GRAVITATIONAL WAVE SCIENCE IN THE LOW-FREQUENCY BAND WITH LISA

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LI-INTERNATIONAL MEETING ON FUNDAMENTAL PHYSICS.
BENASQUE SCIENCE CENTER, SEP 09 - SEP 14, 2024

CSIC
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Institute of Space Sciences
IEEC
EXCELENCIA MARÍA DE MAEZTU

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- Sources of Gravitational Waves for LISA
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- LISA Scientific Operations and Exploitation
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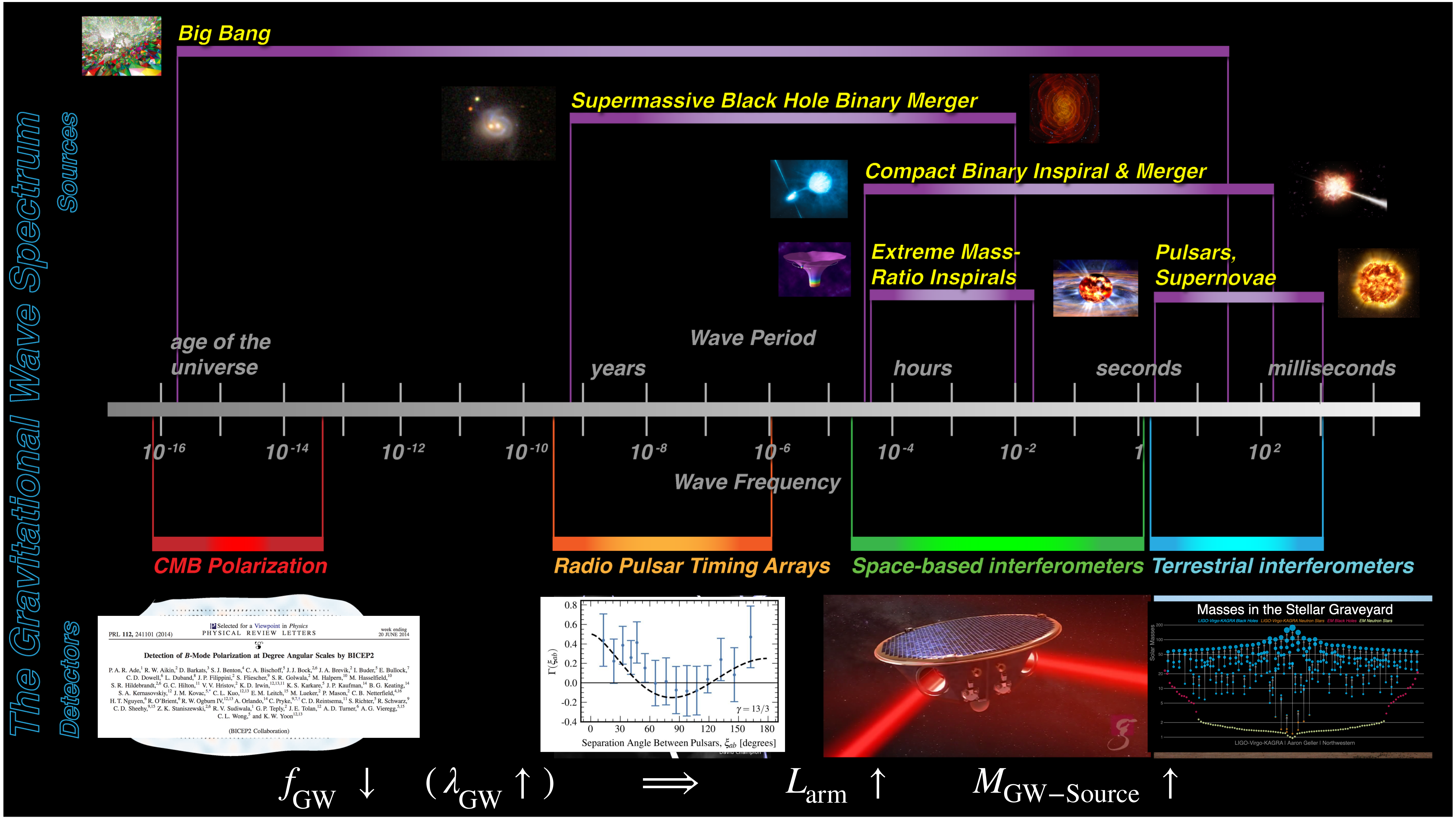
The Gravitational Wave Spectrum



Credit: Ira Thorpe (NASA)

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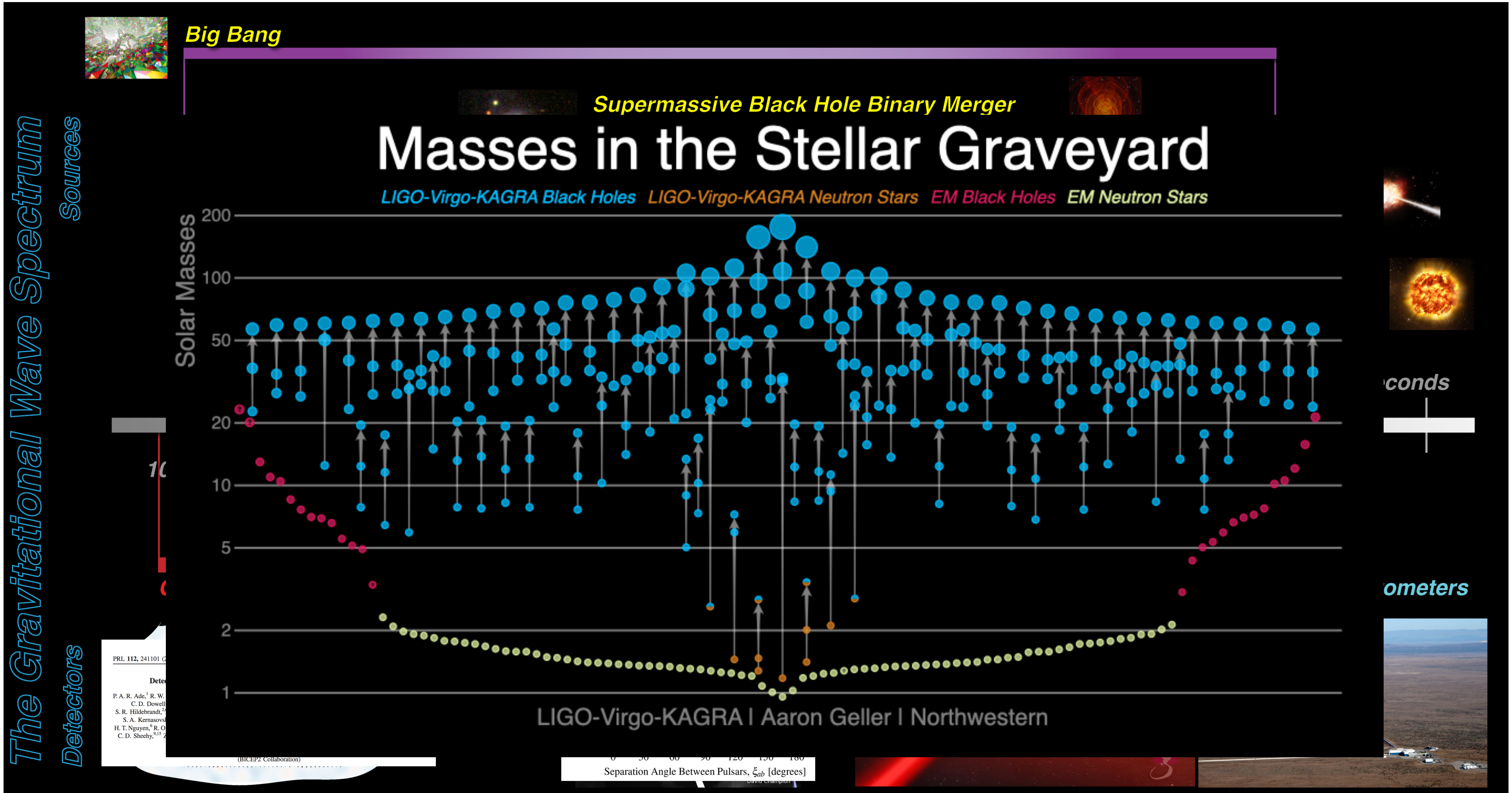

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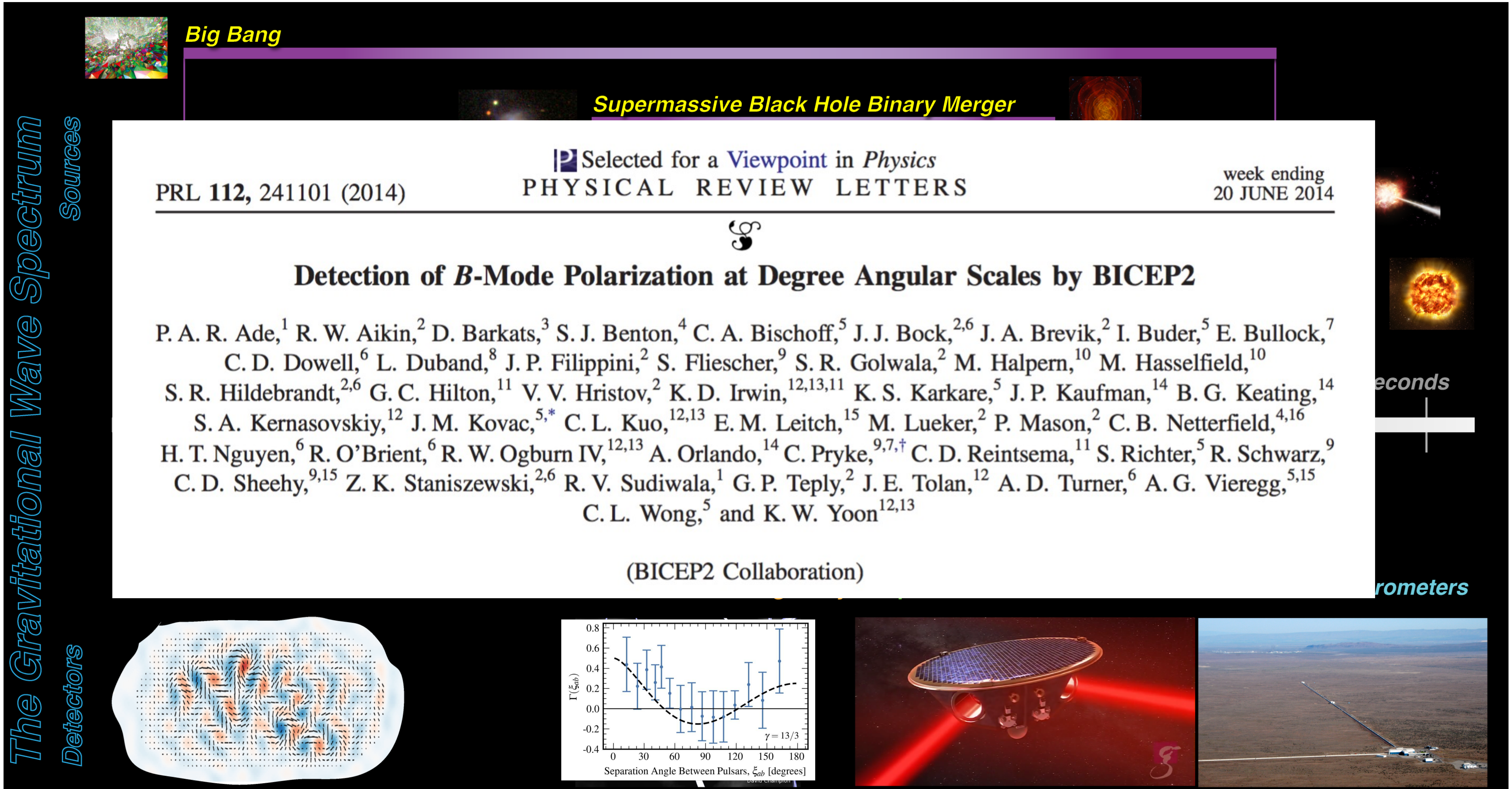

Selected for a Viewpoint in *Physics*
PRL **112,** 241101 (2014) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

Detection of *B*-Mode Polarization at Degree Angular Scales by BICEP2

P. A. R. Ade,[1] R. W. Aikin,[2] D. Barkats,[3] S. J. Benton,[4] C. A. Bischoff,[5] J. J. Bock,[2,6] J. A. Brevik,[2] I. Buder,[5] E. Bullock,[7] C. D. Dowell,[6] L. Duband,[8] J. P. Filippini,[2] S. Fliescher,[9] S. R. Golwala,[2] M. Halpern,[10] M. Hasselfield,[10] S. R. Hildebrandt,[2,6] G. C. Hilton,[11] V. V. Hristov,[2] K. D. Irwin,[12,13,11] K. S. Karkare,[5] J. P. Kaufman,[14] B. G. Keating,[14] S. A. Kernasovskiy,[12] J. M. Kovac,[5,*] C. L. Kuo,[12,13] E. M. Leitch,[15] M. Lueker,[2] P. Mason,[2] C. B. Netterfield,[4,16] H. T. Nguyen,[6] R. O'Brient,[6] R. W. Ogburn IV,[12,13] A. Orlando,[14] C. Pryke,[9,7,†] C. D. Reintsema,[11] S. Richter,[5] R. Schwarz,[9] C. D. Sheehy,[9,15] Z. K. Staniszewski,[2,6] R. V. Sudiwala,[1] G. P. Teply,[2] J. E. Tolan,[12] A. D. Turner,[6] A. G. Vieregg,[5,15] C. L. Wong,[5] and K. W. Yoon[12,13]

(BICEP2 Collaboration)

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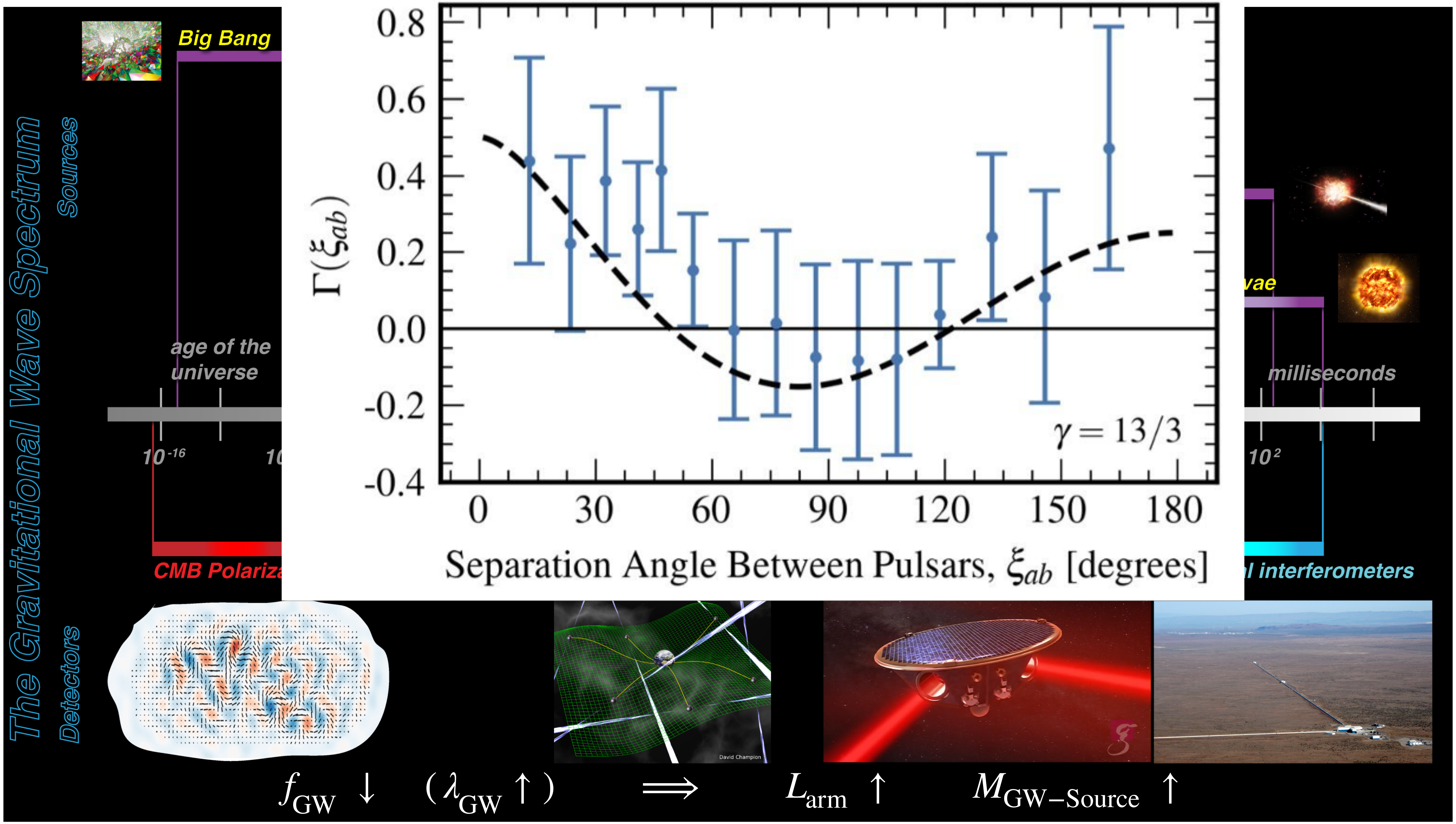

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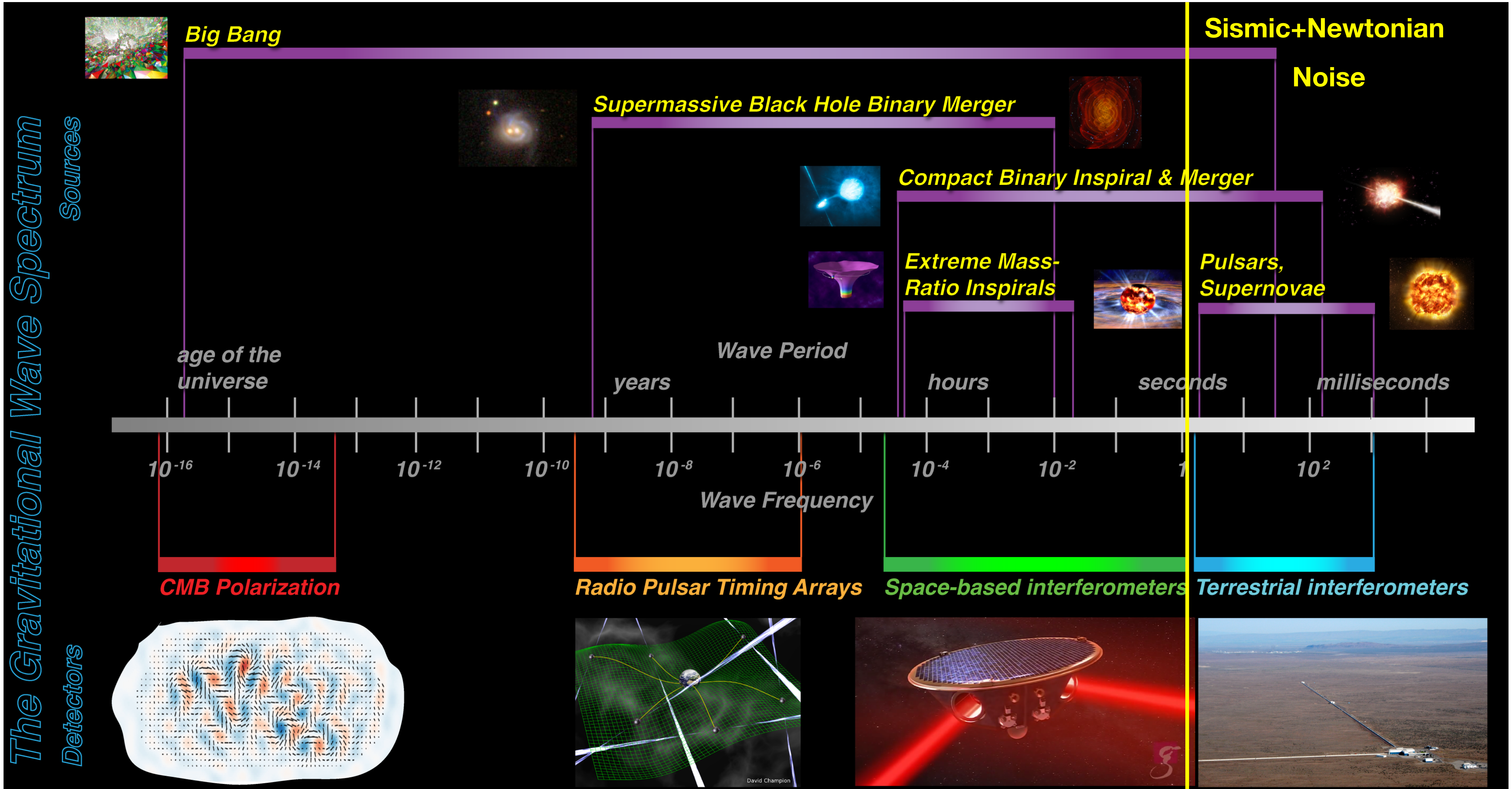

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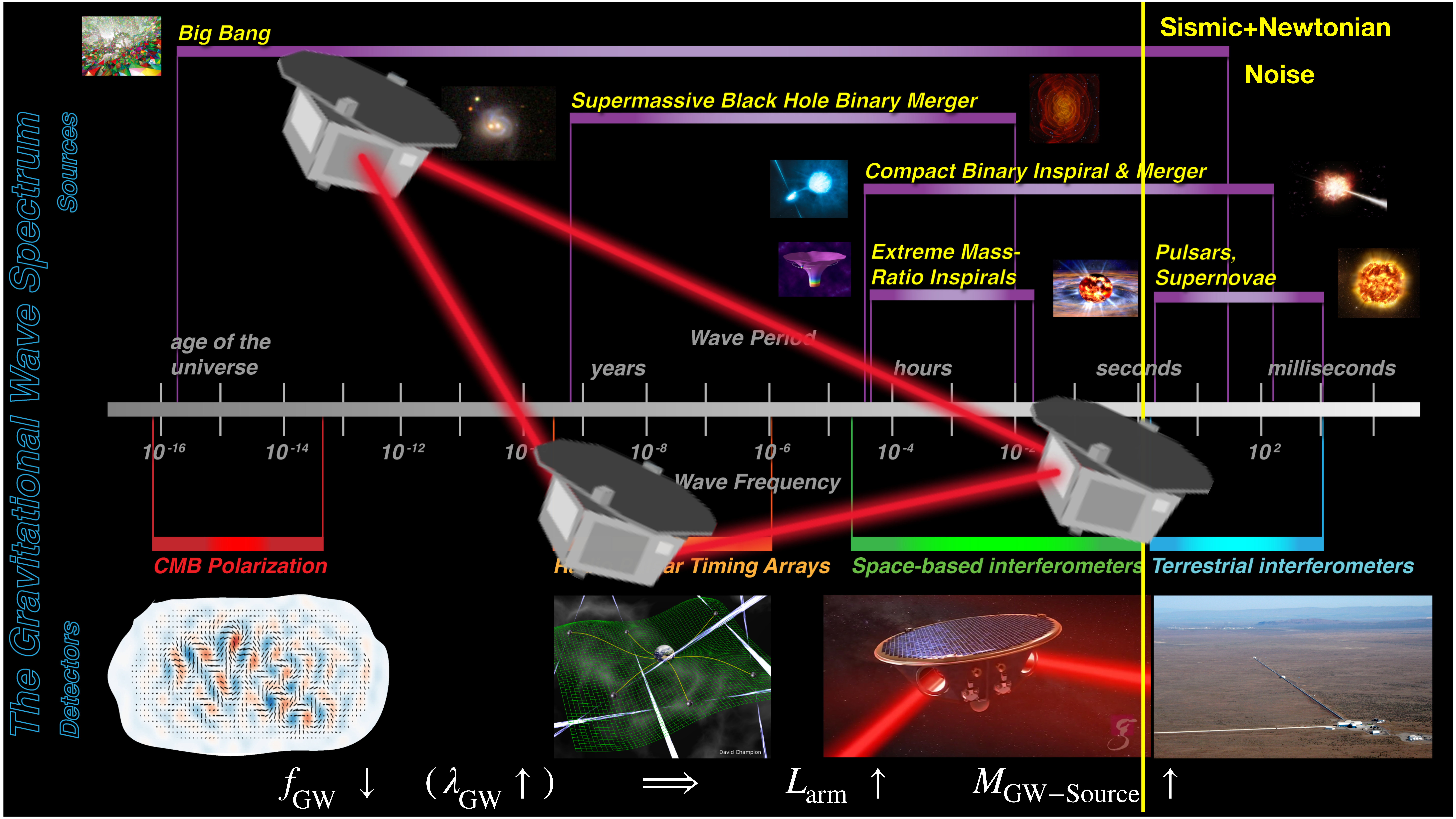

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Gravitational Wave Detection from Space

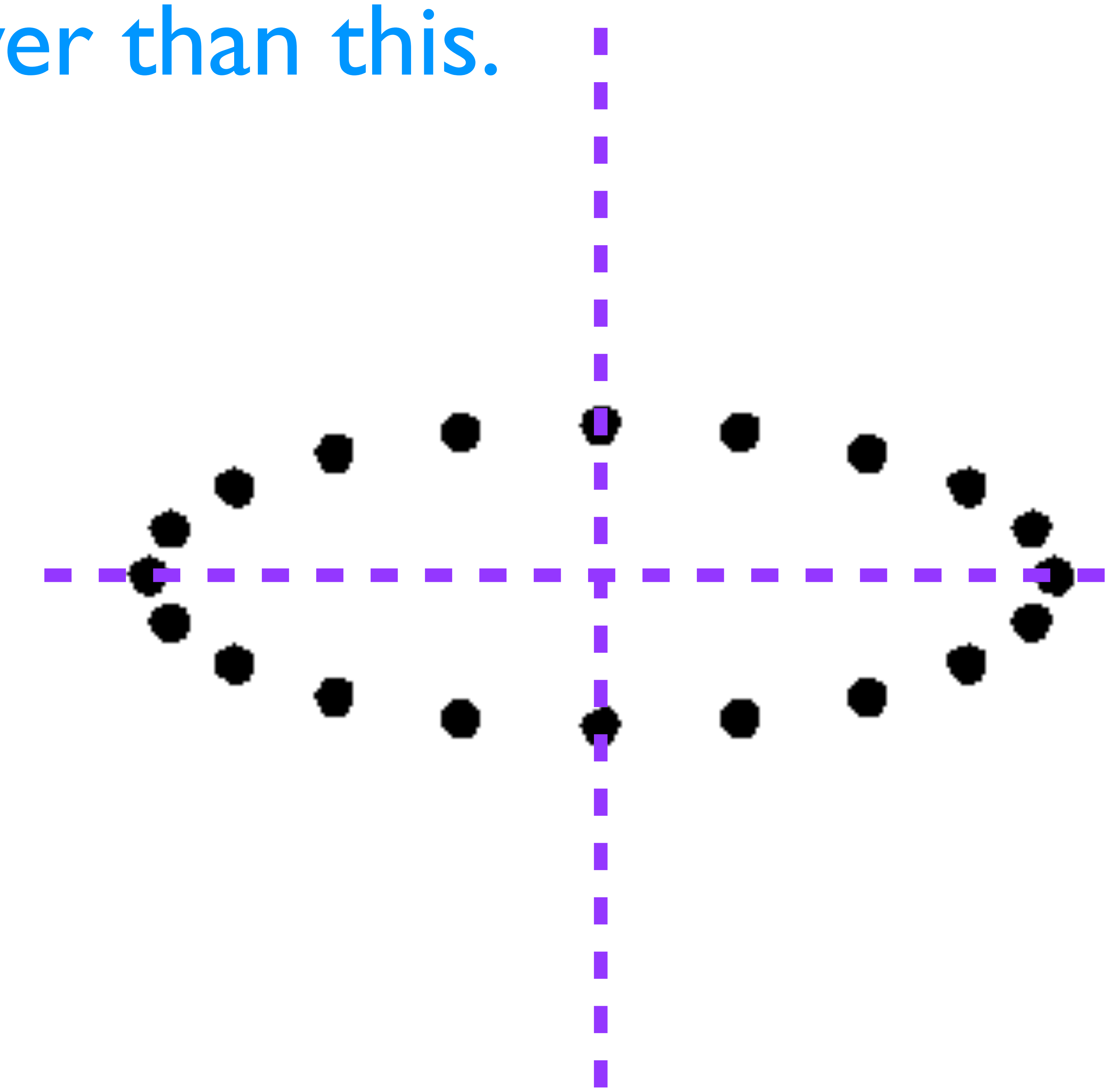
✴ We want to detect GWs via the slowly-oscillating (~1 hour), relative motion they impose onto far apart **free-falling** bodies.

That is, ~ 200 times slower than this.

$$\frac{\delta L}{L} \propto \mathrm{h}_{\mathrm{GW}}$$

$$h_{\mathrm{GW}} \sim 10^{-21}$$

$$\delta L_{\mathrm{LISA}} \sim 10^{-11}\,\mathrm{m}$$



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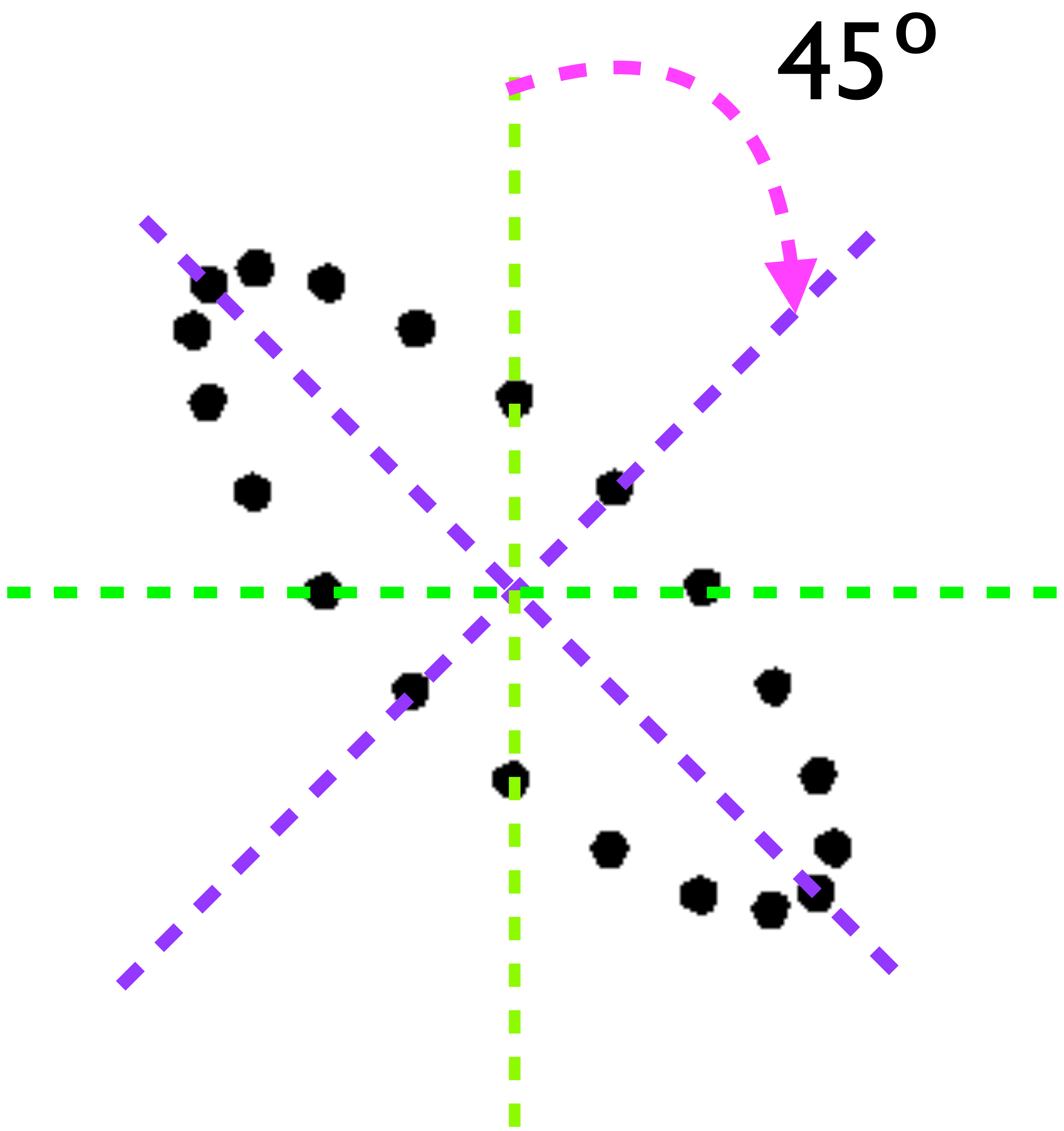

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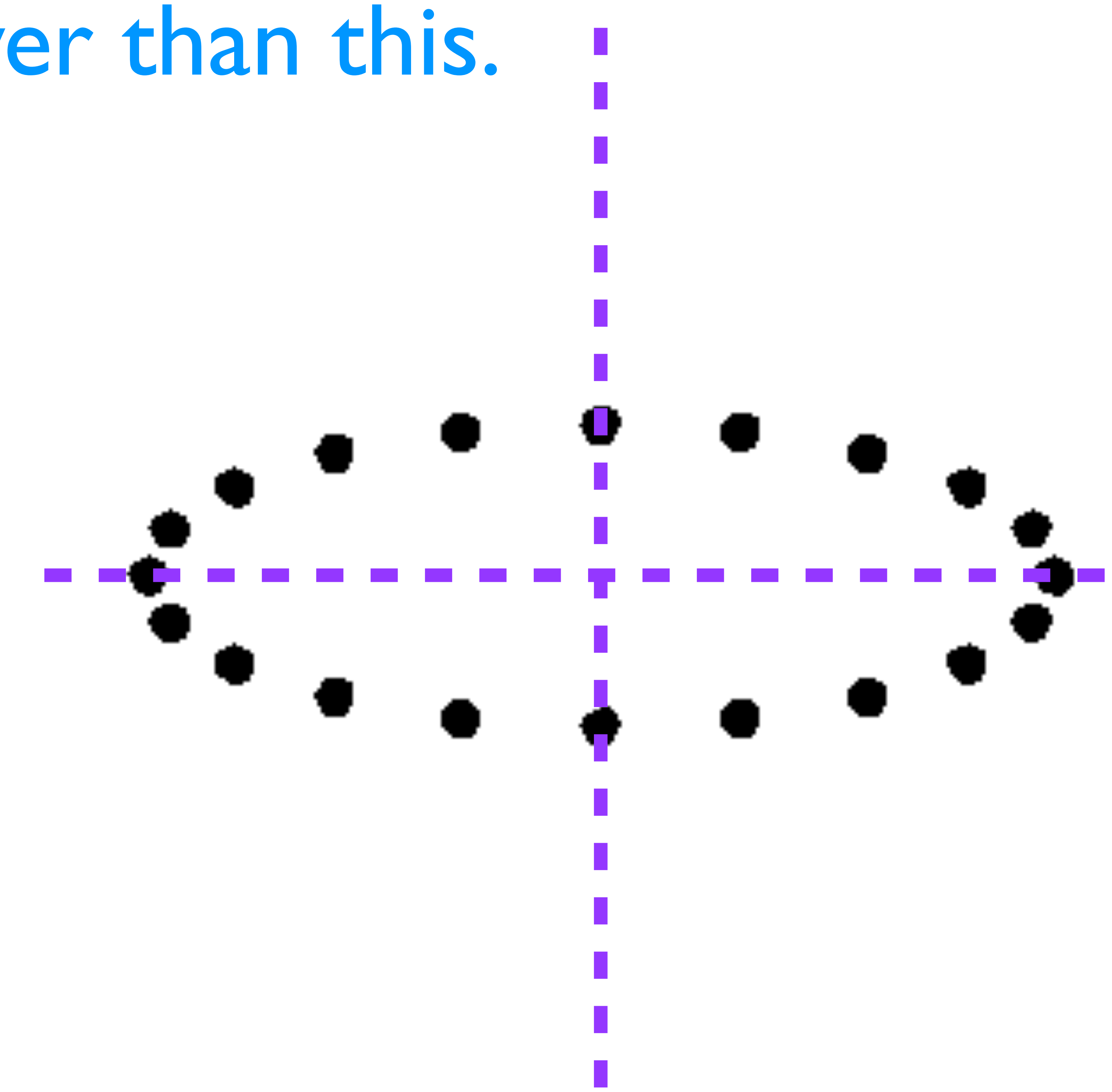

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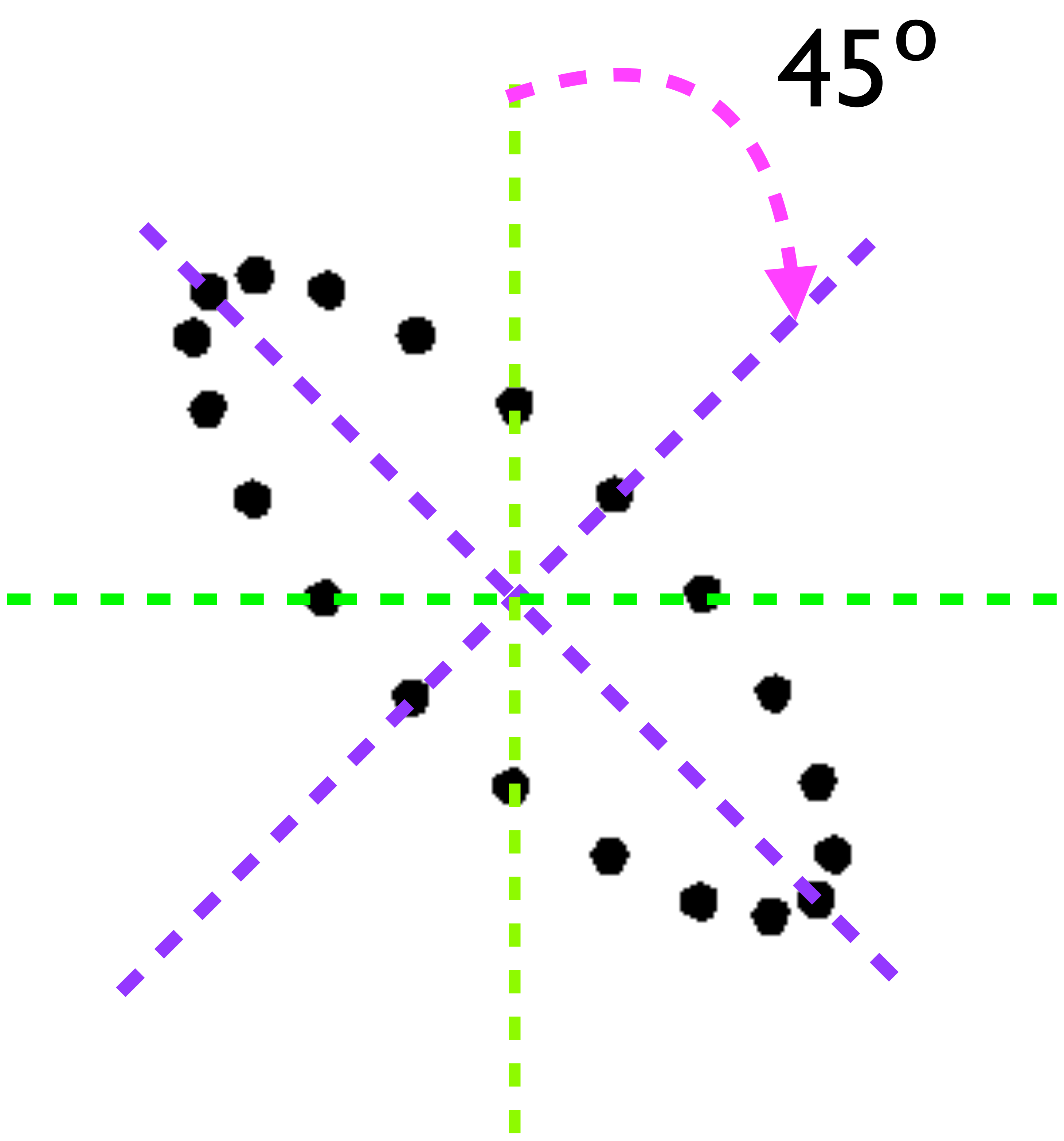

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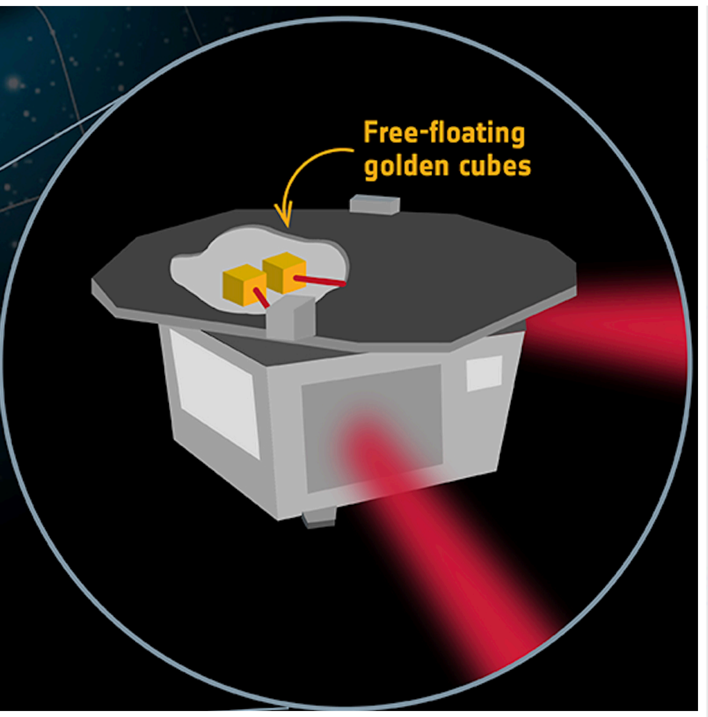
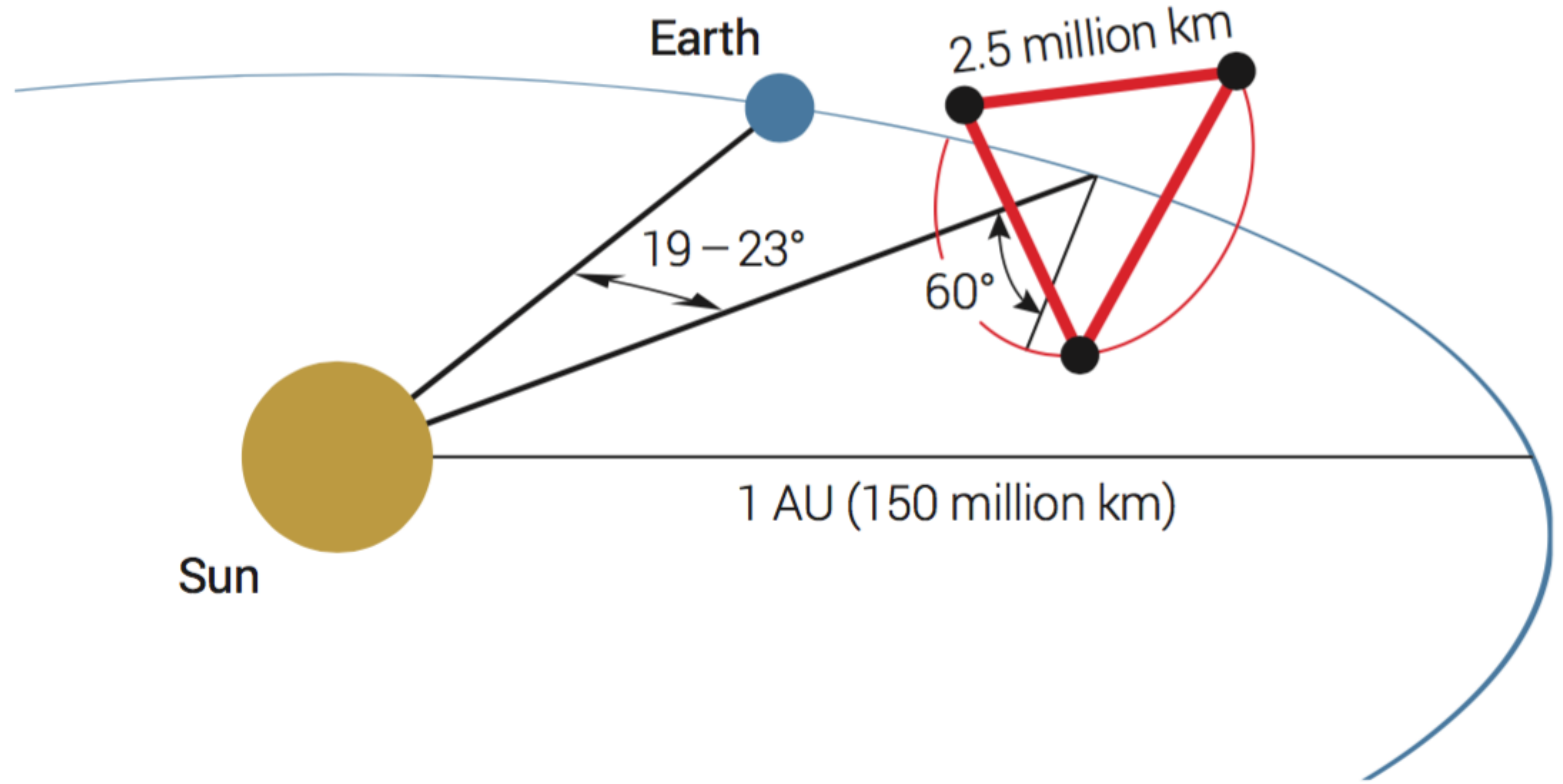
Basics of LISA $\quad 0.1\ \mathrm{mHz} < f < 1\ \mathrm{Hz}$

With such baselines we cannot use mirrors for reflection (***LISA*** **≠LIGO in Space**).
Active mirrors with phase locked laser transponders on the S/C will be implemented.



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 $i \approx 0.96°$



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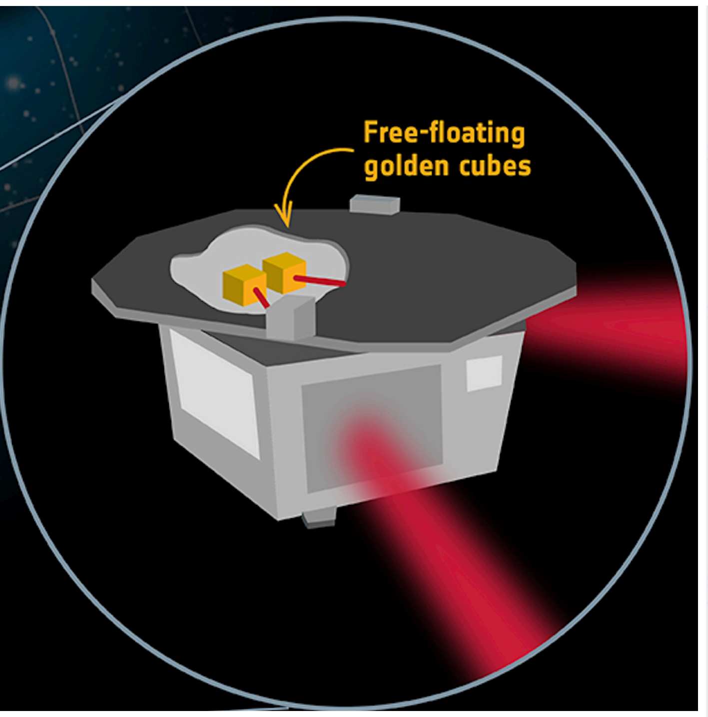

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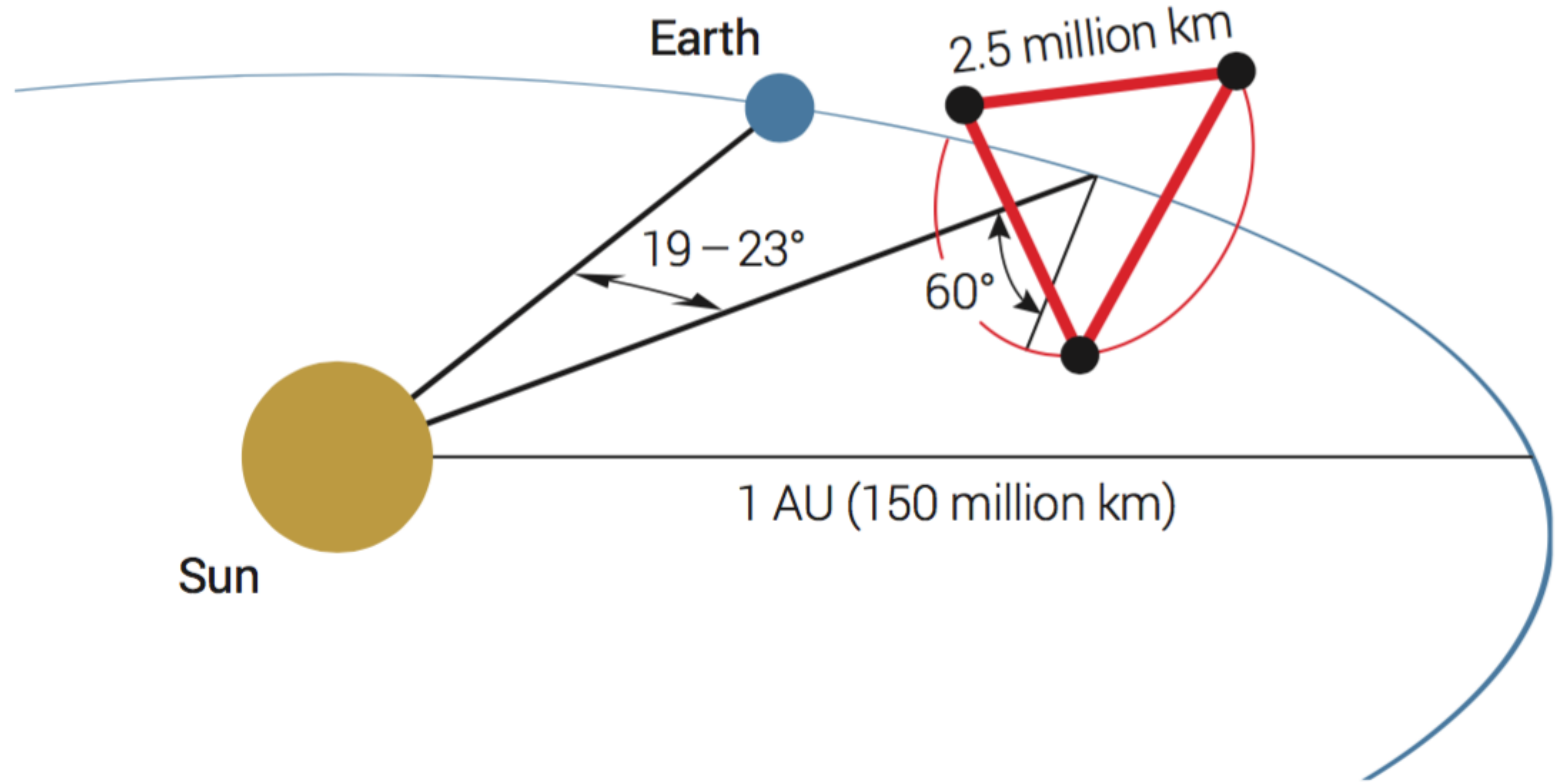

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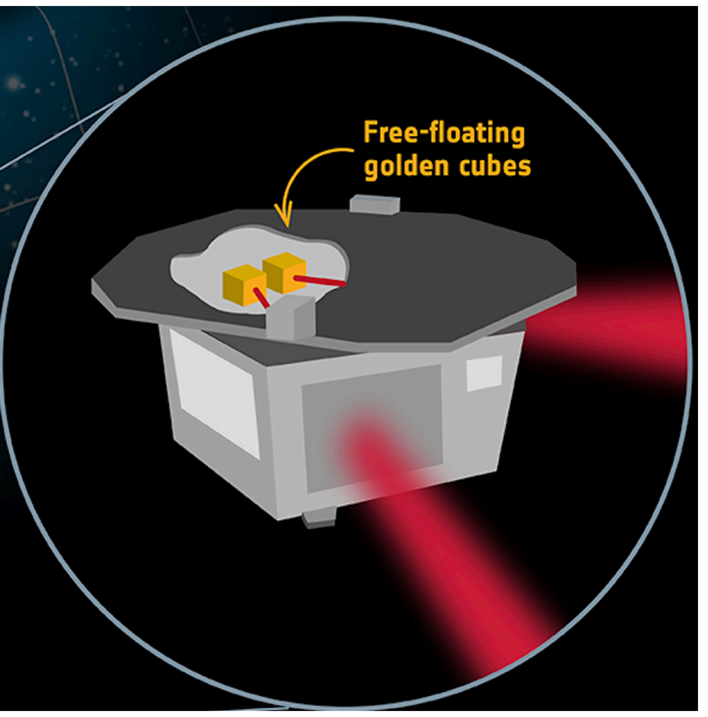
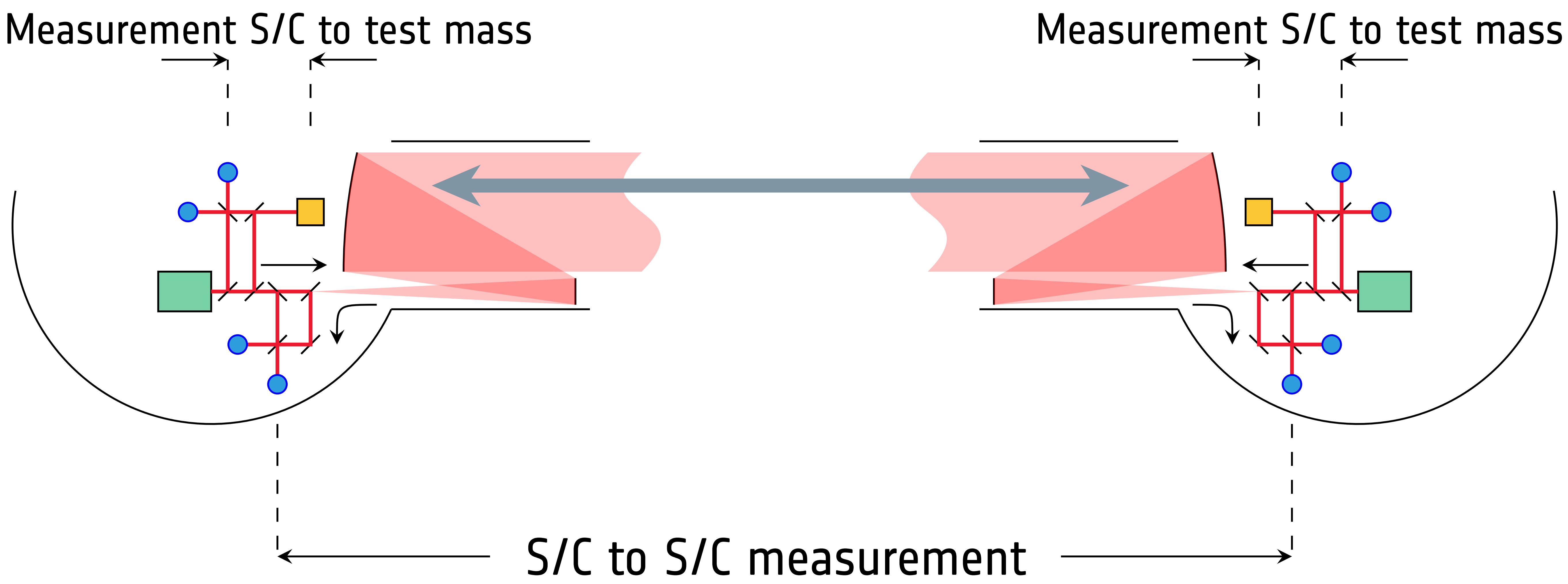
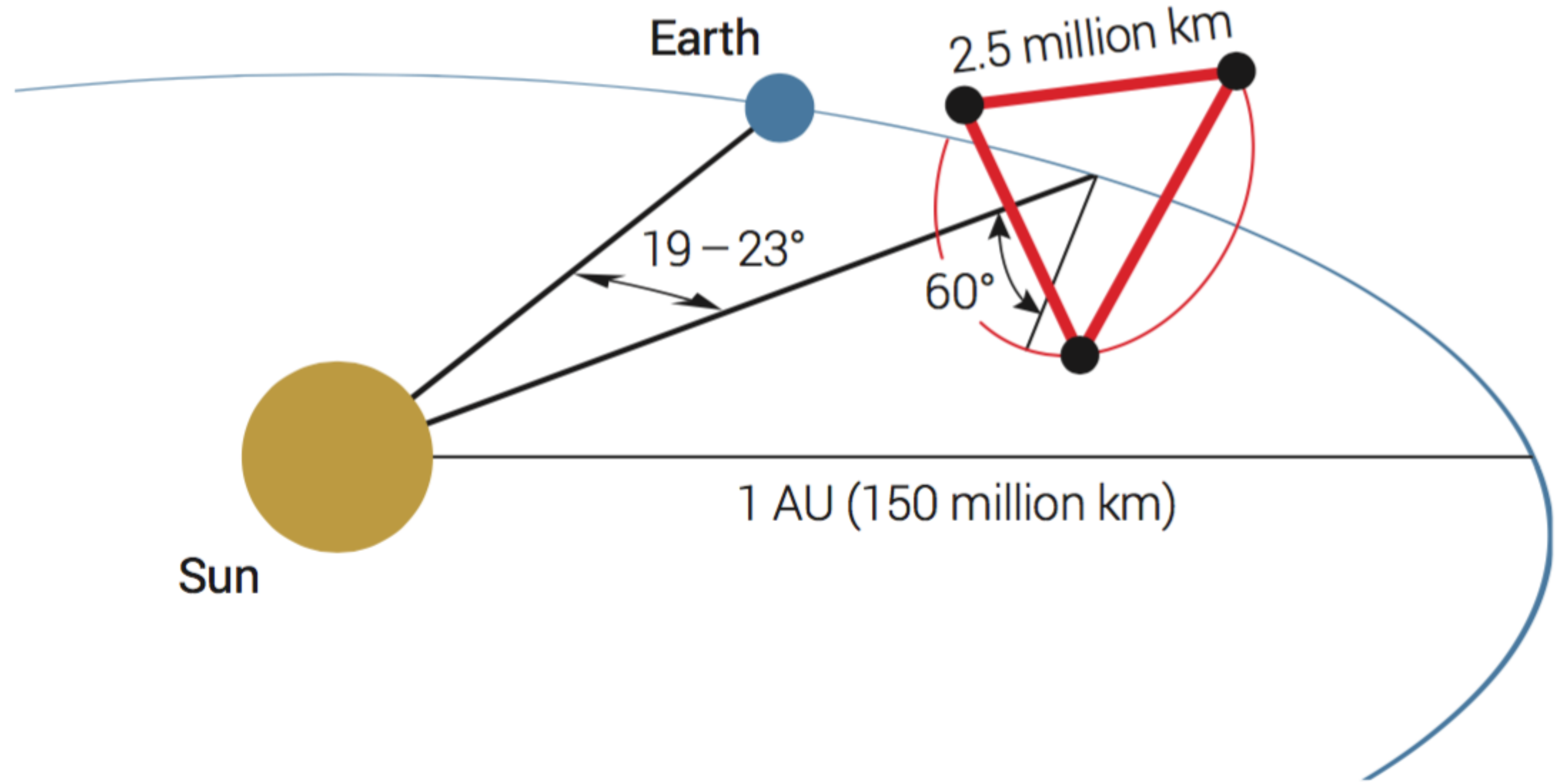
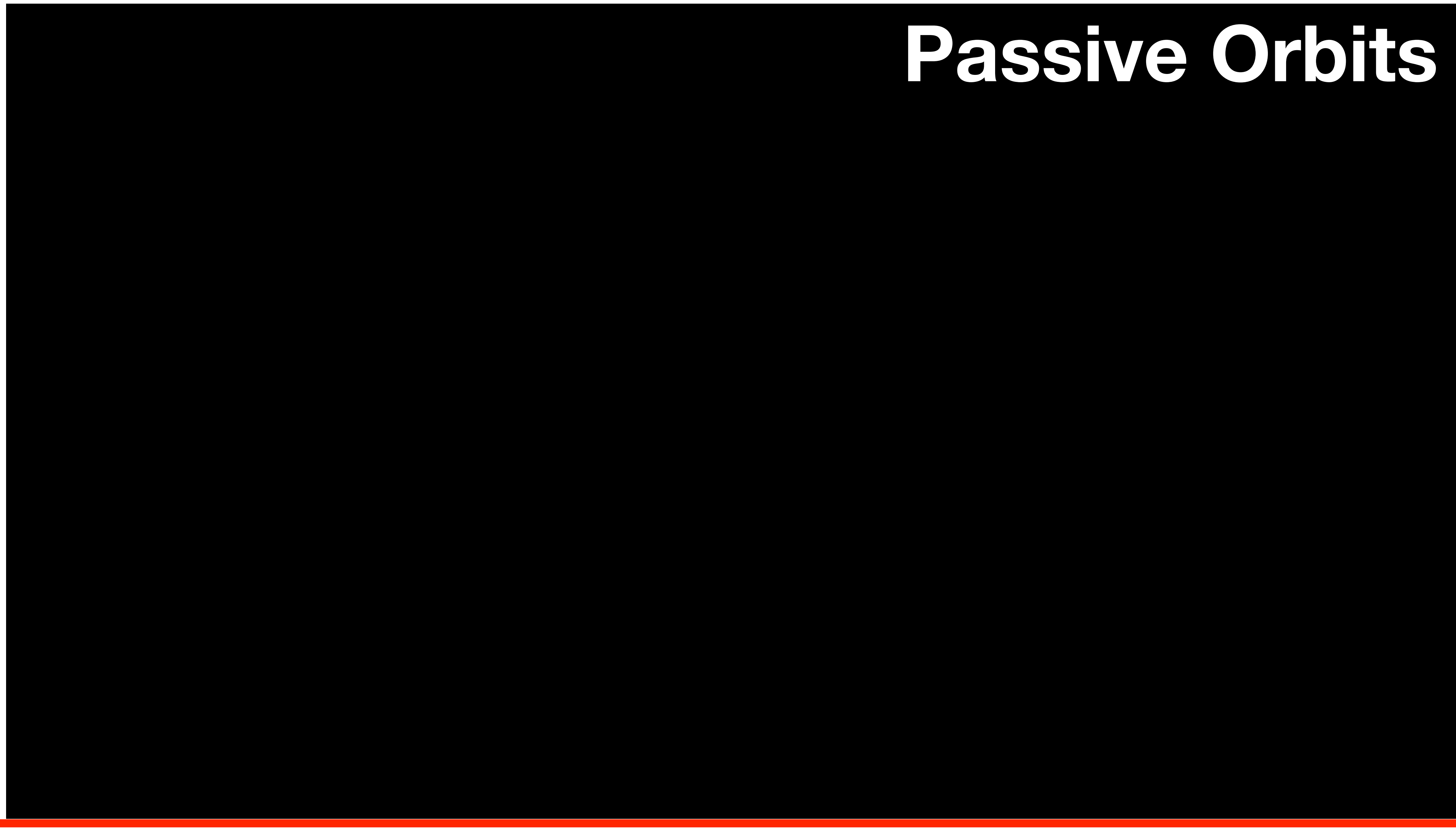


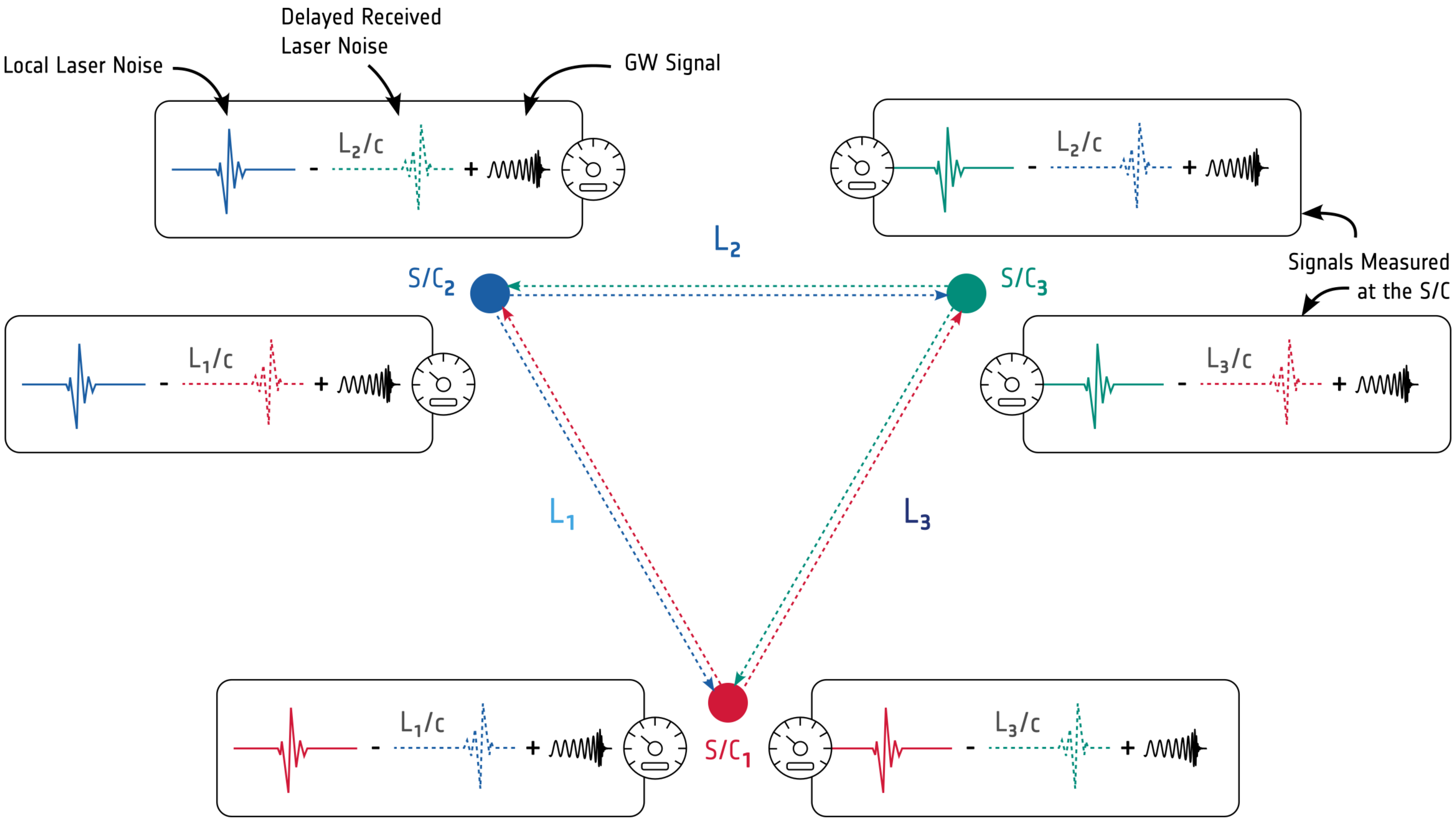


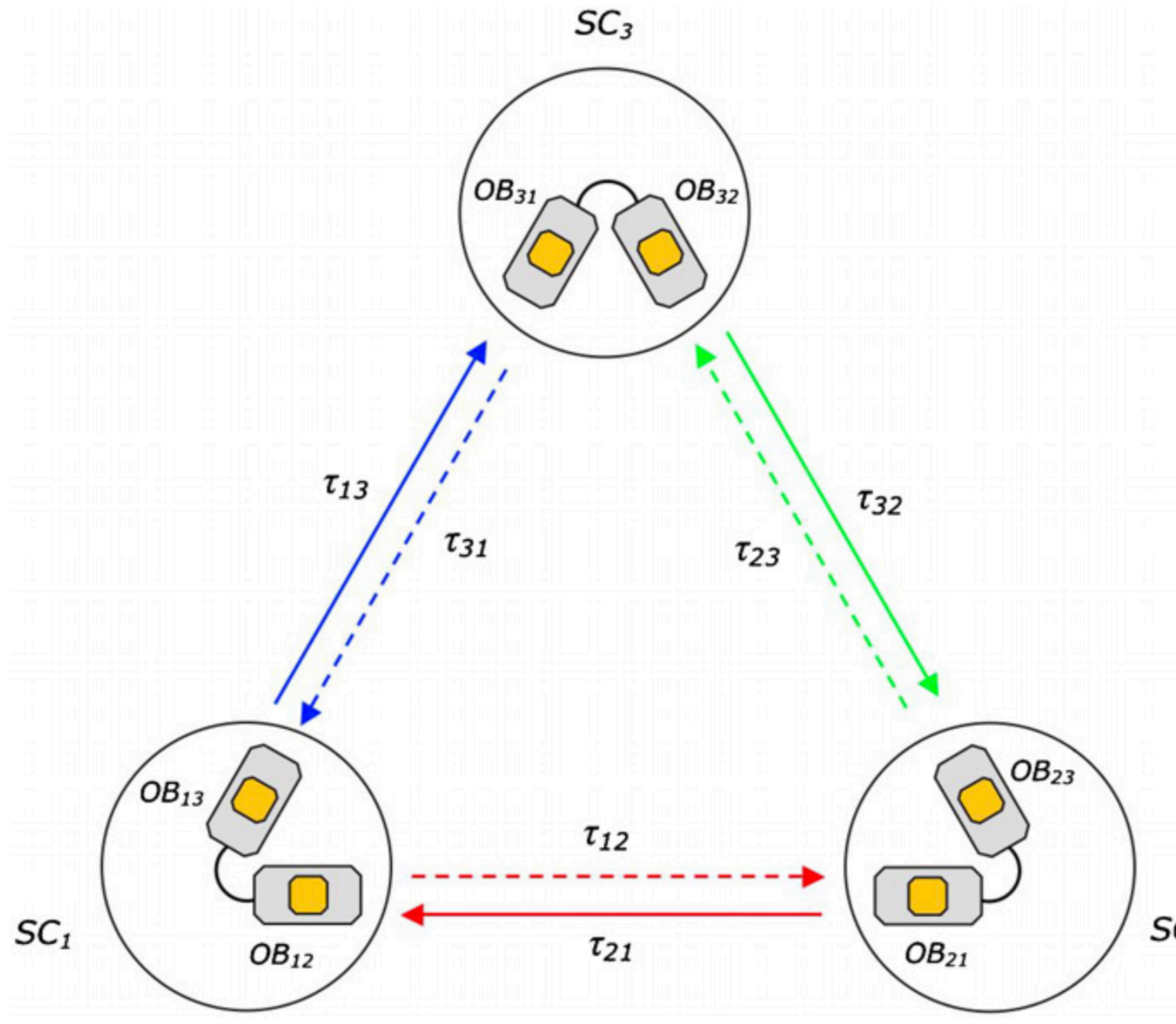


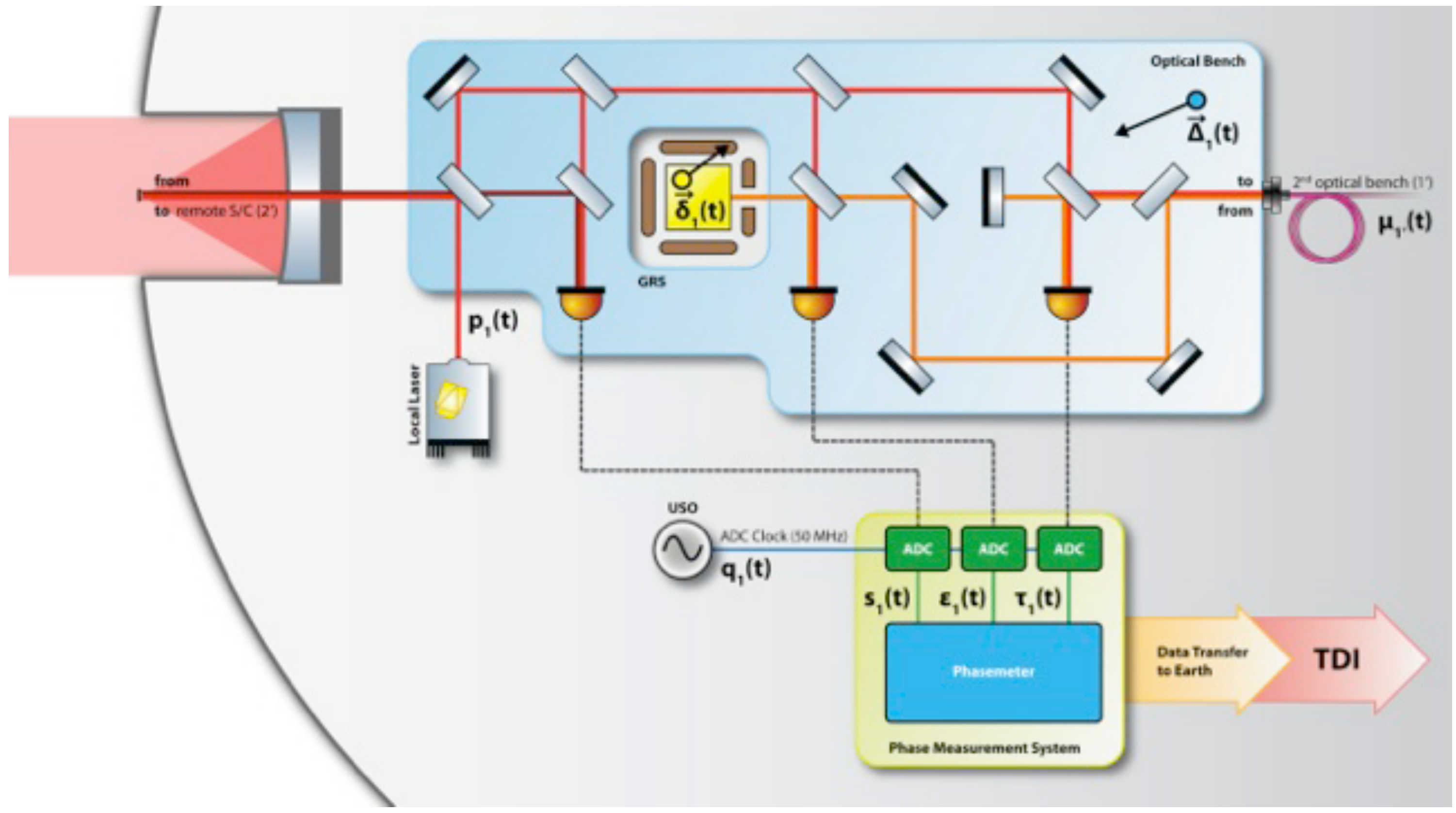


Gravitational Wave Detection from Space

✶**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.







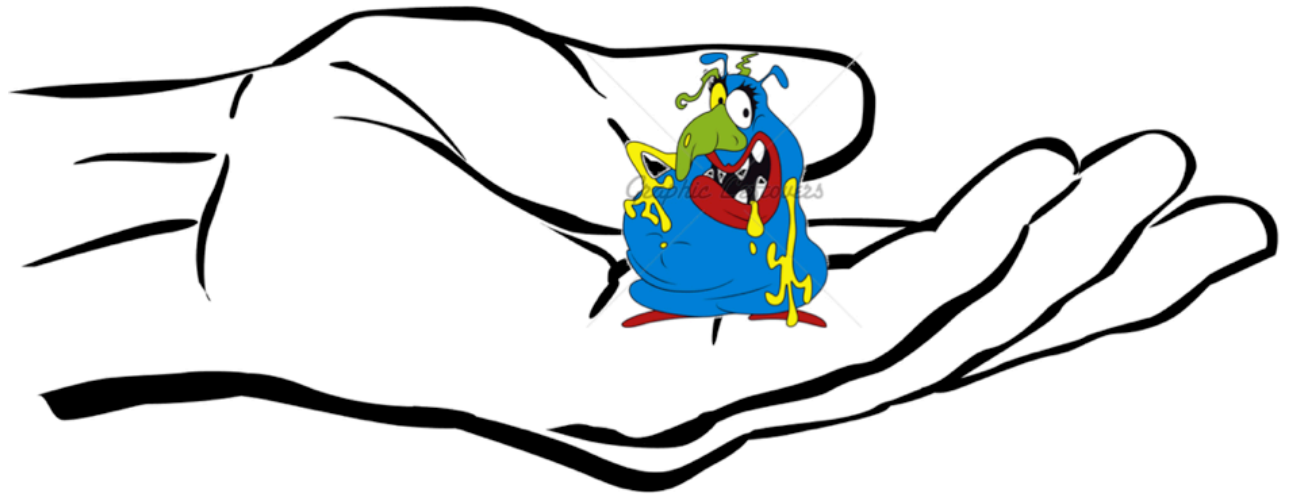
Gravitational Wave Detection from Space

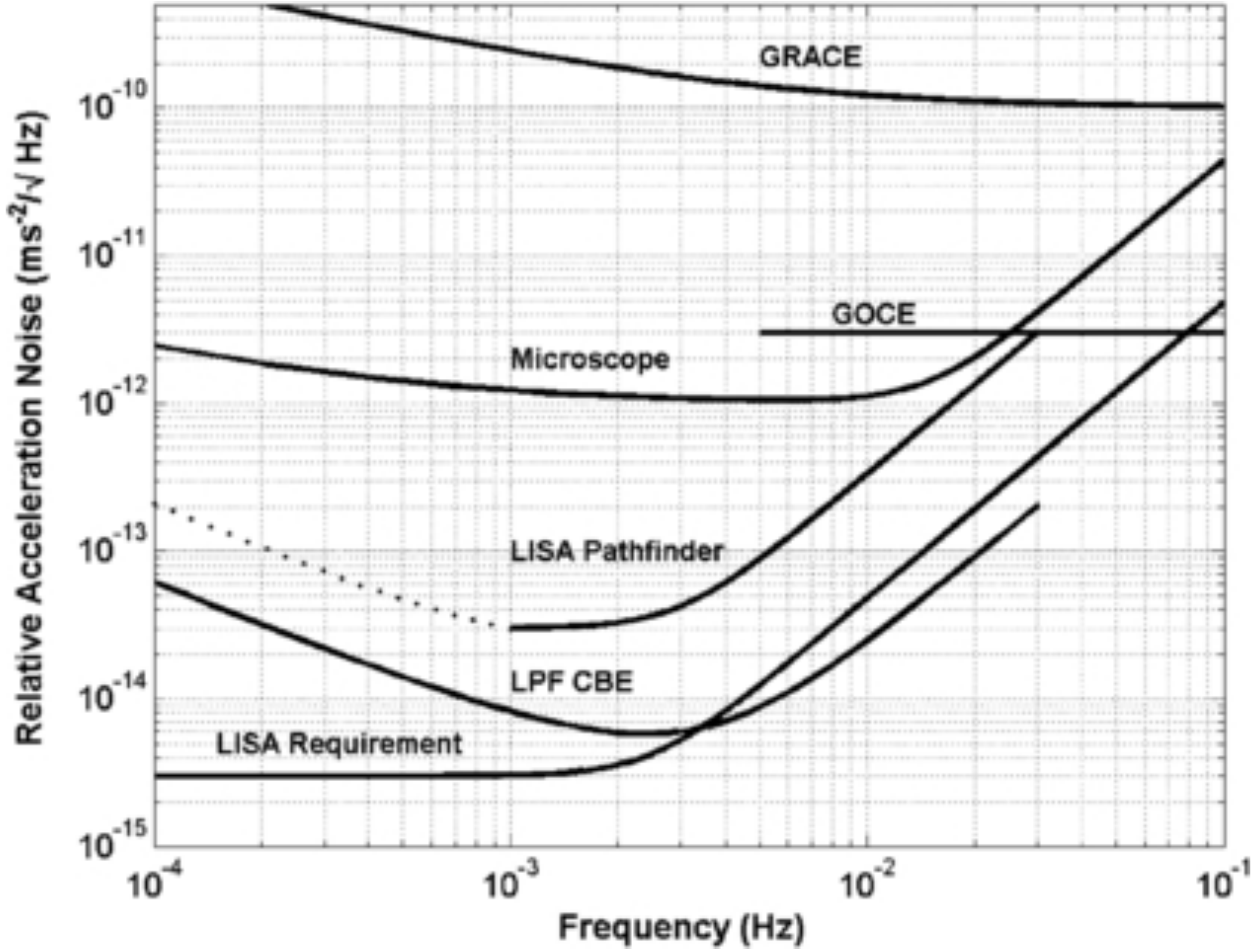
* ✴ Orders of magnitude better than in any other application in differential acceleration sensitivity:

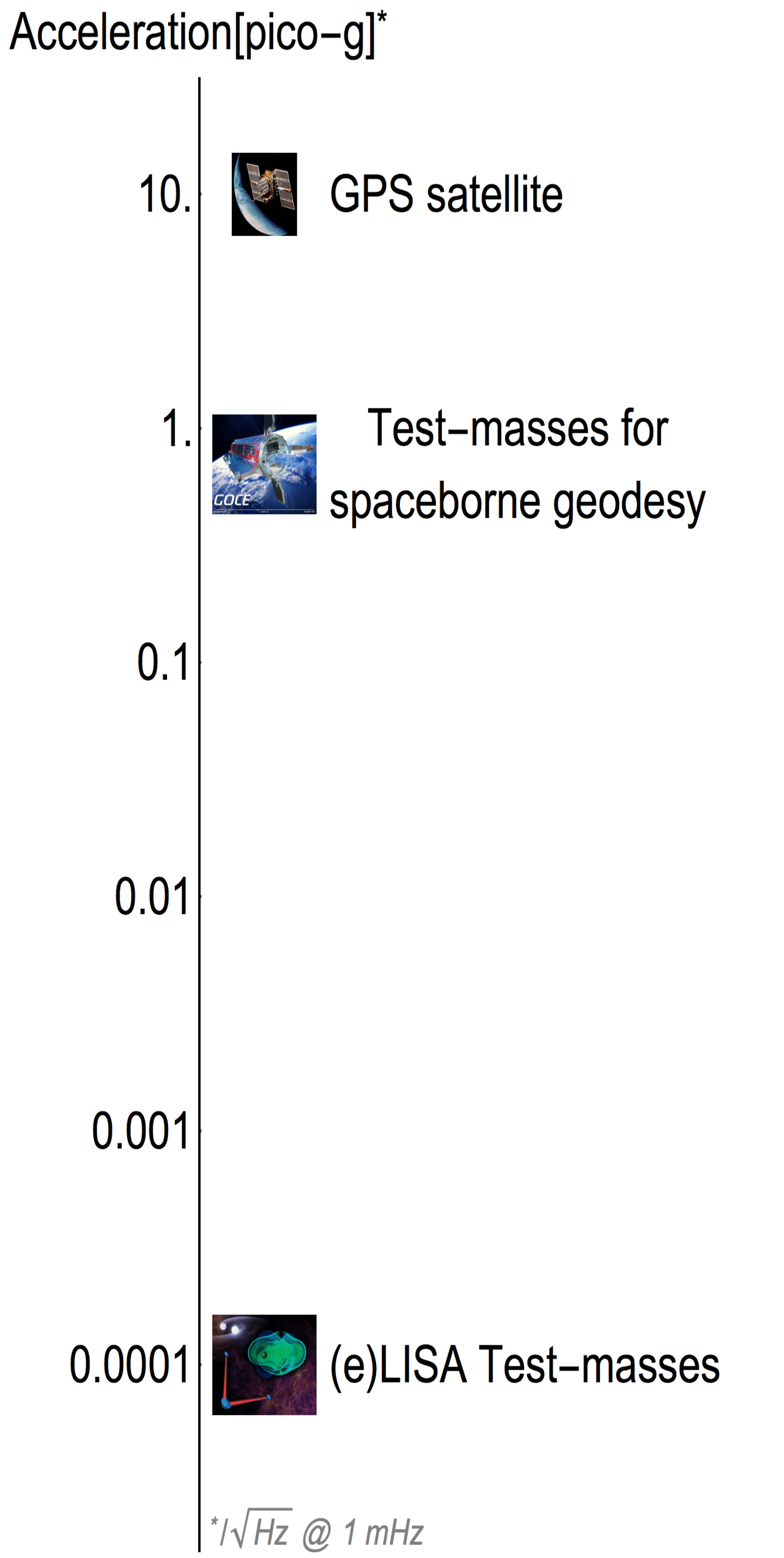
1 pico = 10^{-12} = 0.000 000 000 001

* ✴ 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…







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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 Players

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

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MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN
GOBIERNO DE ESPAÑA
MINISTERIO DE DEFENSA
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESPACIAL ESPAÑOLA

How did we get here?

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Peter Bender

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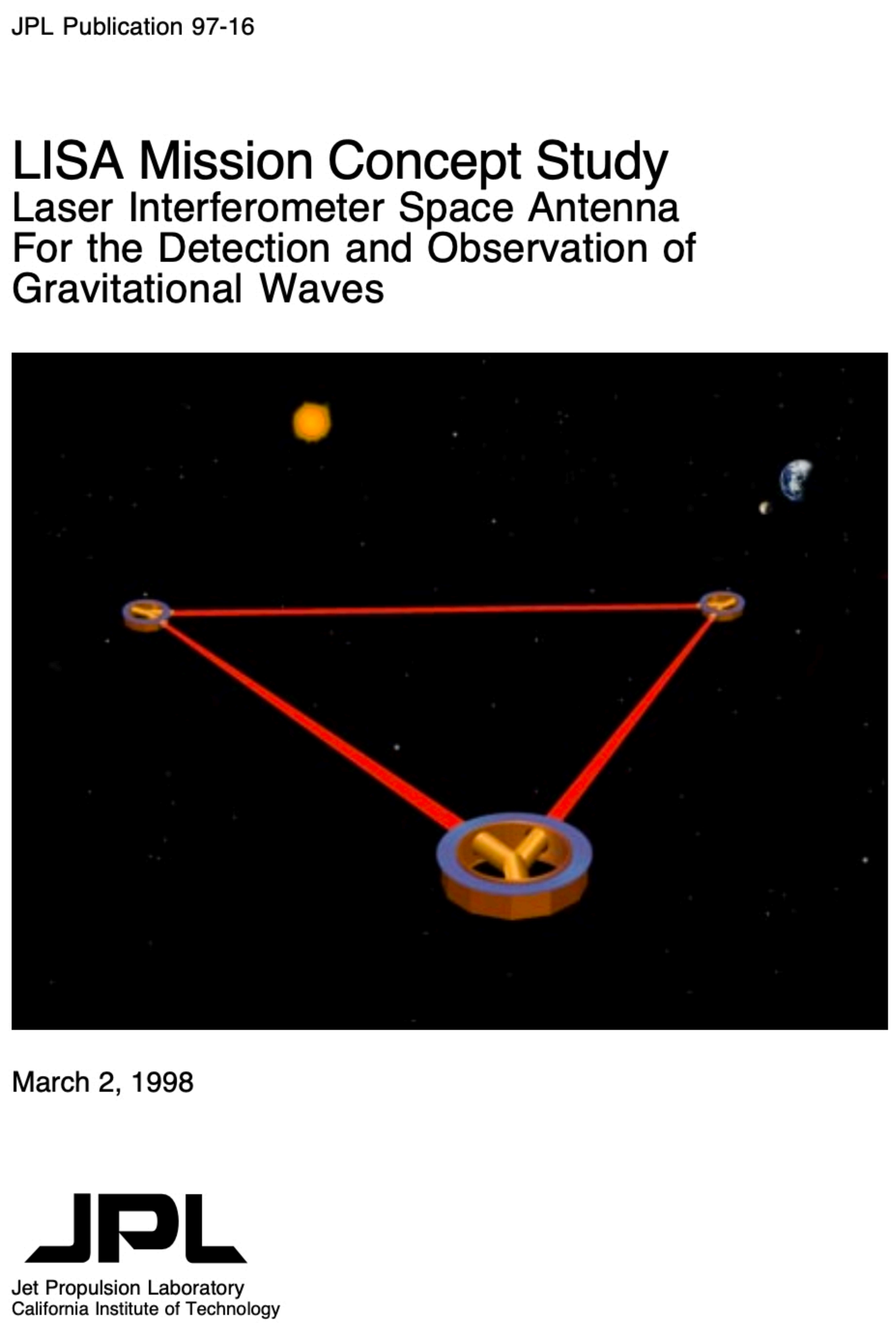

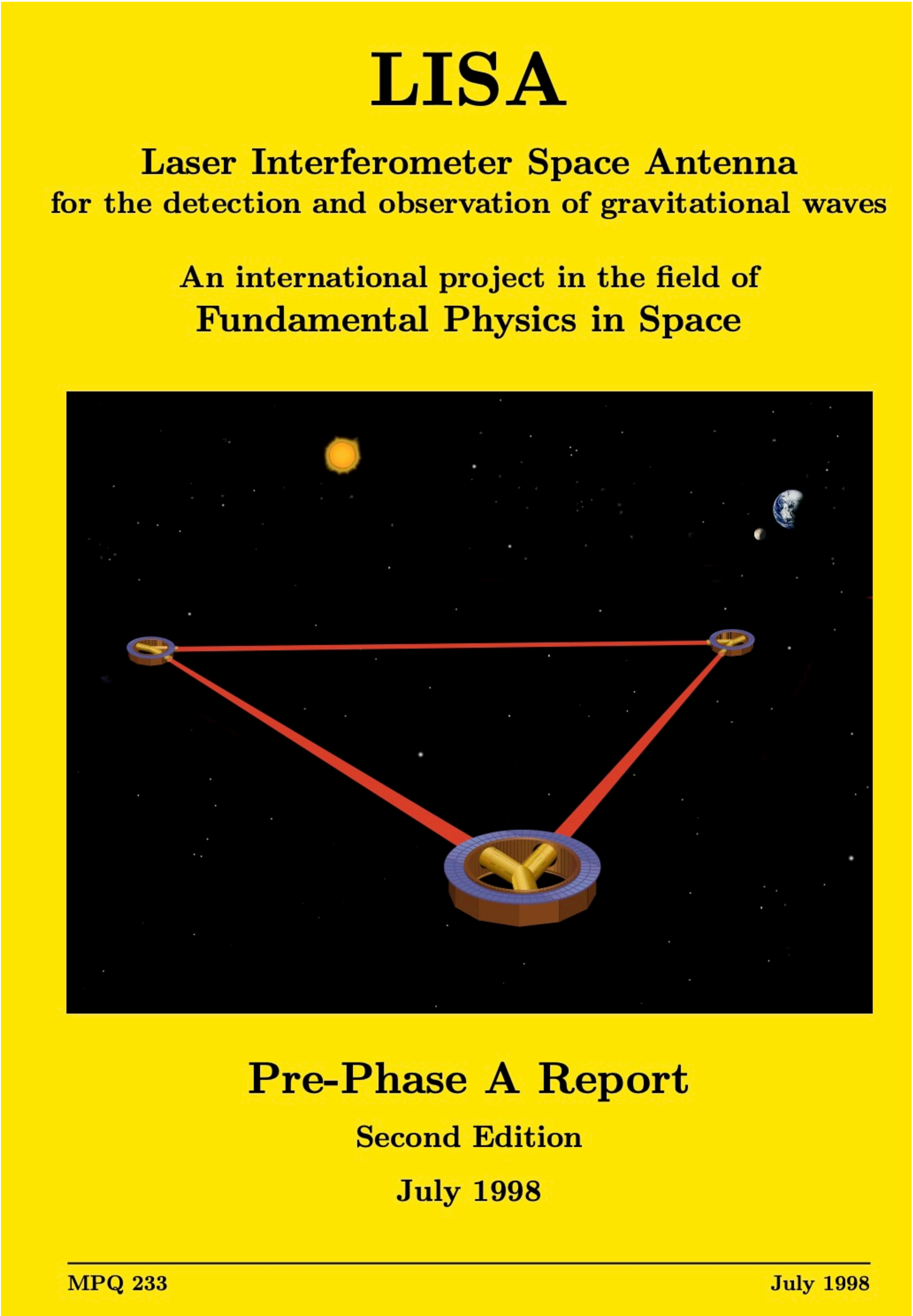

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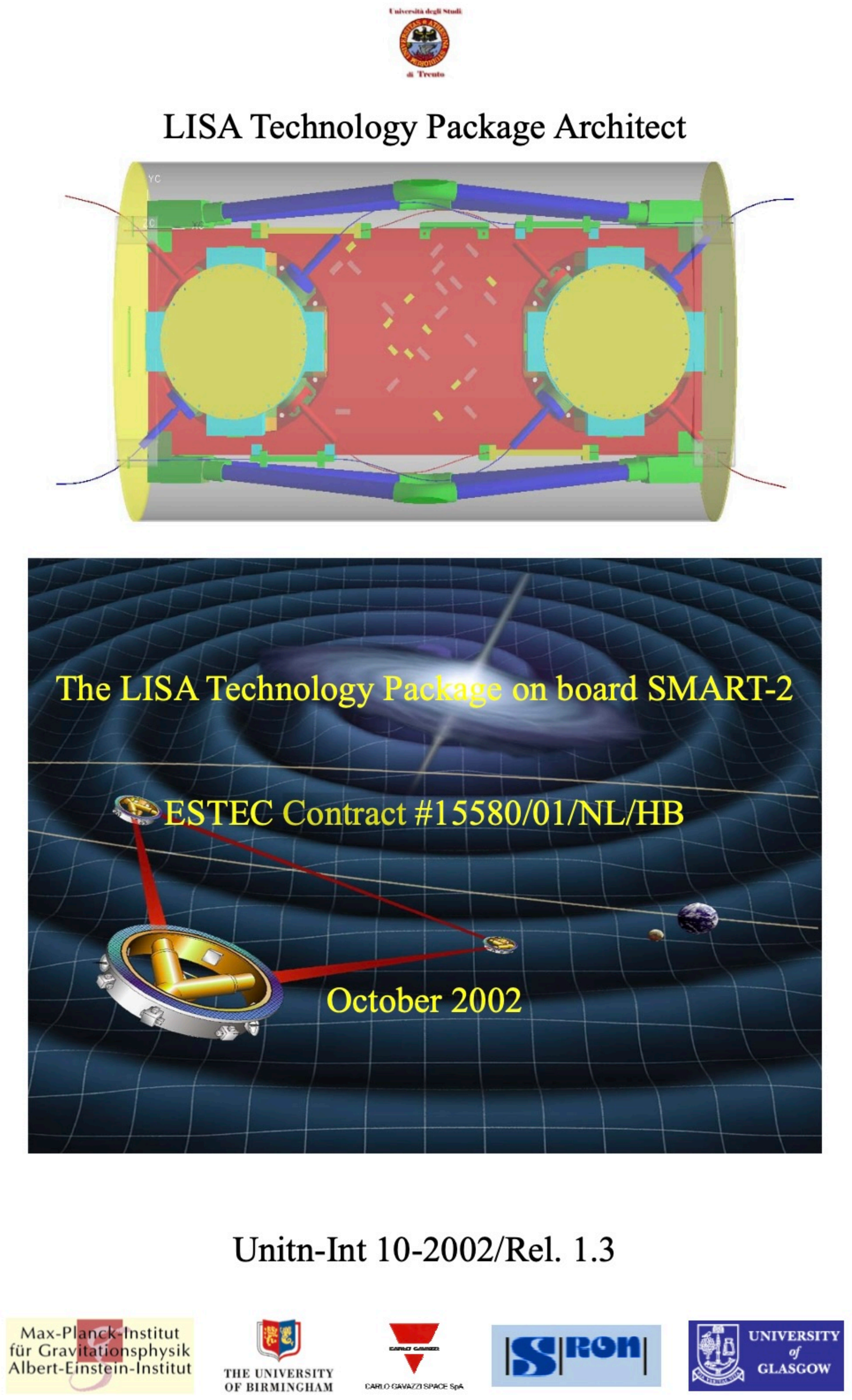

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- ✴ **2013** : Selection of the science themes for the L2 and L3 missions:

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
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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.

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- **2015** : Launch of LISA Pathfinder and first detection of Gravitational Waves by LIGO

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- **2016** : Final Report of the Gravitational Observatory Advisory Team (GOAT) set up by ESA: (ESA website).

The ESA–L3

Gravitational Wave Mission

Gravitational Observatory Advisory Team

Final Report

28 March 2016

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- **2017** : Success of LISA Pathfinder and Selection of LISA

The ESA–L3
Gravitational Wave Mission

Gravitational Observatory Advisory Team

Final Report

28 March 2016

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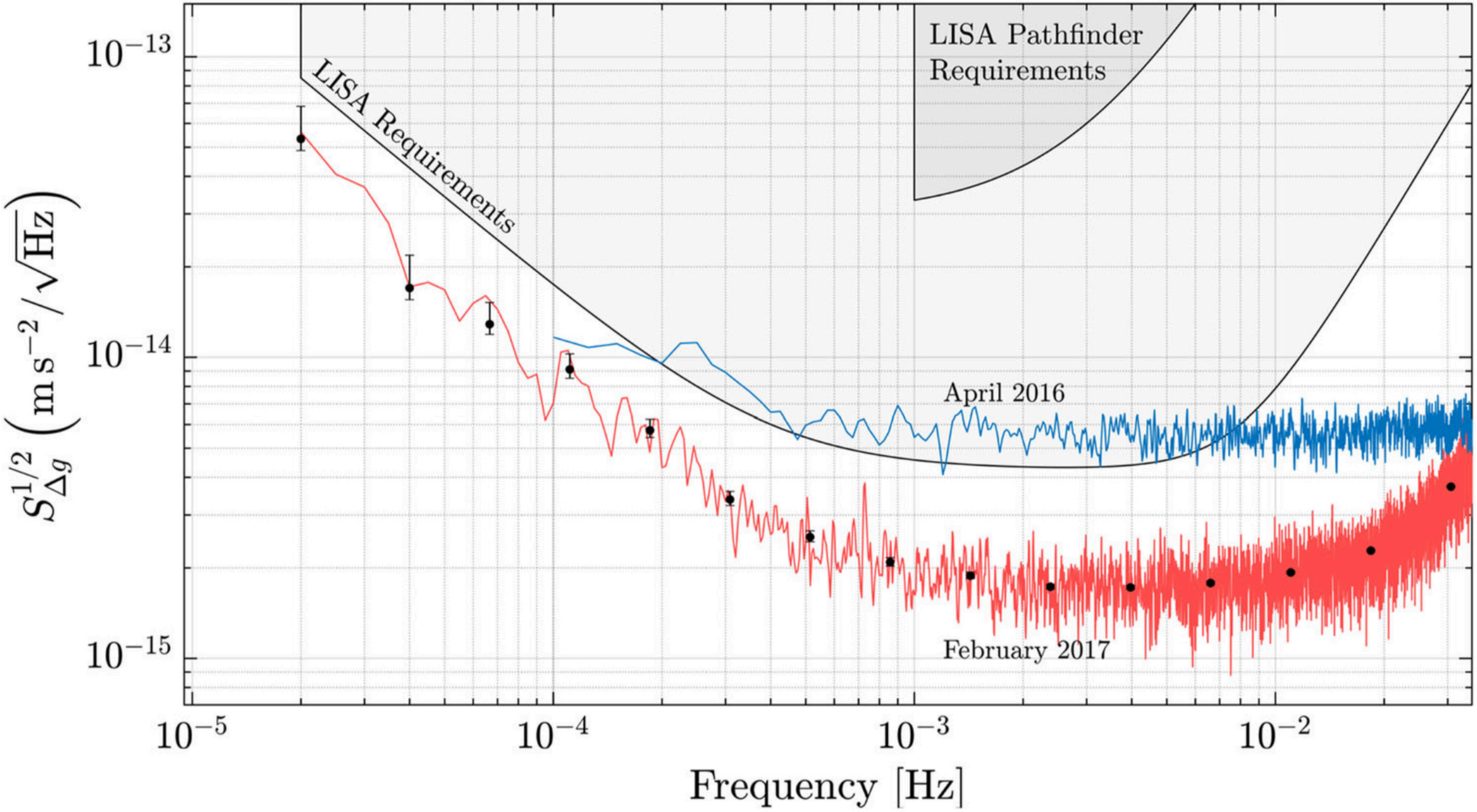
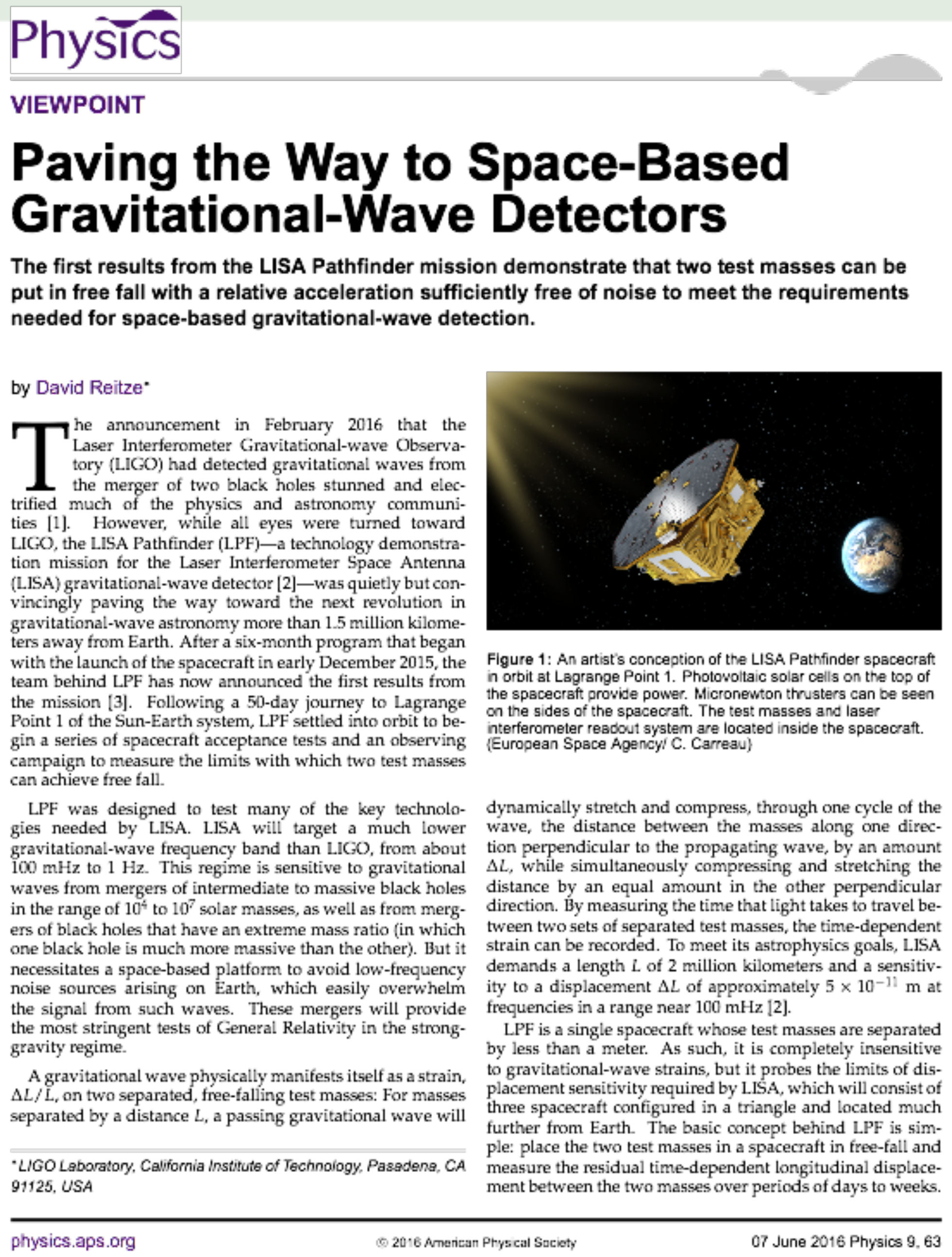
The LISA Pathfinder mission




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.

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

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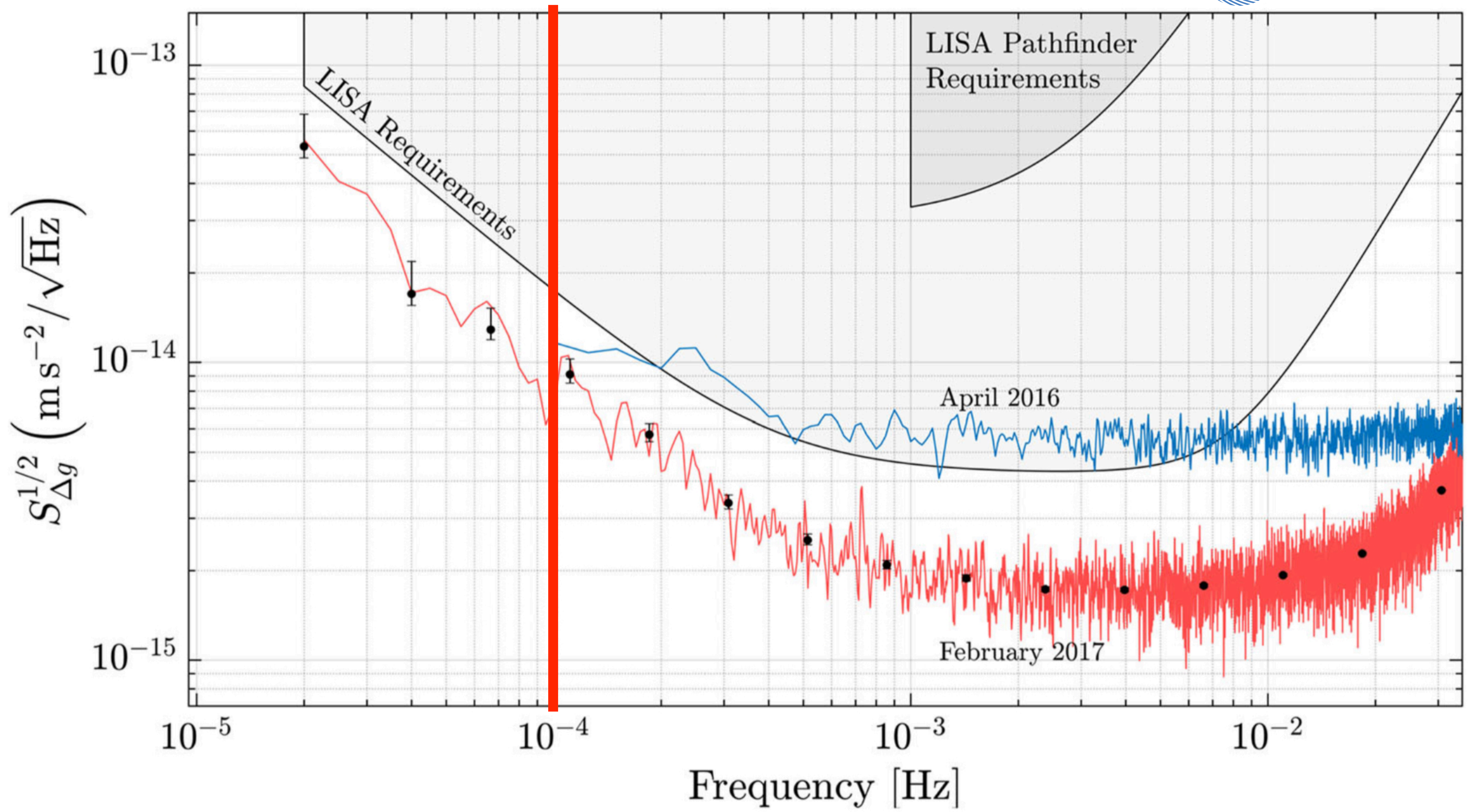
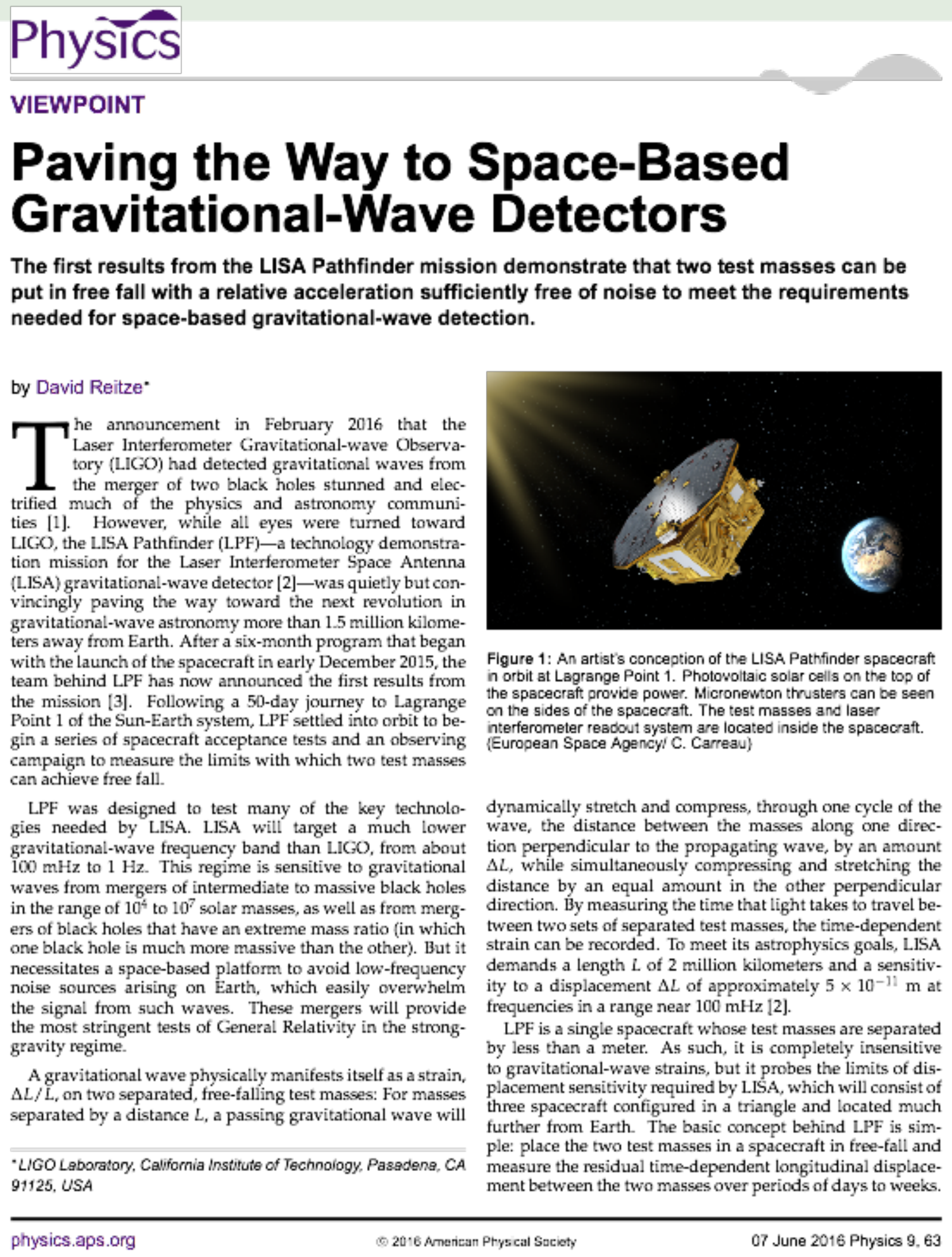
How did we get here?

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)

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lisa pathfinder

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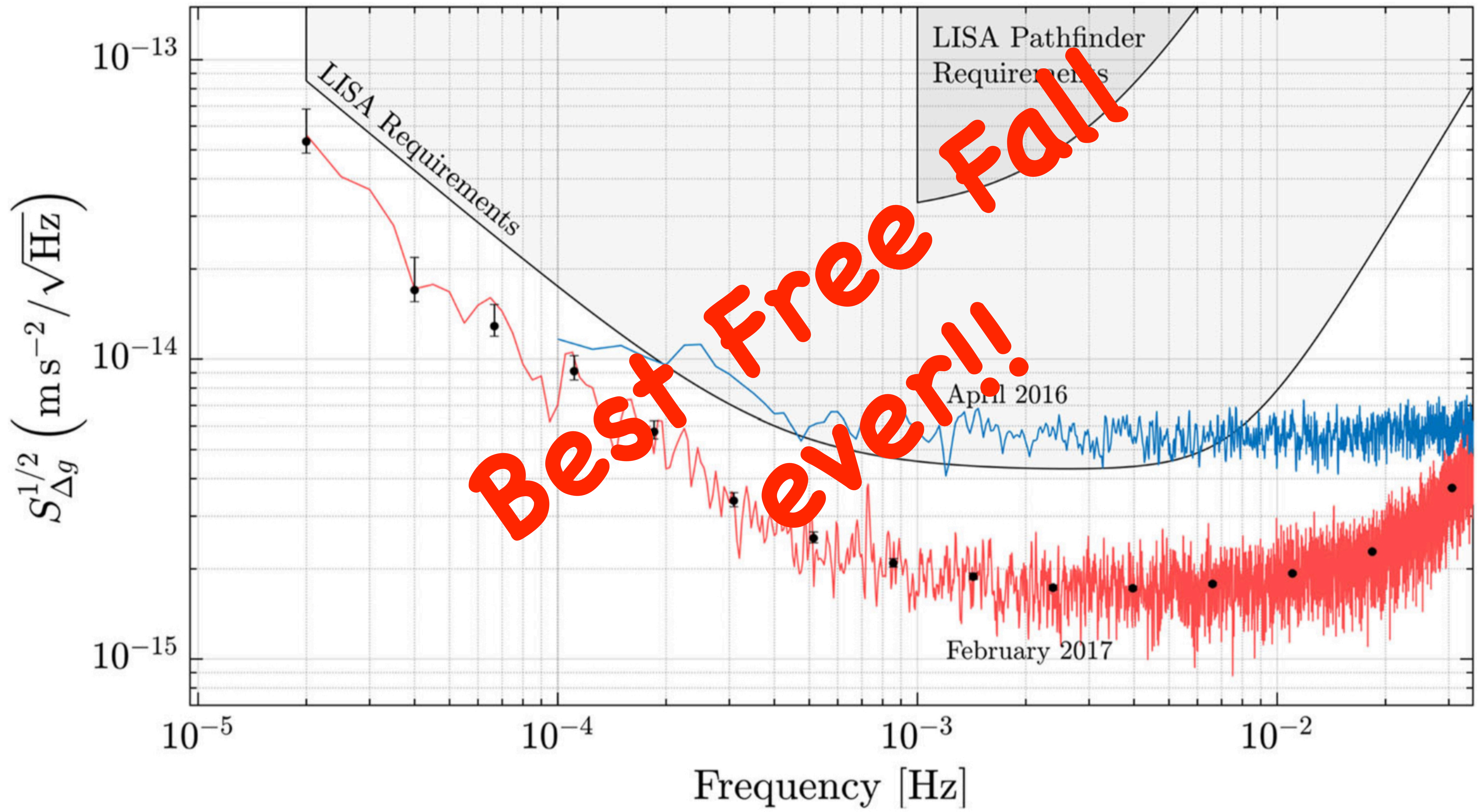

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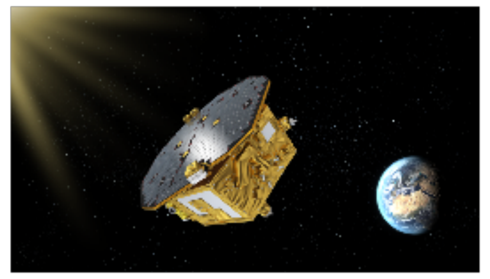

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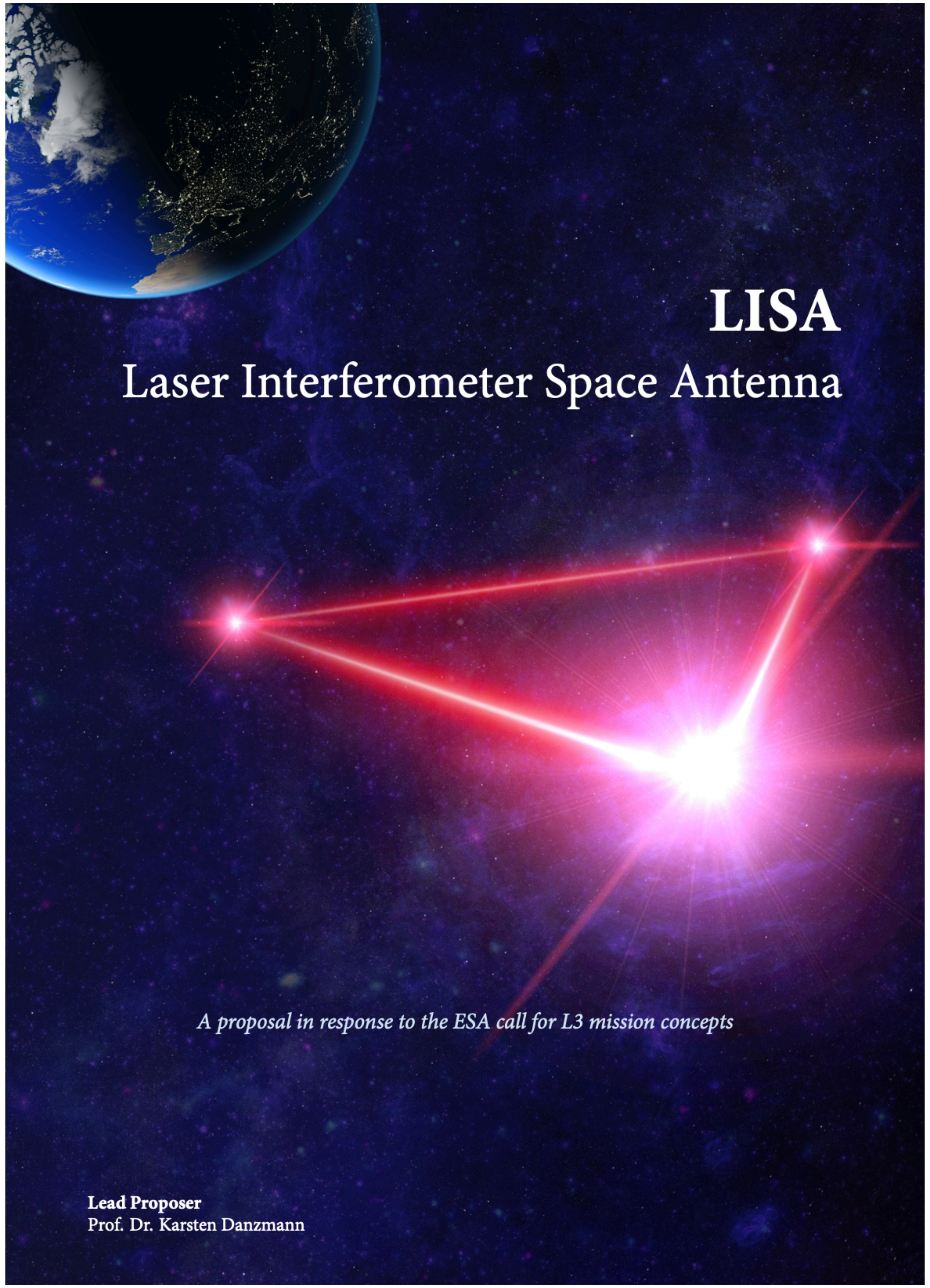

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ESA/SPC(2017)12
Att.: ESA/SSAC(2017)6
Paris, 2 June 2017
(Original: English)

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?

- **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

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- ✳ **2017-2024** : LISA goes through Phases 0, A, B1 up to the adoption, which means it enters the implementation phase! (Phase B2). Expected Launch Date: 2035

How did we get here?

✤ LISA after the selection: Future Missions Department

How did we get here?

✤ LISA after the selection: Future Missions Department

✳ **2017-2024**: LISA went through the **Mission Preparation Phase**: The Assessment Phase (Phases 0 and A) and Definition Phase (Phase B1), separated by the Mission Formulation Review.

How did we get here?

✤ LISA after the selection: Future Missions Department

✳ **2023-2024**: **Mission Adoption Review** (independent ESA review): Evaluated the mission definition maturity, technology readiness and implementation risks. A dedicated review panel was devoted to the mission programmatic elements including cost, schedule and interfaces with partners. Results are made available to the SPC and constitute, together with SSAC scientific assessment, the basis of ESA's recommendation to the SPC to implement the mission.

How did we get here?

✤ LISA after the selection: Future Missions Department

✳ **2024**: **Red Book** (aka, Mission Definition Study Report): **provides a high-level summary of the large number of scientific and technical documents produced as outcome of the definition study for the LISA mission.**

LISA Definition Study Report (Red Book)

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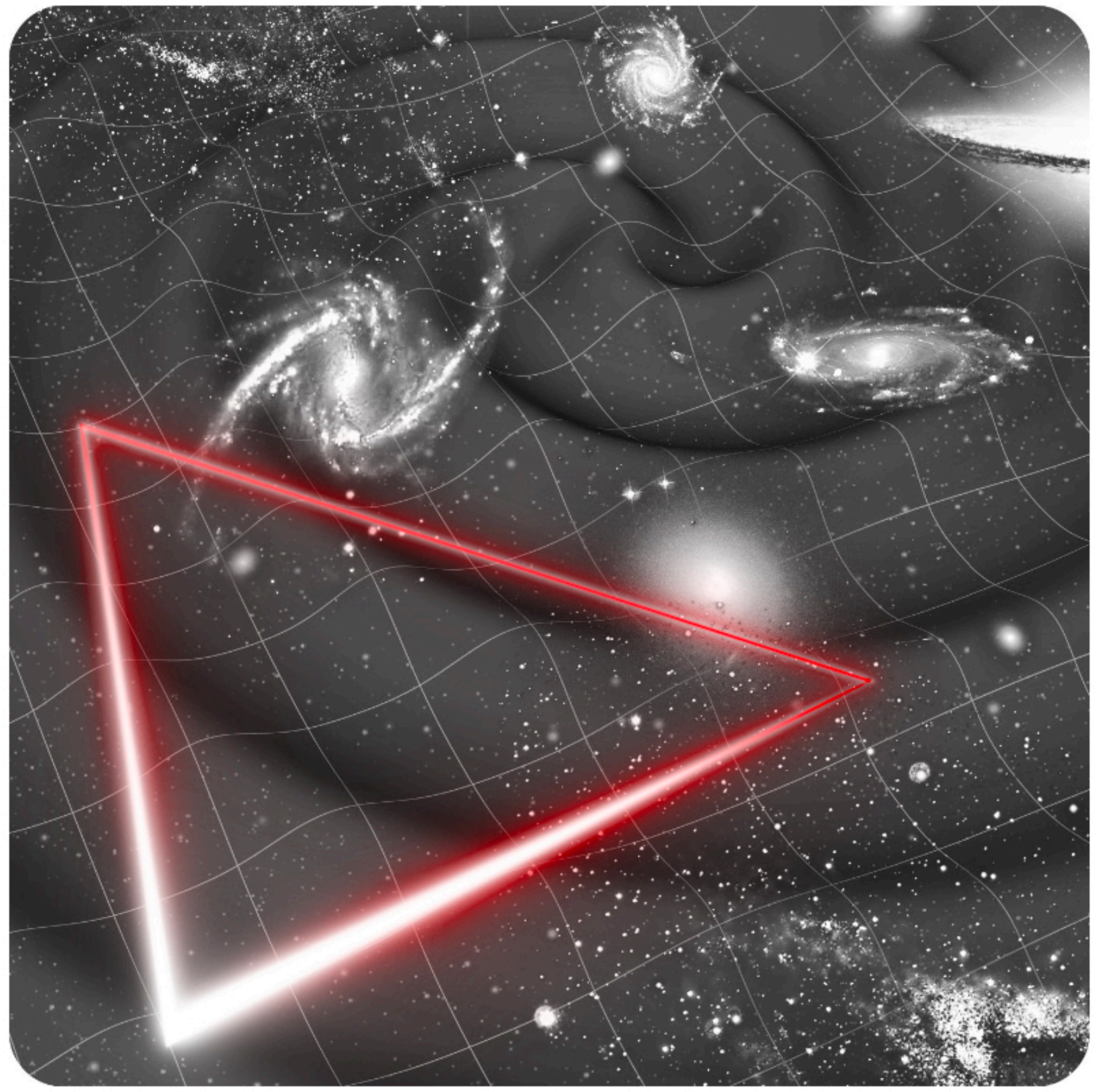
September 2023

LISA
Laser Interferometer Space Antenna



Definition Study Report

THE EUROPEAN SPACE AGENCY

arXiv: 2402.07571

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Antoine Petiteau	IRFU, CEA	Gif-sur-Yvette, France
David Shoemaker	MIT Kavli Institute	Cambridge, United States
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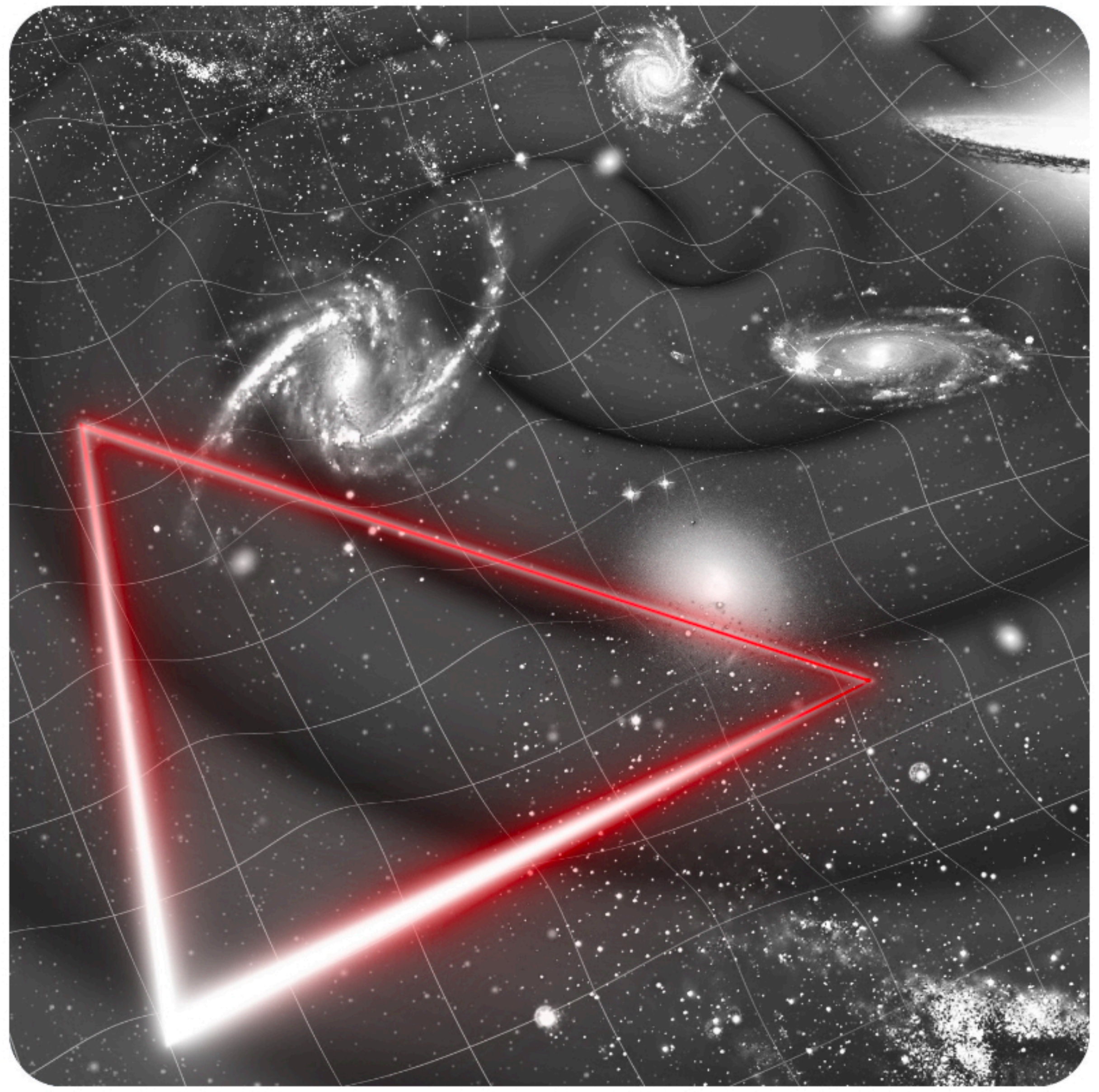

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ESA Study Team		
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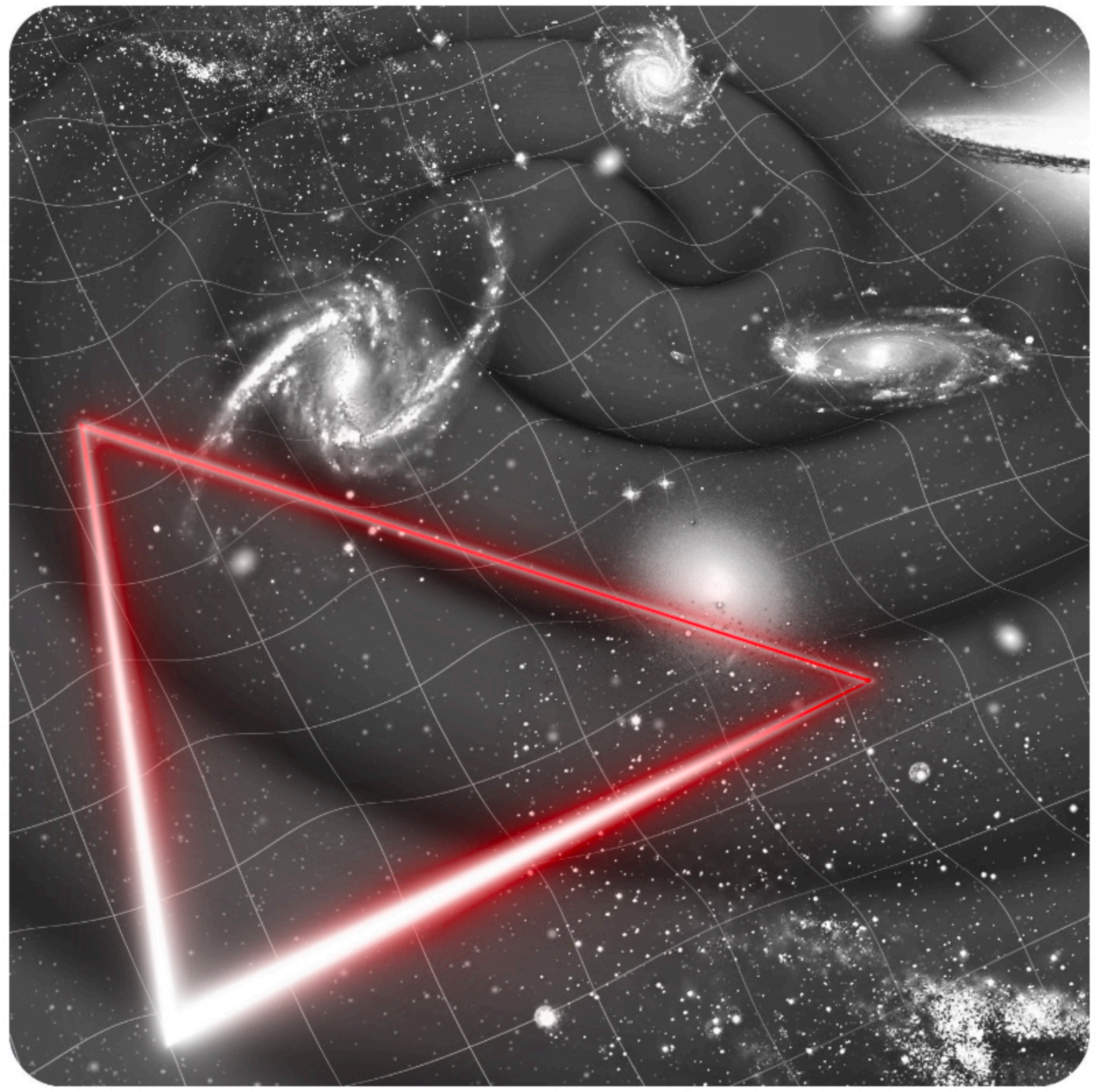

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Main Contents of the LISA Red Book

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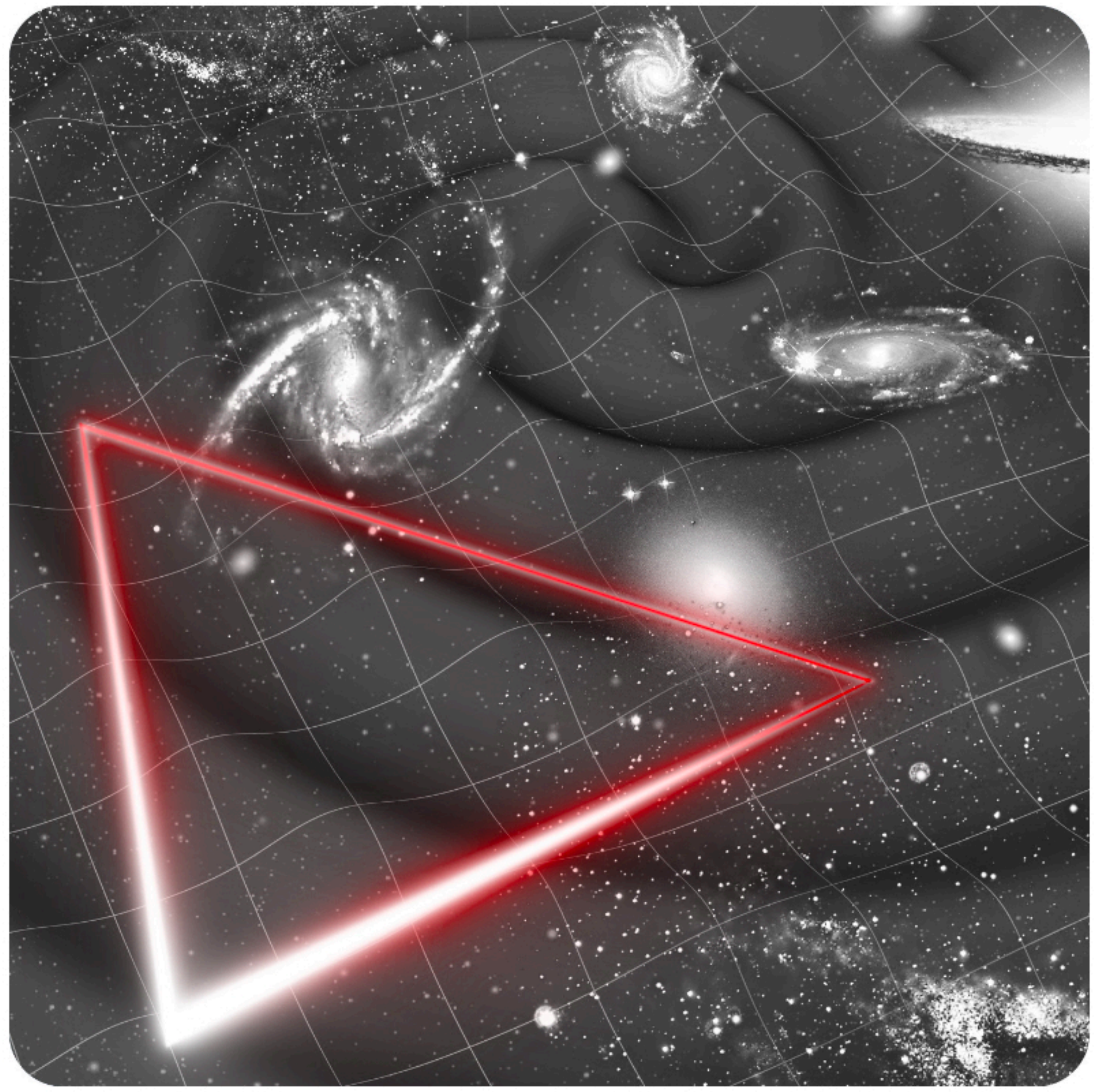

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→ THE EUROPEAN SPACE AGENCY

LISA MISSION OVERVIEW

LISA SCIENCE OBJECTIVES

LISA MISSION REQUIREMENTS

THE LISA INSTRUMENT

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LISA SCIENCE OBSERVATIONS

LISA GROUND SEGMENT AND OPERATIONS

MANAGEMENT

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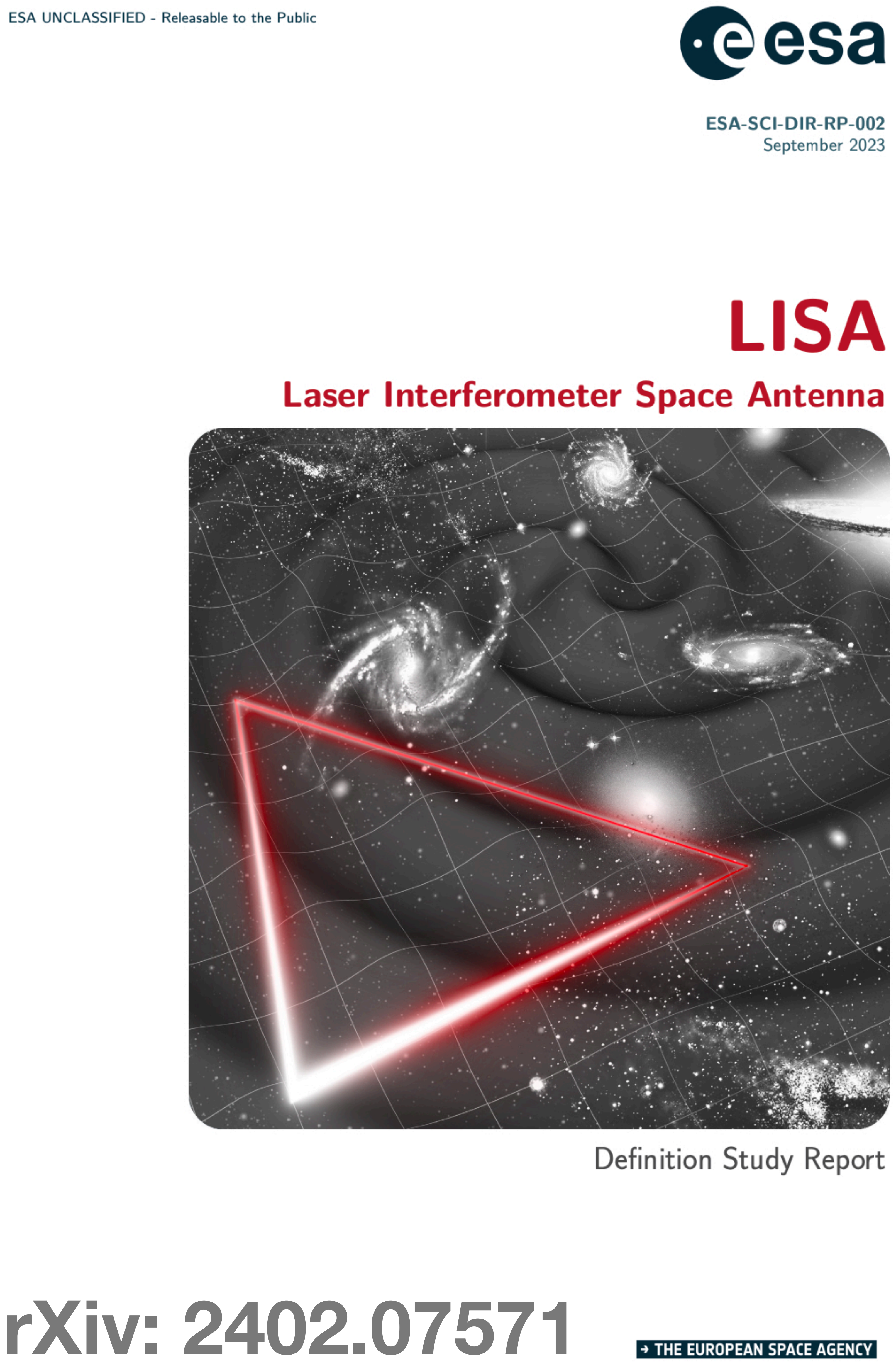

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Science Objectives (SO) of LISA

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

Sources of Gravitational Waves for LISA

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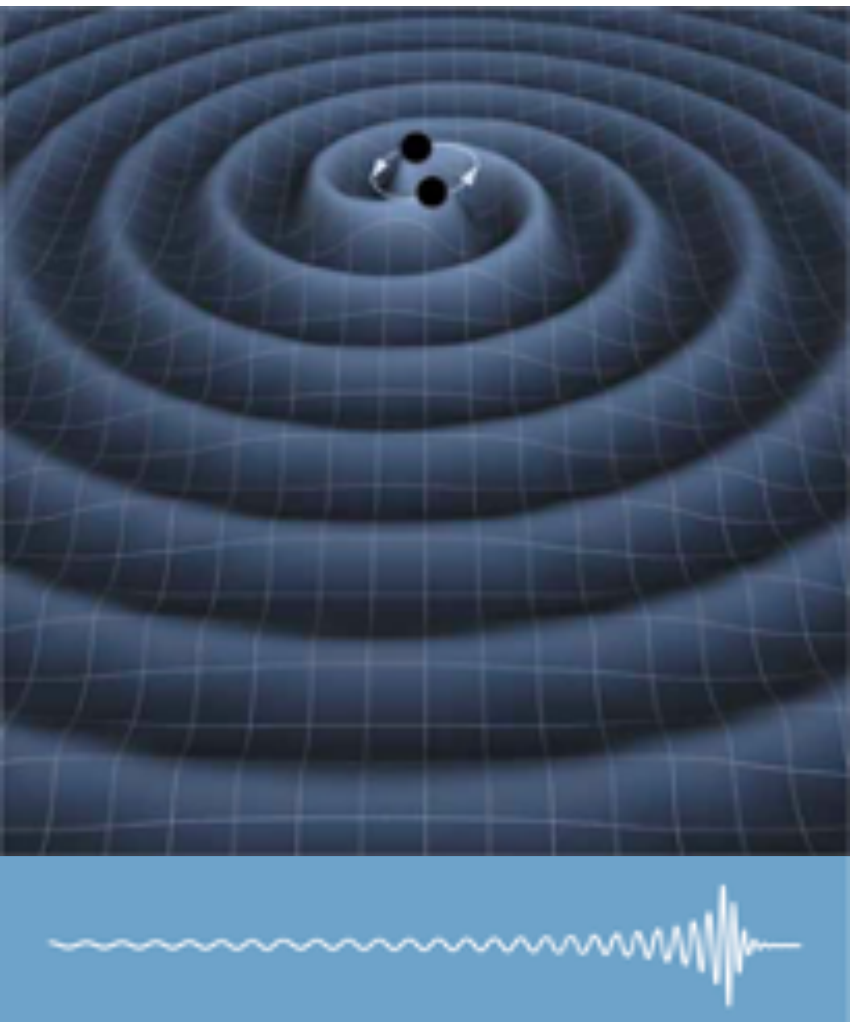

Massive Black Hole Mergers (with masses in the range: $10^4 - 10^7\,M_\odot$)

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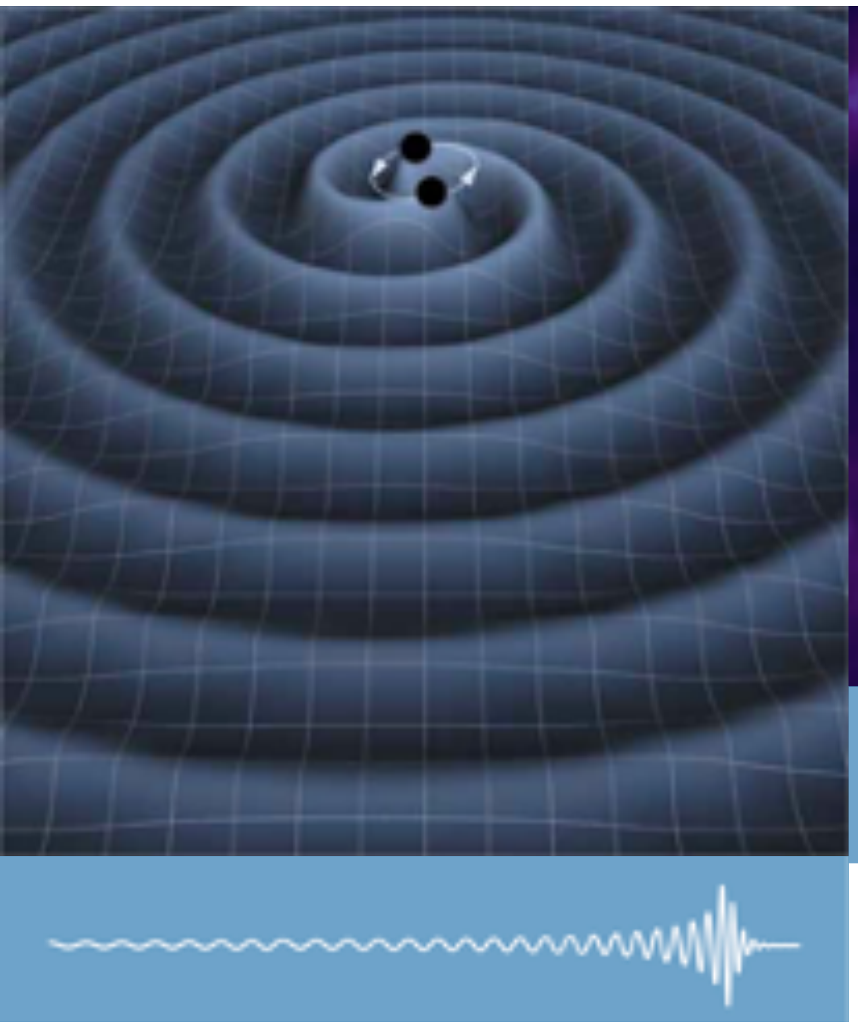

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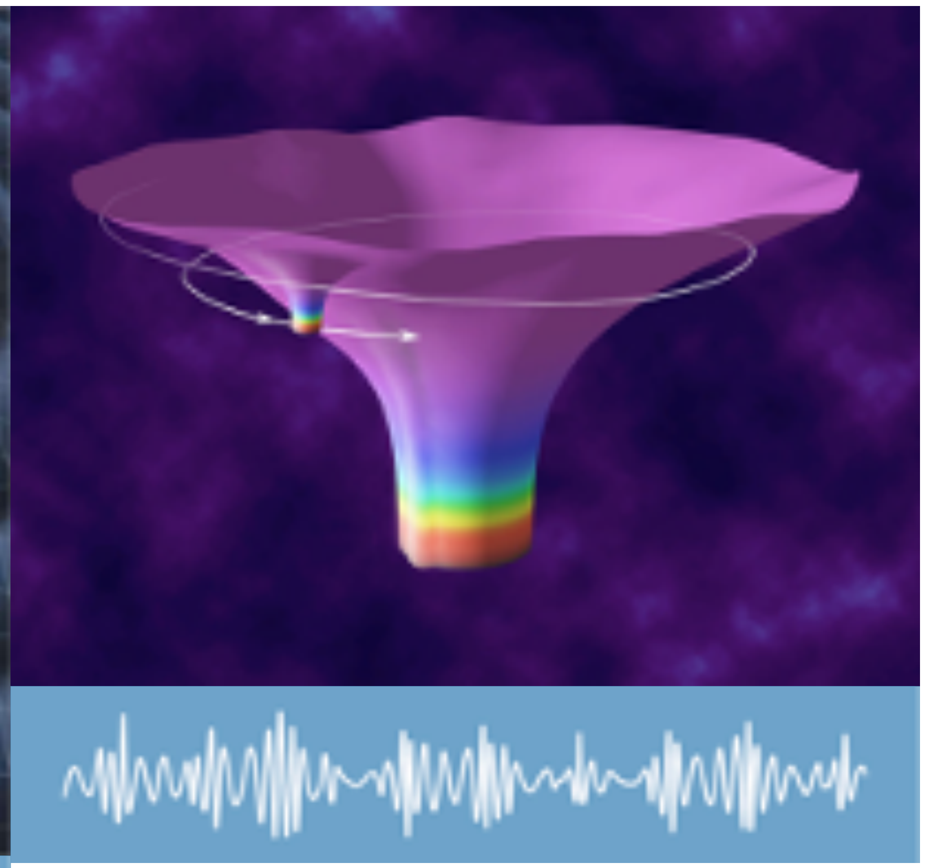

Extreme/ Intermediate Mass Ratio Inspirals (EMRIs/ IMRIs): a BH of $1 - 50\,M_\odot$ / $10^2 - 10^4\,M_\odot$

into an IMBH and/or a MBH

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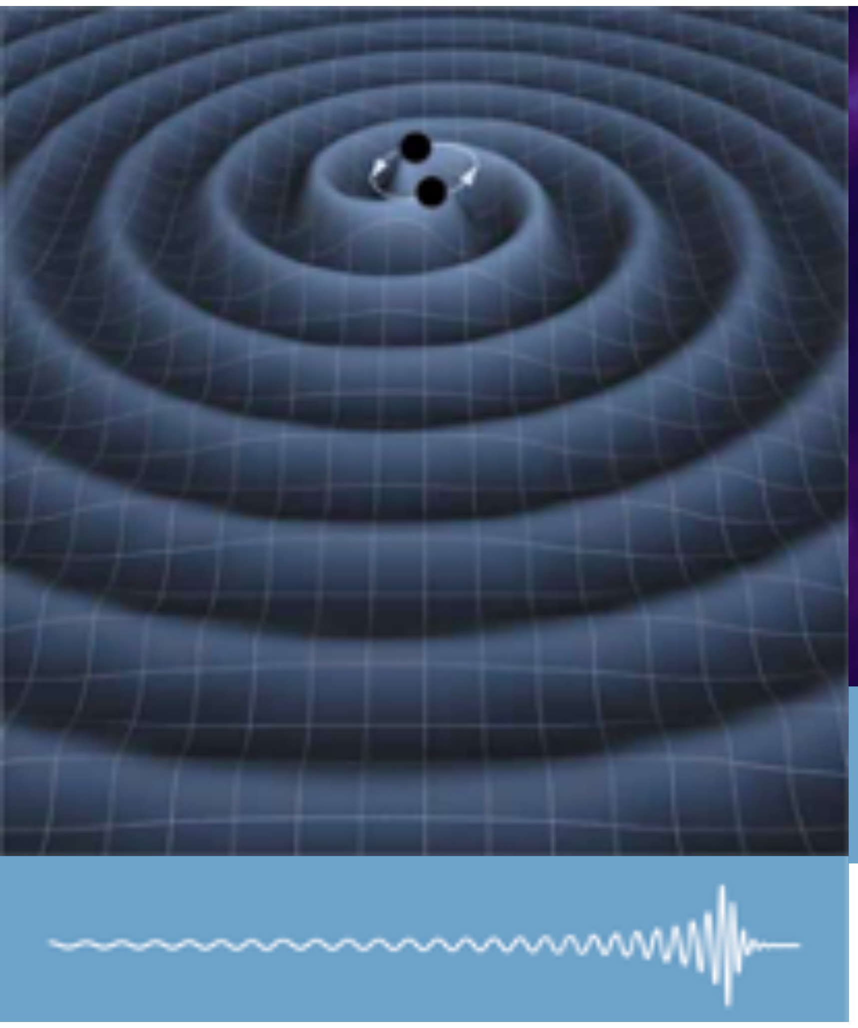

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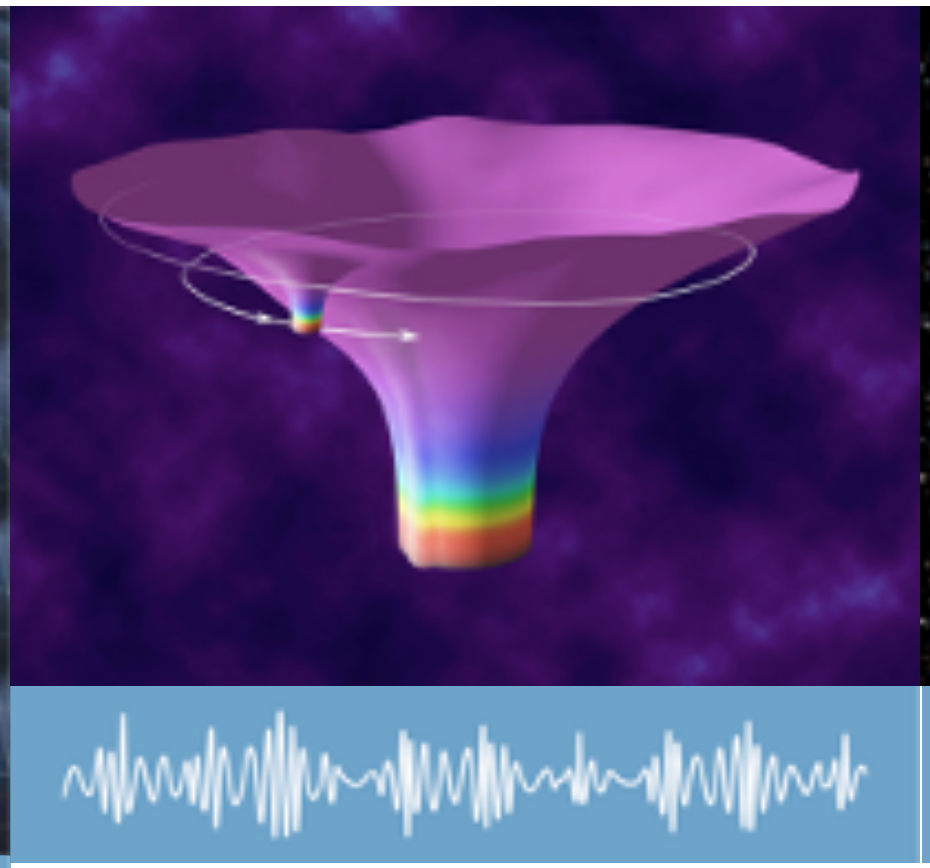

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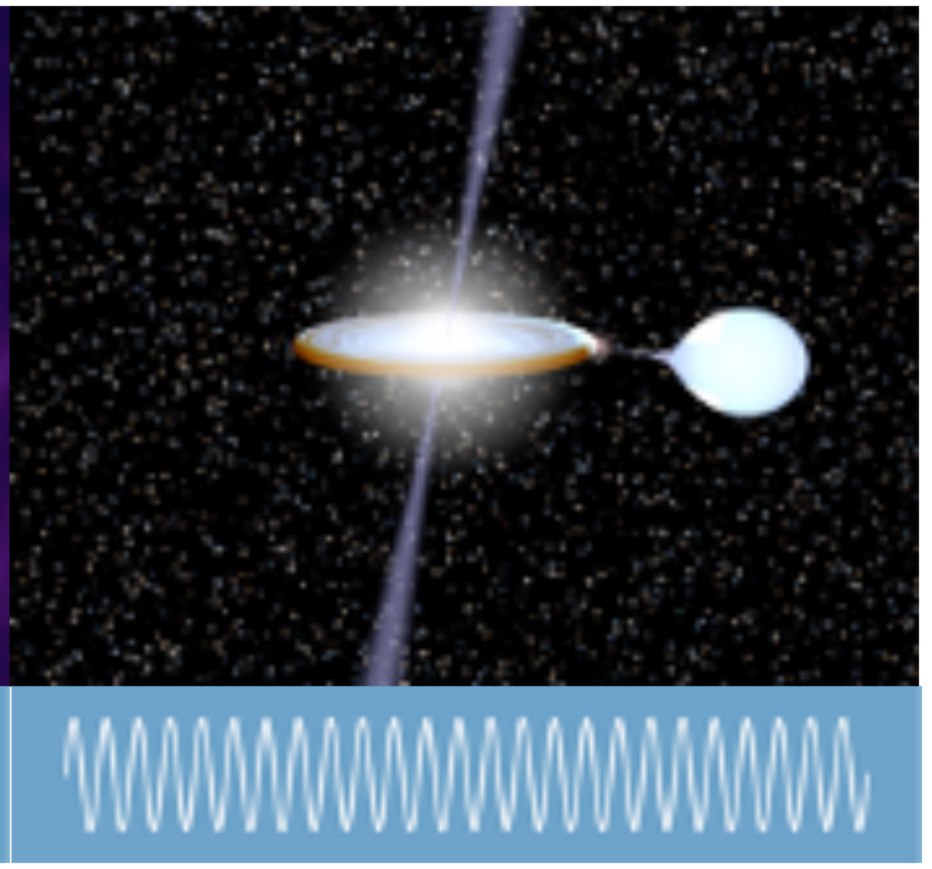
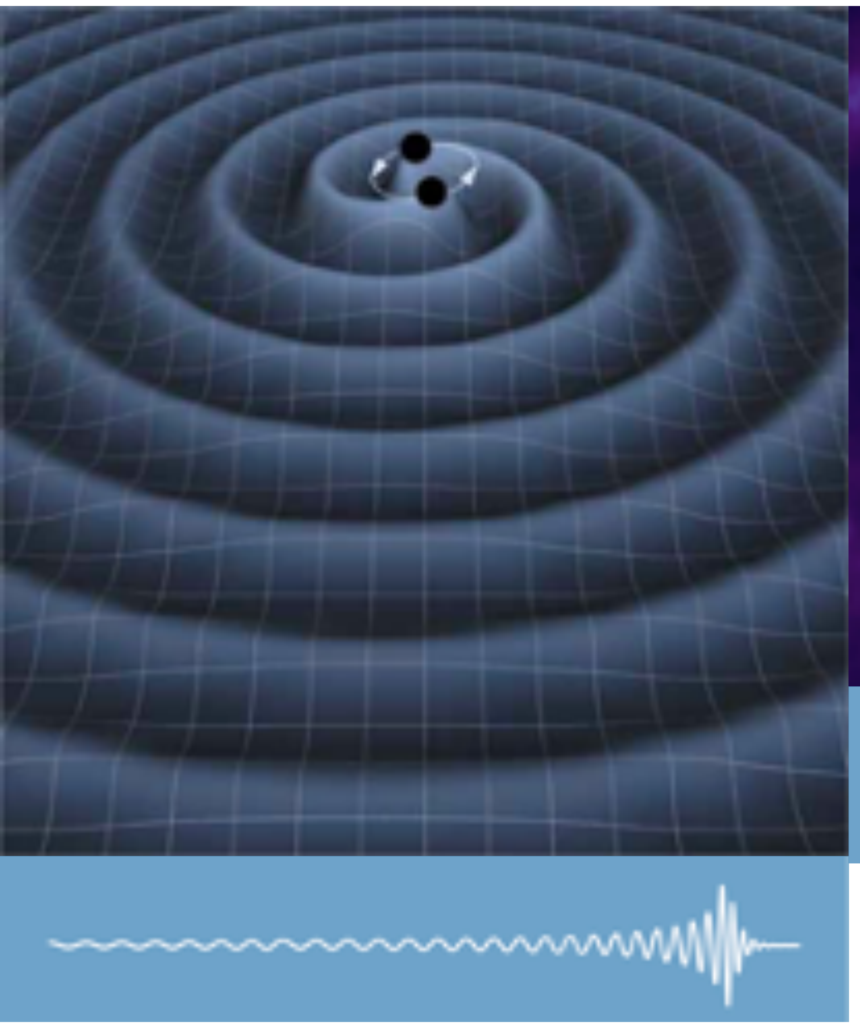


Galactic Binaries in the Milky Way. Population dominated by double WDs.

Verification Binaries: Guaranteed GW Sources!

Sources of Gravitational Waves for LISA



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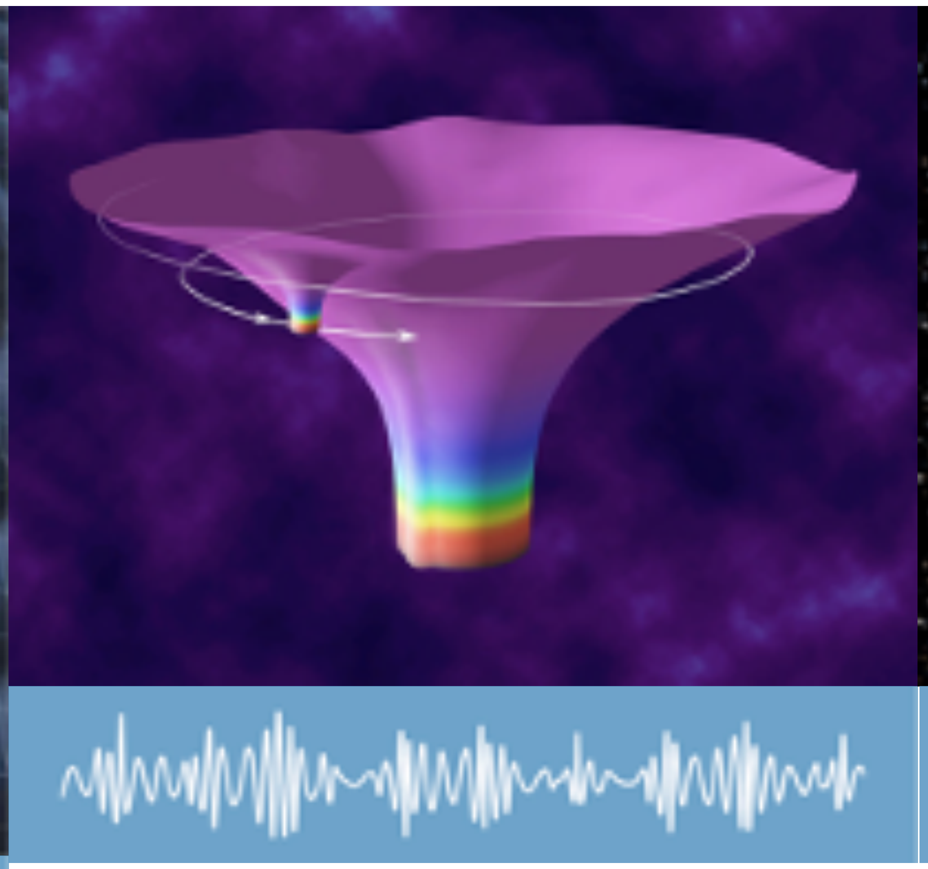

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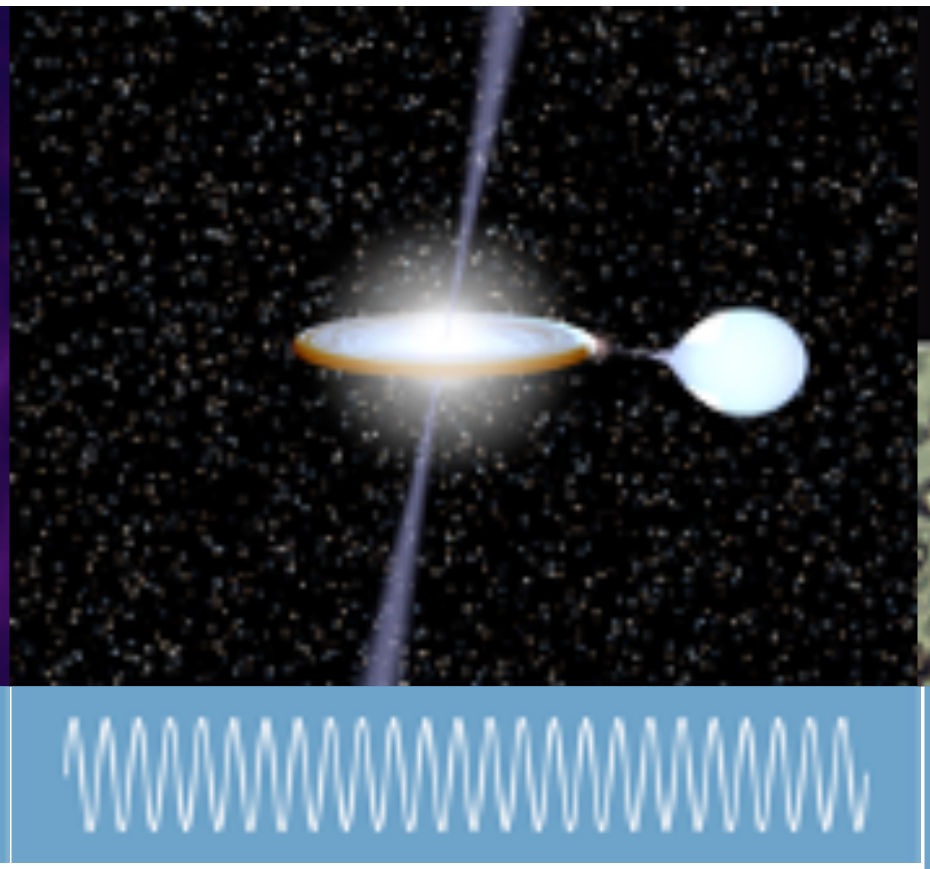

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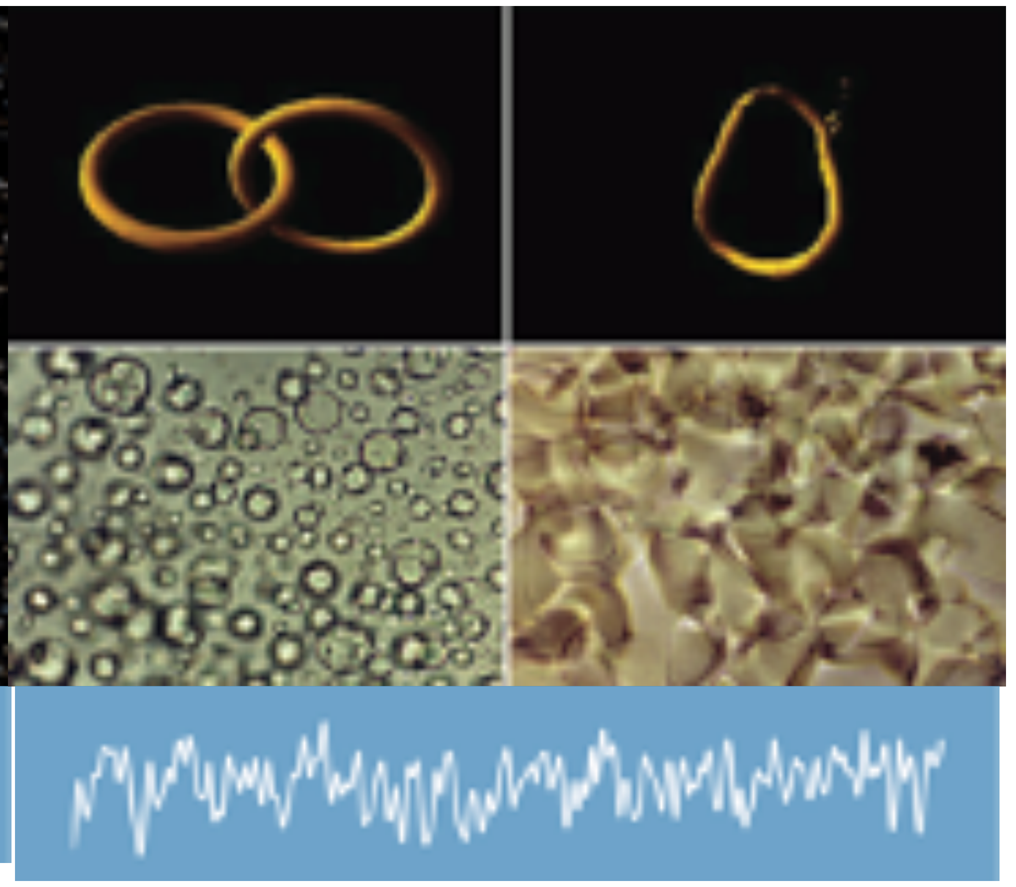
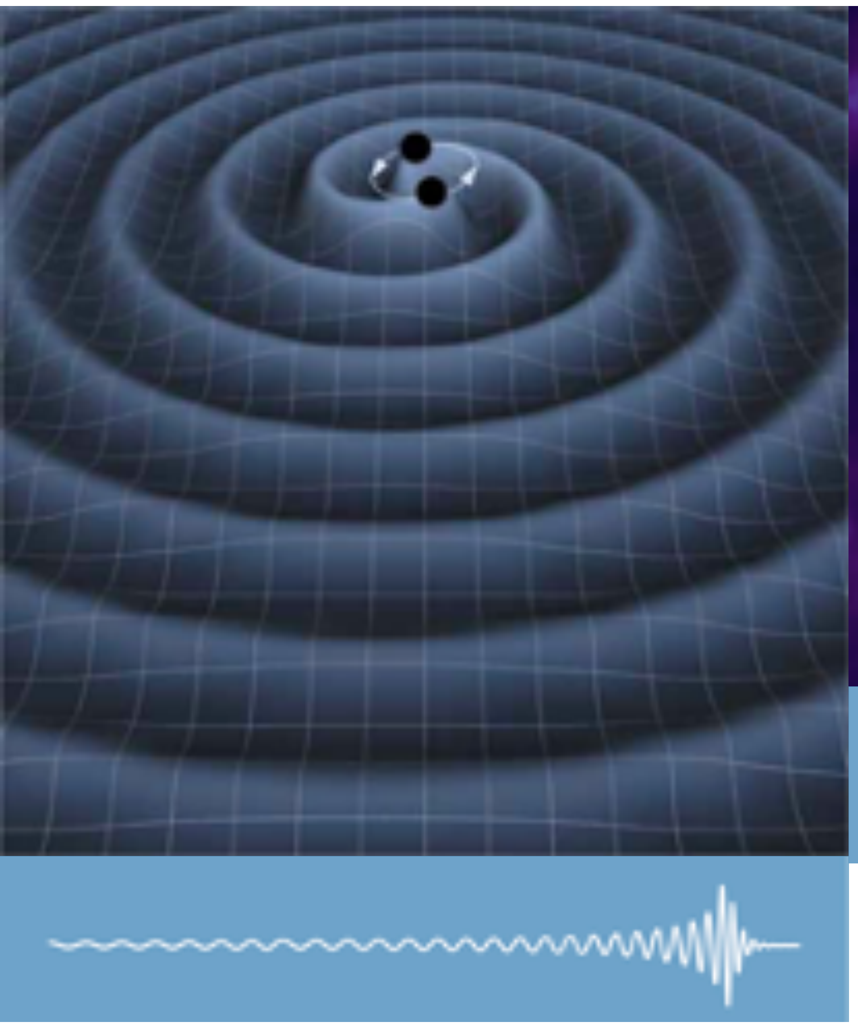


Stochastic GW Foregrounds from Early Universe high-energy Phenomena (Energy Scale ~ 1 TeV)

Sources of Gravitational Waves for LISA



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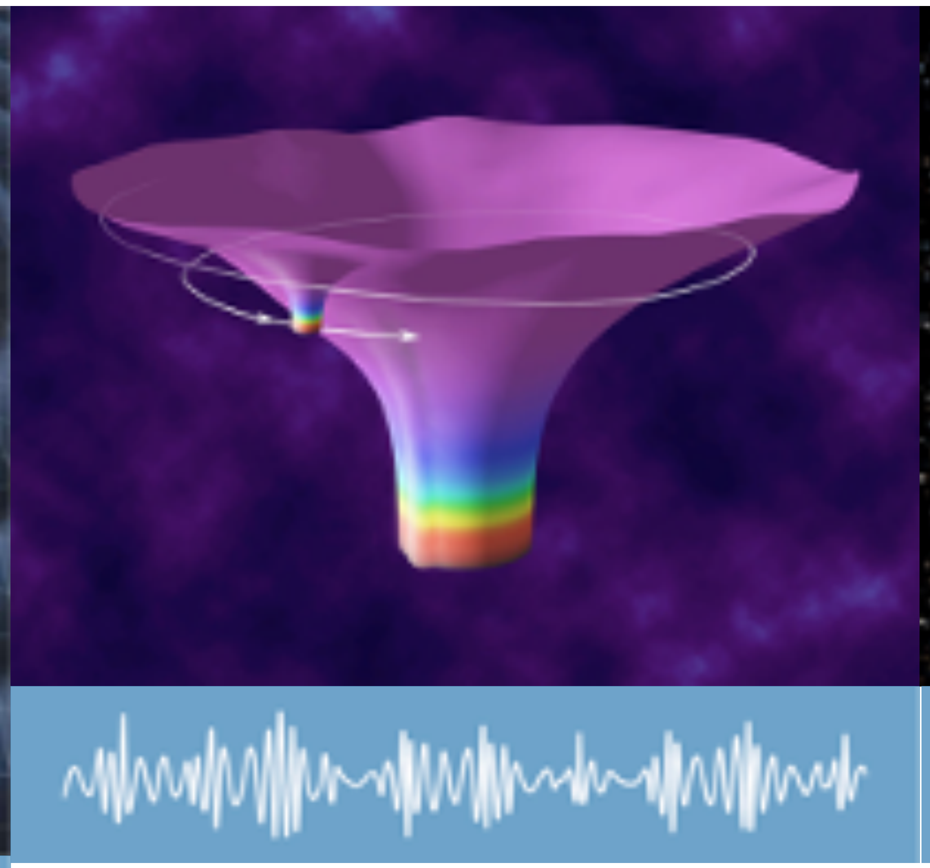

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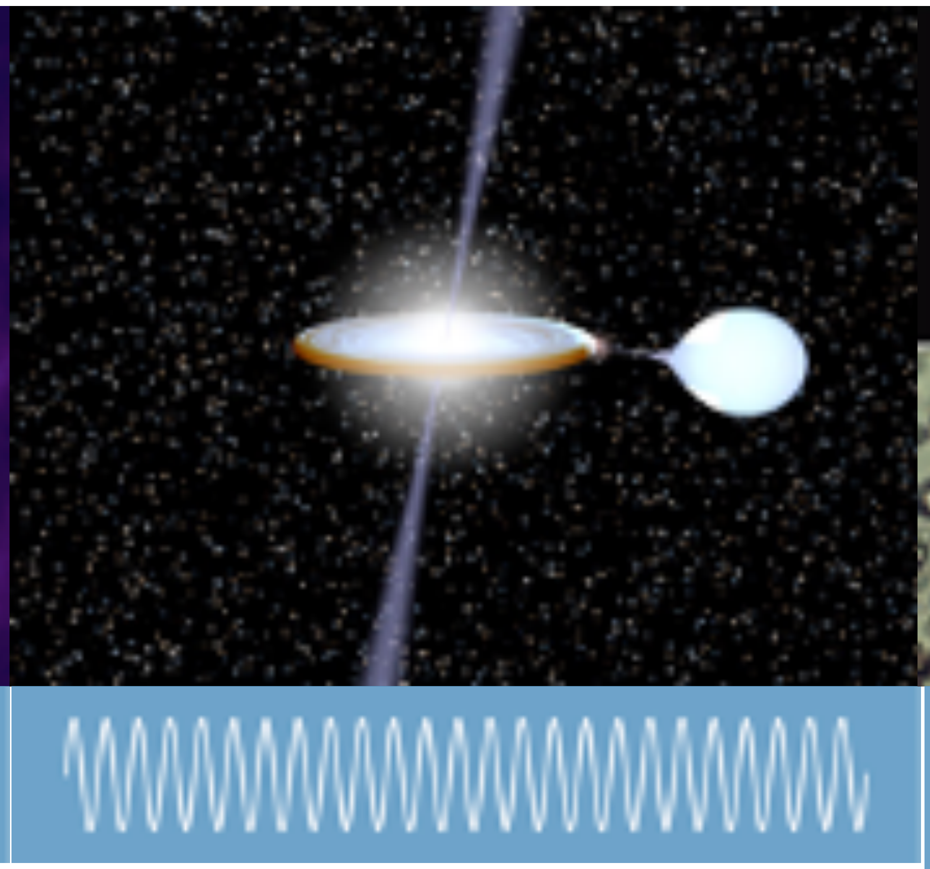

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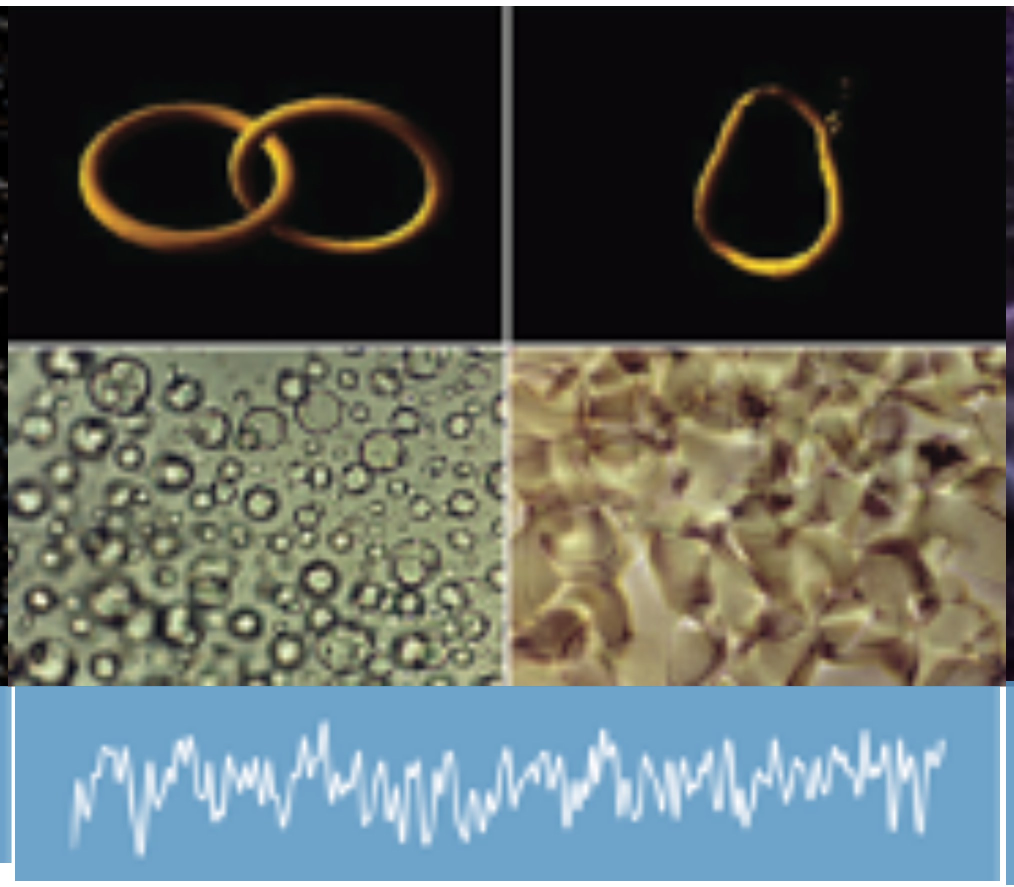
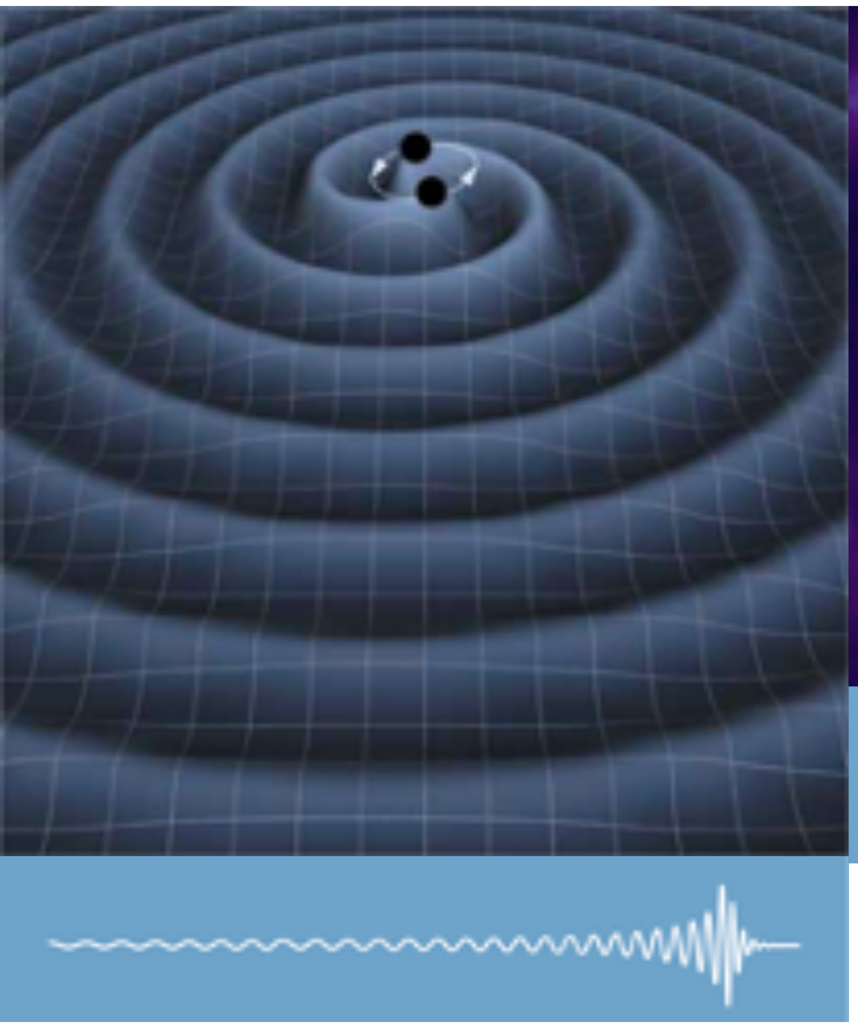


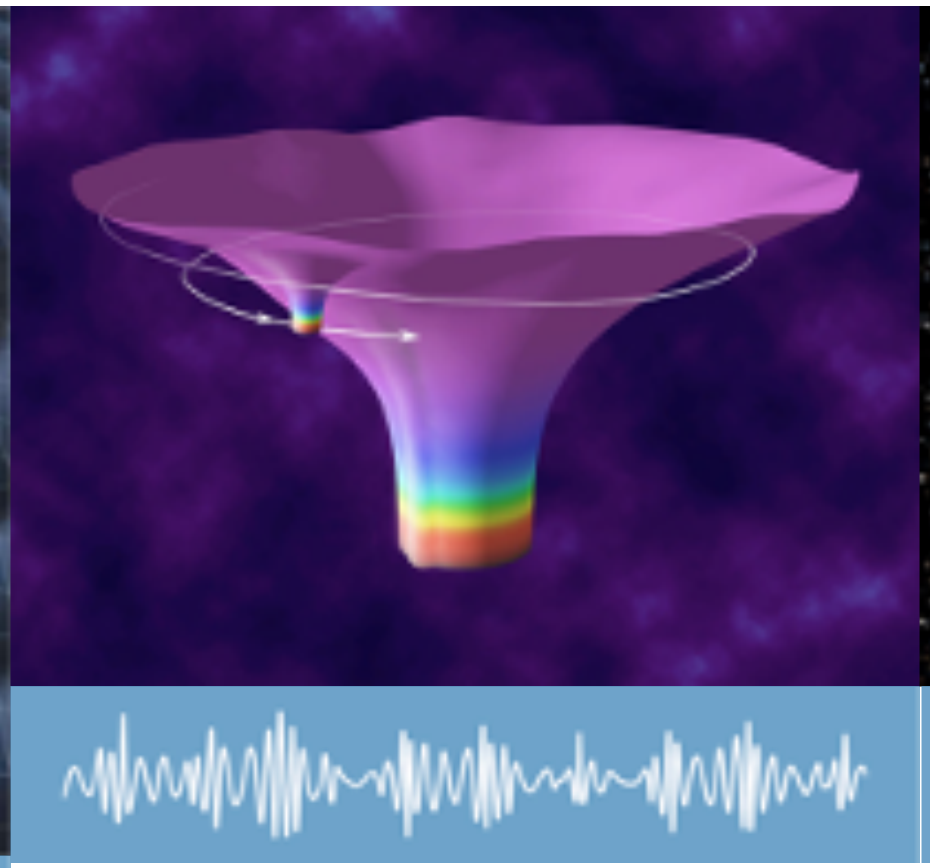
Stochastic GW Foregrounds from Early Universe high-energy Phenomena (Energy Scale ~ 1 TeV)

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

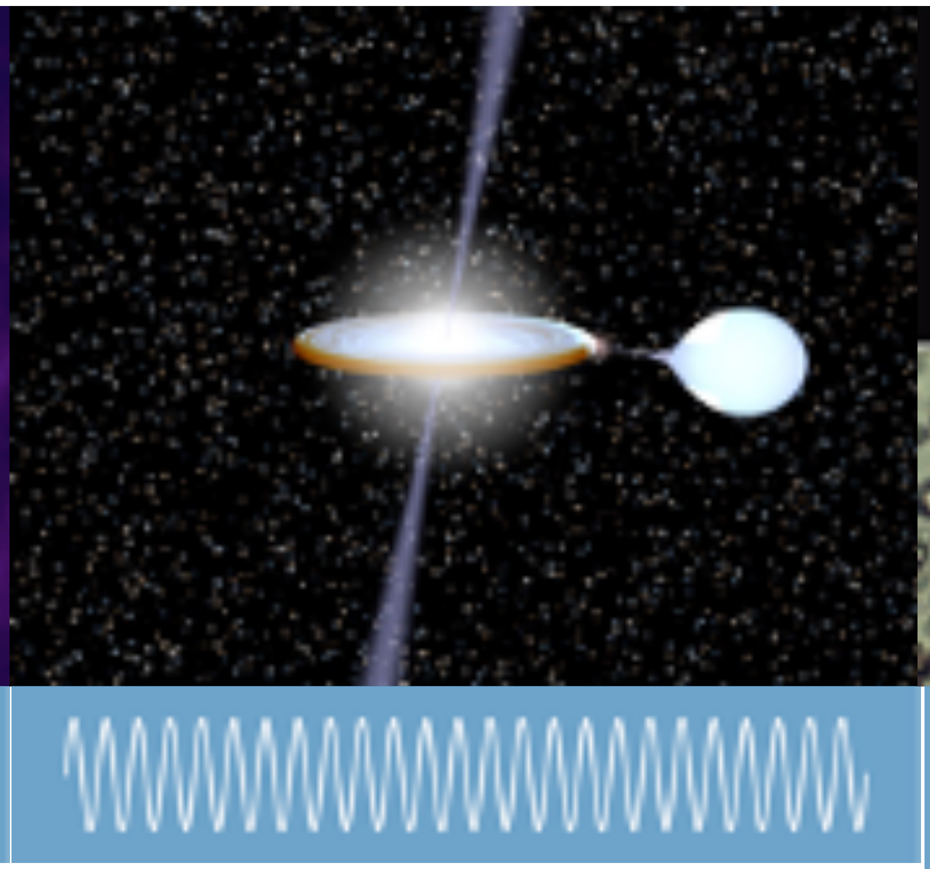
Sources of Gravitational Waves for LISA



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

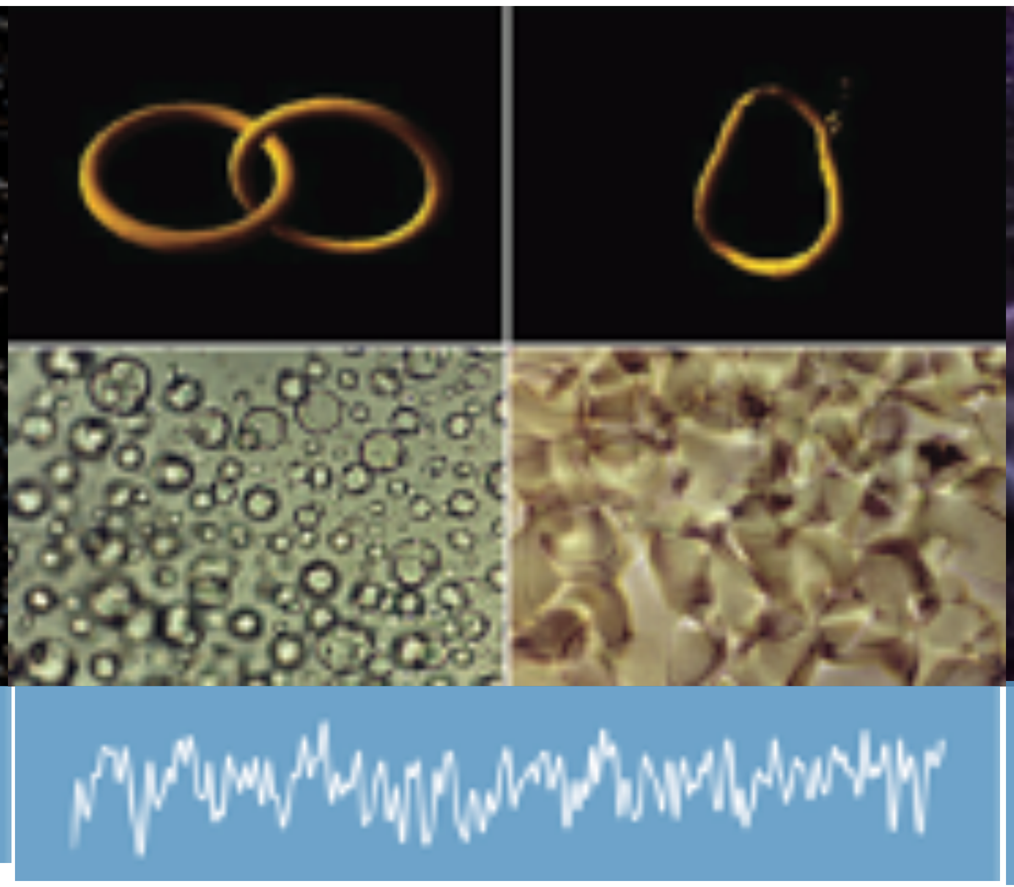


Extreme/ Intermediate Mass Ratio Inspirals (EMRIs/ IMRIs): a BH of $1 - 50\,M_\odot$ / $10^2 - 10^4\,M_\odot$ into an IMBH and/or a MBH



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

Verification Binaries: Guaranteed GW Sources!



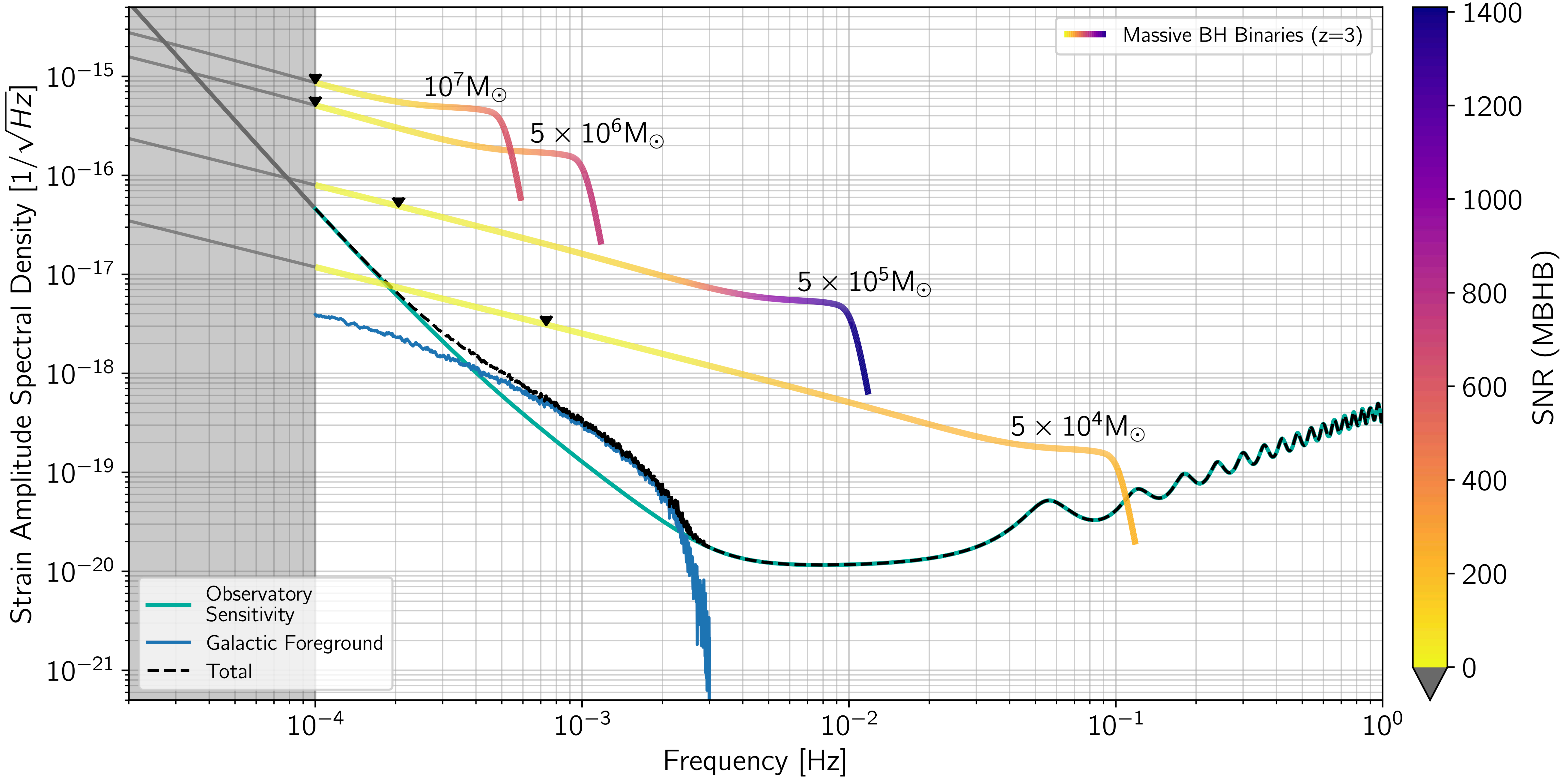
Stochastic GW Foregrounds from Early Universe high-energy Phenomena (Energy Scale ~ 1 TeV)

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

?

The Science of LISA

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



The Science of LISA

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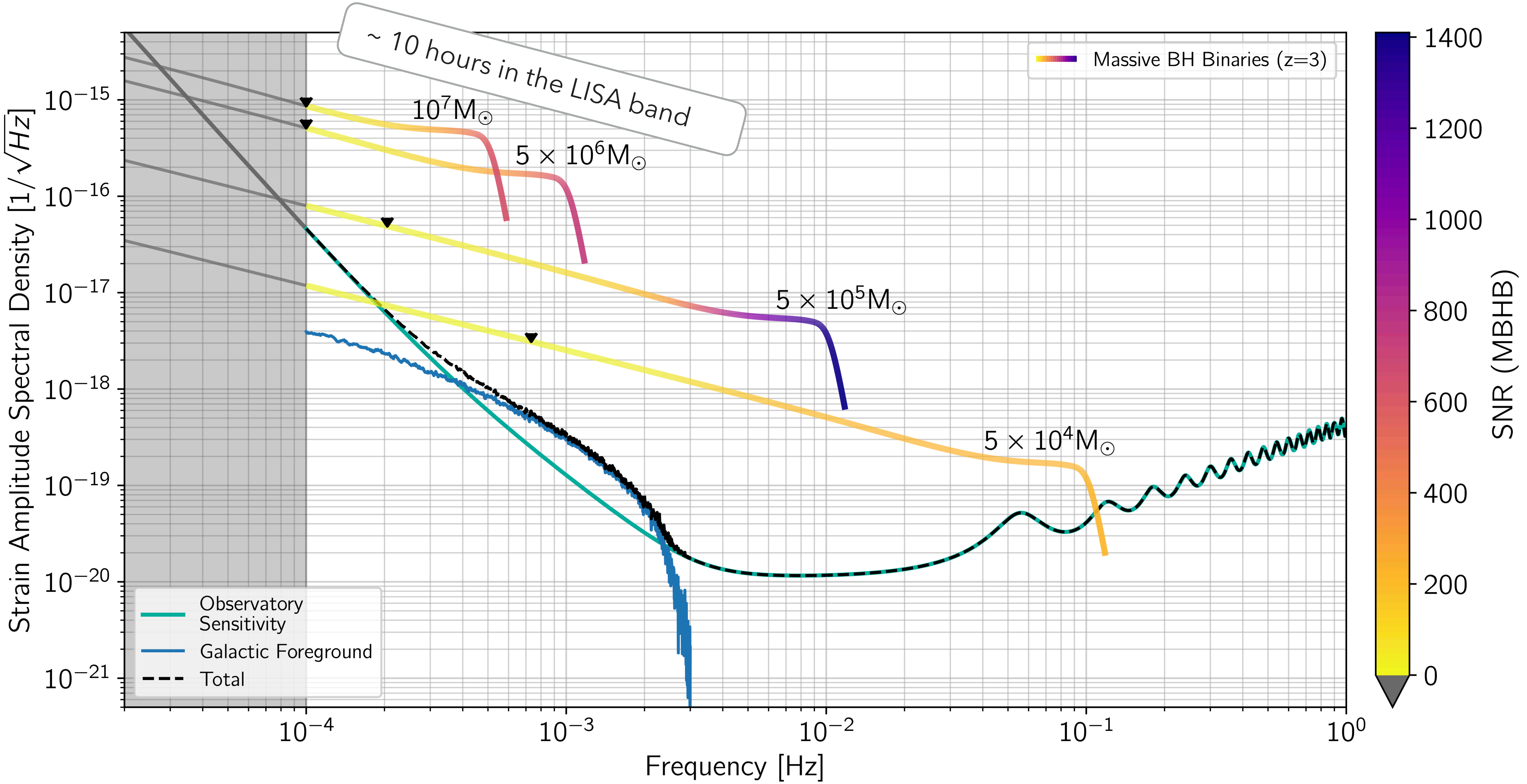

The Science of LISA

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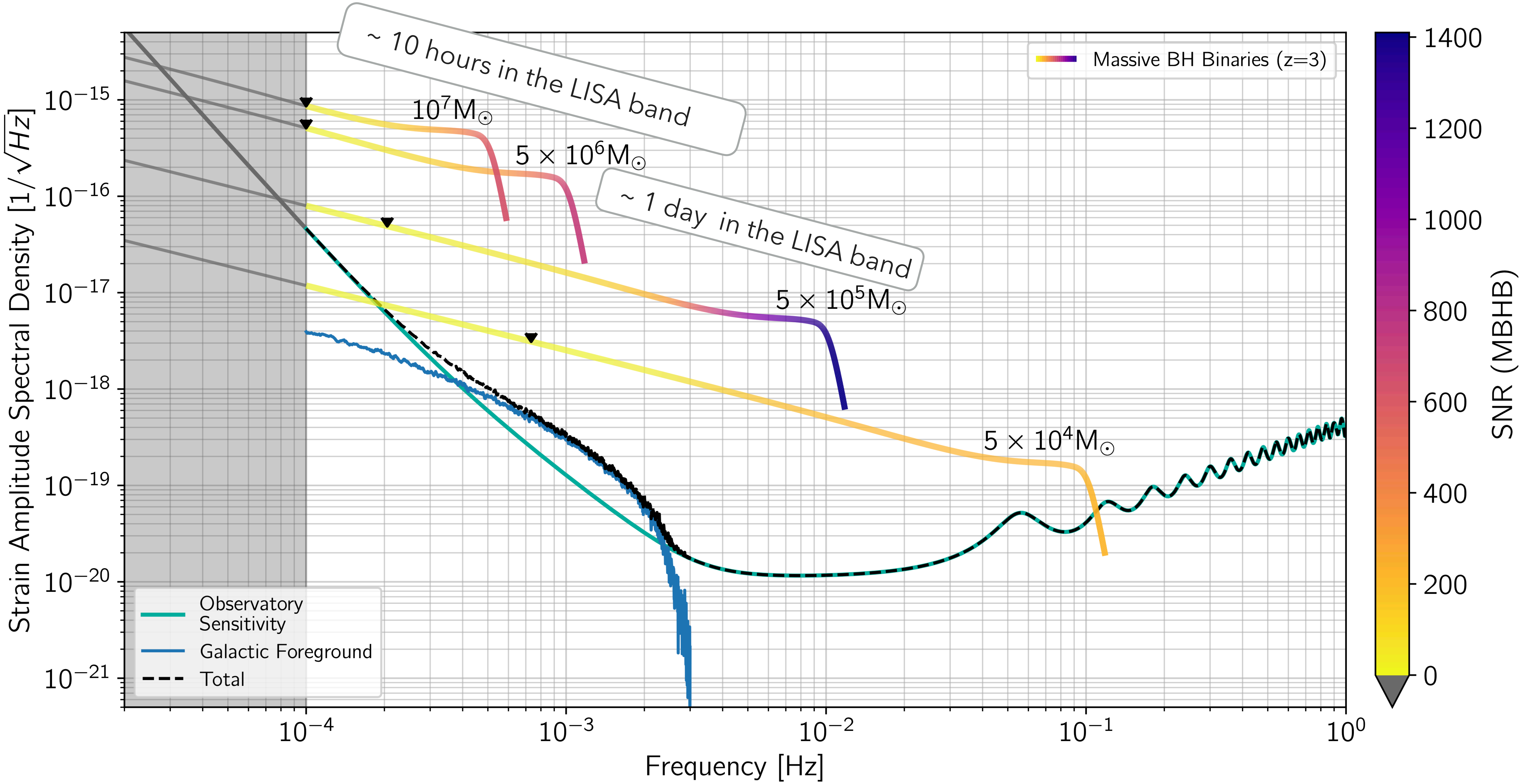

The Science of LISA

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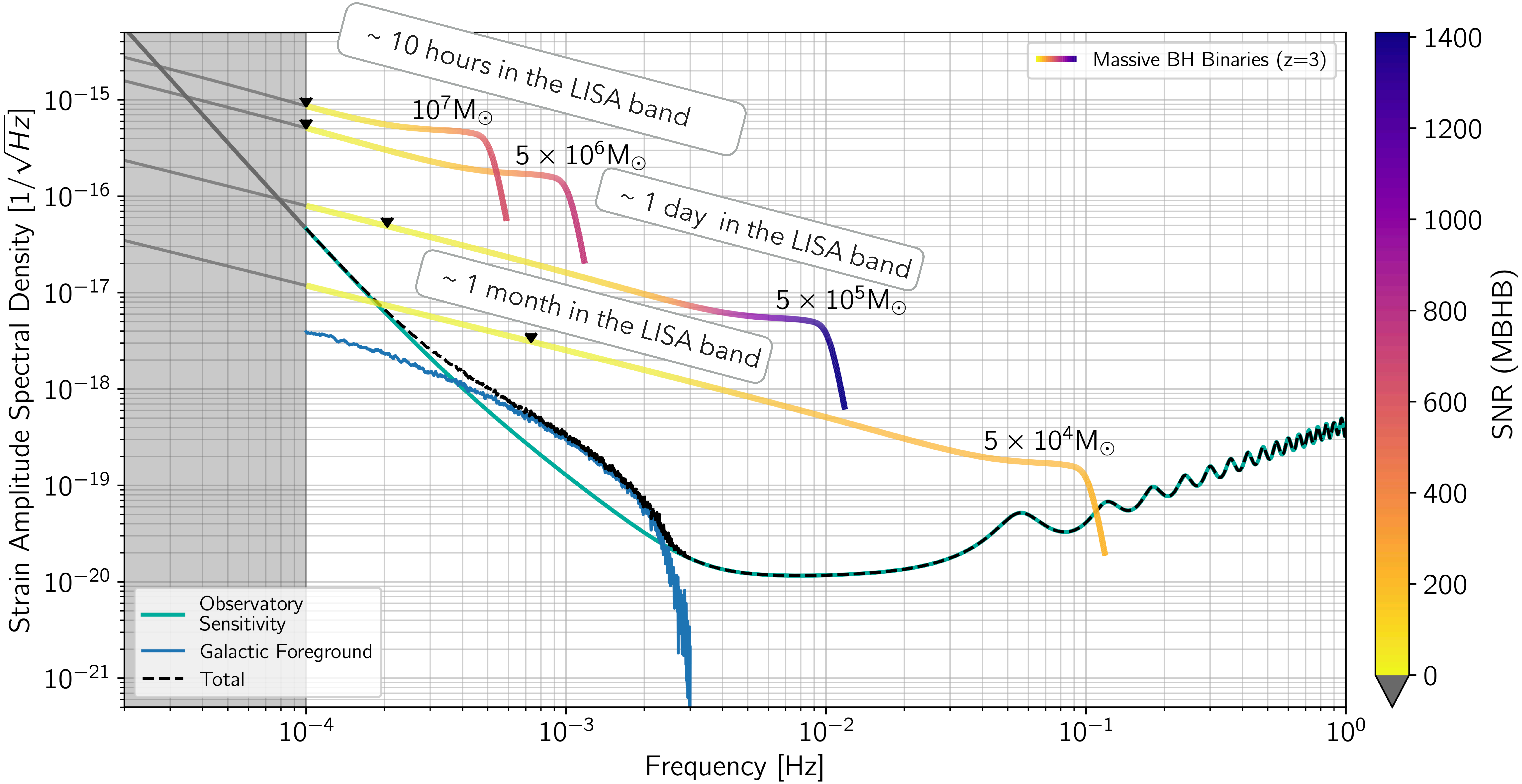

The Science of LISA

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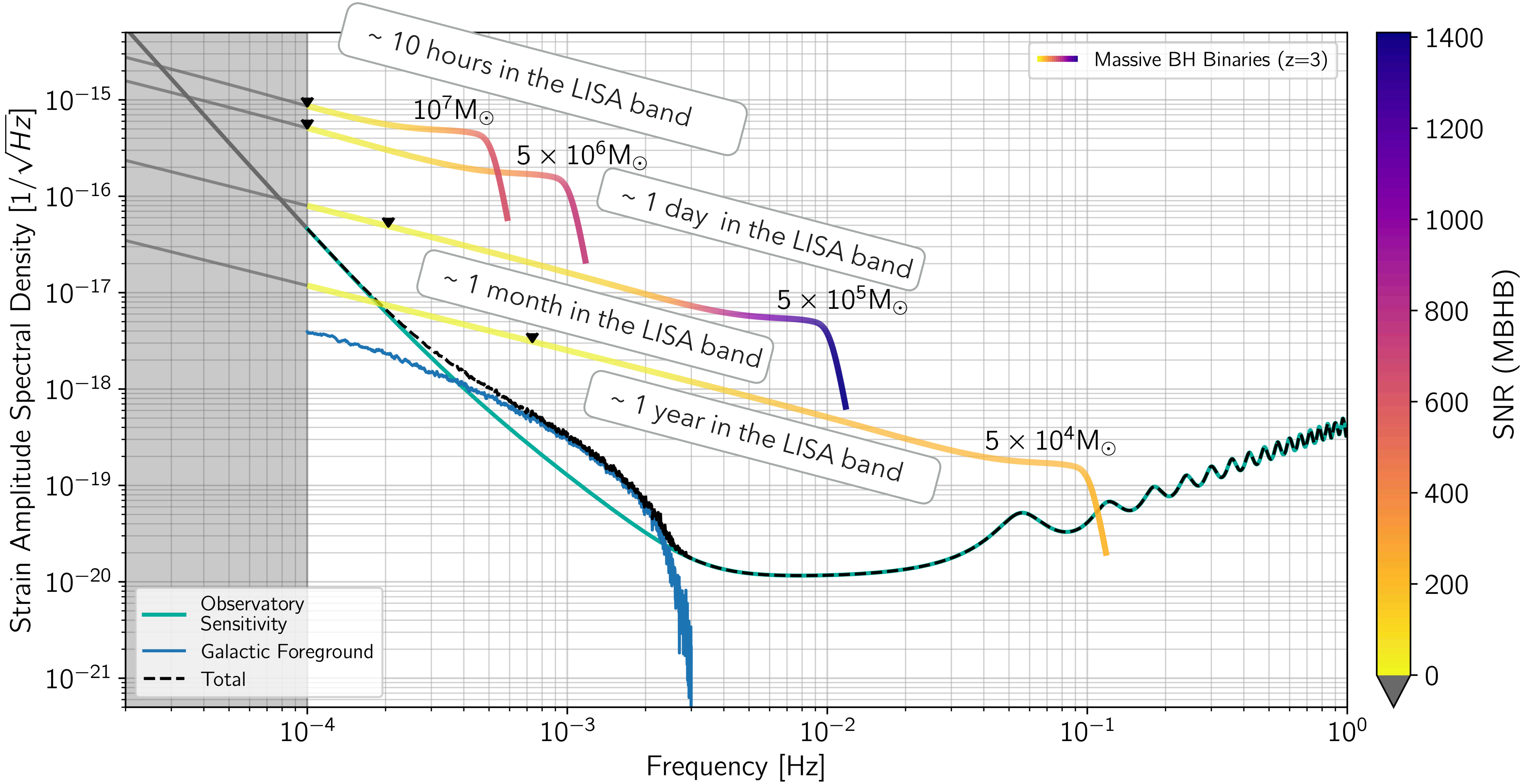


The Science of LISA

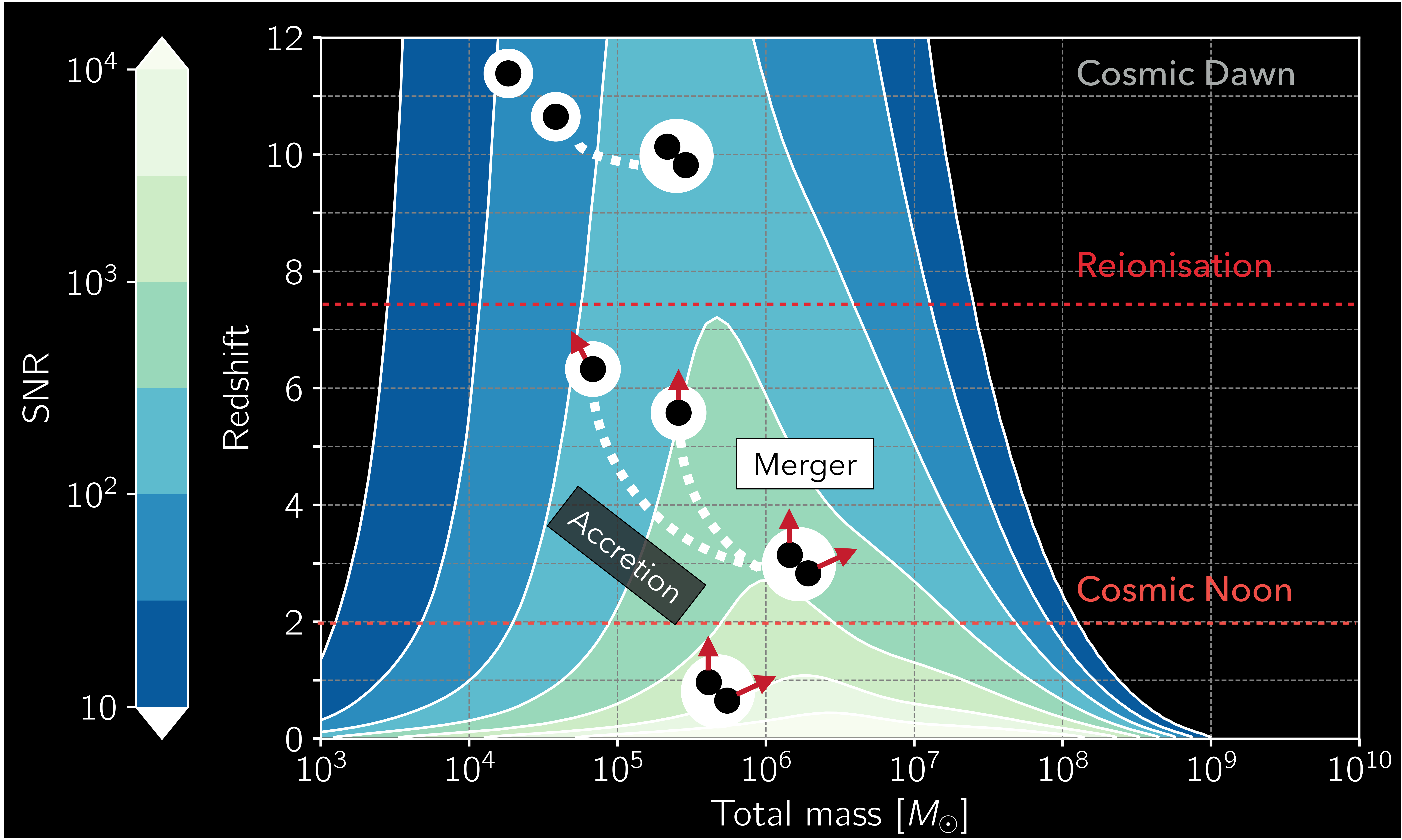
✳ **SO2**: Trace the origins, growth and merger histories of massive Black Holes

✦ 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?

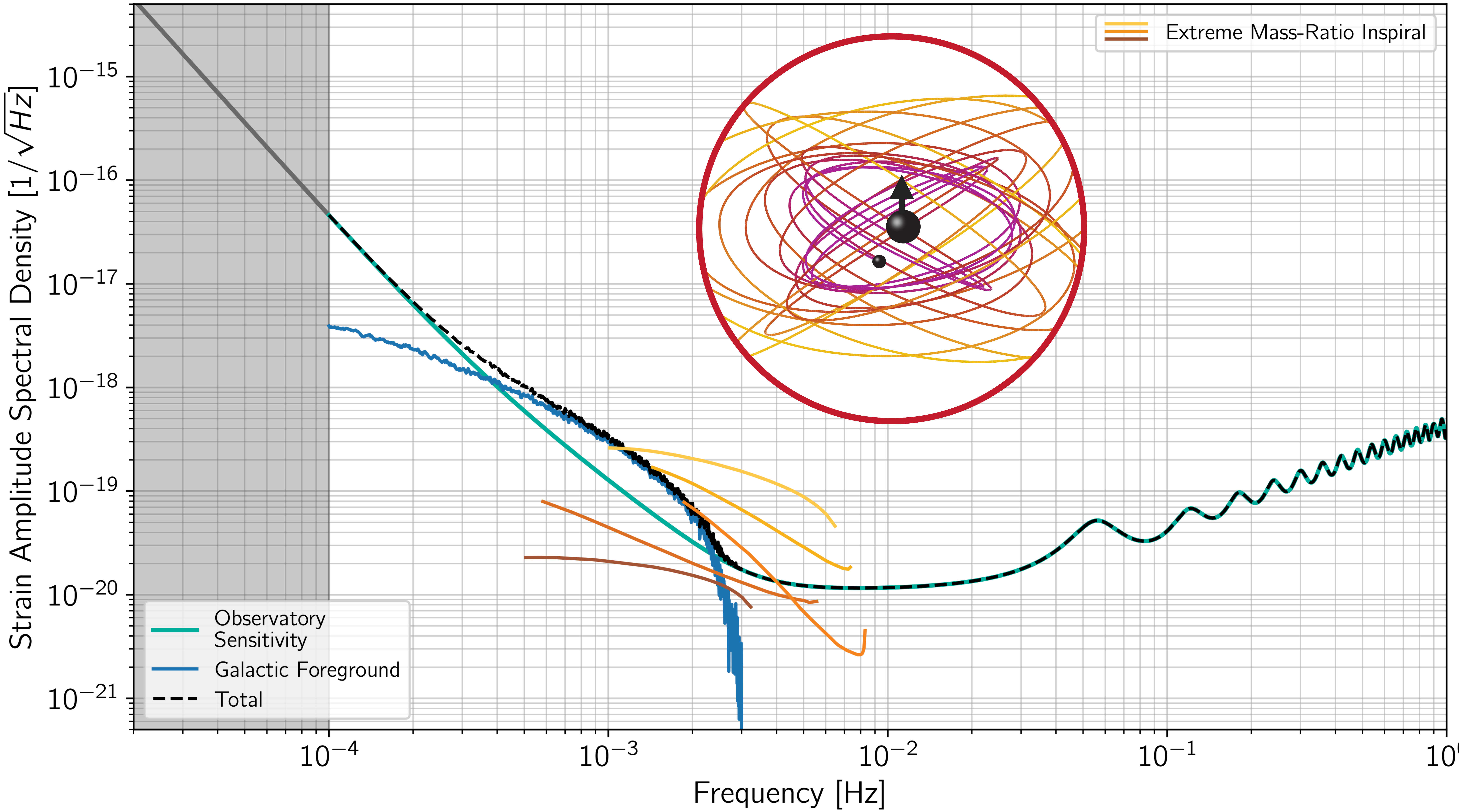


The Science of LISA

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

- ✦ What is the mass and spin distribution of quiescent MBHs in local Universe?
- ✦ Which processes dominate stellar dynamics in the galactic centers near the MBH?
- ✦ Do IMBHs exist?

- **Mass and Spin accuracy ~ 0.001%**



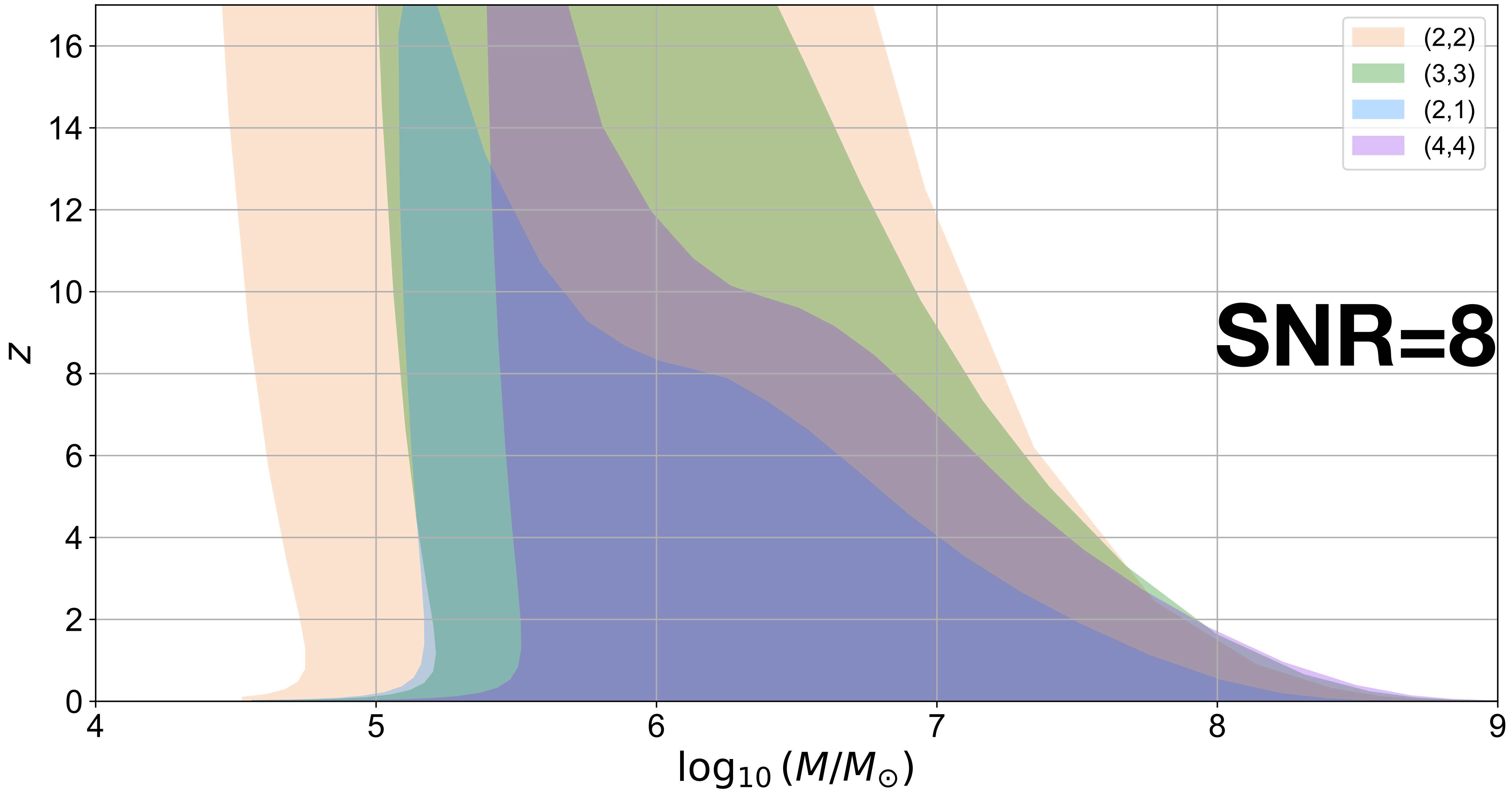
The Science of LISA

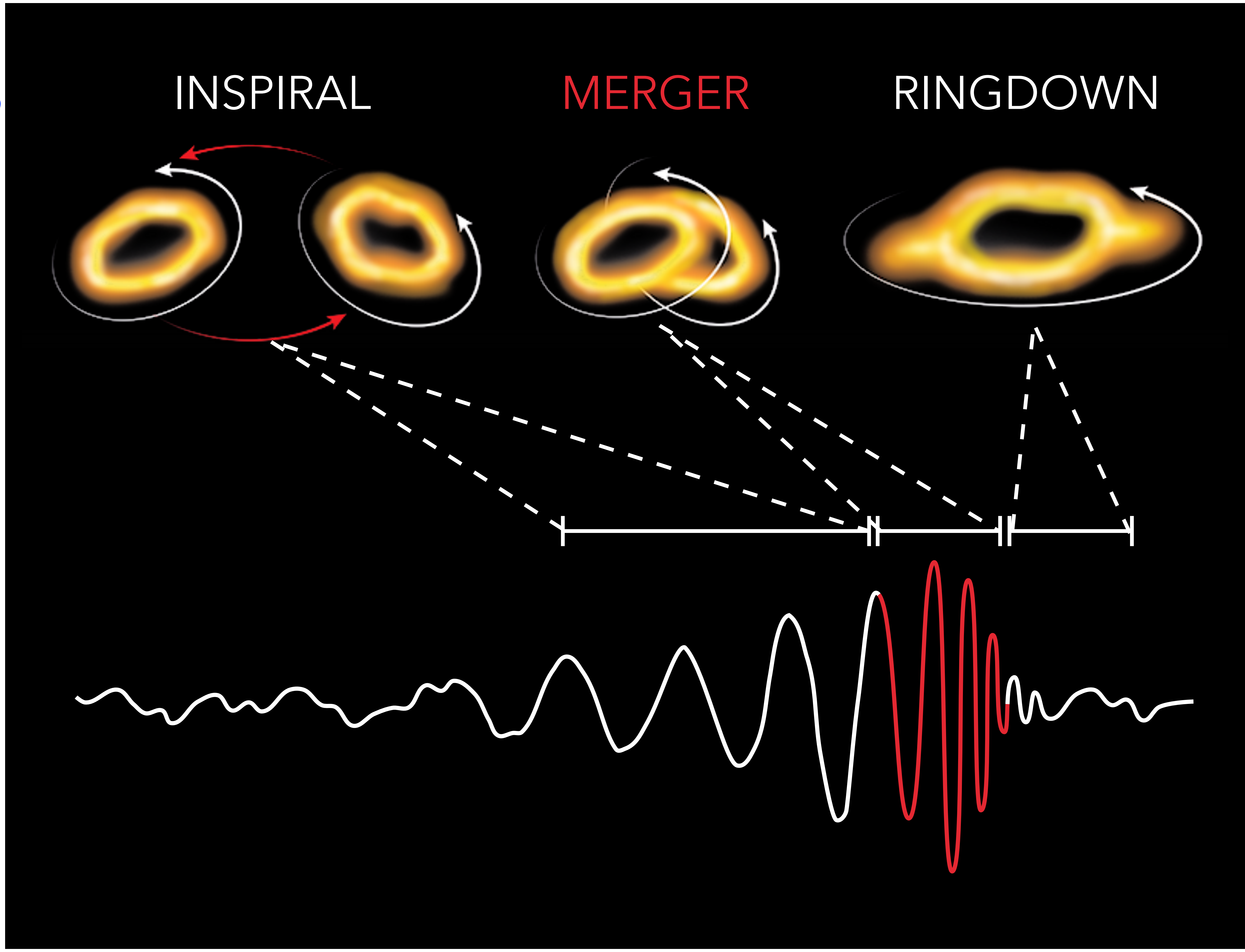
✴ **SO5**: Explore the Fundamental Nature of Gravity and Black Holes

✦ 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?

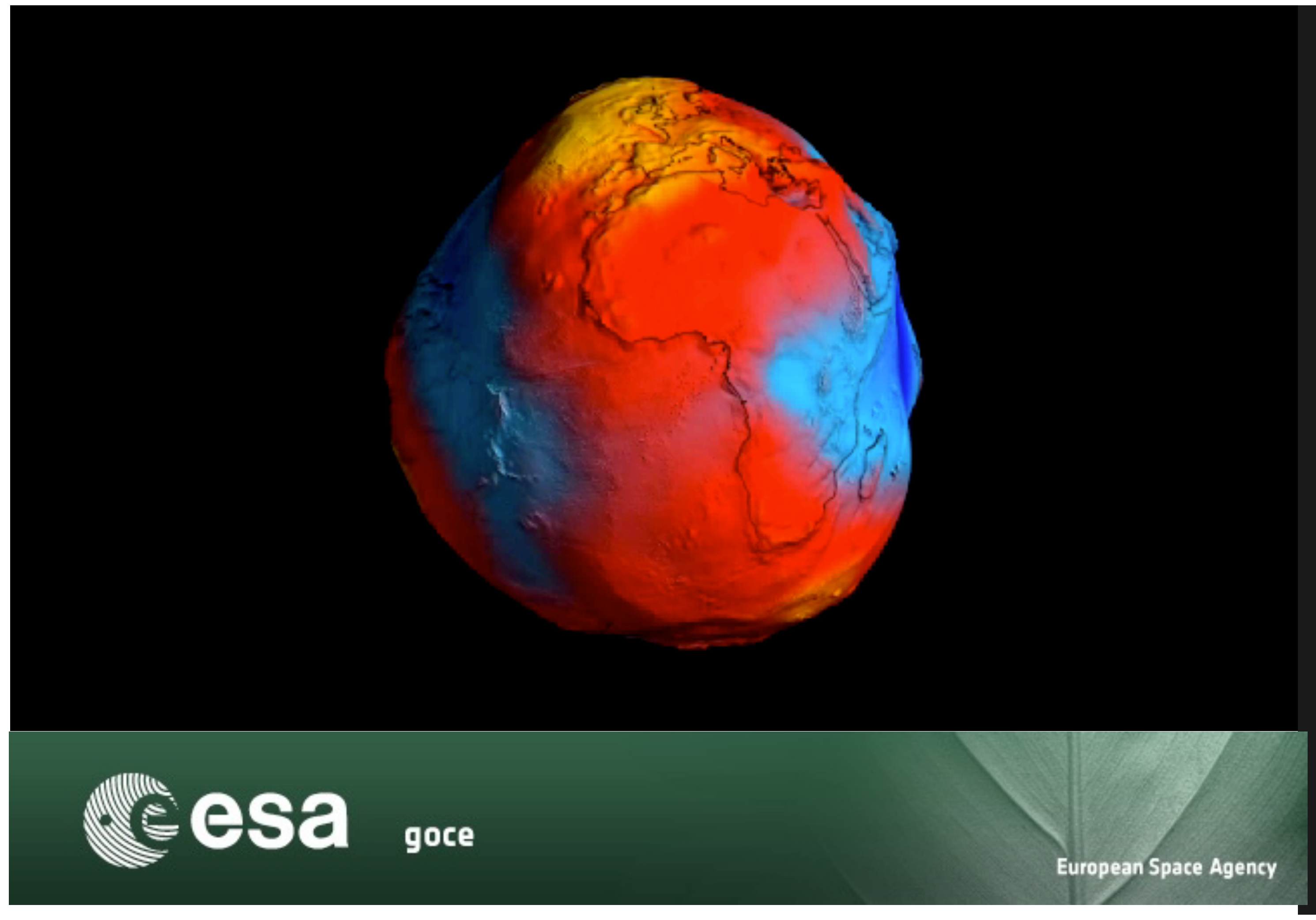




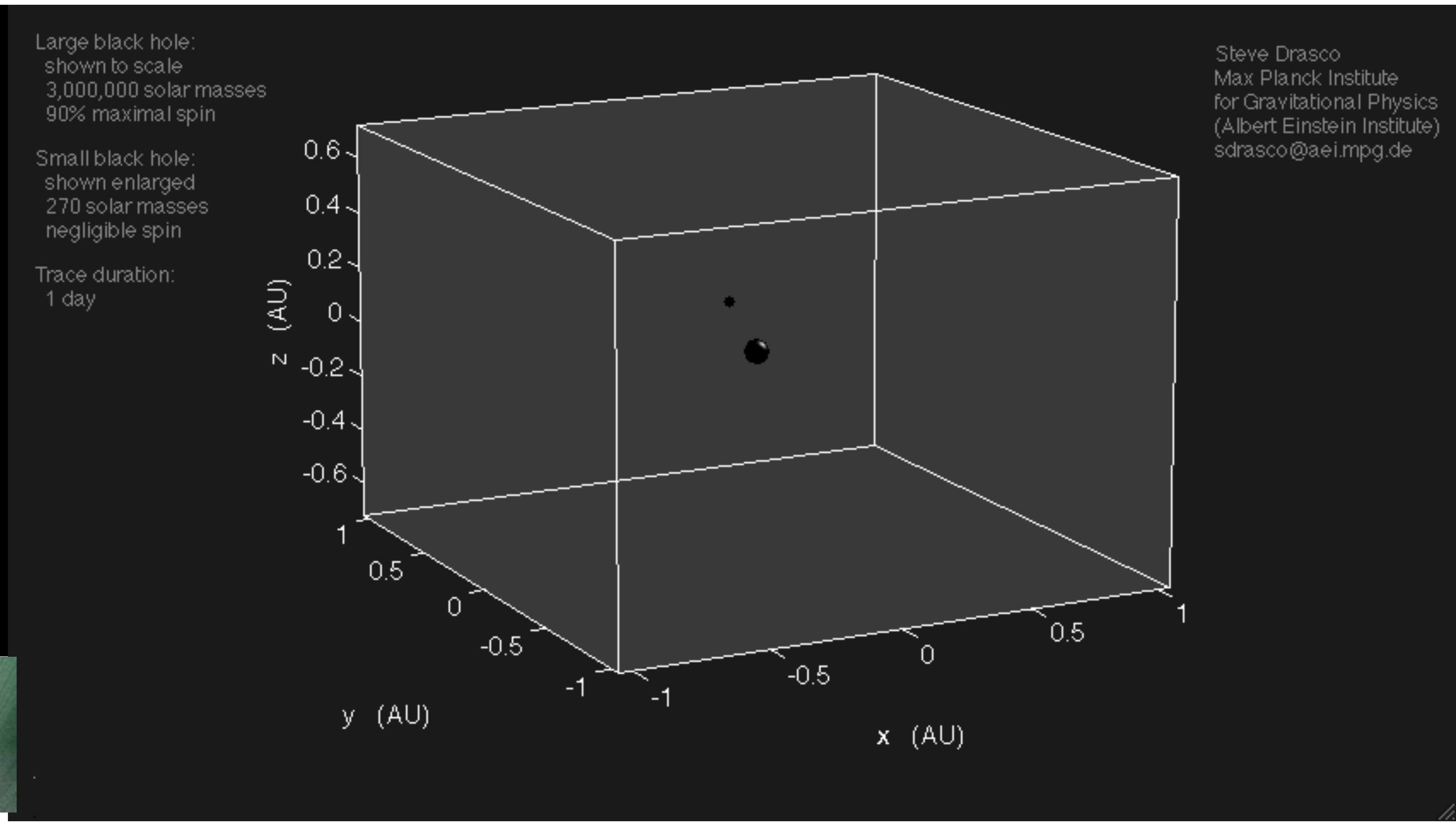
The Science of LISA

✴ **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%**



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!

The Science of LISA

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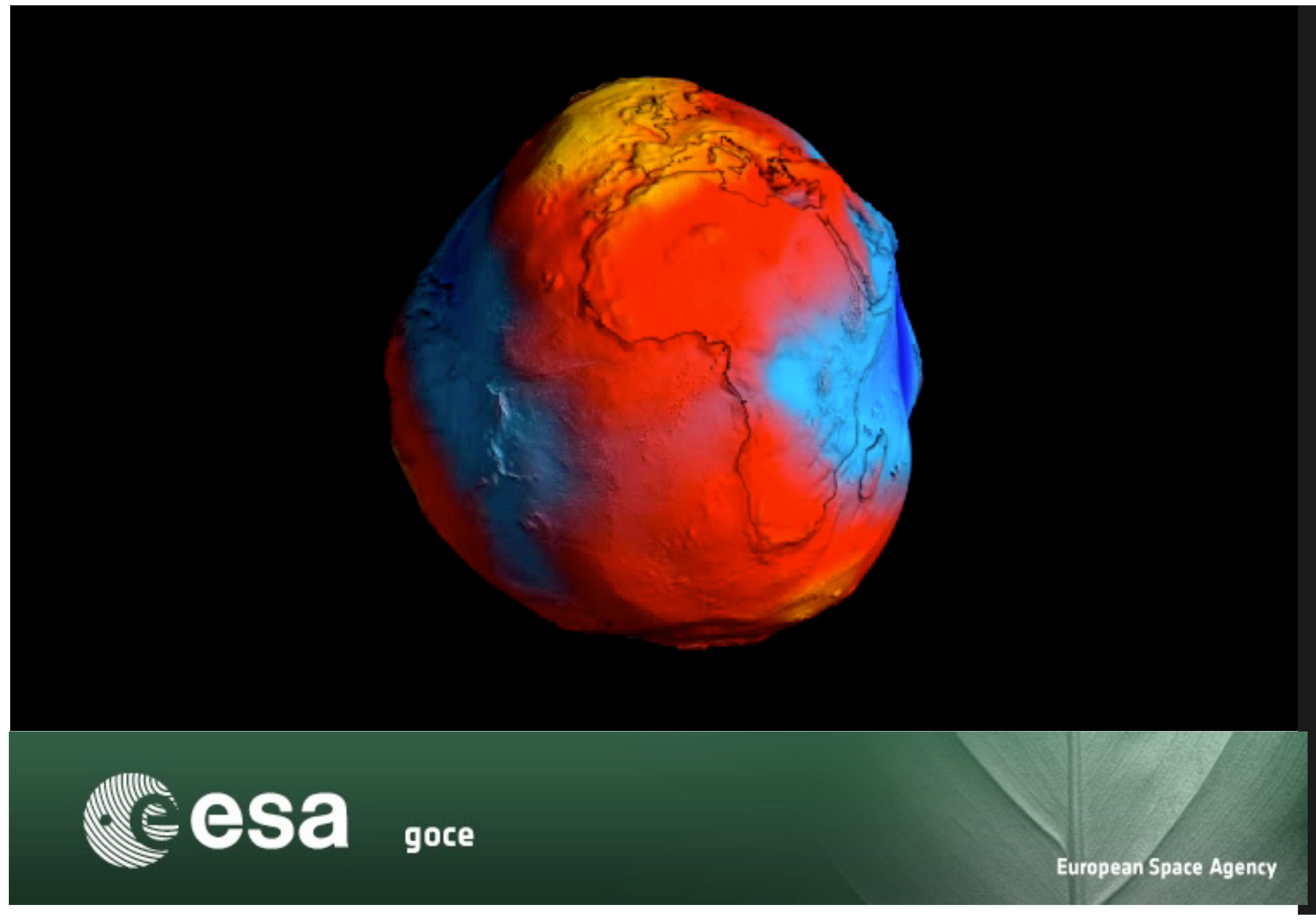

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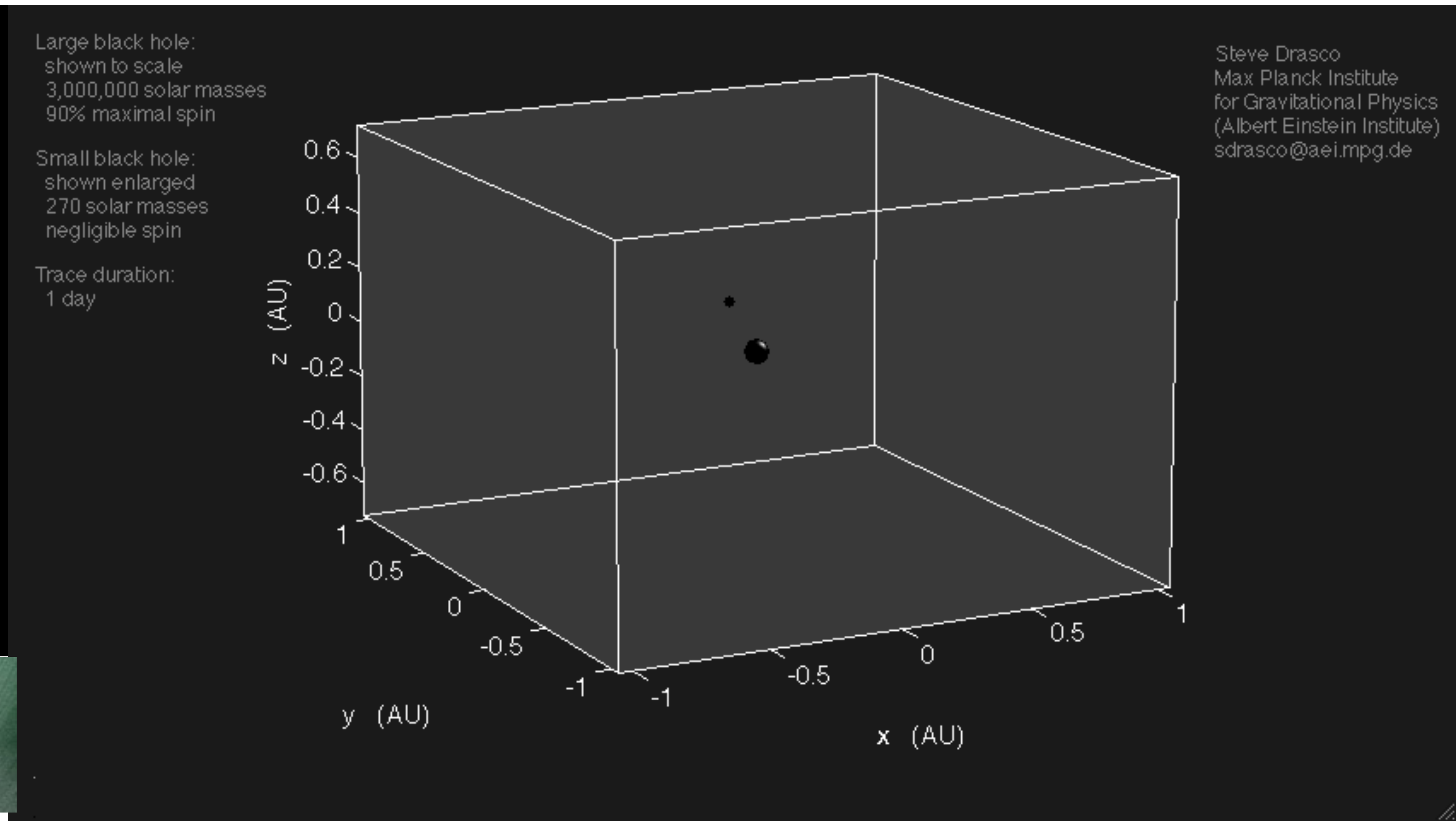


For a Kerr BH in GR:

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

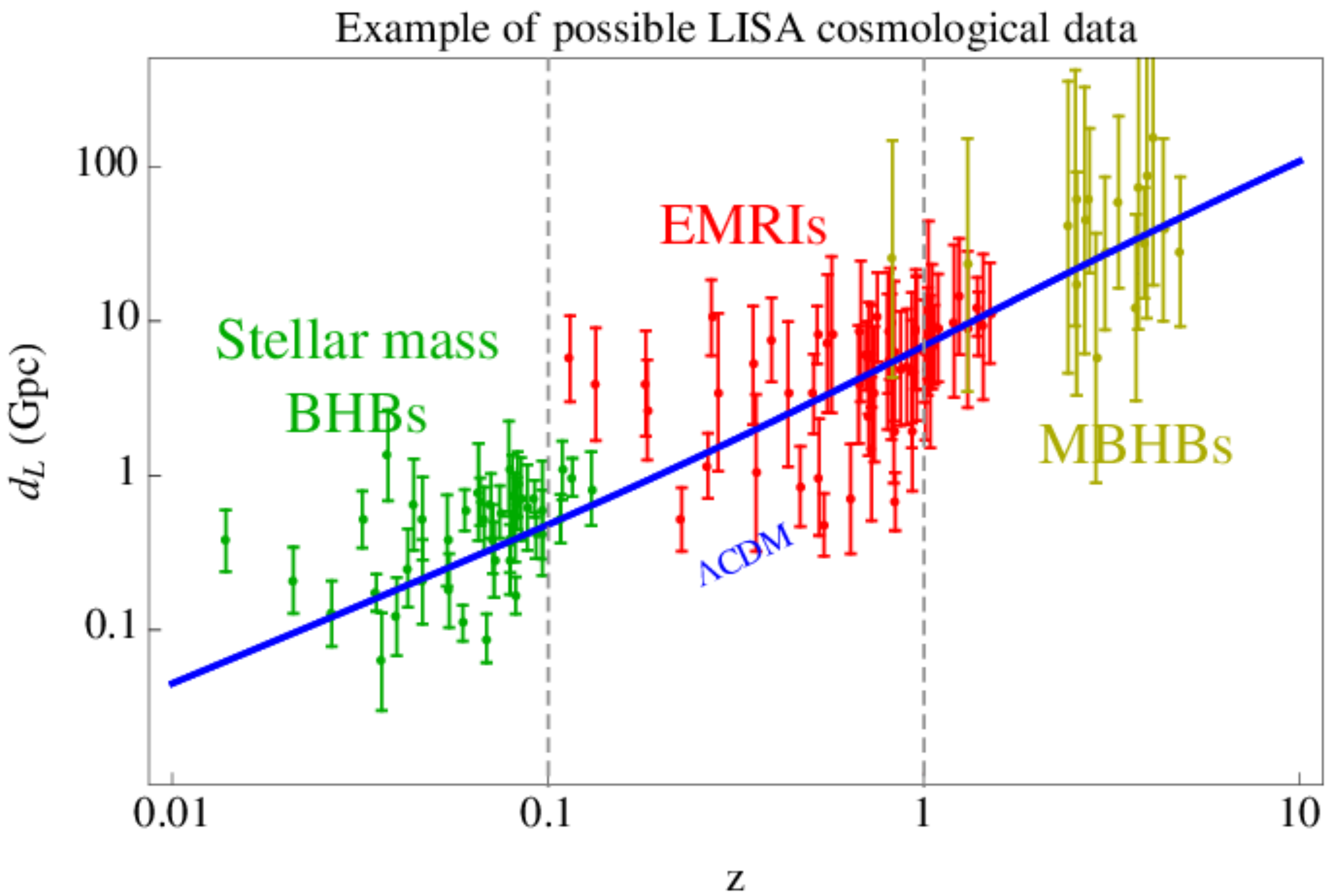
Tests of the Kerr geometry and/or theory of Gravity!

The Science of LISA

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

✦ LISA will probe the expansion history of the Universe, $d_L(z)$, using GW sirens at high redshifts (**WARNING**: provided we can obtain the redshift): SOBH binaries (z < 0.2), EMRIs (z < 1.5), MBHBs (z < 6).

- **No need of calibration**
- **Ho at few % level with observations up to z ~ 3**



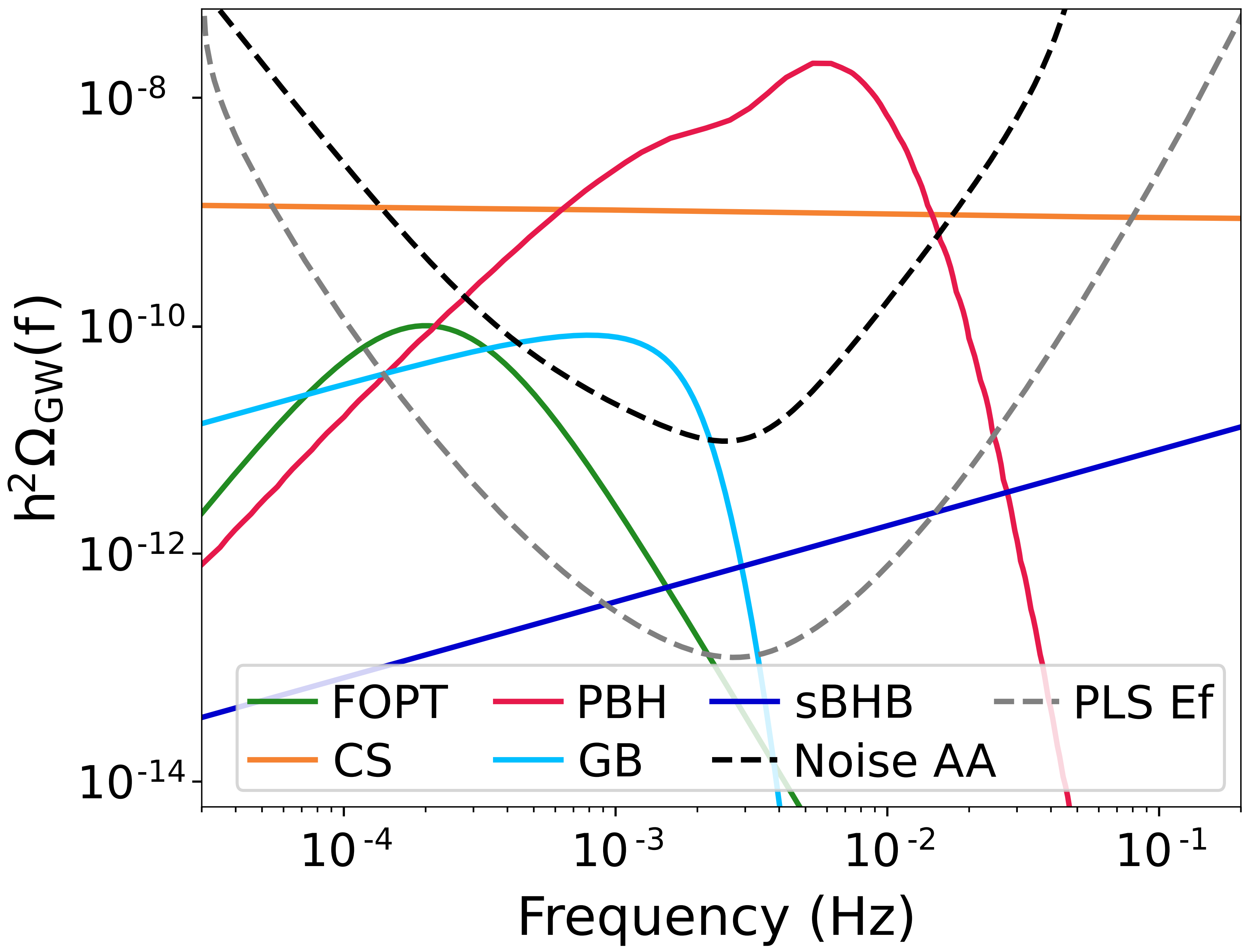
Tamanini et al, JCAP, 04(2016)002

The Science of LISA

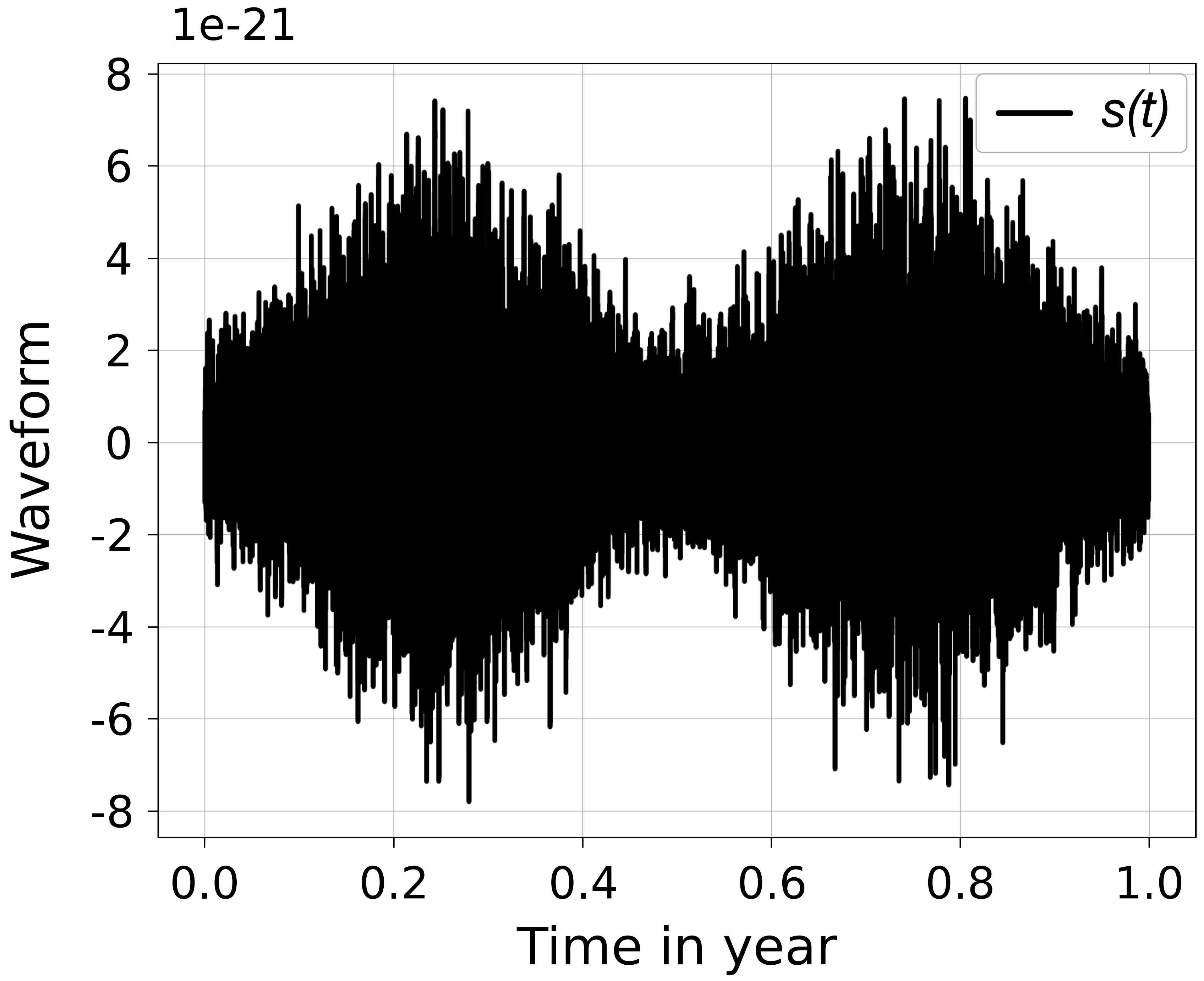
✴ **SO7**: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics

- **Fractional error on $\log(\Omega_{GW})$ from FOPT~ 0.5%**

Primordial BHs (PBH); Cosmic Strings (CS); First-Order Phase Transition (FOPT); Astrophysical stellar-mass BHBs (sBHB);



The Stochastic Galactic foreground

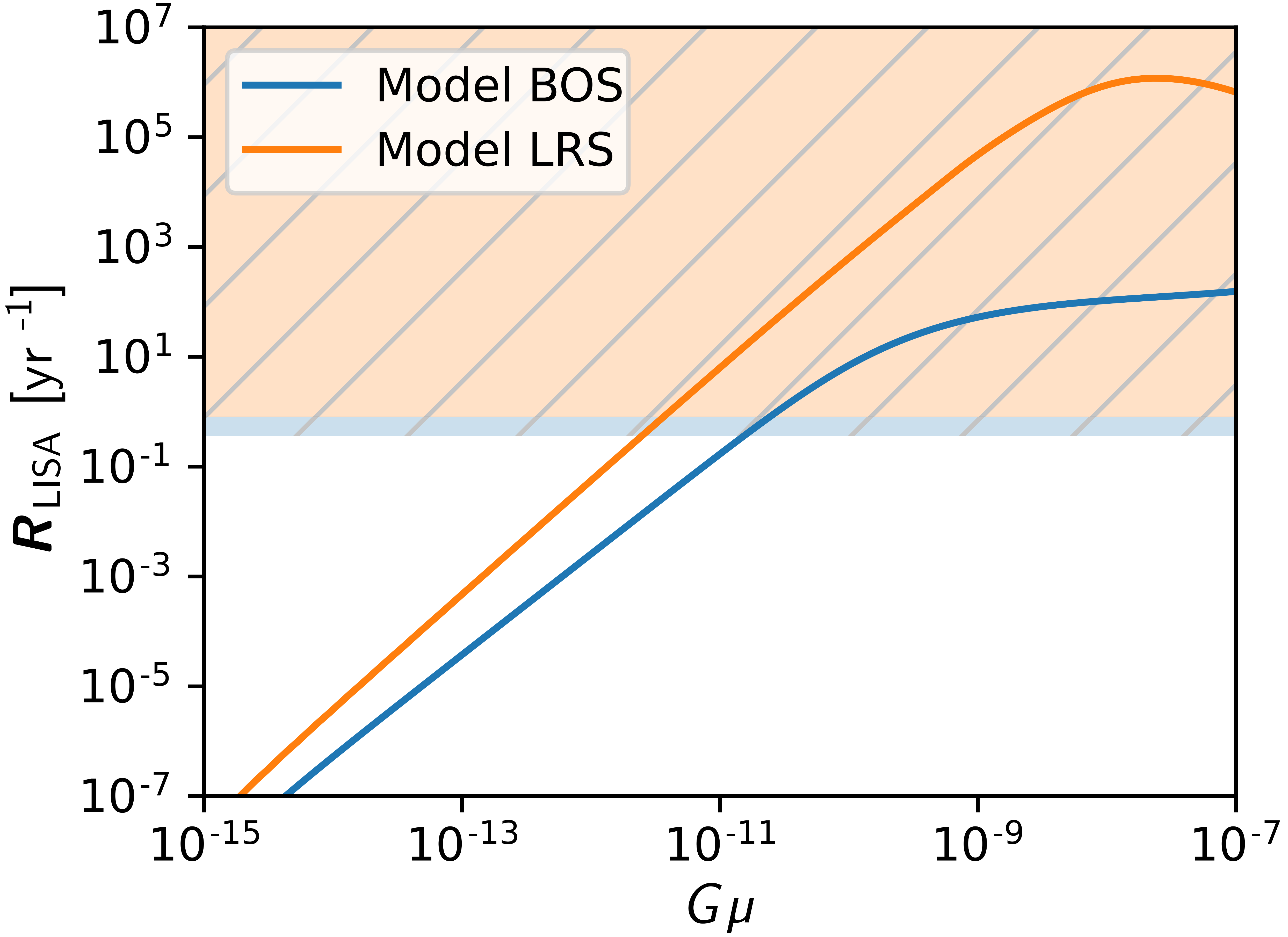


The Science of LISA

✴ **SO8**: Search for GW bursts and unforeseen sources

✦ Are cosmic strings present in the Universe? If so, what is their string tension?

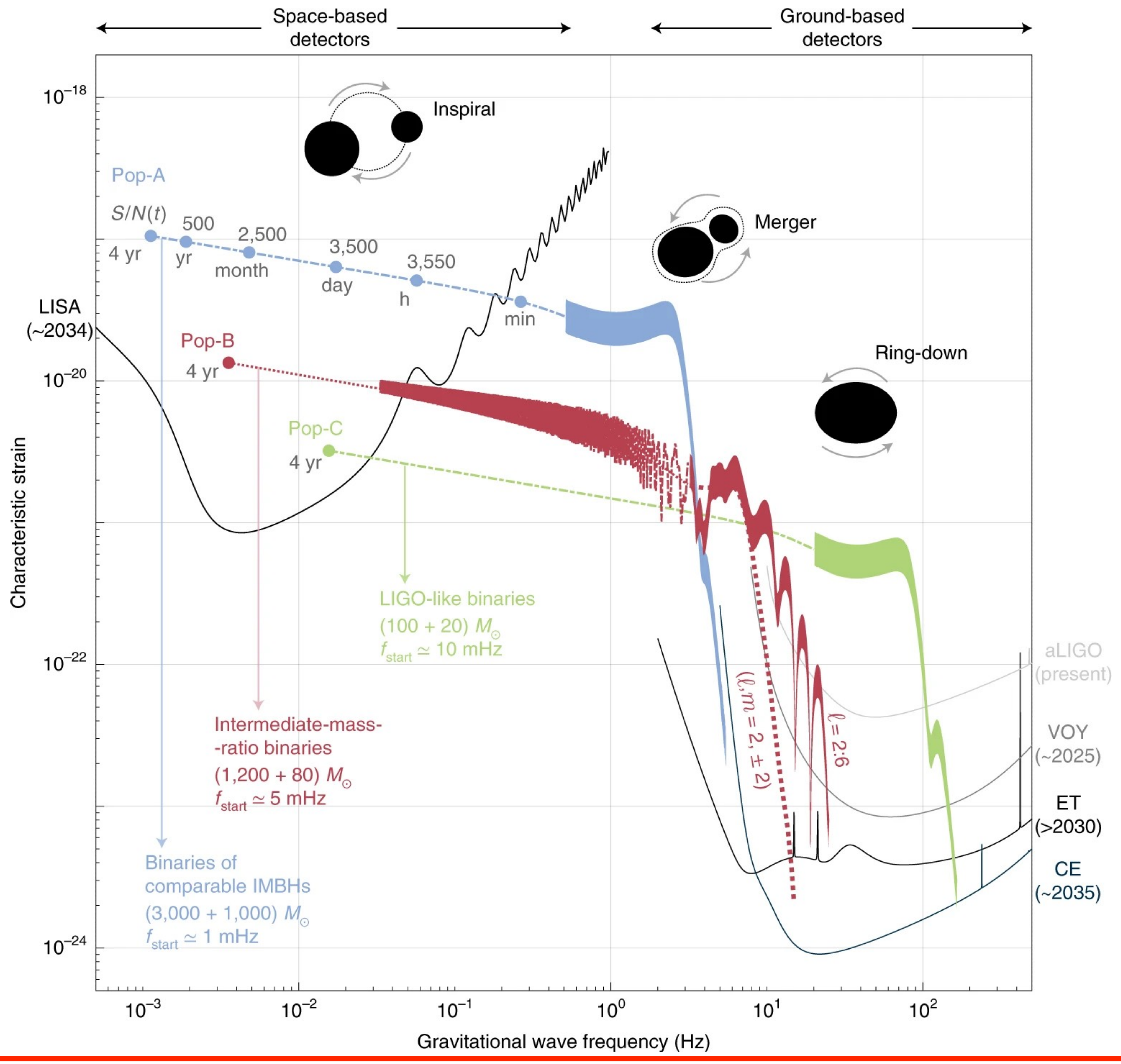
✦ Other unknown sources?



Regions excluded after $T_{\rm obs} = 82\% \times 4.5$ yrs and $T_{\rm obs} = 82\% \times 10$ yrs, for two particular models in the literature (BOS, LRS).

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



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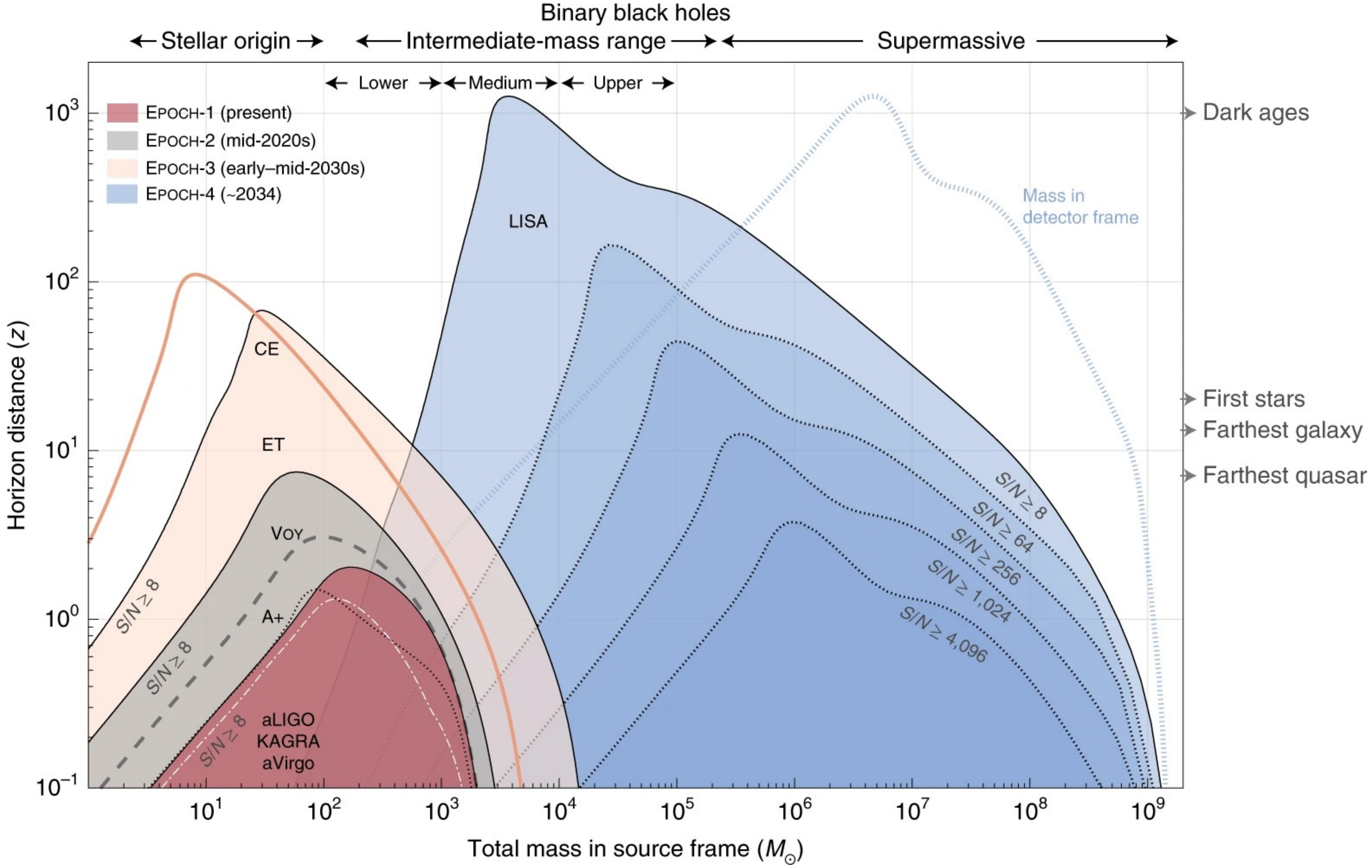
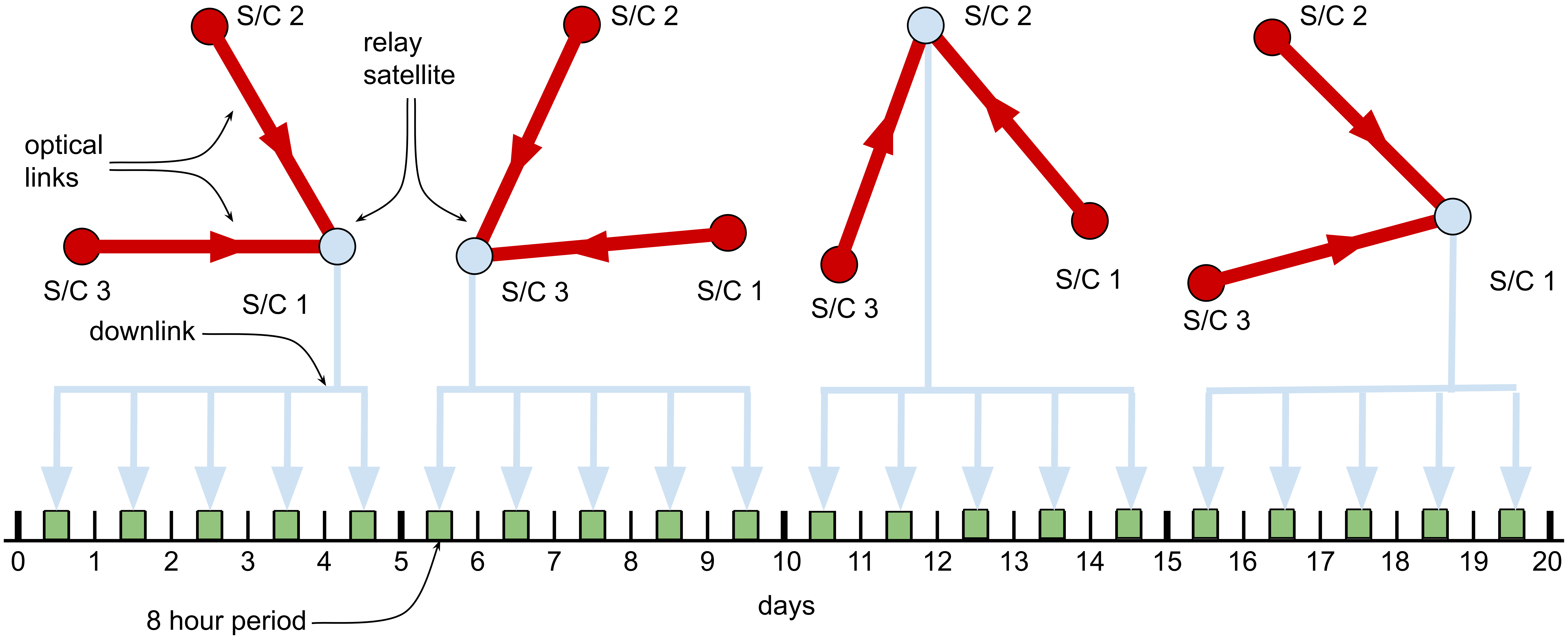
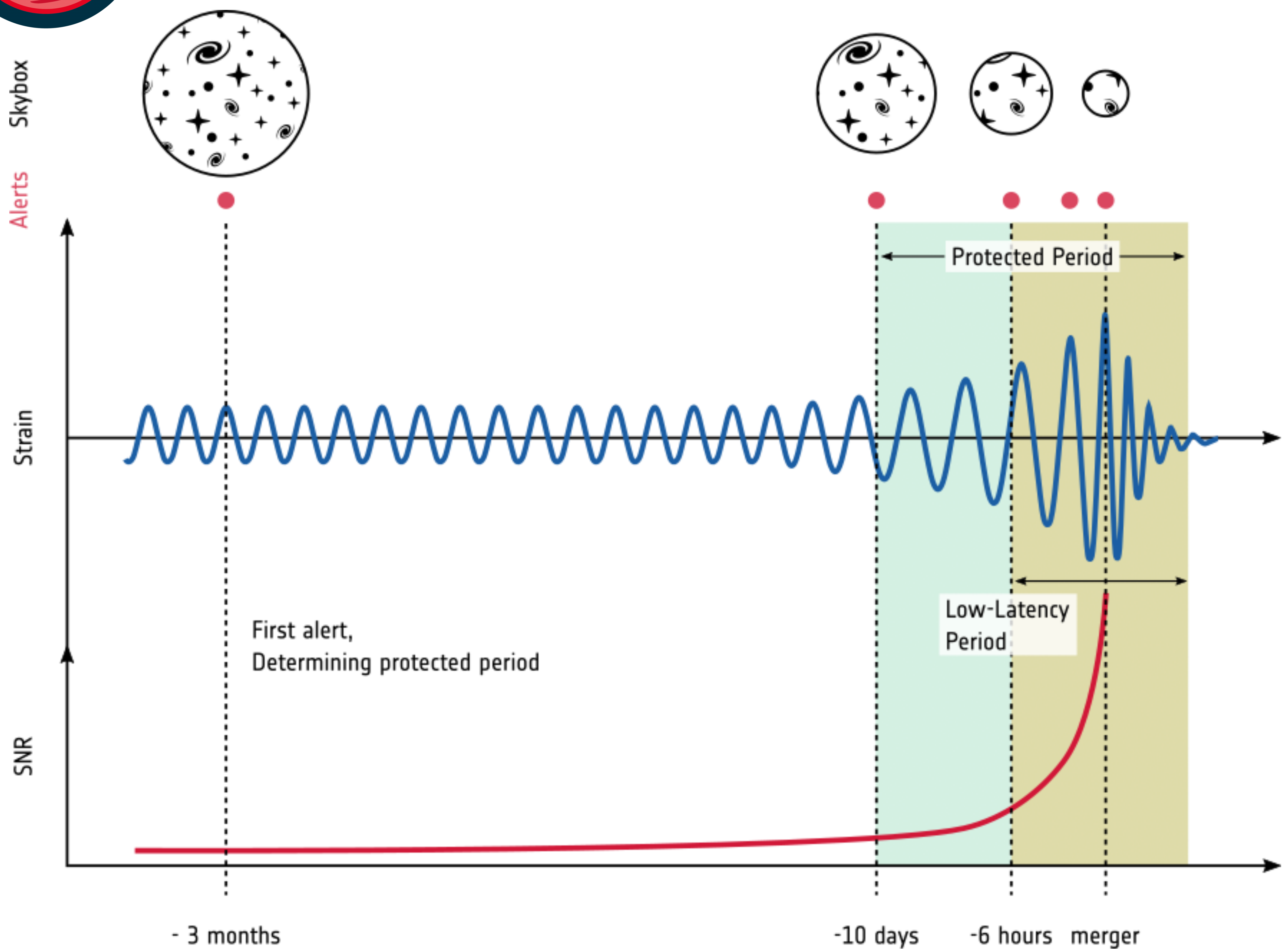


LISA Scientific Operations



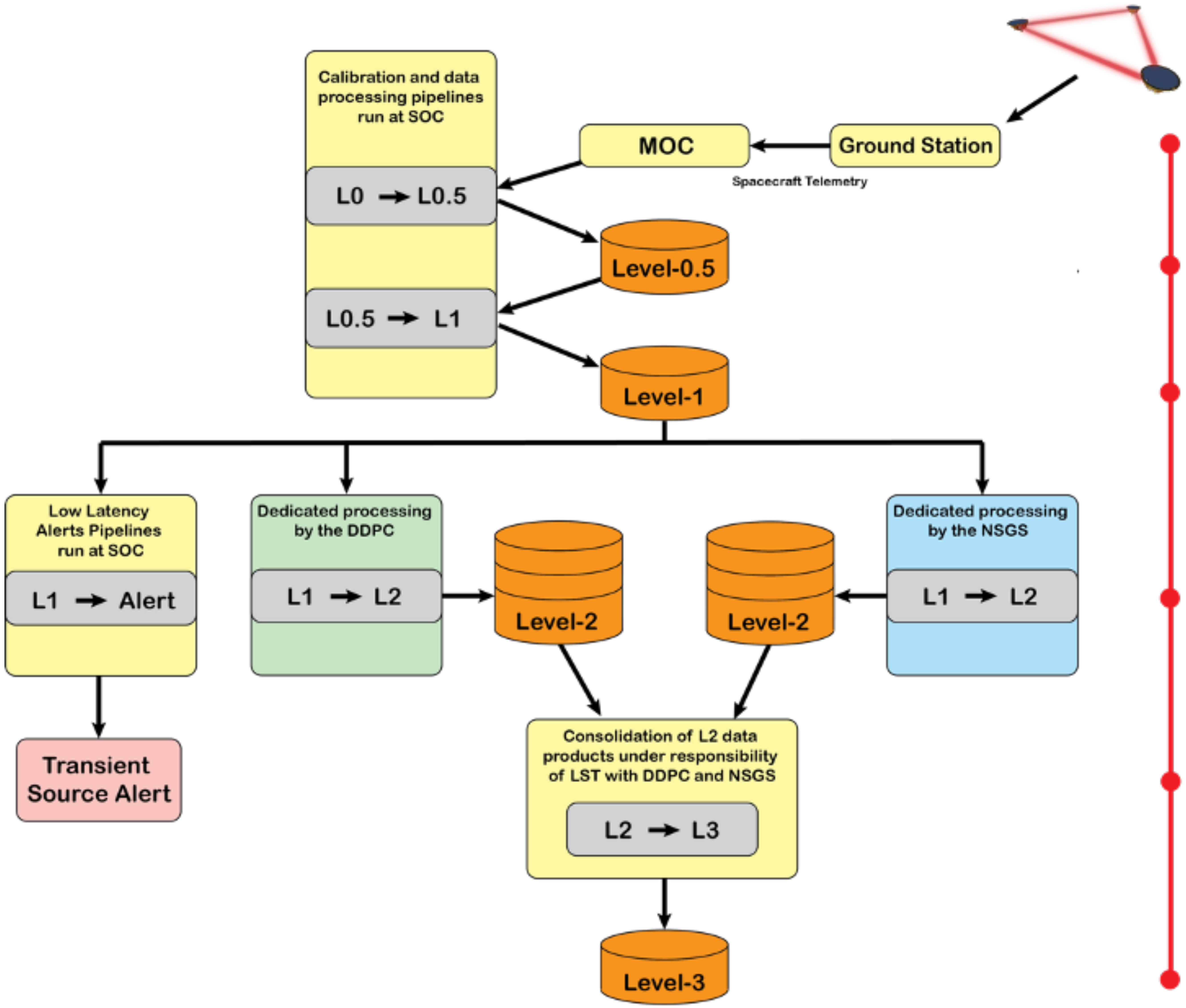
Communication with the constellation is done through one of the spacecraft ("relay") for 5 days, establishing a link for 8 hours a day. During these 5 days, the other spacecraft communicate to the relay spacecraft via the existing laser link. After the 5 days, the next spacecraft serves as relay, completing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

LISA Scientific Operations

- Then, in many cases it is crucial to have *a priori* **theoretical models** $h(t, \vec{\lambda})$ to extract the Gravitational Wave signals from the data, in particular in those situations where the signal is much below the noise.

Short LISA data stream

LISA Scientific Operations

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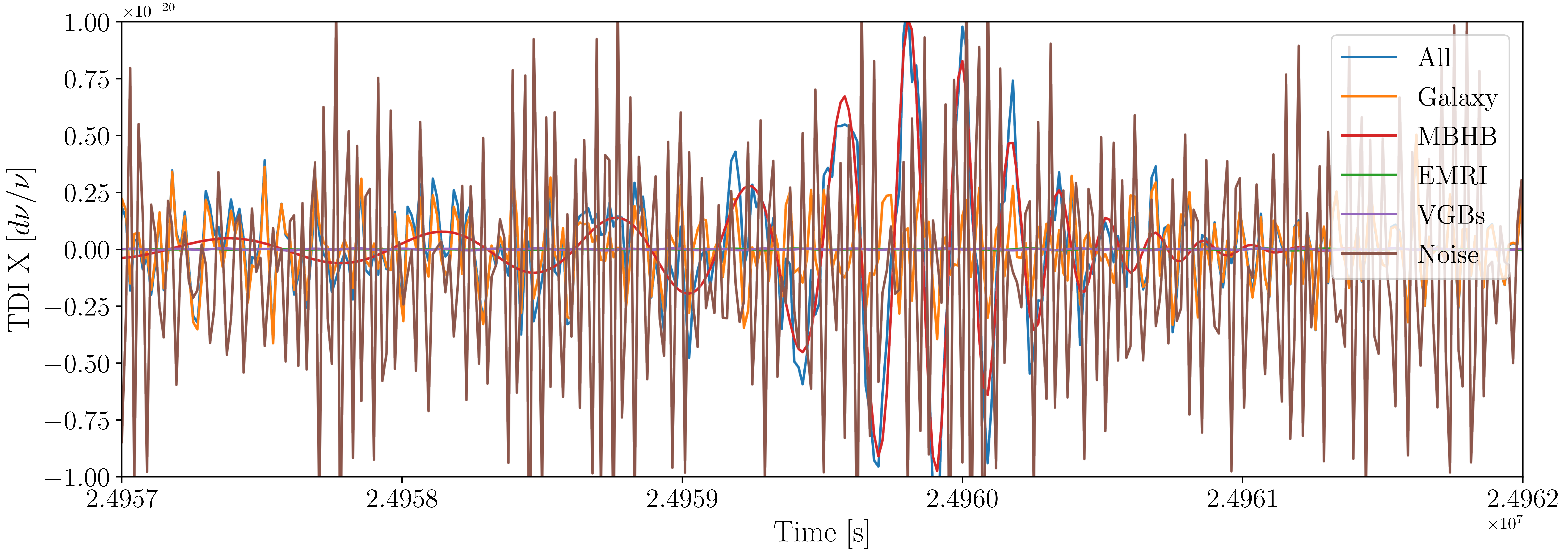
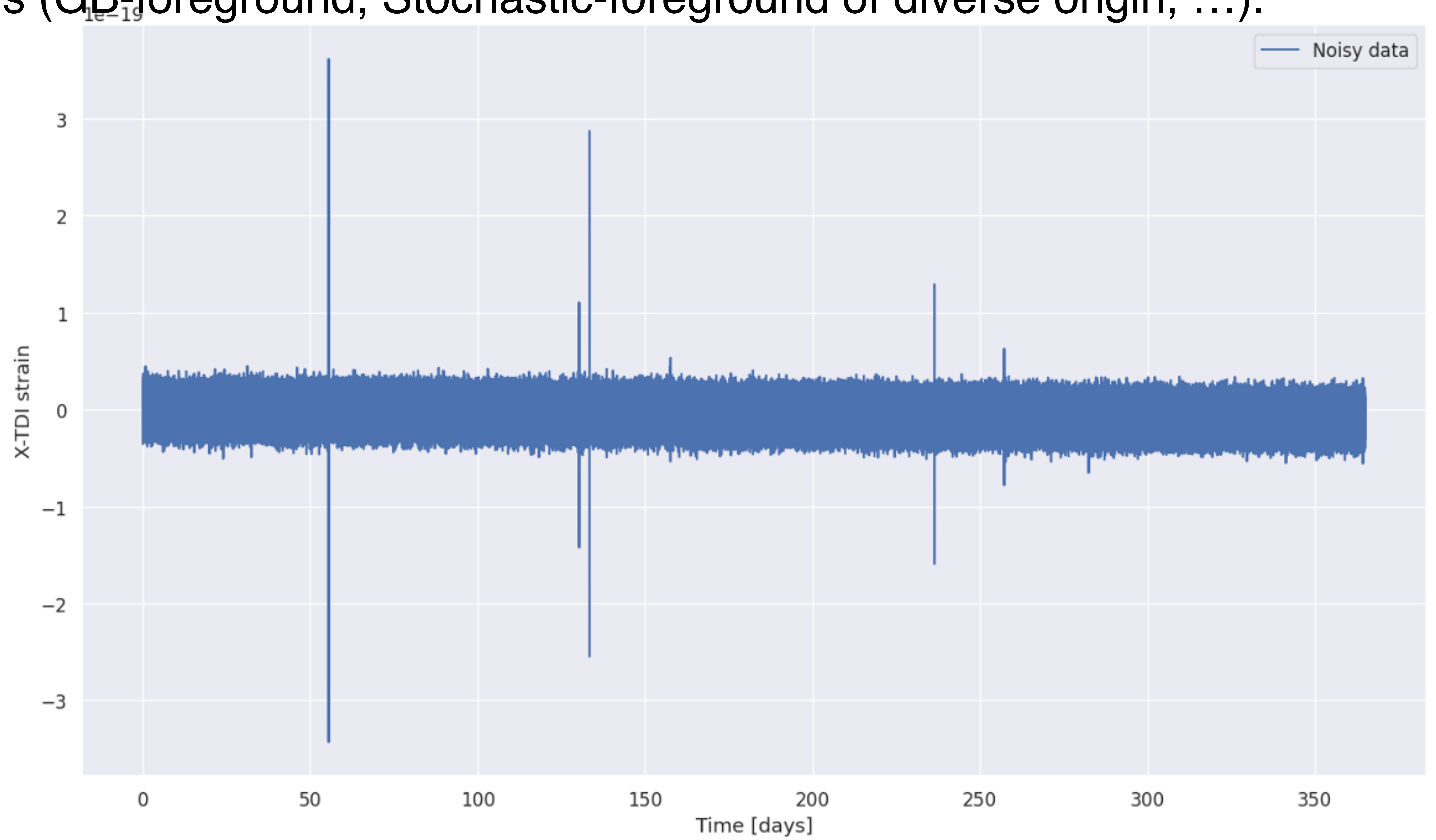
Short LISA data stream



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



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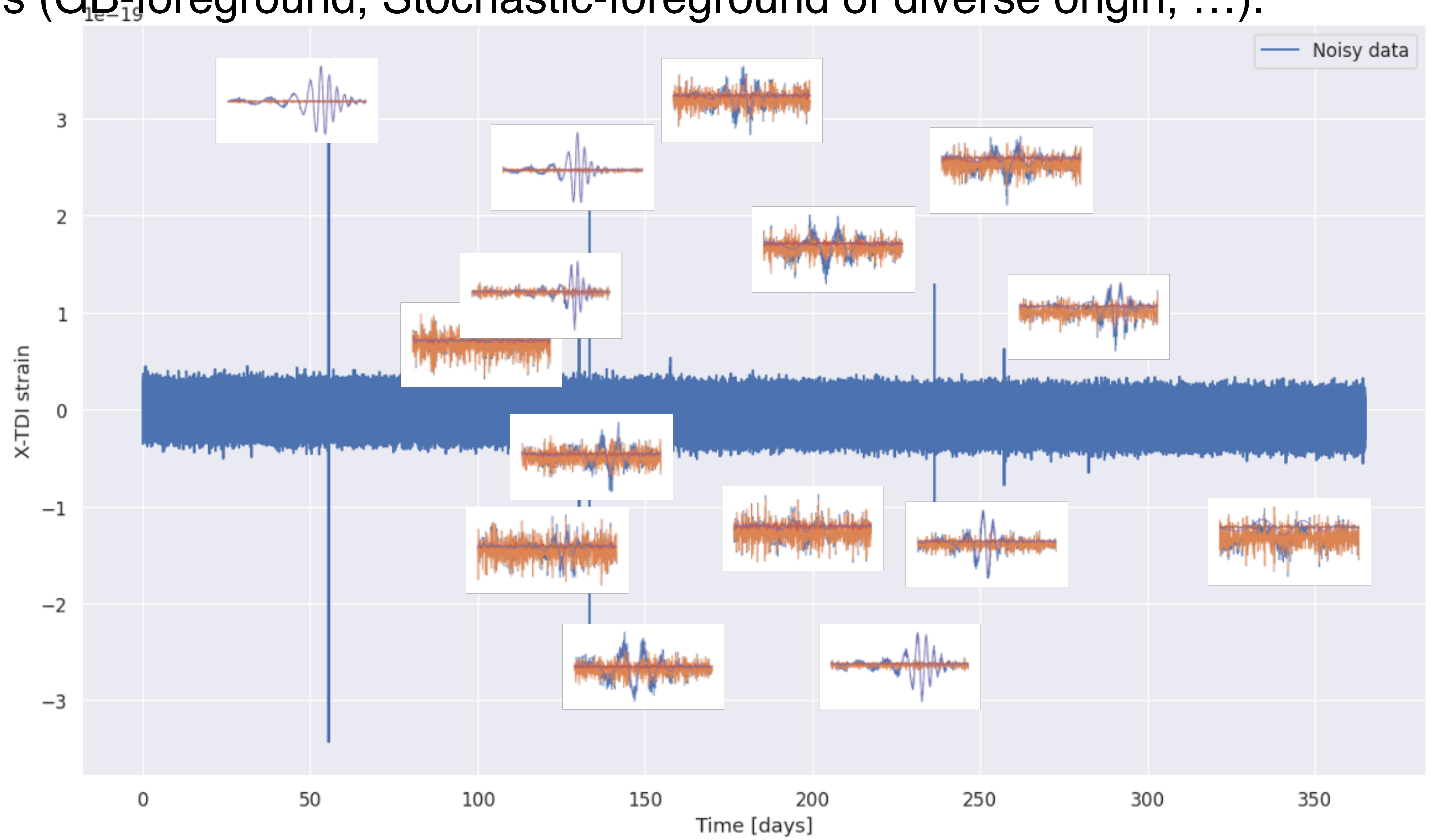
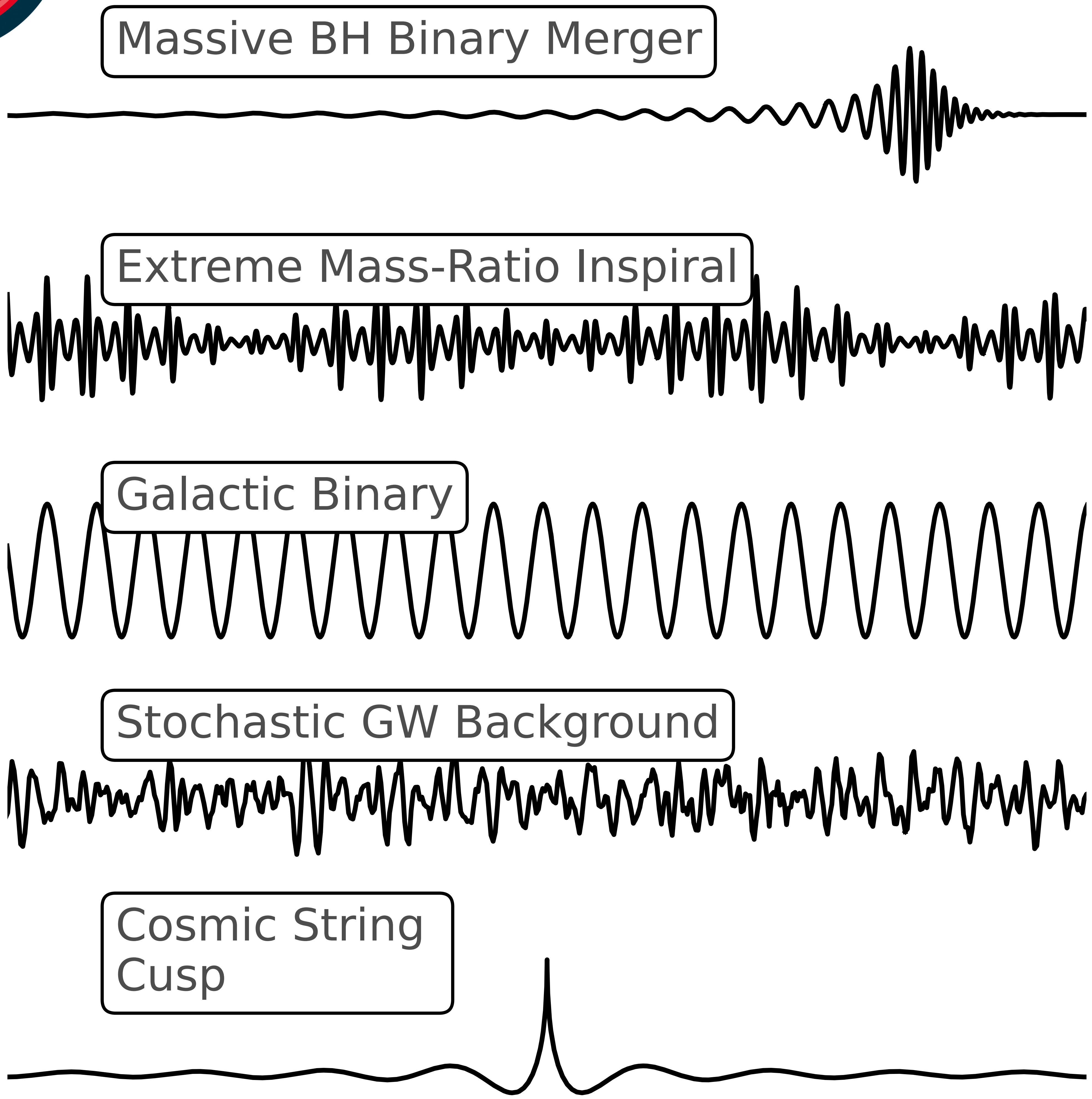
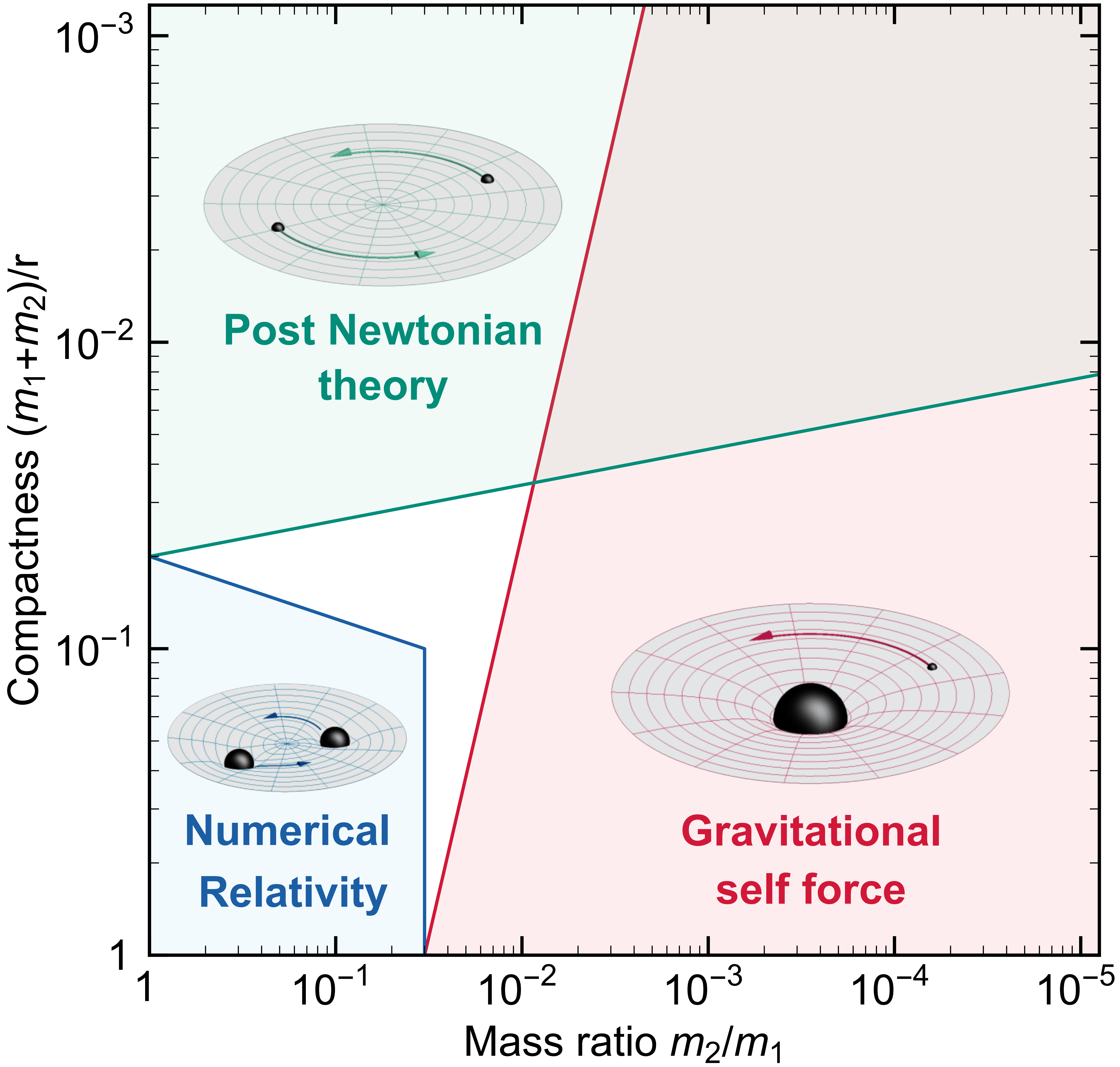


LISA Scientific Operations





The importance of accurate, efficient and effective waveforms!

LISA Scientific Operations

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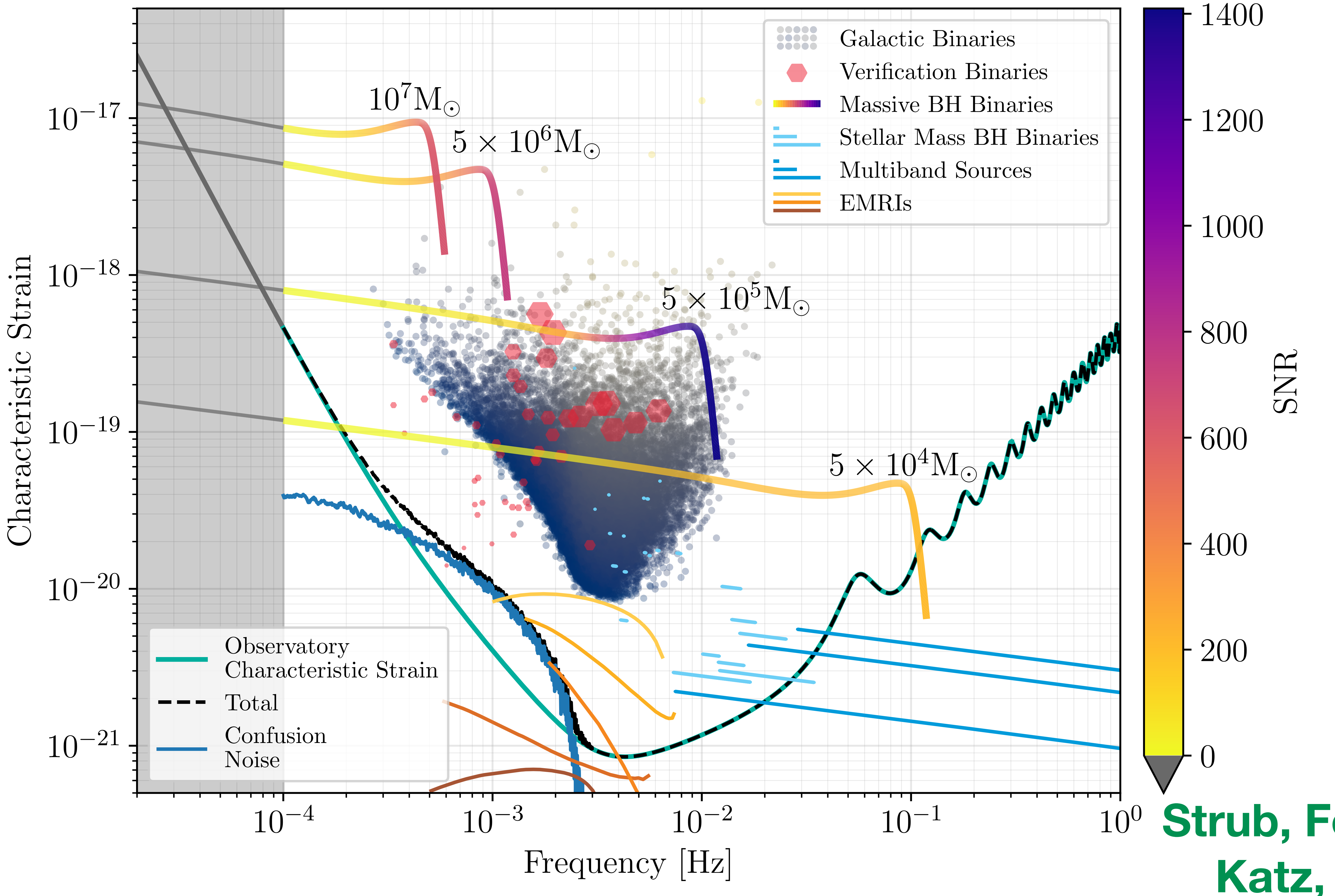

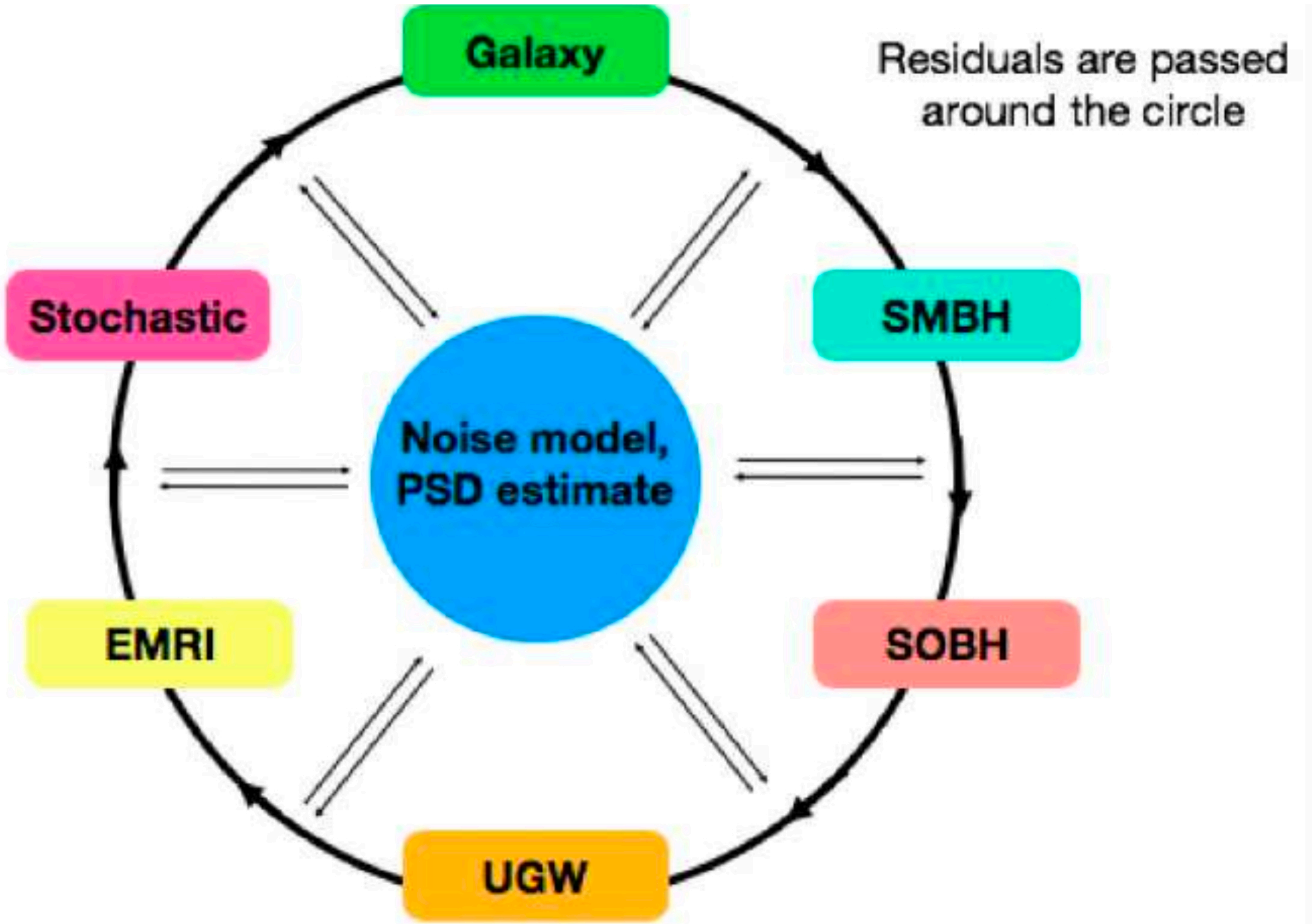

Littenberg & Cornish: 2301.03673
Strub, Ferraioli, Schmelzbach, Stähler & Giardini: 2403.15318
Katz, Karnesis, Korsakova, Gair & Stergioulas: 2405.04690

LISA Scientific Operations

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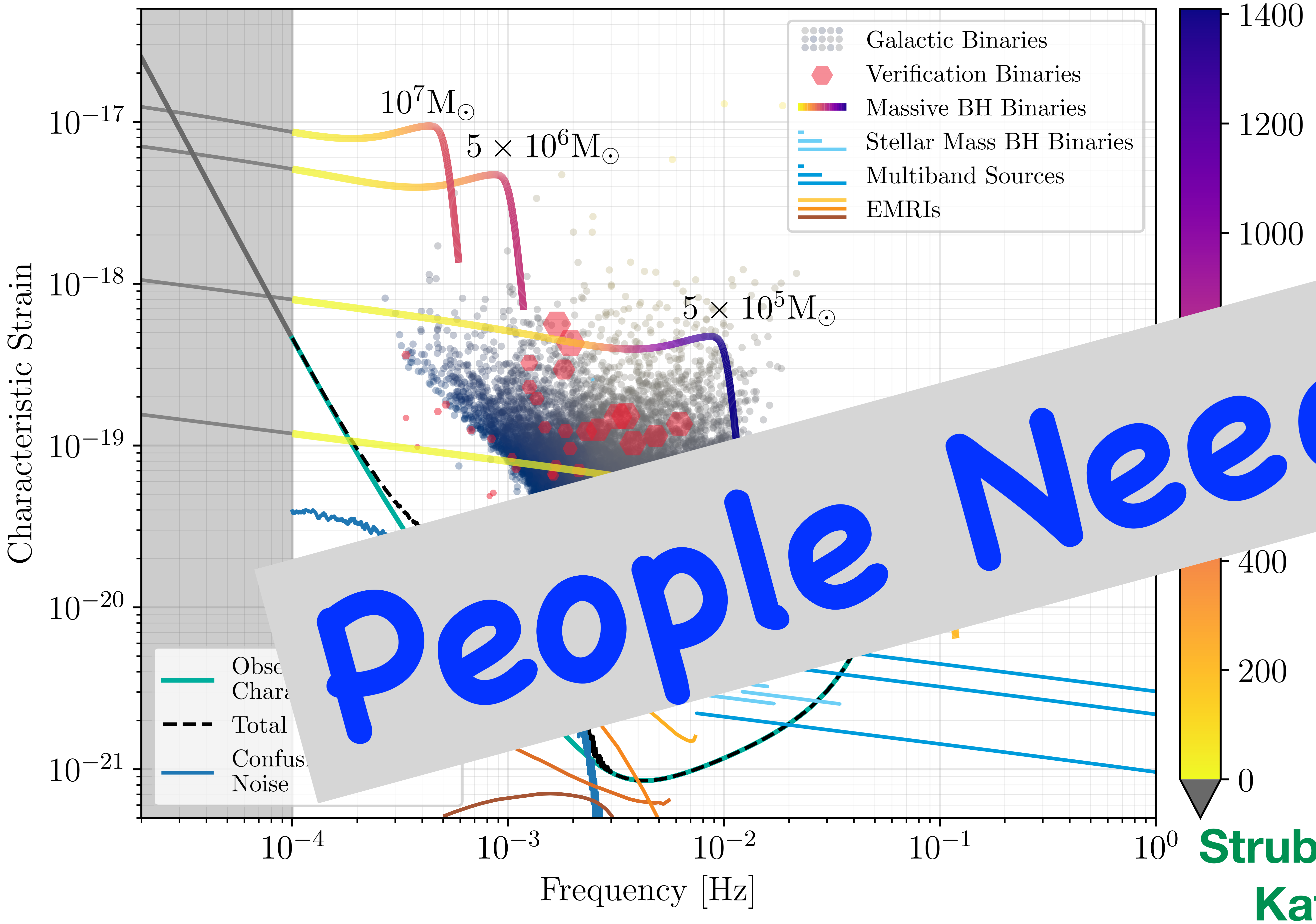

People Needed Here!

Littenberg & Cornish: 2301.03673
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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.

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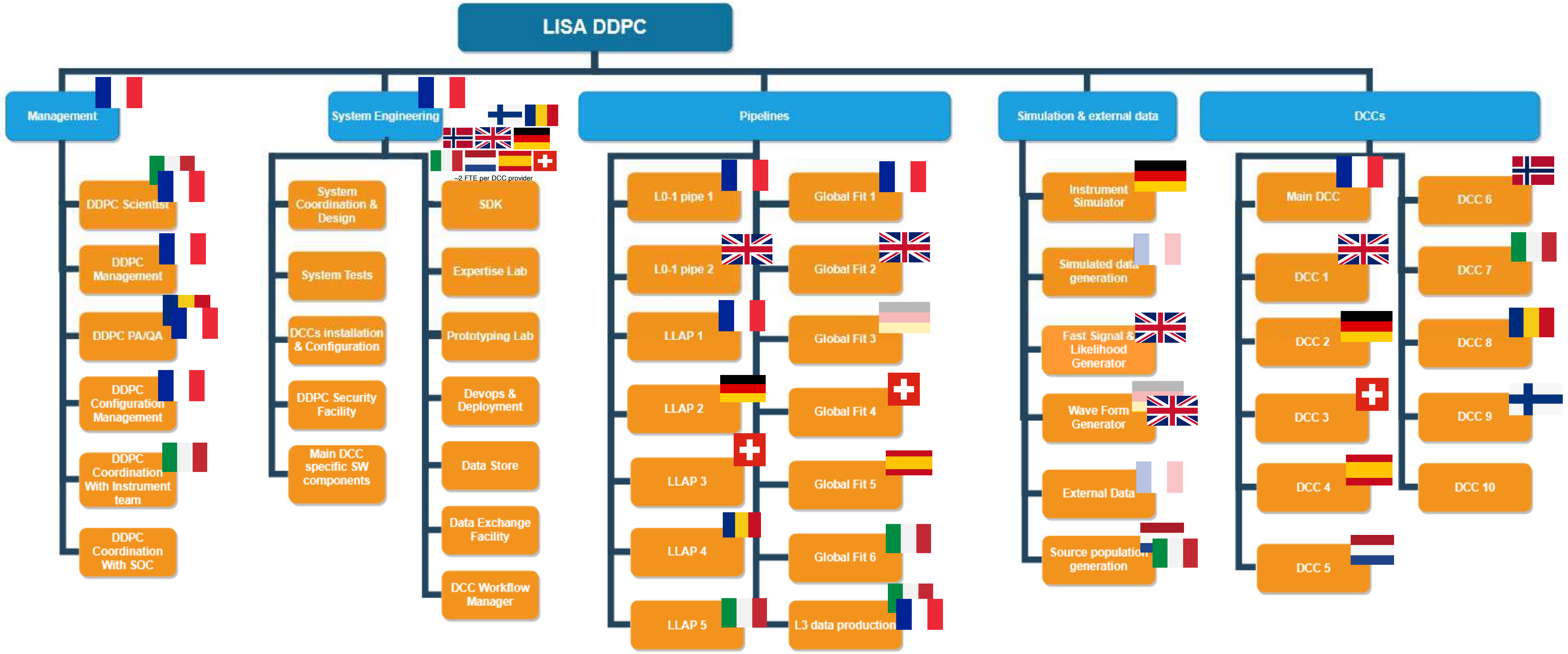
DDPC contribution status (07/03/2023)



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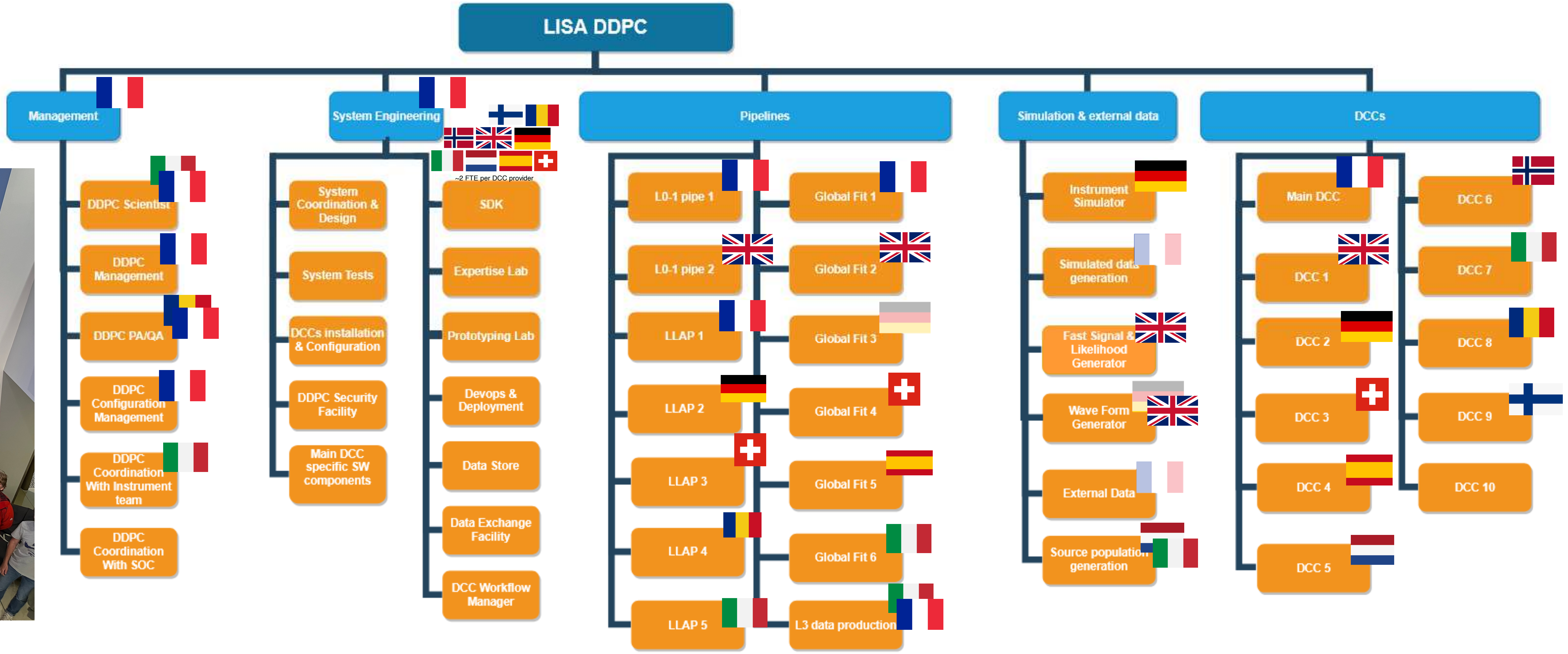
Toulouse (France)

DDPC contribution status (07/03/2023)

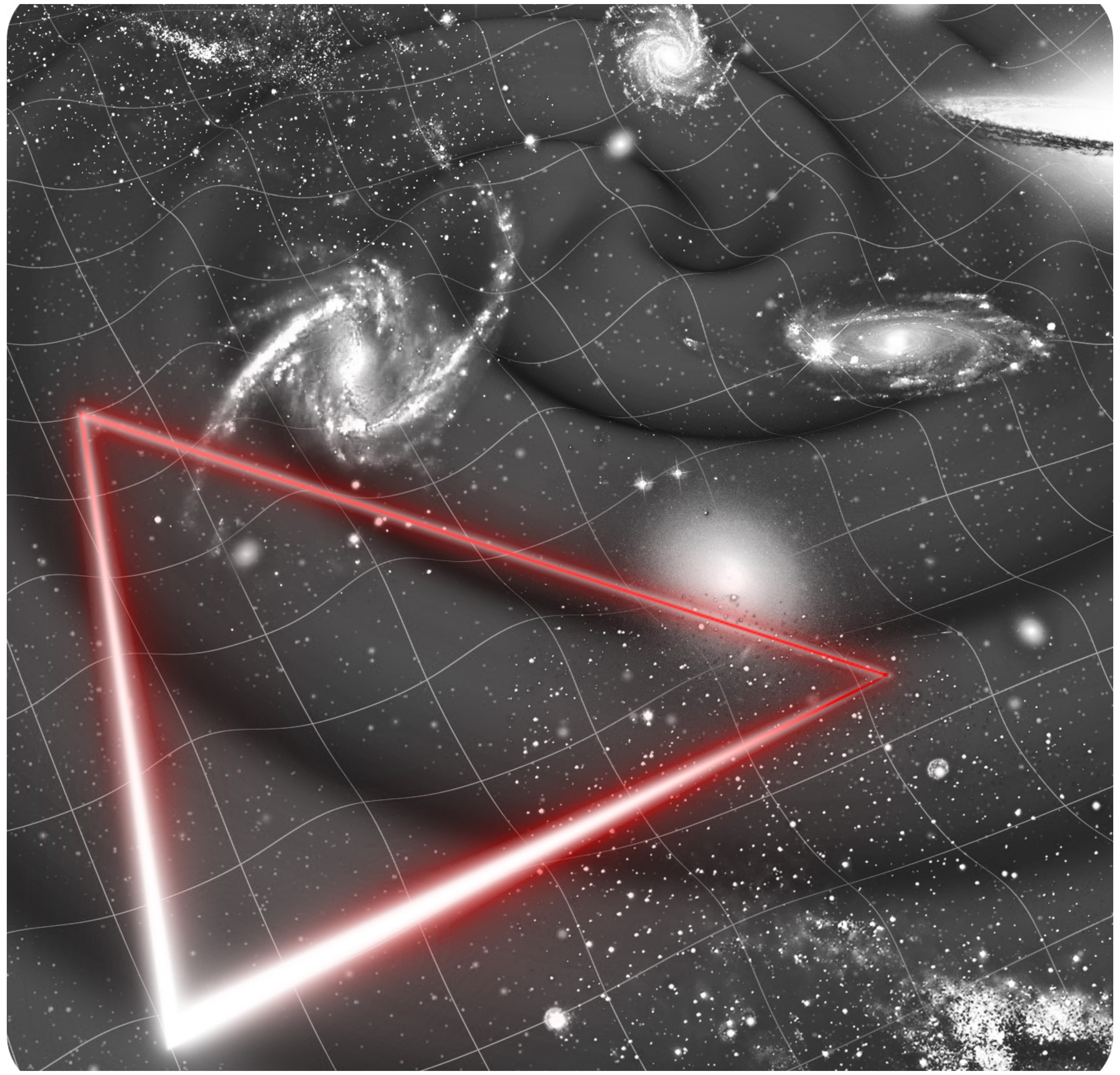


LISA Spain Meeting 2024

✤ **October 15th-16th, 2024. Meeting to bring together the Spanish community interested in working in LISA science.**

REGISTER HERE:

https://indico.ice.csic.es/event/42/



LISA SPAIN MEETING

15-16 October 2024

Organized by the Institute of Space Sciences (ICE-CSIC)

Campus UAB, Carrer de Can Magrans s/n,
08193 Cerdanyola del Vallès (Barcelona)

Local Organizing Committee: C. F. Sopuerta, M. Nofrarias, L. Martí, and S. Husa.

Meeting Website: https://indico.ice.csic.es/event/42/

Institute of Space Sciences — EXCELENCIA MARÍA DE MAEZTU — CSIC — IEEC — AGENCIA ESPACIAL ESPAÑOLA

Institute of Space Sciences — EXCELENCIA MARÍA DE MAEZTU

ICE-CSIC
Campus UAB
Bellaterra
Barcelona

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).

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