Third MODE Workshop on Differentiable Programming for Experiment Design

Challenges of the LISA mission to detect gravitational waves from Space [Carlos F. Sopuerta (ICE, CSIC and IEEC, Spain)]

July 24th, 2023

OUTLINE

I. Gravitational Wave Detection from Space and the LISA Mission

II. LISA Sources and the Science of LISA

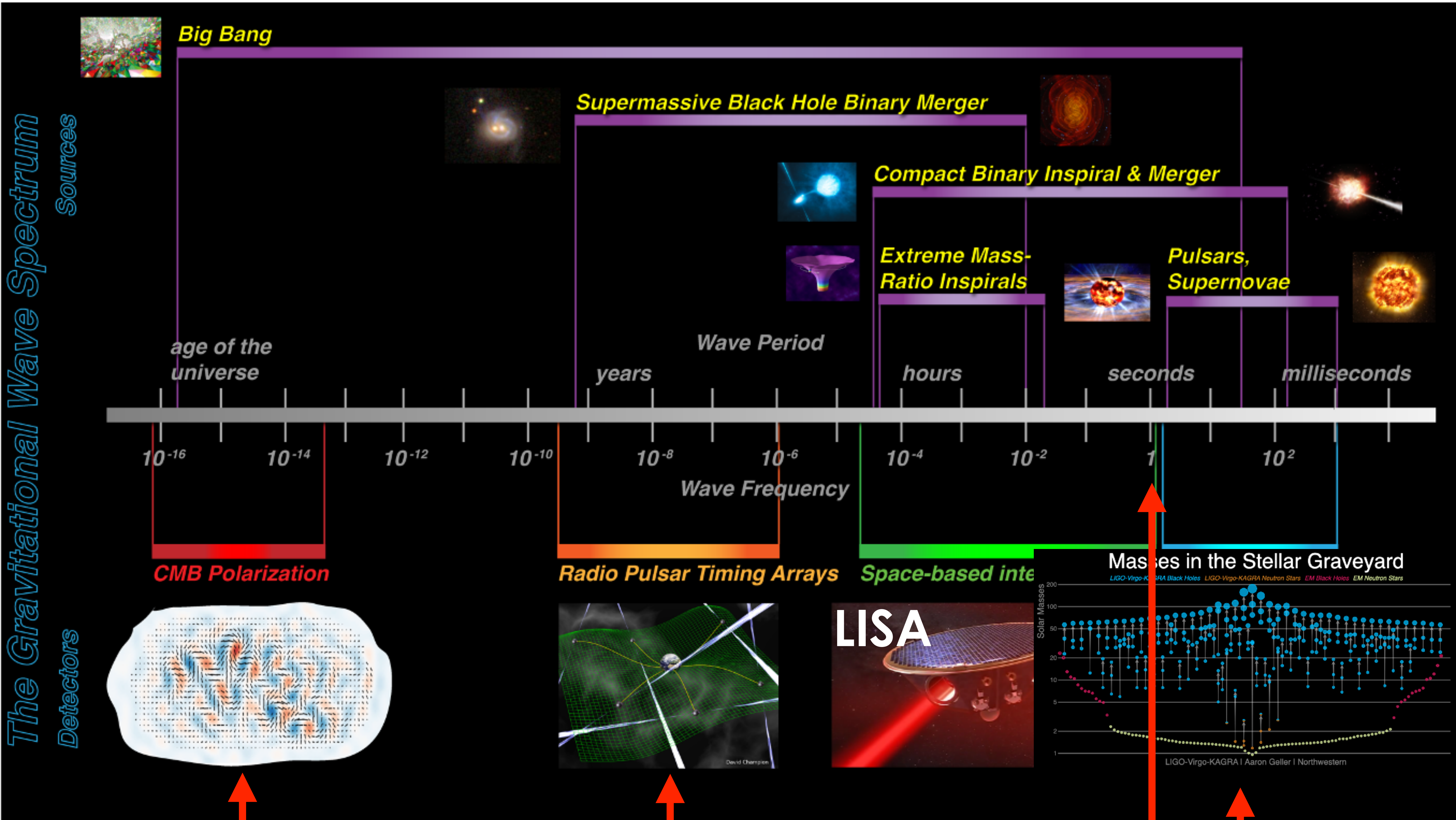
III. LISA Ground Segment and Science Exploitation

IV. Conclusions

Gravitational Wave Detection from Space and the LISA Mission

Gravitational Wave Detection from Space and LISA

Credit: Ira Thorpe (NASA)



2014 BICEP2
2023: PTAs evidence
2015-2023: LIGO-Virgo Detections
Seismic and Gravity Gradient Noises

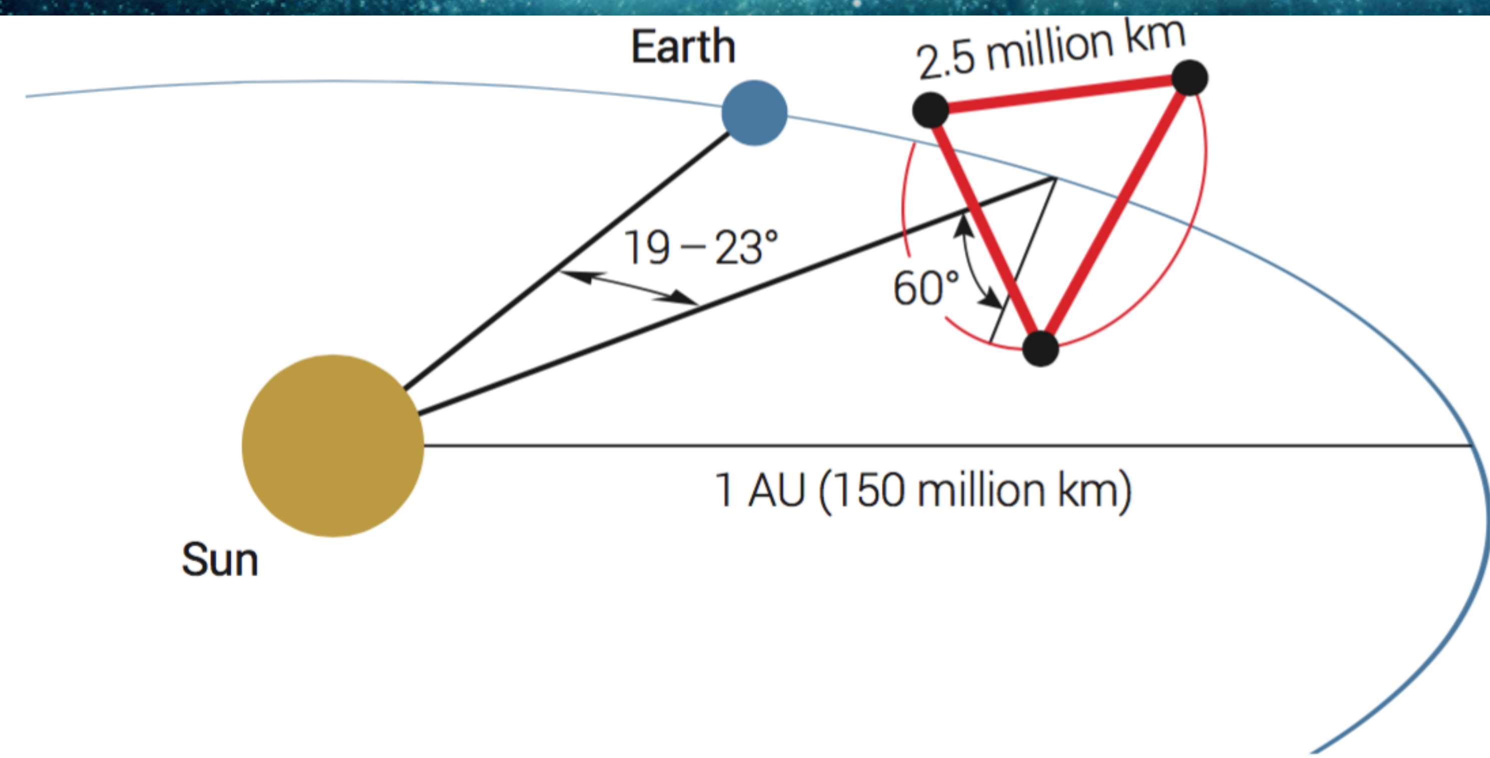
Gravitational Wave Detection from Space and LISA

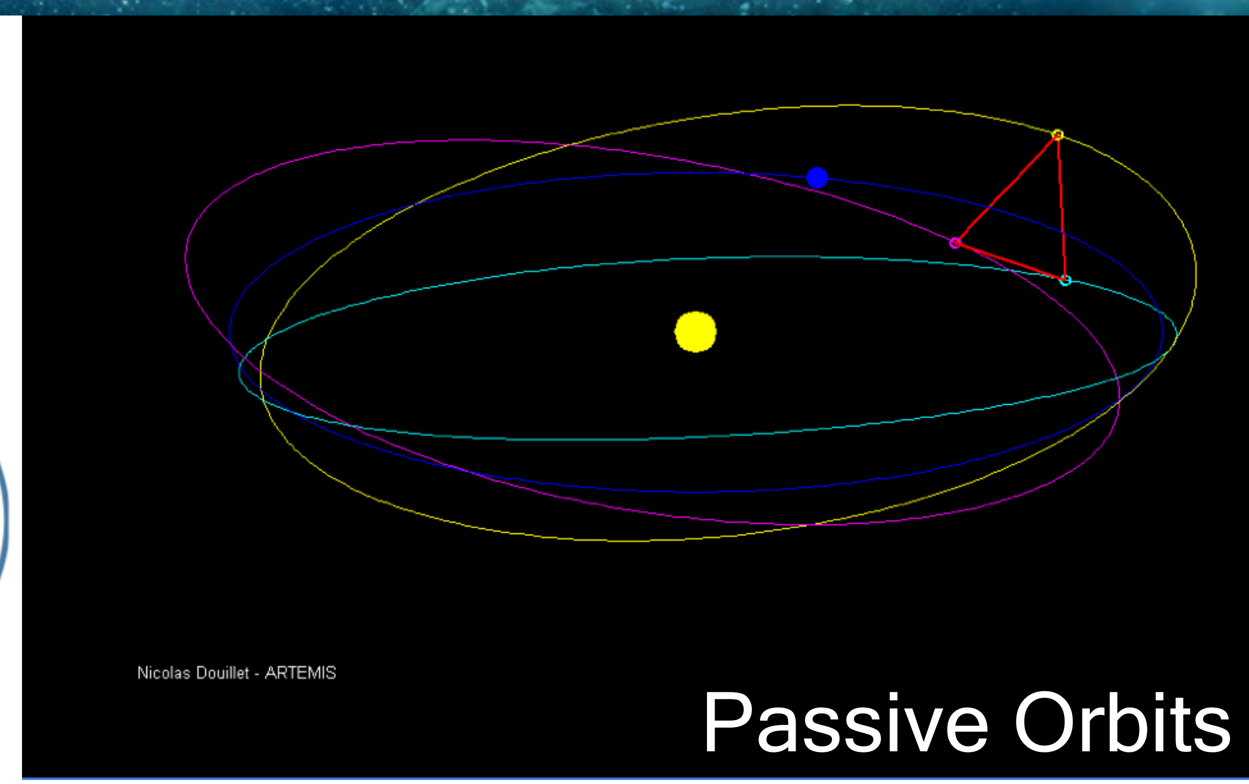
Ground-Based are noise dominated detectors

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

Space-Based are signal-dominated detectors

LISA = Laser Interferometer Space Antenna (~2035)





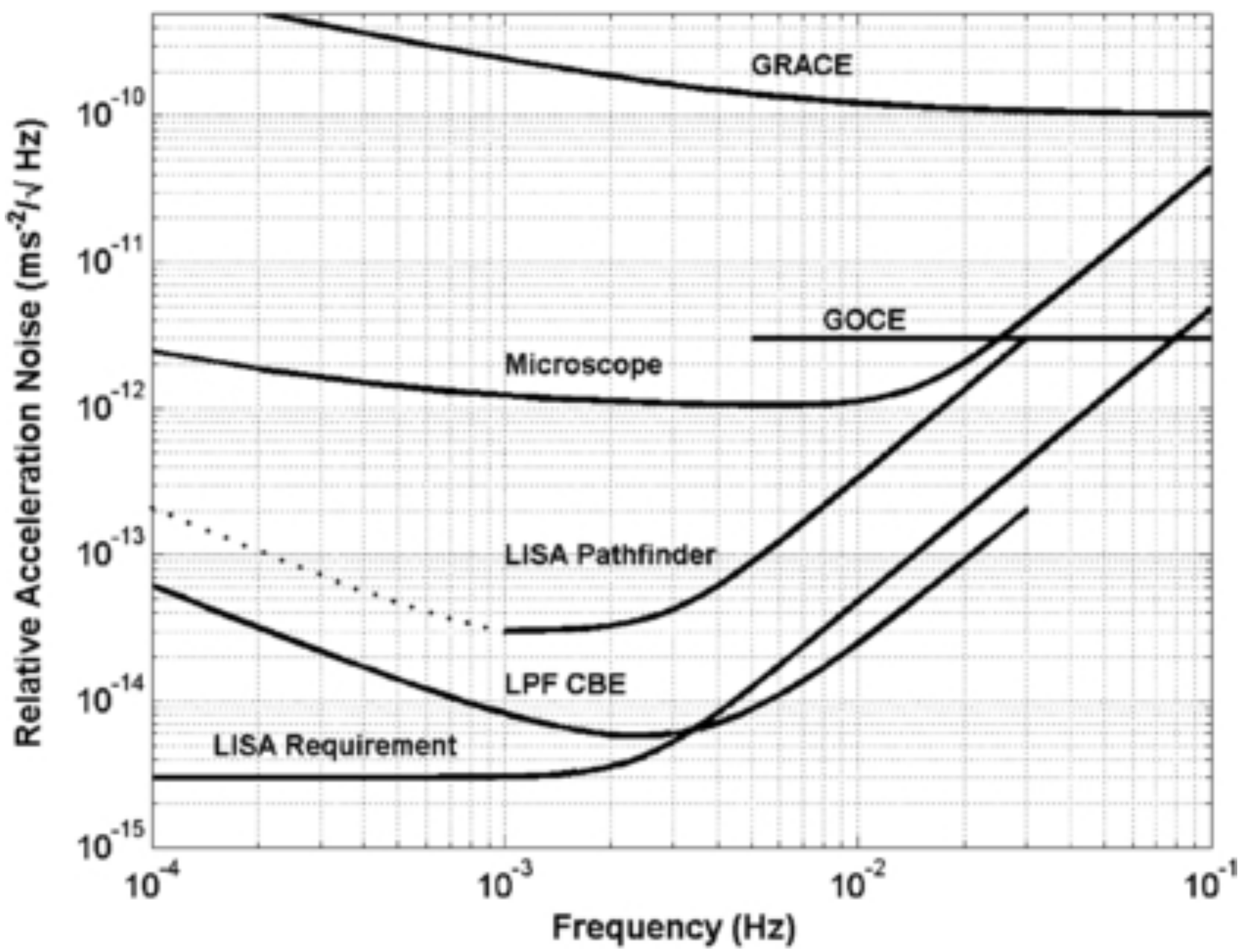
Carlos F. Sopuerta
July 24th, 2023
Institute of Space Sciences (ICE, CSIC)
Institute of Space Studies of Catalonia (IEEC)

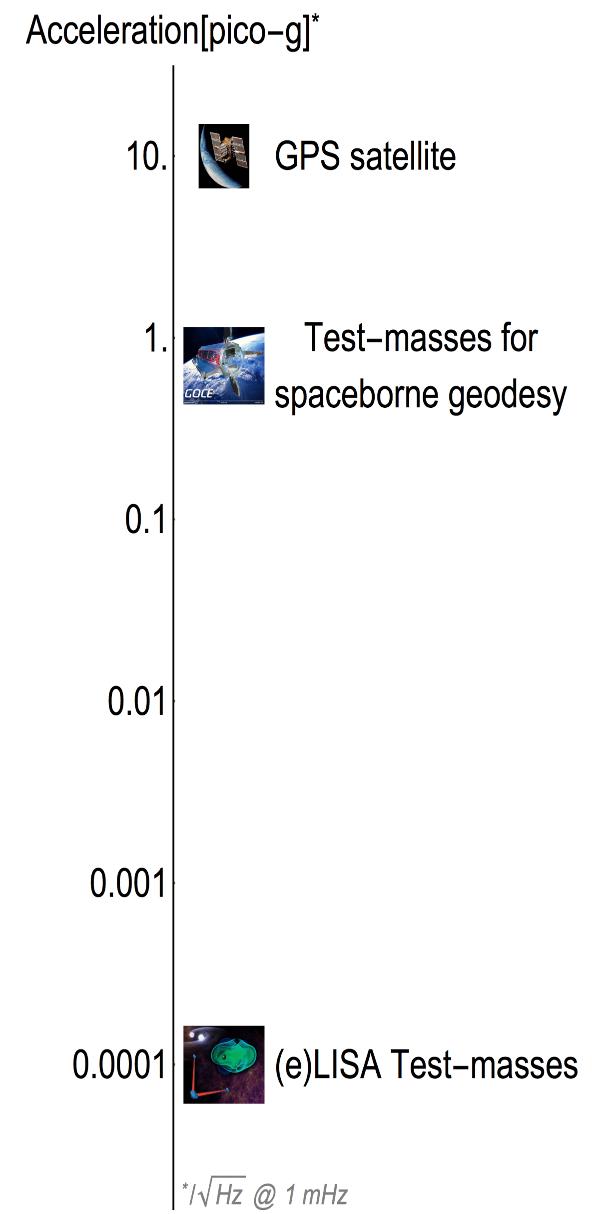
Gravitational Wave Detection from Space and LISA

- To achieve the low-frequency band [0.1 mHz, 1Hz] we need a very long baseline detector (L ~ 1 million km).

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

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





Carlos F. Sopuerta
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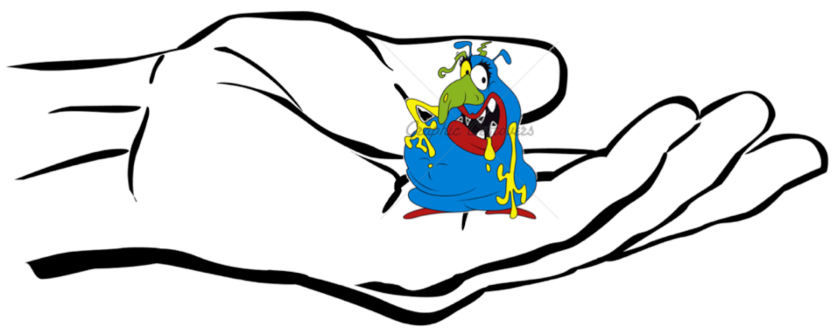
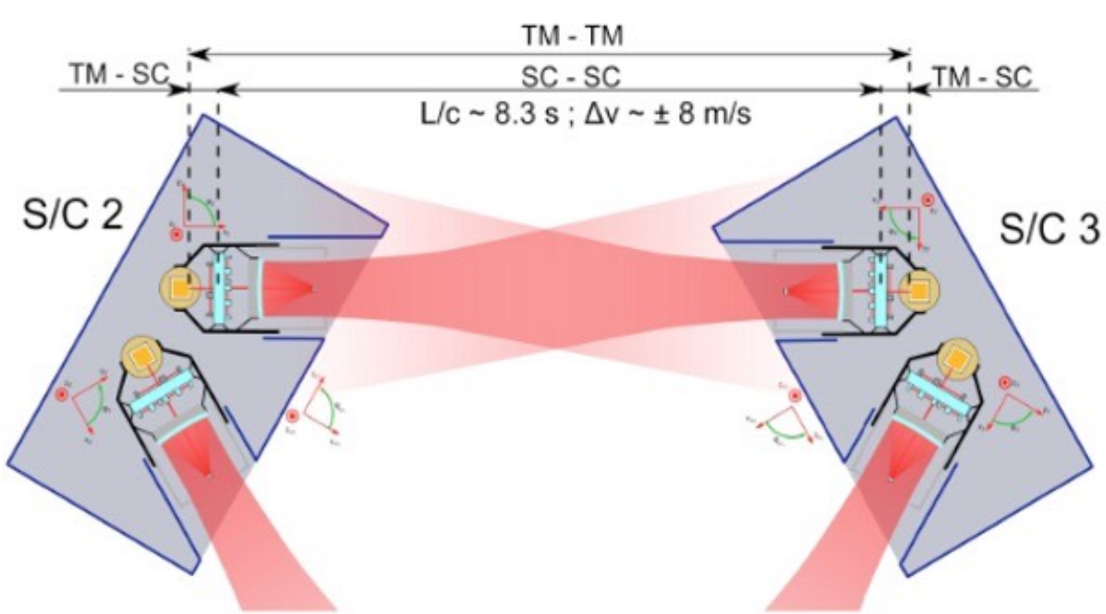
Gravitational Wave Detection from Space and LISA

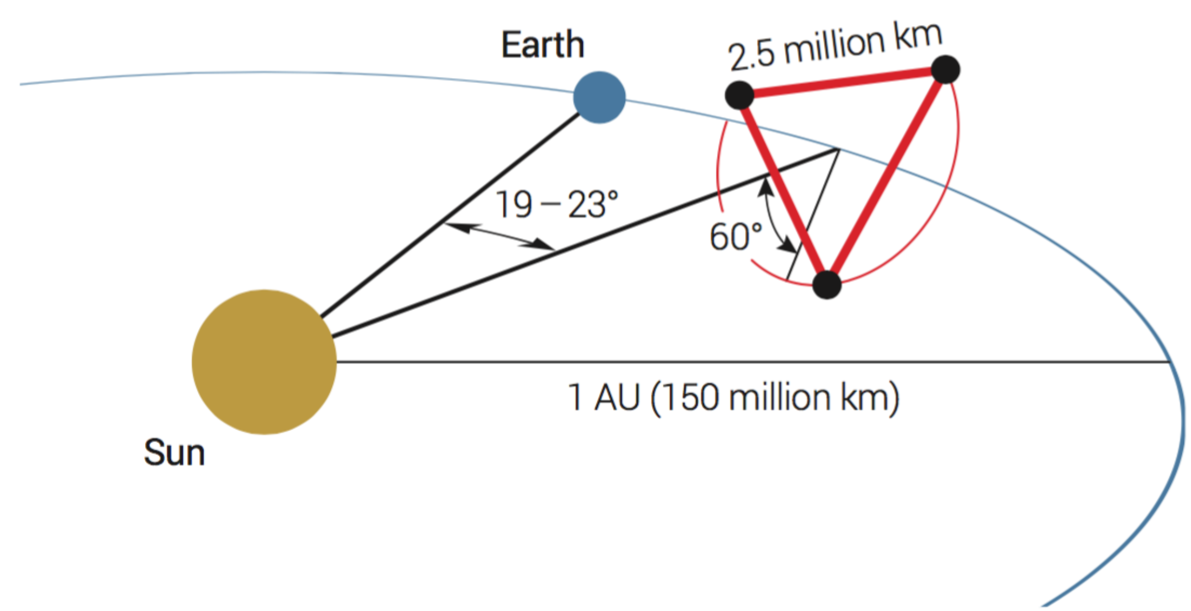
- We need an instrument to detect tiny motion: ~ the size of an atom pick to pick

- No forces allowed above the weight of a bacteria…



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

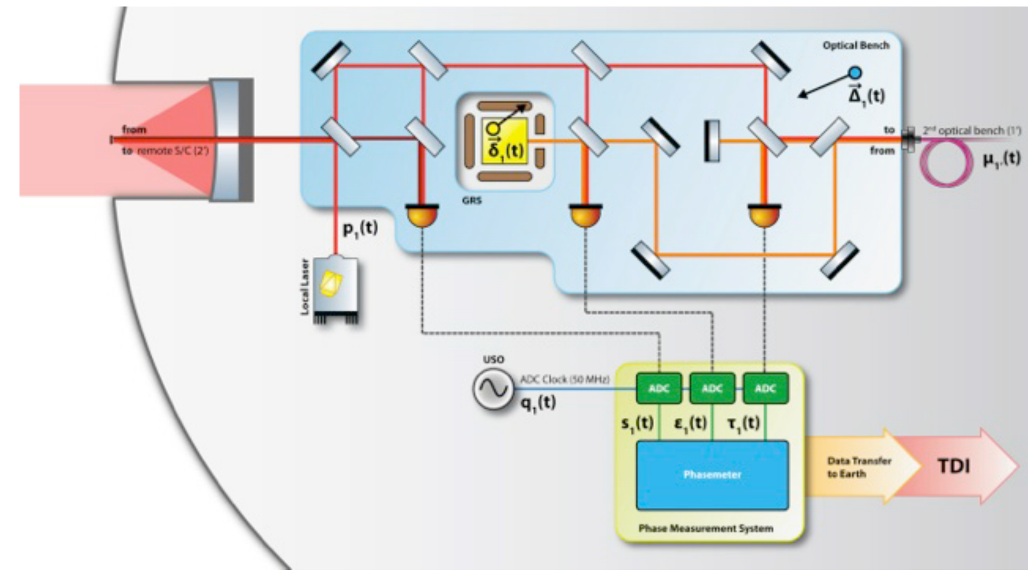


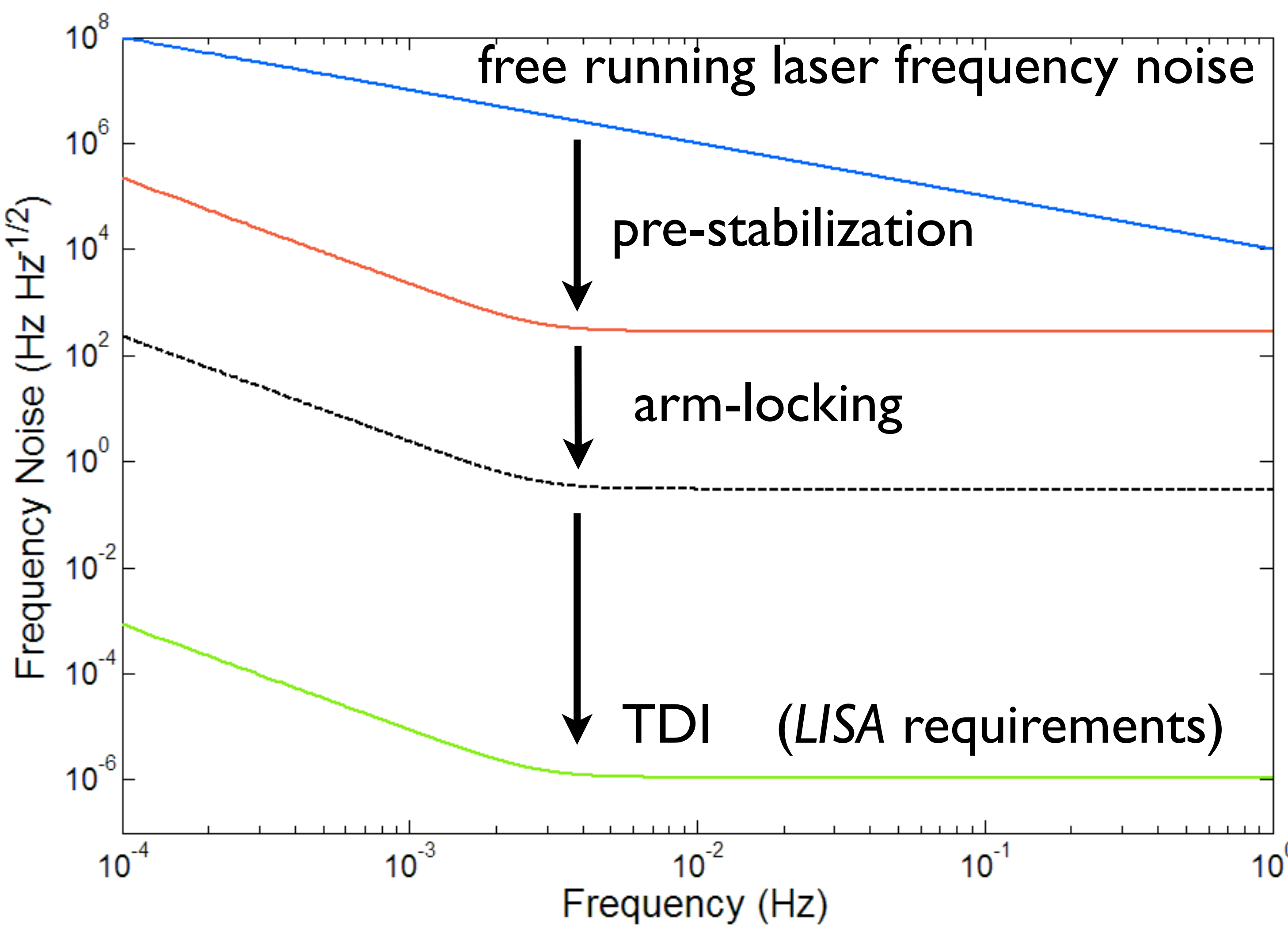


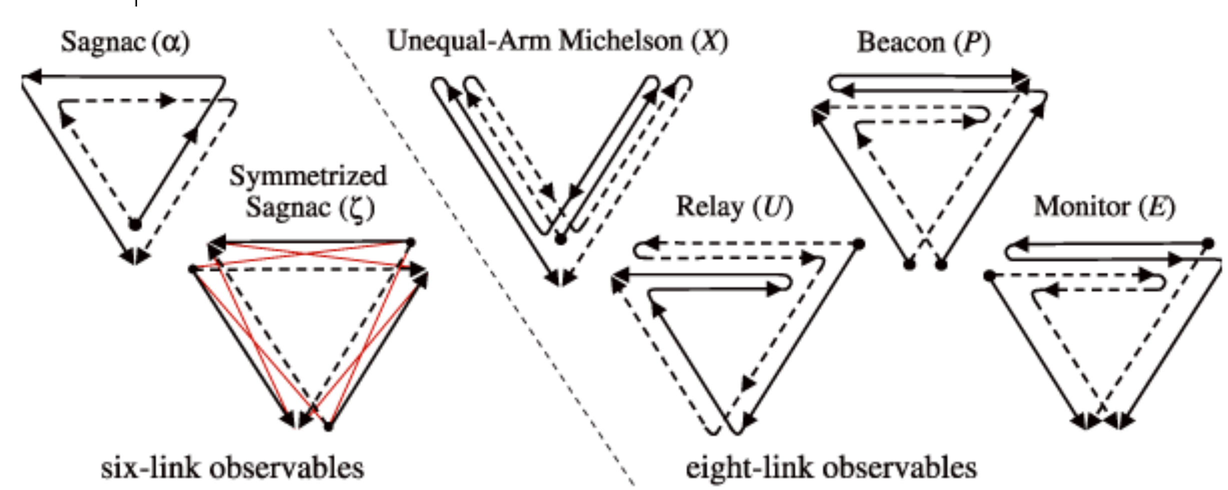
Gravitational Wave Detection from Space and LISA

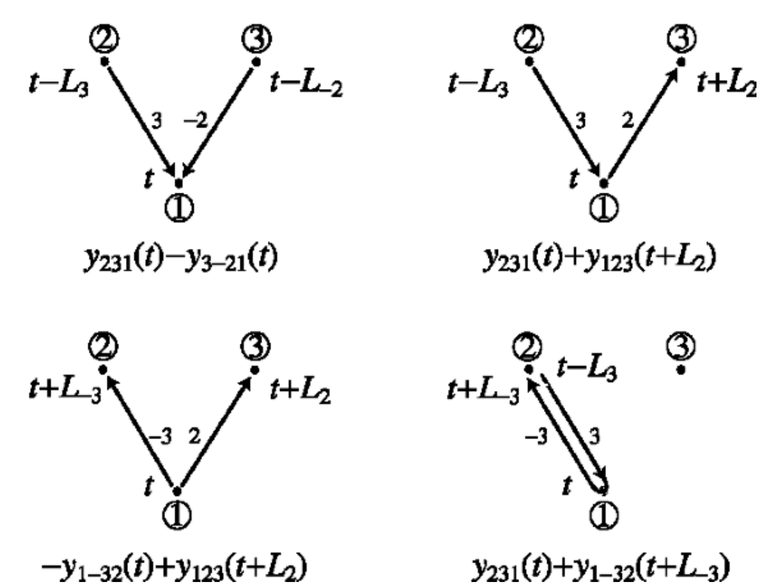
✳ **Time-delay Interferometry (TDI)**:

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.







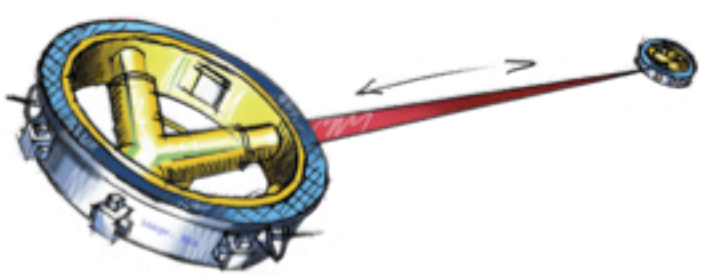


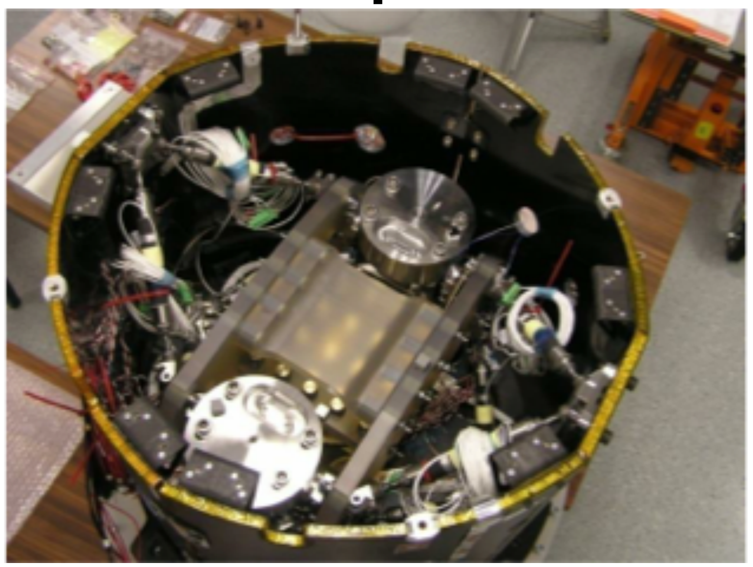
TDI Combinations

The *LISA Pathfinder* mission

2001: Beginning of the ***LISA Pathfinder*** mission, a Technology demonstrator for *LISA* (main items could not be demonstrated on ground):

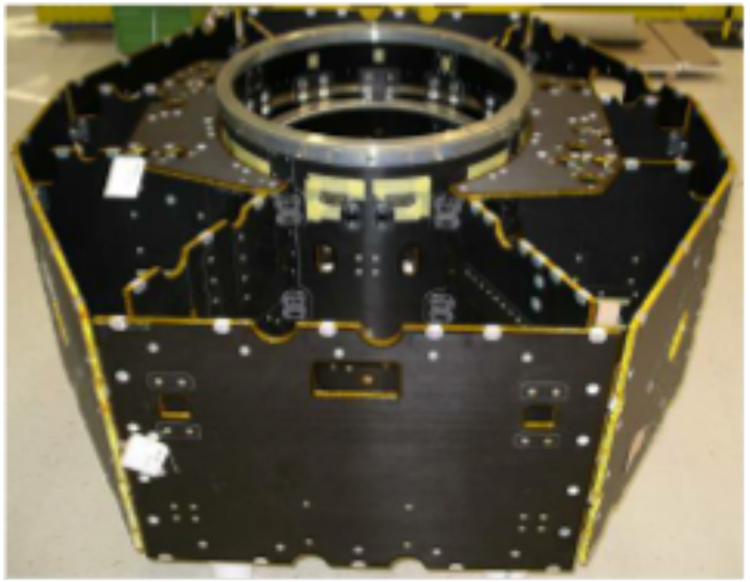
✳ **Basic Idea**: Take one *LISA* arm and squeeze it into one spacecraft





✳The LISA Technology Package (LTP) tested:

- Drag-free technology
- Picometer interferometry
- Other important subsystems and software



Carlos F. Sopuerta
July 24th, 2023
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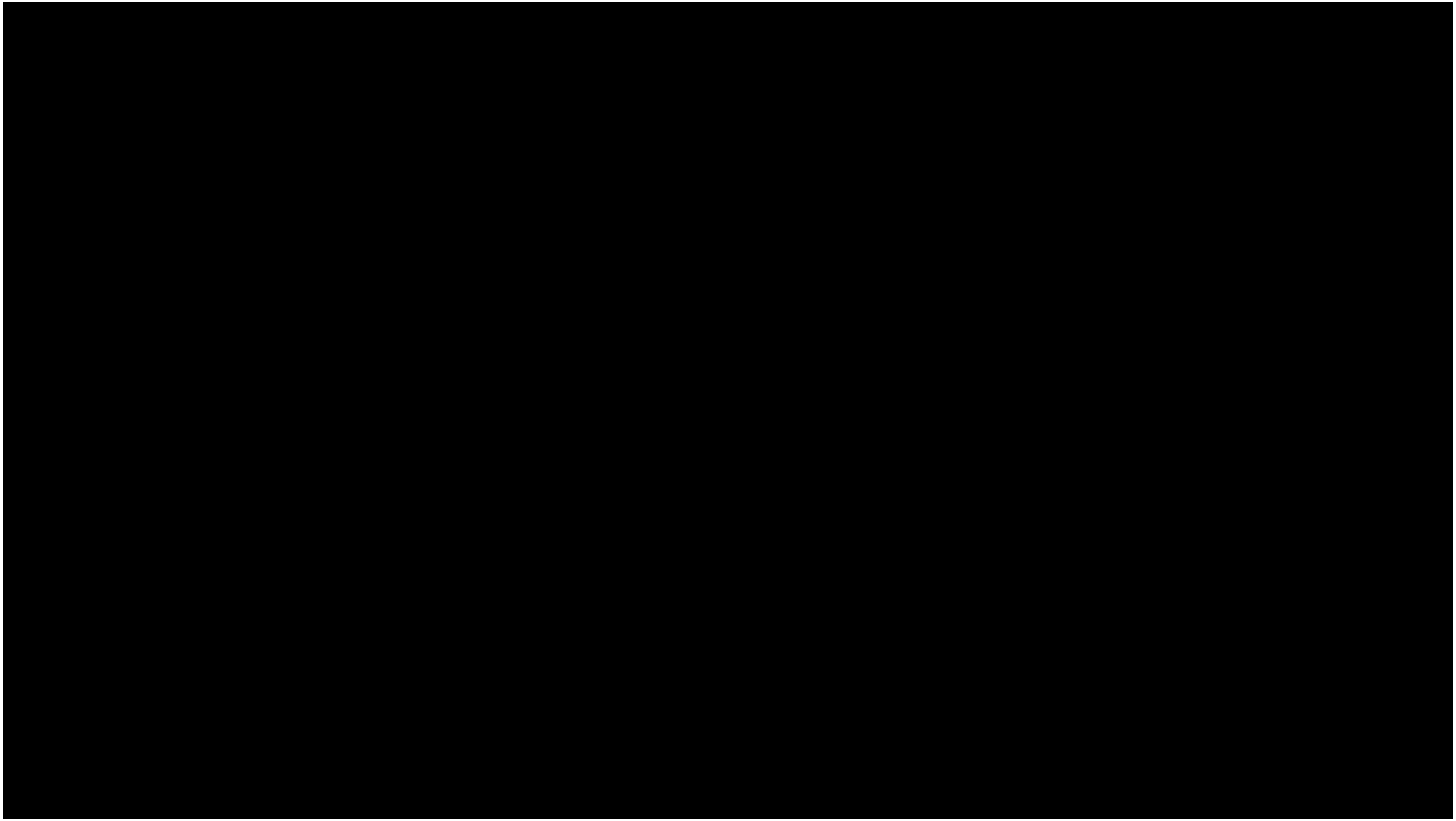
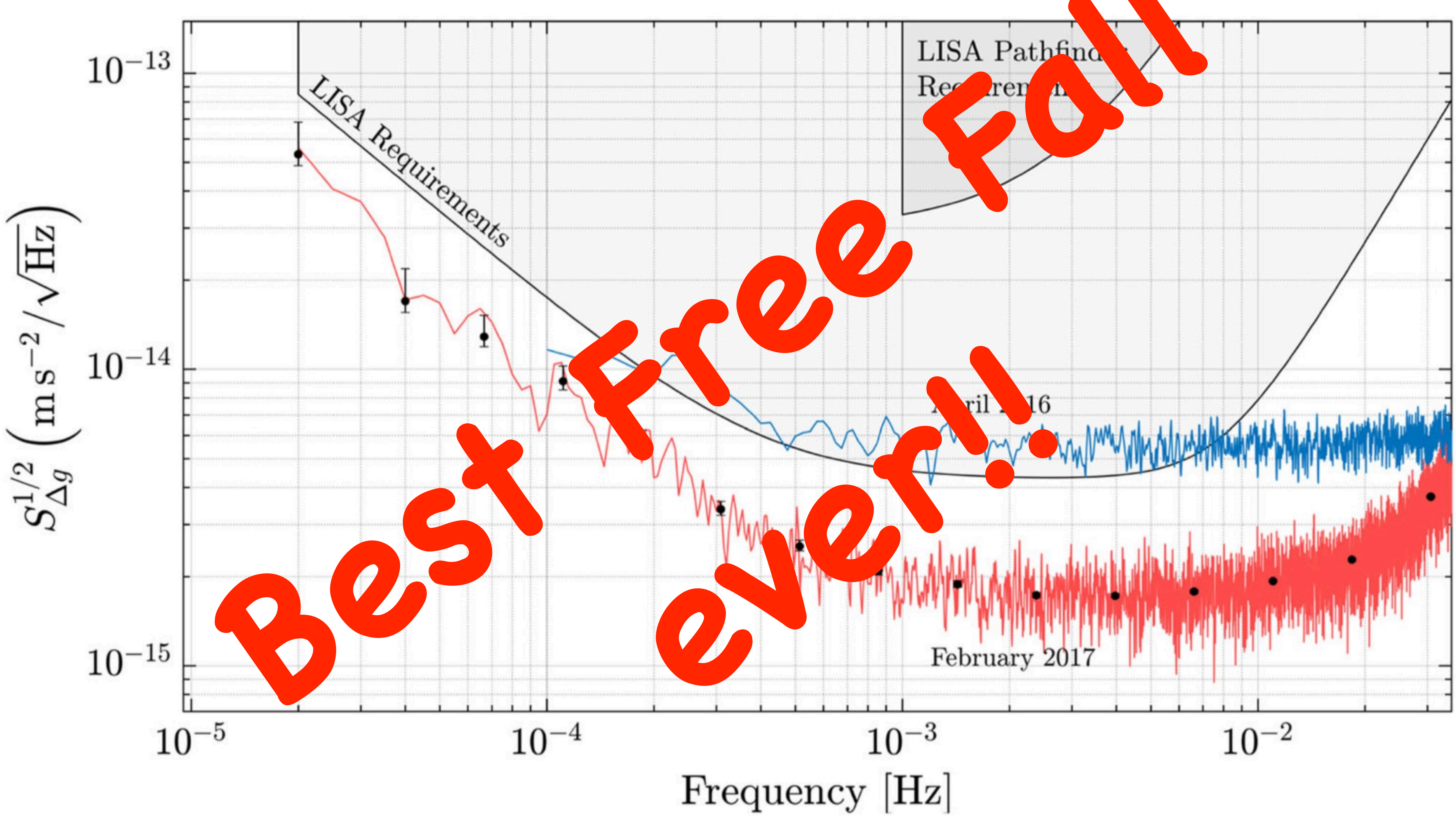
The Experiment:



2017: *LISA Pathfinder* best results [PRL, **120**, 061101 (2018)]:



Gravitational Wave Detection from Space and LISA

- LISA key Milestones:

2017	Mission Proposal Submission to ESA
2017	Mission Selection by ESA SPC
2018	Phase A Kick-Off
2021	Phase A close out: Mission Formulation Review
2022	**Phase B1 Kick-Off**
~~2023~~ -> 2024	**Mission Adoption (Q1)**
End 2024	Mission Implementation, prime starts in Q1 2025
Mid-2030s	Launch

Around 2035

Carlos F. Sopuerta
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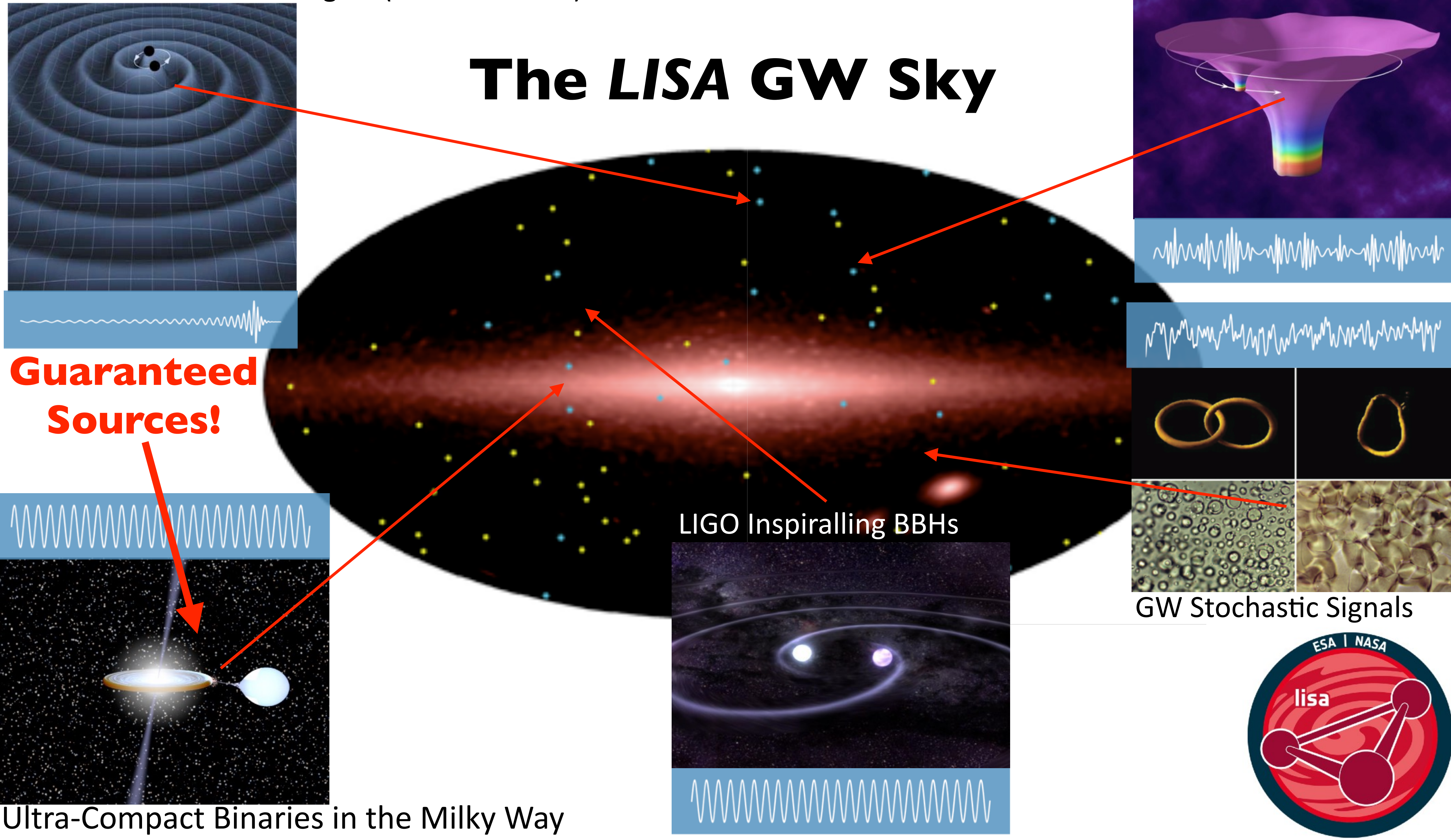
LISA Sources and the Science of LISA

LISA Sources and Science

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

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

Massive Black Holes mergers (10^4 to 10^7 $M_\odot$)



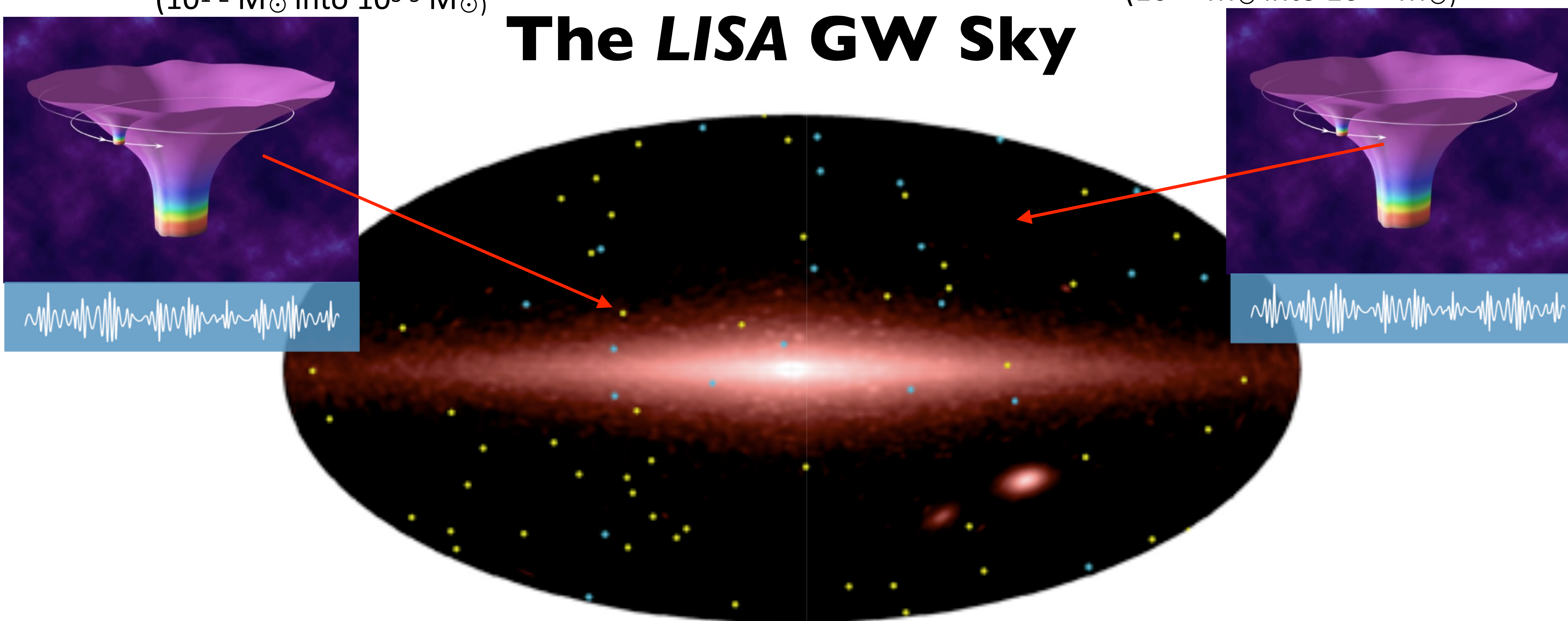
Ultra-Compact Binaries in the Milky Way

LISA Sources and Science

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

Intermediate Mass Ratio Inspirals, IMRIs ($10^{1-2}\,M_\odot$ into $10^{3-5}\,M_\odot$)

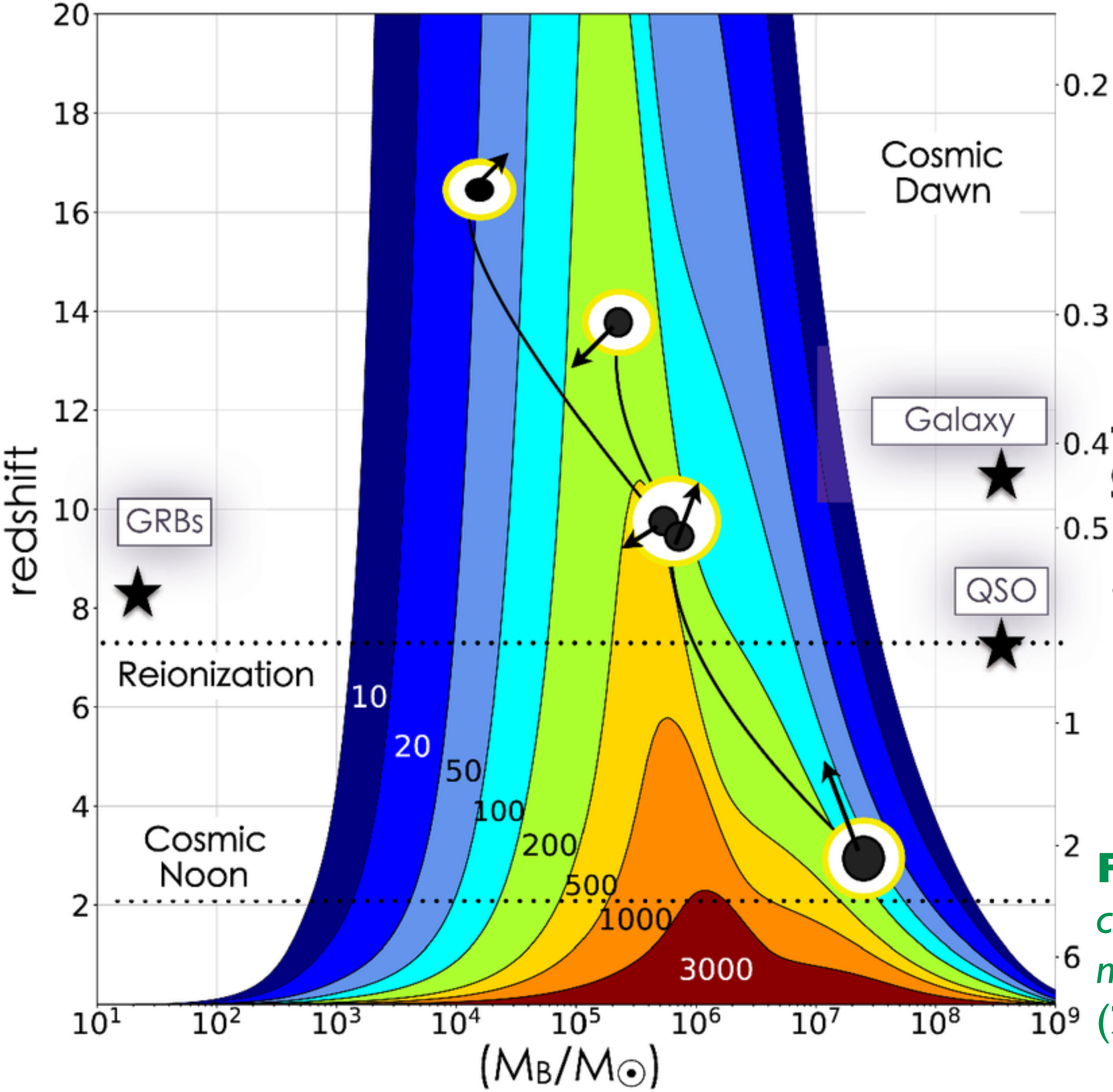
Intermediate Mass Ratio Inspirals, IMRIs ($10^{2-4}\,M_\odot$ into $10^{5-7}\,M_\odot$)

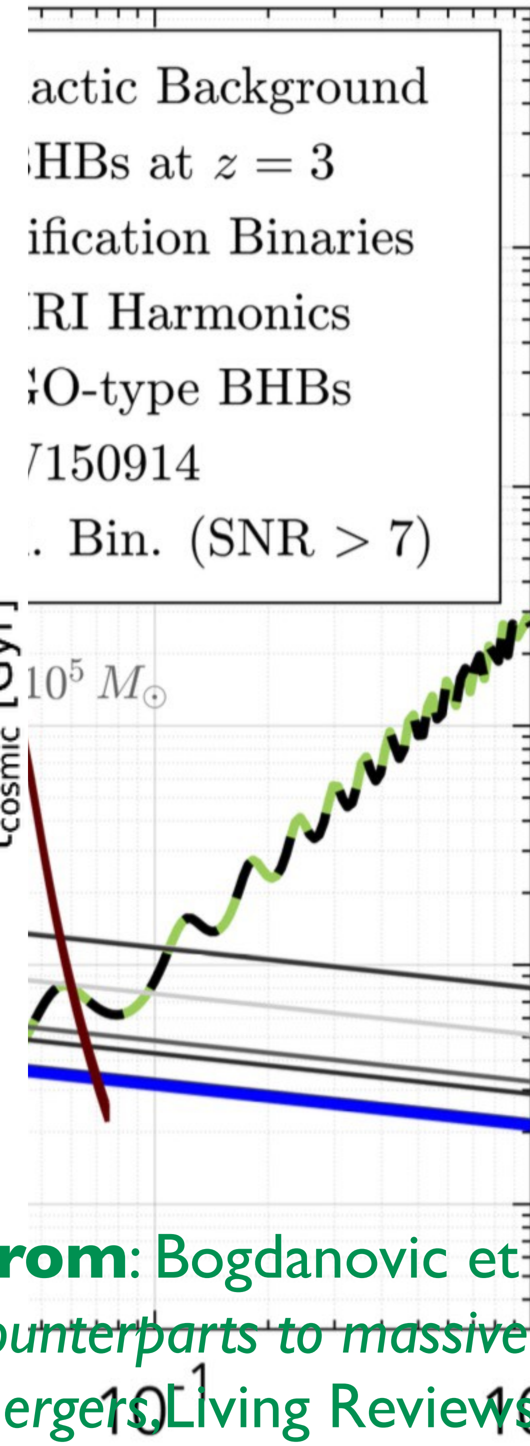


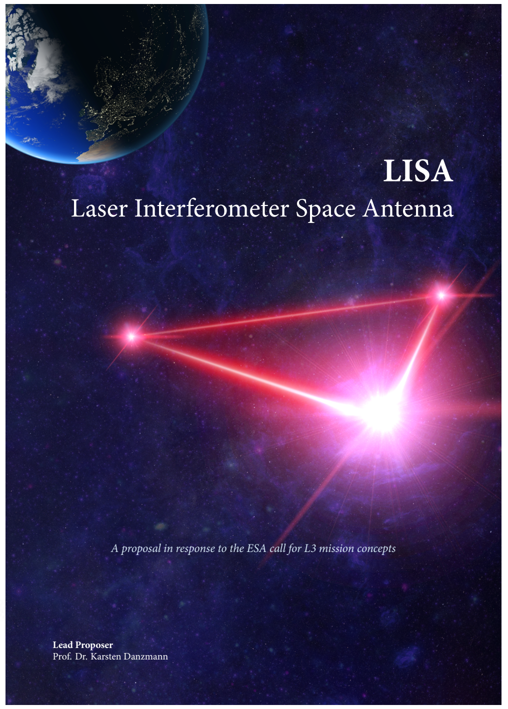
- The GW frequency of these systems is controlled by the mass of the largest black hole (and the separation).
- **Other GW Sources**: Primordial BHs, Extra-dimensional effects, etc. [The unknown!]

LISA Sources and Science

- Expected Sensitivity and Sources:



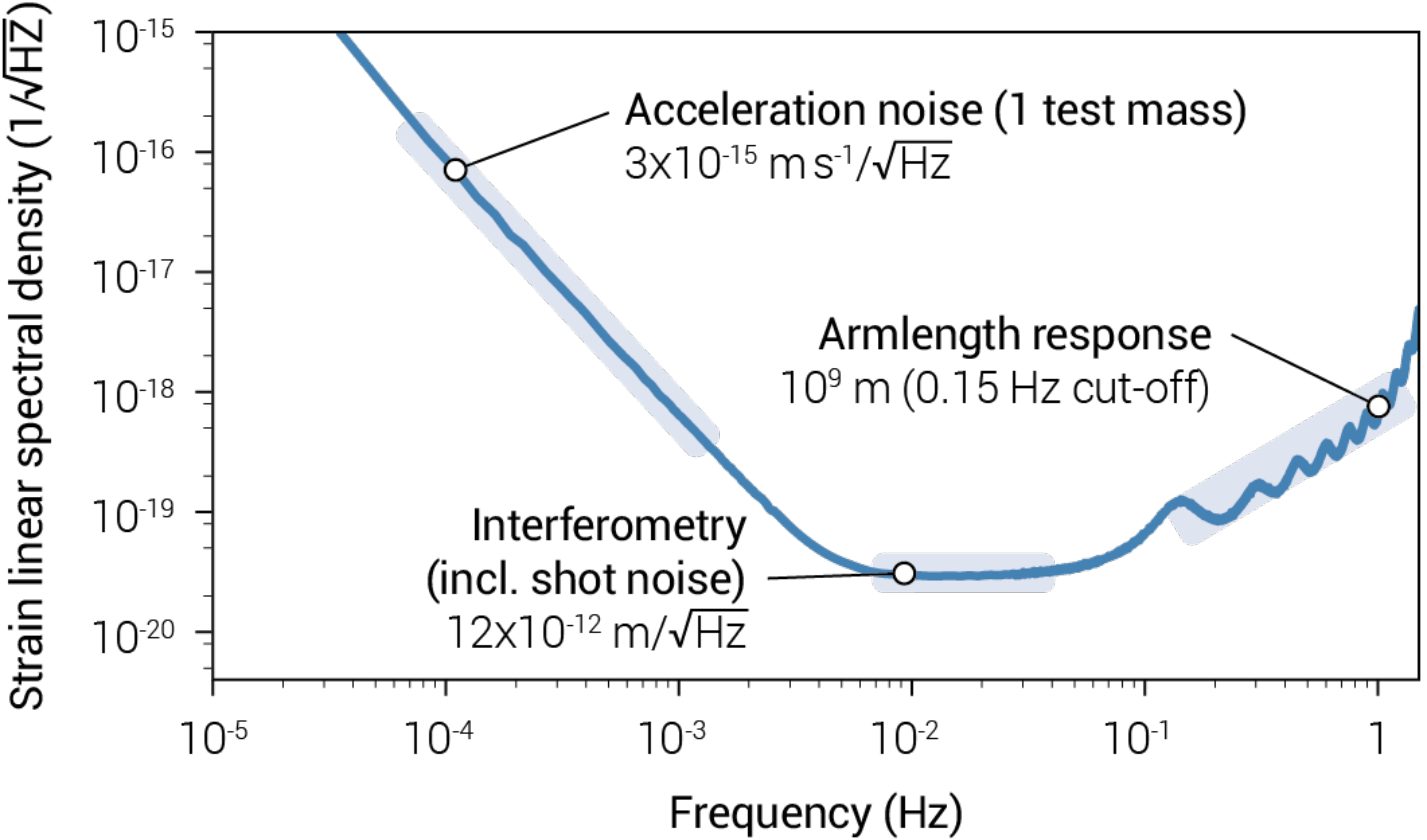




From: Bogdanovic et al, *Electromagnetic counterparts to massive black-hole mergers*, Living Reviews in Relativity, **25**(1) (2022)

LISA Sources and Science

- LISA noise Sensitivity Curve:



LISA Sources and Science

- LISA Science Objectives:

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 across cosmic epochs.

SO3: Probe the dynamics of dense nuclear star clusters using Extreme-Mass-Ratio Inspirals (EMRIs).

SO4: Understand the astrophysics of black hole binaries of stellar origin.

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

SO6: Probe the rate of expansion of the Universe.

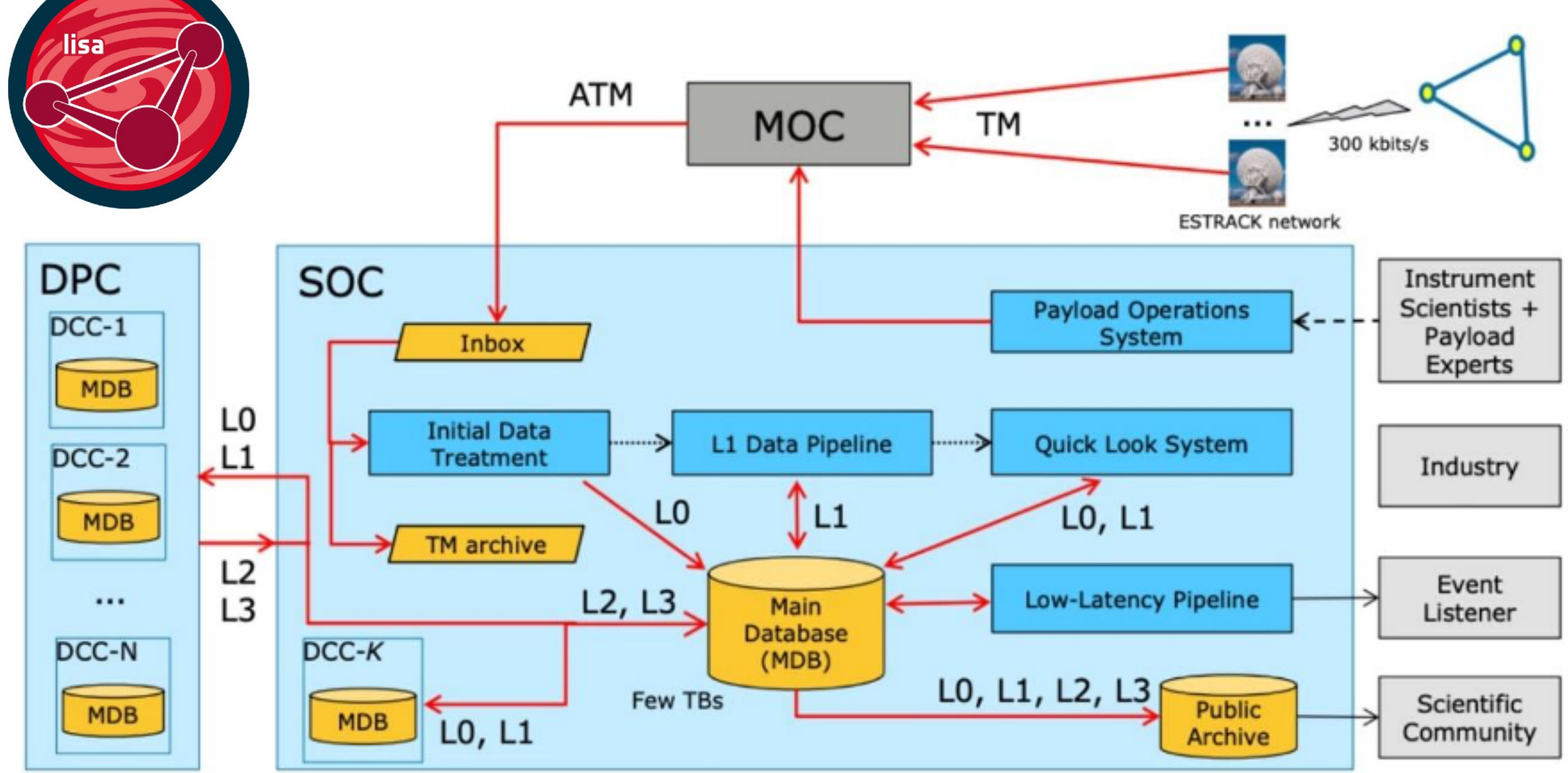
SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics.

SO8: Search for GW bursts and unforeseen sources.

LISA Ground Segment and Science Exploitation

LISA Ground Segment and Data Analysis

* LISA Ground Segment Scheme:



Data Storage is not a problem. Data processing is the Challenge.

LISA Ground Segment and Data Analysis

✳ LISA Data Products (time series):

L0/L0.5 Data: Data from telemetry with some basic processing (data format conversion, clock synchronization, etc.).

L1 Data: Data processed and ready to look for gravitational wave sources: Time-Delay Interferometry, corrected and calibrated.

L2 Data: Identification of the different sources of gravitational waves together with their physical parameters and their a posteriori probability distributions. **Global Fit**: All sources are fitted simultaneously, together with a noise model, to the data. There will be several *global fit* algorithms.

L3 Data: The coherent fusion of all the L2 catalogs in a single one.

LISA Ground Segment and Data Analysis

✳ Basic ideas of LISA Data Analysis:

- The typical time series can be splitted as:

$$s_I(t) = h_I(t, \vec{\lambda}) + n_I(t)\,, \quad I : \text{Label for the different detectors/channels}$$

Where h is the signal (detector response to the GW), $\vec{\lambda}$ are the physical parameters (intrinsic and extrinsic), and n is the noise.

- We assume that the noise is Gaussian and Stationary:

$$< \tilde{n}_I(f)\, \tilde{n}_J(f')^* > = \frac{1}{2}\delta(f - f')\, \delta_{IJ}\, S_n(f)$$

Where ~ denotes Fourier transformation, <> ensemble average, and * complex conjugation. On the right-hand side we have introduced the so-called (single-sided) noise spectral density, which contains all the information about the detector noise.

LISA Ground Segment and Data Analysis

✳ Basic ideas of LISA Data Analysis:

- Then, the probability for the noise to have some realization is:

$$P\left(n = n_o\right) \;\propto\; e^{-\frac{1}{2}\left(n_o \,|\, n_o\right)}$$

where we have introduced the following scalar product:

$$\left(h_1 \,|\, h_2\right) = 2\int_0^\infty df\, \frac{\tilde{h}_1^*(f)\tilde{h}_2(f) + \tilde{h}_1(f)\tilde{h}_2^*(f)}{S_n(f)}$$

Overlap integral of the signals h1 and h2 in the frequency domain.

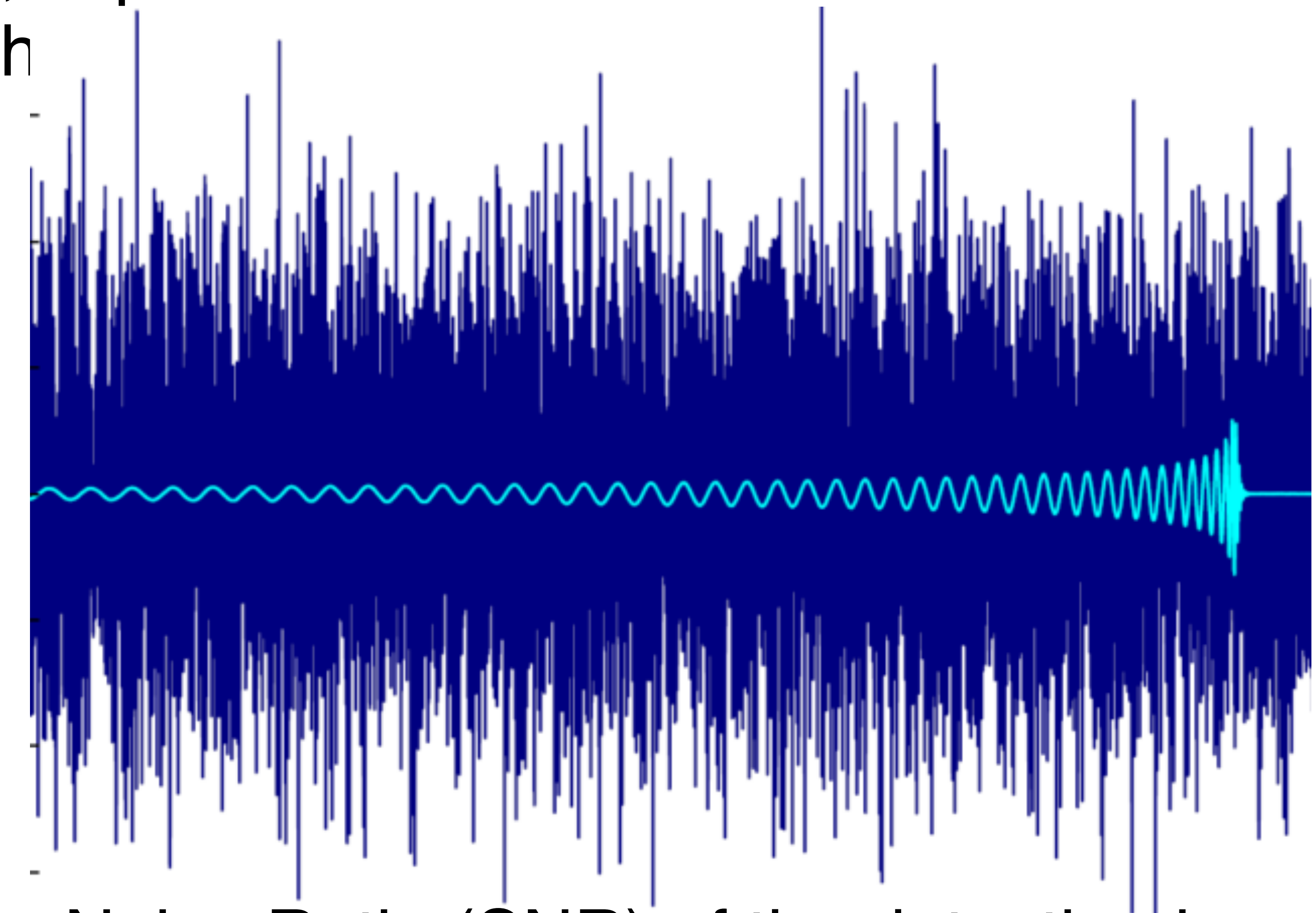
NOTE: The overlap is weighted by the Power Spectral Density

- Therefore, the likelihood that the true parameter values are given by a particular λ, or in other words, the likelihood that our signal is present in the data stream is just given by:

$$P\left(s \,|\, h\right) = P(s \,|\, \vec{\lambda}) \;\propto\; e^{-\frac{1}{2}\left(s(t) - h(t,\vec{\lambda}) \,|\, s(t) - h(t,\vec{\lambda})\right)}$$

LISA Ground Segment and Data Analysis

- Then, in most cases of interest, 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 th



- The Signal-to-Noise Ratio (SNR) of the detection is approximately given by:

$$\mathrm{SNR}[h(t,\vec{\lambda})] = \sqrt{\left(h(t,\vec{\lambda}) \,|\, h(t,\vec{\lambda}) \right)}$$

✳ Basic ideas of LISA Data Analysis:

- This approach emphasizes another important use of the theoretical models (the **gravitational waveforms**): Parameter Estimation (of the physical parameters λ).

- Let us consider that $\vec{\lambda}_{\rm T}$ are the "true" values of the physical parameters $\vec{\lambda}$, and that $\vec{\lambda}_{\rm ML} = \vec{\lambda}_{\rm T} + \delta\vec{\lambda}$ are the best fit parameters in the presence of some realization of the noise. Then, for large SNR, the parameter-estimation errors $\delta\vec{\lambda}$ have the Gaussian probability distribution:

$$P(\delta\vec{\lambda}\,|\,s) \;\propto\; e^{-\frac{1}{2}\Gamma_{ij}\,\delta\lambda^i\,\delta\lambda^j}$$

↑ Fisher Information Matrix

- Basic ideas of LISA Data Analysis:

where Γ_{ij} is the so-called Fisher information matrix, defined by

$$\Gamma_{ij} = \left(\frac{\partial h}{\partial \lambda^i} \,\middle|\, \frac{\partial h}{\partial \lambda^j} \right) \Bigg|_{\vec{\lambda}_{\rm ML}}$$

- For large SNR, the variance-covariance matrix is given by:

$$< \delta\lambda^i \, \delta\lambda^j > \; = \; \left(\Gamma^{-1}\right)^{ij} \; + \; \mathcal{O}(\mathrm{SNR}^{-1})$$

and the “error” in a given parameter λ^i is defined as:

$$\Delta\lambda^i \; \equiv \; \sqrt{< \delta\lambda^i \, \delta\lambda^i >}$$

LISA Ground Segment and Data Analysis

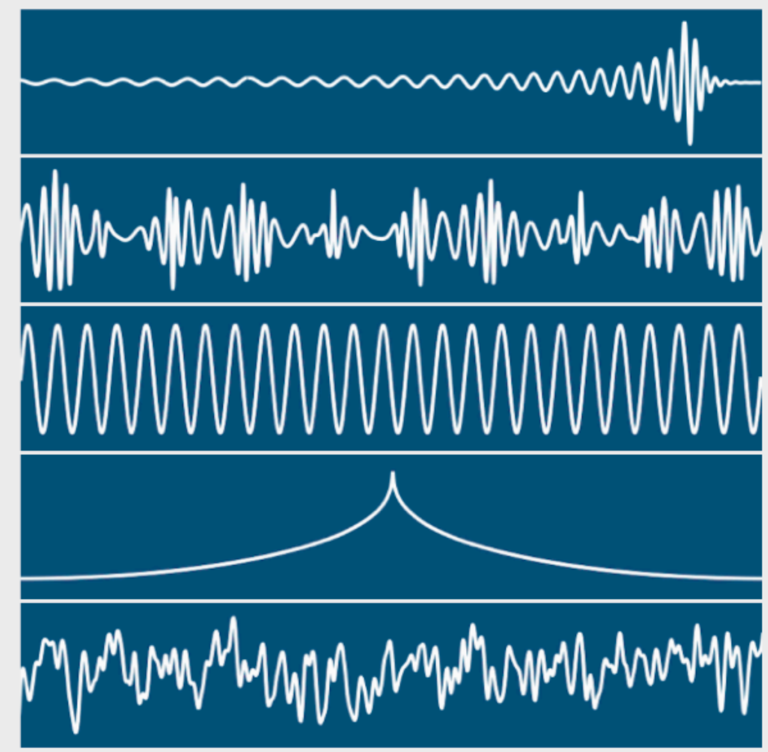
* LISA Data Challenges (Working Group of the LISA Consortium):

(the new) LISA Data Challenges

...or, as we call them, the **LDCs**—an **open, collaborative effort to tackle unsolved problems in LISA data analysis**, while developing software tools that will form the basis of the future LISA data system.

The LDCs are organized by the **LISA Consortium's LDC working group**. Please join us as we write code and specifications to generate challenge datasets, and we work together to search for gravitational-wave sources and estimate their parameters. If you prefer to explore by yourself, develop your algorithms (or improve ours), then submit your methods and results so we can learn from them.

The LDCs are supported by the LISA LISA Data Processing Group (LDPG) at APC Paris.



LISA
CONSORTIUM

Conclusions

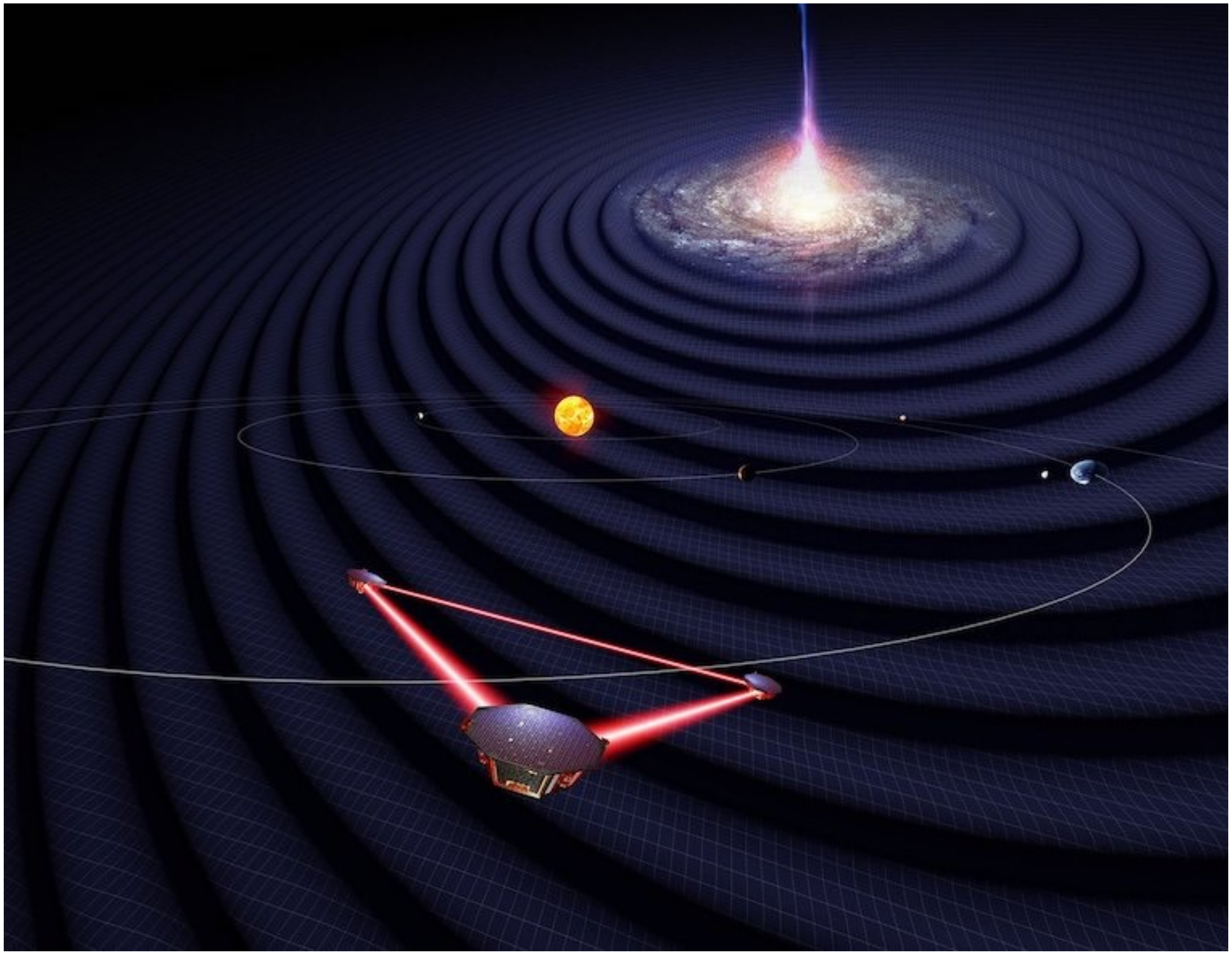
Conclusions

- LISA will be the first ever mission to survey the entire Universe with Gravitational Waves, play a unique and prominent role in the scientific landscape of the 2030s and beyond.

- LISA science case is very broad with a strong impact in: Astrophysics, Cosmology and Fundamental Physics.

- There are many challenges ahead, in particular in the development of algorithms to fit the data to our models (Globat Fit). The LISA Data Challenges Working Group of the LISA consortium provides a collaborative ground to participate.

Thanks a lot for your attention!



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