THE LISA MISSION

ESA | NASA
lisa

Carlos F. Sopuerta

Institute of Space Sciences (ICE, CSIC & IEEC)

CSIC

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Institute of Space Sciences

IEEC

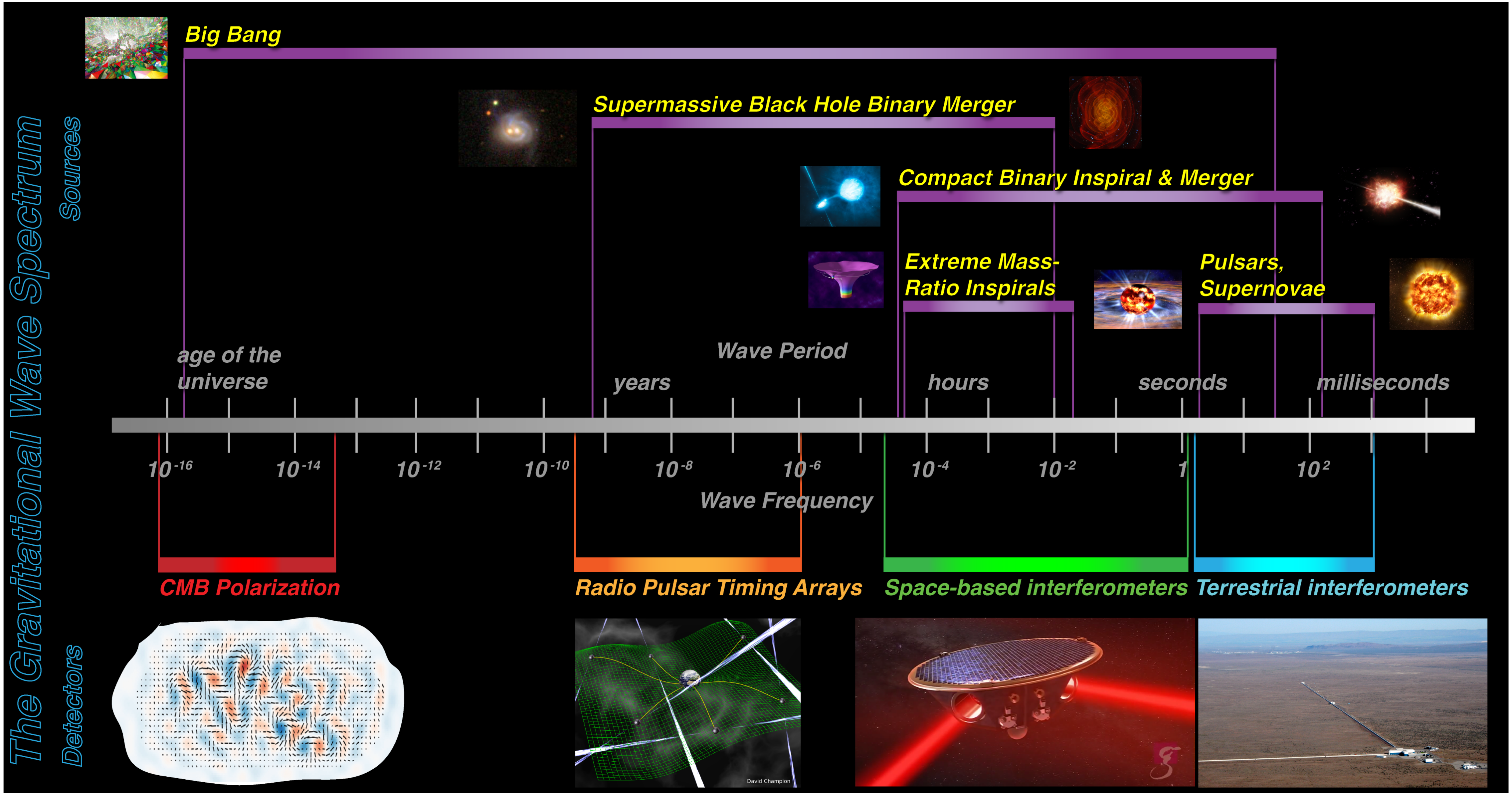
EXCELENCIA MARÍA DE MAEZTU

INDEX

- Basics of LISA (after adoption)
- How did we get here?
- Sources of Gravitational Waves for LISA
- The Science of LISA
- LISA Scientific Operations
- Conclusions

Carlos F. Sopuerta
carlos.f.sopuerta@csic.es
Institute of Space Sciences
(ICE, CSIC & IEEC)

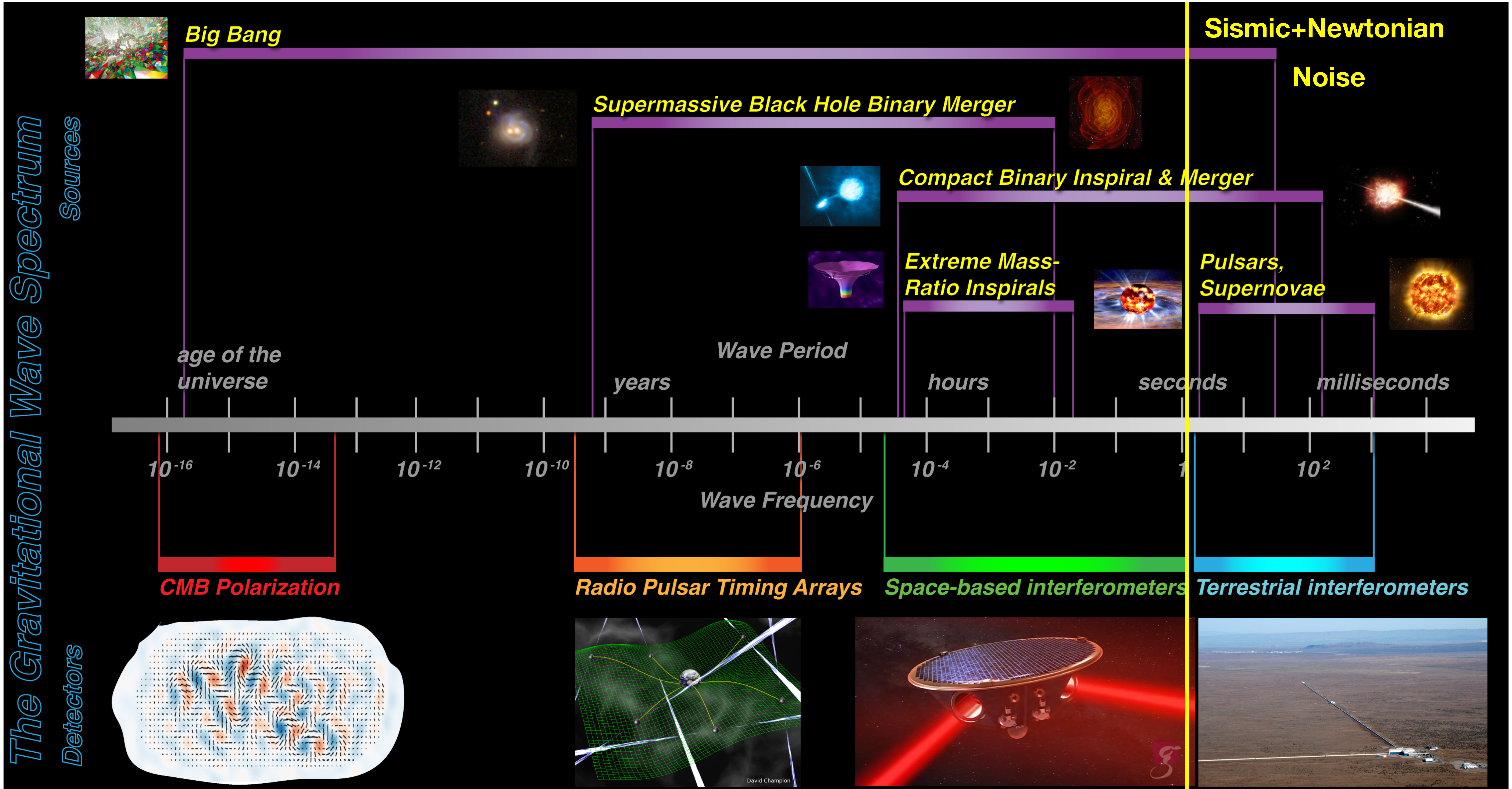
Basics of LISA



$$f_{\rm GW} \downarrow \quad (\lambda_{\rm GW} \uparrow) \quad \Longrightarrow \quad L_{\rm arm} \uparrow \quad M_{\rm GW-source} \uparrow$$

Credit: Ira Thorpe (NASA)

Basics of LISA

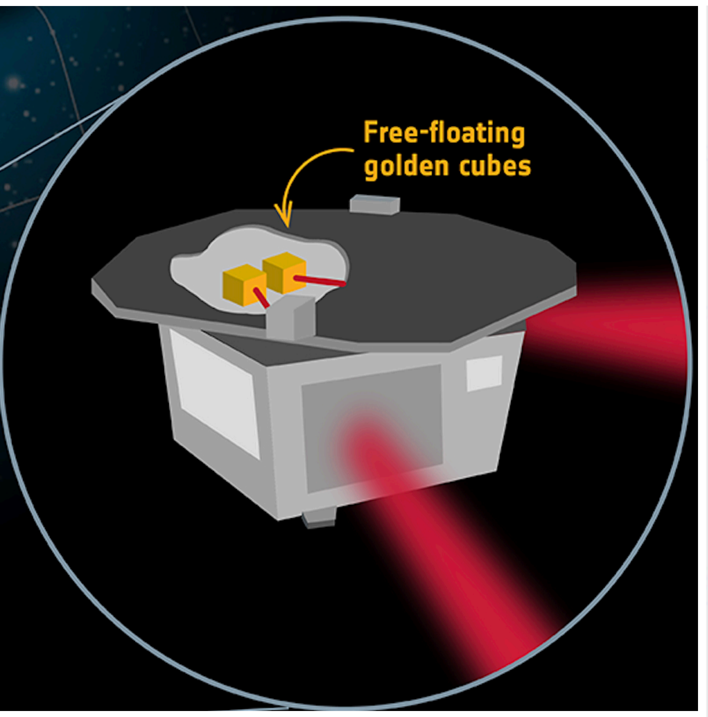


$f_{\rm GW} \downarrow \quad (\lambda_{\rm GW} \uparrow) \quad \Longrightarrow \quad L_{\rm arm} \uparrow \quad M_{\rm GW-source} \uparrow$

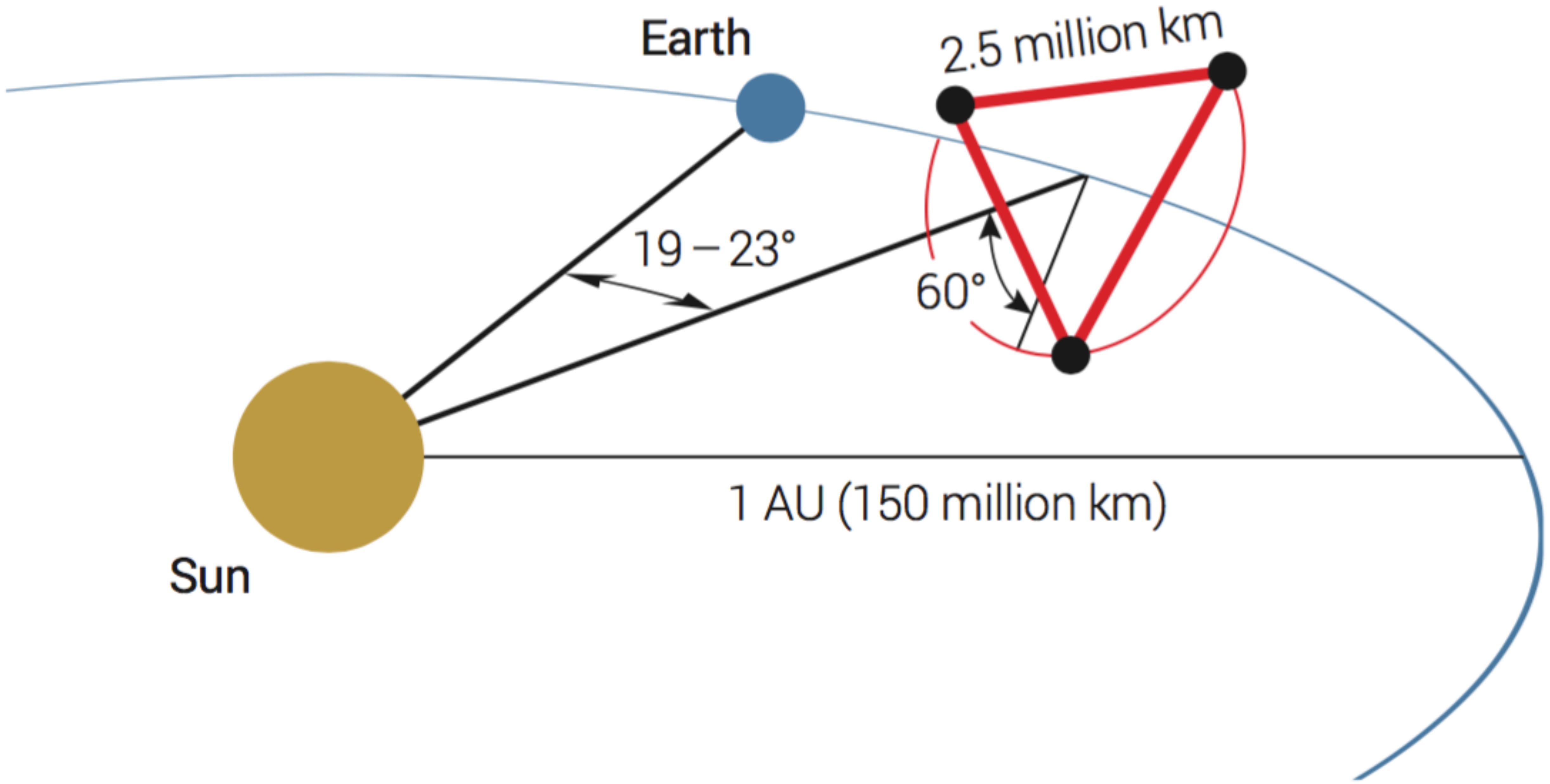
Credit: Ira Thorpe (NASA)

0.1 mHz < f < 1 Hz   Basics of LISA (according to MAR)

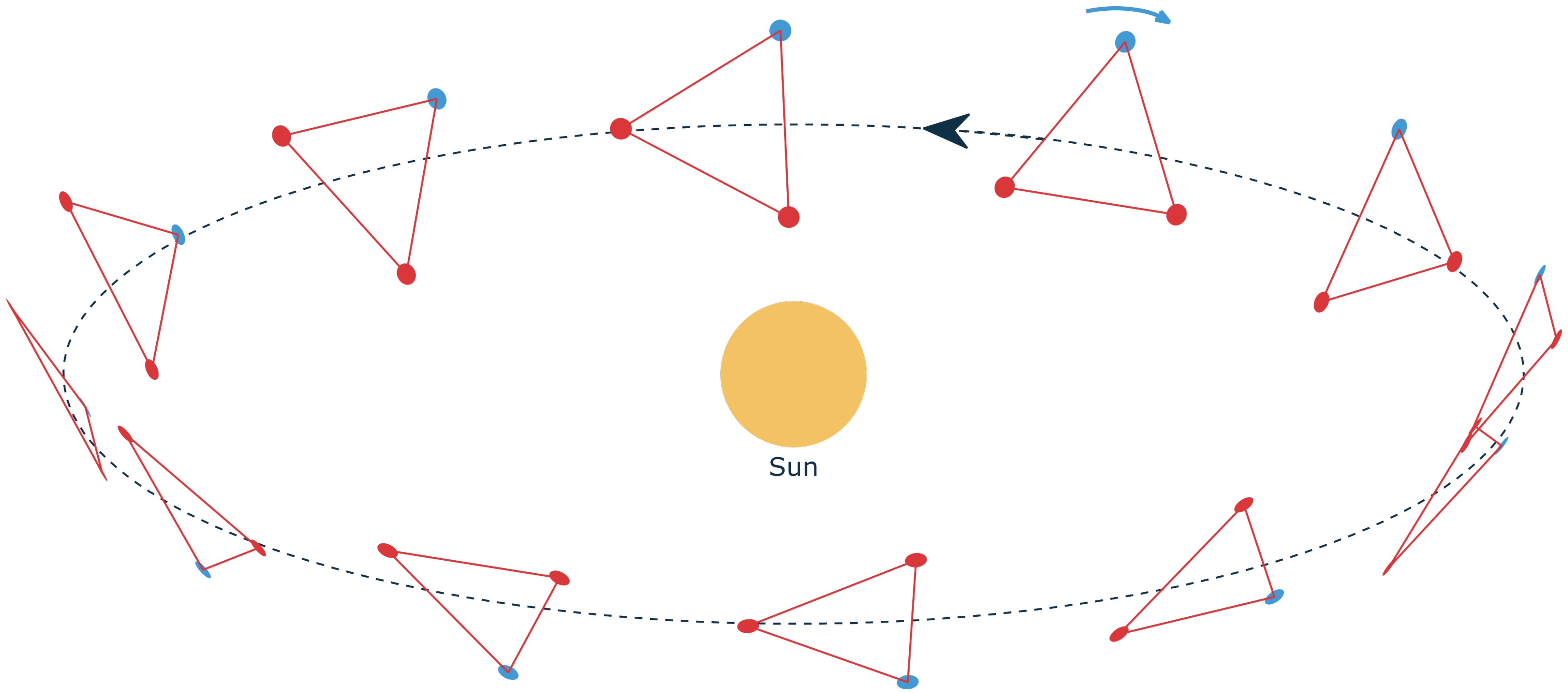
Mission adopted in 2024. Expected Launch in 2035.



Mission	
Duration	4.5 years science orbit • >82 % duty cycle • ~6.25 years including transfer and commissioning
Constellation	Three drag-free satellites forming an equilateral triangle • 2.5×10^6 km separation • trailing/leading Earth by ~20° • inclined by 60° with respect to the ecliptic
Orbits	Heliocentric orbits • semimajor axis ~1 AU • eccentricity $e \approx 0.0096$ • inclination $i \approx 0.96°$



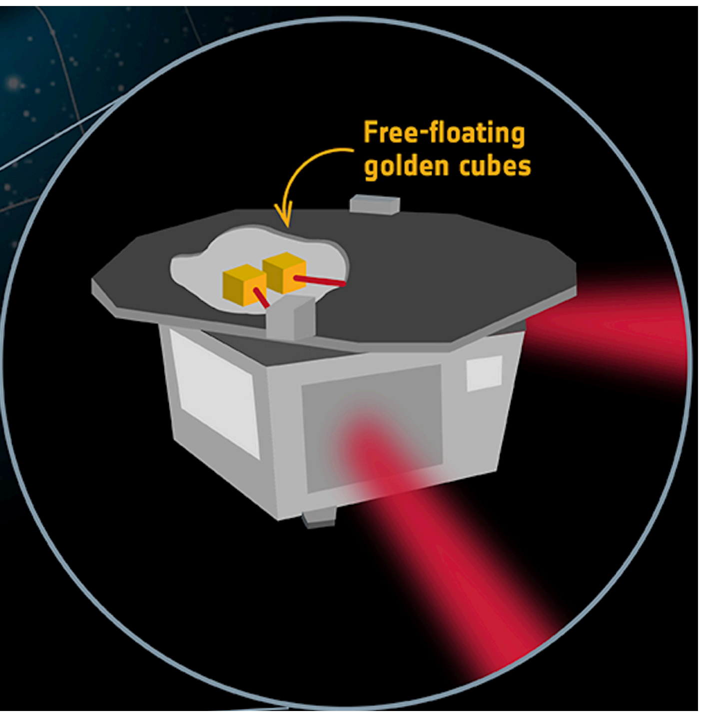
Passive Orbits

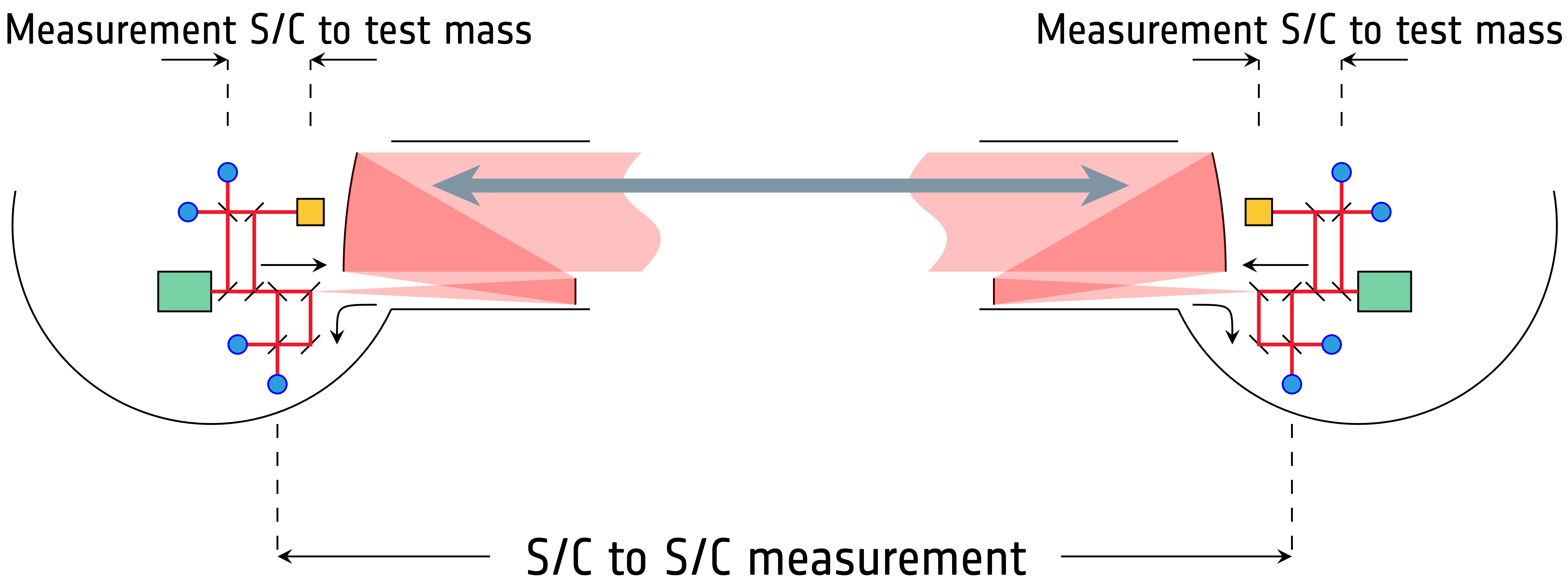


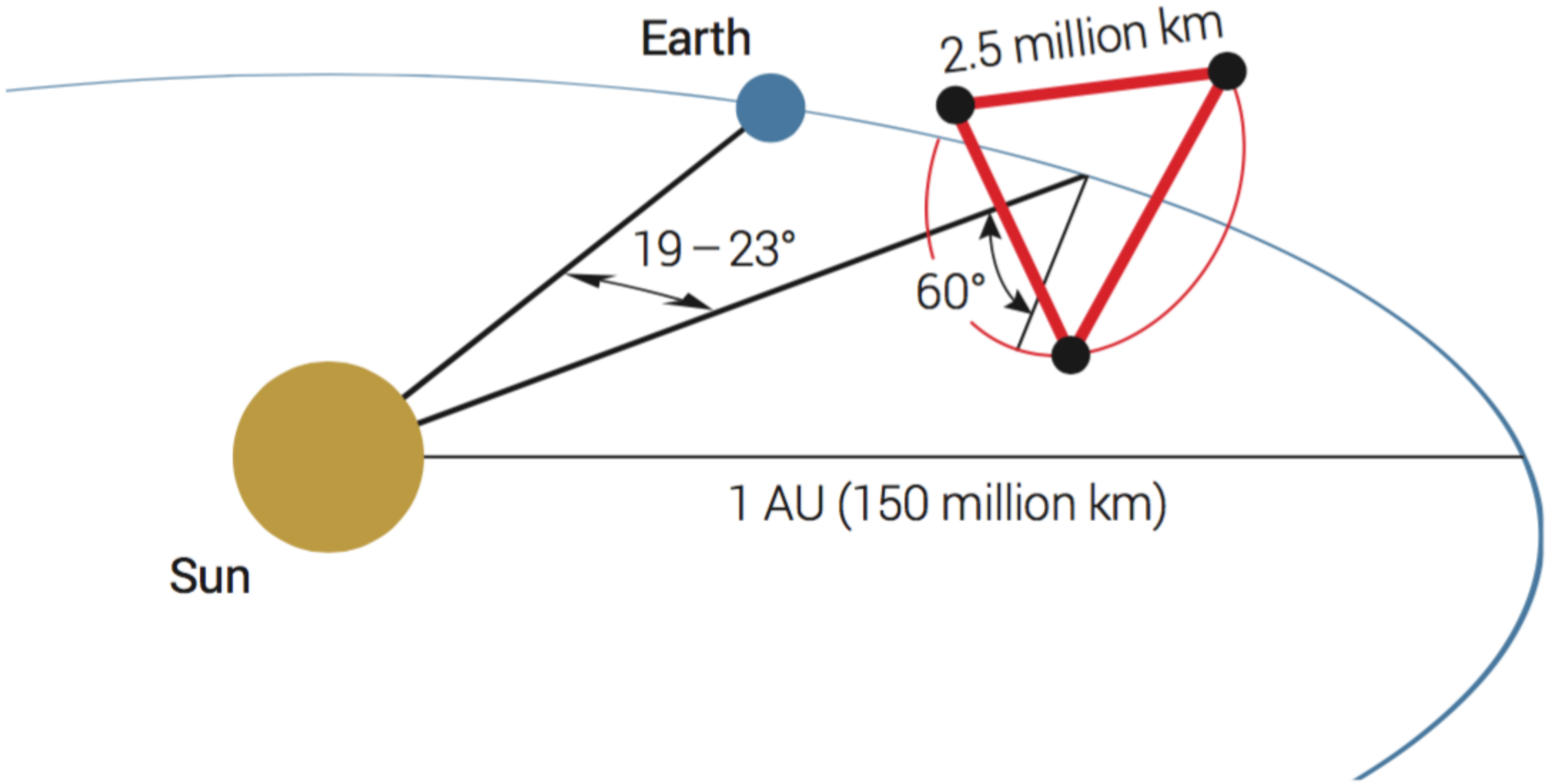
Carlos F. Sopuerta
carlos.f.sopuerta@csic.es
Institute of Space Sciences (ICE, CSIC & IEEC)

0.1 mHz < f < 1 Hz

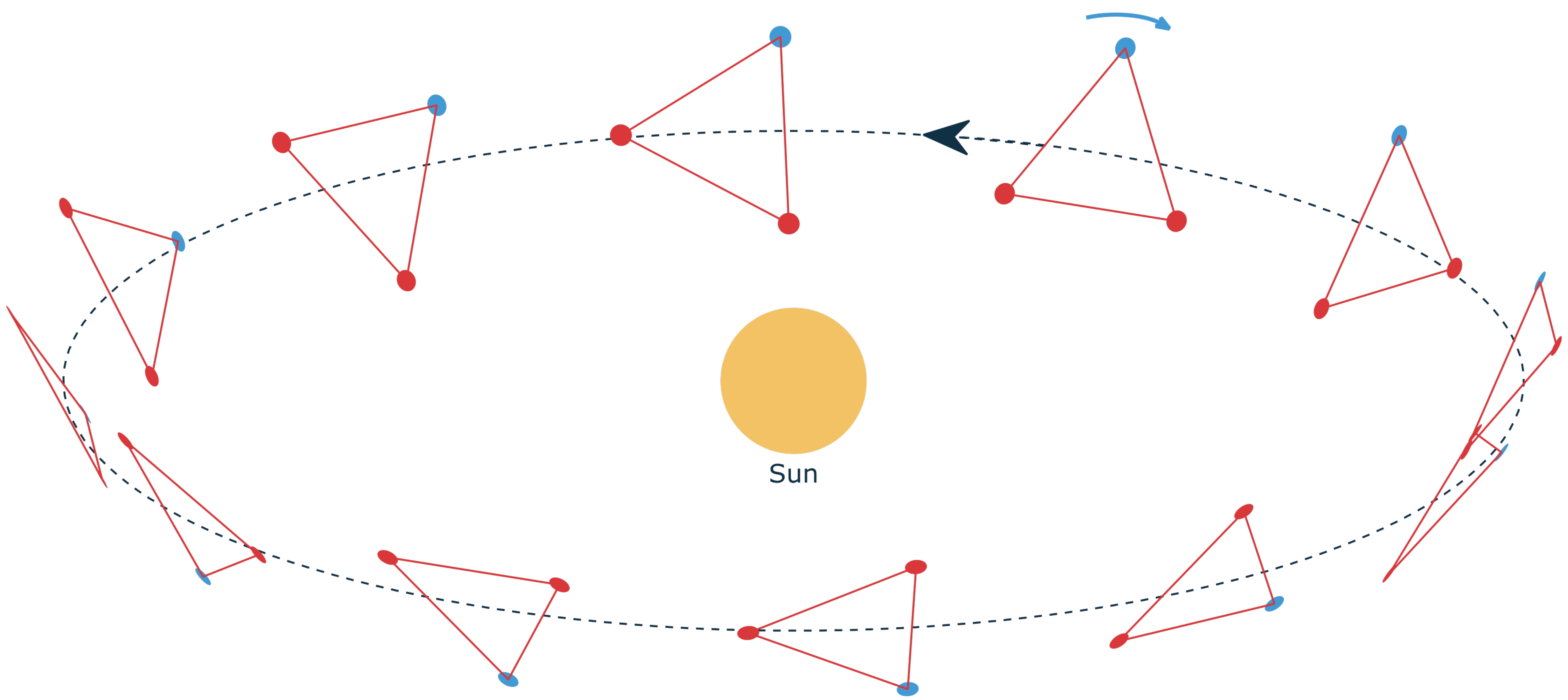
Basics of LISA (according to MAR)







Passive Orbits



Basics of LISA

Main Players

ESA (Lead)	NASA	ESA Member States / Consortium
▪ Mission Implementation Responsibility ▪ Mission Architect ▪ Space Segment ▪ Ground Segment ▪ Launcher ▪ Overall System Engineering ▪ Platform Hardware	▪ Partner to ESA ▪ Telescopes ▪ Laser Systems ▪ Charge Management Devices ▪ Science Data Processing ▪ Performance and Operations Support	▪ Instrument Hardware Contributions (Gravitational Reference Sensor System, Interferometric Detection System, Data and Diagnostics) ▪ Performance Test GSE ▪ Science Data Processing ▪ Performance and Operations Support

Main Instrumental Contributions

Gravitational Reference System

- GRS Head (IT)
- GRS FEE (CH), FEE PCU (IT)
- GRS MCU (IT)
- CMD (NASA via ESA)

Interferometric Detection System

- Optical Bench (UK)
- ePMS (DE)
- IDS AIVT (FR)
- OB-MCU (NL)
- QPRs (NL+BE)
- BAM (BE)
- FSUA (CZ)
- PAAM (DE – TBC)

Instrument Testing GSE

Data and Diagnostics

Basics of LISA

Main Players

ESA (Lead)	NASA	ESA Member States / Consortium
▪ Mission Implementation Responsibility ▪ Mission Architect ▪ Space Segment ▪ Ground Segment ▪ Launcher ▪ Overall System Engineering ▪ Platform Hardware	▪ Partner to ESA ▪ Telescopes ▪ Laser Systems ▪ Charge Management Devices ▪ Science Data Processing ▪ Performance and Operations Support	▪ Instrument Hardware Contributions (Gravitational Reference Sensor System, Interferometric Detection System, Data and Diagnostics) ▪ Performance Test GSE ▪ Science Data Processing ▪ Performance and Operations Support

Main Instrumental Contributions

- Gravitational Reference System
- Interferometric Detection System
- Instrument Testing GSE
- Data and Diagnostics

AEI + AEE

Key hardware elements procured by ESA's member states include the free-falling test masses shielded from external forces, provided by Italy and Switzerland; the picometer-accuracy systems to detect the interferometric signal, provided by Germany, the UK, France, the Netherlands, Belgium, Denmark and the Czech Republic; **and the Science Diagnostics Subsystem (an arsenal of sensors across the spacecraft), provided by Spain**.

OHB Press Release

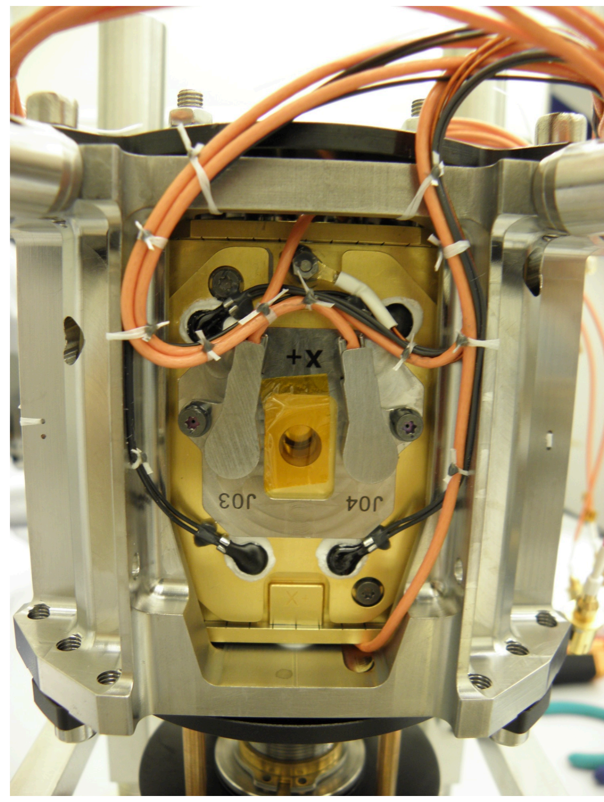
The Science and Diagnostics Subsystem

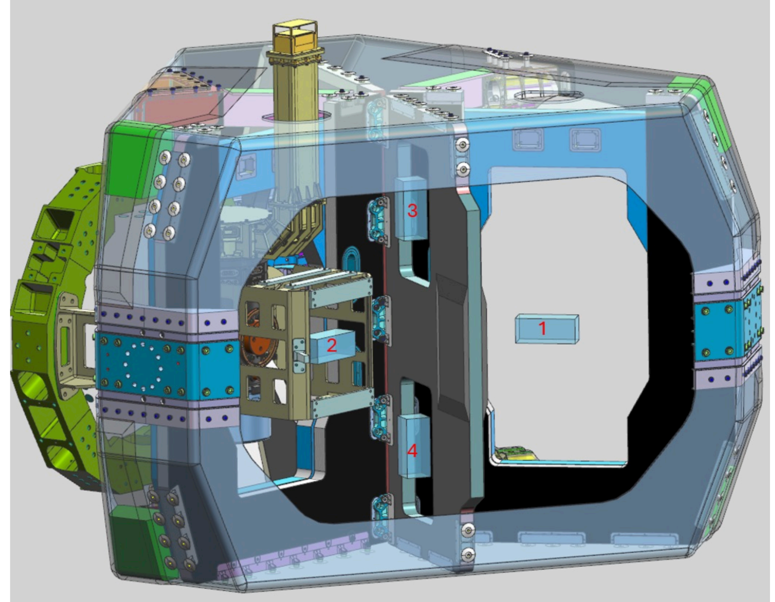
(Heritage of the contribution to LISA Pathfinder)

✳ The primary goal of the **Science Diagnostics Subsystem** (SDS) is to generate scientific information during LISA operations to monitor and characterise the temperature, magnetic and the radiation environment on-board LISA.

144	Temperature sensors	3	Radiation monitors
12	Magnetometers	12	Heaters
3	Audio band EM antennas		

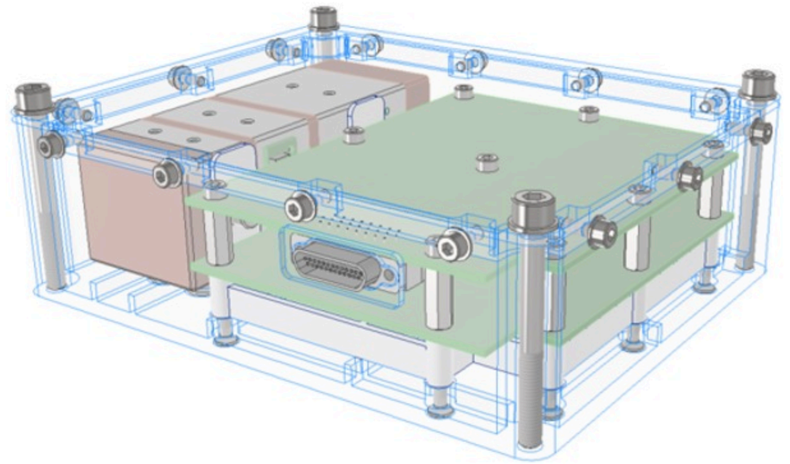
Temperature fluctuations can affect the mission in different ways. From temperature-induced forces in the test mass (radiation pressure, outgassing, etc) to thermo-optical distortions. The Temperature Diagnostics Subsystem will provide a network of high precision sensors to measure these fluctuations on-board (in collaboration with UPC).





Magnetic fluctuations and gradients on-board LISA can couple with the interplanetary magnetic field to produce magnetic-induced forces in the test mass. The SDS will use fluxgate magnetometers and search coils to monitor the magnetic fluctuations on-board.

The **background radiation** can induce charging in the free falling test masses potentially inducing noise in the LISA performance. The objective of the radiation monitor (in collaboration with ICCUB) is to characterise the incoming radiation flux in orbit.



Carlos F. Sopuerta
carlos.f.sopuerta@csic.es
Institute of Space Sciences
(ICE, CSIC & IEEC)

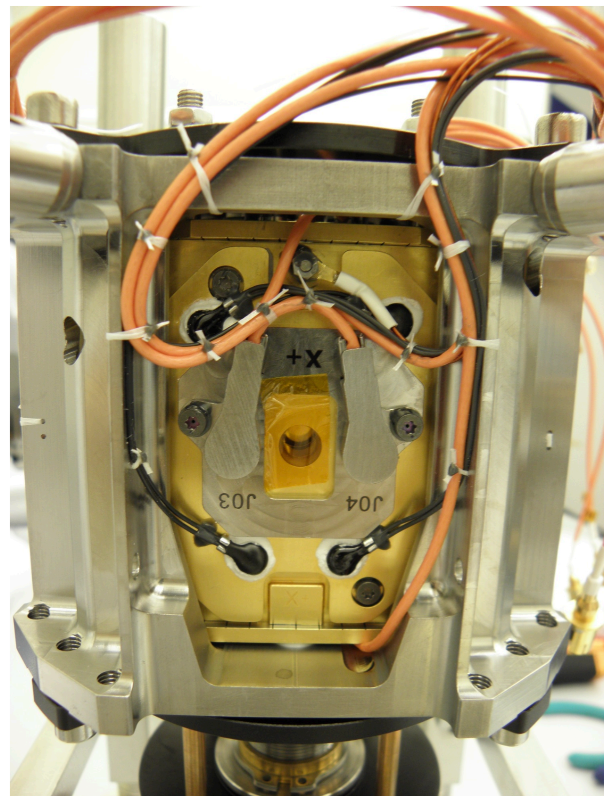
The Science and Diagnostics Subsystem

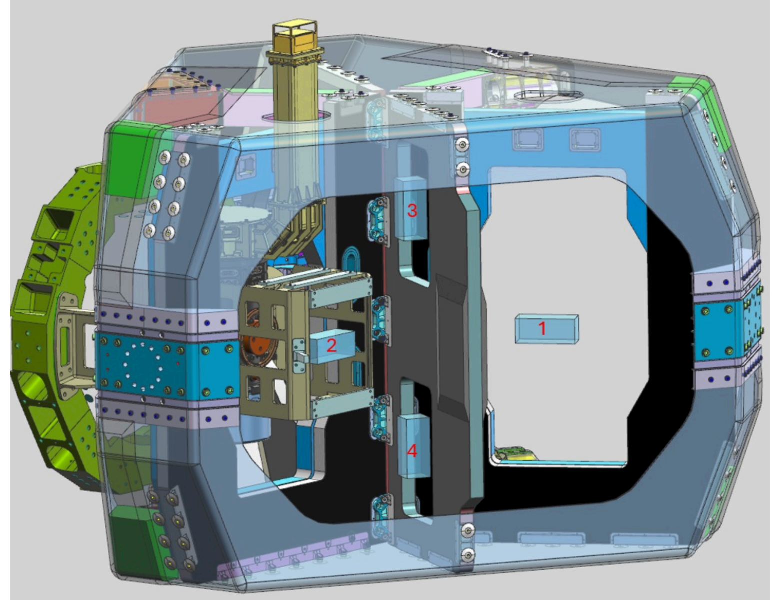
(Heritage of the contribution to LISA Pathfinder)

✴ The primary goal of the **Science Diagnostics Subsystem** (SDS) is to generate scientific information during LISA operations to monitor and characterise the temperature, magnetic and the radiation environment on-board LISA.

144	Temperature sensors	3	Radiation monitors
12	Magnetometers	12	Heaters
3	Audio band EM antennas		

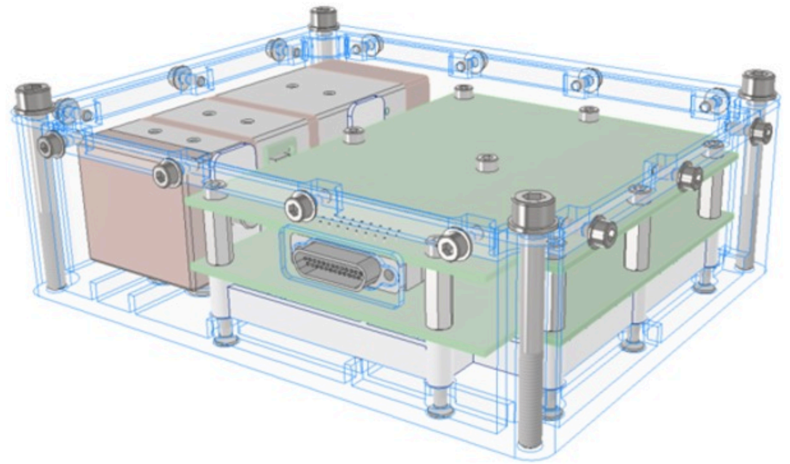
Temperature fluctuations can affect the mission in different ways. From temperature-induced forces in the test mass (radiation pressure, outgassing, etc) to thermo-optical distortions. The Temperature Diagnostics Subsystem will provide a network of high precision sensors to measure these fluctuations on-board (in collaboration with UPC).





Magnetic fluctuations and gradients on-board LISA can couple with the interplanetary magnetic field to produce magnetic-induced forces in the test mass. The SDS will use fluxgate magnetometers and search coils to monitor the magnetic fluctuations on-board.

The **background radiation** can induce charging in the free falling test masses potentially inducing noise in the LISA performance. The objective of the radiation monitor (in collaboration with ICCUB) is to characterise the incoming radiation flux in orbit.



How did we get here?

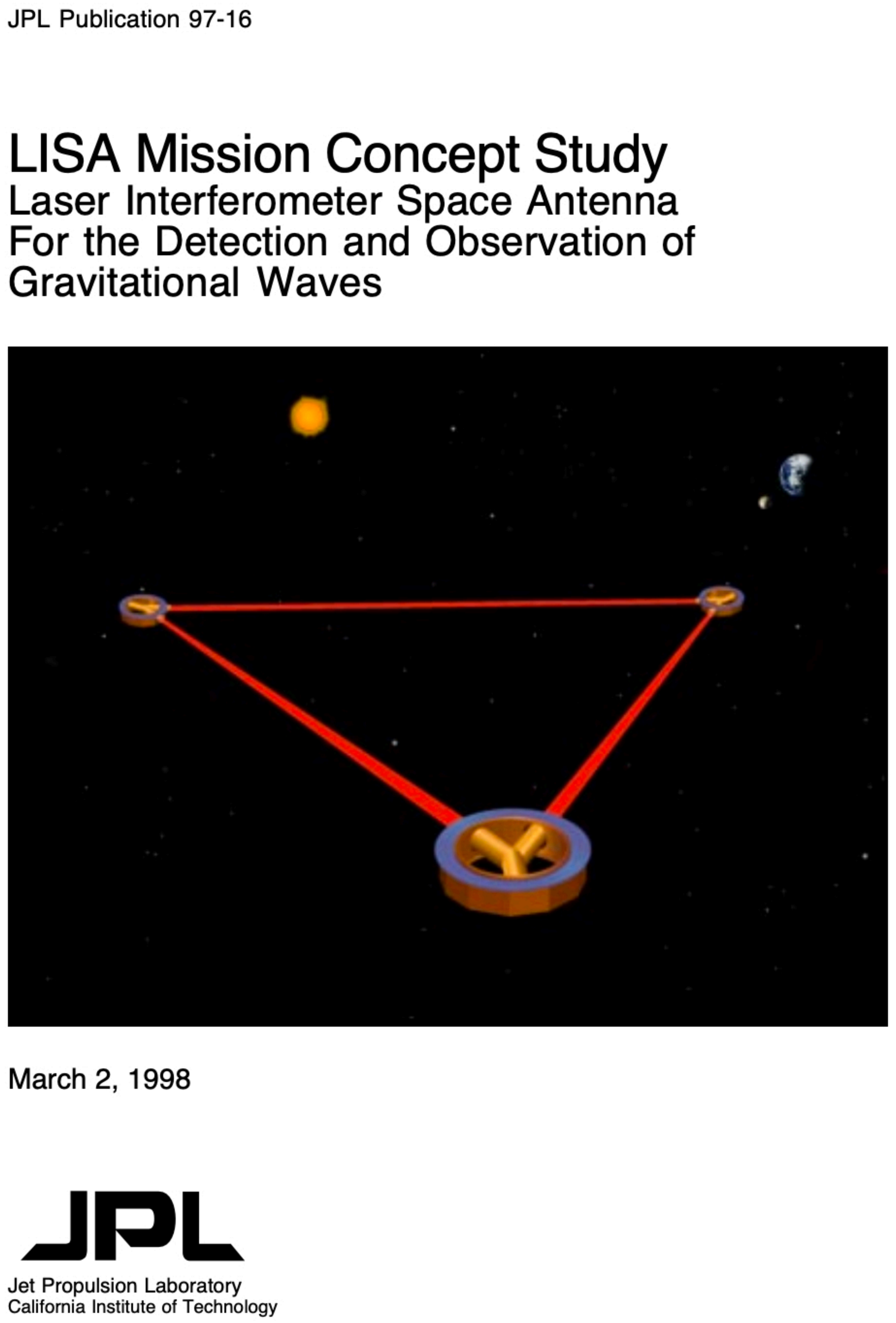
How did we get here?

* **1974-** : First ideas about Gravitational Wave Detection in Space: Bender, Weiss, Drever, etc.

Peter Bender

How did we get here?

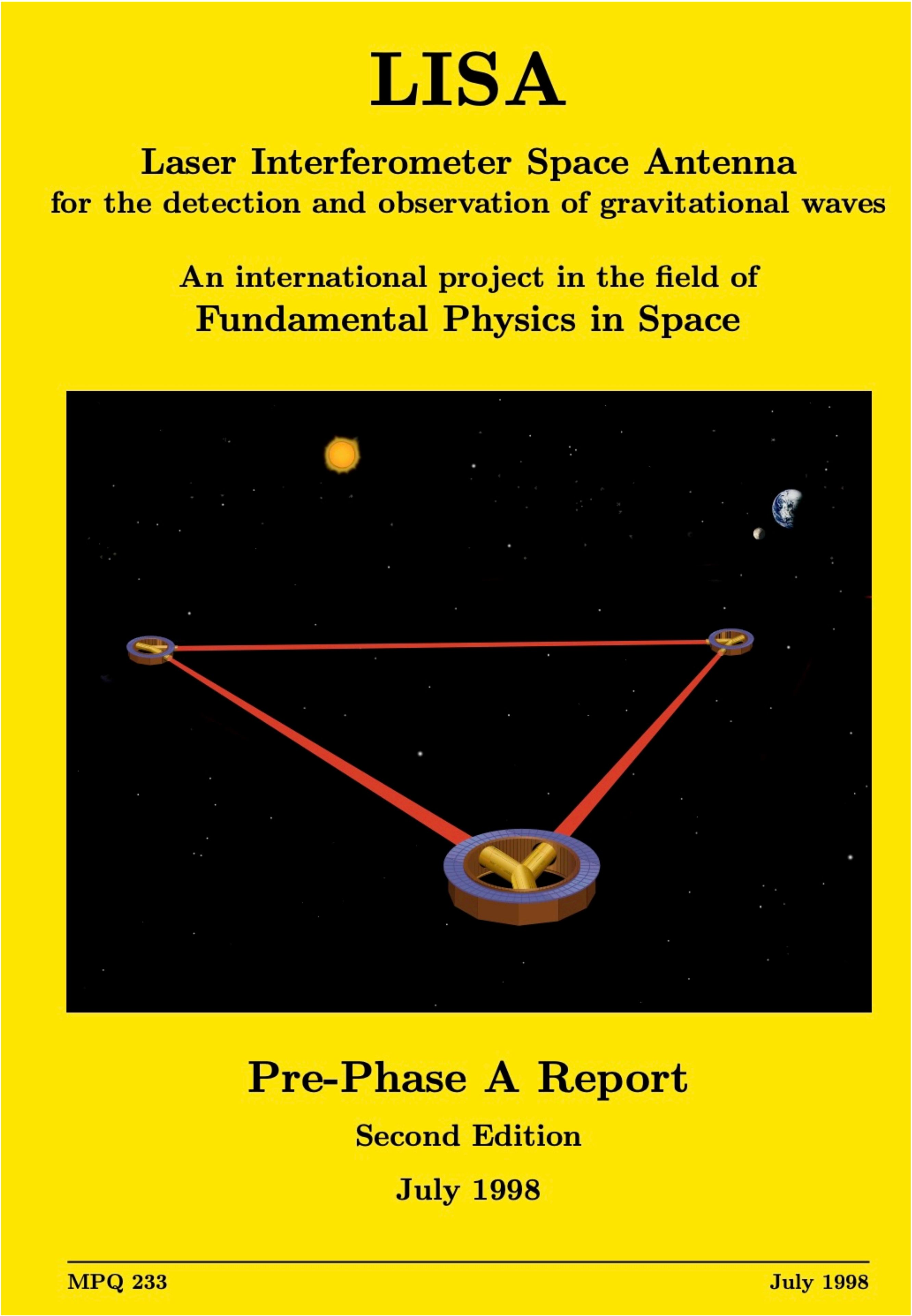
- **1974-** : First ideas about Gravitational Wave Detection in Space: Bender, Weiss, Drever, etc.
- **1998** : First serious LISA studies: JPL and LISA International Team


JPL Publication 97-16

LISA Mission Concept Study
Laser Interferometer Space Antenna
For the Detection and Observation of
Gravitational Waves

March 2, 1998

JPL
Jet Propulsion Laboratory
California Institute of Technology


LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

An international project in the field of
Fundamental Physics in Space

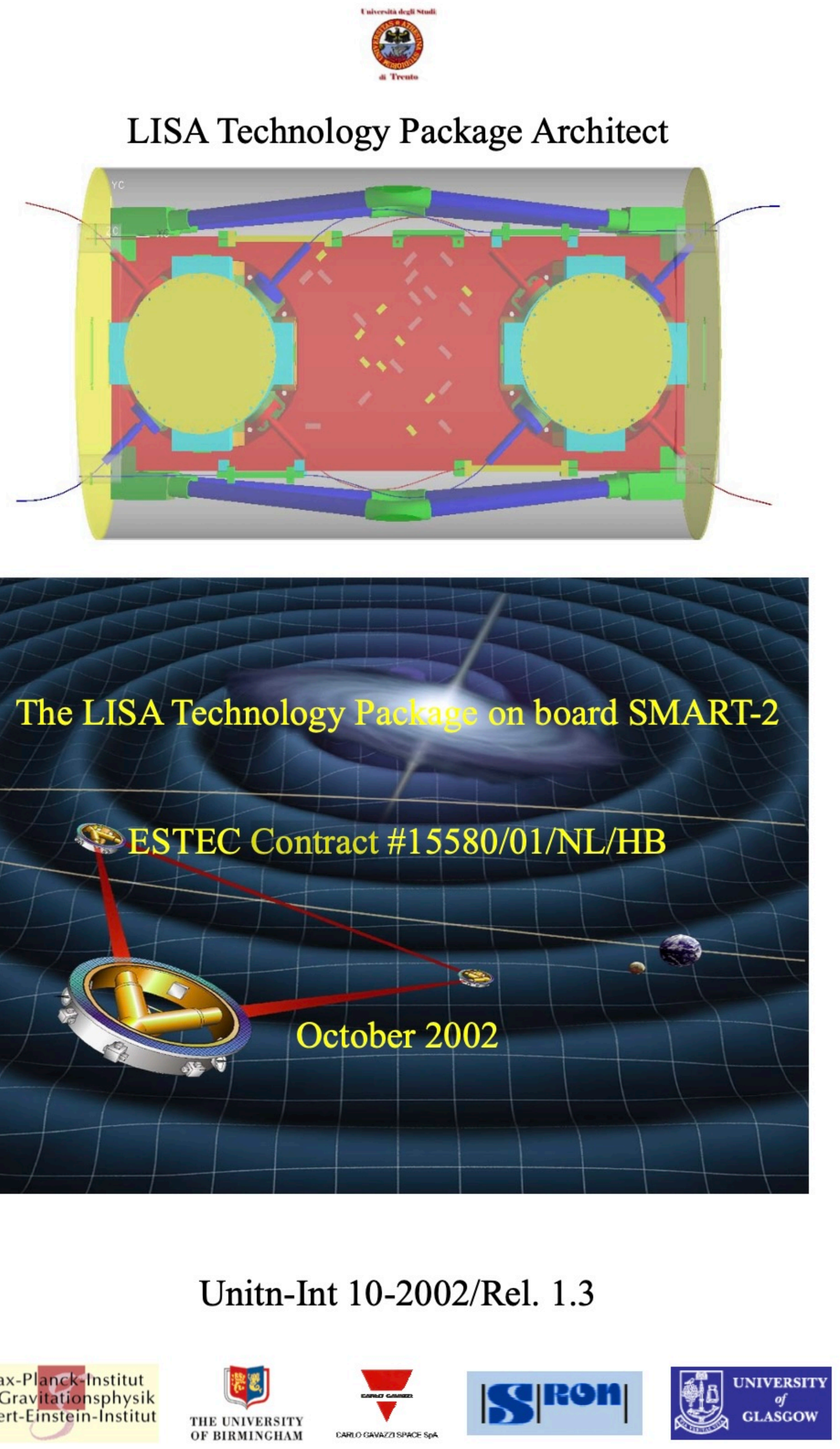
Pre-Phase A Report
Second Edition
July 1998

MPQ 233 July 1998

Carlos F. Sopuerta
carlos.f.sopuerta@csic.es
Institute of Space Sciences
(ICE, CSIC & IEEC)

How did we get here?

- **1974-** : First ideas about Gravitational Wave Detection in Space: Bender, Weiss, Drever, etc.
- **1998** : First serious LISA studies: JPL and LISA International Team
- **2001** : LISA Pathfinder mission to demonstrate LISA main technology



How did we get here?

- **1974-** : First ideas about Gravitational Wave Detection in Space: Bender, Weiss, Drever, etc.
- **1998** : First serious LISA studies: JPL and LISA International Team
- **2001** : LISA Pathfinder mission to demonstrate LISA main technology
- **2004** : Alberto Lobo puts Spain in LISA Pathfinder

Alberto Lobo

How did we get here?

- ✳ **1974-** : First ideas about Gravitational Wave Detection in Space: Bender, Weiss, Drever, etc.
- ✳ **1998** : First serious LISA studies: JPL and LISA International Team
- ✳ **2001** : LISA Pathfinder mission to demonstrate LISA main technology
- ✳ **2004** : Alberto Lobo puts Spain in LISA Pathfinder
- ✳ **2013** : Selection of the science themes for the L2 and L3 missions:

ESA Unclassified – For official use

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

EUROPEAN SPACE AGENCY

SCIENCE PROGRAMME COMMITTEE

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

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

Prof. Dr. Karsten Danzmann
Albert Einstein Institute Hannover
MPI for Gravitational Physics and Leibniz Universität Hannover
Callinstr. 38
30167 Hannover
Germany
karsten.danzmann@aei.mpg.de
Tel.: +49 511 762 2229
Fax: +49 511 762 2784

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.

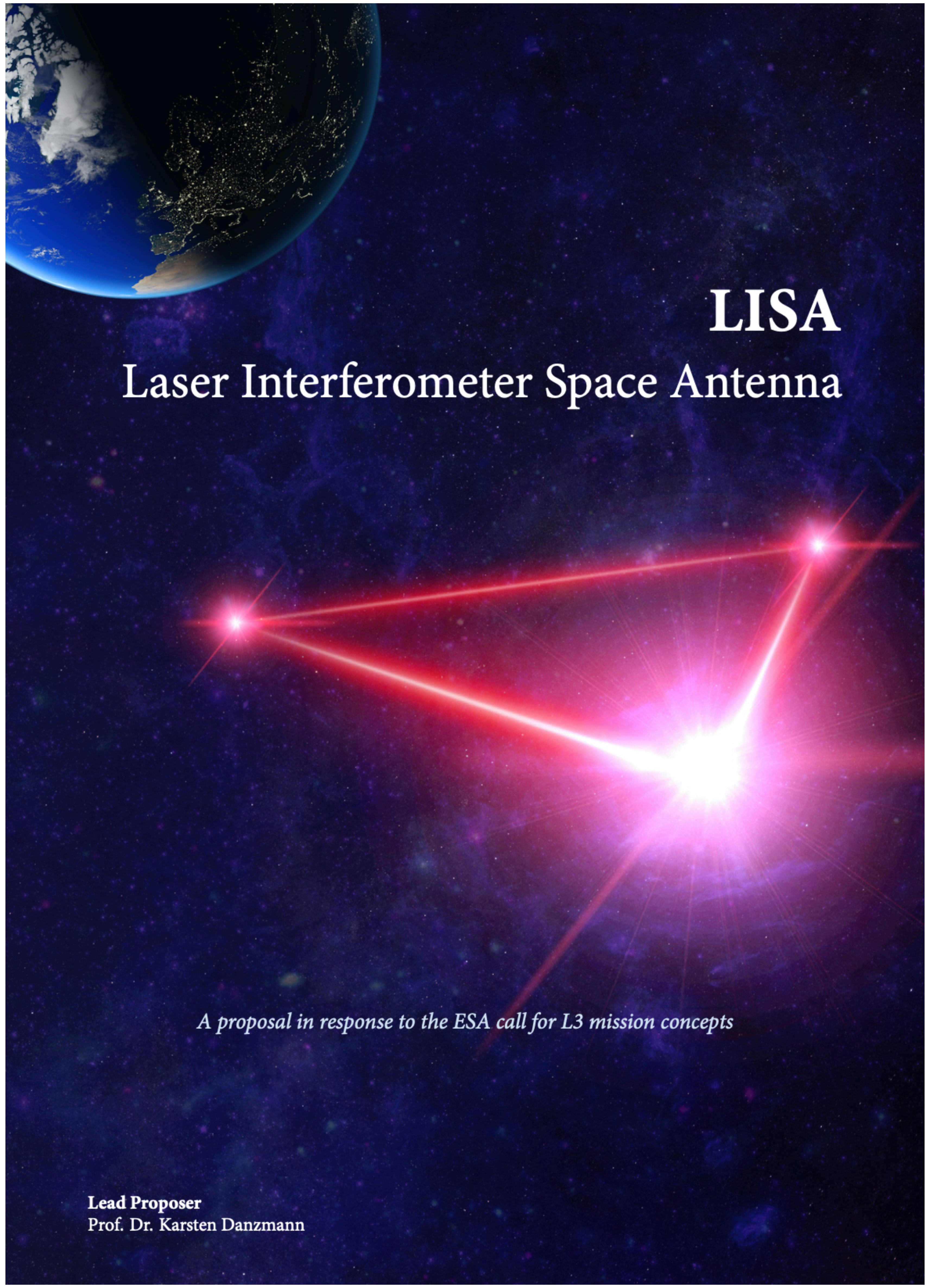
How did we get here?

- **1974-** : First ideas about Gravitational Wave Detection in Space: Bender, Weiss, Drever, etc.
- **1998** : First serious LISA studies: JPL and LISA International Team
- **2001** : LISA Pathfinder mission to demonstrate LISA main technology
- **2004** : Alberto Lobo puts Spain in LISA Pathfinder
- **2013** : Selection of the science themes for the L2 and L3 missions:
- **2015** : Launch of LISA Pathfinder and first detection of Gravitational Waves by LIGO

How did we get here?

- **1974-** : First ideas about Gravitational Wave Detection in Space: Bender, Weiss, Drever, etc.
- **1998** : First serious LISA studies: JPL and LISA International Team
- **2001** : LISA Pathfinder mission to demonstrate LISA main technology
- **2004** : Alberto Lobo puts Spain in LISA Pathfinder
- **2013** : Selection of the science themes for the L2 and L3 missions:
- **2015** : Launch of LISA Pathfinder and first detection of Gravitational Waves by LIGO
- **2017** : Success of LISA Pathfinder and Selection of LISA as the L3 mission

How did we get here?



ESA unclassified – For official use only

ESA/SPC(2017)12
Att.: ESA/SSAC(2017)6
Paris, 2 June 2017
(Original: English)

EUROPEAN SPACE AGENCY

SCIENCE PROGRAMME COMMITTEE

Selection of the L3 mission

Summary

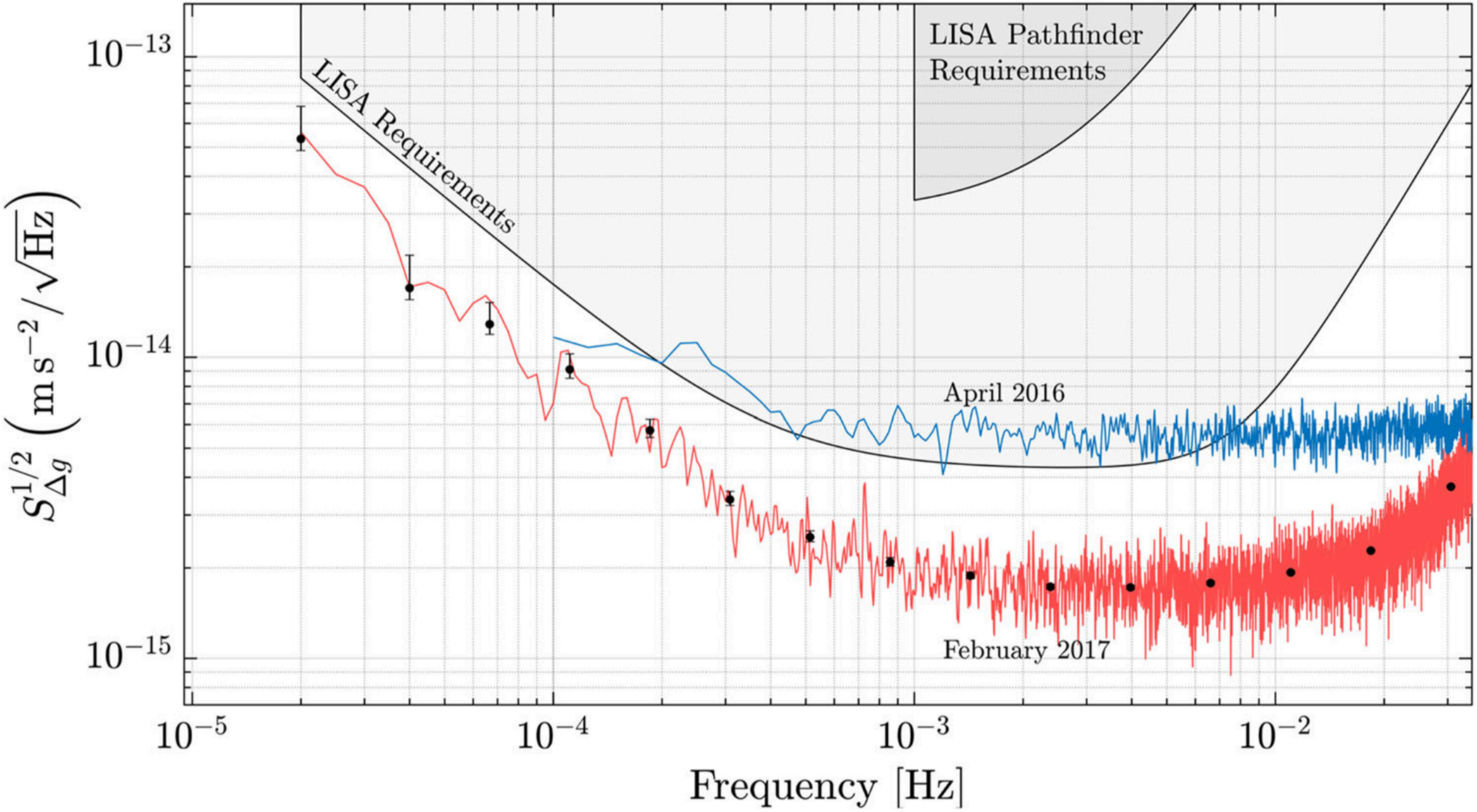
Following the issue of the Call for the L3 Mission a single proposal (named LISA) was received in response. The LISA proposal has been assessed by a dedicated peer review panel for consistency with the L3 science theme and by the Executive for technical and programmatic feasibility. Following the positive outcome of this evaluation, the Executive is herewith proposing to the SPC the selection of the LISA mission for the L3 flight opportunity.

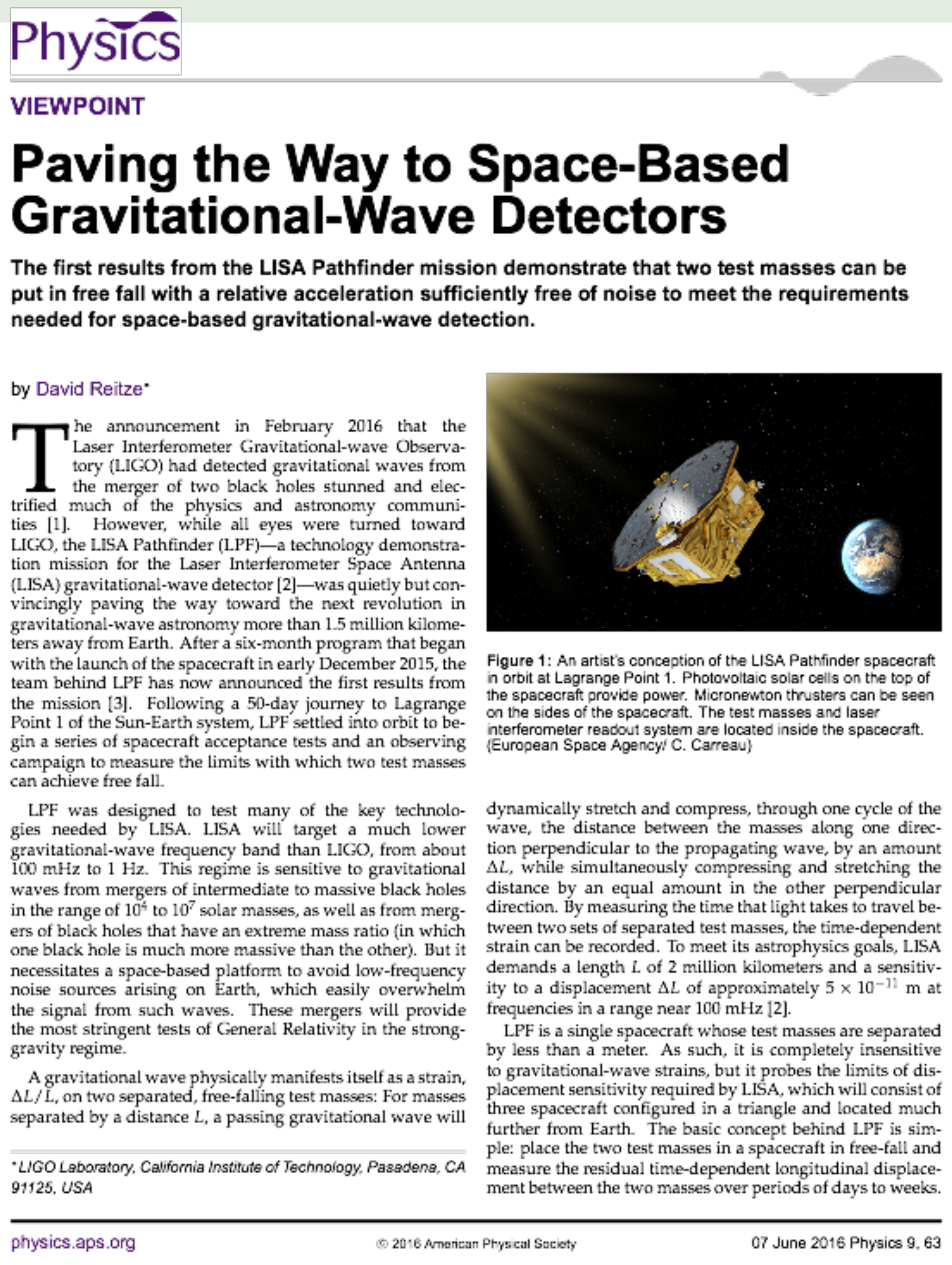
Decision

The SPC is invited to select the LISA mission for the L3 flight opportunity, with a planned launch date in 2034, and with an estimated Cost at Completion (ECaC) of 1.05 B€ (2017 e.c.).

How did we get here?

The LISA Pathfinder mission





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.

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.

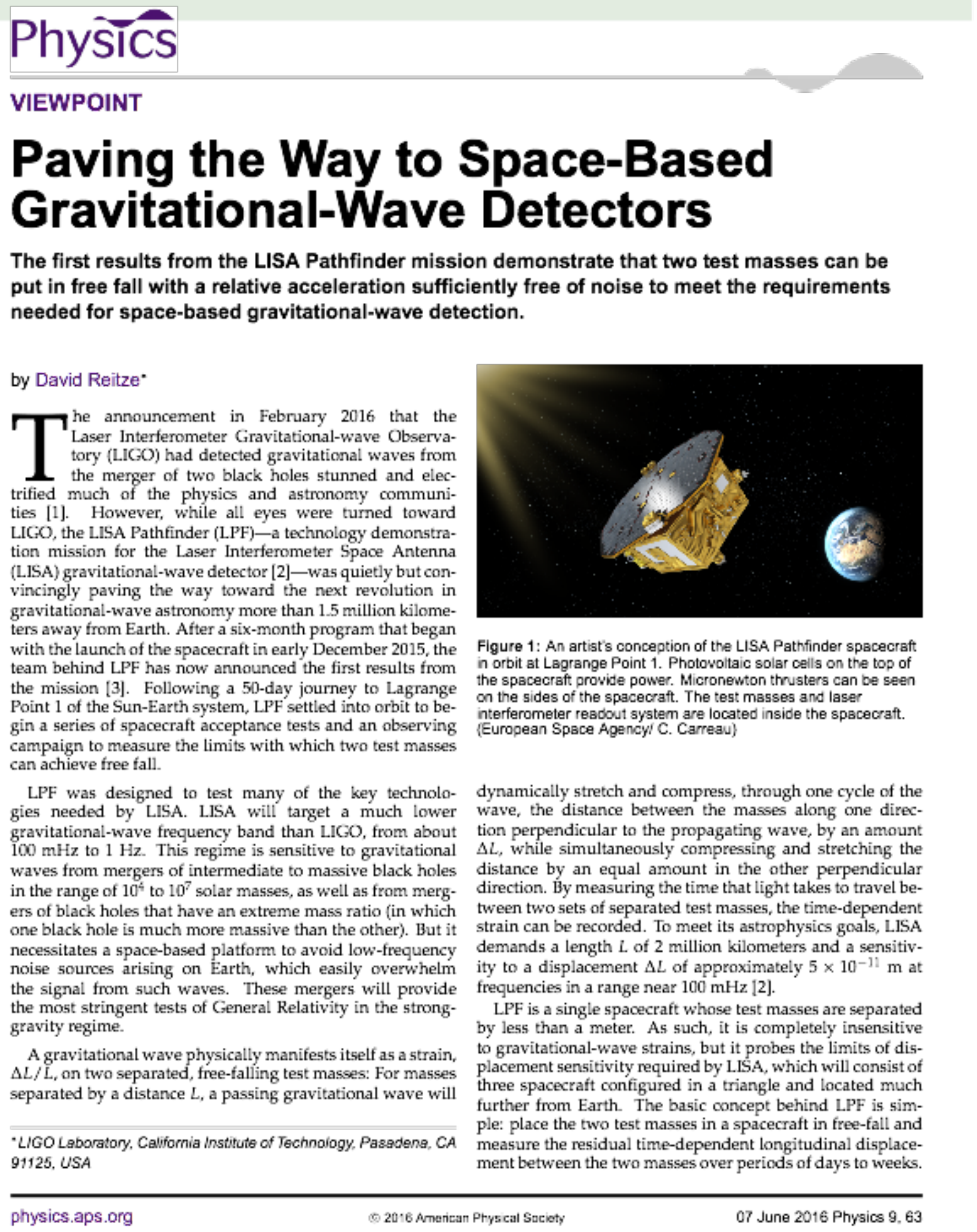
Figure 1: An artist's conception of the LISA Pathfinder spacecraft in orbit at Lagrange Point 1. Photovoltaic solar cells on the top of the spacecraft provide power. Micronewton thrusters can be seen on the sides of the spacecraft. The test masses and laser interferometer readout system are located inside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

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

physics.aps.org © 2016 American Physical Society 07 June 2016 Physics 9, 63

How did we get here?

The LISA Pathfinder mission



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.

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.

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)

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

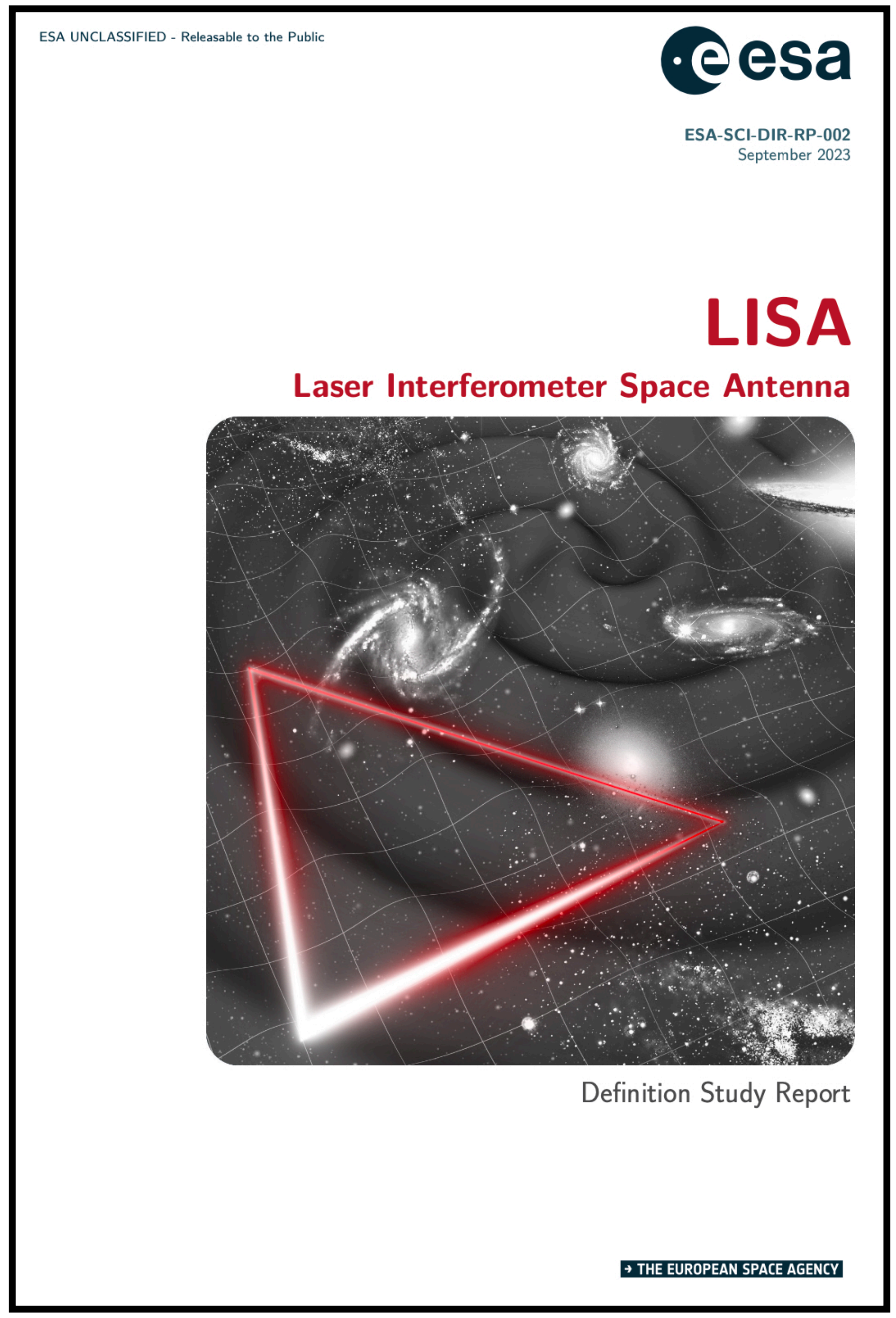
physics.aps.org © 2016 American Physical Society 07 June 2016 Physics 9, 63

10 years of the launch of LISA Pathfinder Celebration

in Barcelona (3-4 December 2025). Stay Tuned!

How did we get here?

- **1974-** : First ideas about Gravitational Wave Detection in Space: Bender, Weiss, Drever, etc.
- **1998** : First serious LISA studies: JPL and LISA International Team
- **2001** : LISA Pathfinder mission to demonstrate LISA main technology
- **2004** : Alberto Lobo introduces Spain in LISA Pathfinder
- **2013** : Selection of the science themes for the L2 and L3 missions:
- **2015** : Launch of LISA Pathfinder and first detection of GWs by LIGO
- **2017** : Success of LISA Pathfinder and Selection of LISA as the L3 mission
- **25 January 2024** : LISA goes through adoption into implementation (Phase B2). Expected Launch Date: 2035



Definition Study Report (arXiv: 2402.07571)

a.k.a. Red Book

LISA Implementation Phase

✴ **6 June 2025**: evolved LISA Consortium Kick-off meeting

LISA CONSORTIUM

The LISA Consortium is an organisation which represents the knowledge, capabilities and interests of the larger scientific community. The LISA Consortium internal structure and participation mechanisms are not regulated by ESA.

The LISA Consortium provides an organizational forum beyond the working groups and Science Topical Panels set up by the LST. It will set up science interest groups which focus on scientific topics which are either not represented in one of the working groups of the LST or will require integrated data sets well beyond the first data release. In addition, it will provide a pool of scientific expertise that can be drawn on as needed to support the implementation of the SGS and the P&O activities. Depending on the number, type and size of the LST working groups, the LISA Consortium might also set up larger science interest groups outside the LST WGs to provide pathways for early career scientists to later join the LST WGs. The LISA Consortium will also publicise LISA science to the public.

The LISA Consortium will nominate a representative to serve as an ex-officio member of the LST, whose role will be to represent the interests of the scientific community working on preparation for LISA science exploitation.

LISA Implementation Phase

✶ **6 June 2025**: evolved LISA Consortium Kick-off meeting

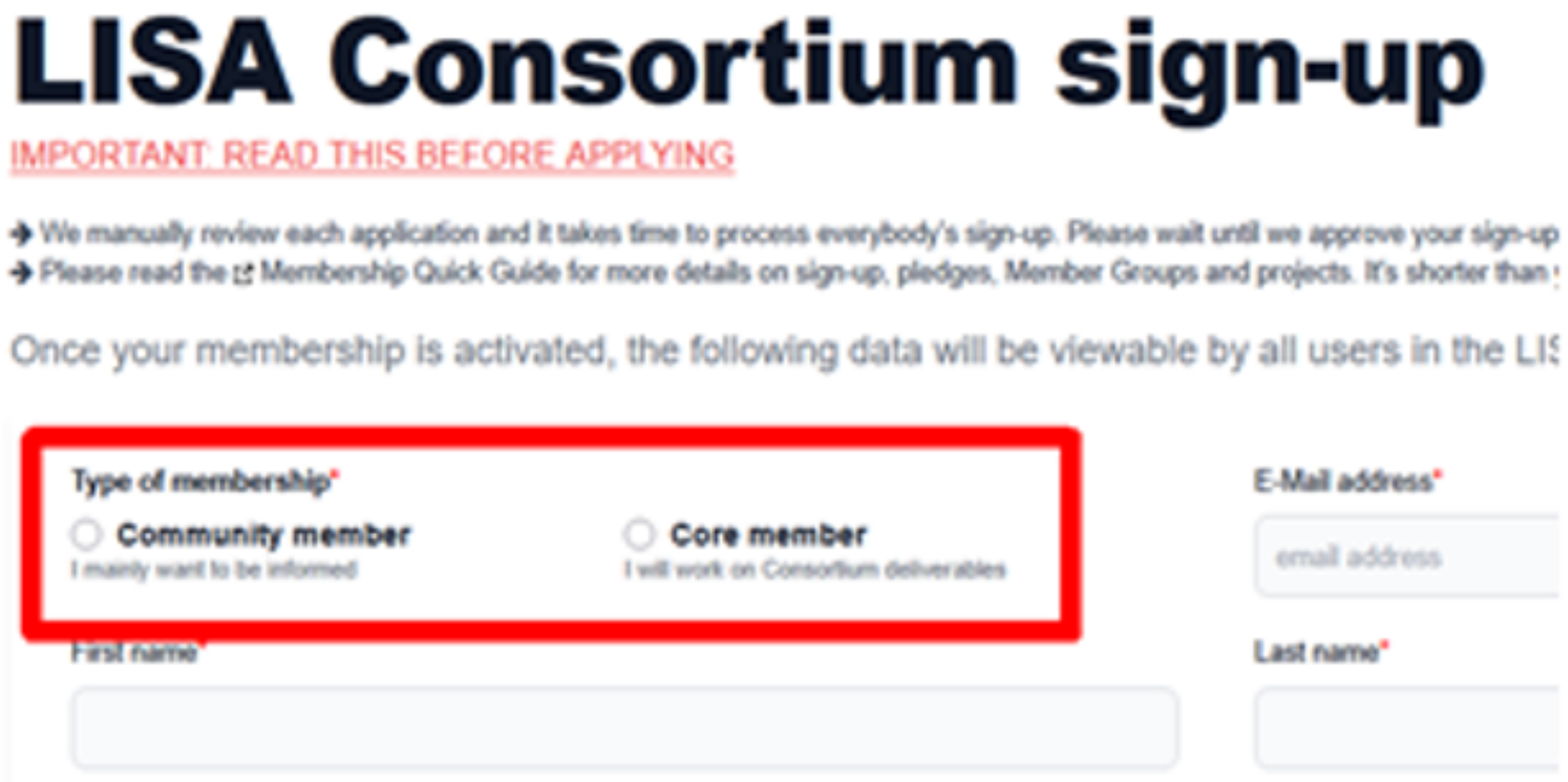
Types of membership (*bylaws*)

Core

- Requires commitment (1 deliverable per year: project/service role).
- Service tracking: 1 **pledge** and 1 **statement** per year.
- Can change to community if quota not reached.

Community

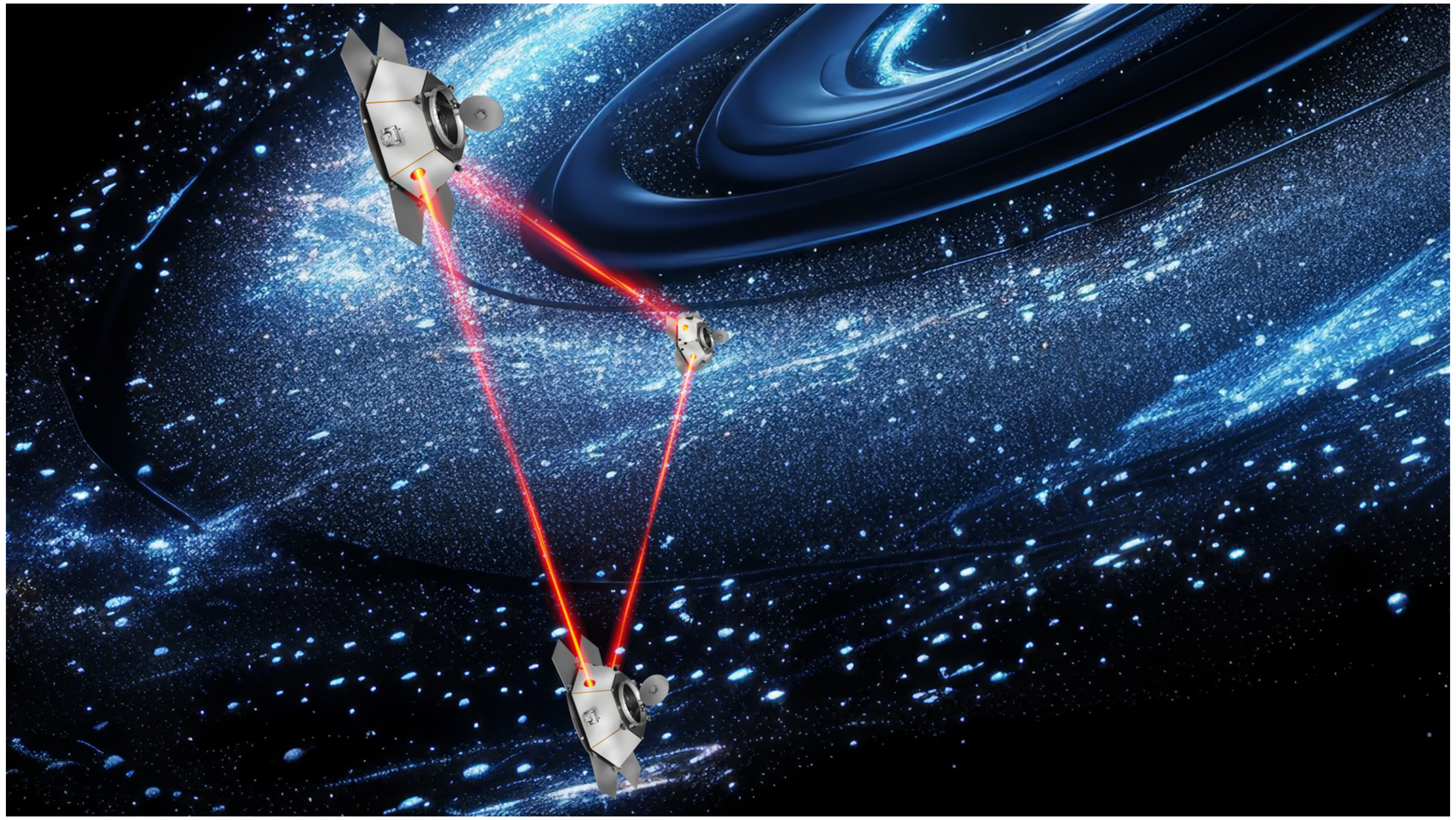
- Mainly to be informed.
- No work on deliverables, no service tracking.
- Can change to core any time.



LISA Implementation Phase

✴ **17 June 2025**: Kick-off of the prime contract for LISA to OHB, worth 839 million Euros

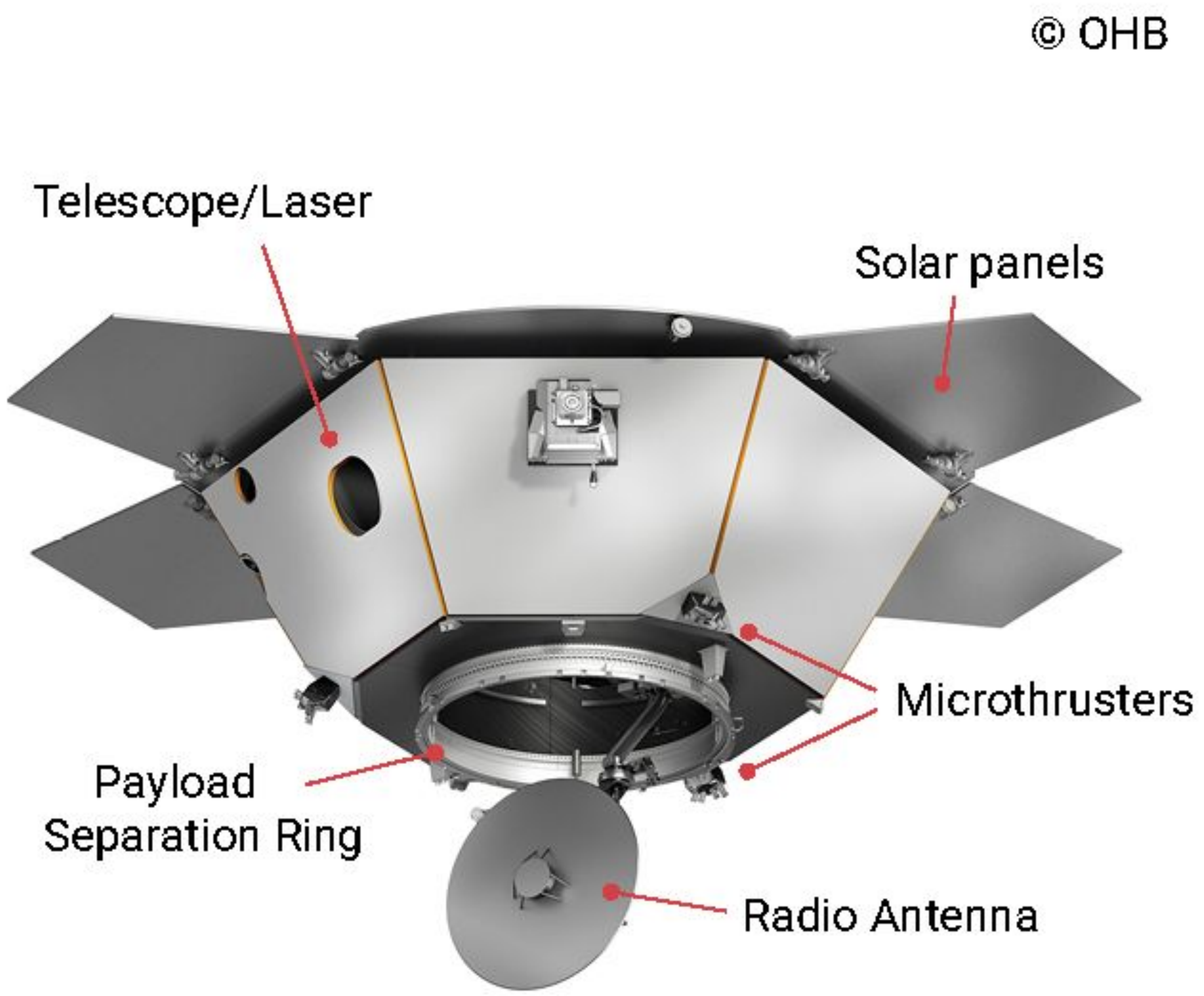
Carole Mundell, ESA's Director of Science and Chiara Pedersoli, CEO of OHB System AG, at the Paris Airshow during the kick-off/ signature event for the LISA mission



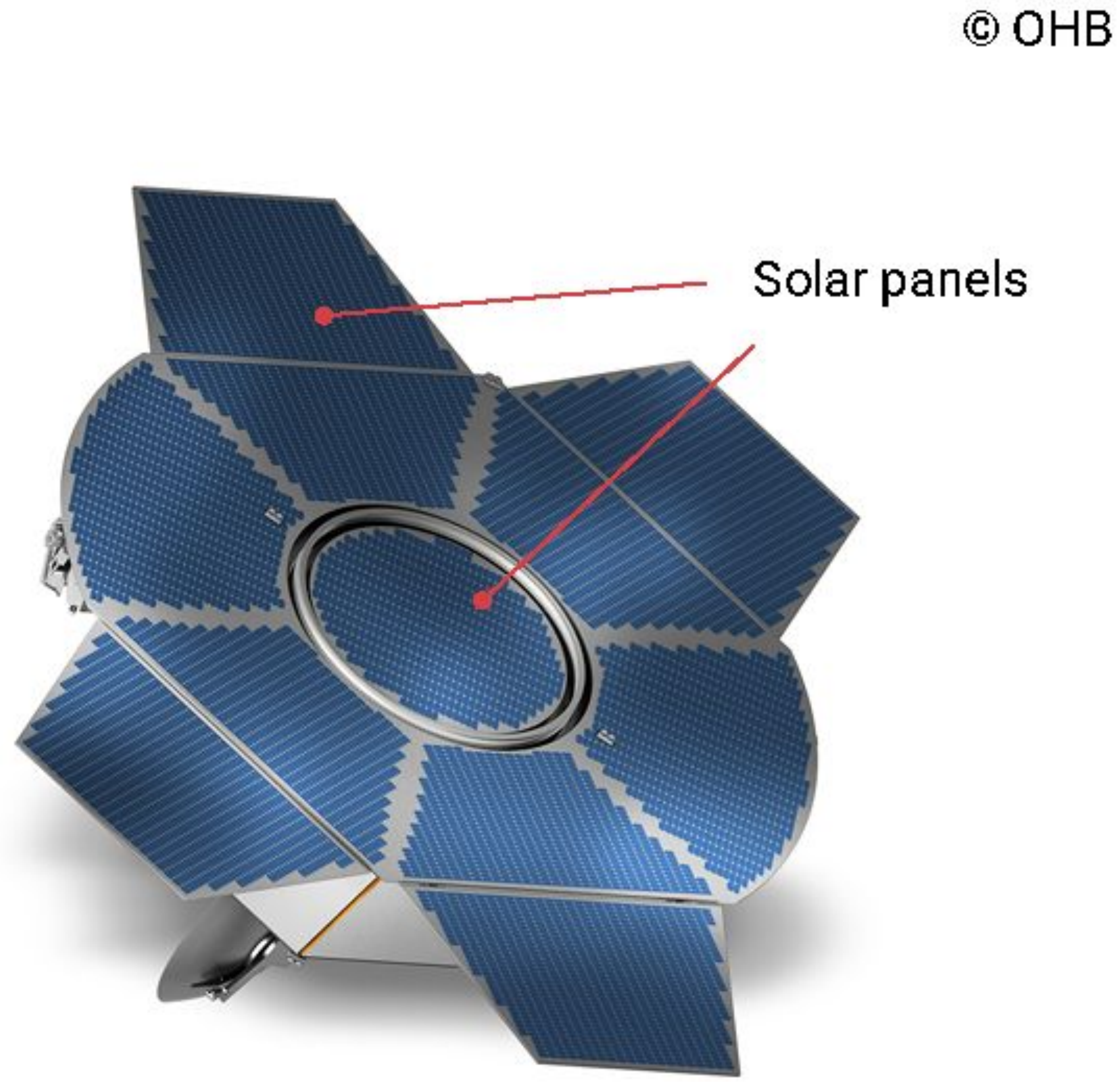
Artistic impression of LISA ©OHB

LISA Implementation Phase

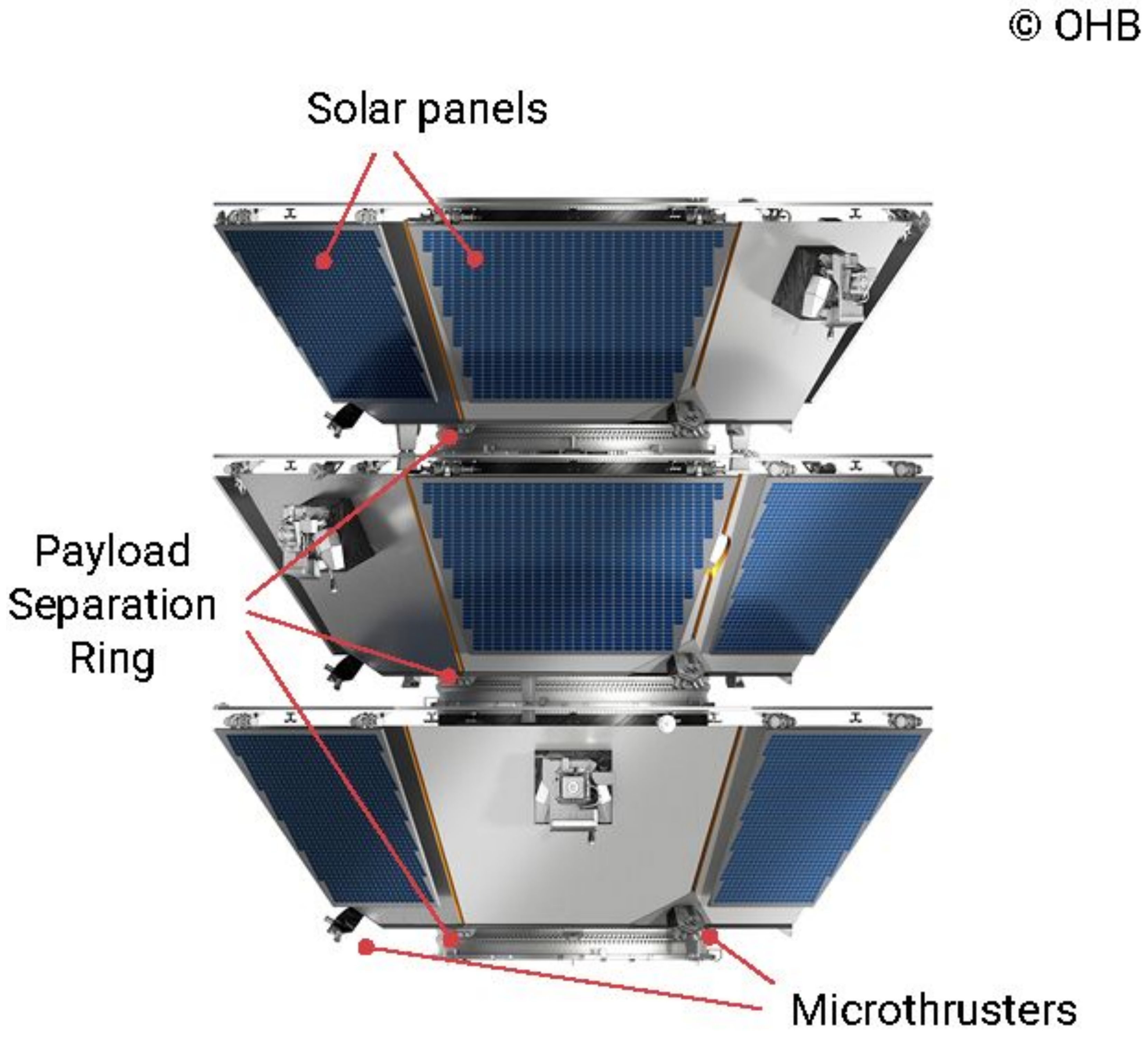
* **17 June 2025**: Kick-off of the prime contract for LISA to OHB, worth 839 million Euros



LISA calling Earth.



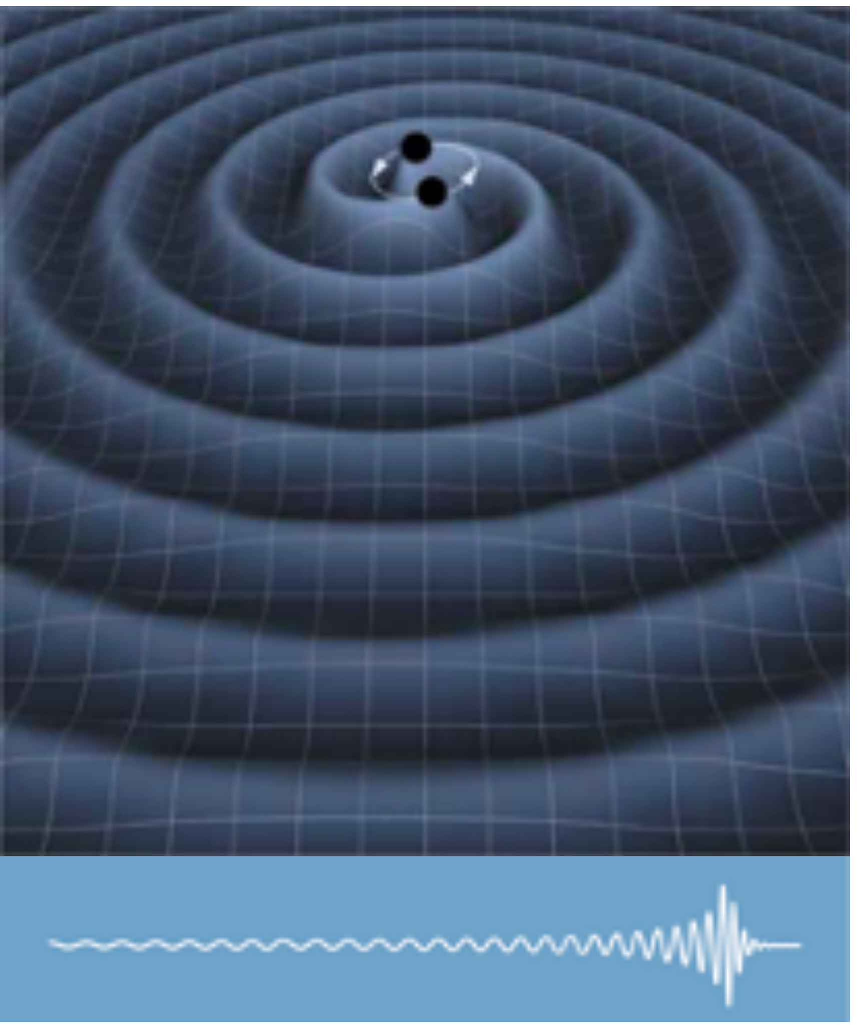
The new shape of the LISA spacecraft.



All 3 LISA spacecraft fit into a single launcher.

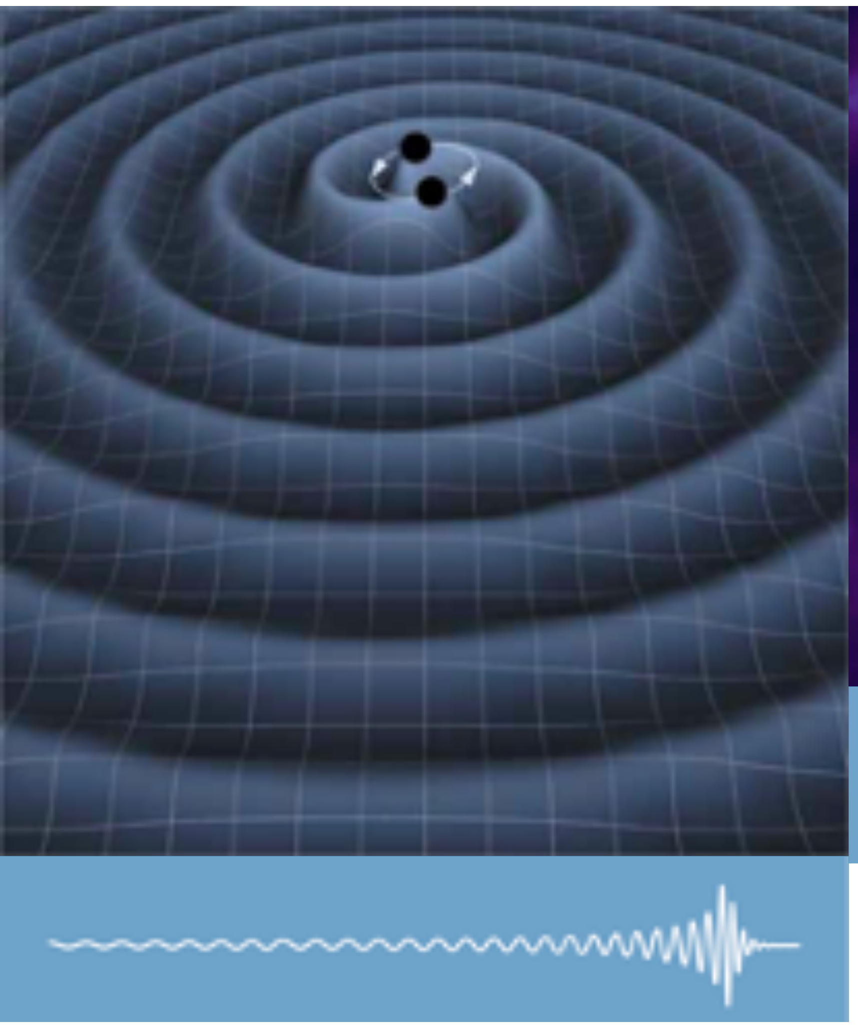
OHB Preliminary Designs

Sources of Gravitational Waves for LISA

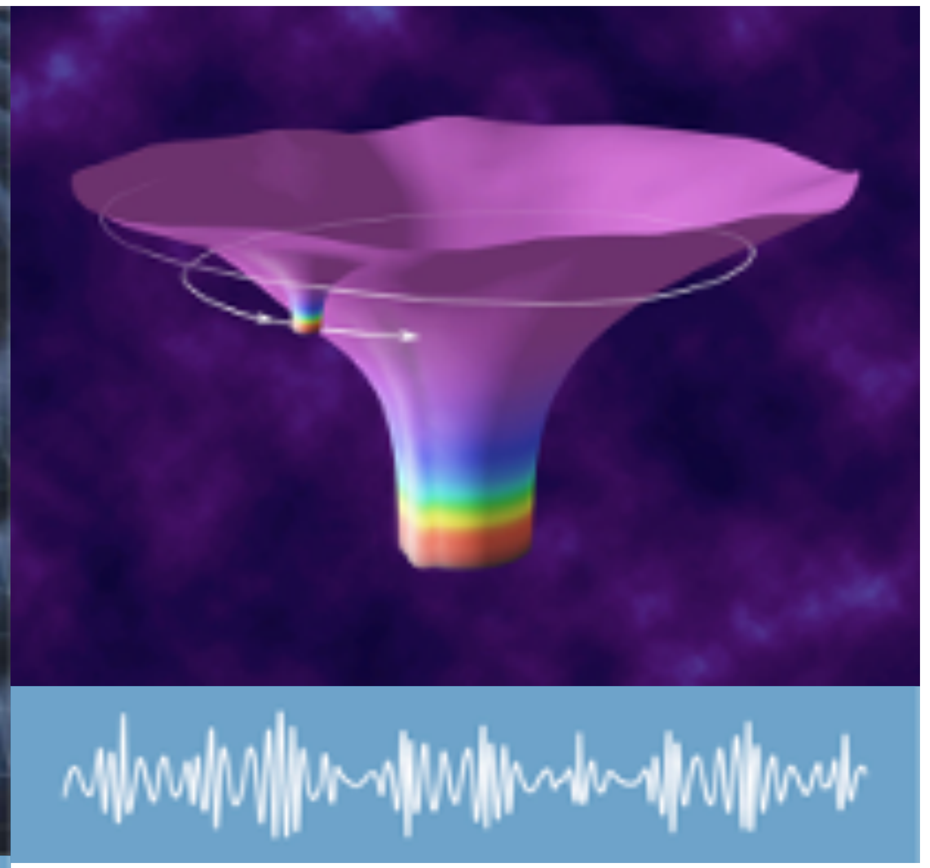


Massive Black Hole Mergers (with masses in the range: $10^4 - 10^7\, M_\odot$)

Sources of Gravitational Waves for LISA

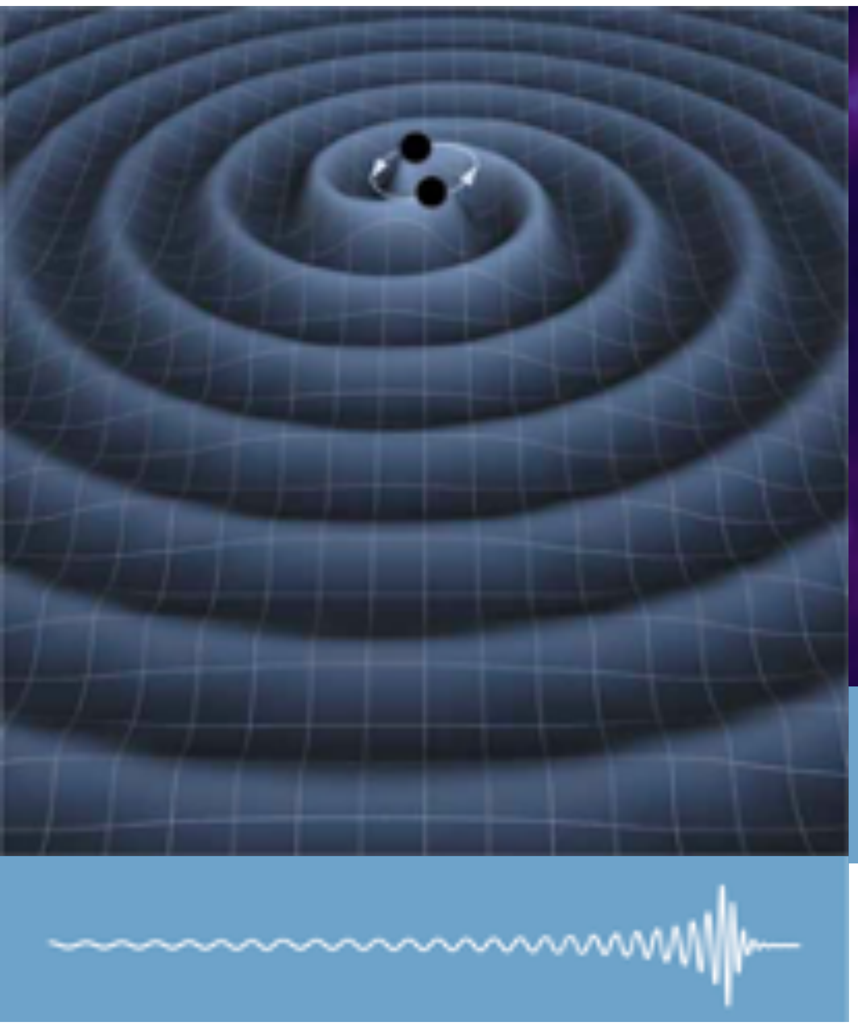


Massive Black Hole Mergers (with masses in the range: $10^4 - 10^7\, M_\odot$)

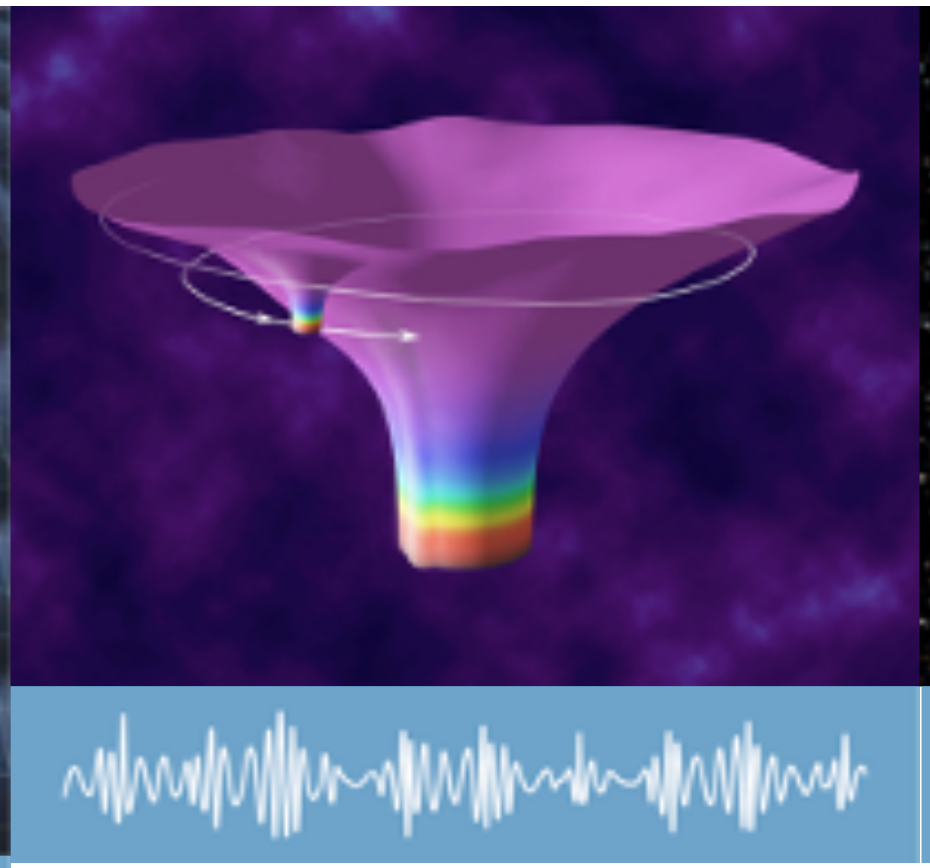


Extreme/ Intermediate Mass Ratio Inspirals (EMRIs/ IMRIs): a BH of $1 - 50\, M_\odot \,/\, 10^2 - 10^4\, M_\odot$ into an IMBH and/or a MBH

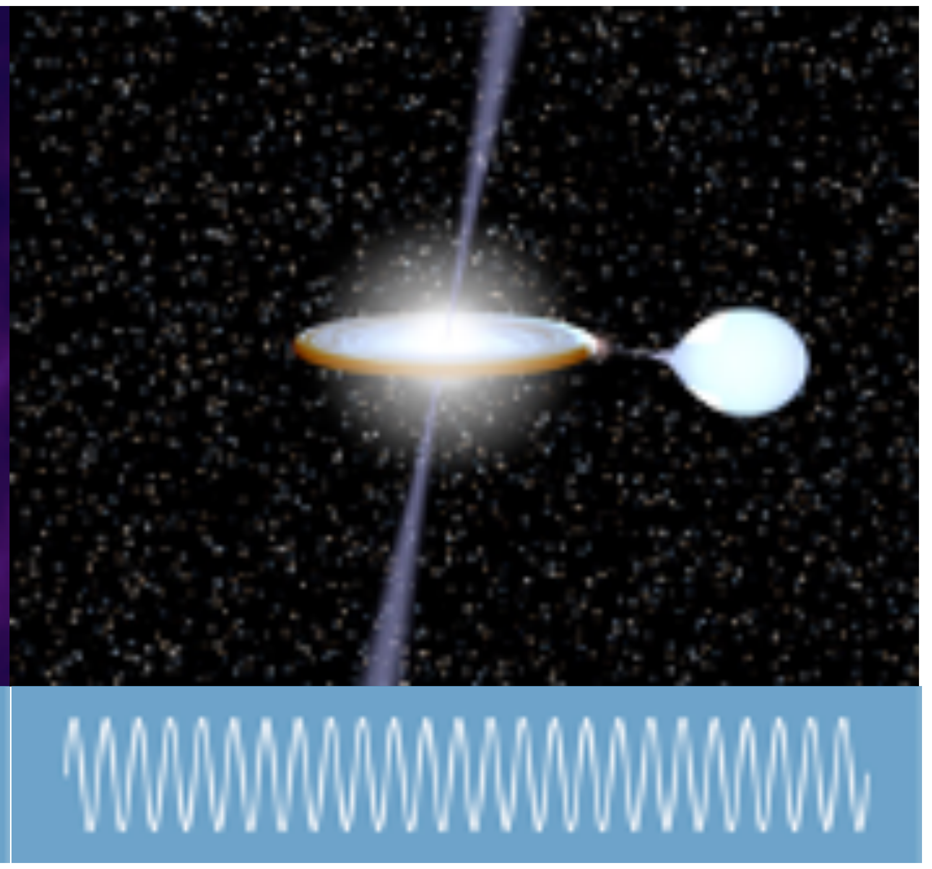
Sources of Gravitational Waves for LISA



Massive Black Hole Mergers (with masses in the range: $10^4 - 10^7\,M_\odot$)



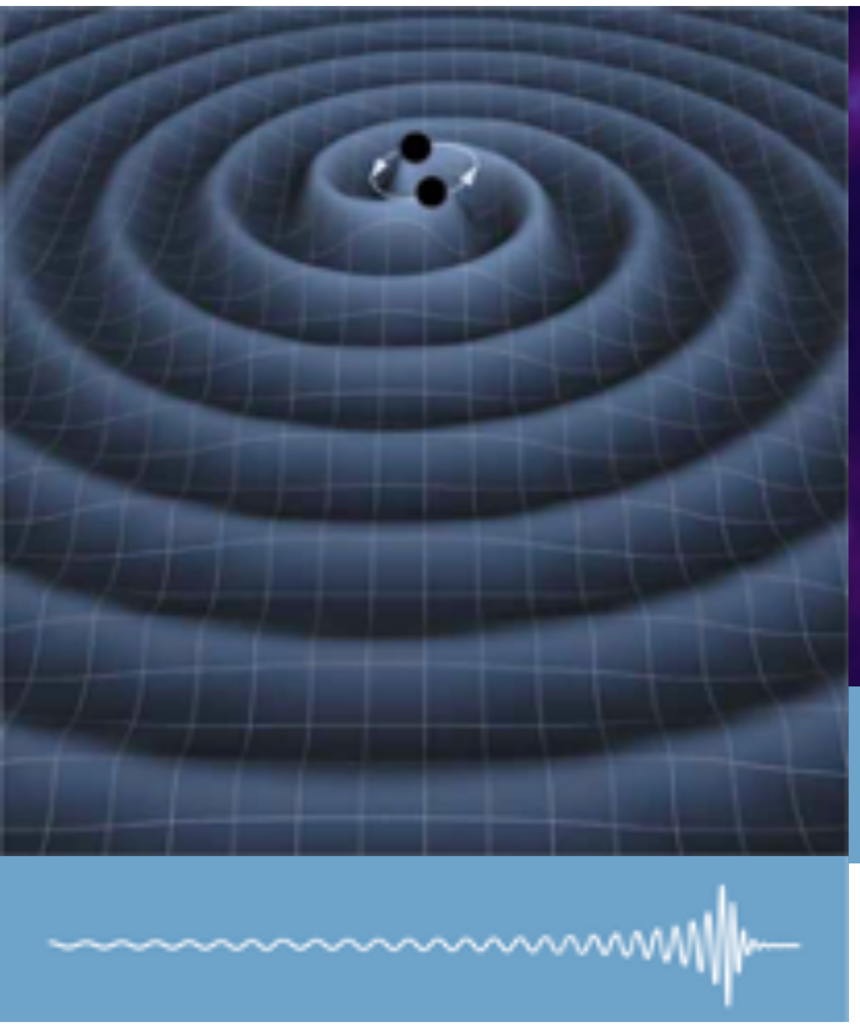
Extreme/ Intermediate Mass Ratio Inspirals (EMRIs/ IMRIs): a BH of $1 - 50\,M_\odot\,/\,10^2 - 10^4\,M_\odot$ into an IMBH and/or a MBH



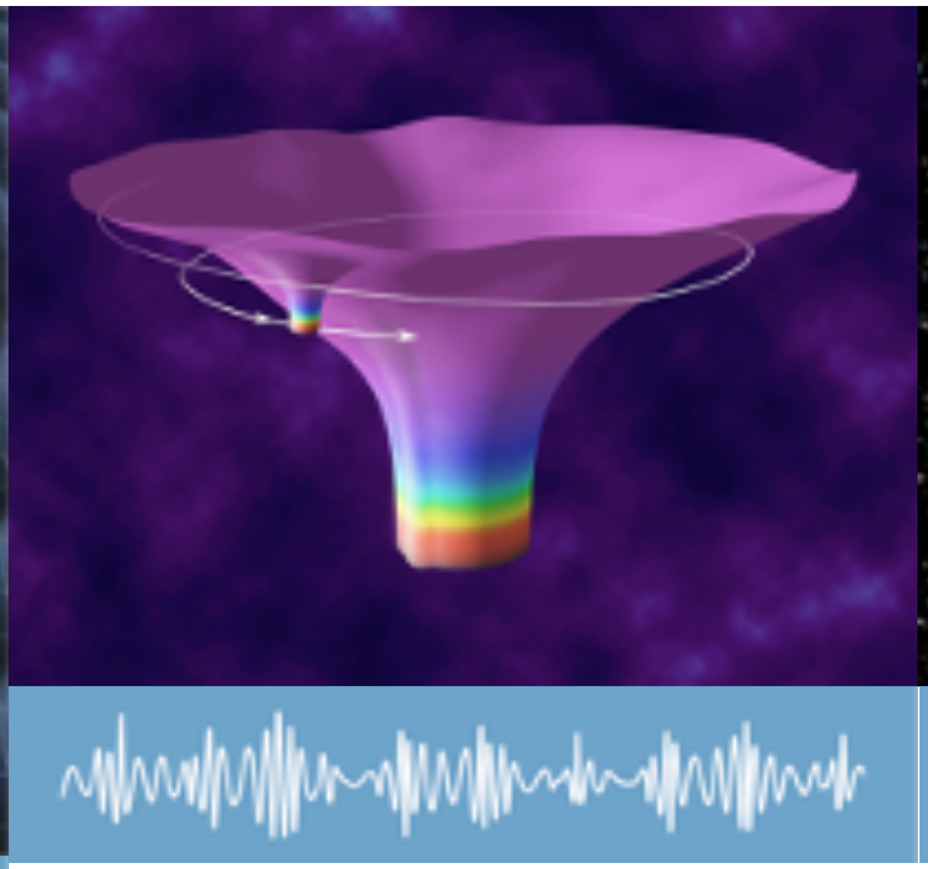
Galactic Binaries in the Milky Way. Population dominated by double WDs.

Verification Binaries: Guaranteed GW Sources!

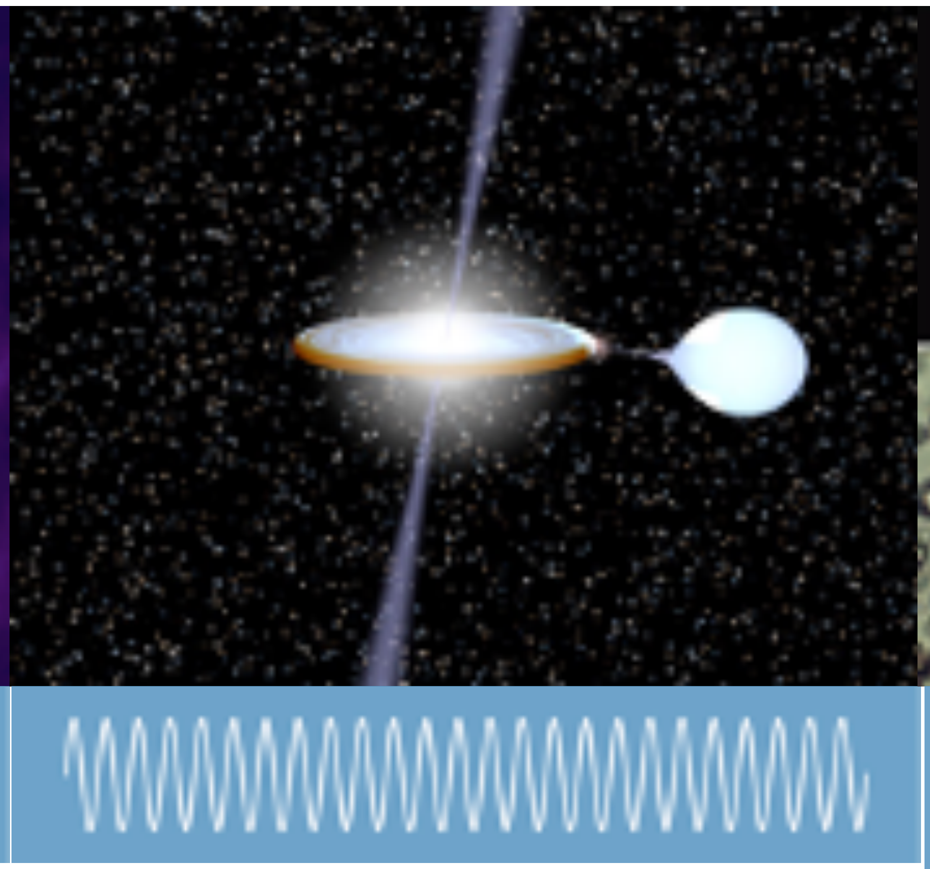
Sources of Gravitational Waves for LISA



Massive Black Hole Mergers (with masses in the range: $10^4 - 10^7 M_\odot$)

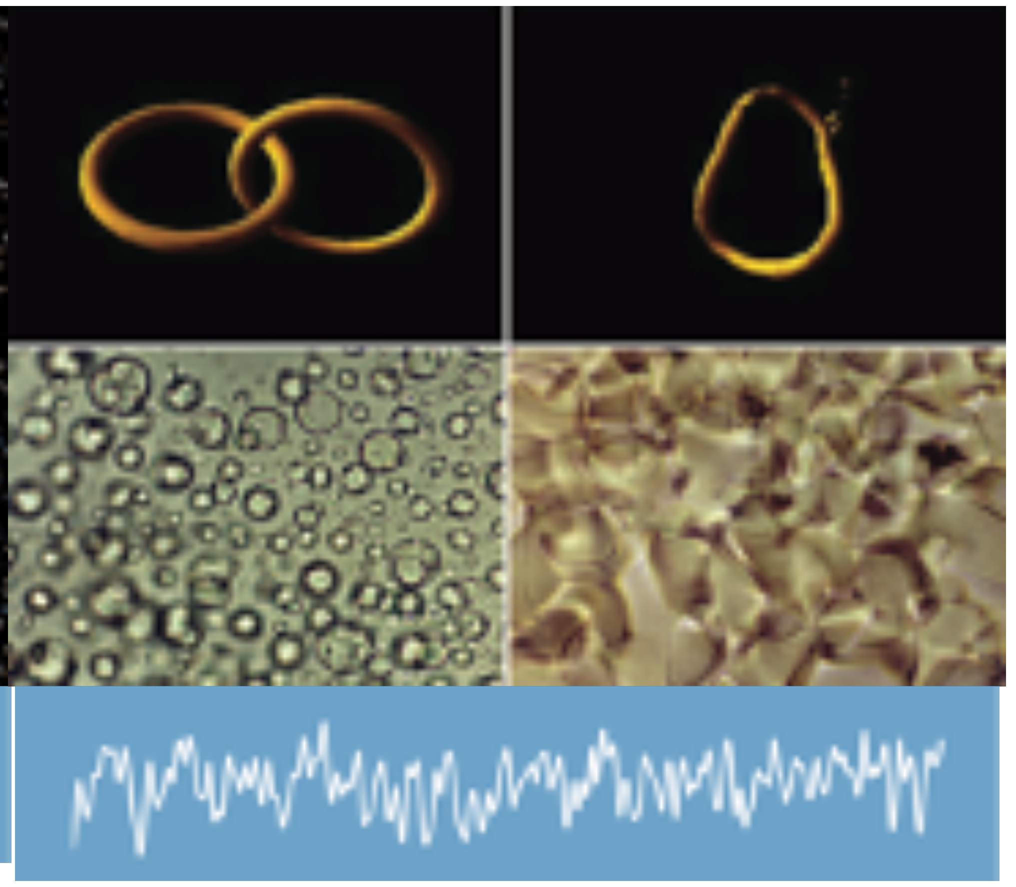


Extreme/ Intermediate Mass Ratio Inspirals (EMRIs/ IMRIs): a BH of $1 - 50\, M_\odot \,/\, 10^2 - 10^4\, M_\odot$ into an IMBH and/or a MBH



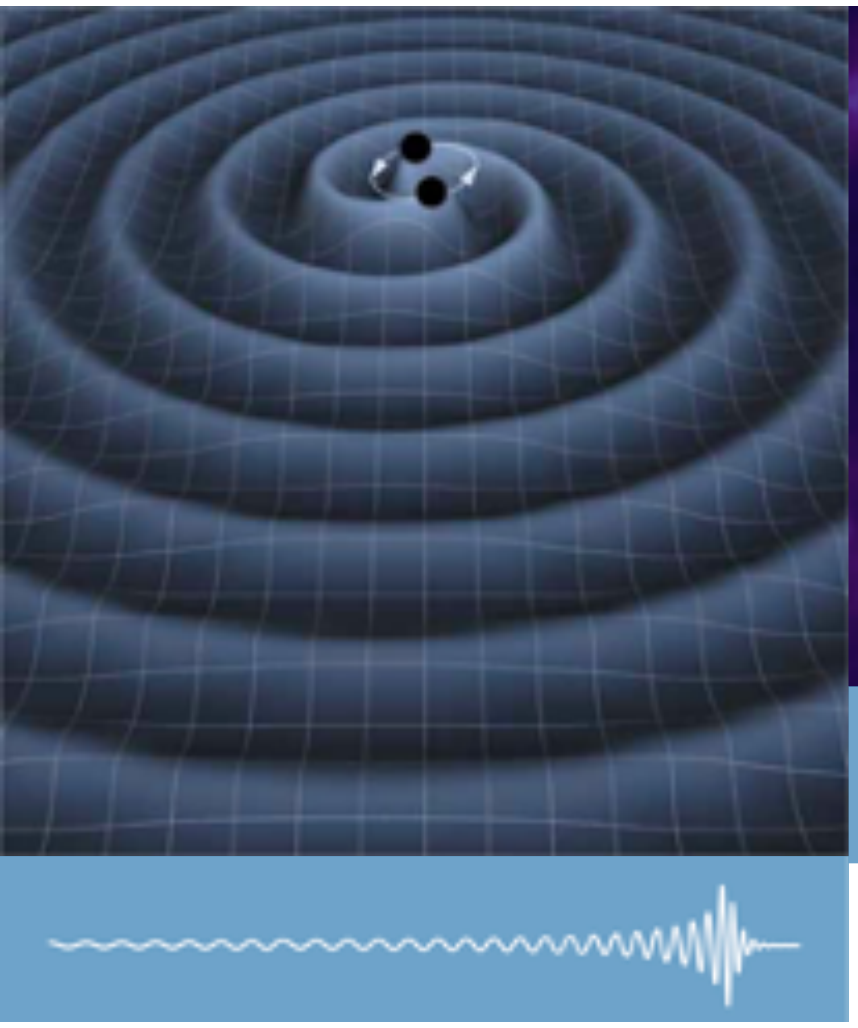
Galactic Binaries in the Milky Way. Population dominated by double WDs.

Verification Binaries: Guaranteed GW Sources!

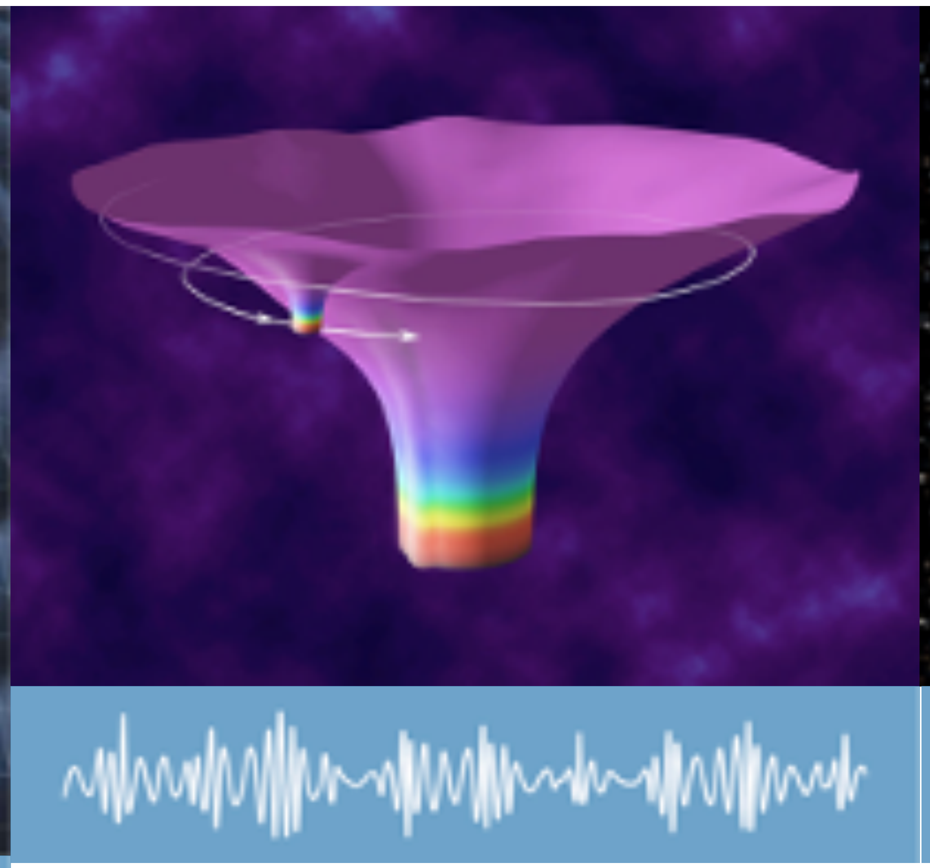


Stochastic GW Foregrounds from Early Universe high-energy Phenomena (Energy Scale ~ 1 TeV)

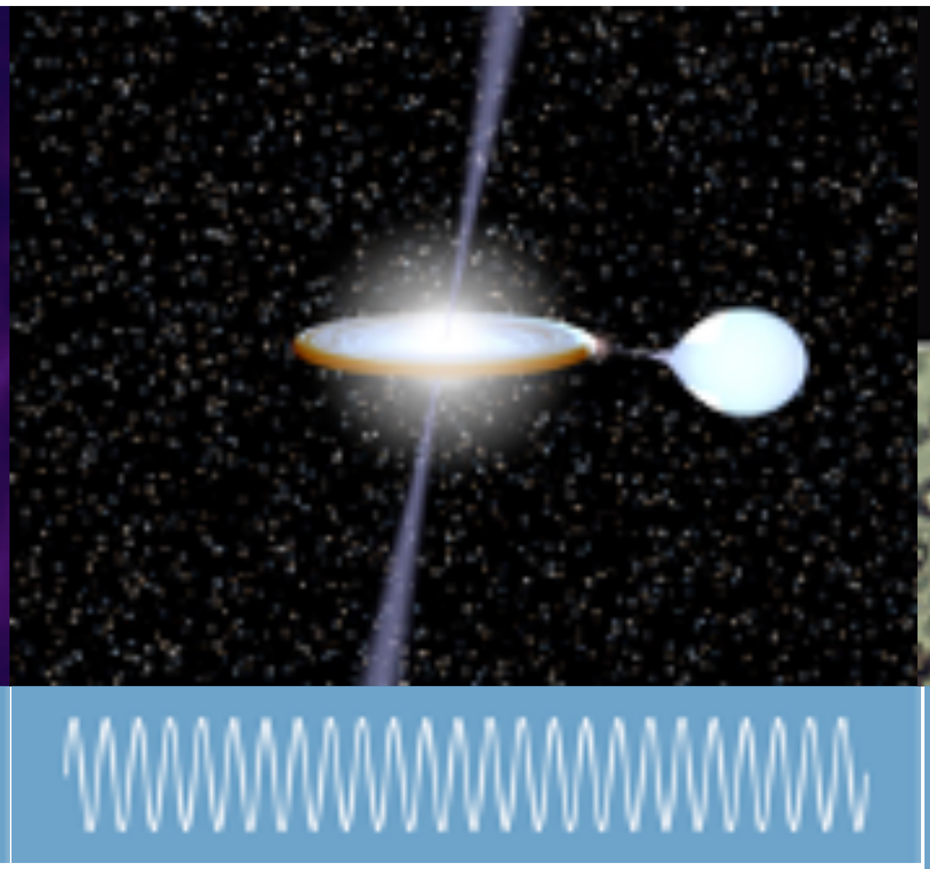
Sources of Gravitational Waves for LISA



Massive Black Hole Mergers (with masses in the range: $10^4 - 10^7\,M_\odot$)

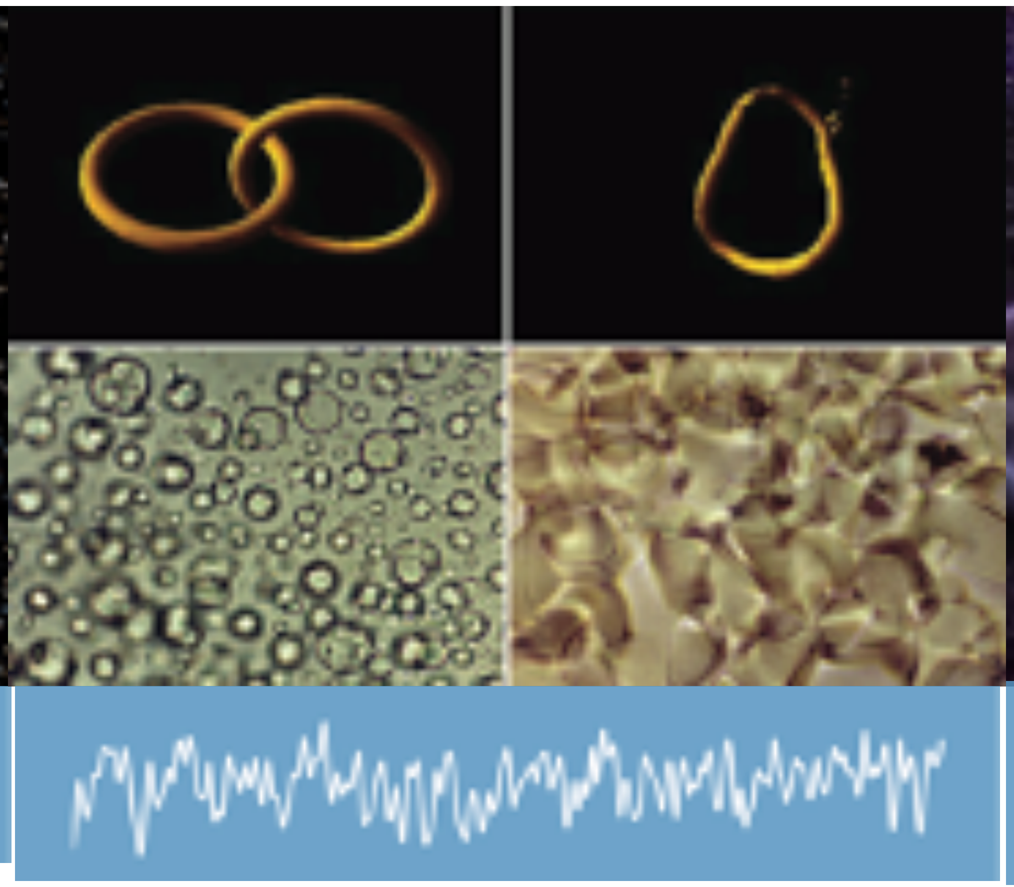


Extreme/ Intermediate Mass Ratio Inspirals (EMRIs/ IMRIs): a BH of $1 - 50\,M_\odot$ / $10^2 - 10^4\,M_\odot$ into an IMBH and/or a MBH



Galactic Binaries in the Milky Way. Population dominated by double WDs.

Verification Binaries: Guaranteed GW Sources!

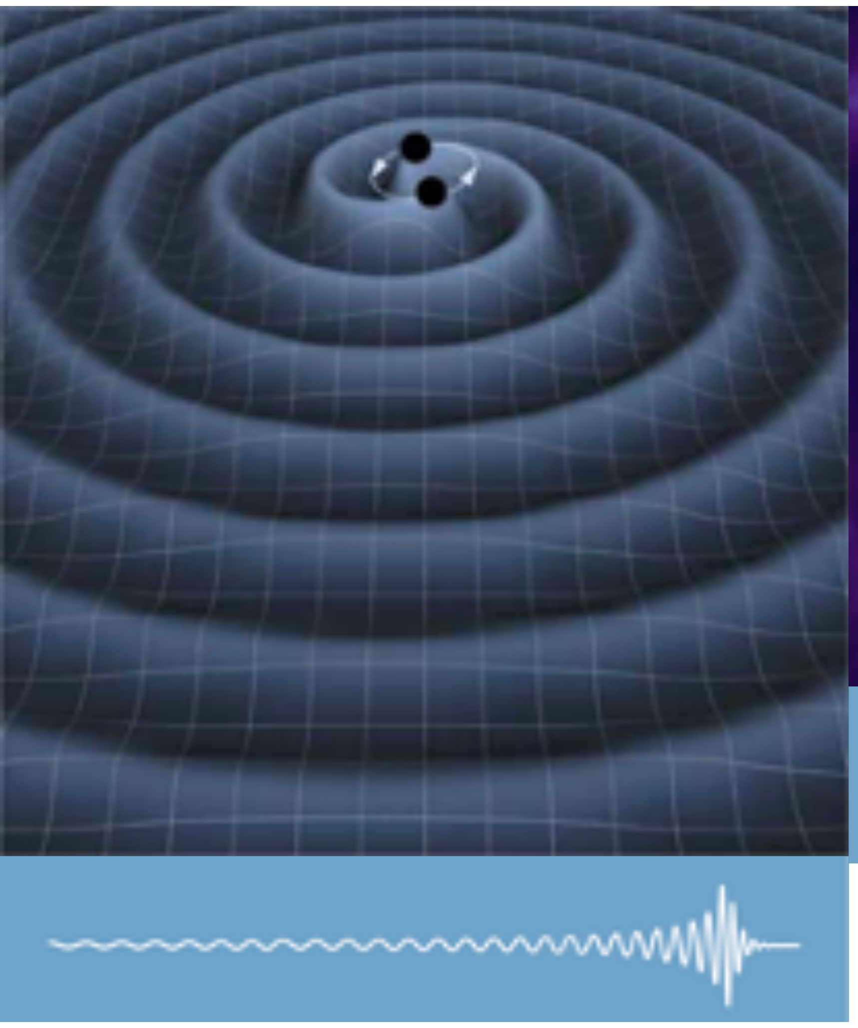


Stochastic GW Foregrounds from Early Universe high-energy Phenomena (Energy Scale ~ 1 TeV)

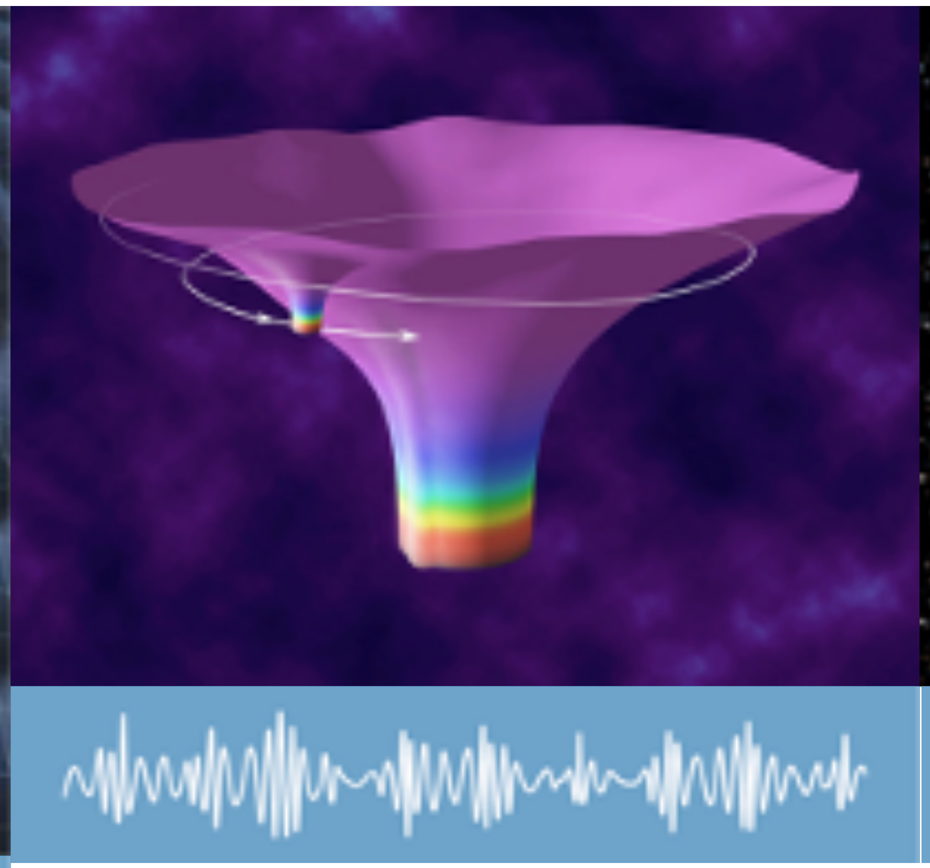
Stellar-Mass Binary BHs in the inspiral phase, before they enter the LIGO-Virgo-KAGRA band.

CSIC
Institute of Space Sciences
EXCELENCIA MARÍA DE MAEZTU
Carlos F. Sopuerta
carlos.f.sopuerta@csic.es
Institute of Space Sciences (ICE, CSIC & IEEC)
22 September 2025
IEEC

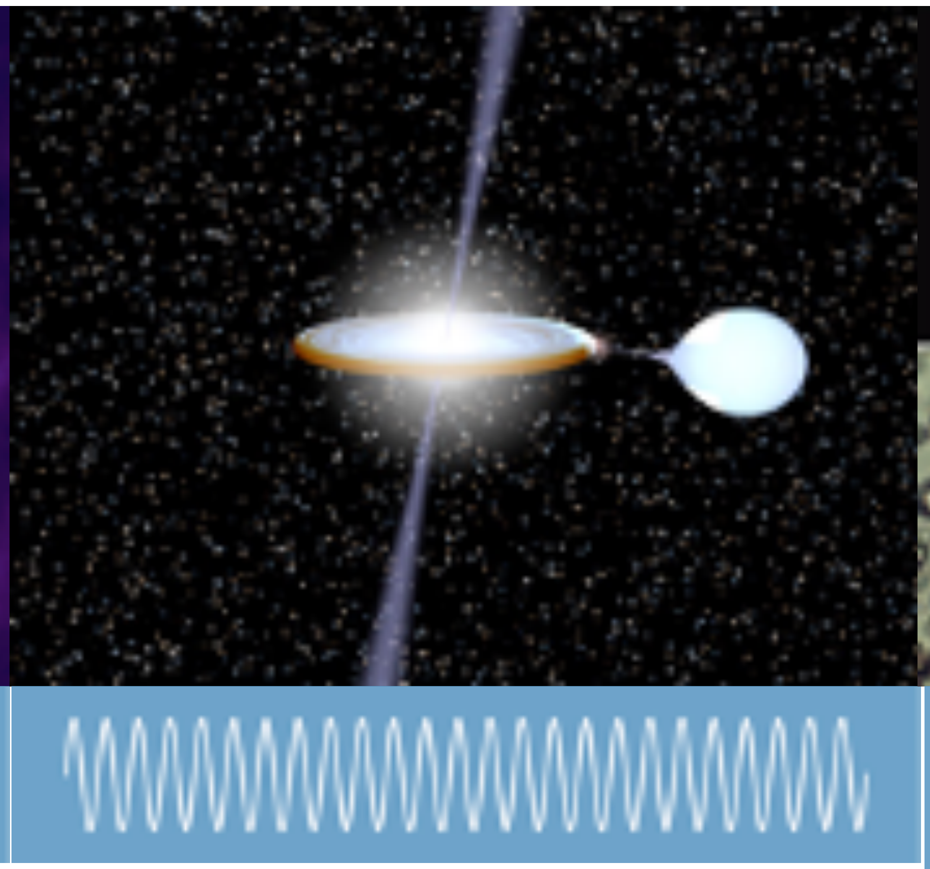
Sources of Gravitational Waves for LISA



Massive Black Hole Mergers (with masses in the range: $10^4 - 10^7\,M_\odot$)

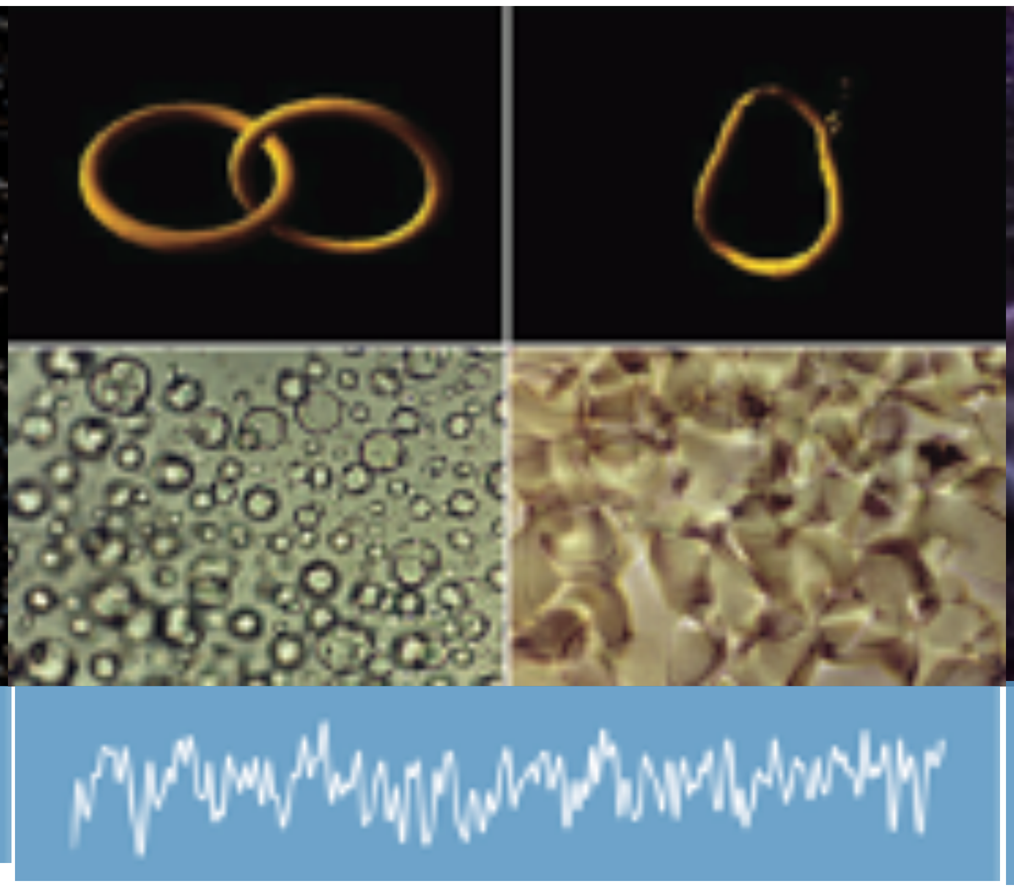


Extreme/Intermediate Mass Ratio Inspirals (EMRIs/IMRIs): a BH of $1 - 50\,M_\odot$ / $10^2 - 10^4\,M_\odot$ into an IMBH and/or a MBH



Galactic Binaries in the Milky Way. Population dominated by double WDs.

Verification Binaries: Guaranteed GW Sources!



Stochastic GW Foregrounds from Early Universe high-energy Phenomena (Energy Scale ~ 1 TeV)

Stellar-Mass Binary BHs in the inspiral phase, before they enter the LIGO-Virgo-KAGRA band.

?

Science Objectives (SO) of LISA

SO1: Study the formation and evolution of compact binary stars and the structure of the Milky Way Galaxy

SO2: Trace the origins, growth and merger histories of massive Black Holes

SO3: Probe the properties and immediate environments of Black Holes in the local Universe using EMRIs and IMRIs

SO4: Understand the astrophysics of stellar-mass Black Holes

SO5: Explore the fundamental nature of gravity and Black Holes

SO6: Probe the rate of expansion of the Universe with standard sirens

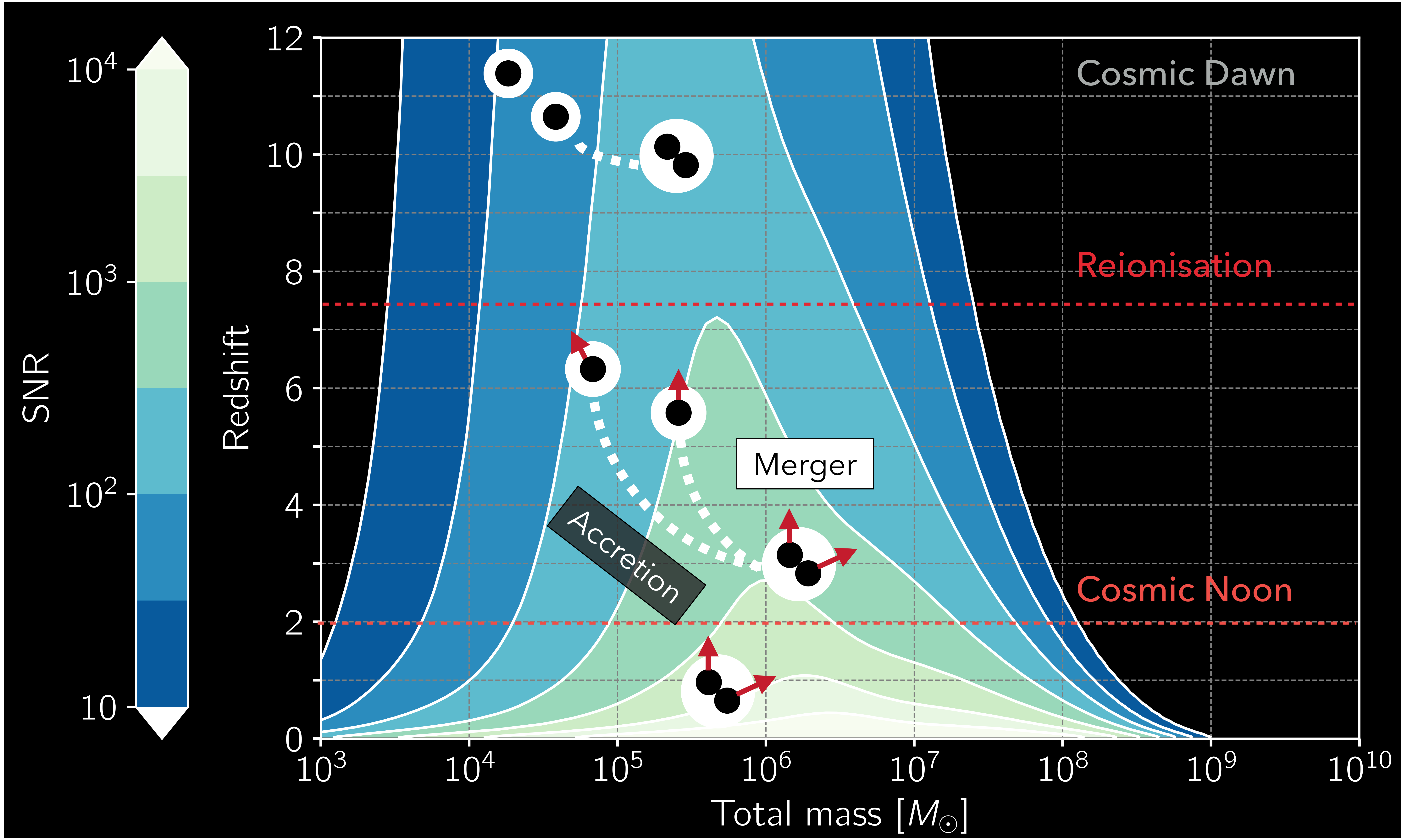
SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics

SO8: Search for GW bursts and unforeseen sources

The Science of LISA

✳ **SO2**: Trace the origins, growth and merger histories of massive Black Holes

- ✦ How were MBHs born and how did they grow?
- ✦ What is the nature of the seeds and how did they form?
- ✦ How do MBHs assemble inside the cosmic web?
- ✦ What are the EM signals of the precursor and post-merger of MBHBs?



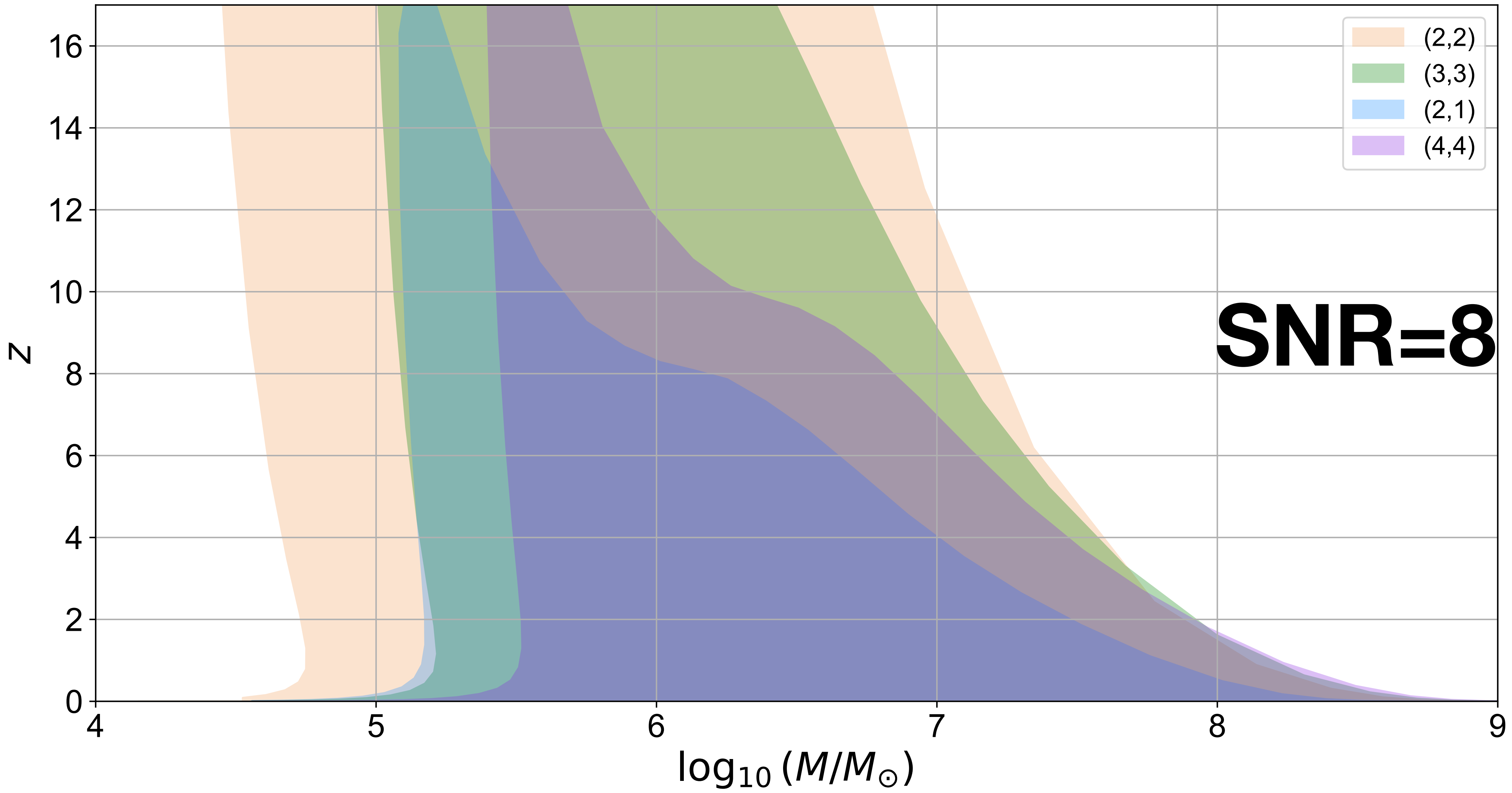
The Science of LISA

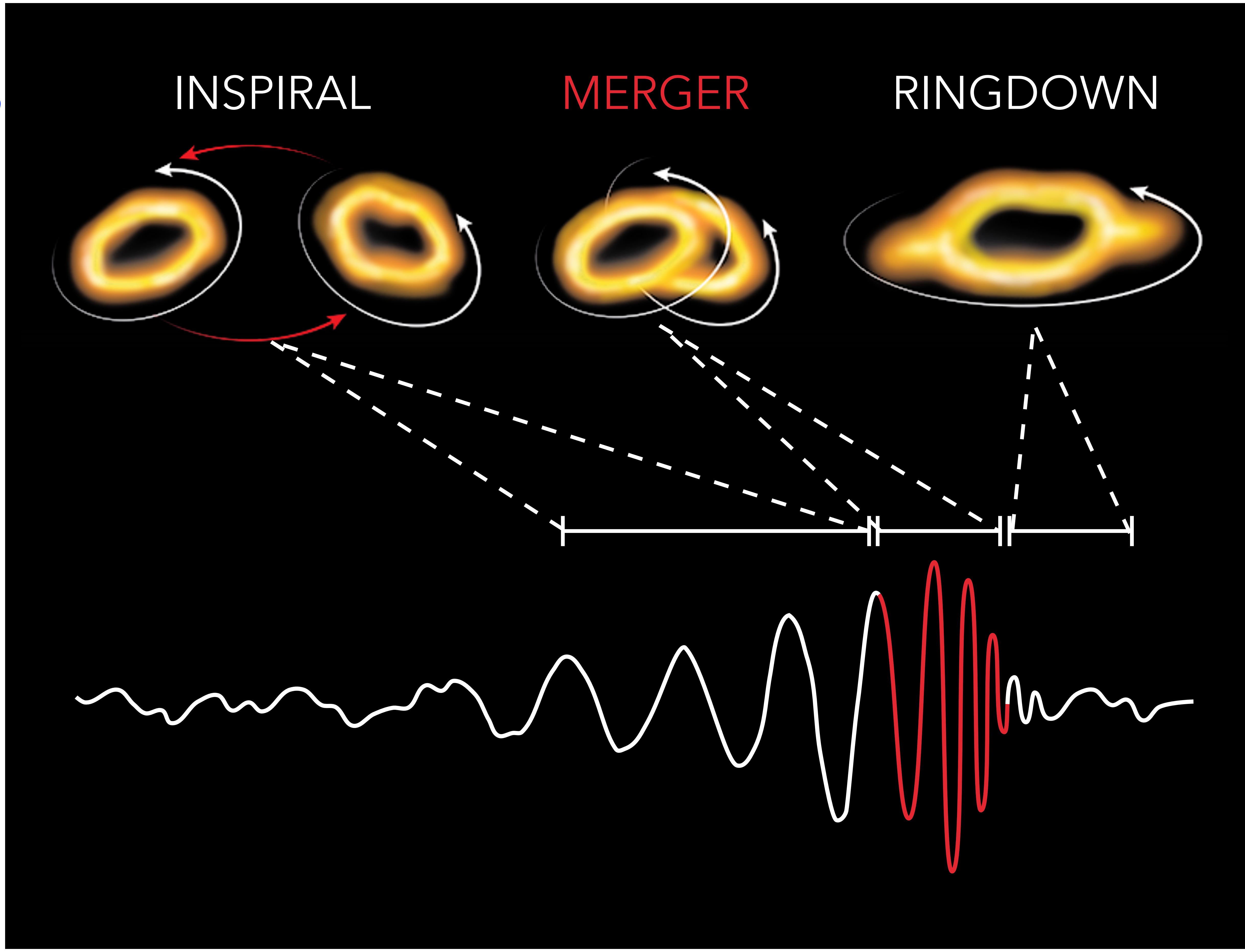
✴ **SO5**: Explore the Fundamental Nature of Gravity and Black Holes

✦ Are the massive objects that merge and their remnants consistent with being rotating MBHs described by the Kerr solution of General Relativity?

✦ **BH spectroscopy**: Quasi-normal modes should be a function of the mass and spin only according to the no-hair conjecture of General Relativity.

✦ Are there Exotic Compact Objects?

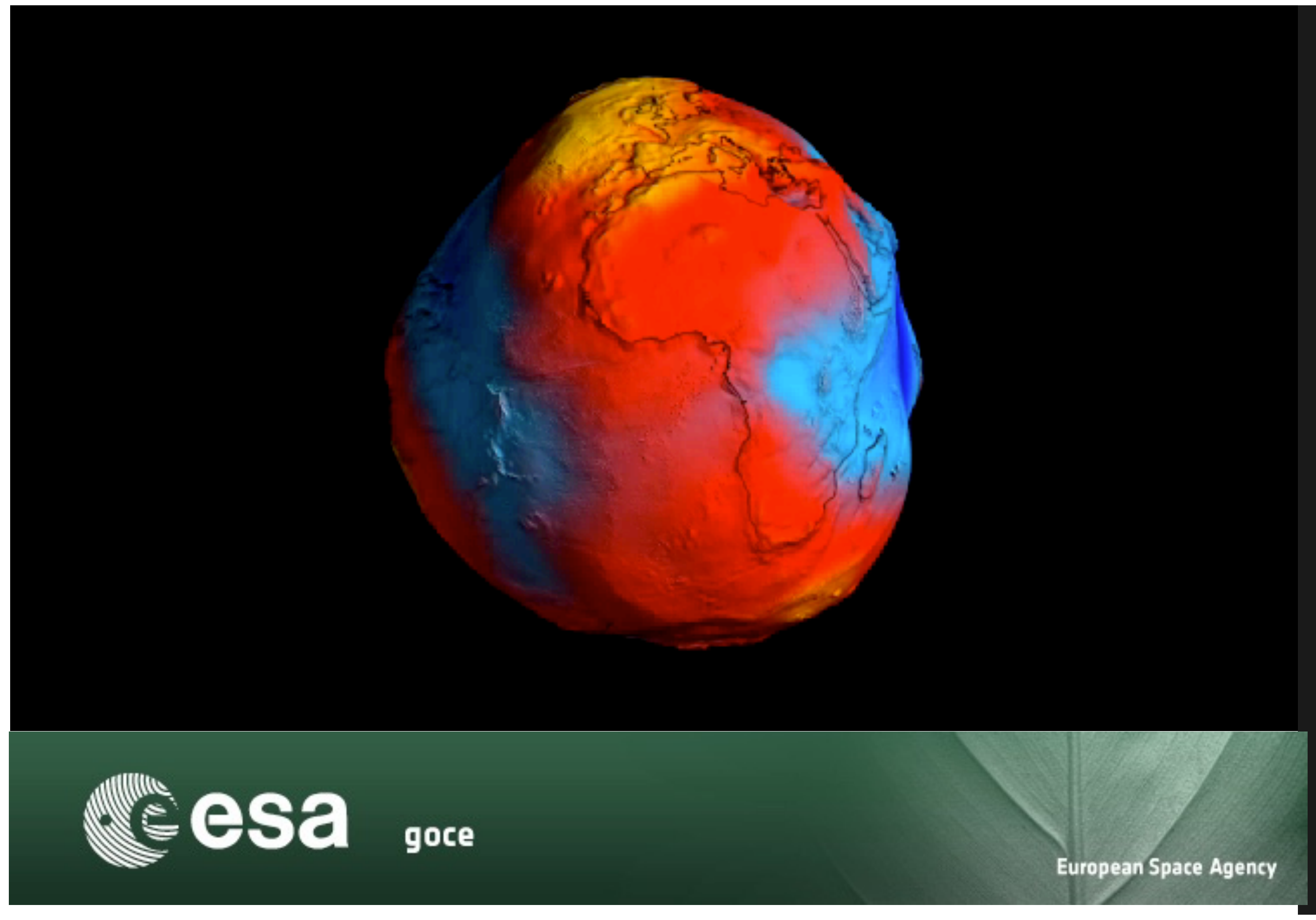




The Science of LISA

✴ **SO5**: Explore the Fundamental Nature of Gravity and Black Holes

- Accuracy in the mass of the MBH ~ 0.001%
- Absolute error in the Spin parameter of the MBH ~ 0.00001
- Accuracy in the Quadrupole moment of the MBH~0.01%



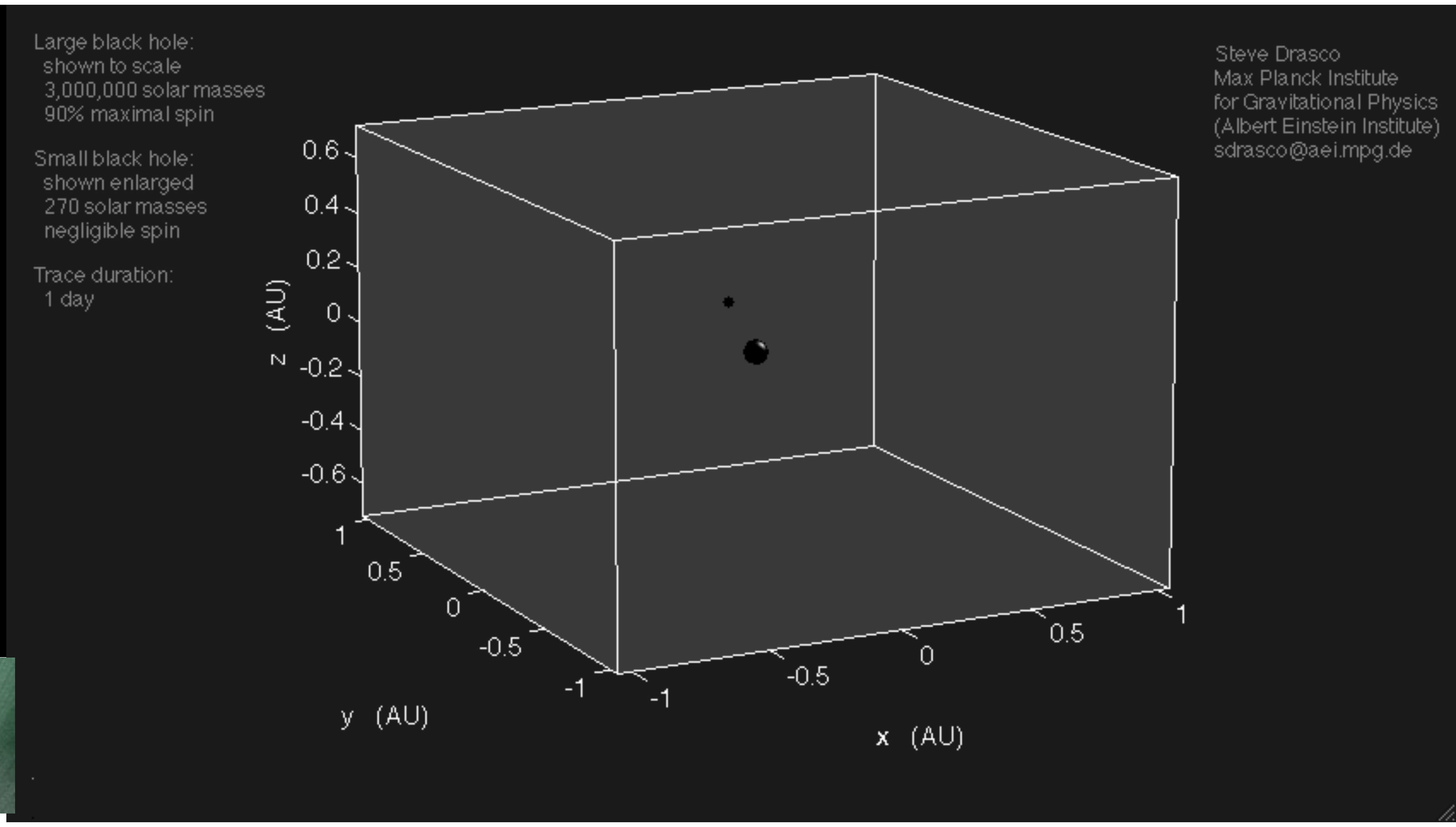
$$V(\vec{r}) = -G \sum_{\ell,m} \frac{M_{\ell m}}{r^{\ell+1}} Y_{\ell m}(\theta,\varphi)$$

$M_{\ell m}$: Multipole moments

GOCE can measure up to

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

EMRI System



For a Kerr BH in GR:

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

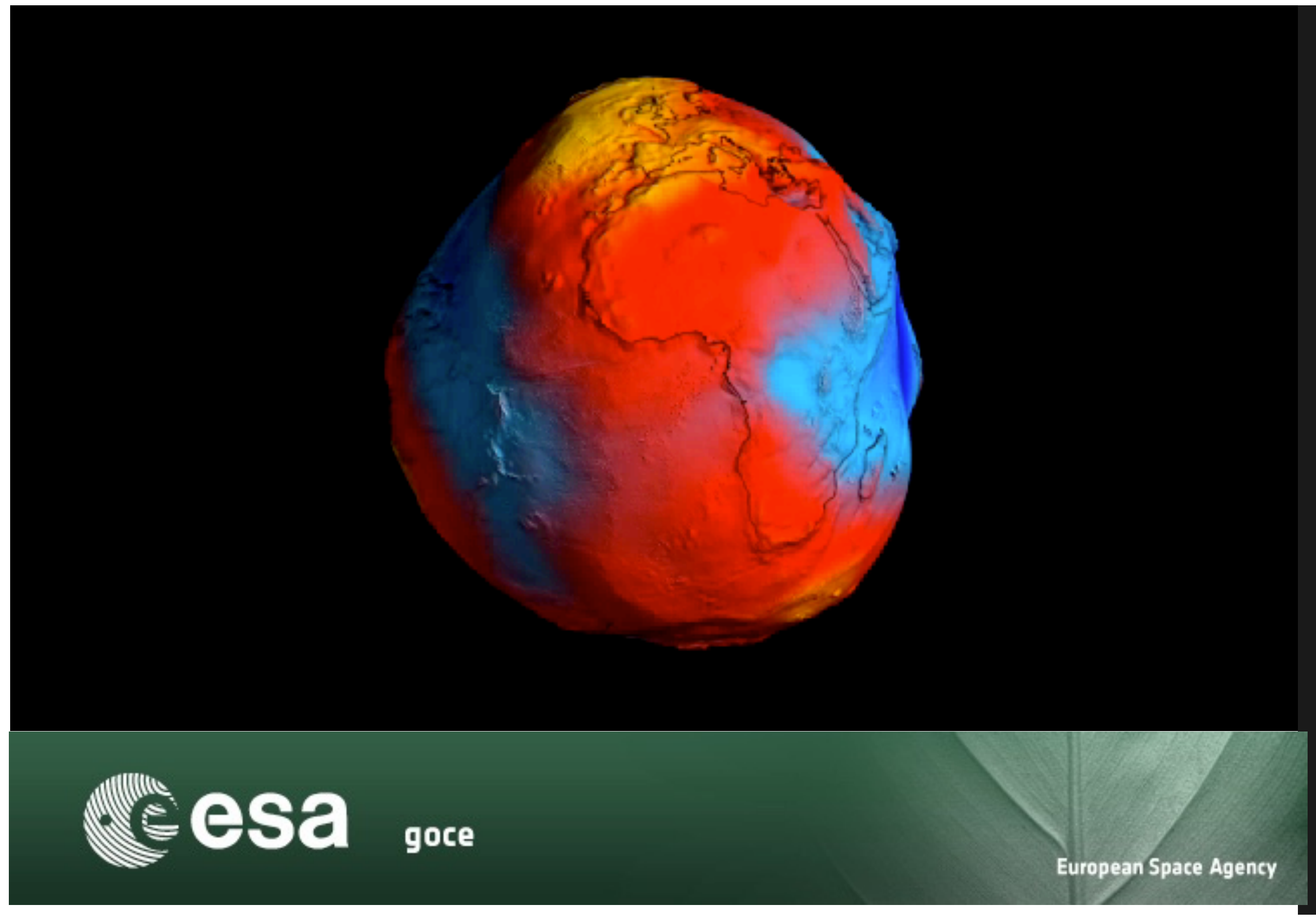
Tests of the Kerr geometry and/or theory of Gravity!

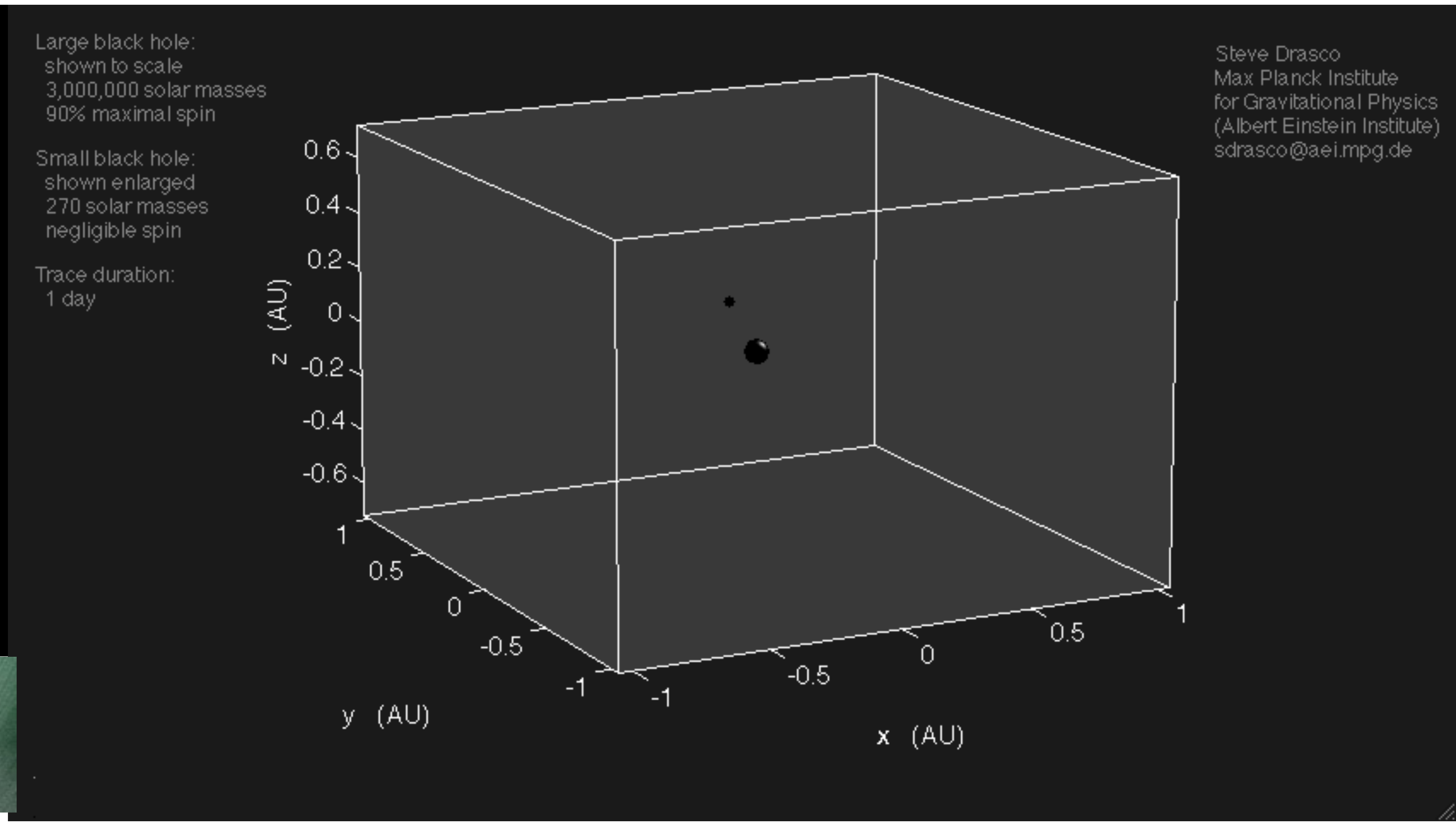
The Science of LISA

✳ **SO5**: Explore the Fundamental Nature of Gravity and Black Holes

- Accuracy in the mass of the MBH ~ 0.001%
- Absolute error in the Spin parameter of the MBH ~ 0.00001
- Accuracy in the Quadrupole moment of the MBH~0.01%

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

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

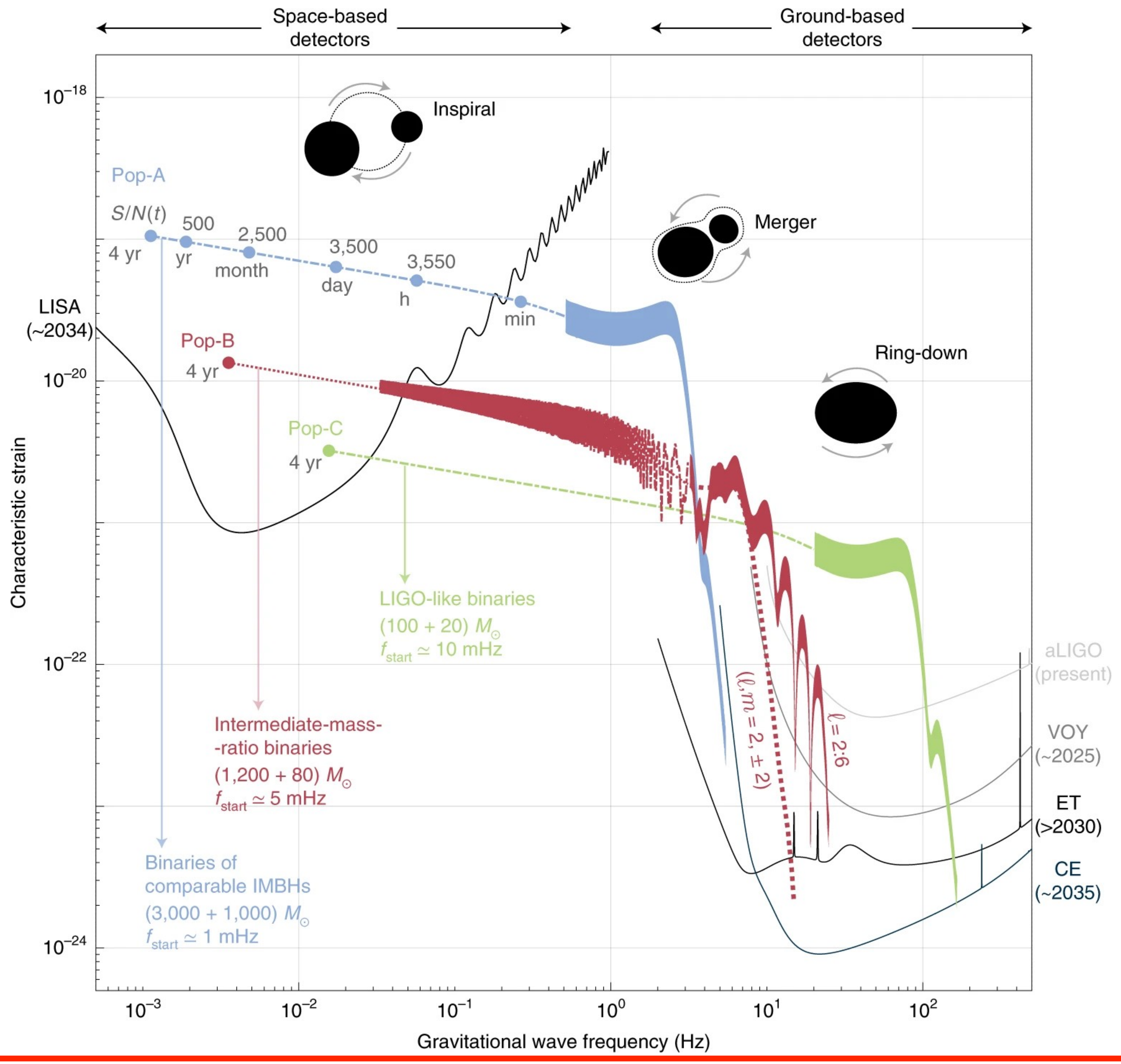
For a Kerr BH in GR:

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

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

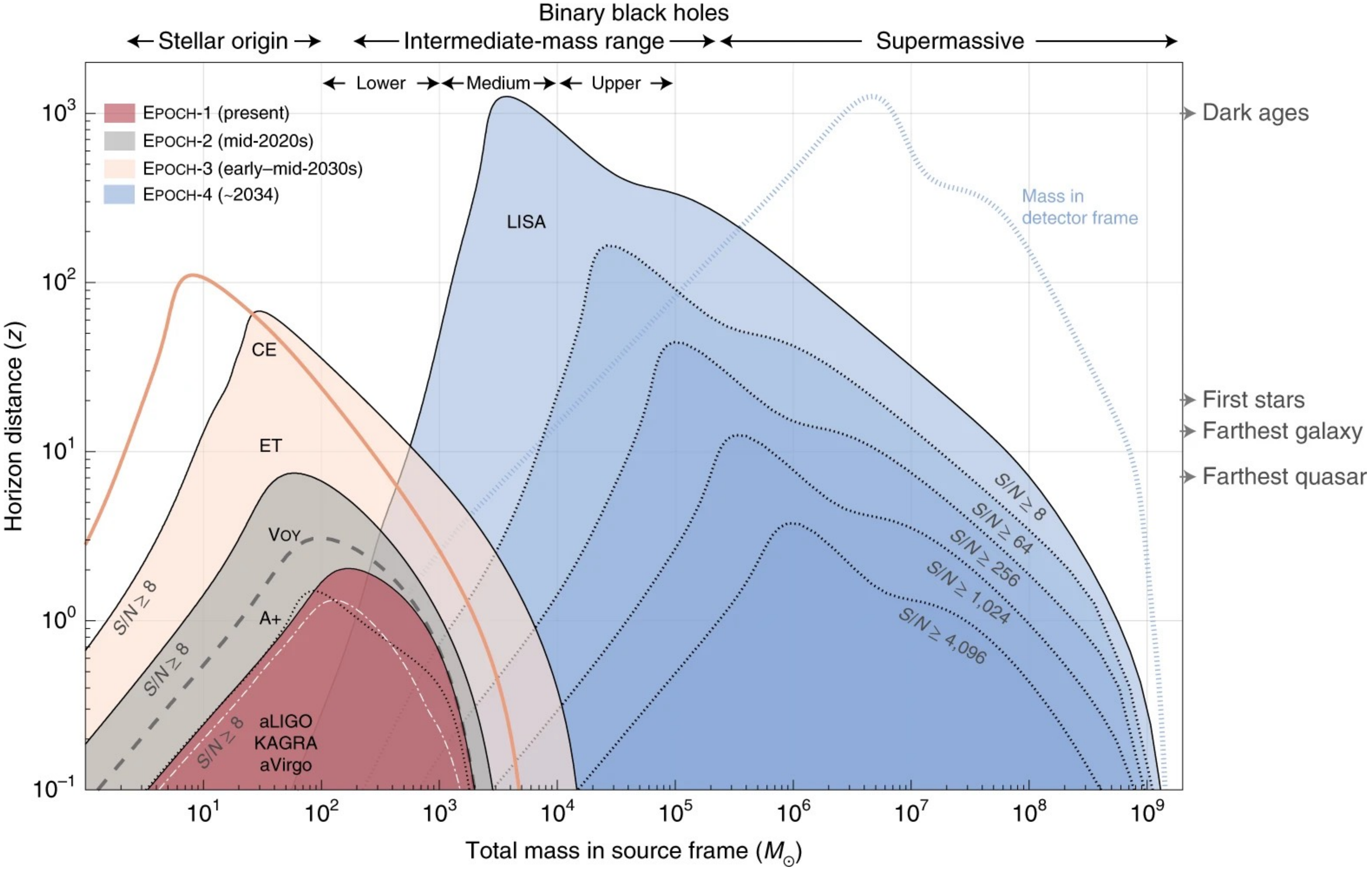
Multiband GW Astronomy with LISA and ET/CE

From: Jani, K., Shoemaker, D. & Cutler, C. (2020): *Detectability of **intermediate-mass black holes** in multiband gravitational wave astronomy*. Nat Astron **4**, 260–265

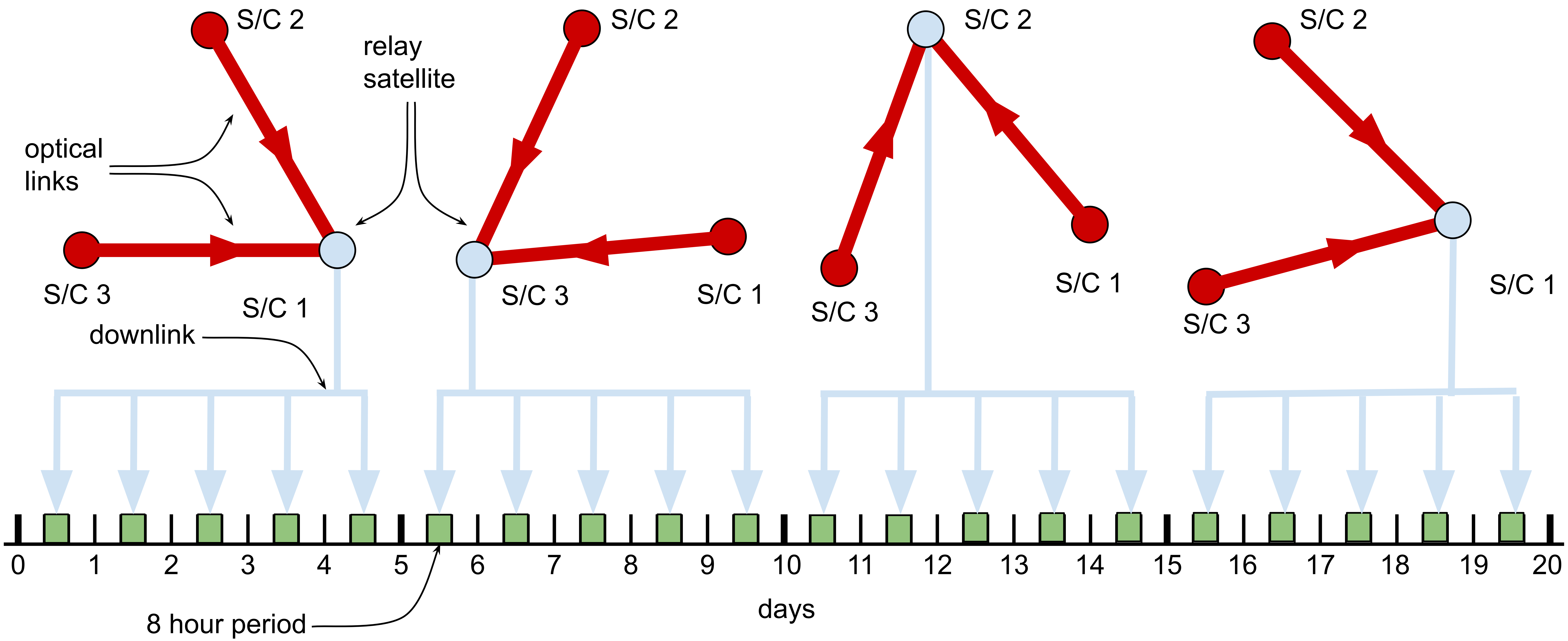


Multiband GW Astronomy with LISA and ET/CE

From: Jani, K., Shoemaker, D. & Cutler, C. (2020): *Detectability of **intermediate-mass black holes** in multiband gravitational wave astronomy*. Nat Astron **4**, 260–265

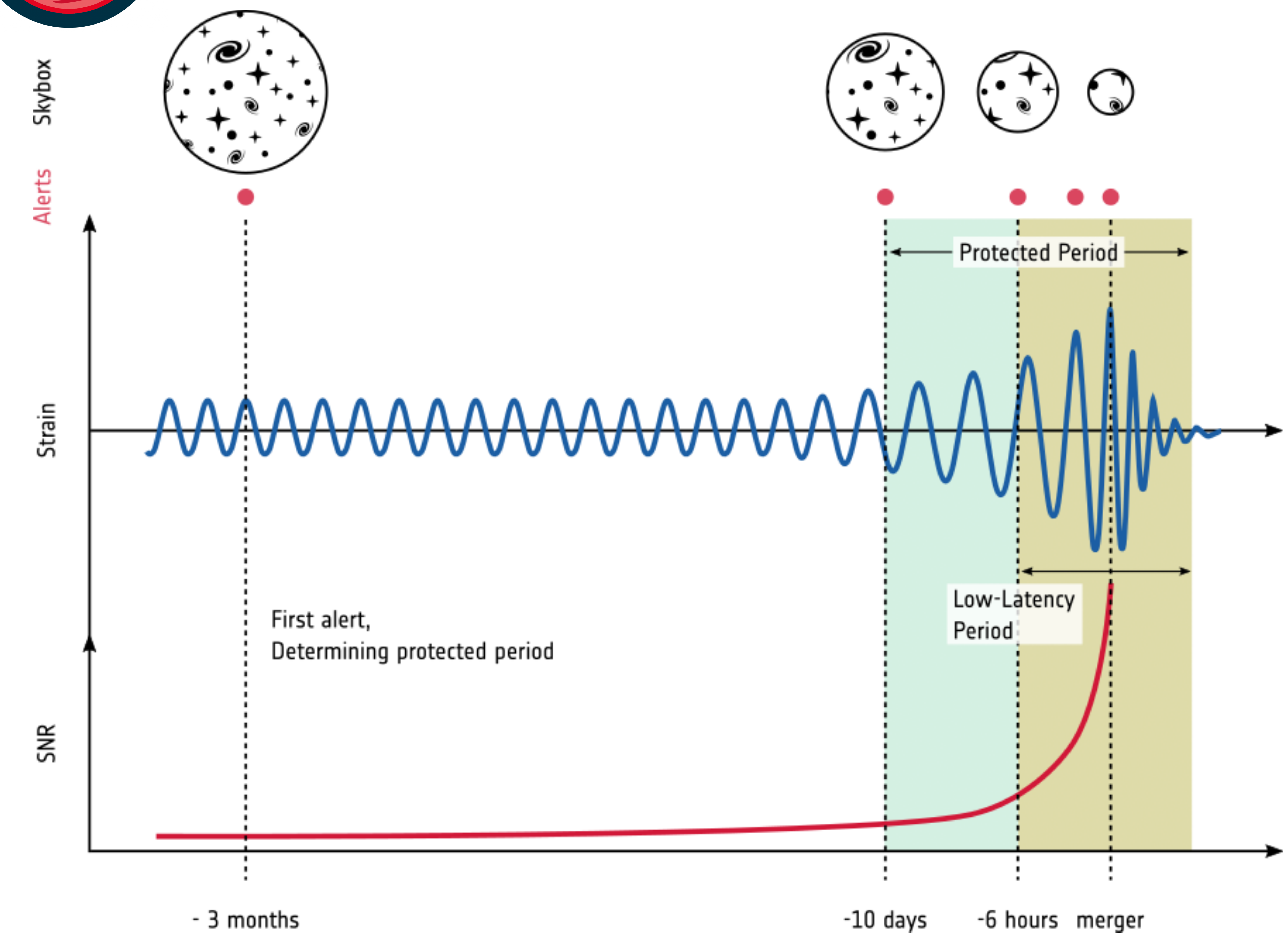


LISA Scientific Operations



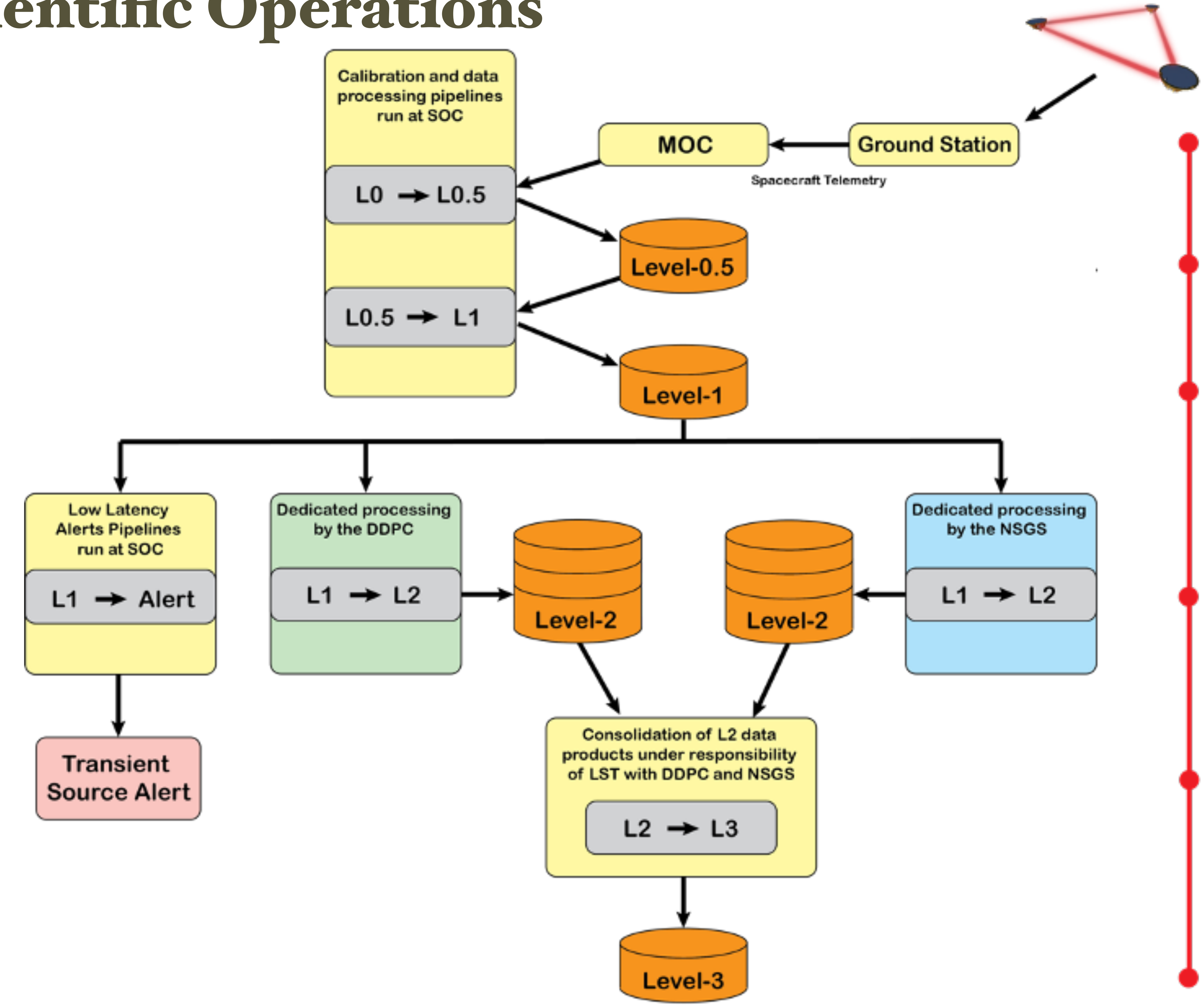
Communication with the constellation is done through one of the spacecraft ("relay") for 5 days, establishing a link for 8 hours a day. During these 5 days, the other spacecraft communicate to the relay spacecraft via the existing laser link. After the 5 days, the next spacecraft serves as relay, completing the cycle after 15 days.

LISA Scientific Operations



The protected period can be requested when the approximate time of the merger of a massive Black Hole binary is known. A few hours before the merger the accumulated signal-to-noise ratio (SNR) increases significantly and the uncertainty region for the sky position ("skybox") shrinks significantly to the point where other observatories can start observations. The low-latency period allows to monitor the continuously shrinking skybox and to update the alerts.

LISA Scientific Operations



- **L0 Telemetry: unprocessed at full resolution**
  Time ordered and time-stamped to UTC
- **Level 0.5: Calibrated instrument data**
  Time ordered and time-stamped to UTC
- **Level 1: Time-Delay Interferometry (TDI) combinations**
  At a minimum, A, E, T, X, Y, Z, Sagnac
- **Level 2: Individual detected sources**
  Including posterior probability densities and waveforms
- **Alerts: Transient source alert**
  Including waveform, estimated masses, distance, and sky location
- **Level 3: Catalogue of detected sources**
  Includes the coherent merging of the L2 data products

Carlos F. Sopuerta
carlos.f.sopuerta@csic.es
Institute of Space Sciences
(ICE, CSIC & IEEC)

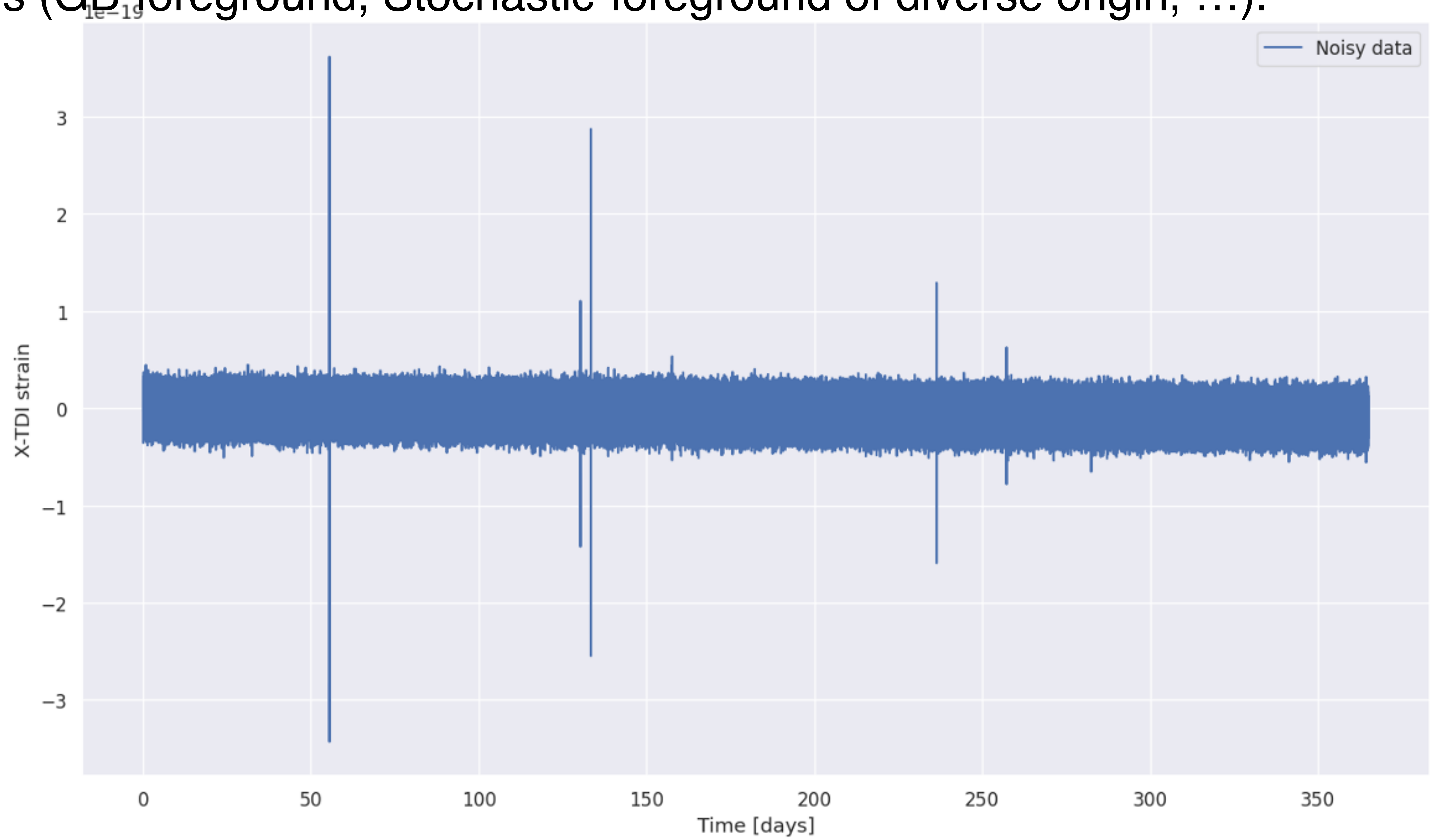
LISA Scientific Operations

✦Distributed Data Processing Centre (DDPC) Structure

LISA Scientific Operations

✴ The **Global Fit Problem**: Fit the LISA Data to a model that includes: An instrumental noise model; All the resolvable GW sources (MBHBs, GBs-including VBs, EMRIs, SOBHBs, others?); All the GW foregrounds (GB-foreground, Stochastic-foreground of diverse origin, …).

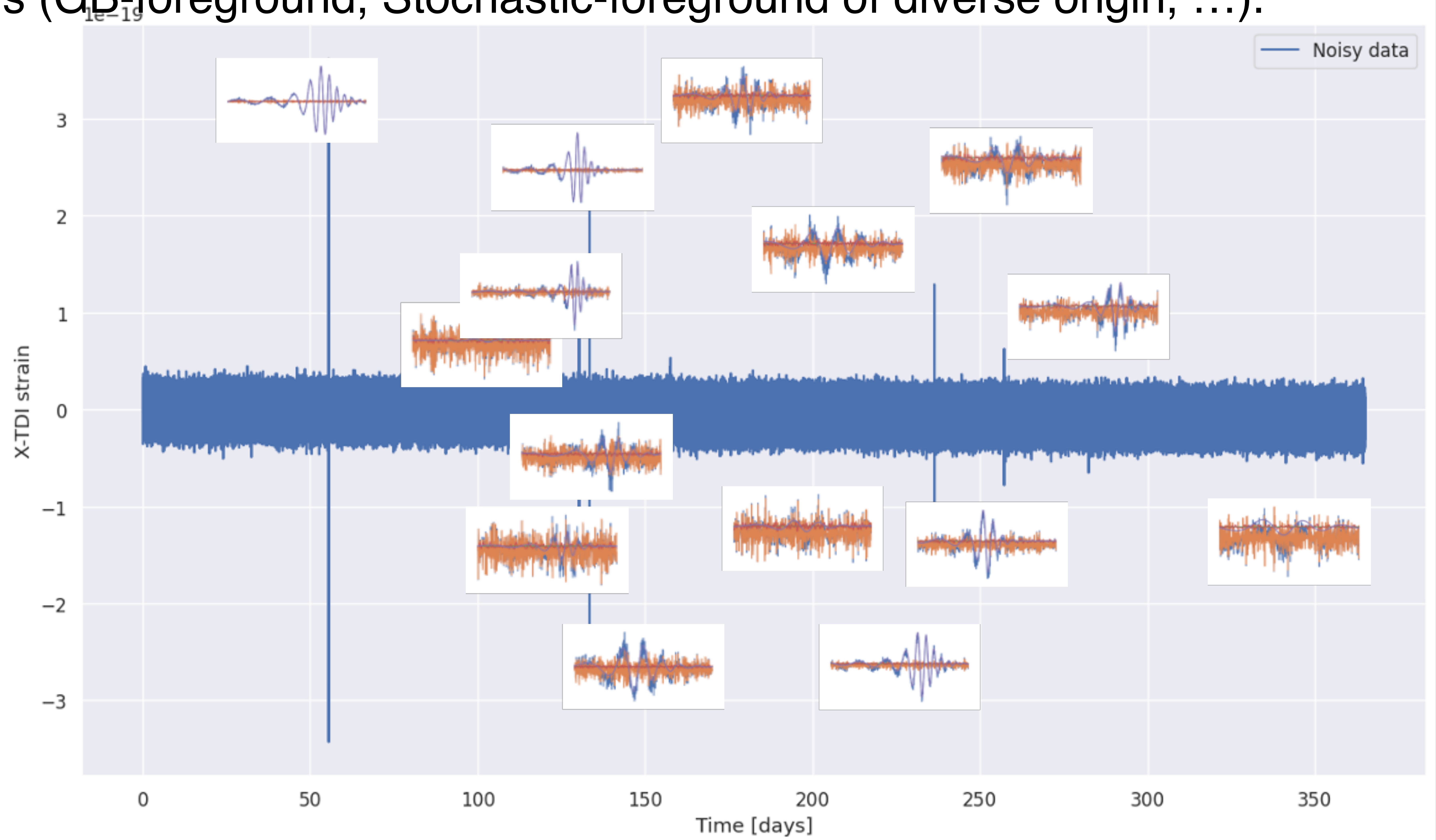
Long LISA data stream



LISA Scientific Operations

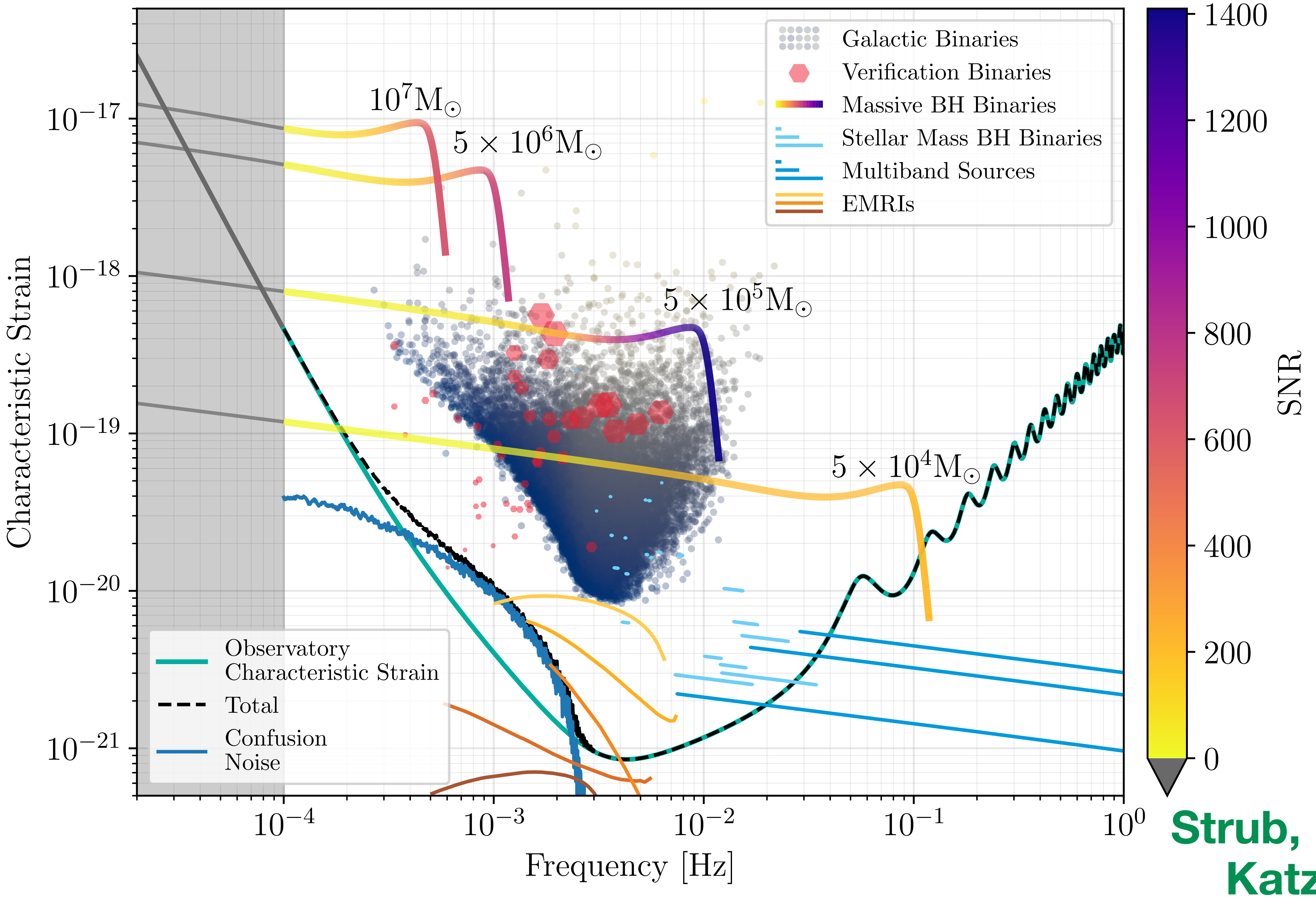
✳ The **Global Fit Problem**: Fit the LISA Data to a model that includes: An instrumental noise model; All the resolvable GW sources (MBHBs, GBs-including VBs, EMRIs, SOBHBs, others?); All the GW foregrounds (GB-foreground, Stochastic-foreground of diverse origin, …).

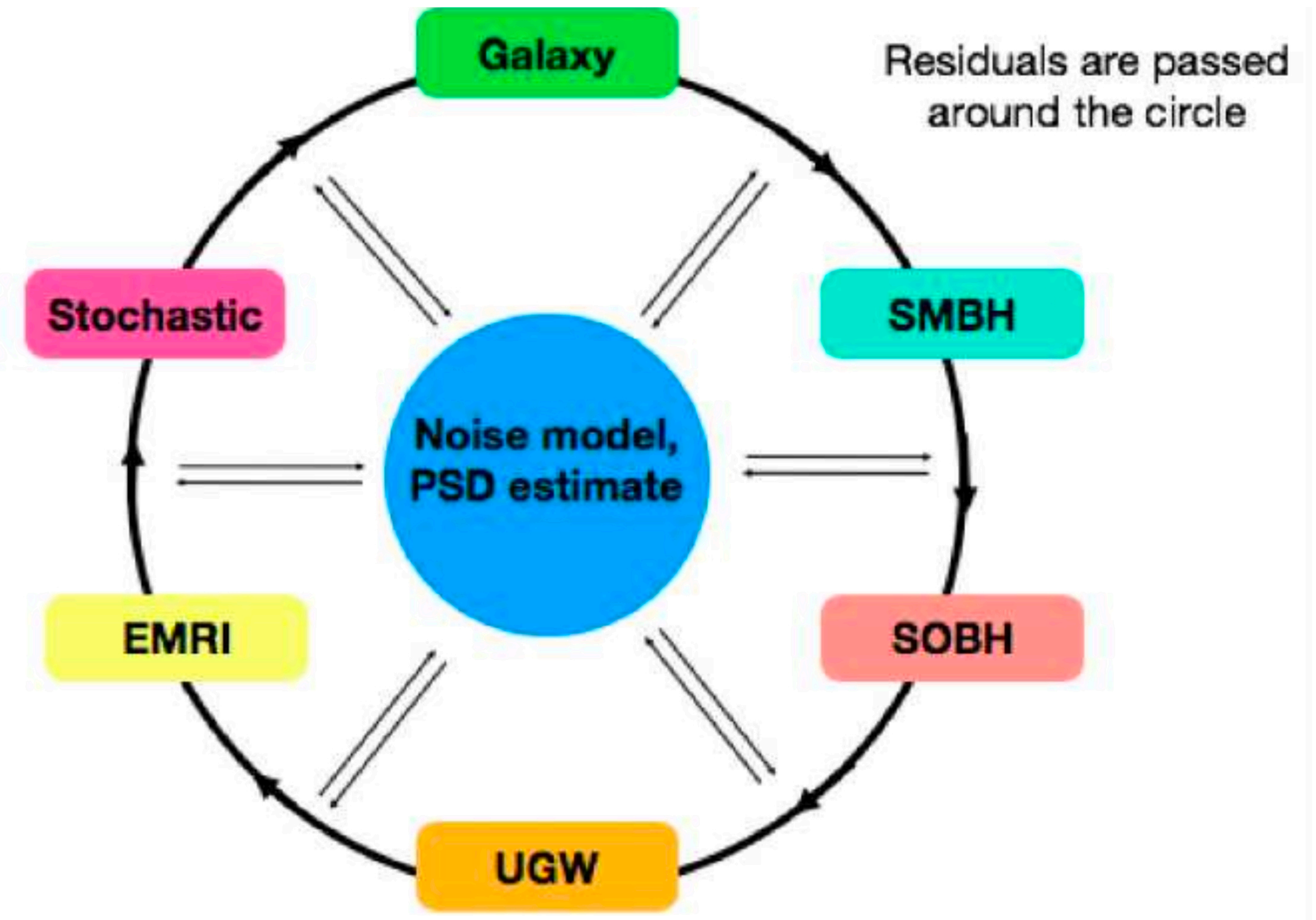
Long LISA data stream



LISA Scientific Operations

✳ The **Global Fit Problem**: Fit the LISA Data to a model that includes: An instrumental noise model; All the resolvable GW sources (MBHBs, GBs-including VBs, EMRIs, SOBHBs, others?); All the GW foregrounds (GB-foreground, Stochastic-foreground of diverse origin, …).





Littenberg & Cornish: 2301.03673
Strub, Ferraioli, Schmelzbach, Stähler & Giardini: 2403.15318
Katz, Karnesis, Korsakova, Gair & Stergioulas: 2405.04690
Deng, Babak, Le Jeune, Marsat, Plagnol & Sartirana: 2501.10277

LISA Scientific Operations

✦ Spanish Contribution to the LISA Ground Segment, as established in the Multi-Lateral Agreement (MLA) between ESA and member states:

Spain

- Be responsible for the development of 1 instance of the following pipelines of the DDPC:
    - Global Fit Pipeline;
- Be responsible for the deployment in Spain of 1 DCC and contribute to the system engineering work packages;
- Contribute to the software and data processing (contribution to other work packages than listed before) of the SGS and to the operations.

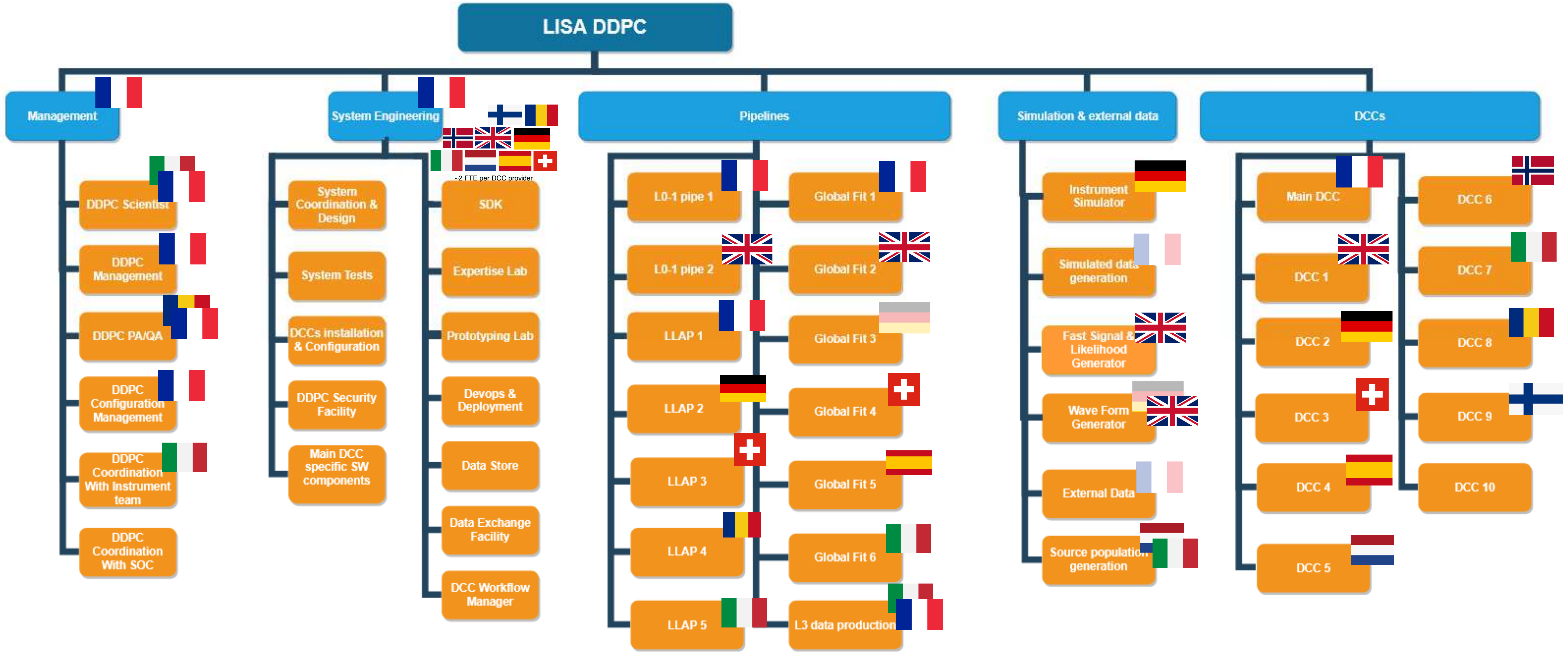
LISA Scientific Operations

✦ Spanish Contribution to the LISA Ground Segment, as established in the Multi-Lateral Agreement (MLA) between ESA and member states:

Spain

- Be responsible for the development of 1 instance of the following pipelines of the DDPC:
  - Global Fit Pipeline;
- Be responsible for the deployment in Spain of 1 DCC and contribute to the system engineering work packages;
- Contribute to the software and data processing (contribution to other work packages than listed before) of the SGS and to the operations.

DDPC contribution status (07/03/2023)



LISA Scientific Operations

✦ Spanish Contribution to the LISA Ground Segment, as established in the Multi-Lateral Agreement (MLA) between ESA and member states:

Spain

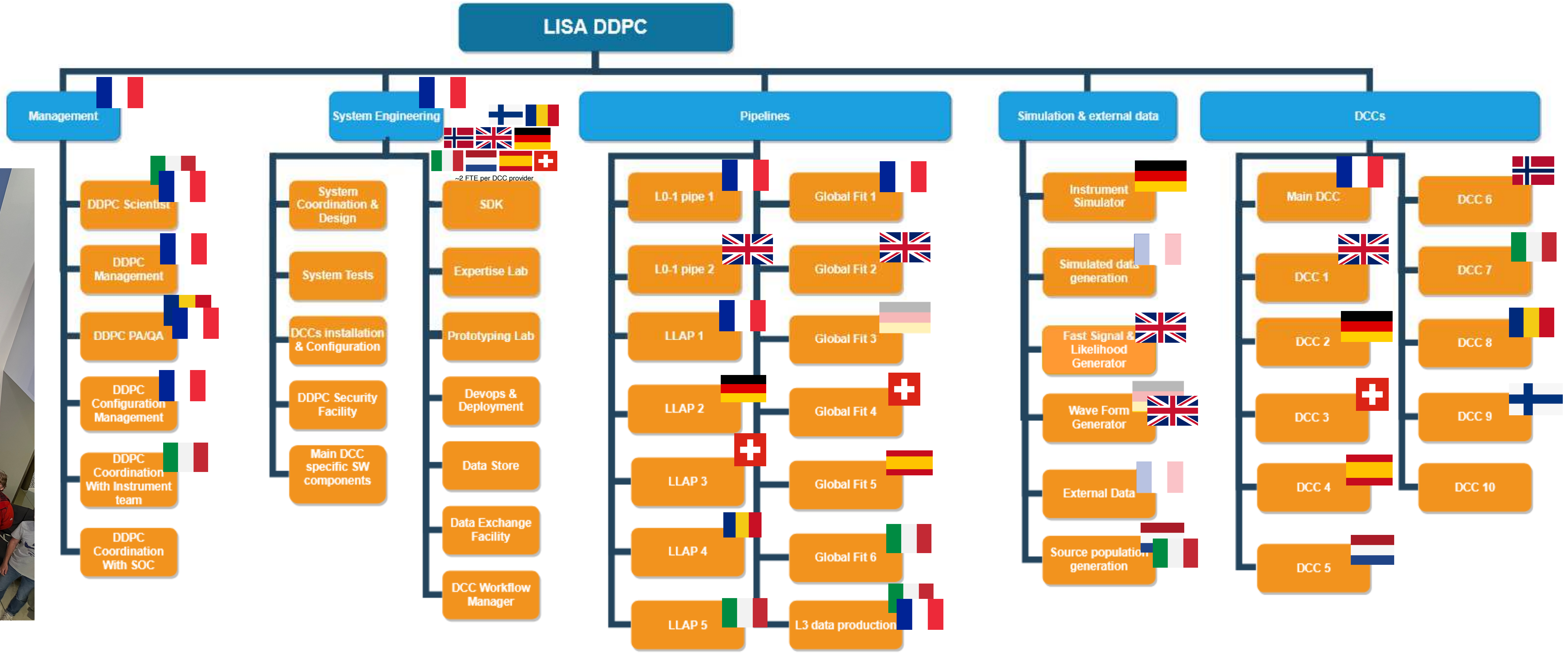
- Be responsible for the development of 1 instance of the following pipelines of the DDPC:
  - Global Fit Pipeline;
- Be responsible for the deployment in Spain of 1 DCC and contribute to the system engineering work packages;
- Contribute to the software and data processing (contribution to other work packages than listed before) of the SGS and to the operations.

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

ESA | NASA lisa

Toulouse (France)

DDPC contribution status (07/03/2023)



Carlos F. Sopuerta
carlos.f.sopuerta@csic.es
Institute of Space Sciences (ICE, CSIC & IEEC)

LISA Spain Meeting 2024

✤ **The main goal of these meetings is to bring together the Spanish community interested in working in LISA science and to support the Spanish contribution to the mission.**

LISA Spain Meeting 2024

- **The main goal of these meetings is to bring together the Spanish community interested in working in LISA science and to support the Spanish contribution to the mission.**
- **First Meeting: October 15th-16th, 2024. At the Institute for Space Sciences (Bellaterra, Barcelona) ~ 100 people.**

Carlos F. Sopuerta
carlos.f.sopuerta@csic.es
Institute of Space Sciences
(ICE, CSIC & IEEC)

LISA Spain Meeting 2024

- **The main goal of these meetings is to bring together the Spanish community interested in working in LISA science and to support the Spanish contribution to the mission.**
- **Next Meeting: October 23rd-24th, 2025. At the CSIC main Campus (Madrid)**

Spanish Community involved in LISA

•**IEEC (UB + UPC + ICE-CSIC)**: Instrument lead, Data Analysis, Waveforms, Science Exploitation/interpretation, DDPC contribution, DCC contribution. Contact: Carlos F. Sopuerta, Miquel Nofrarias (CSIC), Juan J. Ramos-Castro (UPC), J.Portell (UB). All the IEEC legs participate in the LISA Consortium.
•**UIB**: Data Analysis, Waveforms, DDPC contribution. In the LISA Consortium. Contact: Alicia Sintes.
•**UV**: Data Analysis. Contact: Milton Ruiz, Pablo Cerdá-Durán, José A. Font, Daniela Doneva. In the LISA Consortium.
•**IFIC**: Science Exploitation (cosmology), Data Analysis. Contact: Daniel Figueroa, Roberto Ruiz de Austri. In the LISA Consortium.
•**EHU-UPV**: Science Exploitation/interpretation. Contact: José Juan Blanco-Pillado. In the LISA Consortium.
•**IAC**: Multimessenger astronomy with LISA. Contact: Josefa Becerra González. Interested in the search for LISA electromagnetic counterpats.
•**UPV**: LISA Astrophysics. Contact: Pau Amaro-Seoane In the LISA Consortium.
•**UM**: LISA Fundamental Physics. Contact: Kostas Glampedakis. In the LISA Consortium.
•**UAM/IFT-CSIC**: LISA Cosmology and Fundamental Physics. Data Analysis. Contact: Juan García-Bellido. In the LISA Consortium.
•**IFCA**: LISA Astrophysics. Contact: José M. Diego. In the LISA consortium.
•**IEM-CSIC**: LISA Cosmology and Science exploitation. Contact: Gianluca Calgani. Guillermo A. Mena. In the LISA Consortium.
•**IAA-CSIC**: Multimessenger astronomy with LISA. Contacts:Angela Gardini, Alberto J. Castro-Tirado, Carlos Barceló. In the LISA Consortium.
•**CIEMAT**: Data Analysis and science exploitation. Contact: Nicanor Colino. In the ET collaboration.
•**IGFAE**: Data Analysis and science exploitation. Contact: Thomas Dent. In the LISA Consortium.
•**UCA**: LISA Instrumental investigations. Contact: Ignacio Mateos. In the LISA Consortium.
•**ULS**: Data Analysis. Contact: Francisco Rivas. Work in LISA Pathfinder. In the LISA Consortium.
•**IFAE**: LISA Cosmology and Science exploitation/interpretation. Contact: Diego Blas. In the LISA Consortium
•**USAL**: LISA Astrophysics. Contact: M. Angeles Perez García In the ET collaboration.
•**US**: Characterization of LISA noise. Contact: Guillermo Pacheco. In the LISA Consortium
•**UCM**: Fundamental Physics with LISA. Contact: Padro Martín Moruno. In the LISA Consortium.
•**USC**: LISA Data Analysis. Contact: Thomas Dent.
•**UPM**: Cosmology with LISA. Contact: Ester Ruiz Morales. In the LISA Consortium.
•**UGR**: Cosmology and Fundamental Physics with LISA. Contact: Mikael Chala. In the LISA Consortium.

BSC: Interested in DCC Contribution, Data Analysis methods.
PIC: Interested in DCC Contribution.

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 and beyond.**

Acknowledgements

Many Thanks for your attention!

✤ **Work in LISA has been supported by contracts PID2019-106515GB-I00 and PID2022-137674NB-I00 (MCIN/AEI/10.13039/501100011033) and 2017-SGR-1469 and 2021-SGR-01529 (AGAUR, Generalitat de Catalunya). This work has been also partially supported by the program *Unidad de Excelencia María de Maeztu* CEX2020-001058-M (Spanish Ministry of Science and Innovation).**

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

AGENCIA ESTATAL DE INVESTIGACIÓN

EXCELENCIA MARÍA DE MAEZTU

AGAUR Agència de Gestió d'Ajuts Universitaris i de Recerca