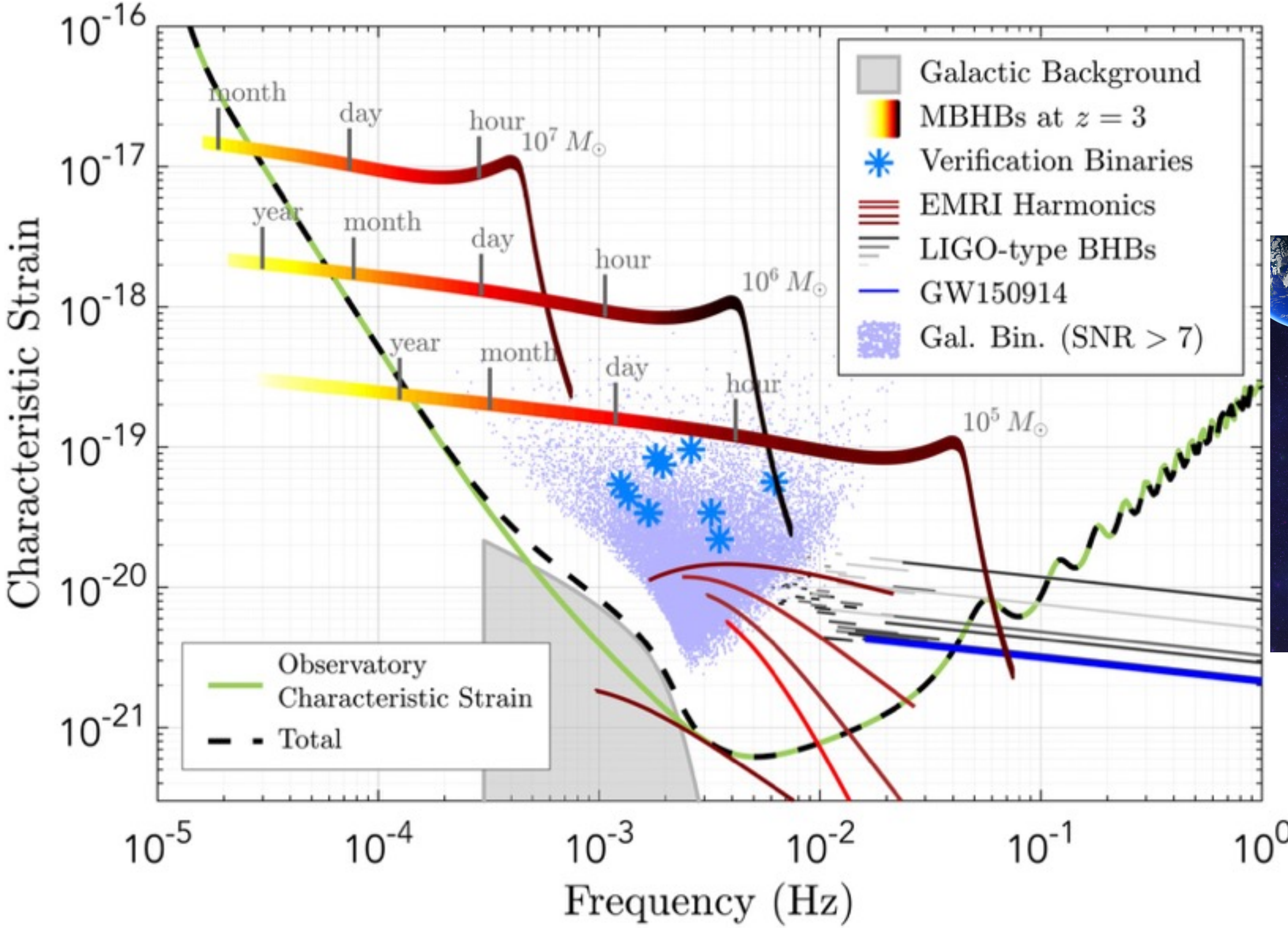


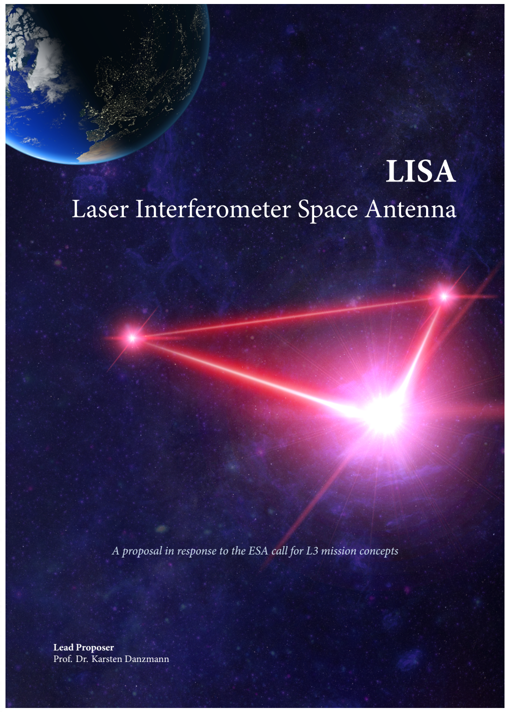
Figure 15: The schedule developed as part of the GOAT committee exercise.

The ESA-L3 mission (LISA)

The ESA-L3 mission (LISA)

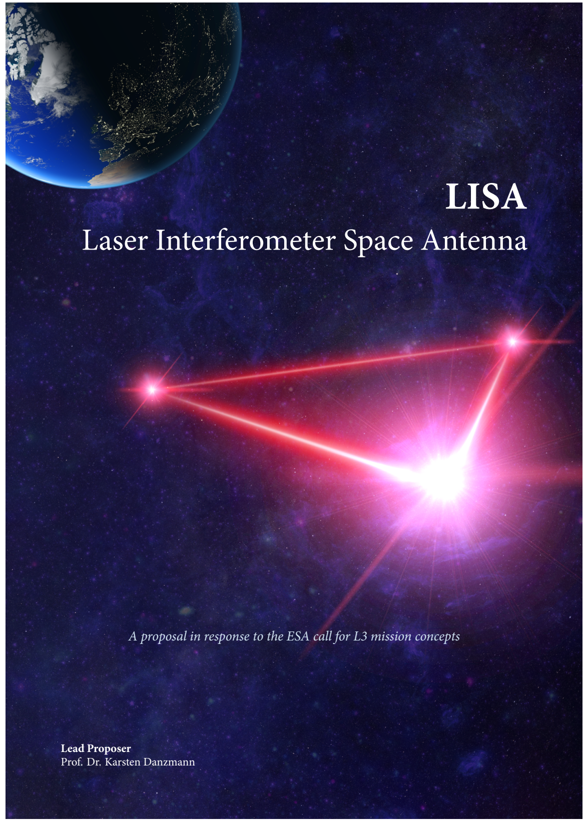
- Expected Sensitivity and Sources:

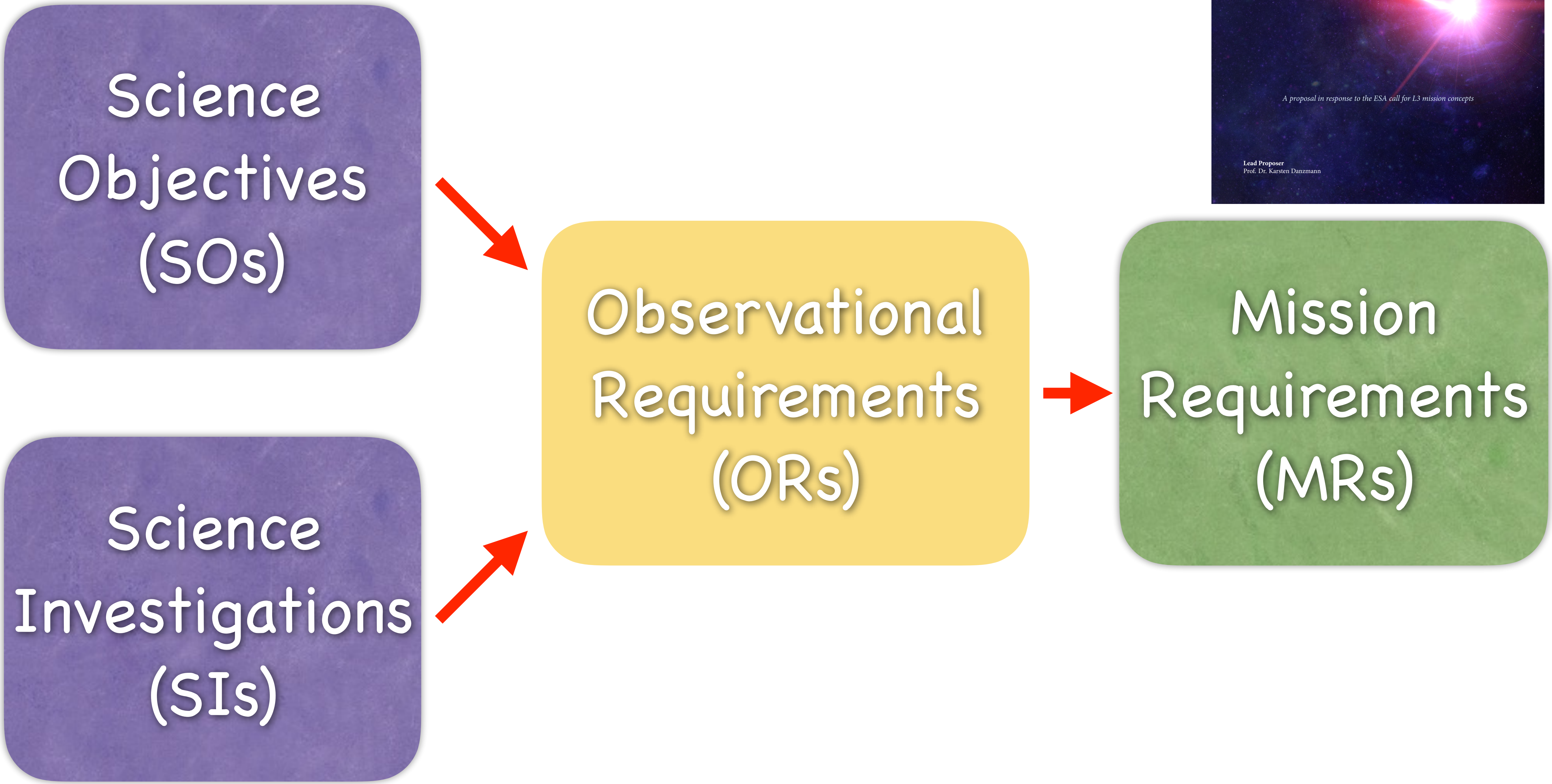




The ESA-L3 mission (LISA)

- LISA sensitivity design to address "*The Gravitational Universe*" science program:





The ESA-L3 mission (LISA)

- **SO1**: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.

  - Numerous compact binaries in the Milky Way galaxy emit continuous and nearly monochromatic GW signals in the source frame.
  - These Galactic Binaries comprise primarily <u>white dwarfs</u> but also <u>neutron stars</u> and <u>stellar-origin black holes</u> in various combinations.
  - Several *verification binaries* are currently known for which joint gravitational and electromagnetic observations can be done and many more will be discovered in the coming years, e.g., by Gaia and LSST.

The ESA-L3 mission (LISA)

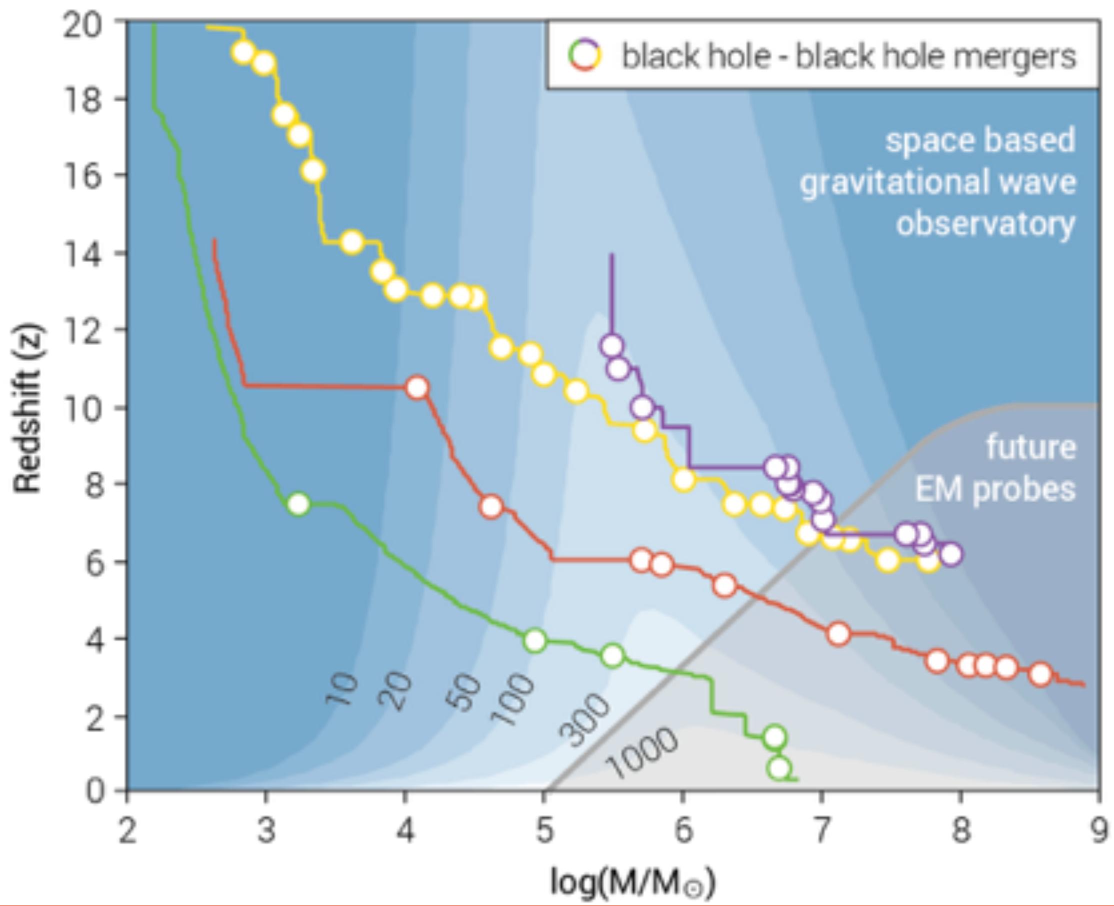
- **SO1**: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.

- **SI1.1**: Elucidate the formation and evolution of Galactic Binaries by measuring their period, spatial and mass distributions.

- **SI1.2**: Enable joint gravitational and electromagnetic observations of GBs to study the interplay between gravitational radiation and tidal dissipation in interacting stellar systems.

The ESA-L3 mission (LISA)

- **SO2**: Trace the origin, growth and merger history of massive black holes across cosmic ages.
  - The origin of Massive Black Holes (MBHs) powering active nuclei and lurking at the centres of today's galaxies is unknown.
  - They grow from seeds to the current MBHs by accretion episodes, and by repeated merging, thus participating in the clustering of cosmic structures, inevitably crossing the entire LISA frequency spectrum.



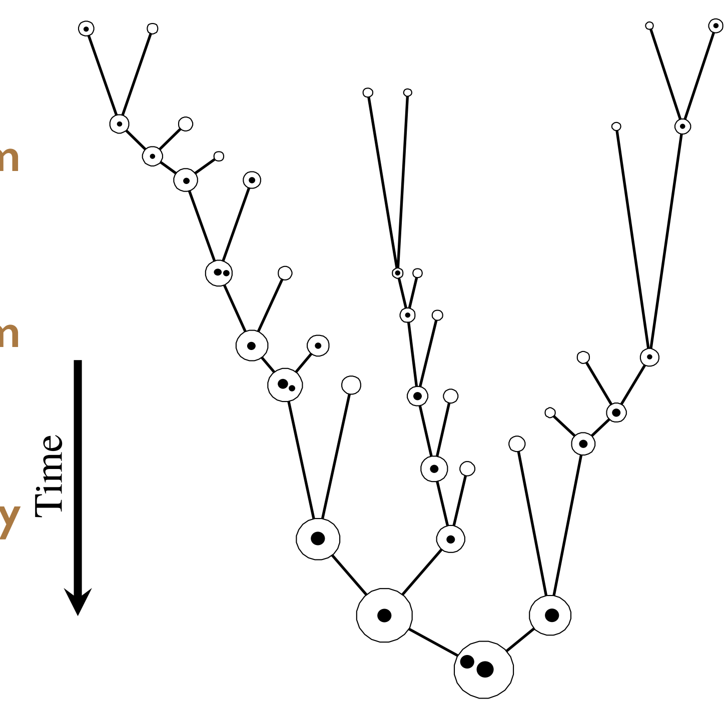
The tracks show the mass-redshift evolution of selected supermassive black holes:

- BH powering a QSO at z=6 starting from a massive seed (blue).

- BH powering a QSO at z=6 starting from a collapsed Pop III seed (yellow).

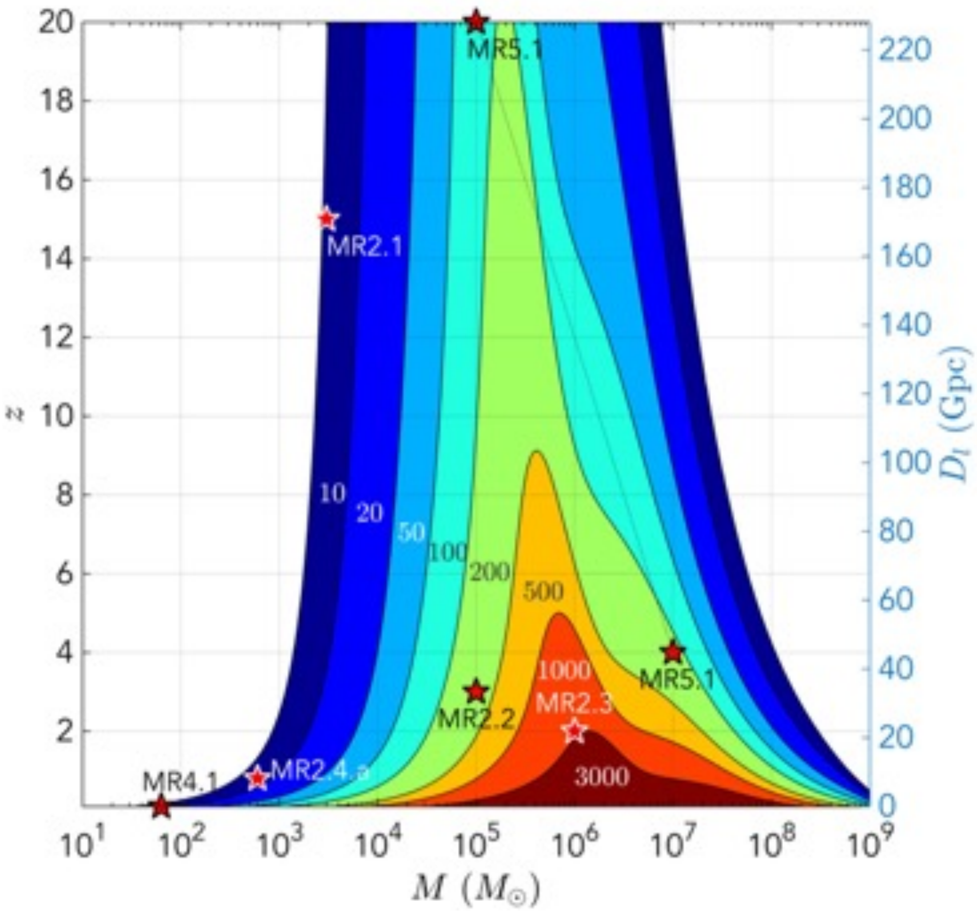
- Typical 10^9 M⊙ in a giant elliptical galaxy (red).

- A Milky Way type black hole (green).



The ESA-L3 mission (LISA)

- **SO2**: Trace the origin, growth and merger history of massive black holes across cosmic ages.
  - Mergers and accretion influence their spins in different ways thus informing us about their way of growing.
  - The GW signal is transient, lasting from months to days down to hours. The signal encodes information on the inspiral and merger of the two spinning MBHs and the ring-down of the new MBH that formed.



Massive black hole binary coalescences: Contours of constant SNR for the baseline observatory in the plane of total source-frame mass, M, and redshift, z (left margin assuming Planck cosmology), and luminosity distance, D_L (right margin), for binaries with constant mass ratio of q = 0.2.

The ESA-L3 mission (LISA)

- **SO2**: Trace the origin, growth and merger history of massive black holes across cosmic ages.

  - **SI2.1**: Search for seed black holes at cosmic dawn.

OR2.1 Have the capability to detect the inspiral of MBHBs in the interval between a few $10^3\,M_\odot$ and a few $10^5\,M_\odot$ in the source frame, and formation redshifts between 10 and 15. Enable the measurement of the source frame masses and the luminosity distance with a fractional error of 20% to distinguish formation models.

MR2.1: Ensure the strain sensitivity is better than $1.6\times10^{-20}\,\mathrm{Hz}^{-1/2}$ at 3.5 mHz and $1\times10^{-20}\,\mathrm{Hz}^{-1/2}$ at 9 mHz, to enable the observation of binaries at the low end of this parameter space with a SNR of at least 10. Such a "threshold" system would have a mass of $3000\,M_\odot$, mass ratio $q = 0.2$, and be located at a redshift of 15. All other MBHBs in OR2.1 with masses in the quoted range and mass ratios higher than this and/or at lower redshift, will then be detected with higher SNR yielding better parameter estimation.

The ESA-L3 mission (LISA)

- **SO2**: Trace the origin, growth and merger history of massive black holes across cosmic ages.

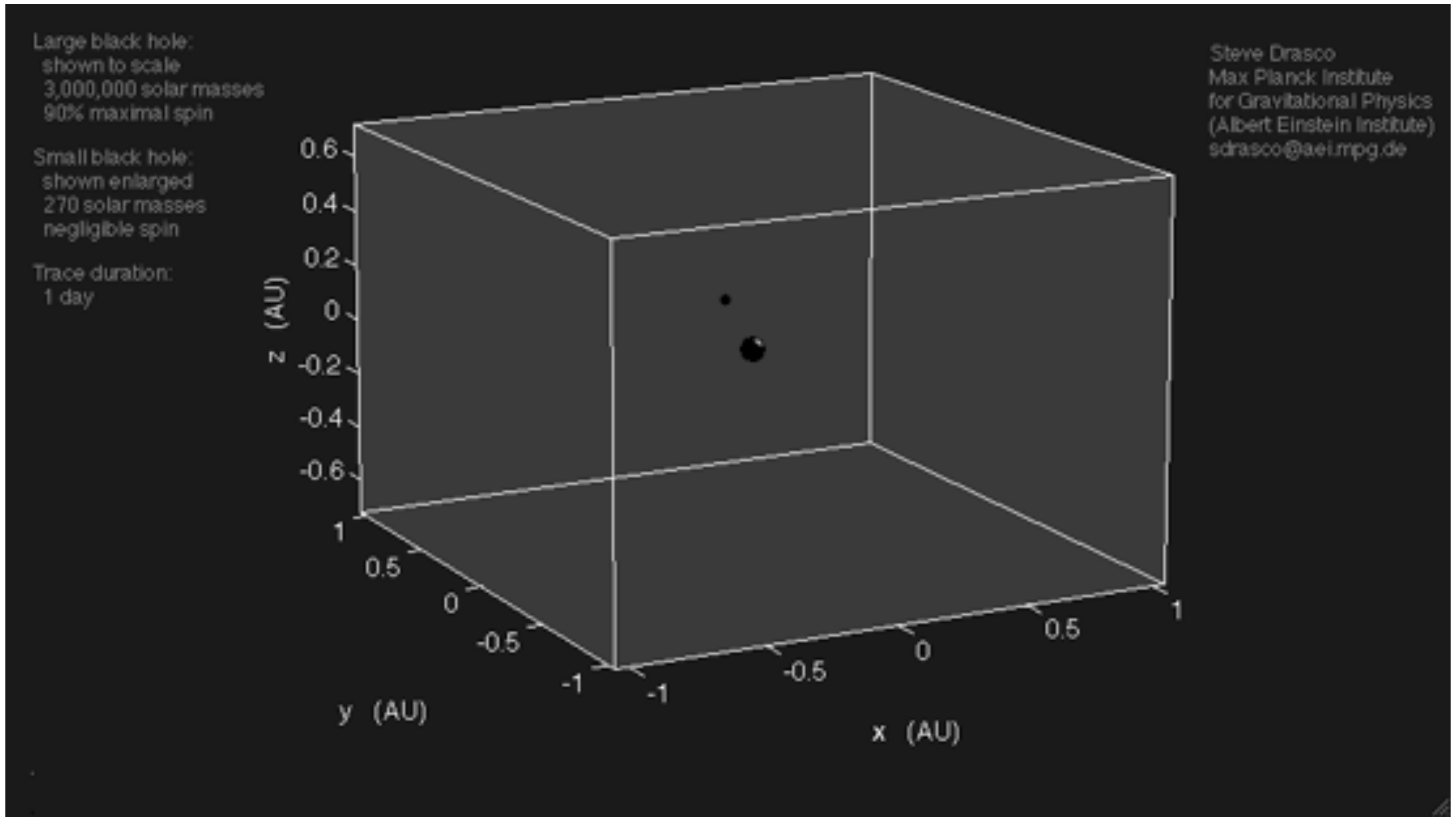
  - **SI2.2**: Study the growth mechanism of MBHs from the epoch of the earliest quasars.

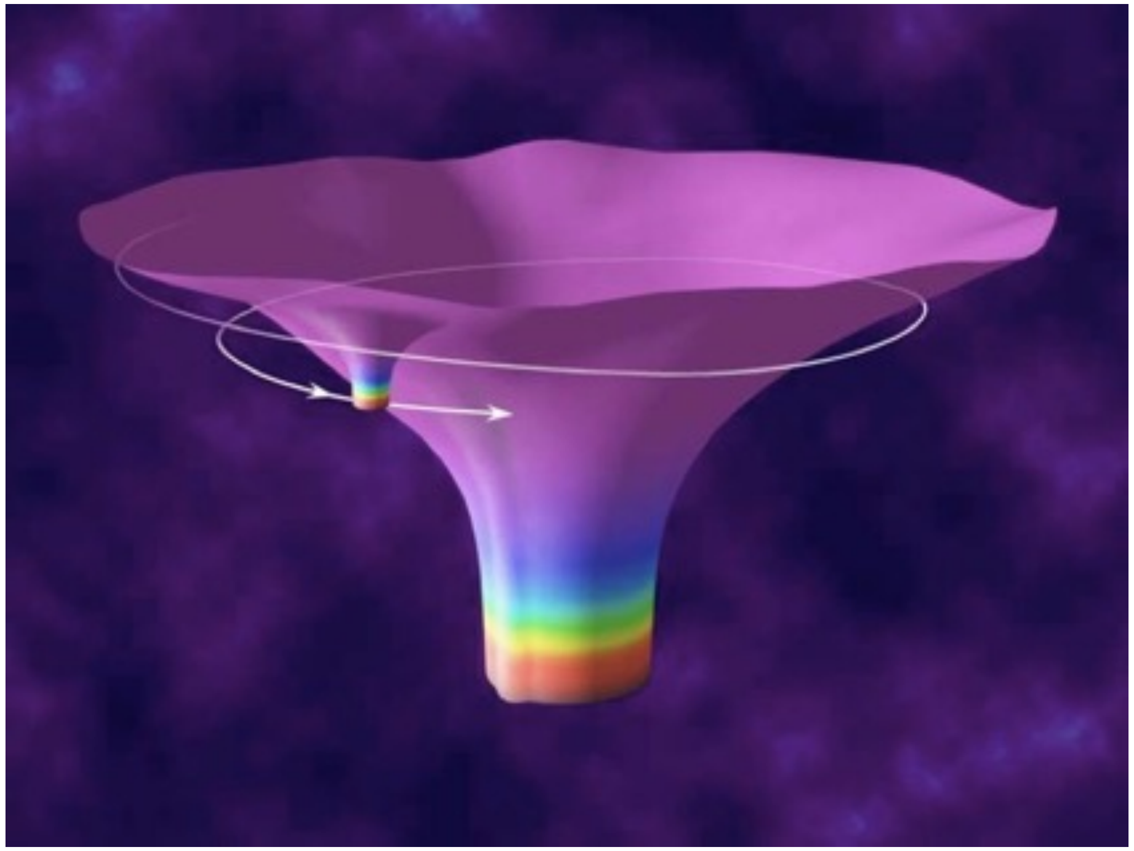
  - **SI2.3**: Observation of Electromagnetic counterparts to unveil the astrophysical environment around merging binaries.

  - **SI2.4**: Test the existence of Intermediate Mass Black Hole Binaries (IMBHBs).

The ESA-L3 mission (LISA)

- **SO3**: Probe the dynamics of dense nuclear clusters using EMRIs.
  - Extreme Mass Ratio Inspirals (EMRIs) describe the long-lasting inspiral (from months to a few years) and plunge of Stellar Origin Black Holes (SOBHs), with mass range 10−60 M⊙, into MBHs of 10^5−10^6M⊙ in the centre of galaxies.
  - The orbits of EMRIs are generic and highly relativistic. The SOBH spends 10^3 − 10^5 orbits in close vicinity of the MBH, and the orbit displays extreme forms of periastron and orbital plane precession.





The ESA-L3 mission (LISA)

- **SO3**: Probe the dynamics of dense nuclear clusters using EMRIs.

- The large number of orbital cycles allows ultra precise measurements of the parameters of the binary system as the GW signal encodes information about the spacetime of the central massive object.

- **SI3.1**: Study the immediate environment of Milky Way like MBHs at low redshift.

The ESA-L3 mission (LISA)

- **SO4**: Understand the astrophysics of stellar origin black holes.

- Following the LIGO discovery of SOBHs in the mass range from 10 to 30 $M_\odot$ merging in binary systems in the nearby Universe, a new science objective arises for LISA, which was not originally part of *The Gravitational Universe*.

- **SI4.1**: Study the close environment of SOBHs by enabling multi-band and multi-messenger observations at the time of coalescence.

- **SI4.2**: Disentangle SOBH binary formation channels.

The ESA-L3 mission (LISA)

- **SO5**: Explore the fundamental nature of gravity and black holes.

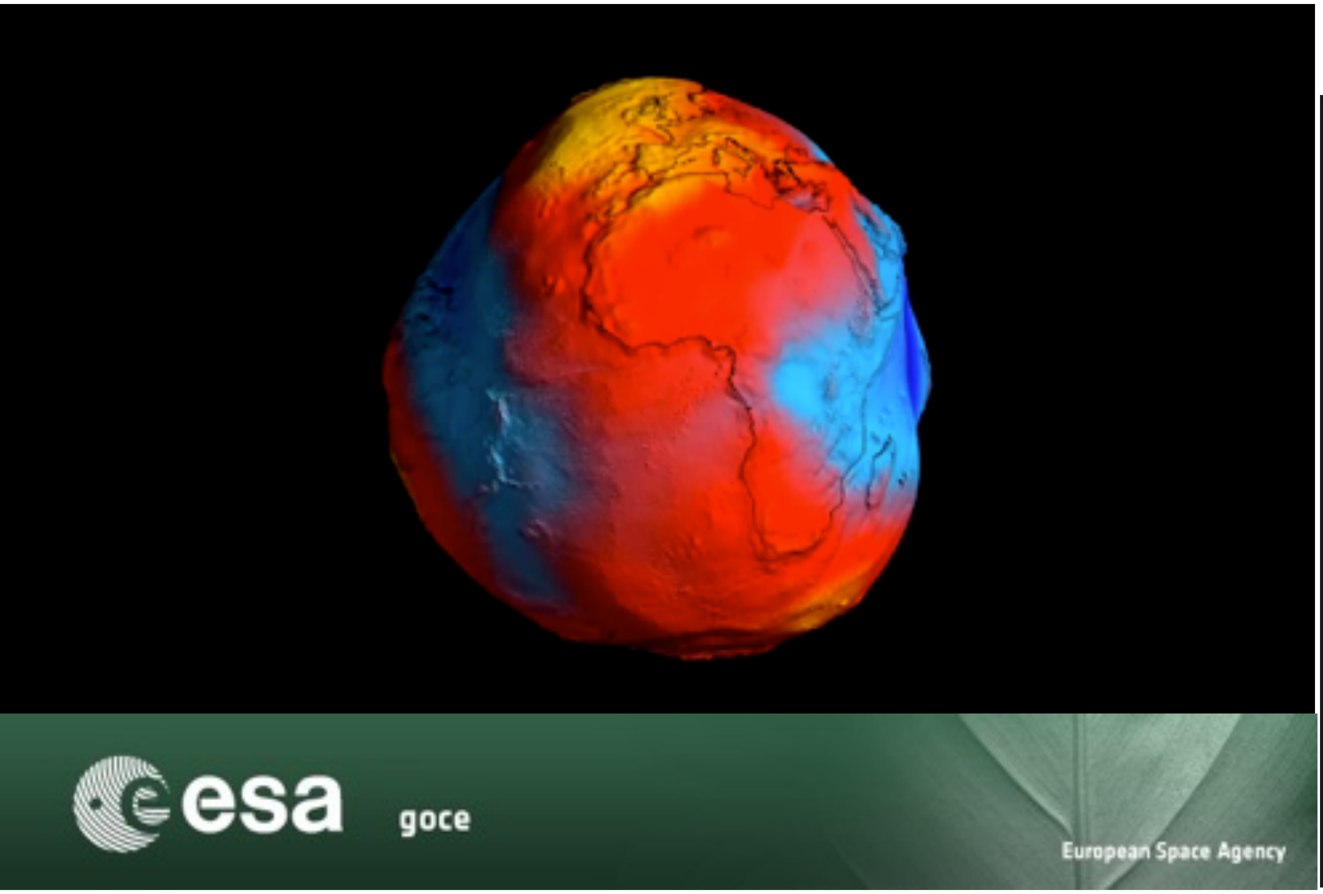
- MBHBs and EMRIs enable us to perform tests of GR in the strong field regime and dynamical sector.

- Precision tests require *Golden Binaries*, that is, MBHBs with very high (> 100) SNR in the post-merger phase or EMRIS with SNR > 50.

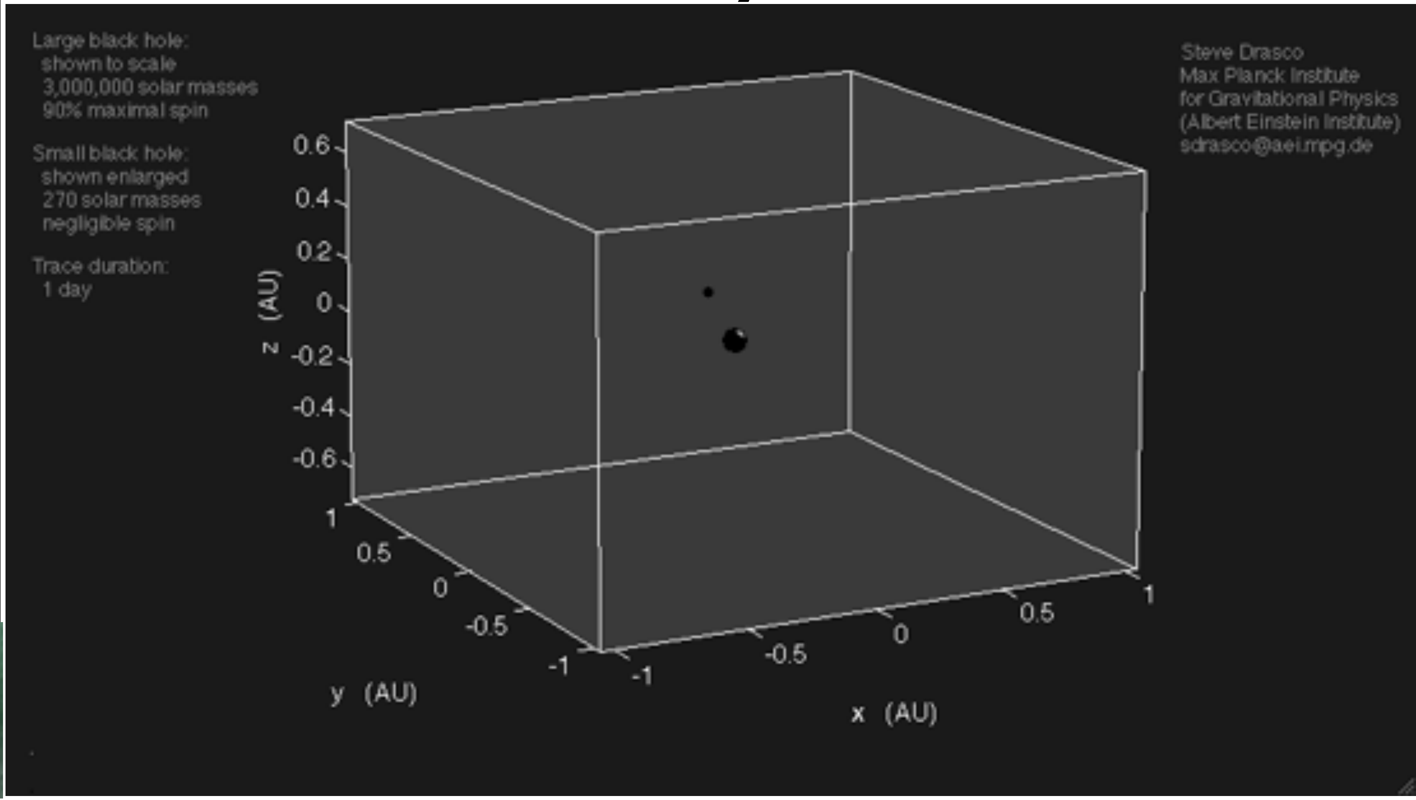
- **SI5.1**: Use ring-down characteristics observed in MBHB coalescences to test whether the post-merger objects are the black holes predicted by GR.

The ESA-L3 mission (LISA)

- **SI5.2:** Use EMRIs to explore the multipolar structure of MBHs.



EMRI System



$$V(\vec{r}) = -G \sum_{\ell\,,m} \frac{M_{\ell m}}{r^{\ell+1}}\, Y_{\ell m}(\theta,\varphi)$$

$M_{\ell m}$: Multipole moments

GOCE can measure up to

$\ell_{\rm MAX} \sim 200$

$\ast$ For a Kerr BH in GR:

$$M_\ell + i\, J_\ell = M_\bullet \left(i\, \frac{S_\bullet}{M_\bullet\, c}\right)^\ell$$

Tests of the Kerr geometry and/or theory of Gravity!

The ESA-L3 mission (LISA)

- **SO5**: Explore the fundamental nature of gravity and black holes.

  - **SI5.3**: Testing for the presence of beyond-GR emission channels.

  - **SI5.4**: Test the propagation properties of GWs.

  - **SI5.5**: Test the presence of massive fields around massive black holes with masses > $10^3 M_\odot$.

The ESA-L3 mission (LISA)

- **SO6**: Probe the rate of expansion of the Universe.

- LISA will probe the expansion of the Universe using GW sirens at high redshifts: SOBH binaries ($z < 0.2$), EMRIs ($z < 1.5$), MBHBs ($z < 6$).

- **SI6.1**: Measure the dimensionless Hubble parameter by means of GW observations only.

- **SI6.2**: Constrain cosmological parameters through joint GW and EM observations.

The ESA-L3 mission (LISA)

- **SO7**: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics.

- One of the LISA goals is the direct detection of a stochastic GW background of cosmological origin (like for example the one produced by a first-order phase transition around the TeV scale) and stochastic foregrounds.

- The shape of the signal gives an indication of its origin, while an upper limit allows to constrain models of the early Universe and particle physics beyond the standard model.

- **SI7.1**: Characterise the astrophysical stochastic GW background.

- **SI7.2**: Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background.

The ESA-L3 mission (LISA)

- **SO8**: Search for GW bursts and unforeseen sources.

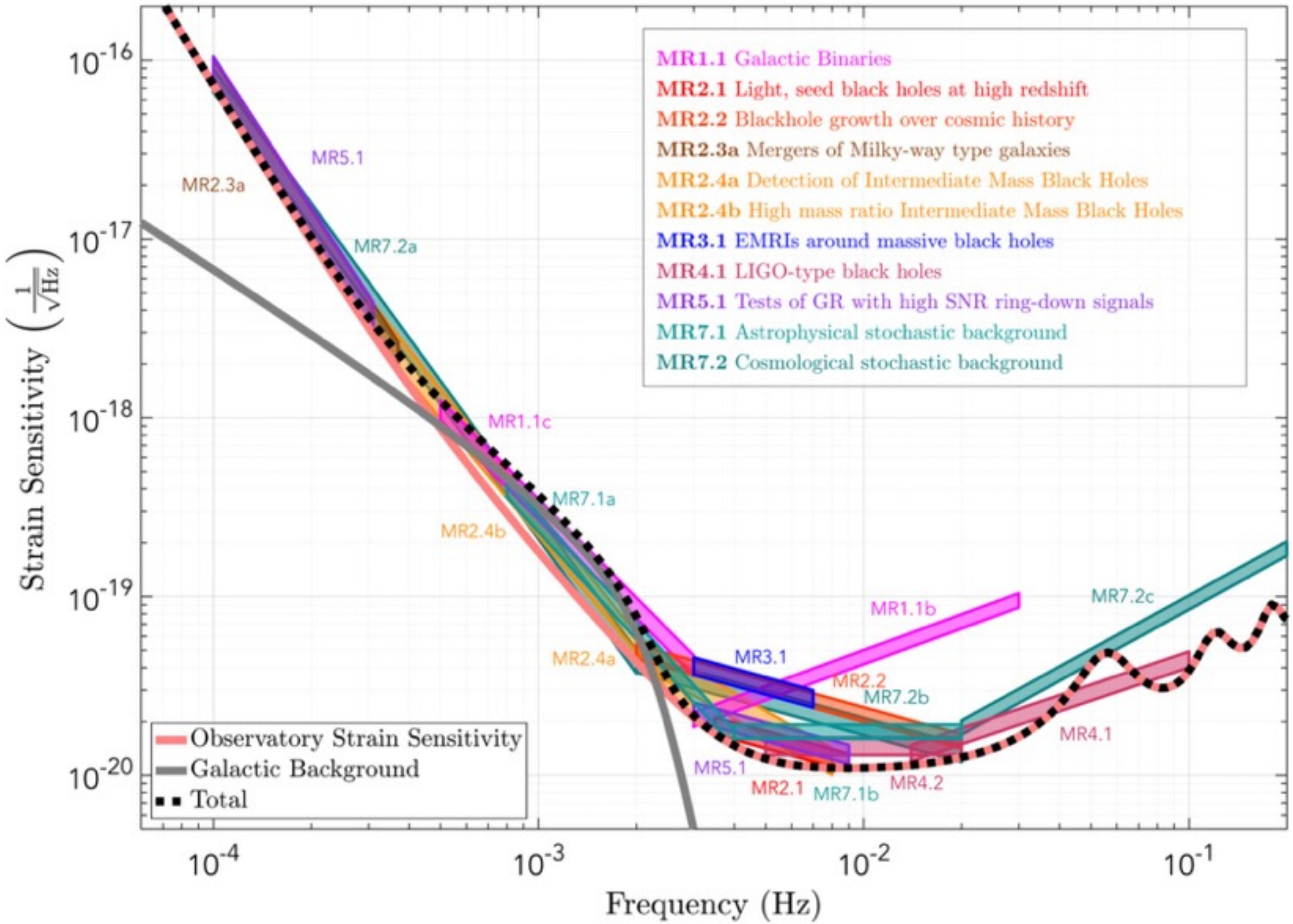
- LISA will lead us into uncharted territory, with the potential for many new discoveries. Distinguishing unforeseen, unmodelled signals from possible instrumental artifacts will be one of the main challenges of the mission, and will be crucial in exploring new astrophysical systems or unexpected cosmological sources.

- **SI8.1**: Search for cusps and kinks of cosmic strings.

- **SI8.2**: Search for unmodelled sources.

The ESA-L3 mission (LISA)

- Final LISA Mission Requirements:



Conclusions

Conclusions

- LISA will be the first ever mission to survey the entire Universe with Gravitational Waves.

- LISA will allow us:
  To investigate the formation of binary systems in the Milky Way;
  to detect the guaranteed signals from the verification binaries;
  to study the history of the Universe out to redshifts beyond 20, when the Universe was less than 200 million years old;
  to test gravity in the dynamical sector and strong-field regime with unprecedented precision;
  and to probe the early Universe at TeV energy scales.

- LISA will play a unique and prominent role in the scientific landscape of the 2030s.

Thanks for your Attention!