

Space-based GW detectors: LISA

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Why go to space?

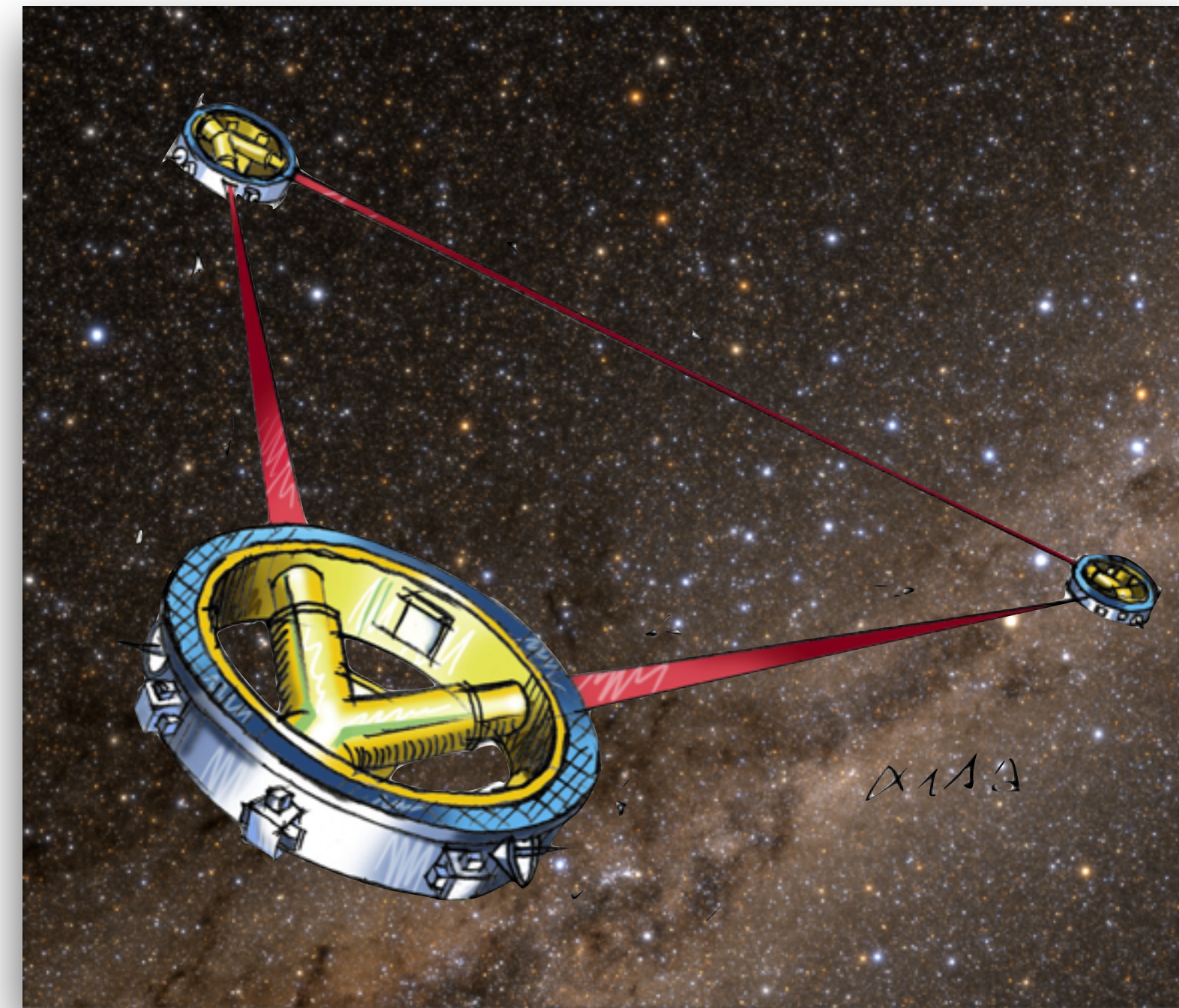
- **Challenges of space:**
 - Getting there is expensive
 - Instruments must be engineered to work by themselves
 - It takes a really long time to achieve this
- **So why do it?**

Opening a new GW band



NASA/STScI

- Avoid terrestrial disturbances
- Access new spectral bands



Credit: ESA-C. Vijoux

- Avoid terrestrial disturbances
- Access new spectral bands

Why go to space?

Same reasons as for EM telescopes

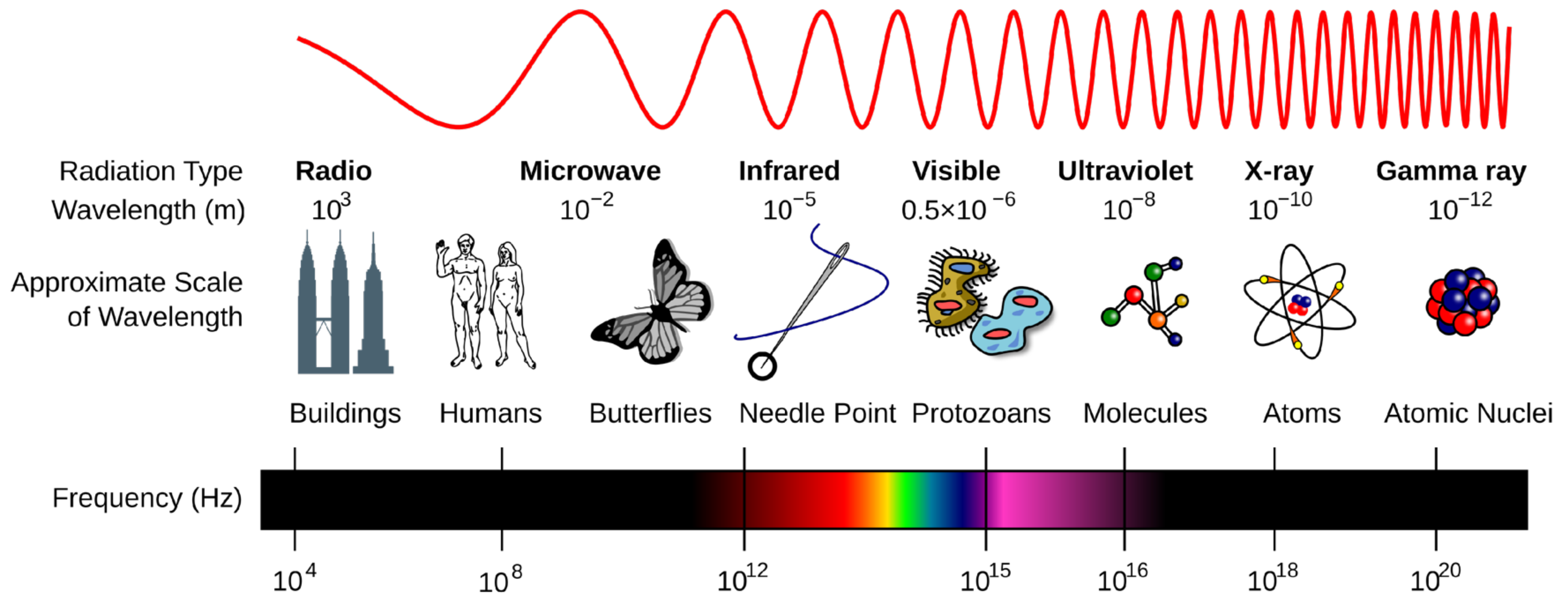
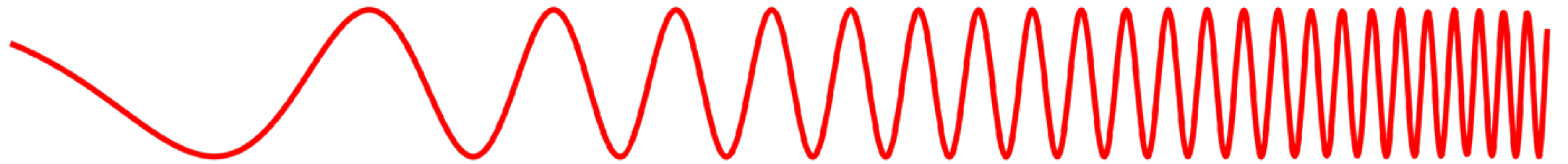


Image:Wikimedia Commons

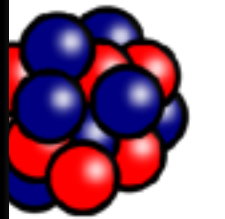
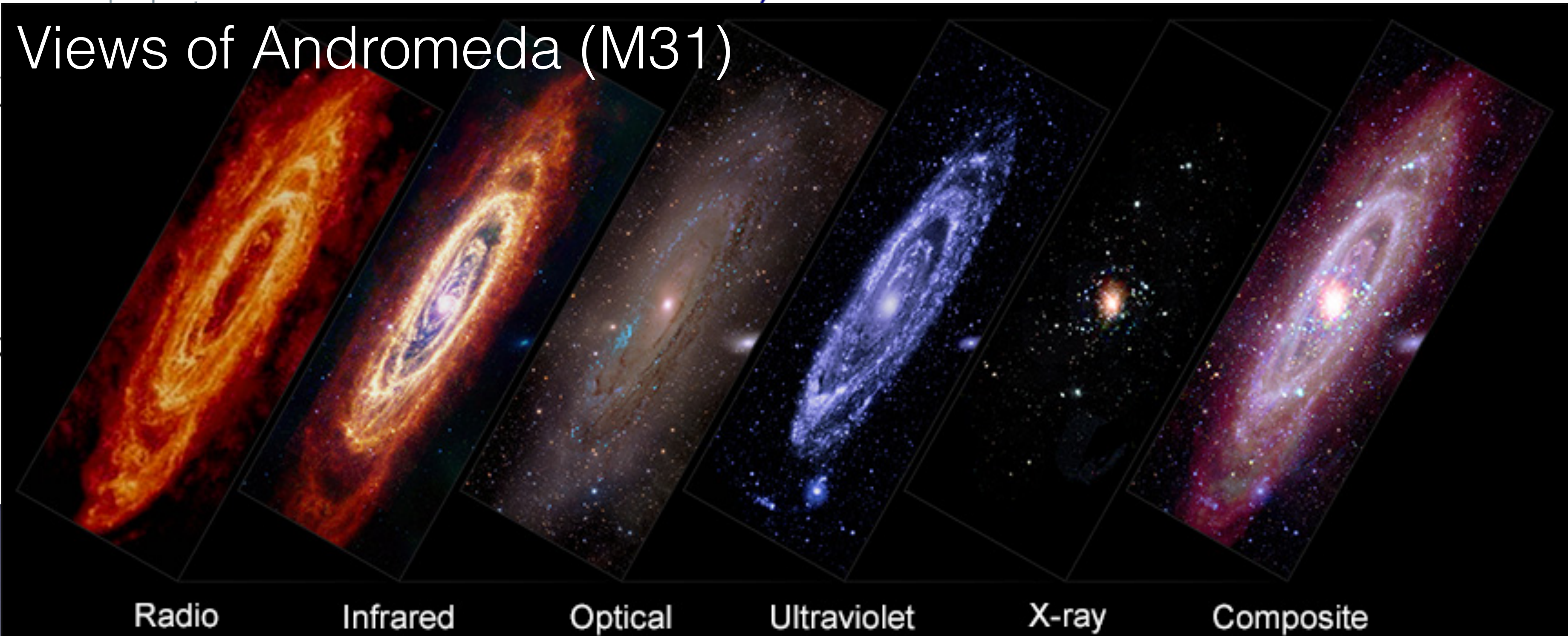


Radiation Type	Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma ray
Wavelength (m)	10^3	10^{-2}	10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}

Approximate Scale
of Wavelength

Frequency (Hz)

Views of Andromeda (M31)



Atomic Nuclei



20

Media Commons

Credit: **X-ray**: NASA/CXO/UMass/Z. Li & Q.D. Wang, ESA/XMM-Newton; **Infrared**: NASA/JPL-Caltech/WISE, Spitzer, NASA/JPL-Caltech/K. Gordon (U. Az), ESA/Herschel, ESA/Planck, NASA/IRAS, NASA/COBE; **Radio**: NSF/GBT/WSRT/IRAM/C. Clark (STScI); **Ultraviolet**: NASA/JPL-Caltech/GALEX; **Optical**: Andromeda, Unexpected © Marcel Drechsler, Xavier Strottner, Yann Sainty & J. Sahner, T. Kottary. **Composite image processing**: L. Frattare, K. Arcand, J. Major

Gravitational Wave Spectrum

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

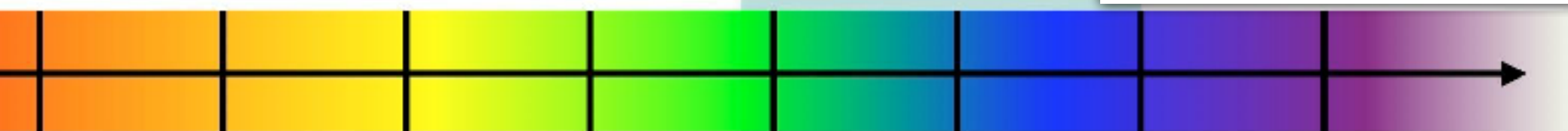
Compact Binary Galaxy

Compact objects captured by Supermassive Black Holes

years

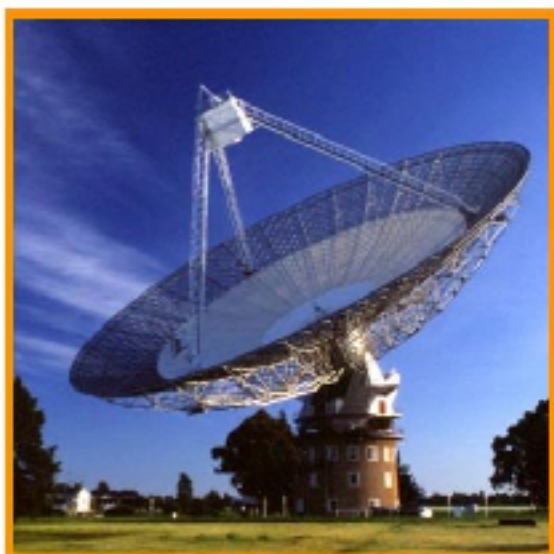
hours

sec

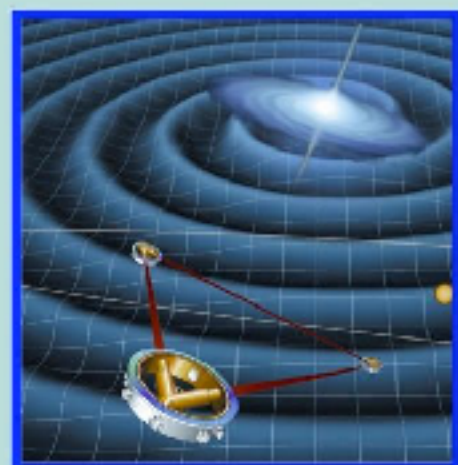


12 -10 -8 -6 -4 -2 0 +2

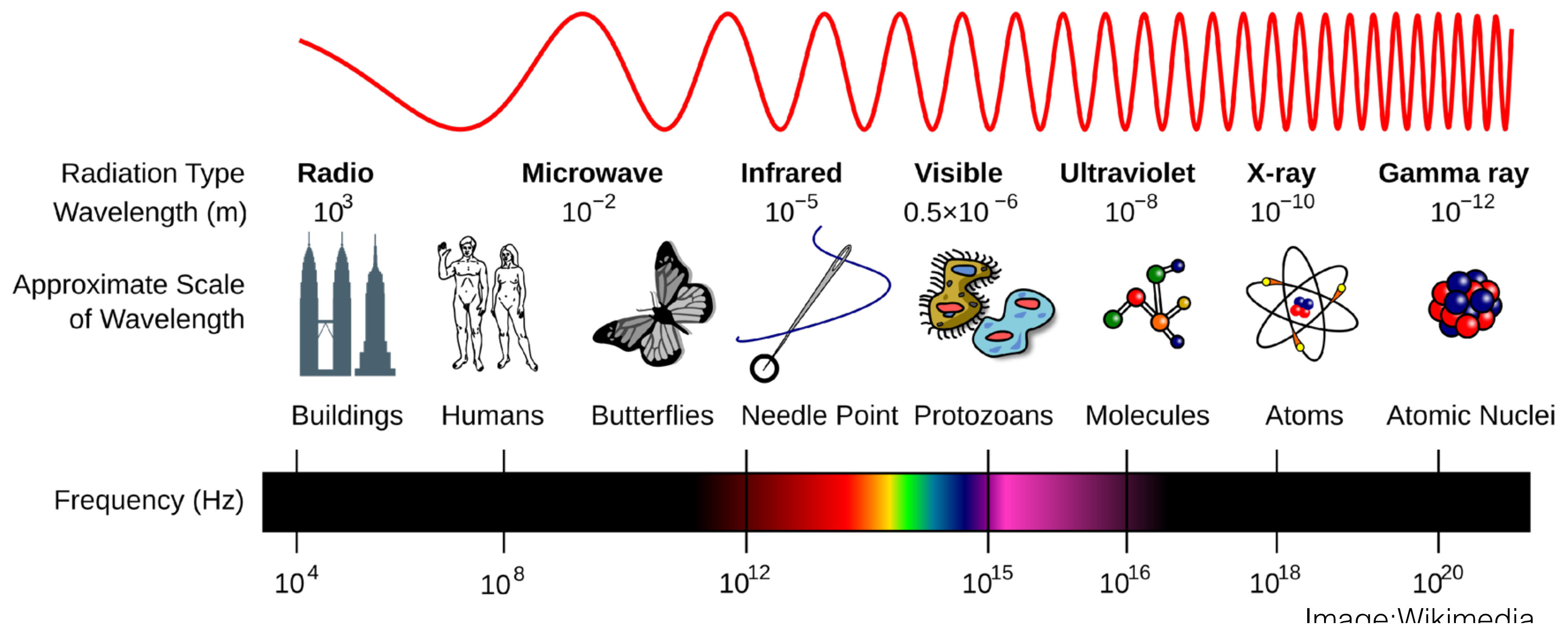
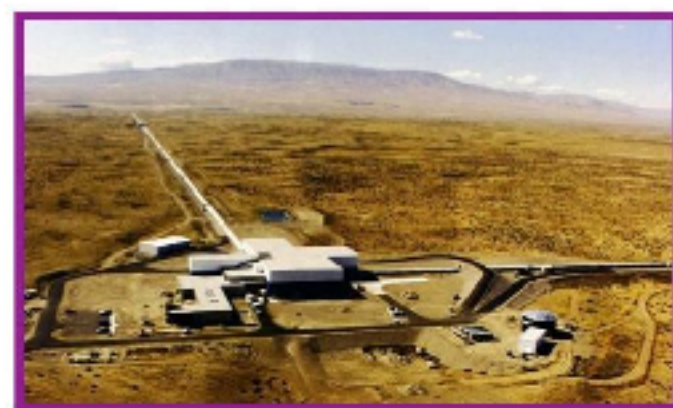
Pulsar Timing



Space Interferometers



Terrestrial interferometers



Pause

Science in the MHz band

The science of LISA

- ▶ **S01:** Study the formation and evolution of **compact binary stars** in the Milky Way Galaxy.
- ▶ **S02:** Trace the origin, growth and merger history of **massive black holes** across cosmic ages
- ▶ **S03:** Probe the properties and immediate **environments of black holes** in the local Universe using **Extreme Mass Ratio Inspirals** and **Intermediate Mass Ratio Inspirals**.
- ▶ **S04:** Understand the **astrophysics of stellar origin black holes**.
- ▶ **S05:** Explore the **fundamental nature of gravity and black holes**.
- ▶ **S06:** Measure the rate of **expansion** of the Universe.
- ▶ **S07:** Understand **stochastic GW backgrounds** and their implications for the **early Universe** and **TeV-scale particle physics**.
- ▶ **S08:** Search for GW **bursts** and **unforeseen** sources.

Astrophysics

**Fundamental
Physics**

Cosmology

The science of LISA

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- ▶ S02: Trace the origin, growth and merger history of massive black holes across cosmic ages
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Astrophysics

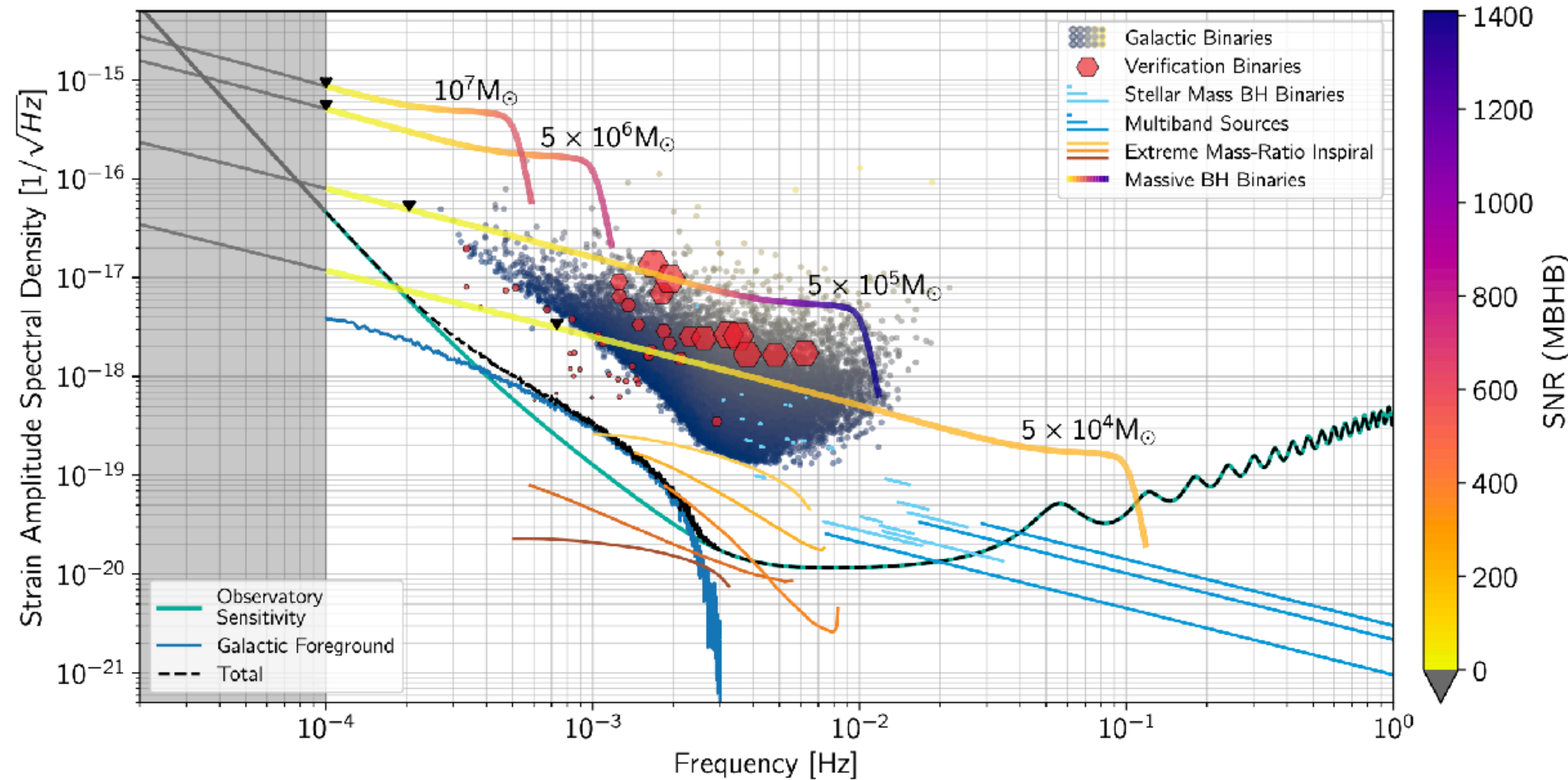
Fundamental
Physics

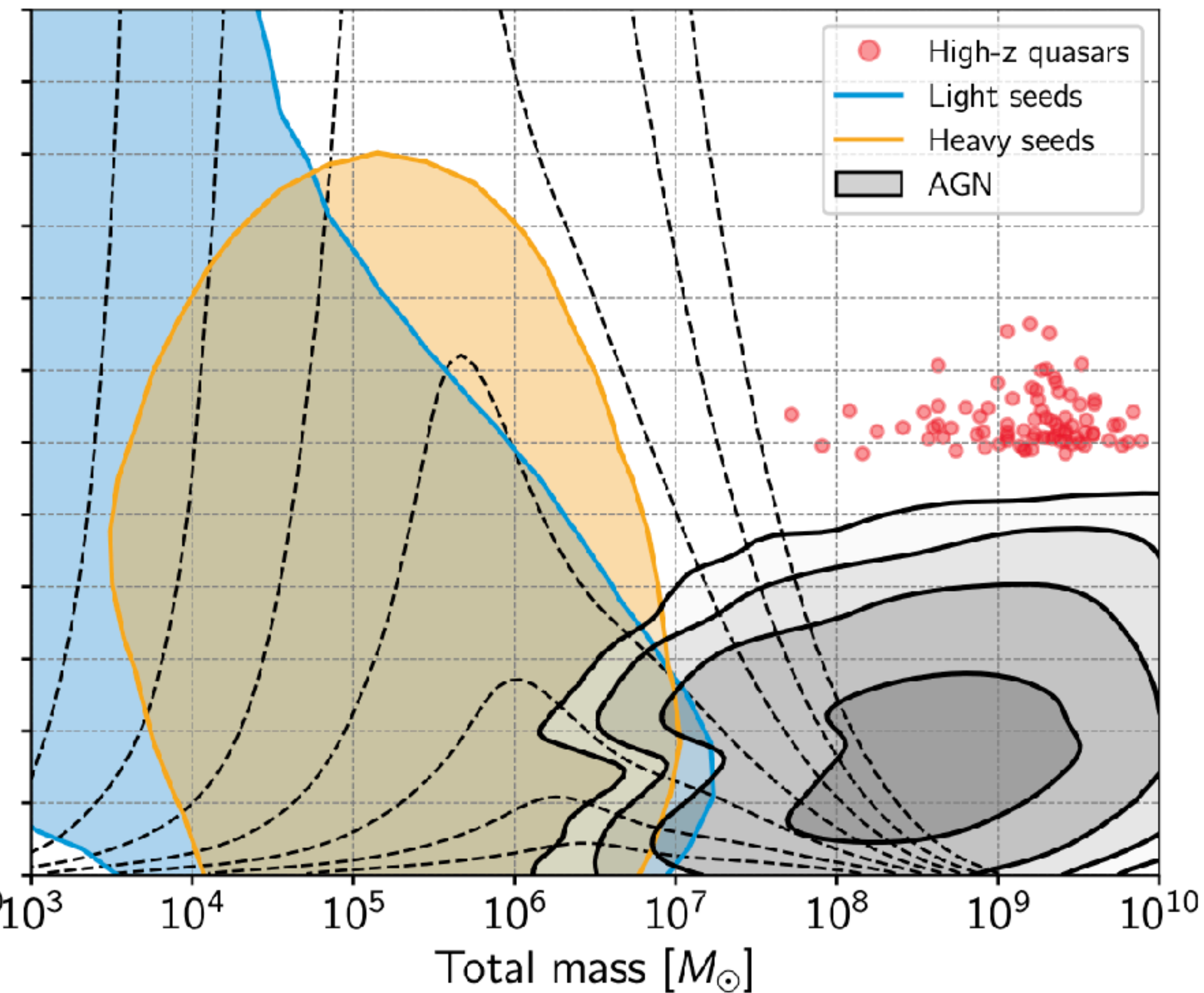
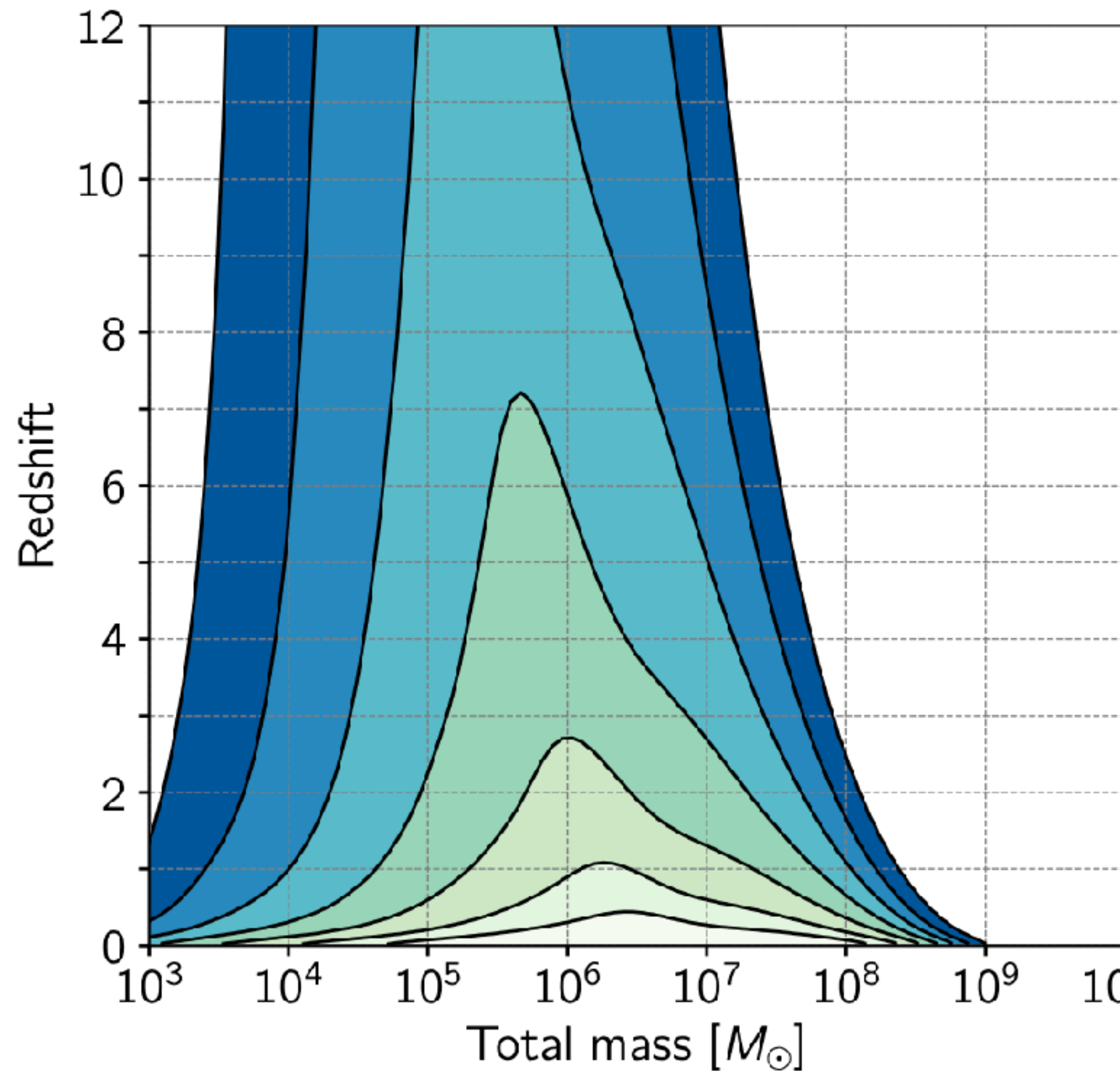
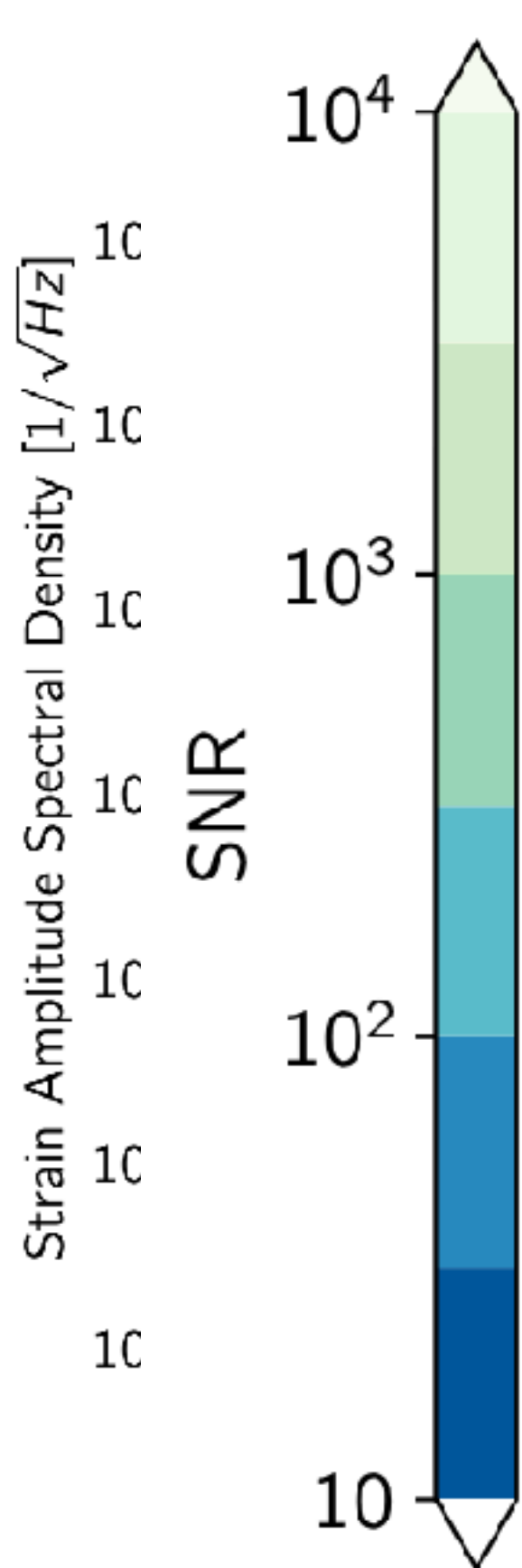
Cosmology

LISA Sources & Noise

Everything in one plot

- Horizontal axis: GW frequency
- Vertical axis: GW amplitude
- Solid Green line: Instrument limit
- Blue arc: GW foreground
- colored dots: persistent sources
- colored tracks: transient sources

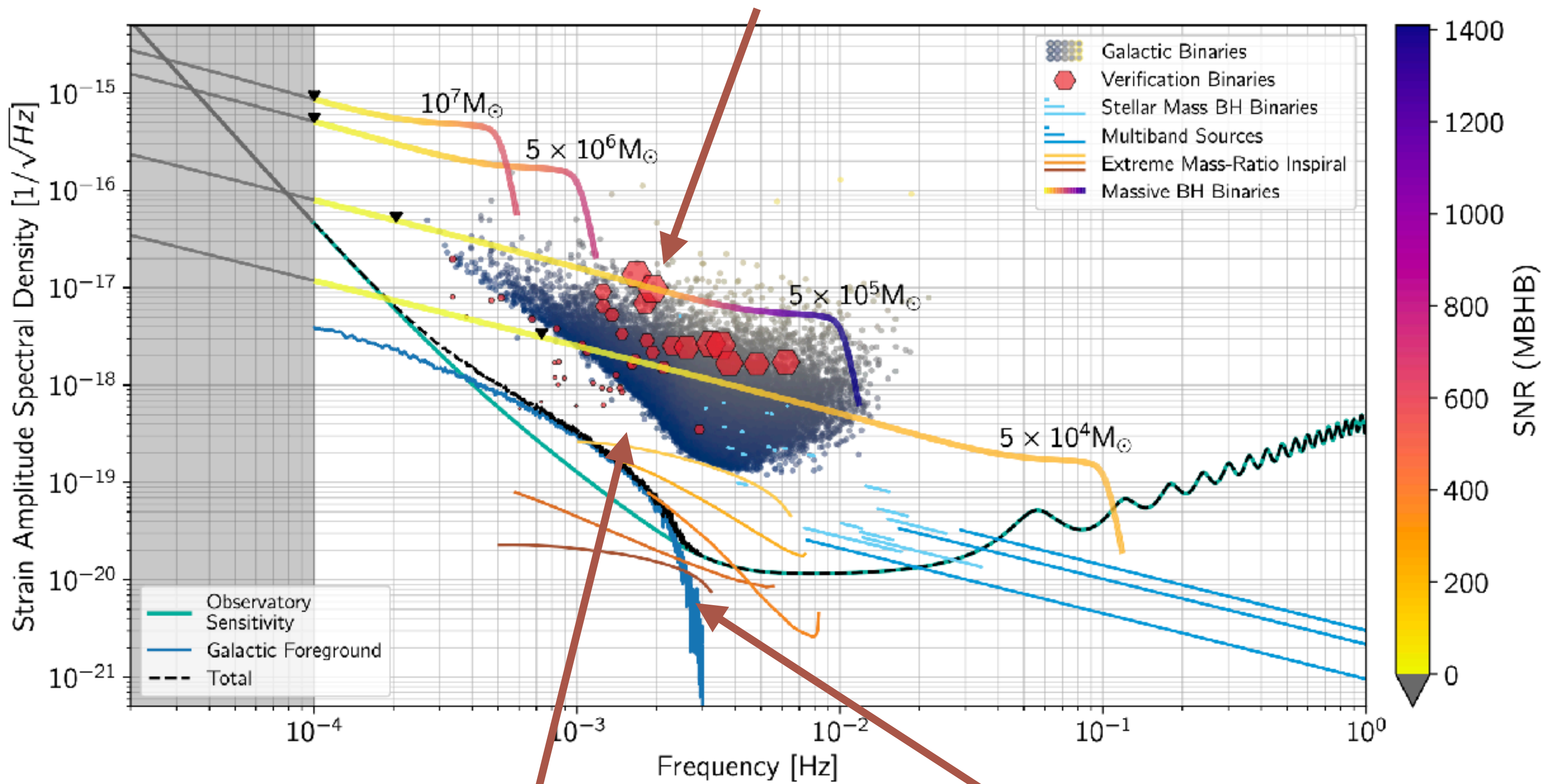




Massive Black Hole Binaries

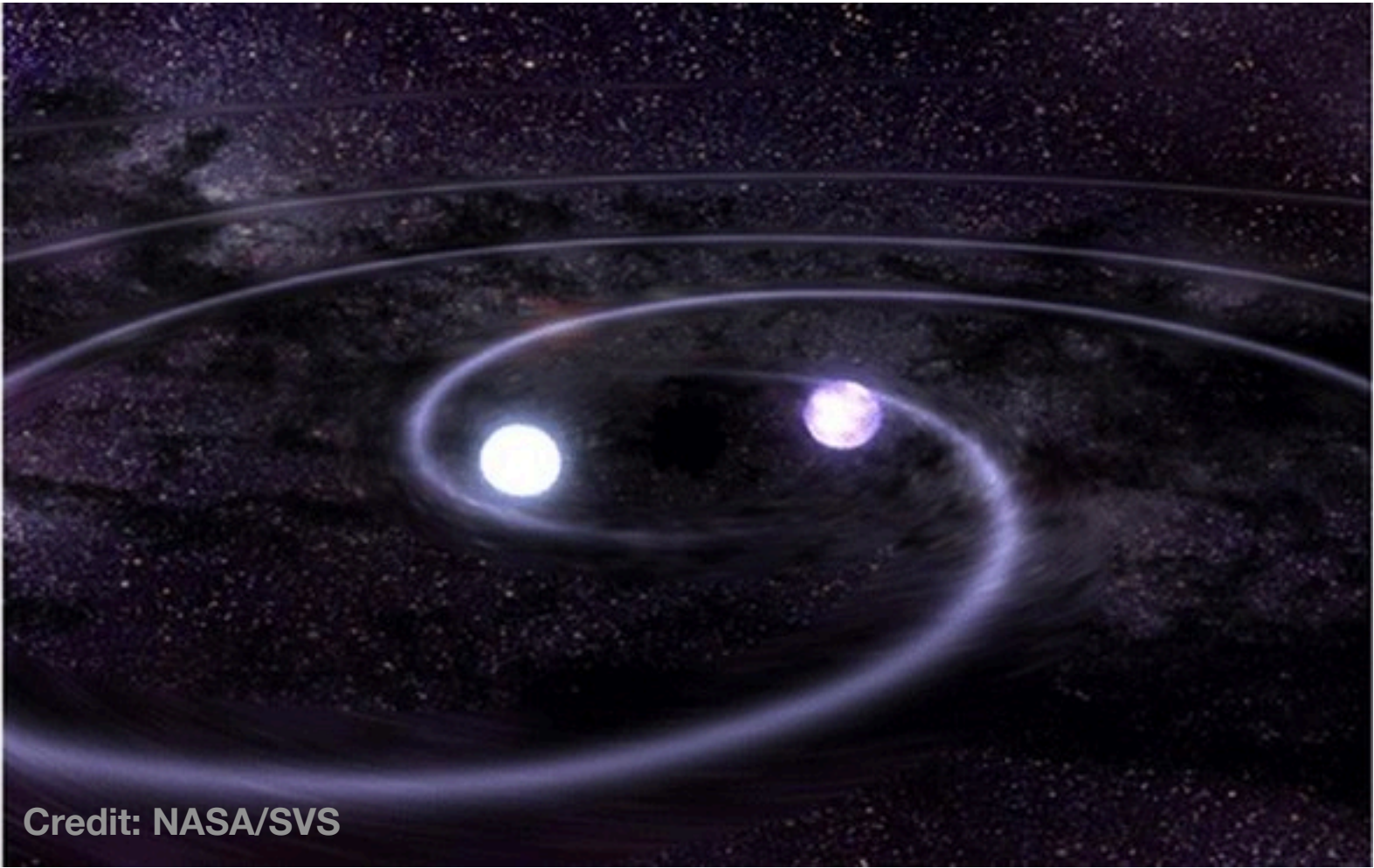


Galactic Binaries that we have already found
By EM observations!

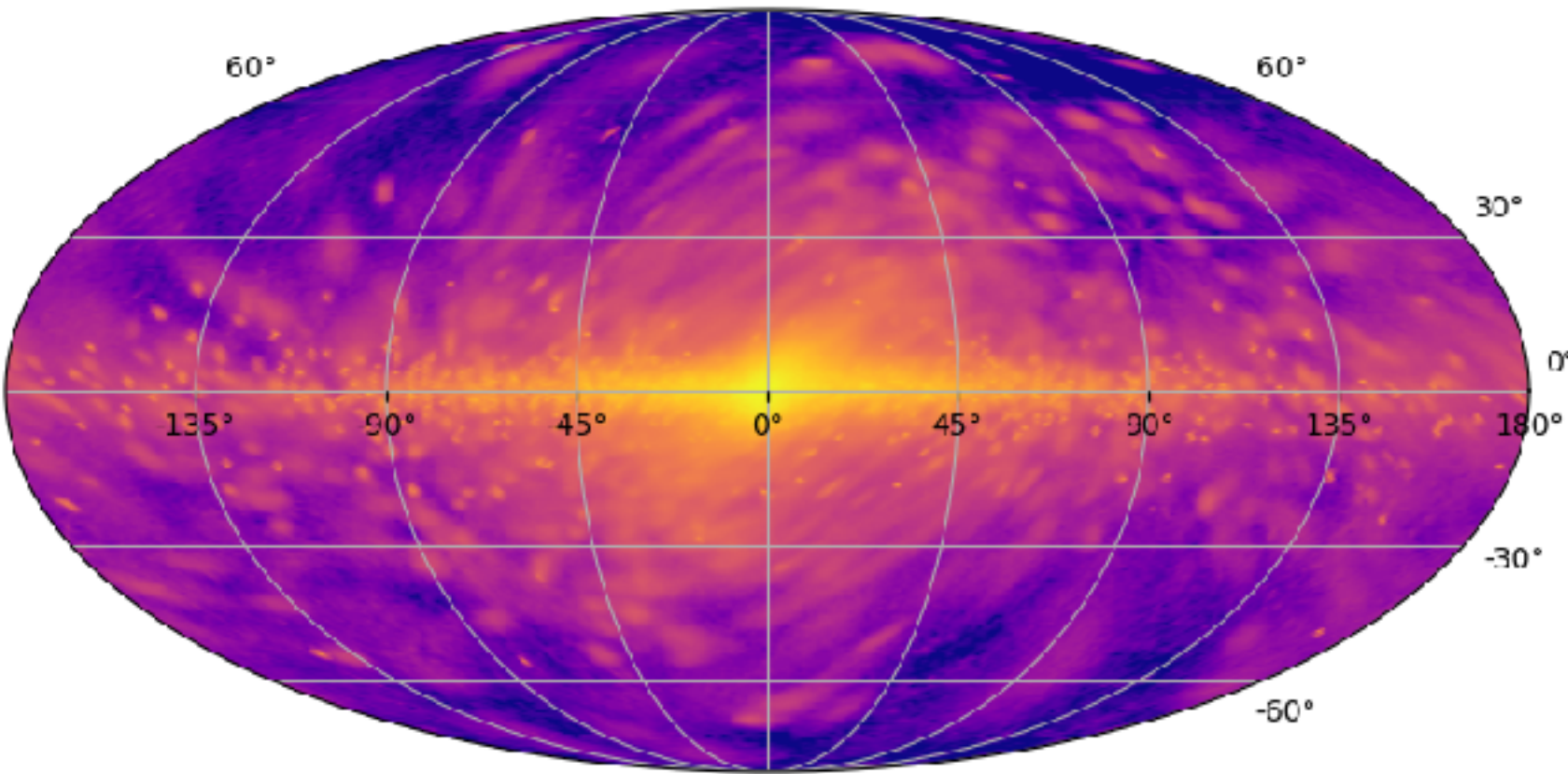


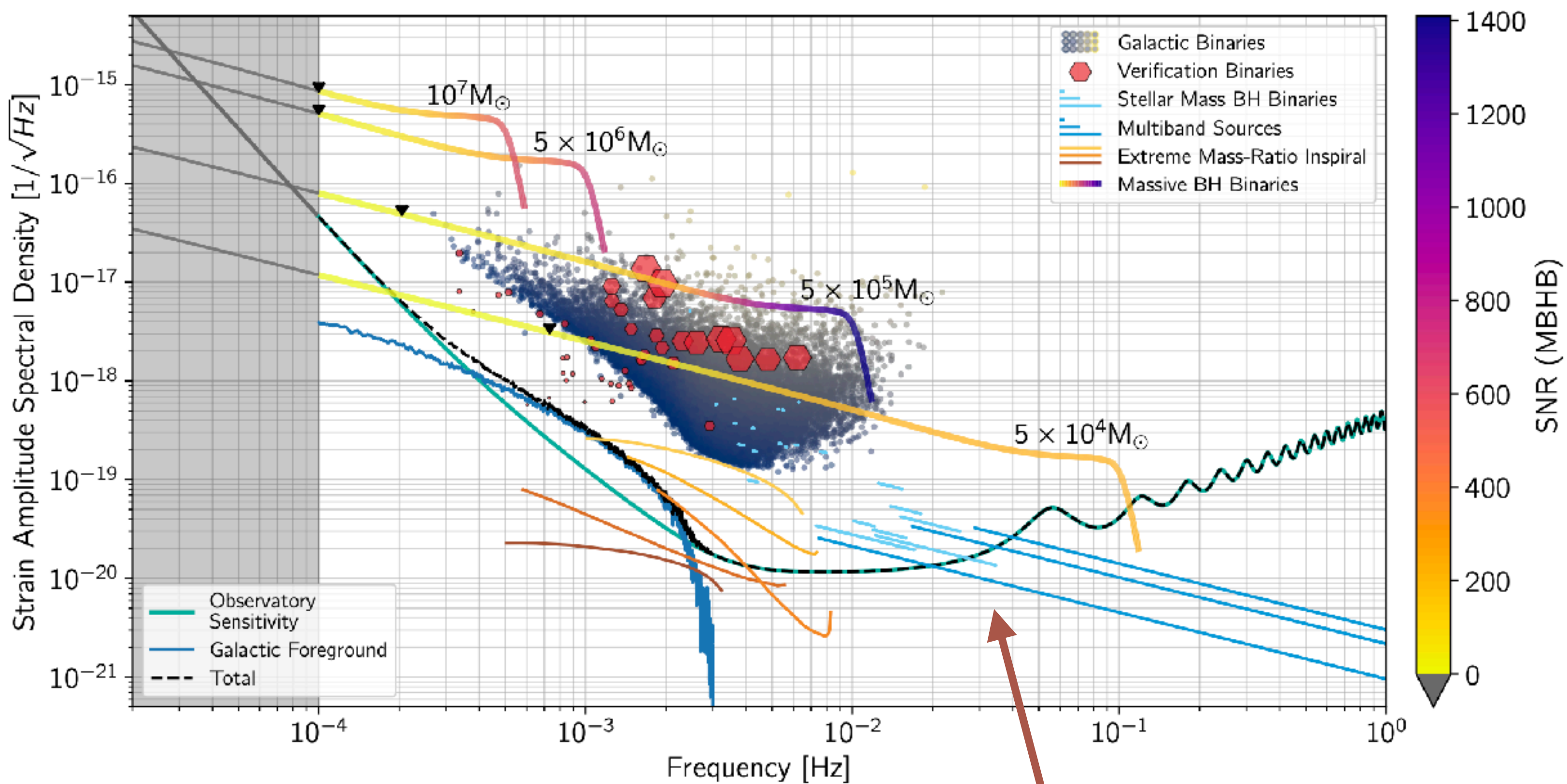
Galactic Binaries

Galactic binary stochastic
confusion

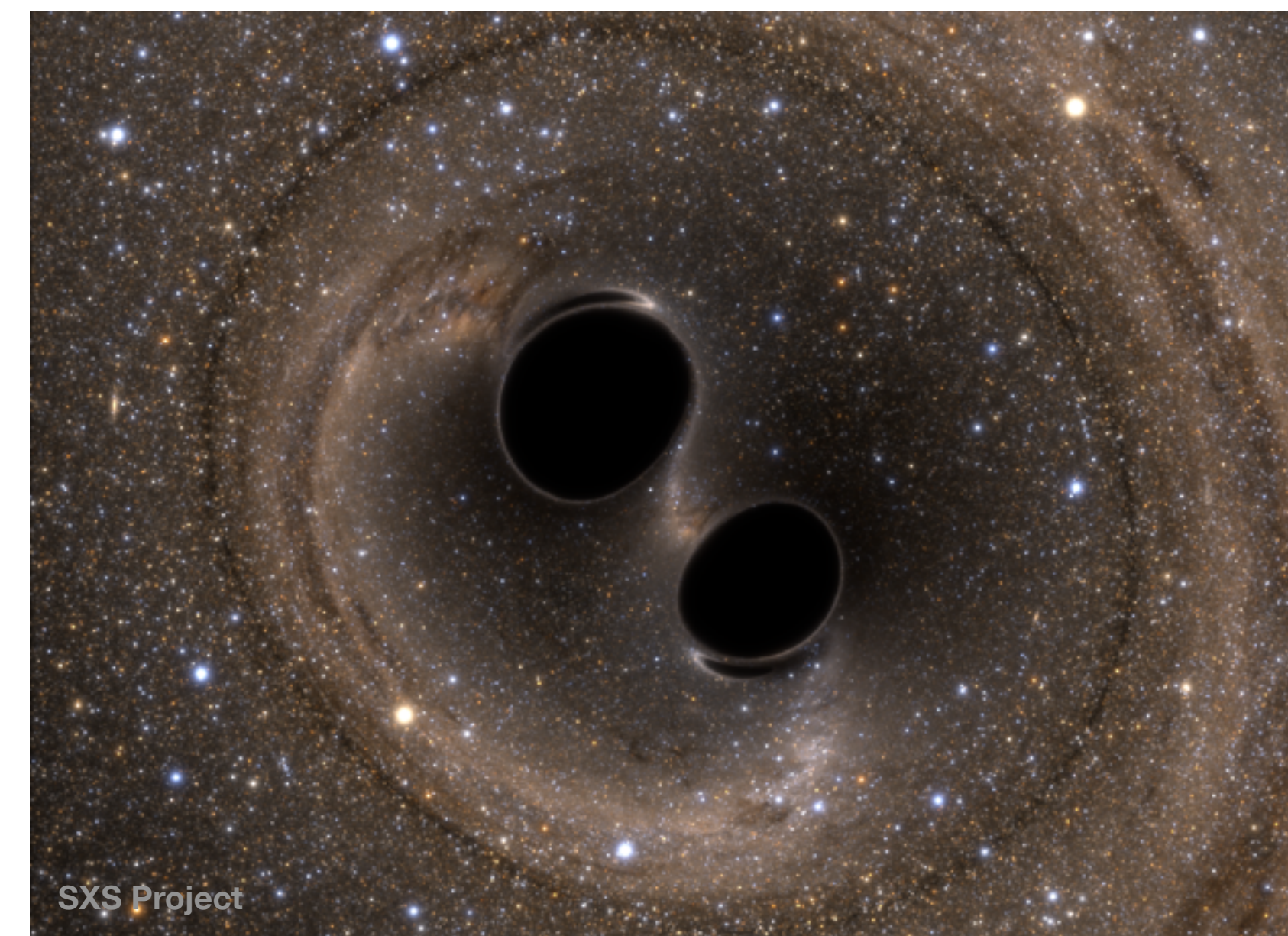


top: artist's rendition of merging white dwarf binary. bottom: recovered localization probability from a search of simulated LISA galactic binary data (Thorpe/Littenberg/Lackeos)

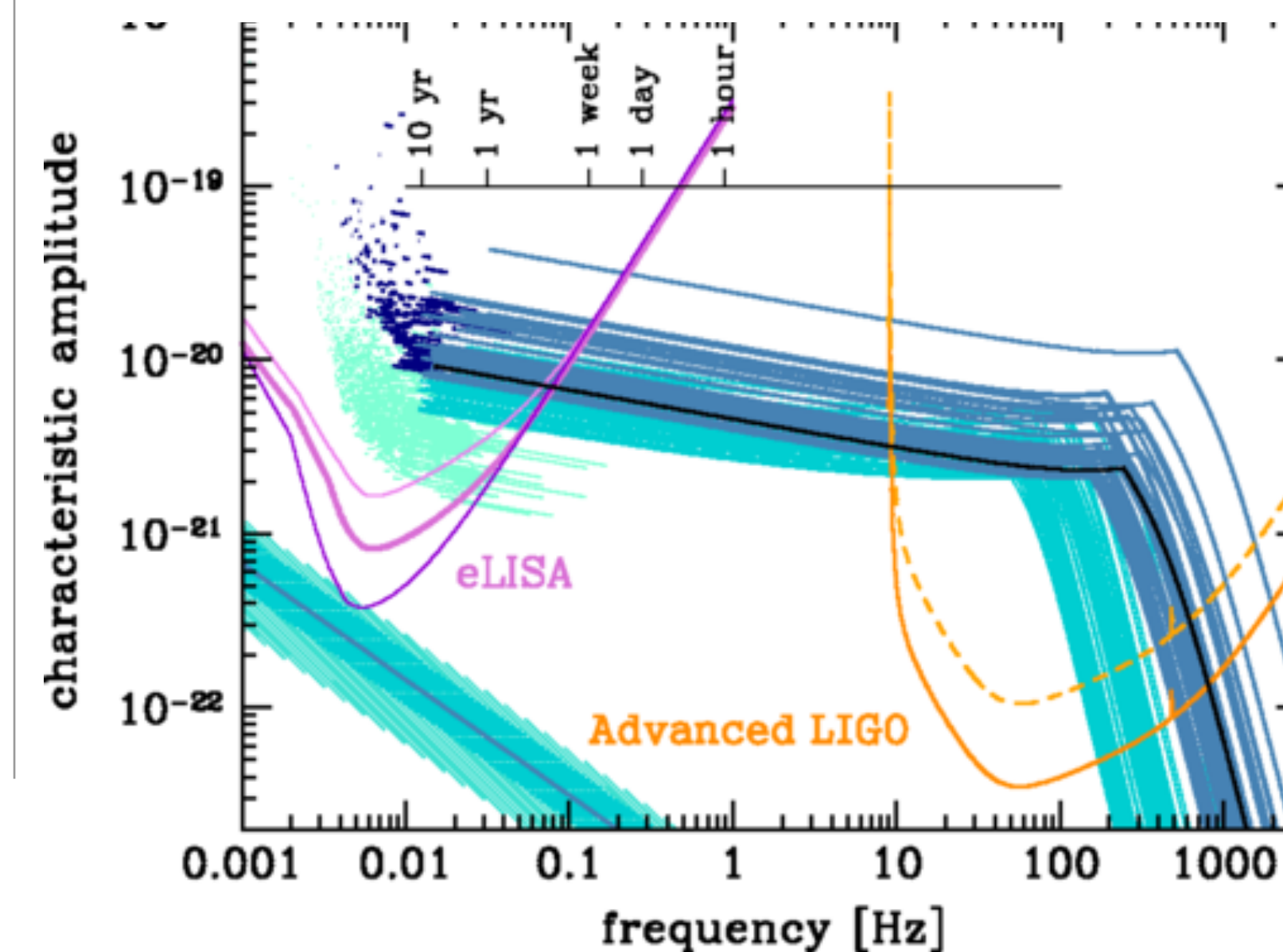


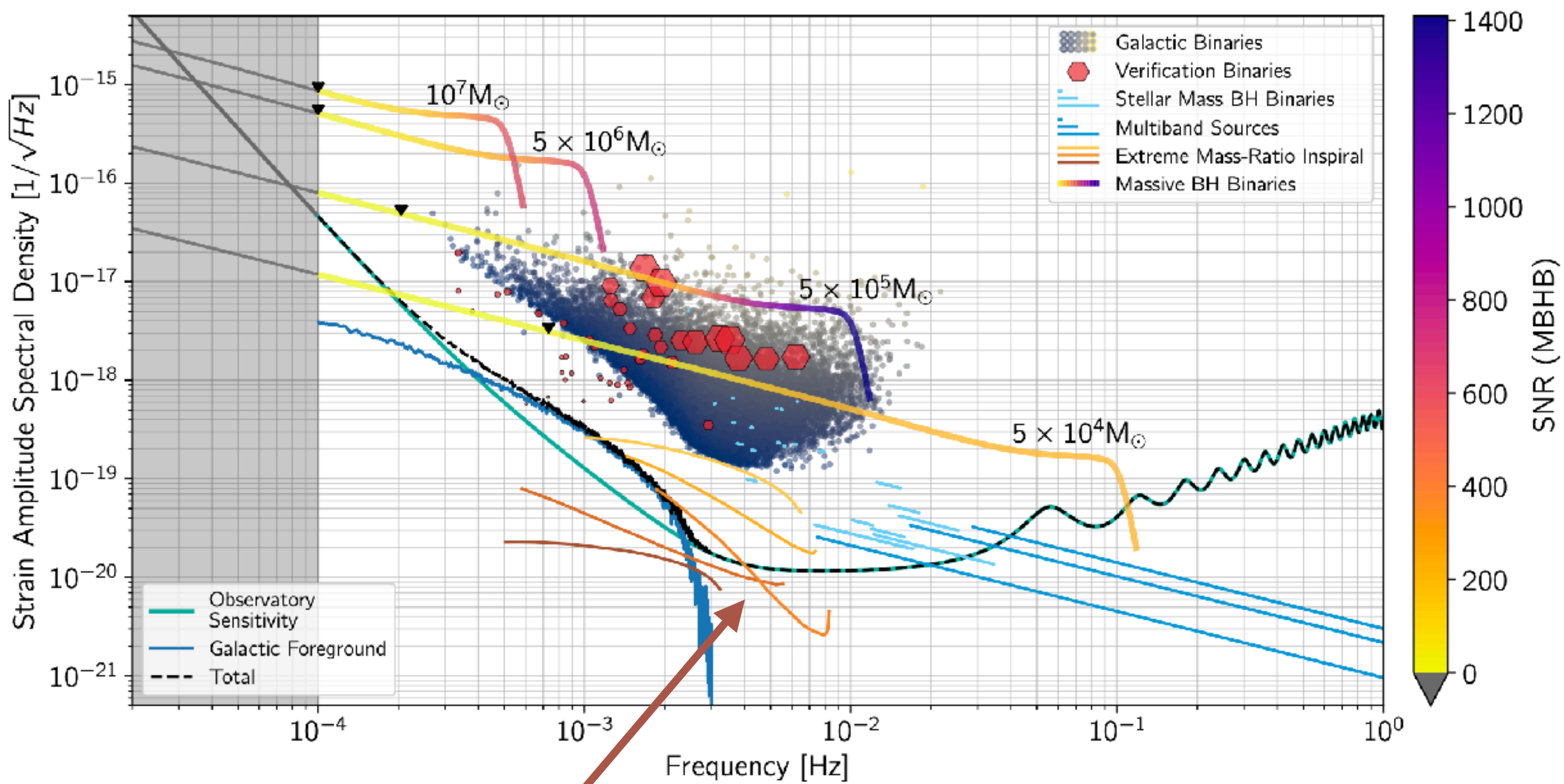


Stellar-scale BH binaries
 — — > multiband GW astronomy

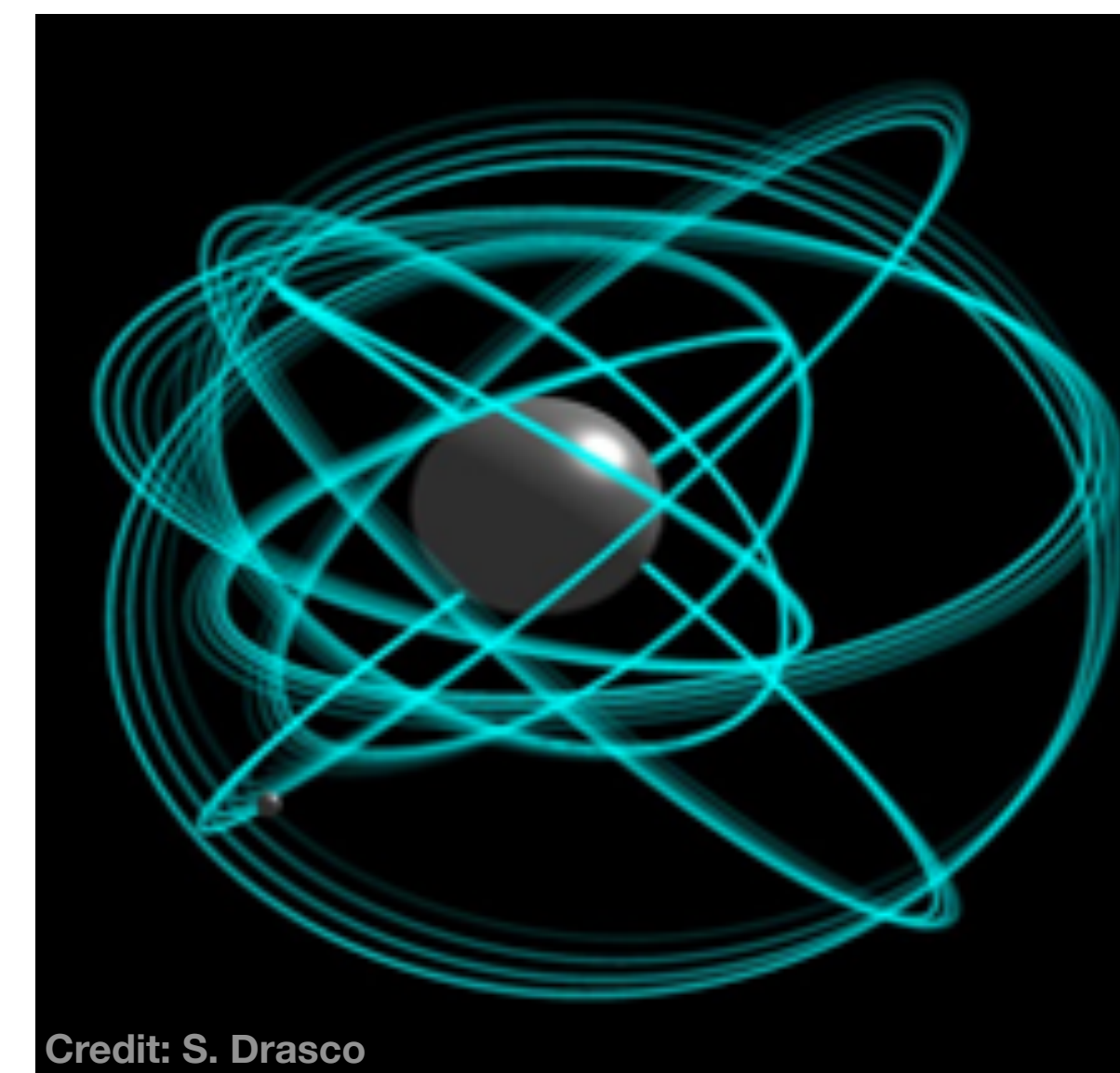


top: visualization of merging black holes. **bottom:** comparison of BH tracks for space-based and terrestrial interferometers.

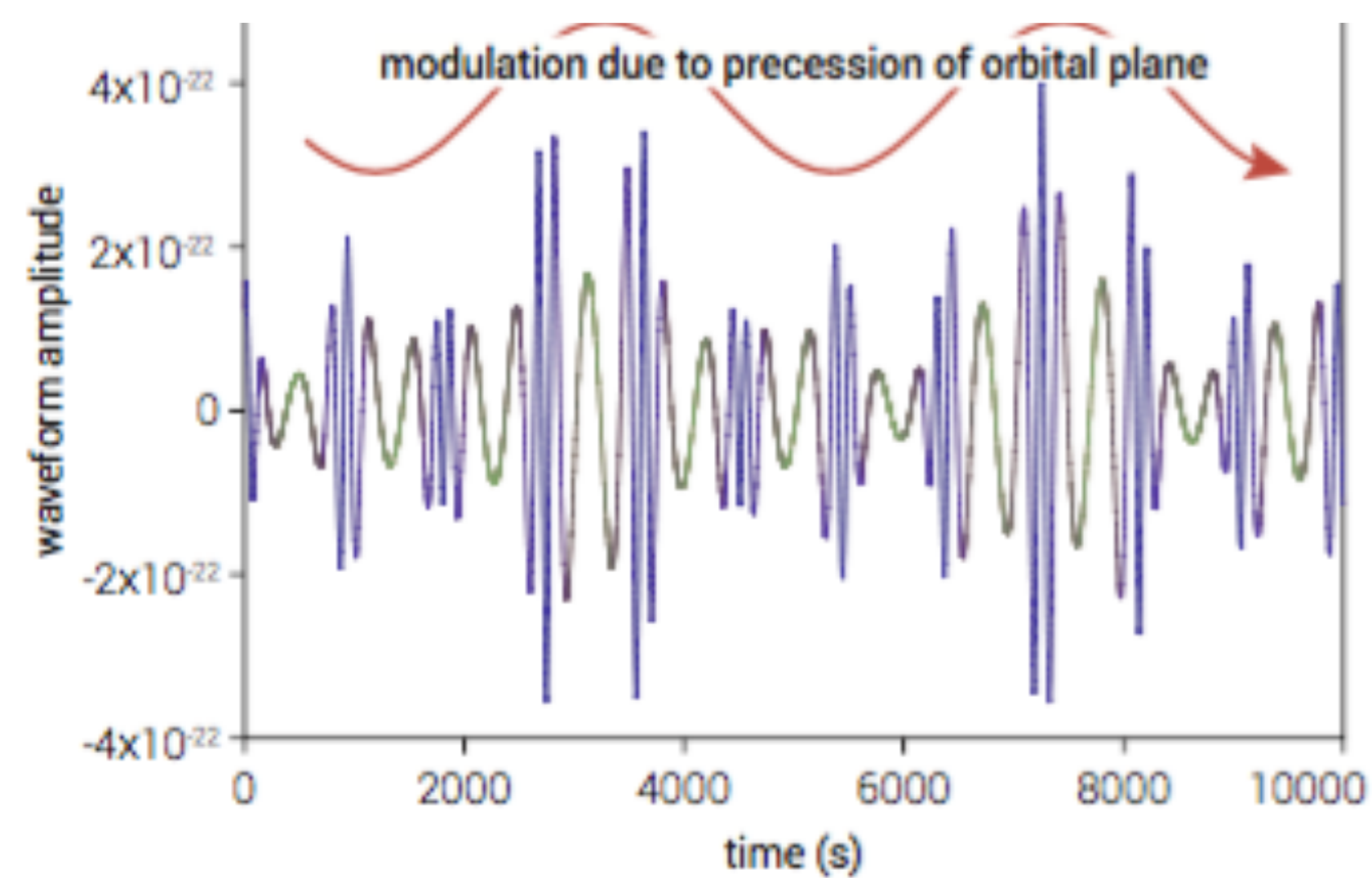




Extreme mass ratio inspirals

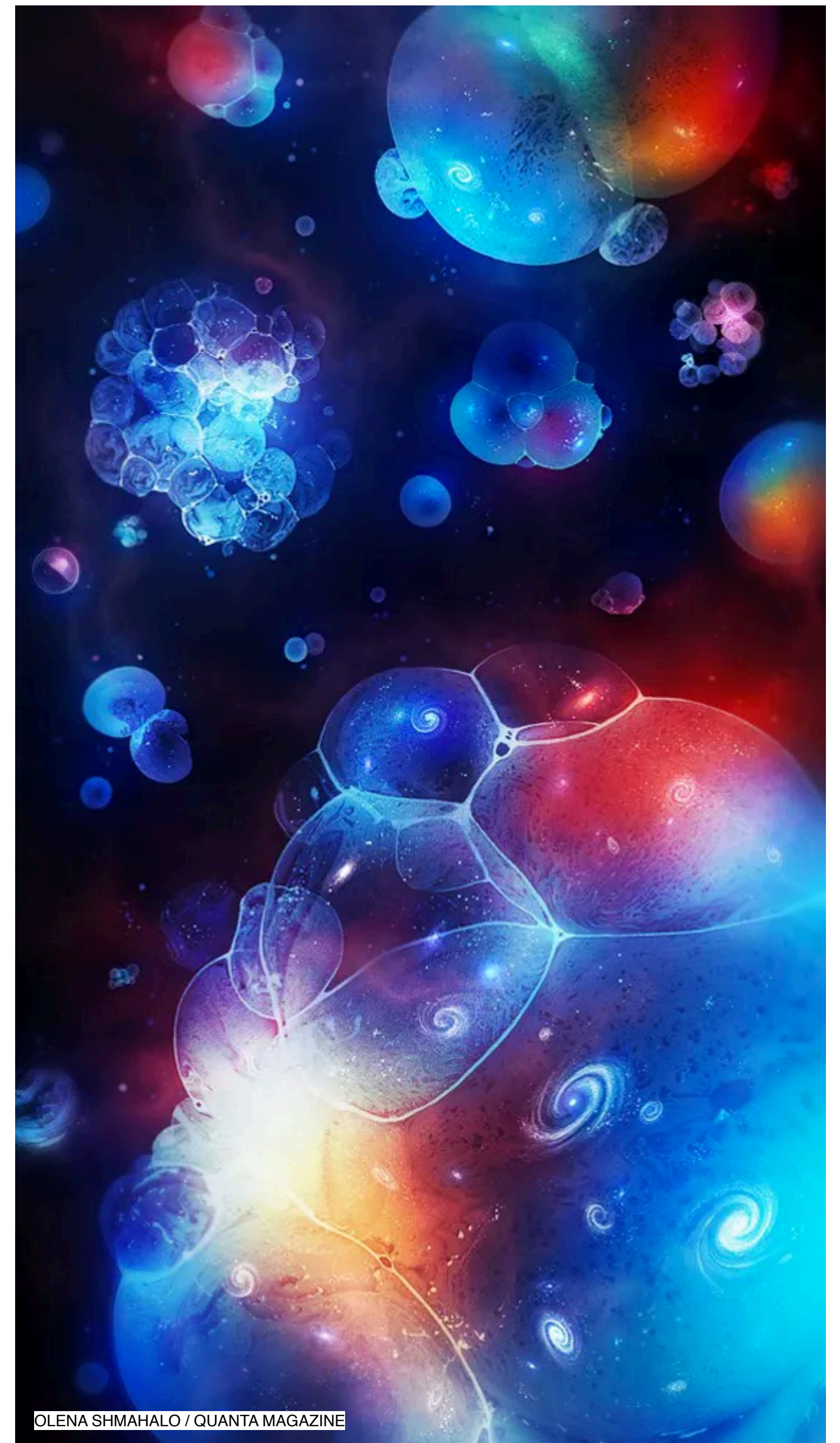


top: visualization of EMRI orbit. **bottom:** representative EMRI waveform showing modulation from extreme precession effects



Backgrounds / Discovery Space

- “Unknowns, both known and unknown”
- Astrophysical
 - Intermediate mass black holes
- Physics
 - Inflationary GWs
 - Cosmic string cusps
 - vacuum transitions

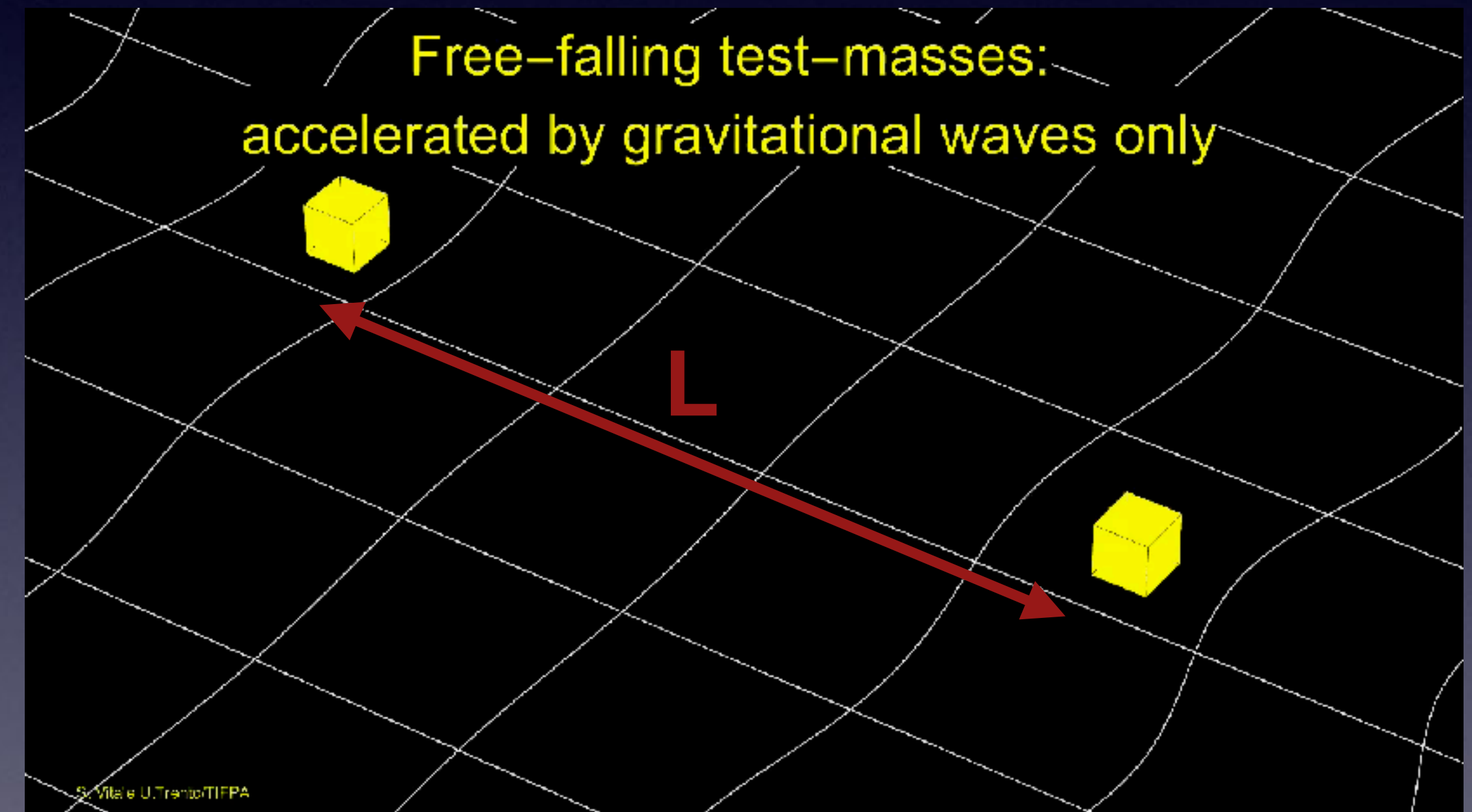


Pause

How to detect GW in MHz
band?: LISA

Basic challenges of GW measurement

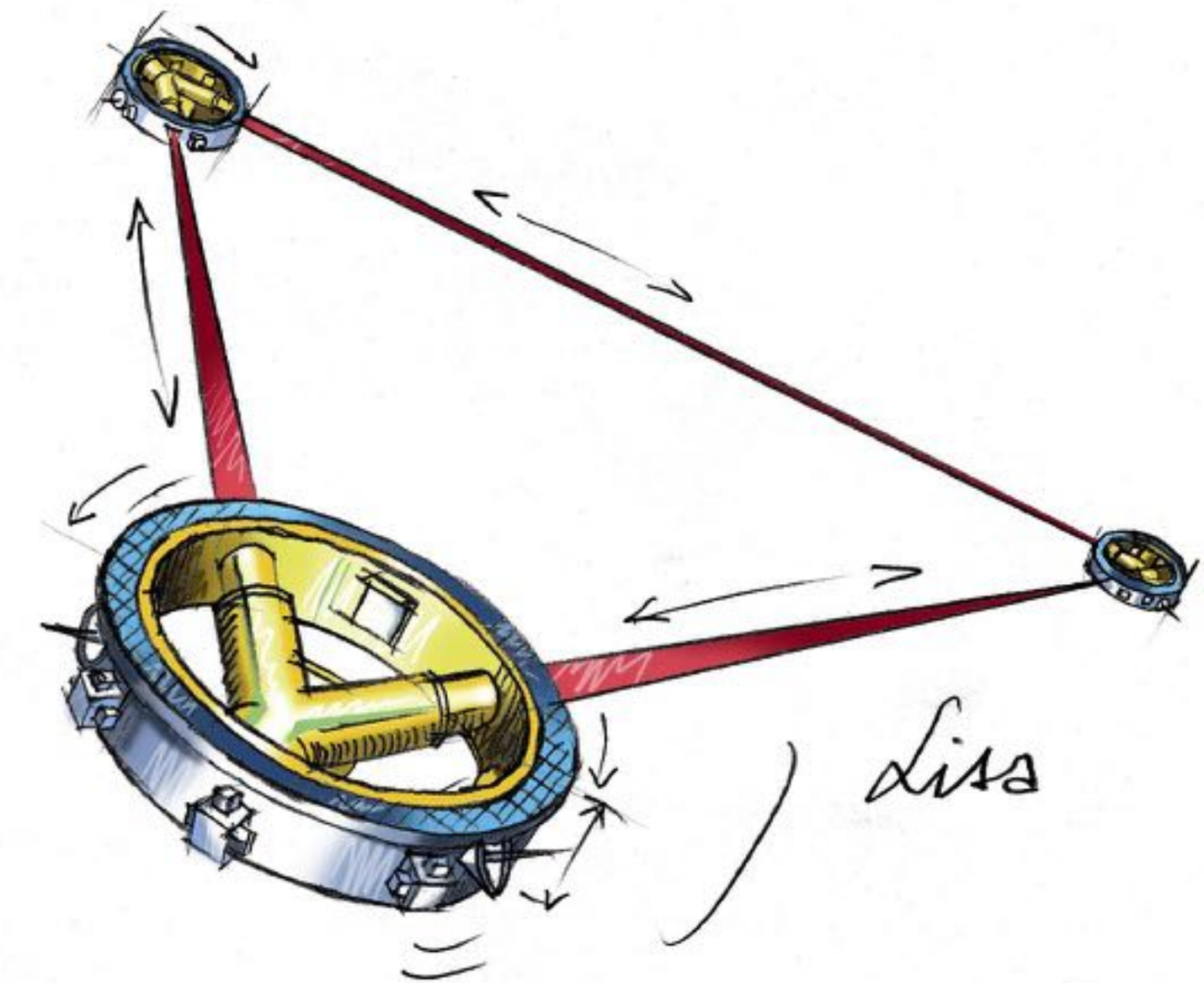
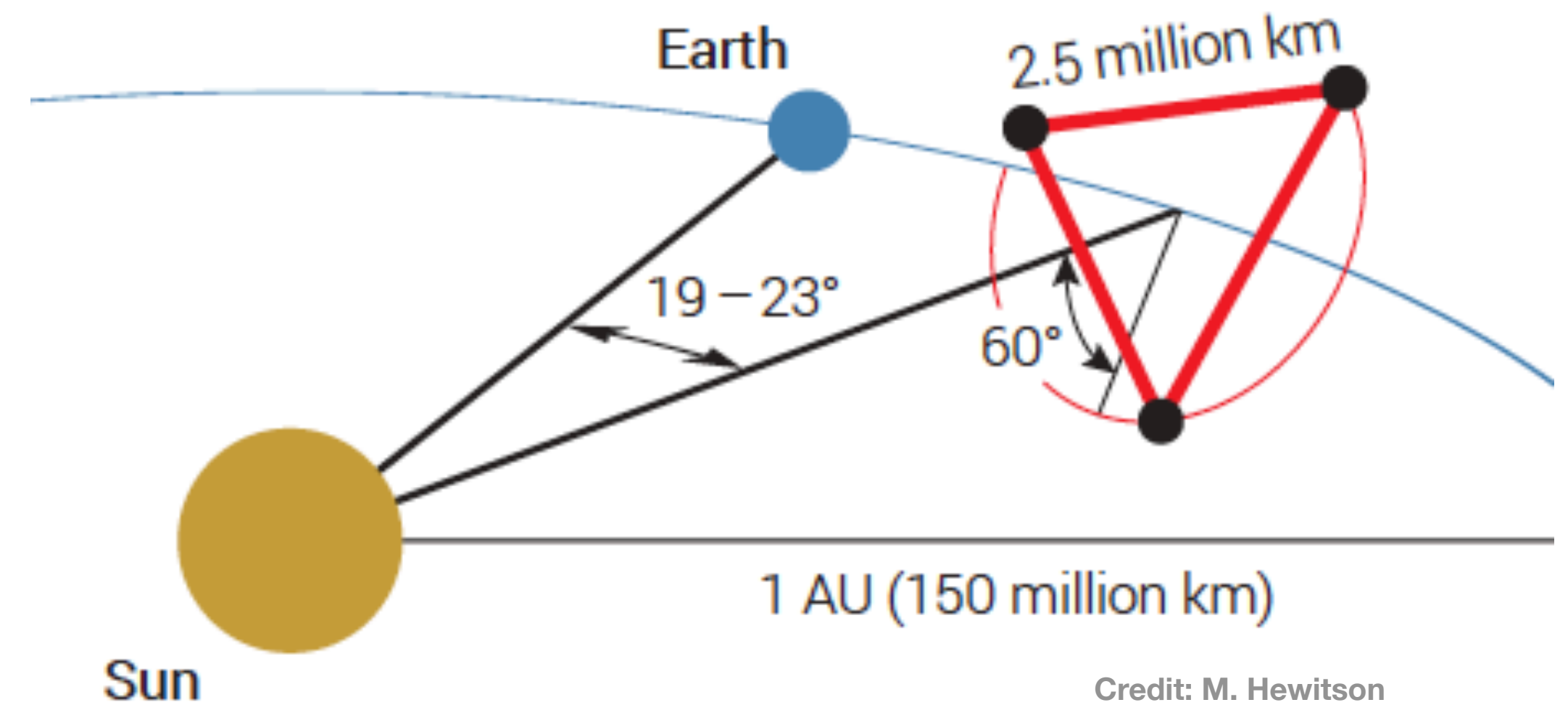
- **Basic objective:**
Precisely measure the relative motion of free-falling masses
 - **Precisely measure:** $\Delta L/L \lesssim 10^{-20}$
 - **Free-falling:** minimize non-gravitational forces
 - **LISA:**
 - $L \sim 2.5 \times 10^9$ m
 - $\Delta L \sim 10^{-11}$ m
 - $a \sim 3 \times 10^{-15}$ m/s²
- Yay space!



The LISA concept

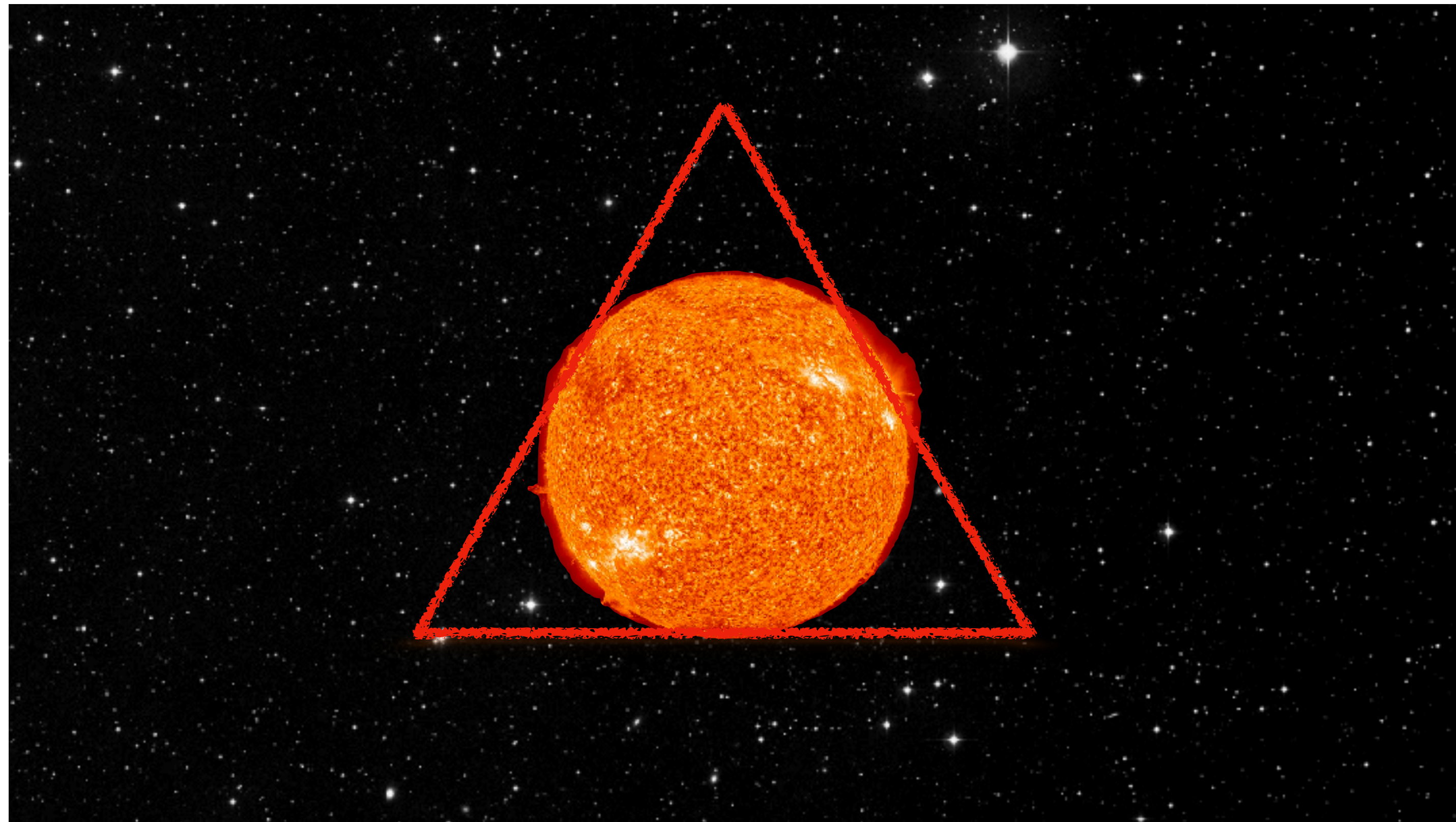
Decades of Development

- million-kilometer scale triangular observatory
- drag-free test masses as inertial references
- laser interferometry monitors distances for picometer-scale GW perturbations
- matched filtering used to disentangle thousands of overlapping sources

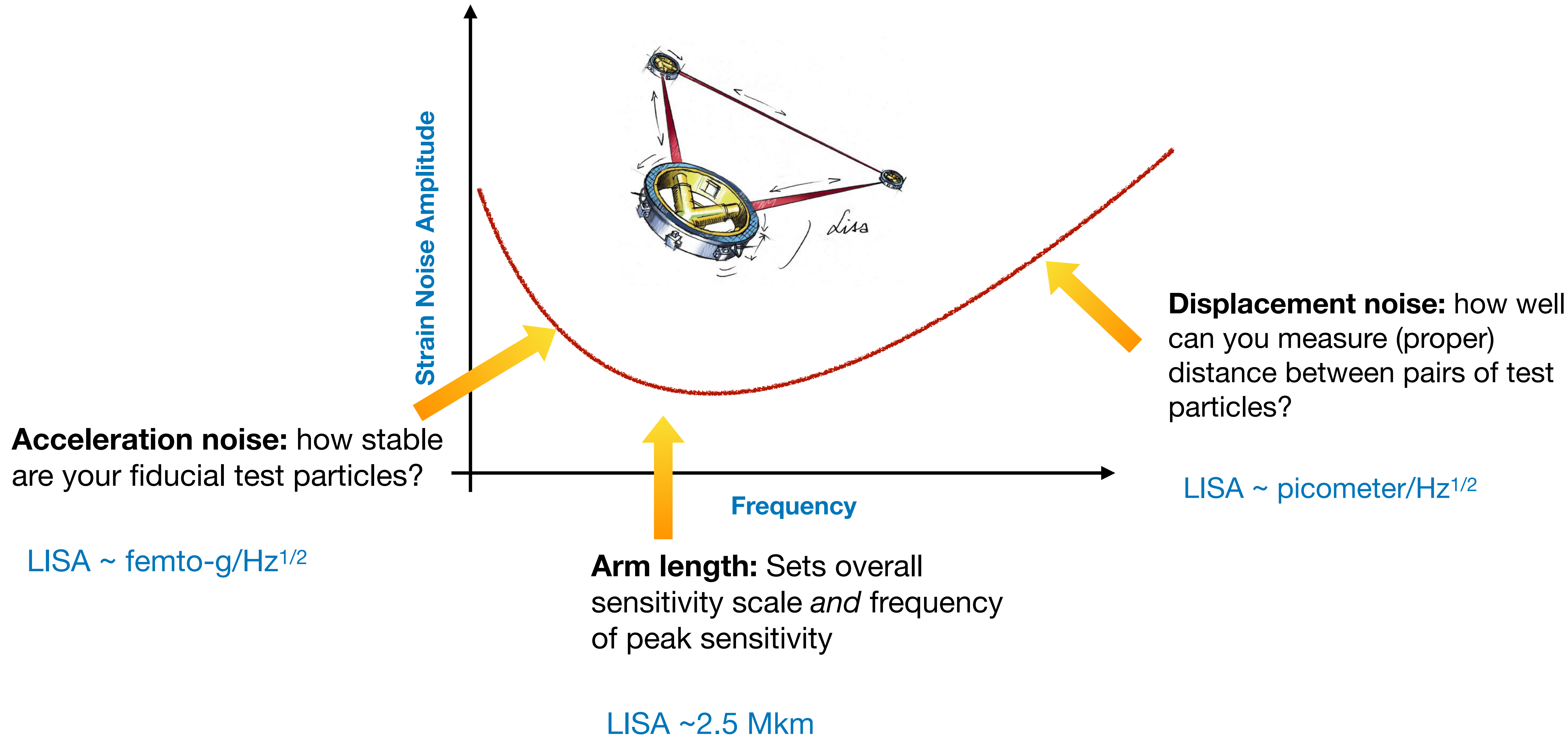


LISA is huge!

Arguably largest instrument ever conceived



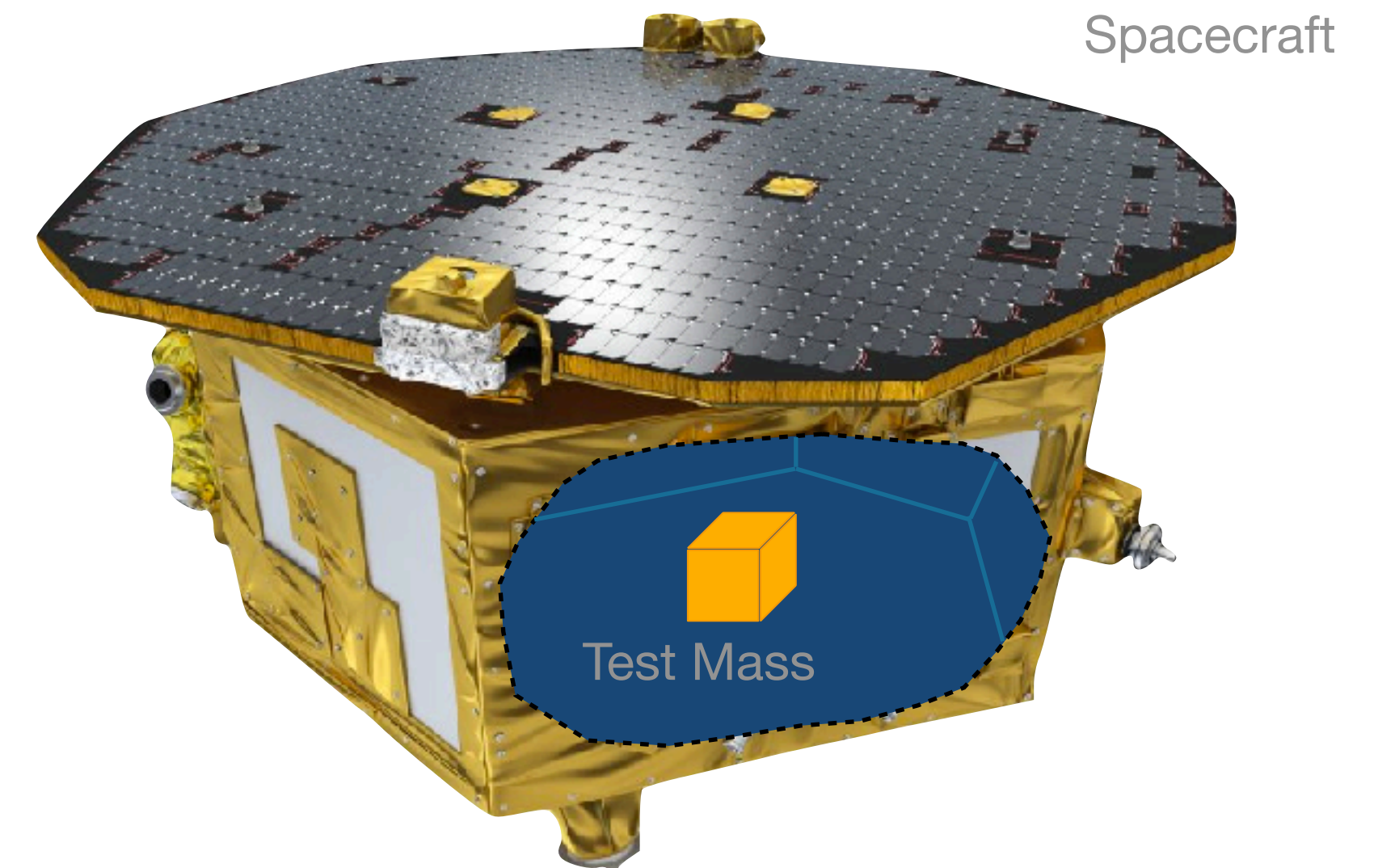
Fundamentals of GW Interferometers



Acceleration noise

‘drag-free’ flight

- Test mass placed inside hollow cavity* within spacecraft
- sensors monitor relative position of test mass and spacecraft



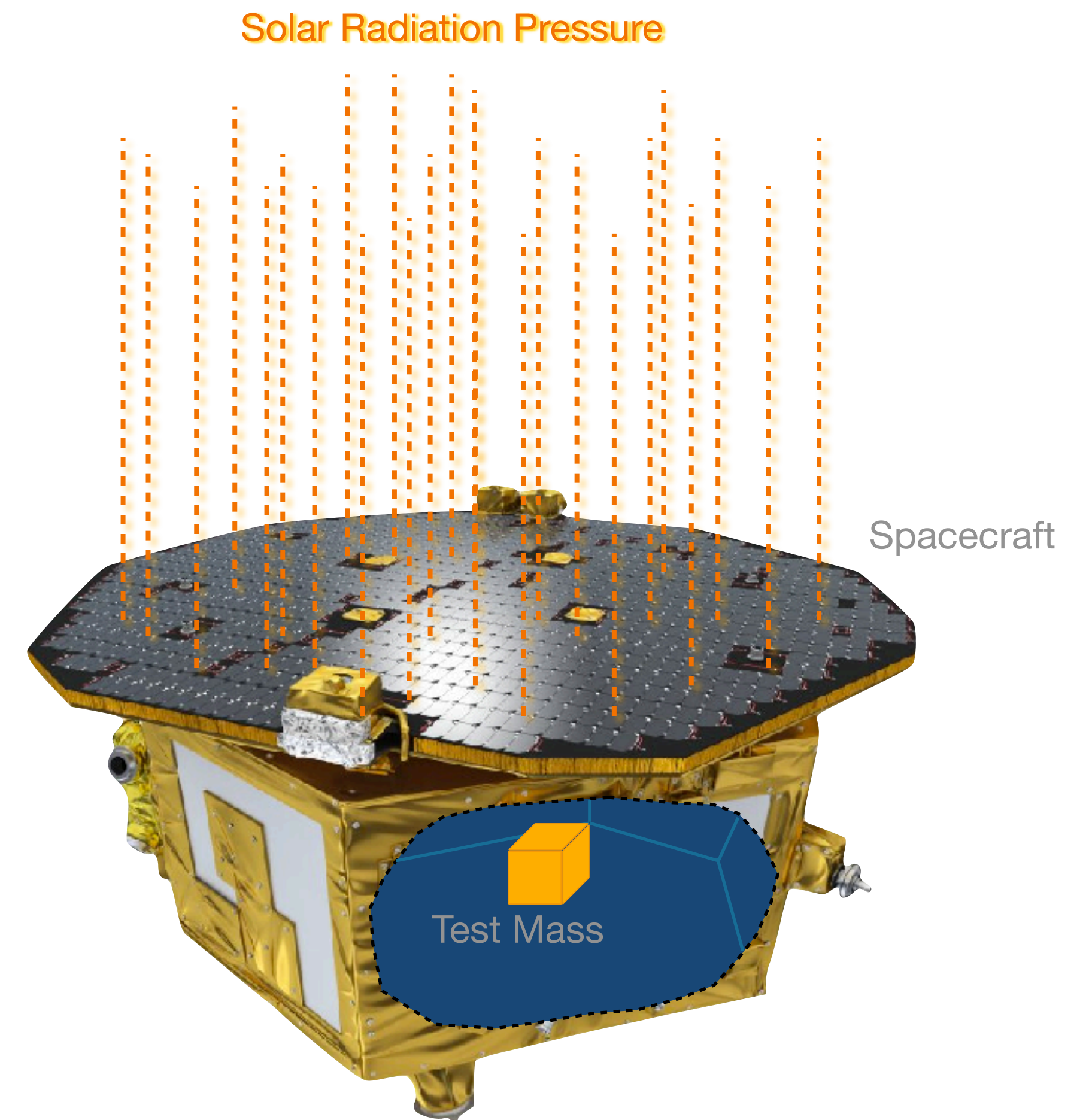
LPF Rendering: ESA Medialab

* cavity consists of a few mm gaps on all sides of the test mass

Acceleration noise

‘drag-free’ flight

- External disturbance (e.g. solar radiation pressure) causes spacecraft to drift towards test mass

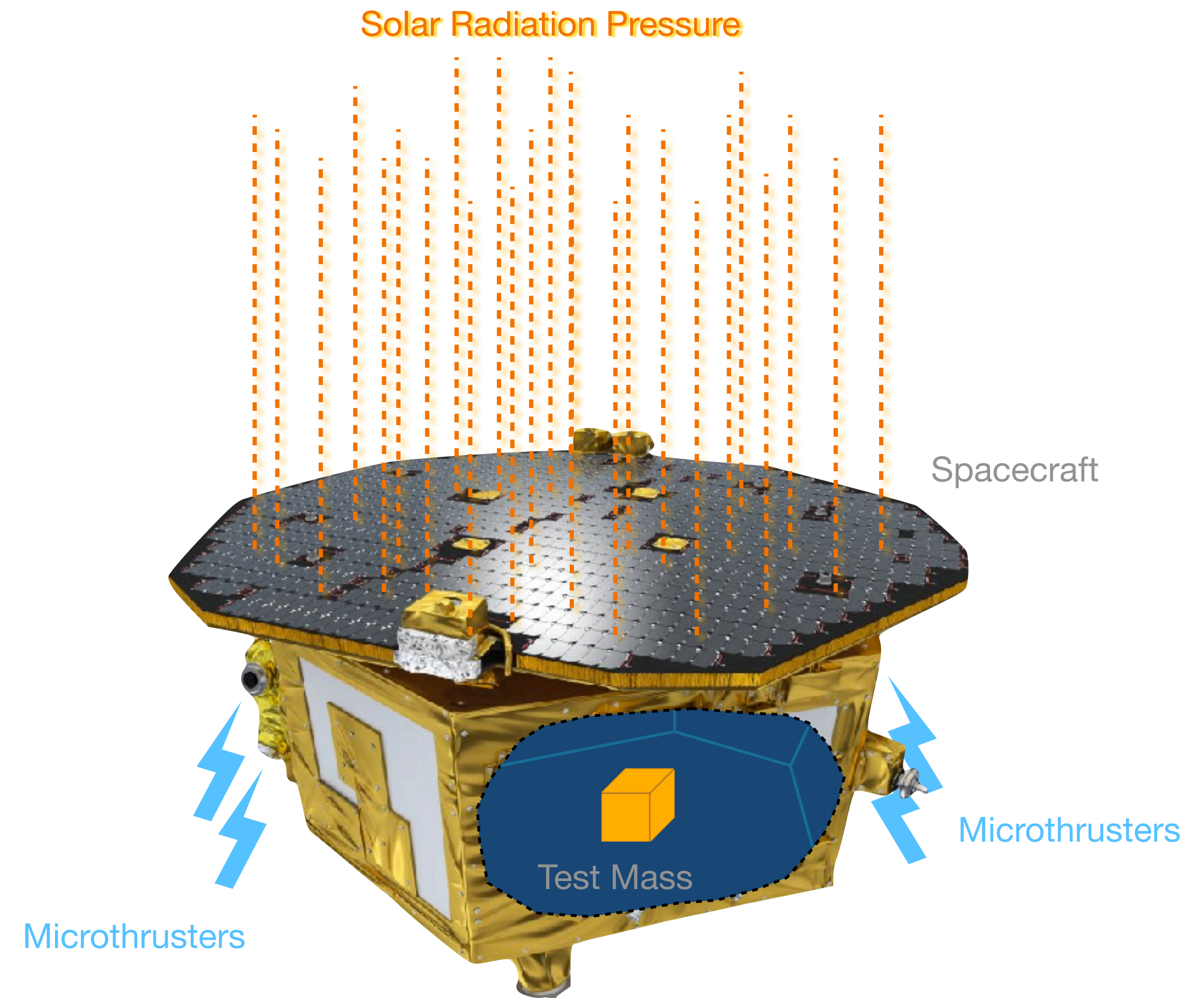


LPF Rendering: ESA Medialab

Acceleration noise

‘drag-free’ flight

- Control system fires micro thrusters to counteract disturbance.
- Test mass remains centered within cavity

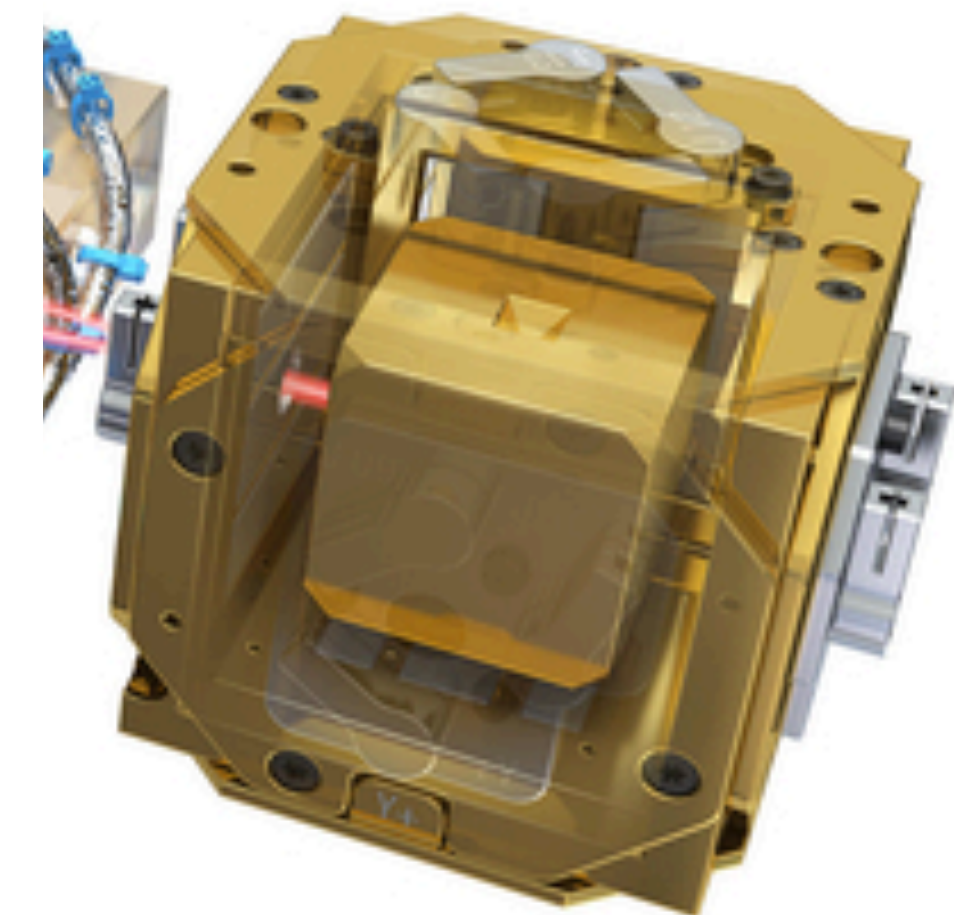
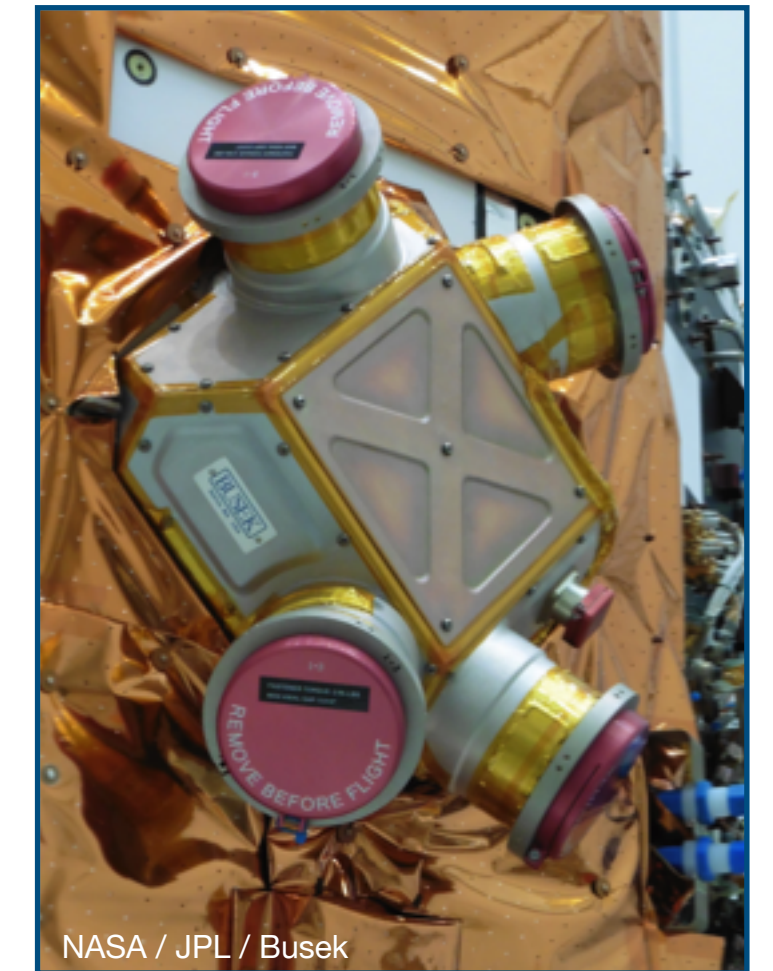
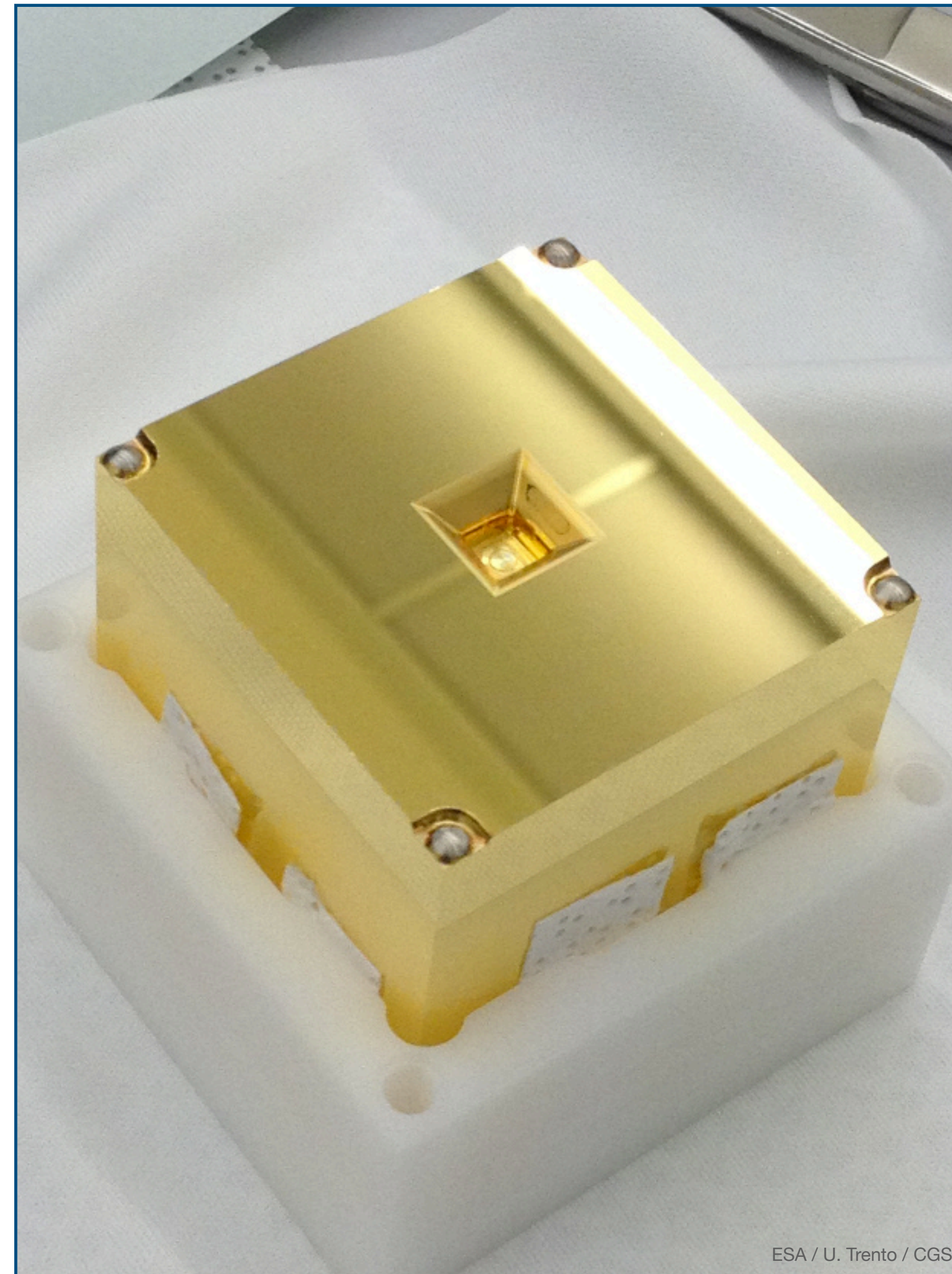


LPF Rendering: ESA Medialab

LISA Pathfinder

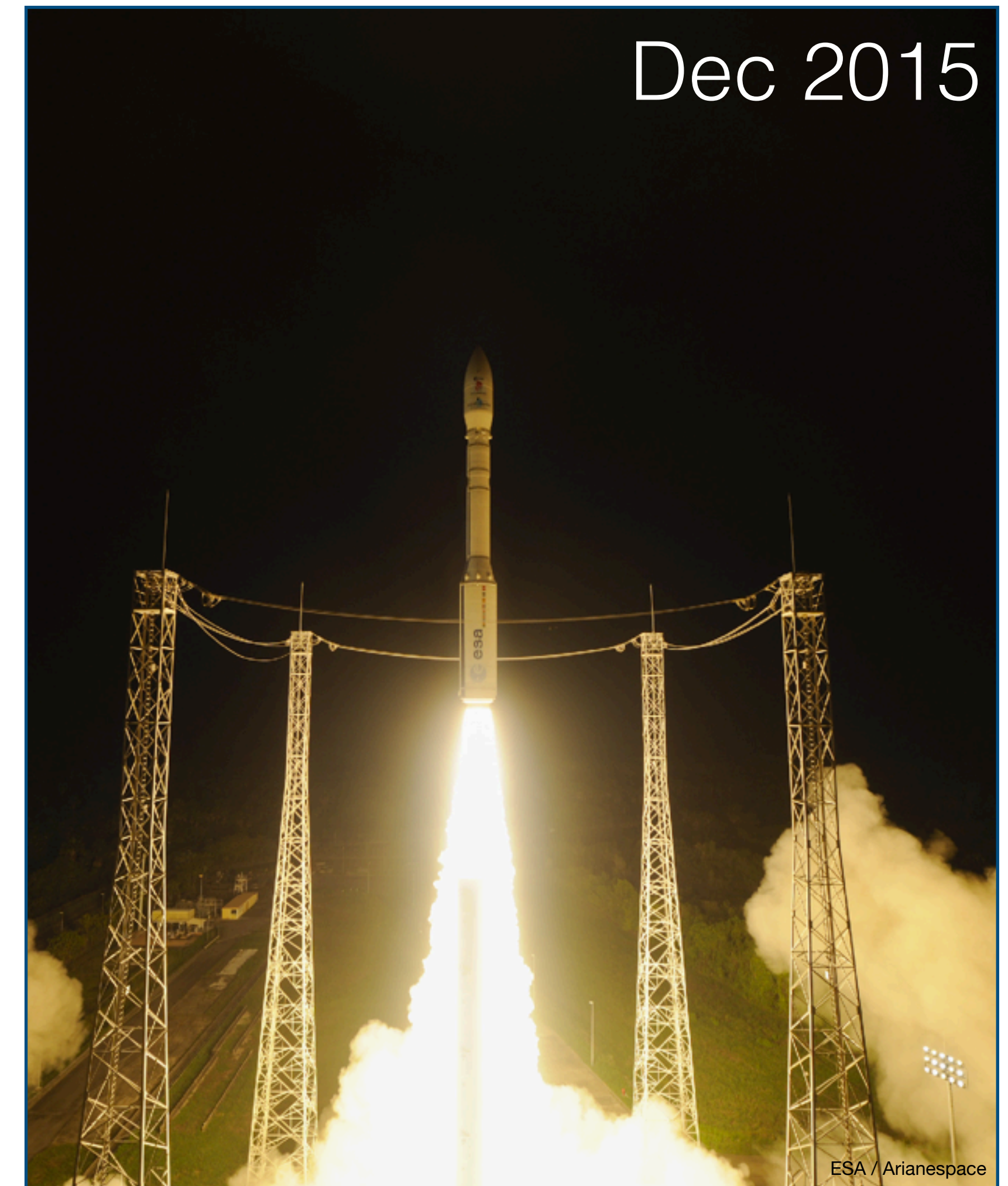
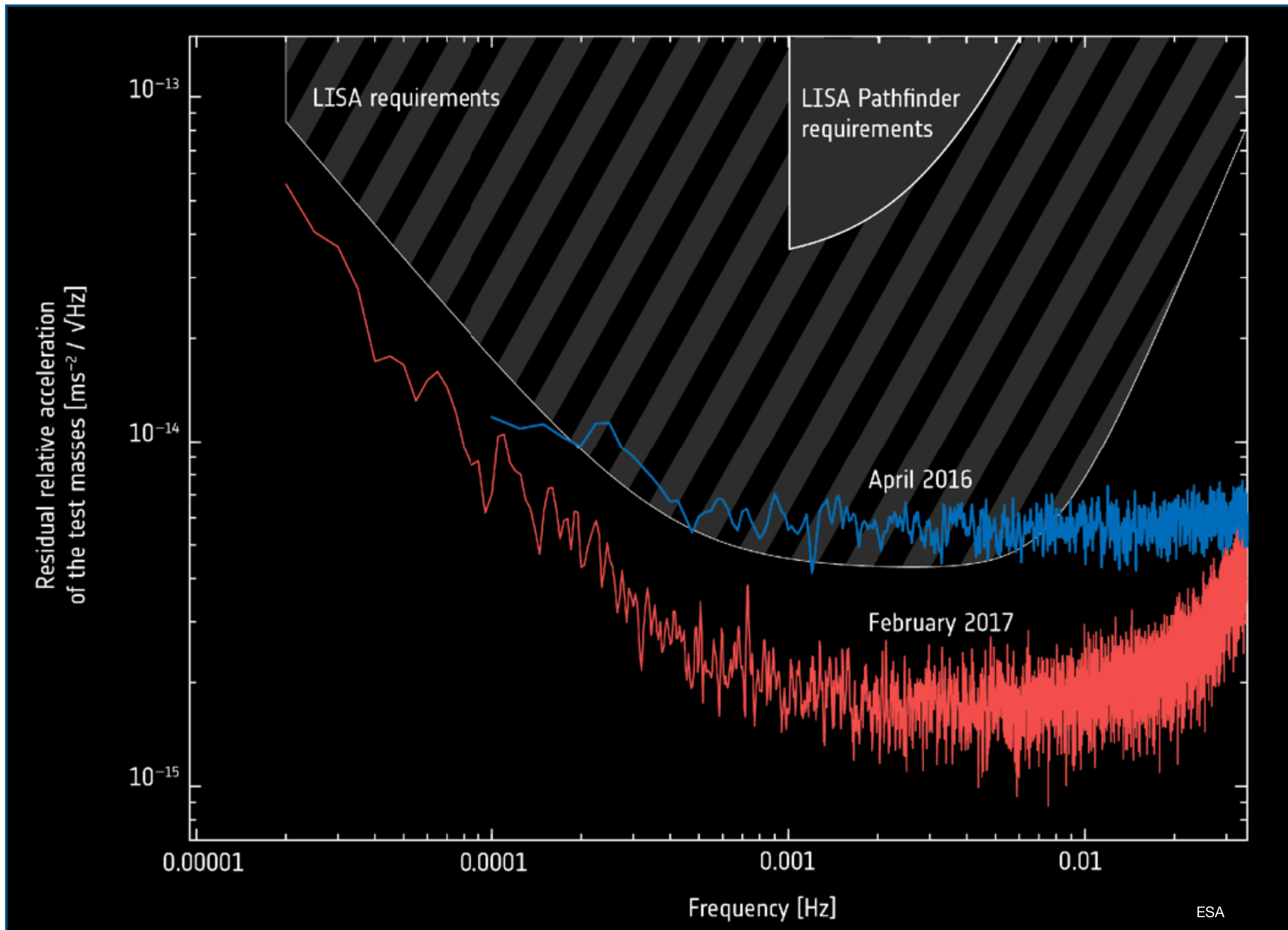
Demonstration of drag-free flight

- ESA-led technology demonstrator
- Single LISA arm in one spacecraft
- (Most of) the noise, none of the GW signal!



LISA Pathfinder Results

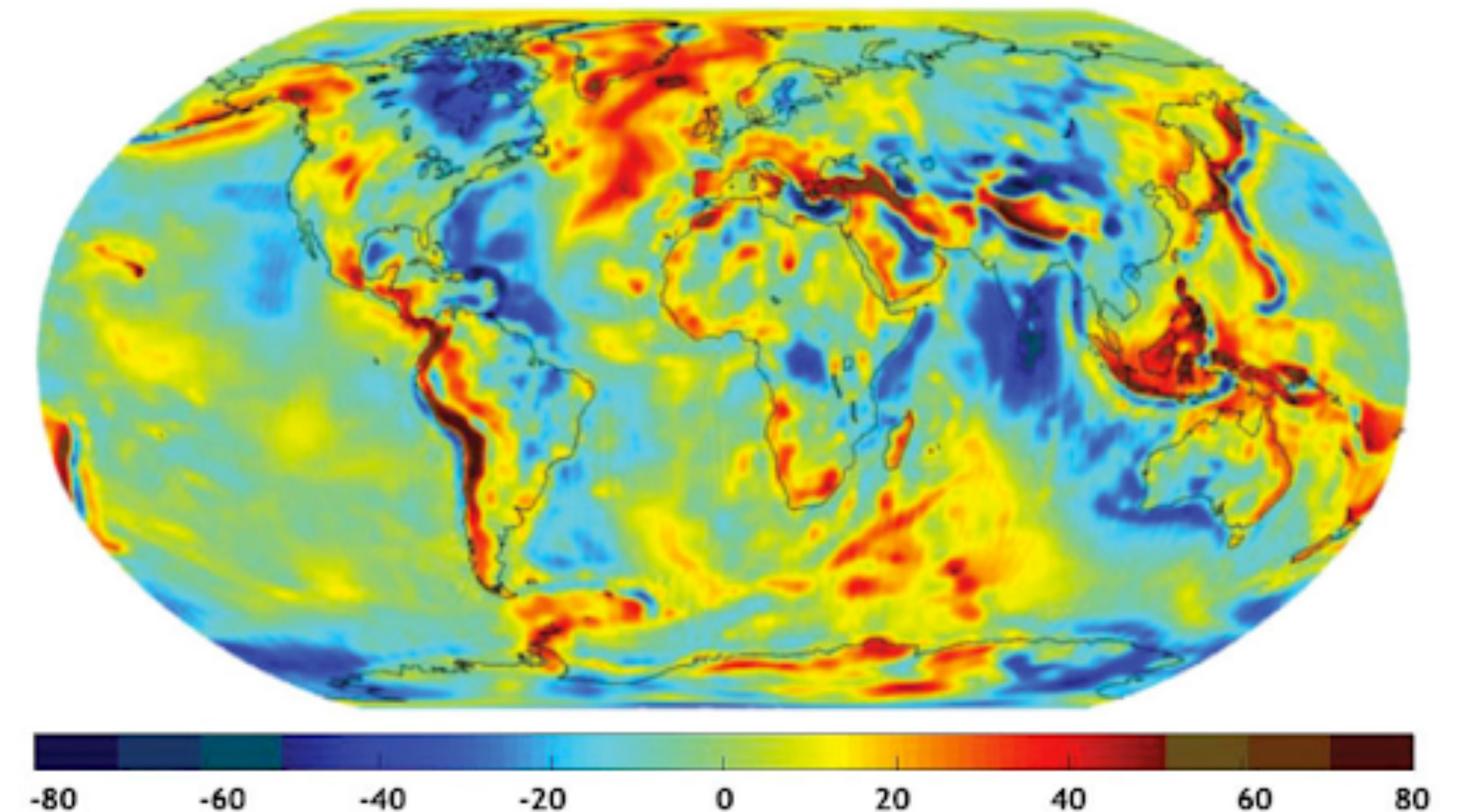
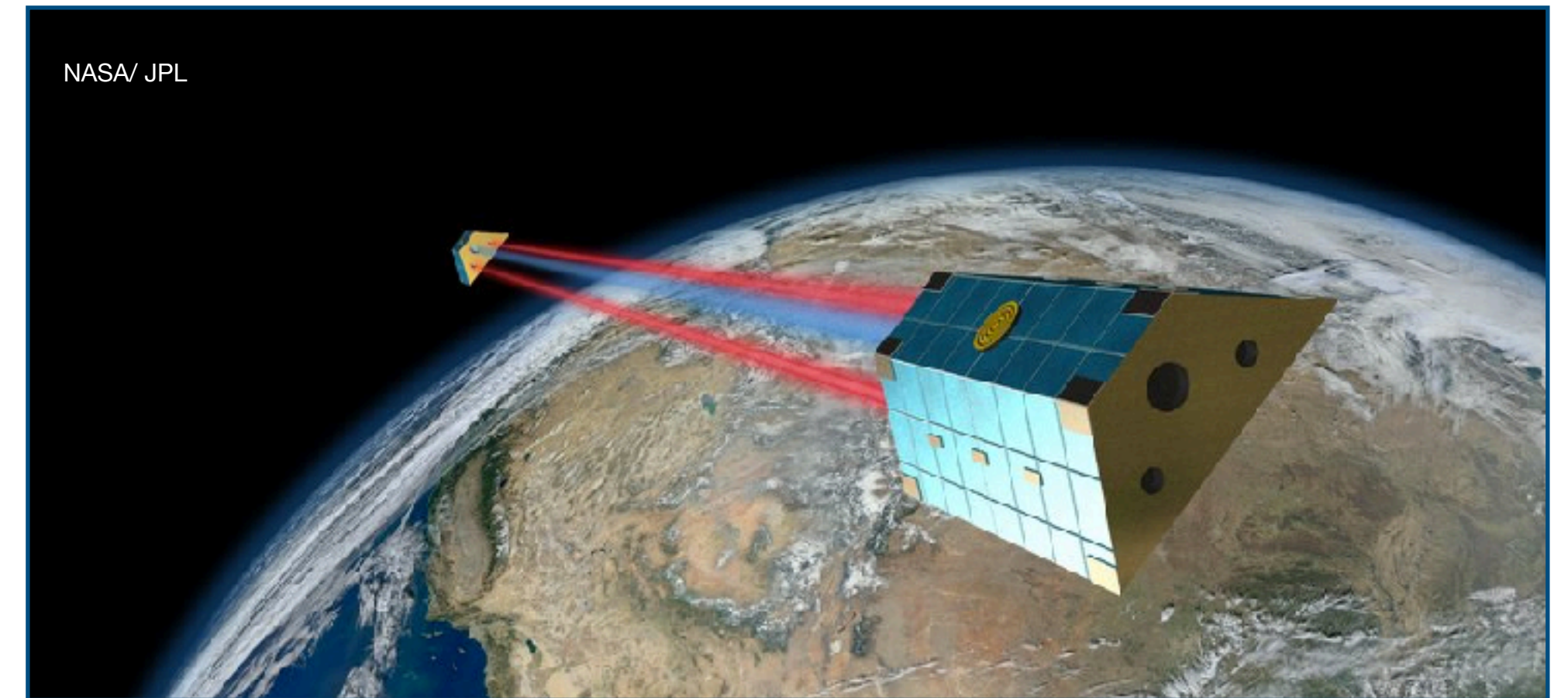
Far exceed Pathfinder goals, validate performance at LISA levels



GRACE-FO LRI

Interferometry Demonstrator

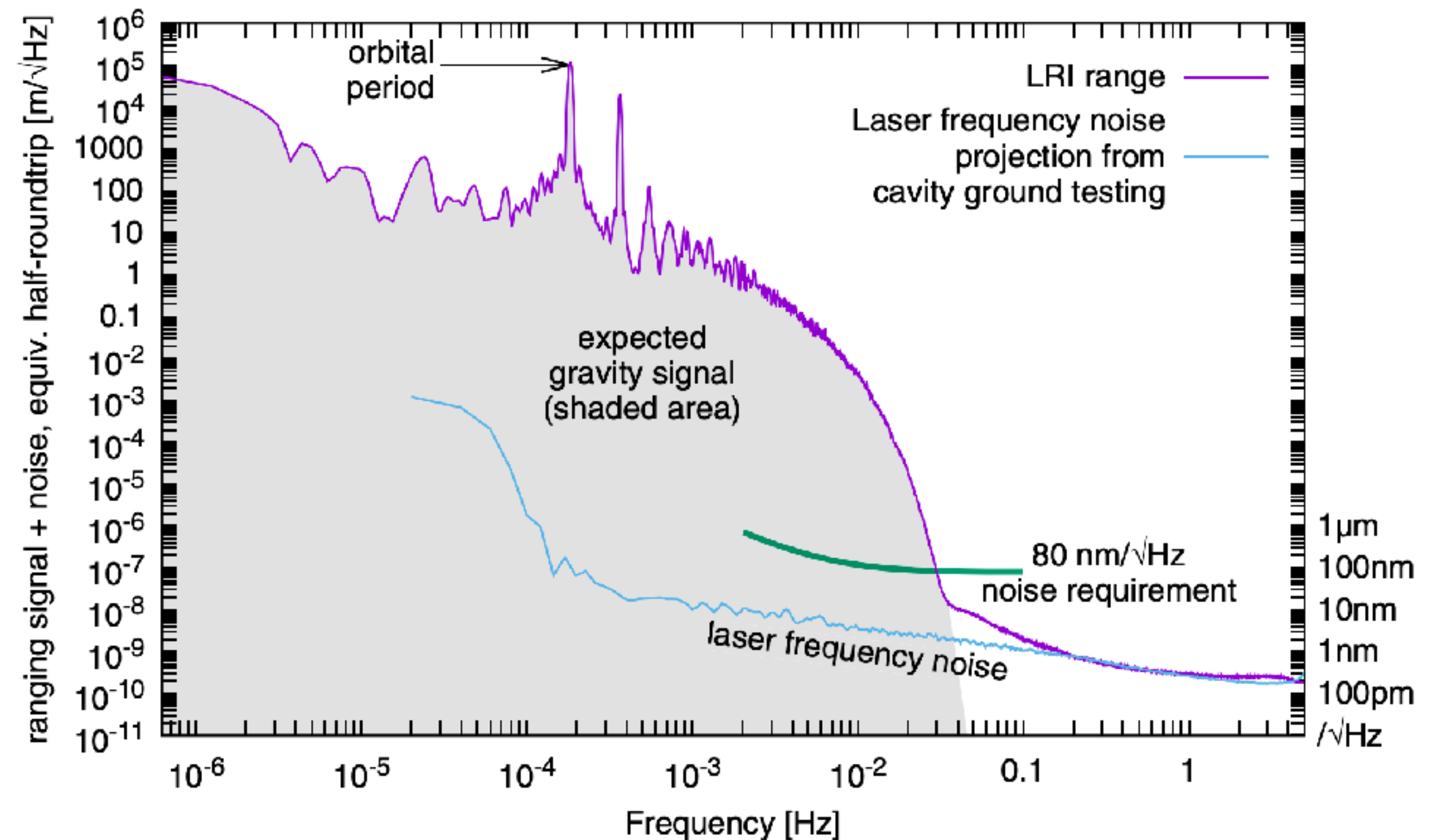
- Replacement for GRACE geodesy mission
- 2 spacecraft in low-Earth ($\sim 500\text{km}$) orbit, separated by 220km
- Displacements measure Earth's gravitational field
- Laser link, based on LISA technology, supplements primary microwave link



GRACE-FO LRI Results

A LISA interferometry demo

- Earth signal is *much* larger than LISA's gravitational wave signal - and always on
- Only one arm - precision limited by laser stability
- Relevant components & experience
 - similar laser
 - similar receiver
 - operations experience

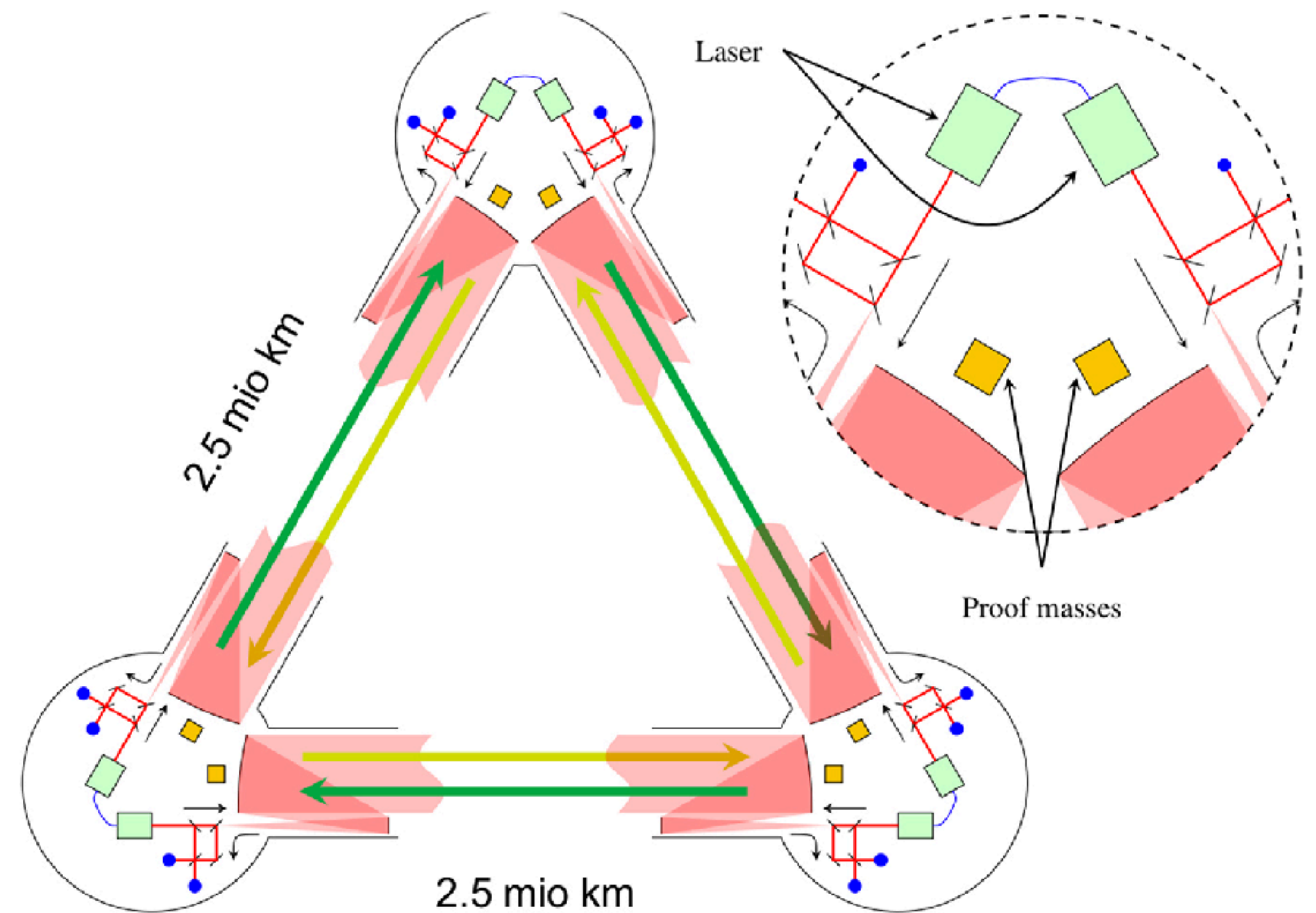


In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer

Phys. Rev. Lett. **123**, 031101

LISA Displacement Noise

- Heterodyne interferometry with $\sim 1\mu\text{m}$ light
- Six “one-way” measurements between pairs of spacecraft
- Telescopes reduce diffraction loss, still only receive about 10^{-10} of the transmitted power.
- Passively stable orbits maintain arm lengths to $\sim 0.5\%$ (10^5 km)
- On ground “Time Delay Interferometry” processing surpasses residual laser frequency noise.



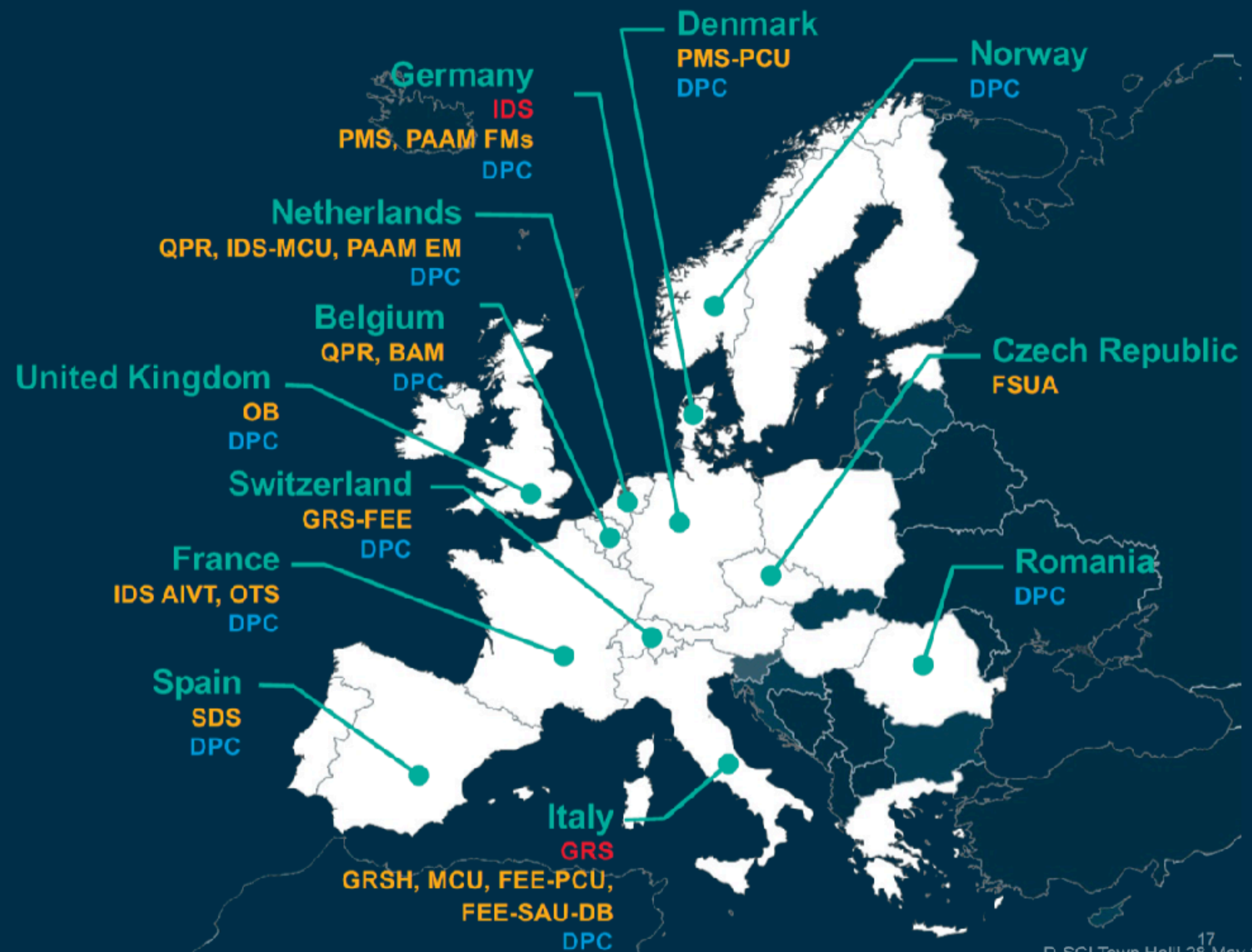
Schematic of the LISA interferometric measurement (T. Schuldt)

Pause

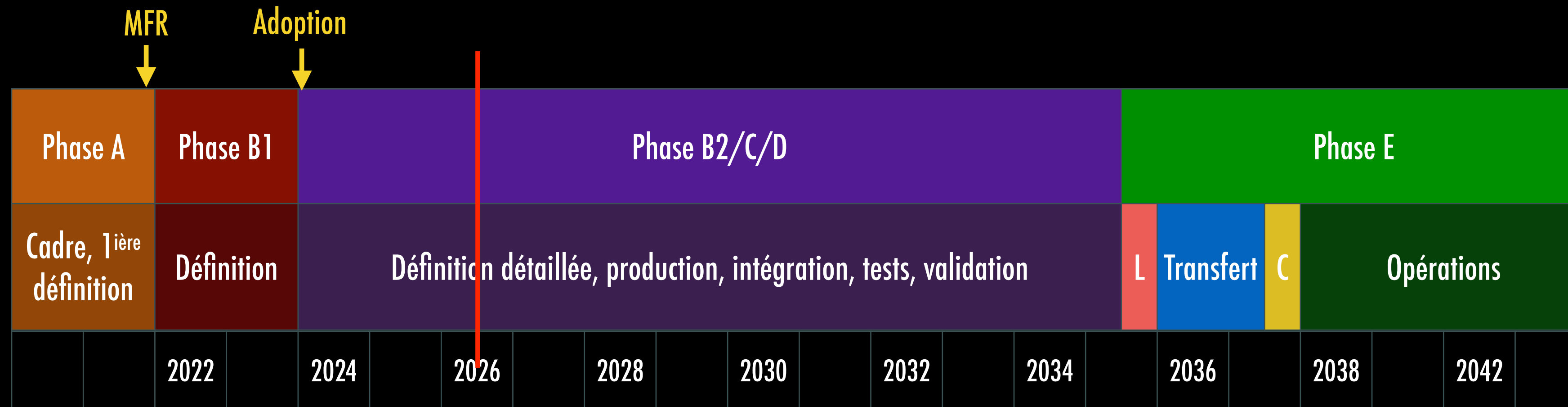
LISA Mission Status



Contributions as per MLA, MoU
IDS/GRS System Responsibility
Hardware contributions
Ground Segment, Science Data Processing Contribution

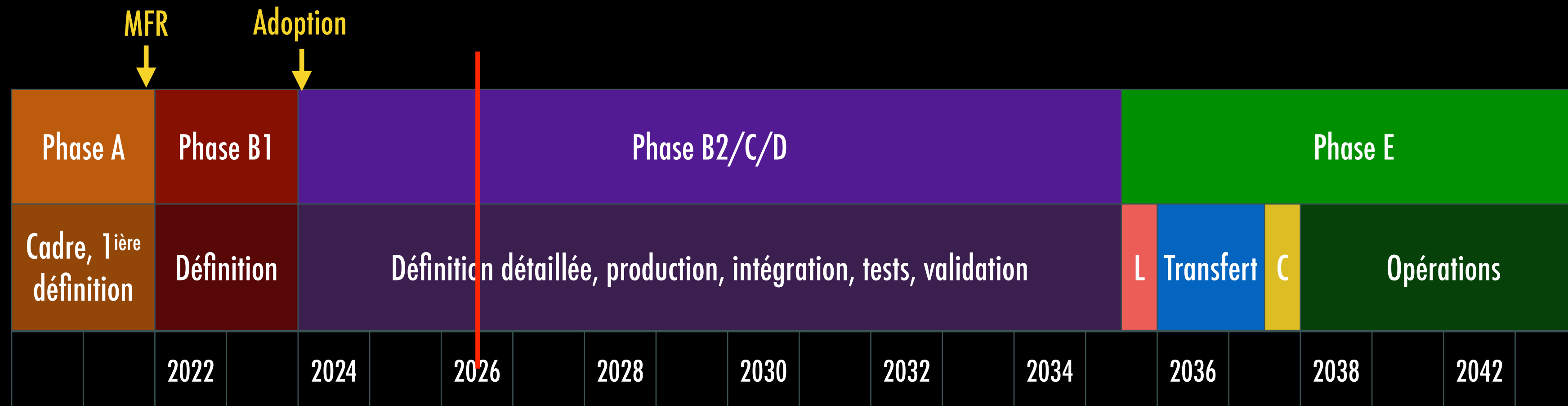
D-SCI Town Hall | 17
28 May 2024

The roadmap to LISA



- ▶ 1970s-80s: Basic concept development that became LISA
- ▶ 1993: First proposal to ESA/NASA
- ▶ **20/06/2017: mission approved** by ESA after the success of LISA Pathfinder and the first detection of GWs.
- ▶ **End 2021: success** of the ESA **Mission Formulation Review**
- ▶ **25/01/2024: success** of the **Mission Adoption Review** and **adoption by ESA: design validated** and we have the **resources to build the instrument**
- ▶ 2024 **LISA Science Team** in place
- ▶ Long building phase of multiple MOSAs (6 flight models) + spacecrafts + data processing sys
- ▶ **Launch 2035**
- ▶ 1.5 years of orbital transfer
- ▶ **4.5 years of nominal mission** + 6.5 years of possible extension

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Some challenges of LISA data processing

Challenges of LISA data processing

- **Instrumental noise:**

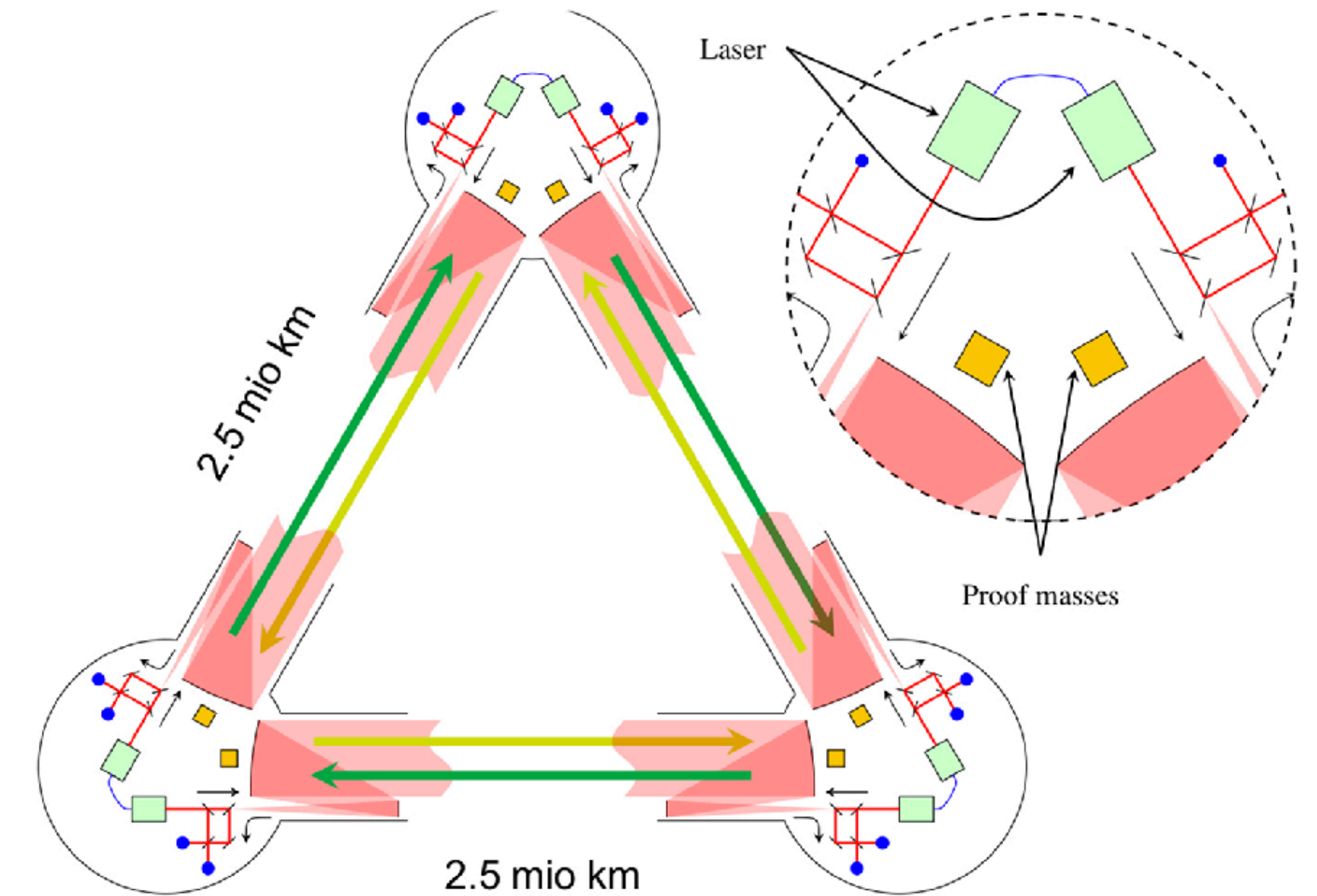
- Must first reduce dominant (laser) noise before data is useful → (Time Delay Interferometry)
- No repointing or second instrument for noise comparison:
 - reliant on well-modeled Bayesian inference

- **Science analysis:**

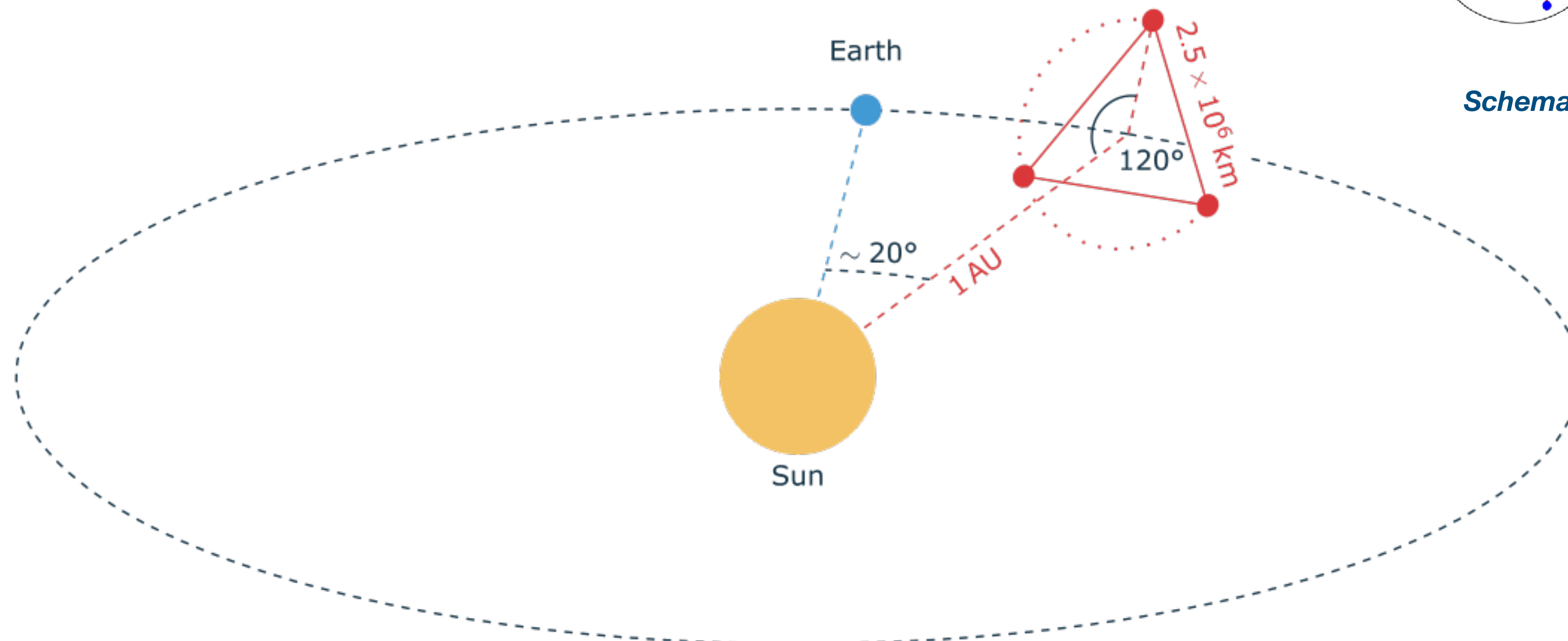
- All signals and noises overlapping in data. → global inference analysis
- Some science depends on rapid response: Low-latency alerts
- Simplified accessible view of the data as Catalogs
- Some science could rely on coordination with other GW or EM observatories

LISA Data Processing Challenge 1: Initial noise reduction

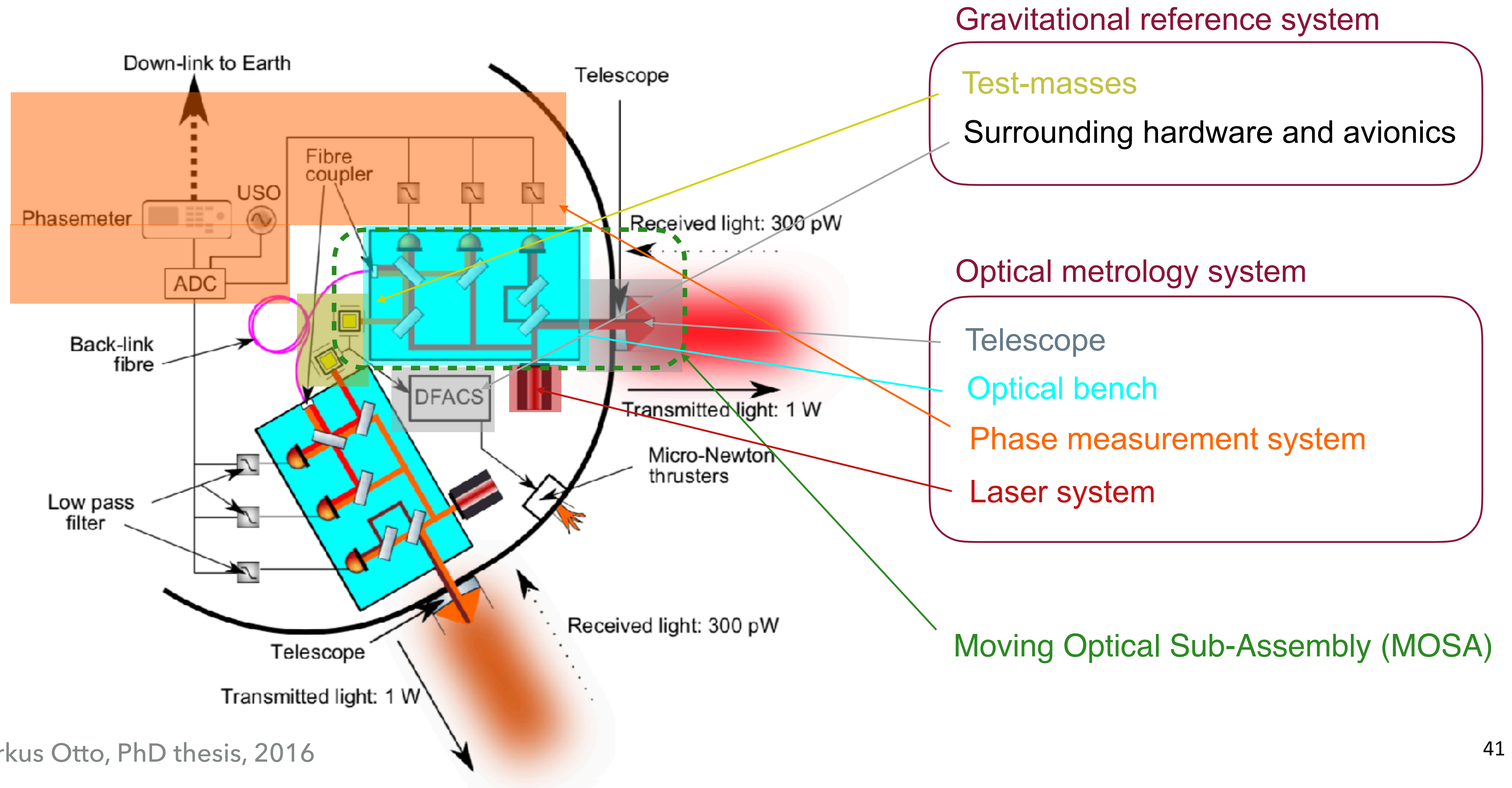
- **Core concept of LISA includes:**
 - 3 spacecraft
 - 6 laser assemblies (internally redundant)
 - 6 optical bench assemblies
 - 6 gravitational reference systems with test-masses
 - 18 interferometers / heterodyne phasemeters
 - ... and a lot more



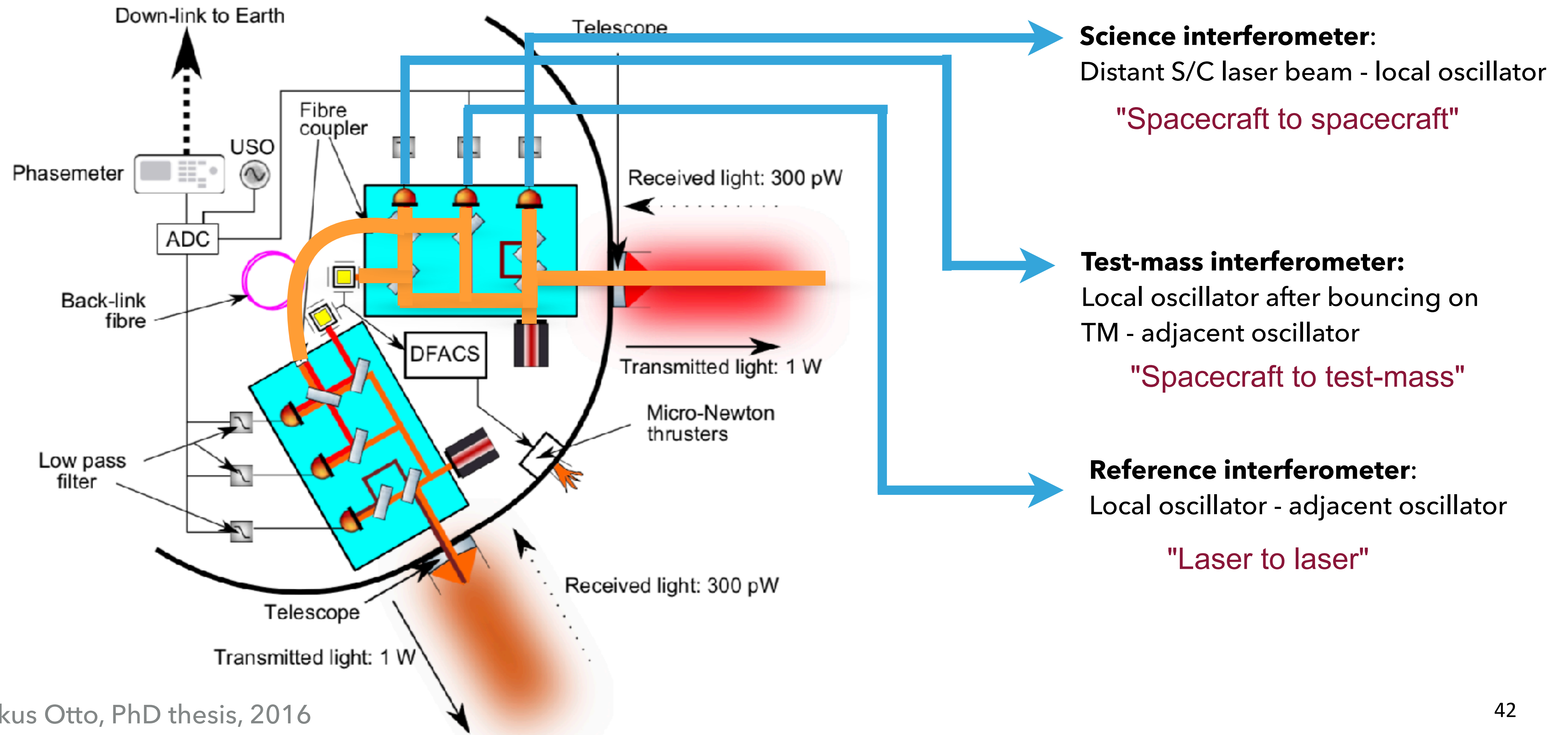
Schematic of the LISA interferometric measurement (T. Schuldt)



LISA Data Processing Challenge 1: Initial noise reduction



LISA Data Processing Challenge 1: Initial noise reduction



LISA Data Processing Challenge 1: Initial noise reduction

Laser frequency noise

$$\sqrt{S_\nu} \approx 300 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \text{ @3 mHz}$$

vs $\nu_0 \sim 300\text{THz}$

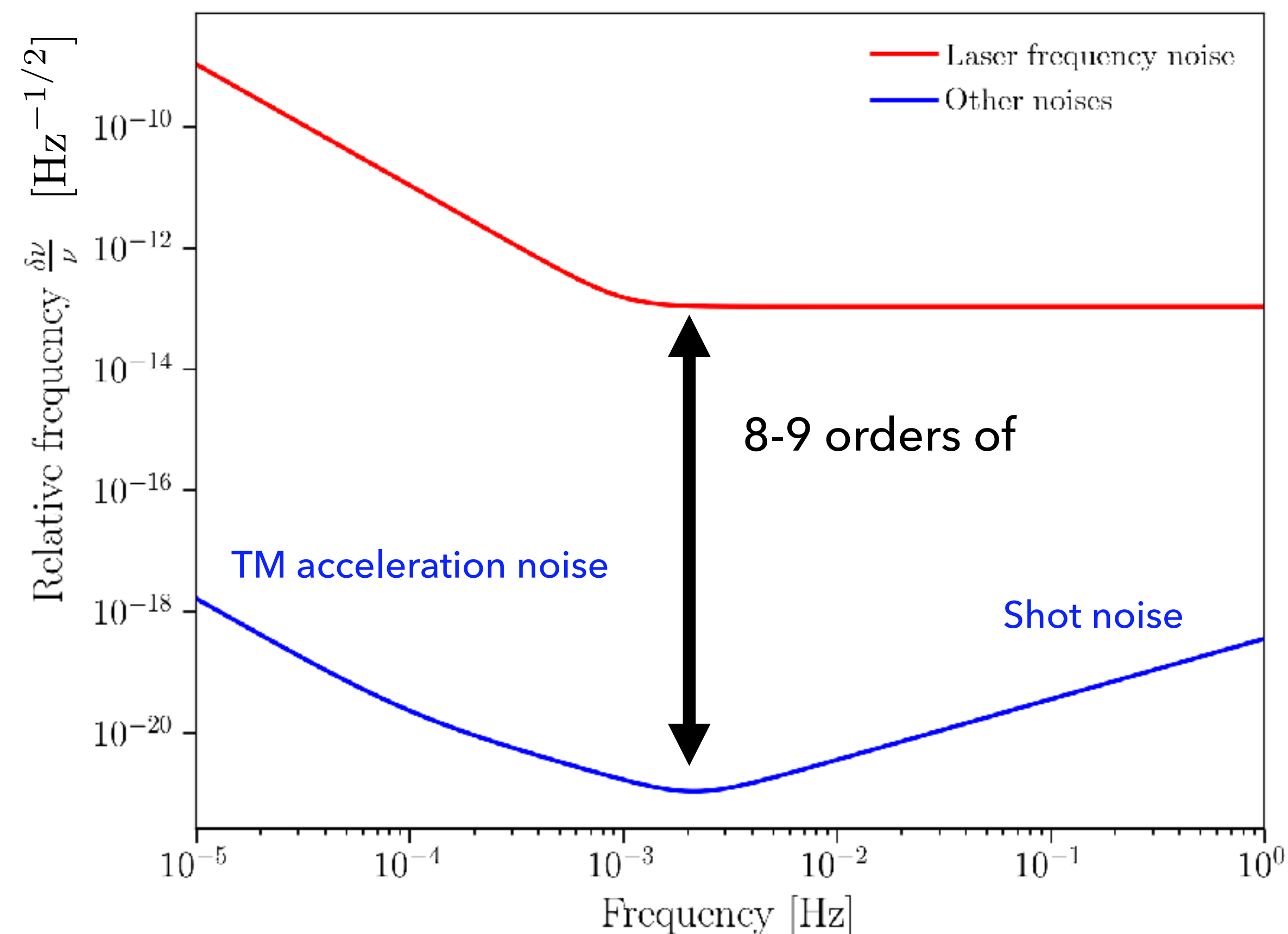


Gravitational strain noise

$$\sqrt{S_h} \sim 2 \times 10^{-12} \text{ Hz}^{-1/2}$$

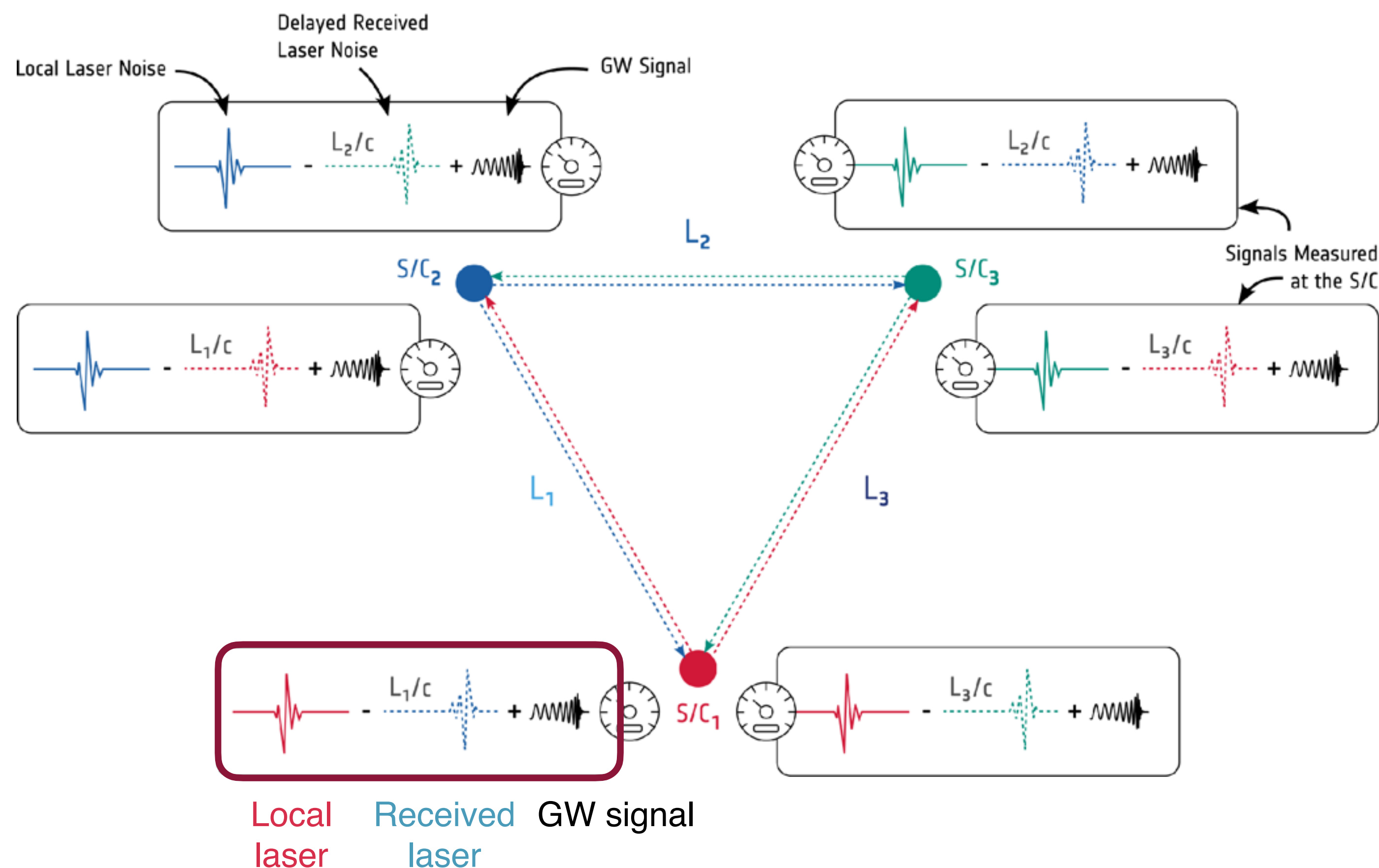
$$\gg 10^{-21} \text{ Hz}^{-1/2}$$

Too large to detect GWs!

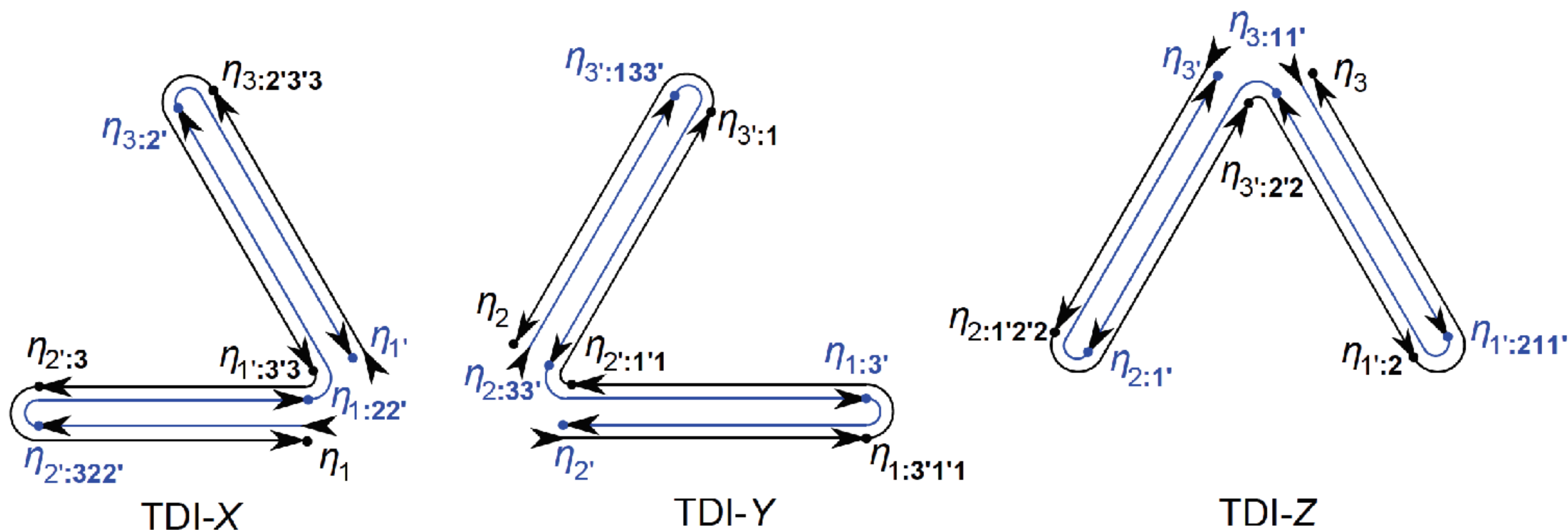


LISA Data Processing Challenge 1: Initial noise reduction

- Combinations of the single link measurements can cancel the laser noise
- ...without canceling the GWs



LISA Data Processing Challenge 1: Initial noise reduction



LISA Data Processing Challenge 1: Initial noise reduction

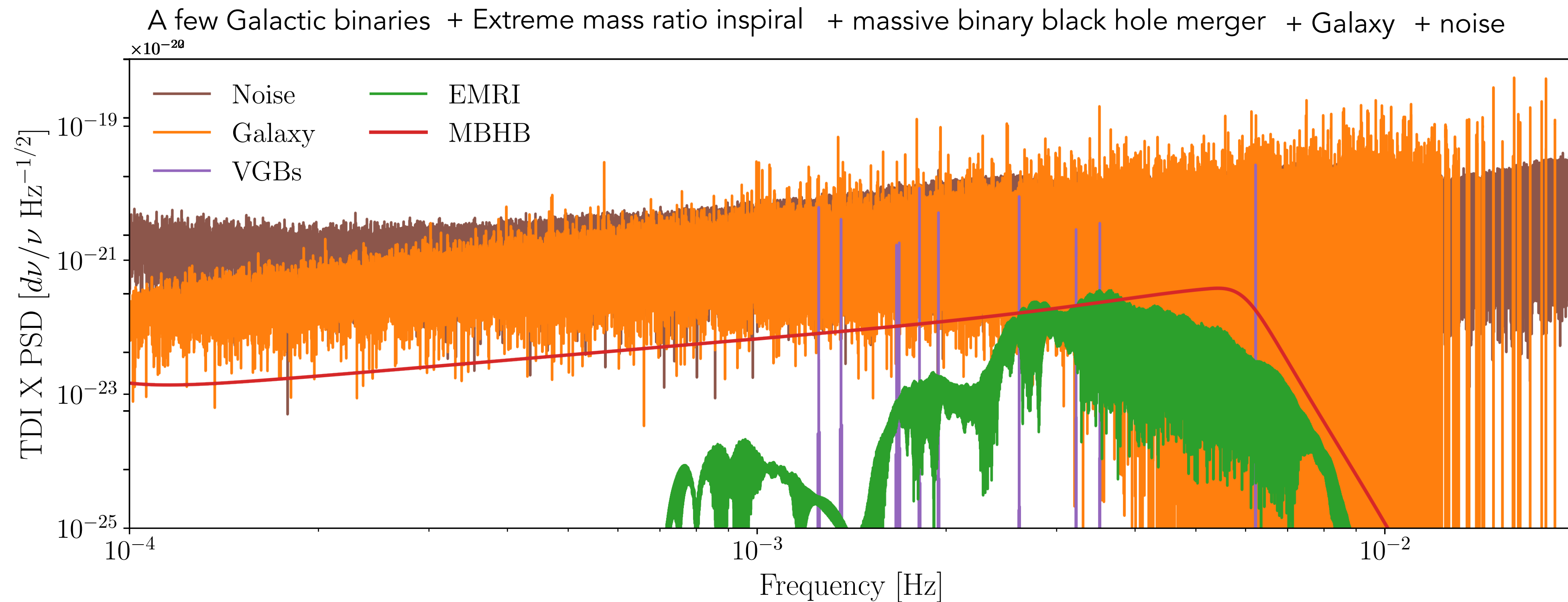
- **TDI requires adding signals with delays...**
 - **So, how can we know the delays?**

LISA Data Processing Challenge 1: Initial noise reduction

- **TDI requires adding signals with delays...**
 - **So, how can we know the delays?**
 - **LISA needs an additional mechanism for ranging measurements**

LISA Data Processing Challenge 2: Global inference

- The challenge of data analysis



LISA Data Processing Challenge 2: Global inference

- The favored strategy to analyse the TDI data is based on Bayesian statistics

$$p(\boldsymbol{\theta}, k | \boldsymbol{d}) = \frac{p(\boldsymbol{d} | \boldsymbol{\theta}, k) p(\boldsymbol{\theta}, k)}{p(\boldsymbol{d})}$$

Model parameters $\rightarrow$ $\boldsymbol{\theta}$

Number of model components $\rightarrow$ k

Data vector, for example $\boldsymbol{d}=(X, Y, Z)$ $\rightarrow$ $\boldsymbol{d}$

- Where one must define a likelihood function: for example, Gaussian

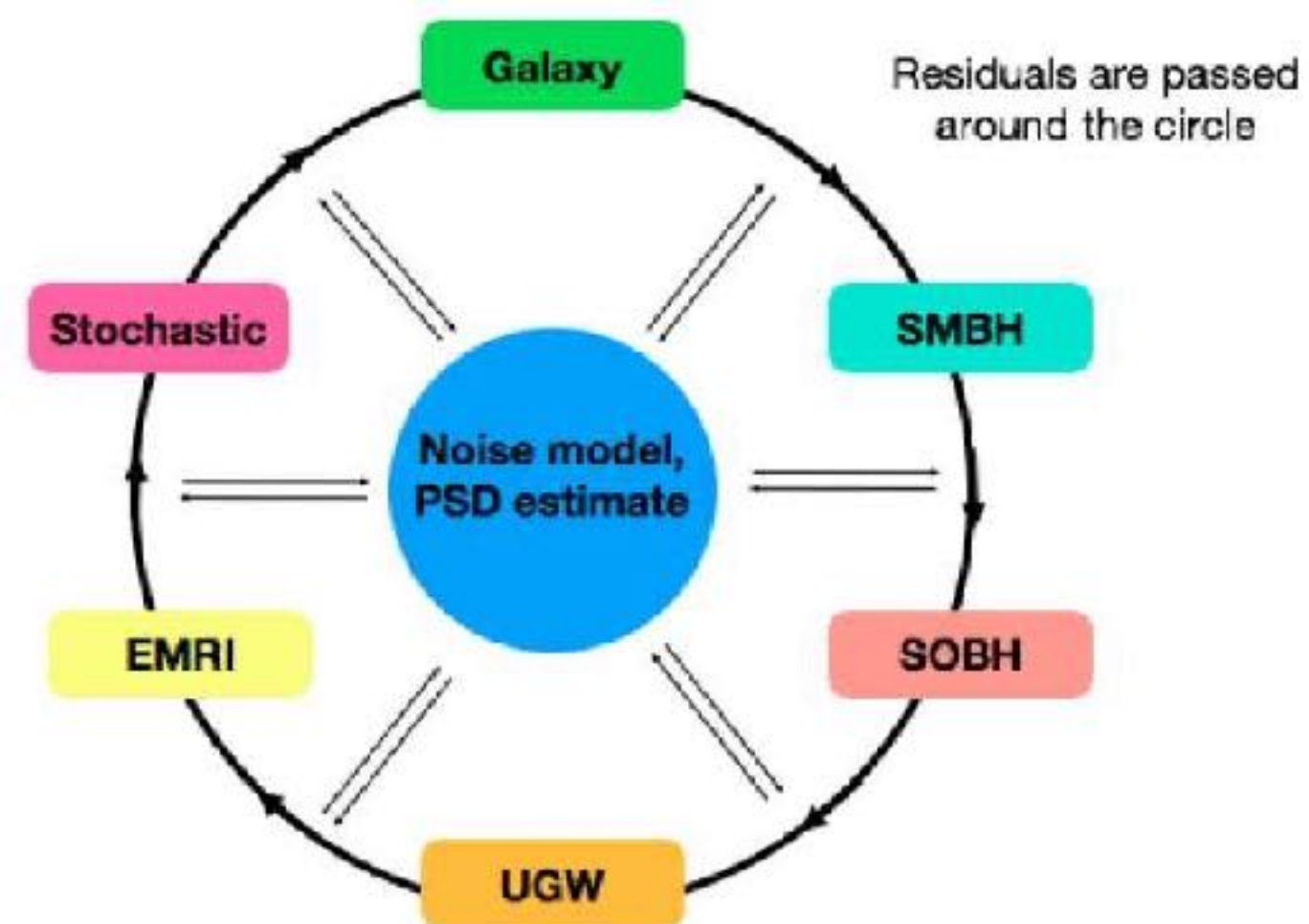
$$p(\boldsymbol{d} | \boldsymbol{\theta}, k) = \frac{1}{\sqrt{(2\pi)^N |\boldsymbol{\Sigma}(\boldsymbol{\theta})|}} \exp \left\{ (\boldsymbol{d} - \boldsymbol{h}(\boldsymbol{\theta}, q))^{\dagger} \boldsymbol{\Sigma}(\boldsymbol{\theta}, p)^{-1} (\boldsymbol{d} - \boldsymbol{h}(\boldsymbol{\theta}, q)) \right\}$$

GW signals: $\boldsymbol{h}(\boldsymbol{\theta}, q) = \sum_{j=1}^q \boldsymbol{h}_j(\boldsymbol{\theta}_j)$

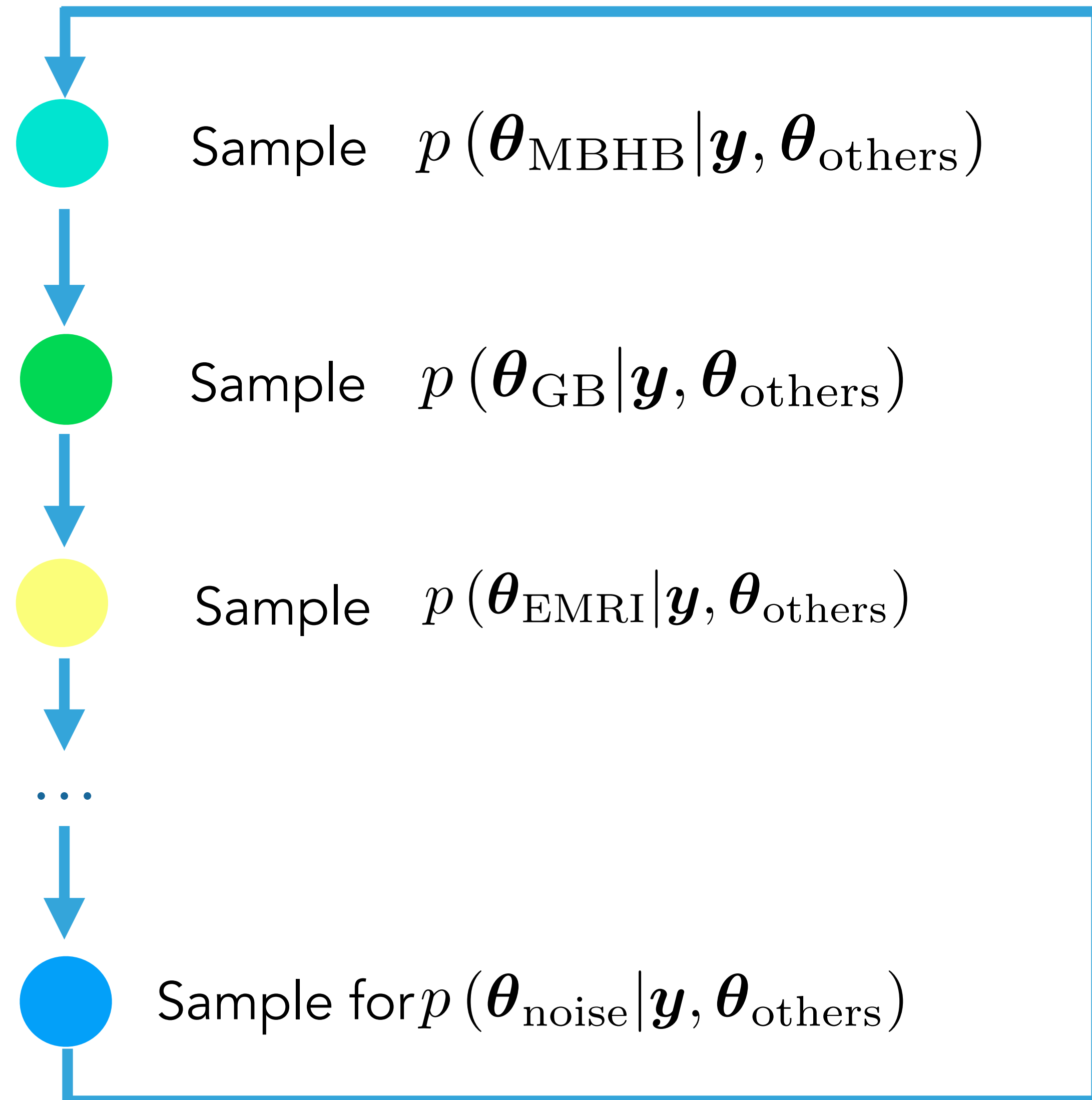
Stochastic processes: $\boldsymbol{\Sigma}(\boldsymbol{\theta}) = \sum_{i=1}^p \boldsymbol{\Sigma}_i(\boldsymbol{\theta}_i)$

$$k = p + q$$

LISA Data Processing Challenge 2: Global inference



Blocked Gibbs scheme:
iterative sampling over
subset of parameters



LISA Data Processing Challenge 2: Global inference

- **LISA's inference must account for instrument noise (among stochastic processes)...**
 - **So, how do we know the instrument noise?**
 - We don't. We have to infer it.

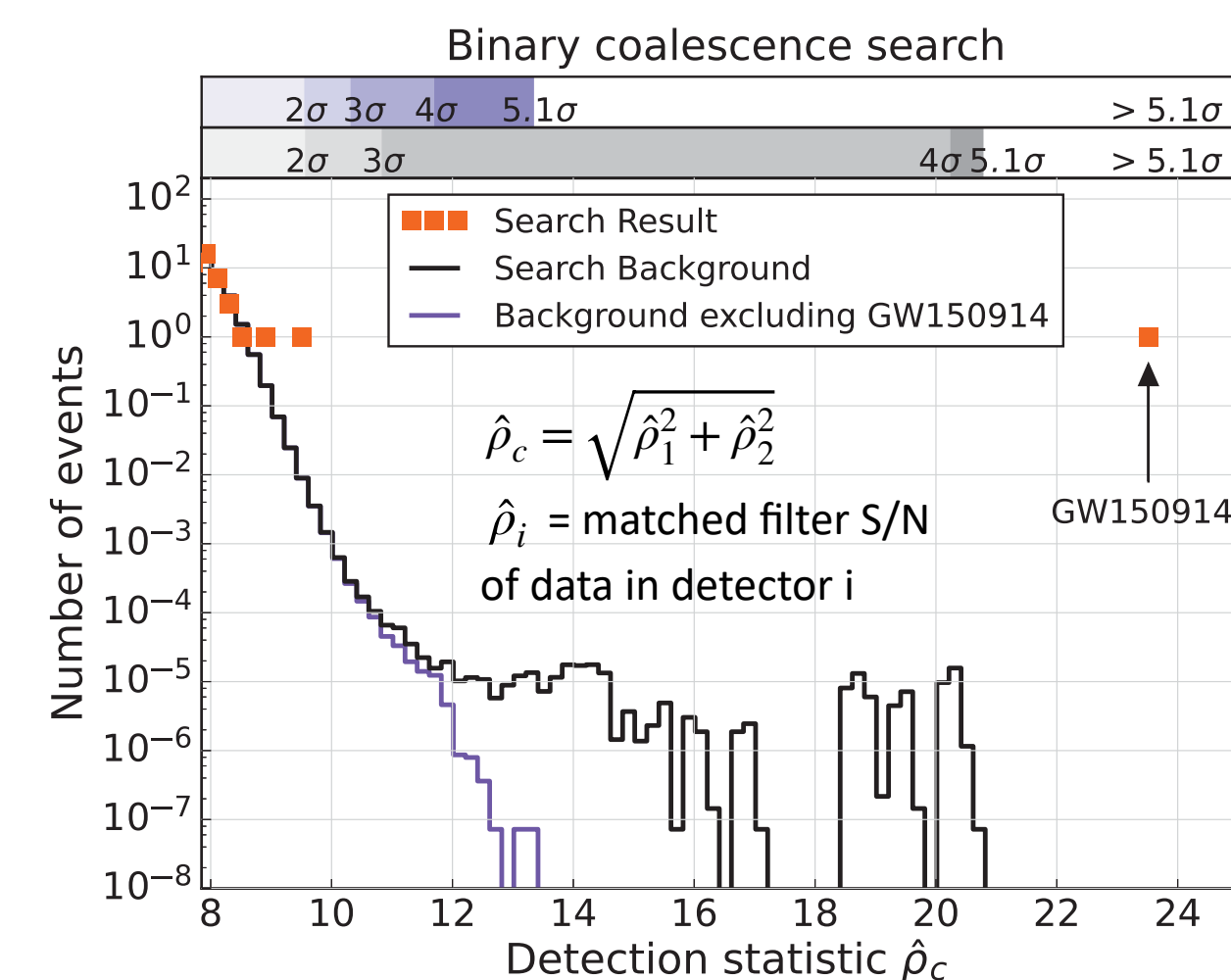
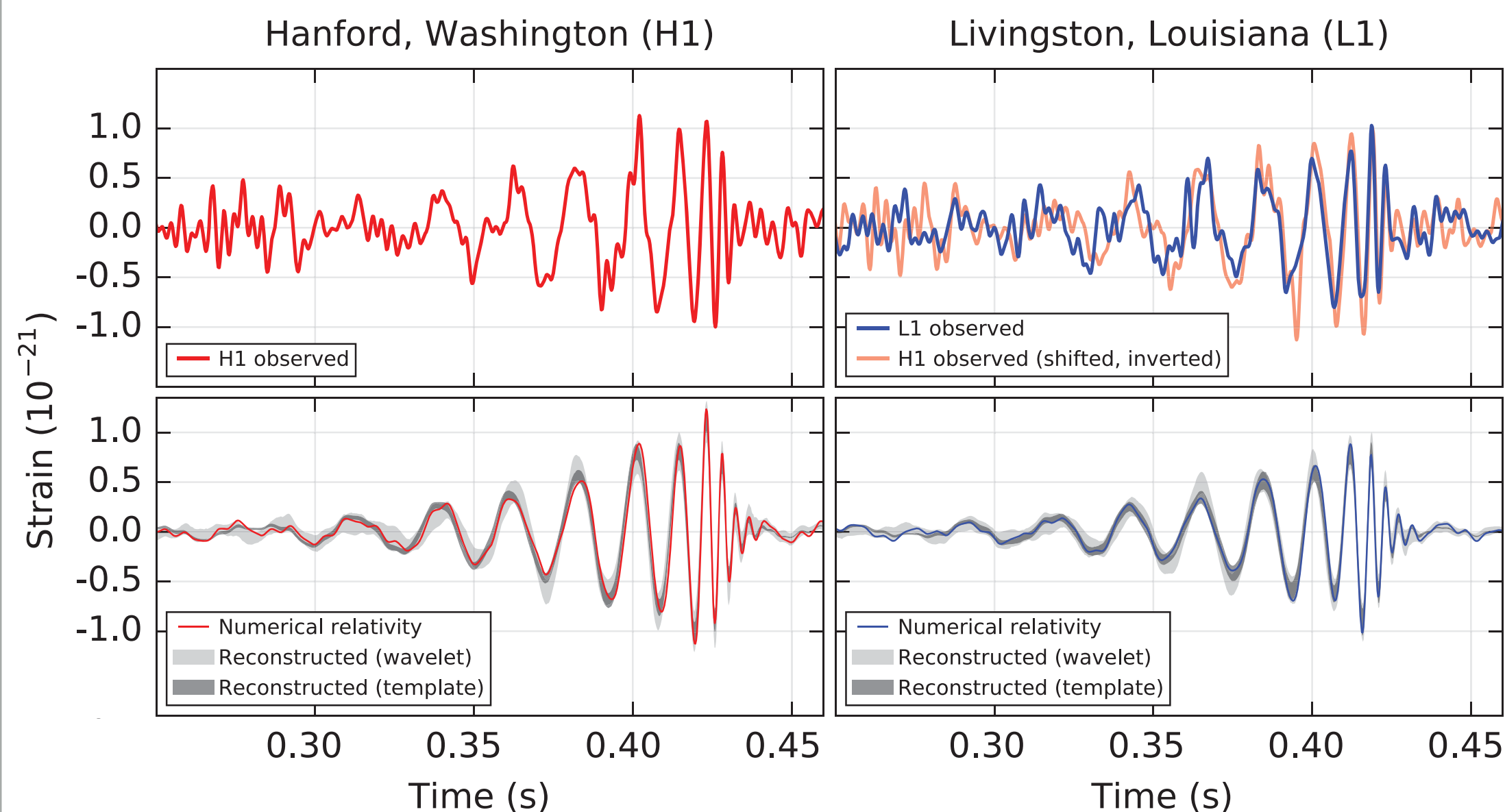
LISA Data Processing Challenge 2: Global inference

- **LISA's inference must account for instrument noise (among stochastic processes)...**
 - **So, how do we know the instrument noise?**

LISA Data Processing Challenge 3: Knowing the noise

- Slide from Joe Romano today:

Why was GW150914 so convincing?

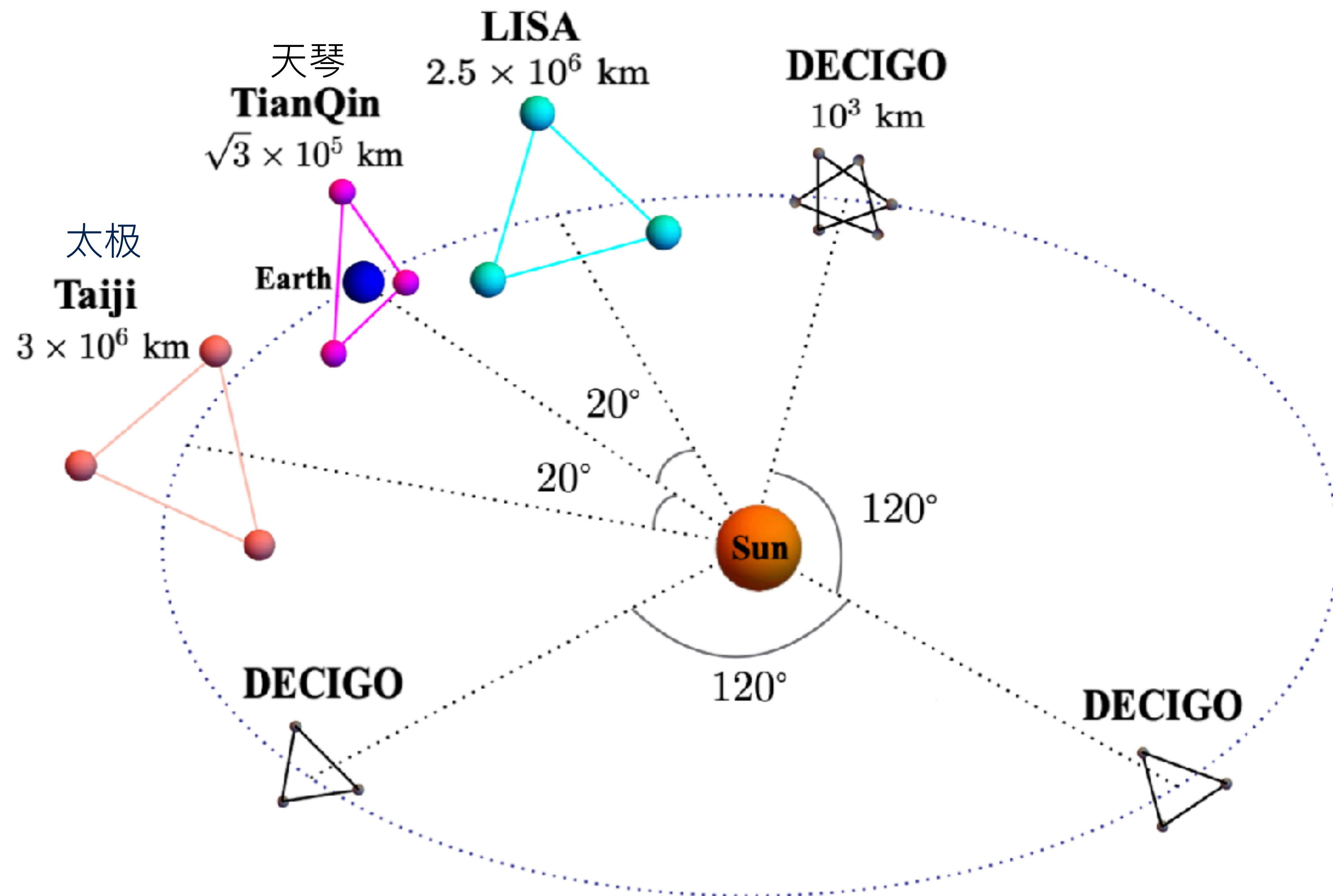


1. observed signal is consistent across detectors
2. observed signal agrees with predictions
3. observed signal is unlikely due to noise alone ($< 1/5$ million)

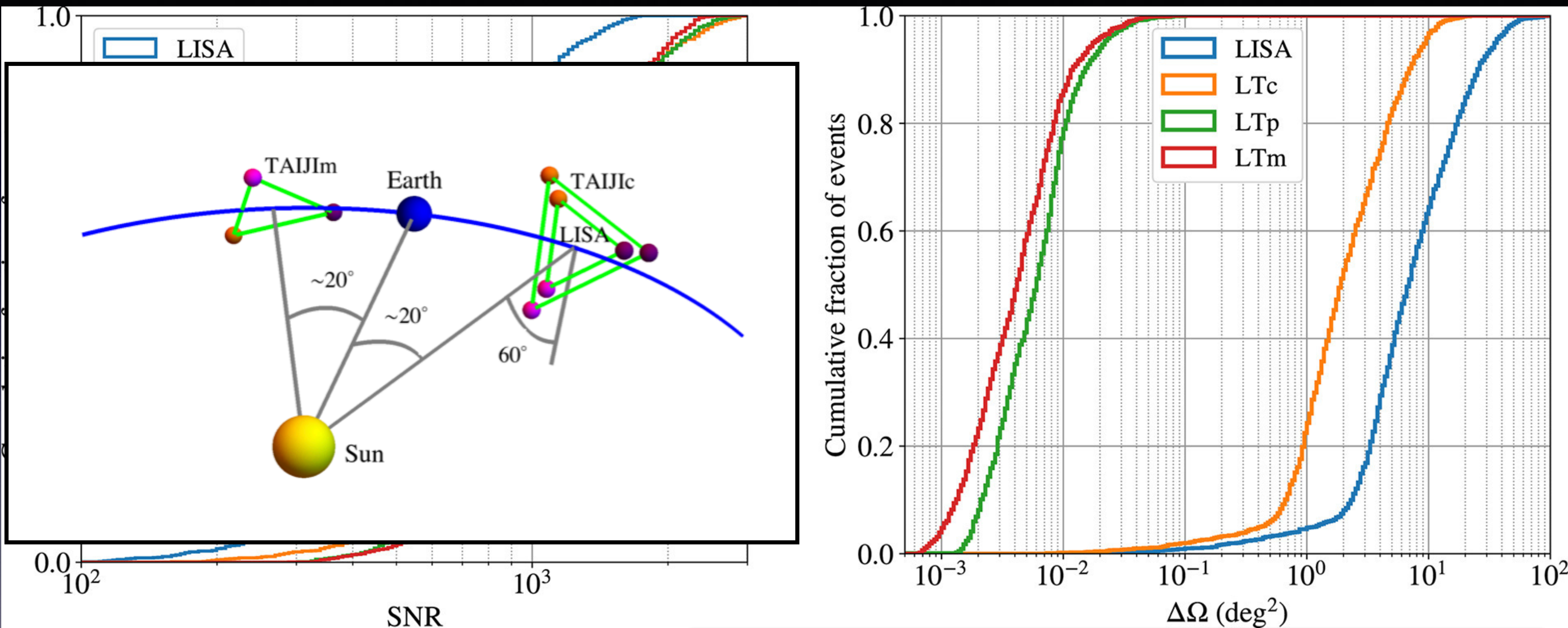
LISA Data Processing Challenge 4: Joint observations

- **Potential science opportunities:**
 - Complementary **EM+GW** understanding of **galactic binary** systems
 - Complementary **EM+GW** understanding of **massive black hole** systems
 - Standard siren **cosmological inference** with **EM** redshifts
 - Enhanced inference combined with 3G ground-based GW observations
 - Enhanced localization combined with other space-based GW observations
 - ...
- **Challenges:**
 - How do we formalize the interpretation of external data as LISA (prior) information?
 - How do we coordinate the data sharing?
 - ...

Some space-based GW mission concepts



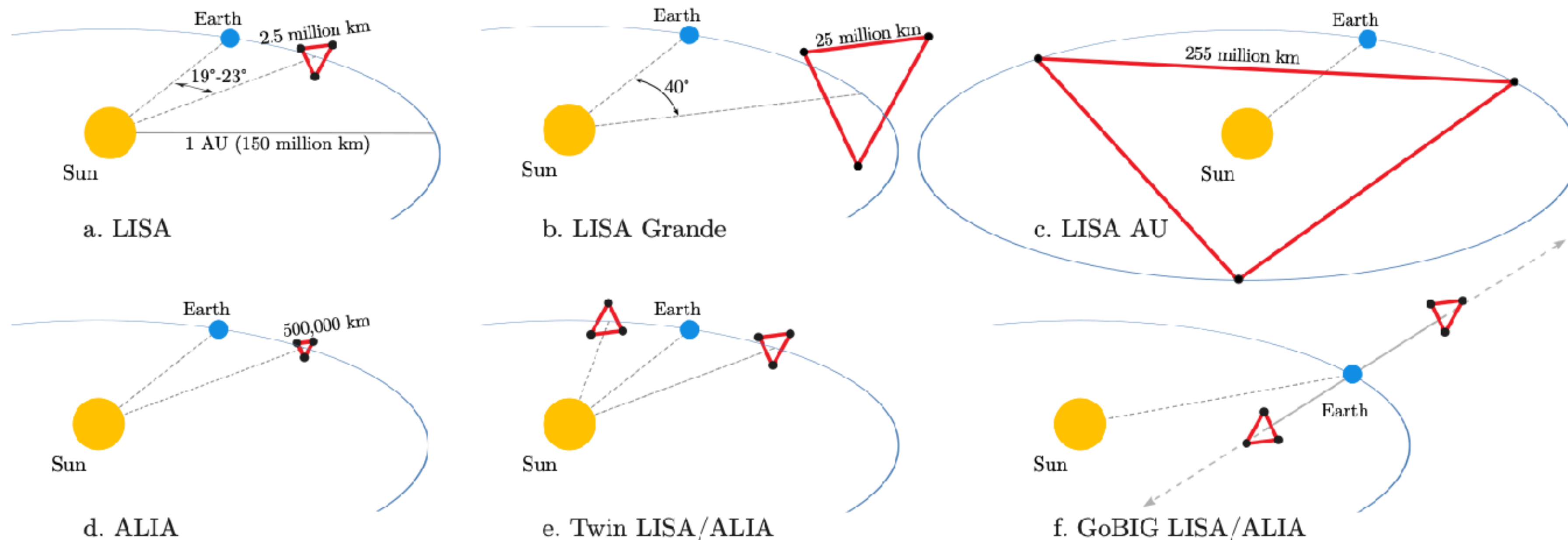
Space-based network observations of MBHBs



SNR and sky localization precision for a simulated population of MBHBs with LISA and with a network of LISA plus one version of Taiji. Wang+ 2021 <https://doi.org/10.1103/PhysRevD.104.024012>

LISA Data Processing Challenge 4: Joint observations

- Joint observation with another instrument is valuable for sky-localization
- A larger constellation, or farther apart constellations will be best
- **Where could you put a LISA-like constellation for better mHz sky localization?**



LISA Data Processing Challenge 4: Joint observations

- Joint observation with another instrument is valuable for sky-localization
- A larger constellation, or farther apart constellations will be best
- **Where could you put a LISA-like constellation for better mHz sky localization?**

Pause

LISA data processing plan

Realizing LISA Data Processing

Project responsibility to generate 3 main levels of data products:

- L1: Initially processed data (TDI)
- L2: Global inference and alerts
- L3: Catalogs for non-LISA-experts

ESA-coordinated EU and NASA efforts:

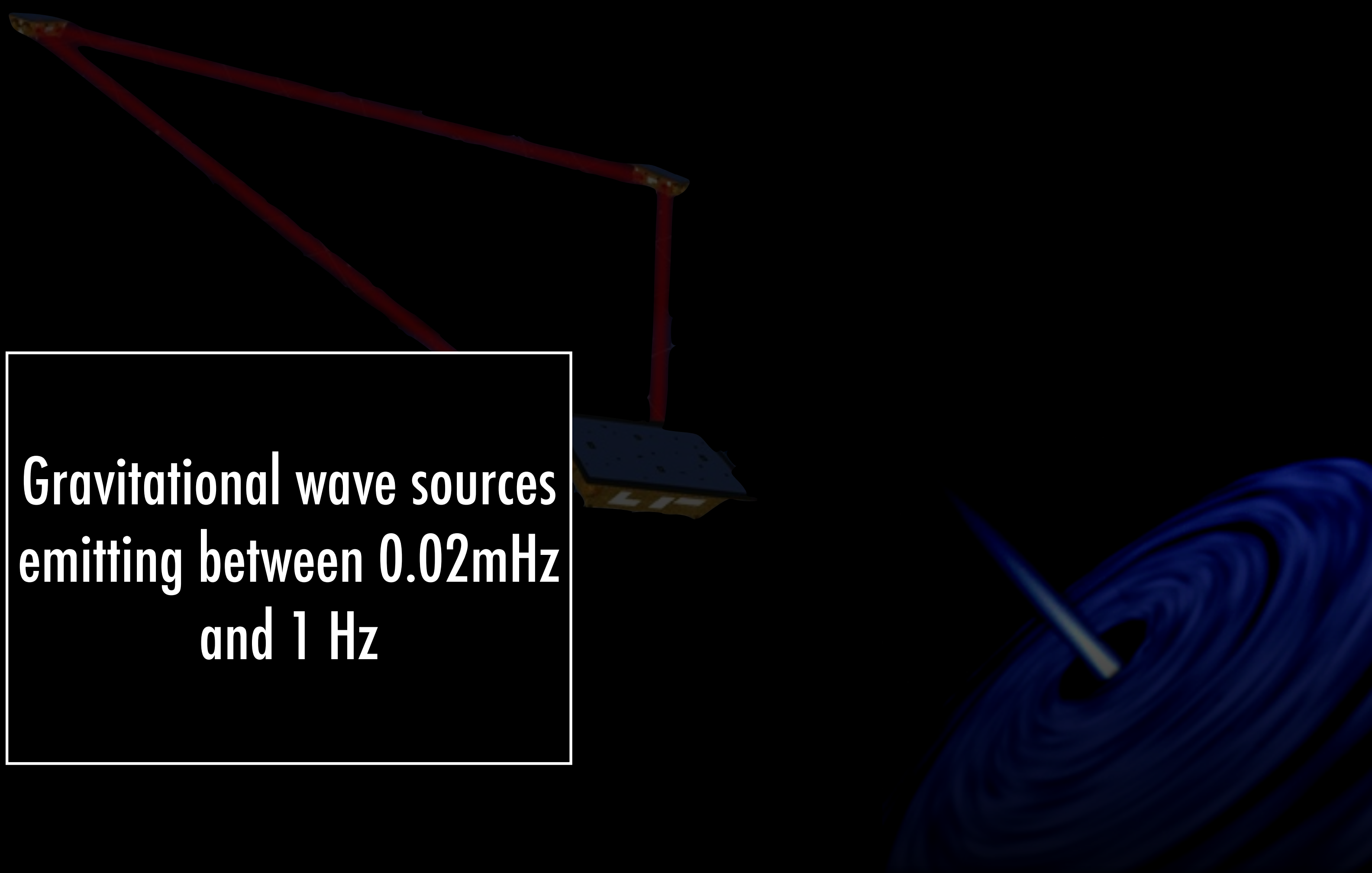
- Plus more work will be needed from the open science community
- EU part → **Distributed Data Computing Center (DDPC)**

Flexibility: first data of this kind challenge:

- Multiple approaches, multiple pipelines
- Quick development from prototyping to production

Processing LISA's Data

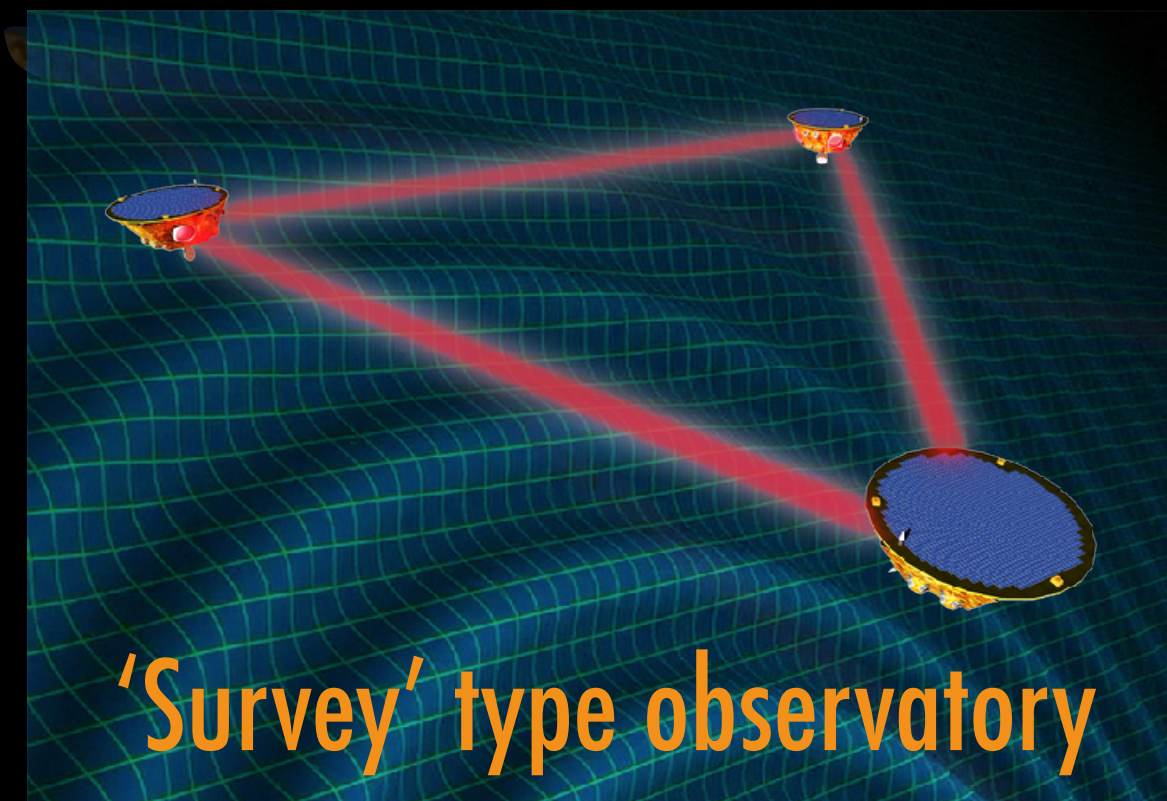
Data

The background of the slide features a 3D rendering of the LISA spacecraft, which is a triangular formation of three spacecraft connected by long arms, shown in a dark blue color. In the bottom right corner, there is a visualization of a gravitational wave, depicted as a blue, swirling, and distorted surface.

Gravitational wave sources
emitting between 0.02mHz
and 1 Hz

Processing LISA's Data

Data

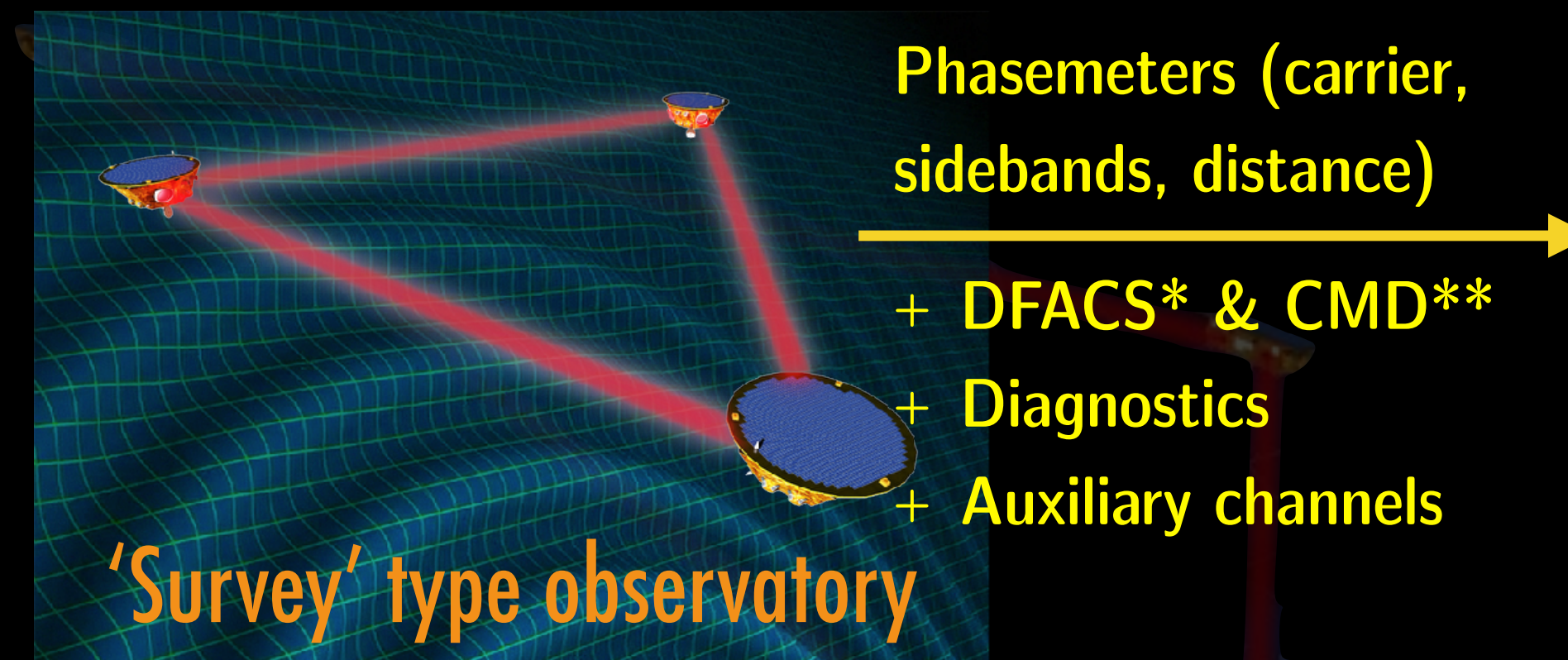


Gravitational wave sources
emitting between 0.02mHz
and 1 Hz

Processing LISA's Data



Data



Gravitational wave sources
emitting between 0.02mHz
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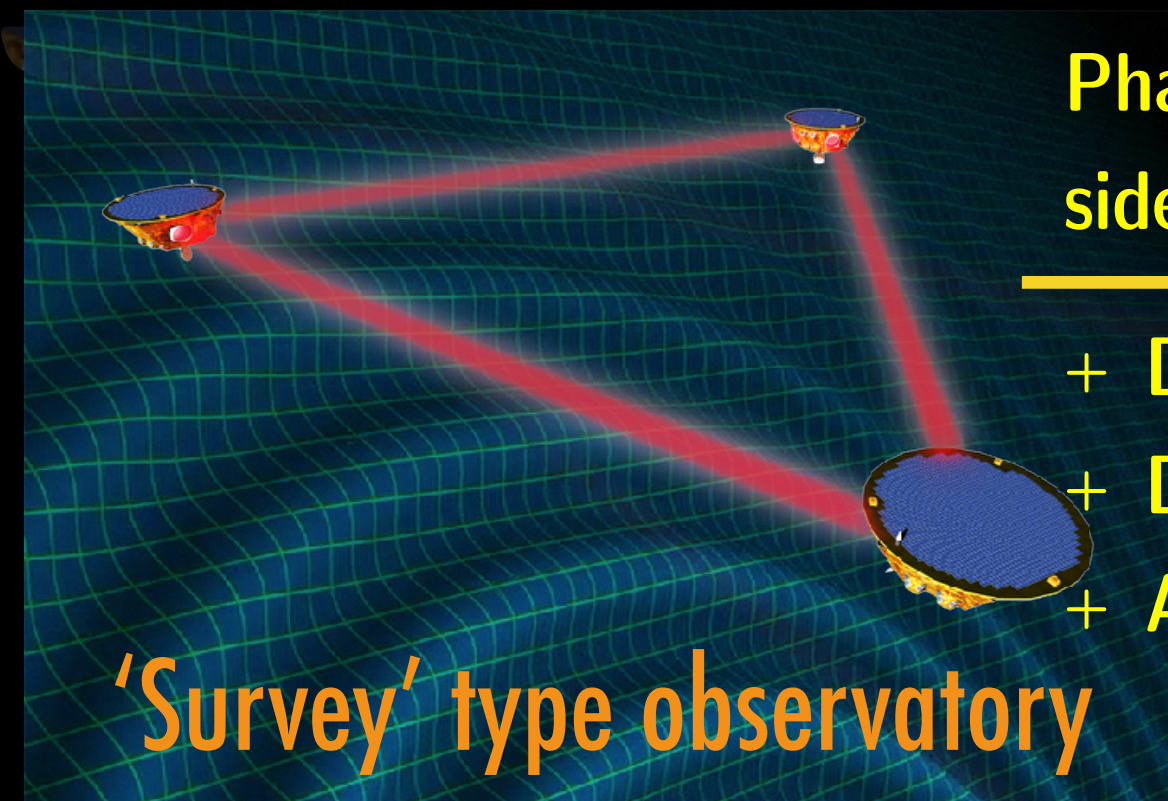
* Drag-Free Attitude Control System

** Charge Management Device

Processing LISA's Data



Data



Phasemeters (carrier,
sidebands, distance)

- + DFACS* & CMD**
- + Diagnostics
- + Auxiliary channels



Gravitational wave sources
emitting between 0.02mHz
and 1 Hz

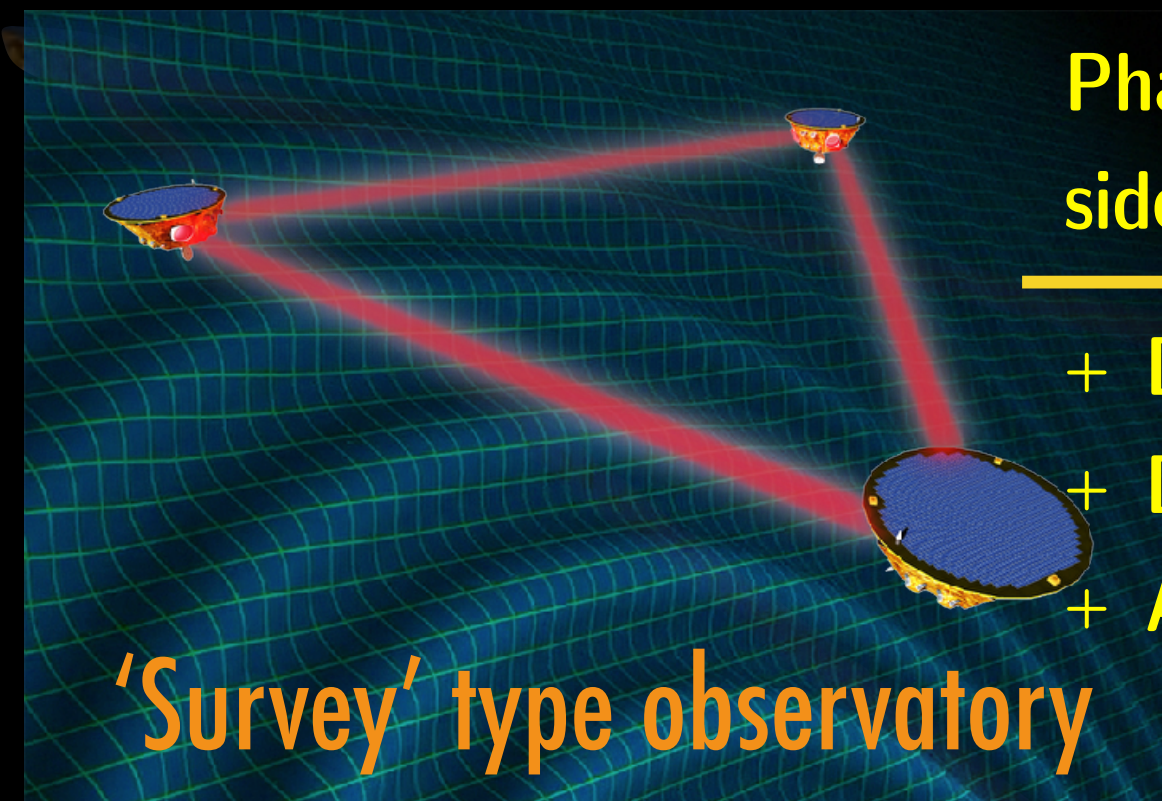
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Processing LISA's Data



Data



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Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry
reduction of laser noise

Gravitational wave sources
emitting between 0.02mHz
and 1 Hz

3 TDI channels with 2 " ~independents"

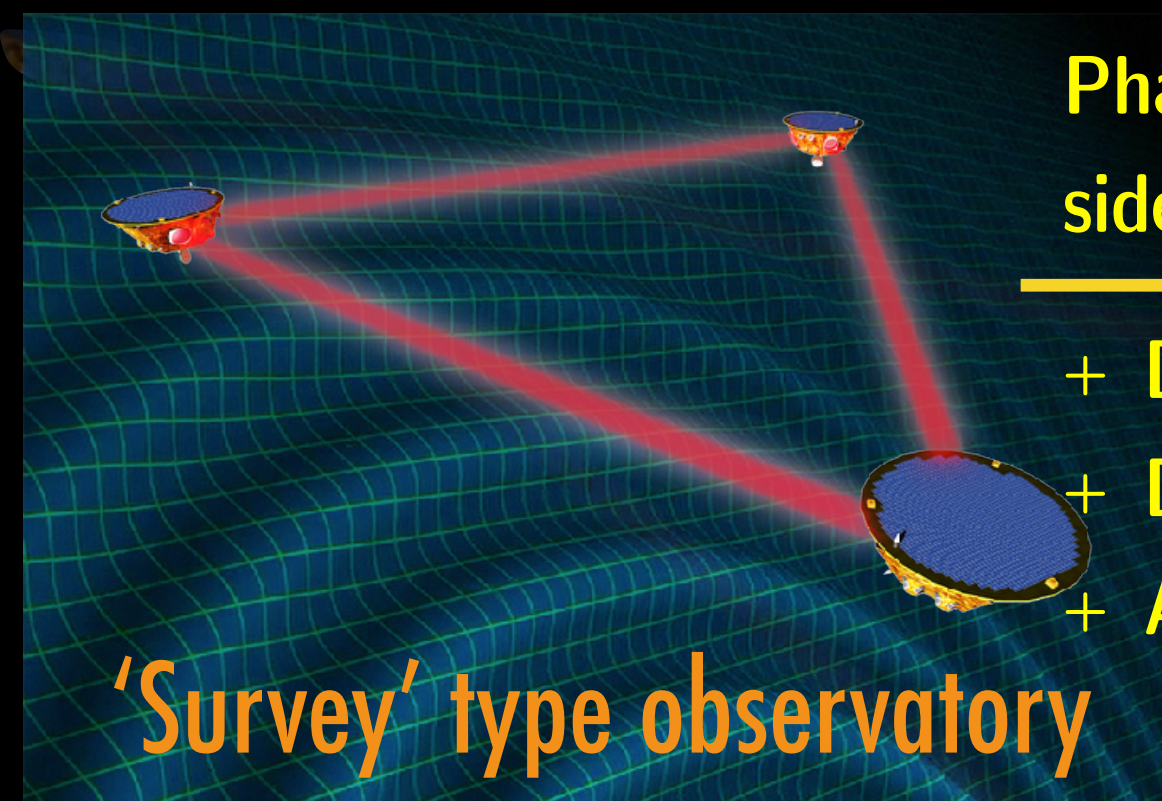
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Processing LISA's Data



Data



Phasemeters (carrier, sidebands, distance)

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Calibrations corrections
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reduction of laser noise

3 TDI channels with 2 " ~independents"

Data Analysis of GWs

Catalogs of GWs sources
with their waveform

Gravitational wave sources
emitting between 0.02mHz
and 1 Hz

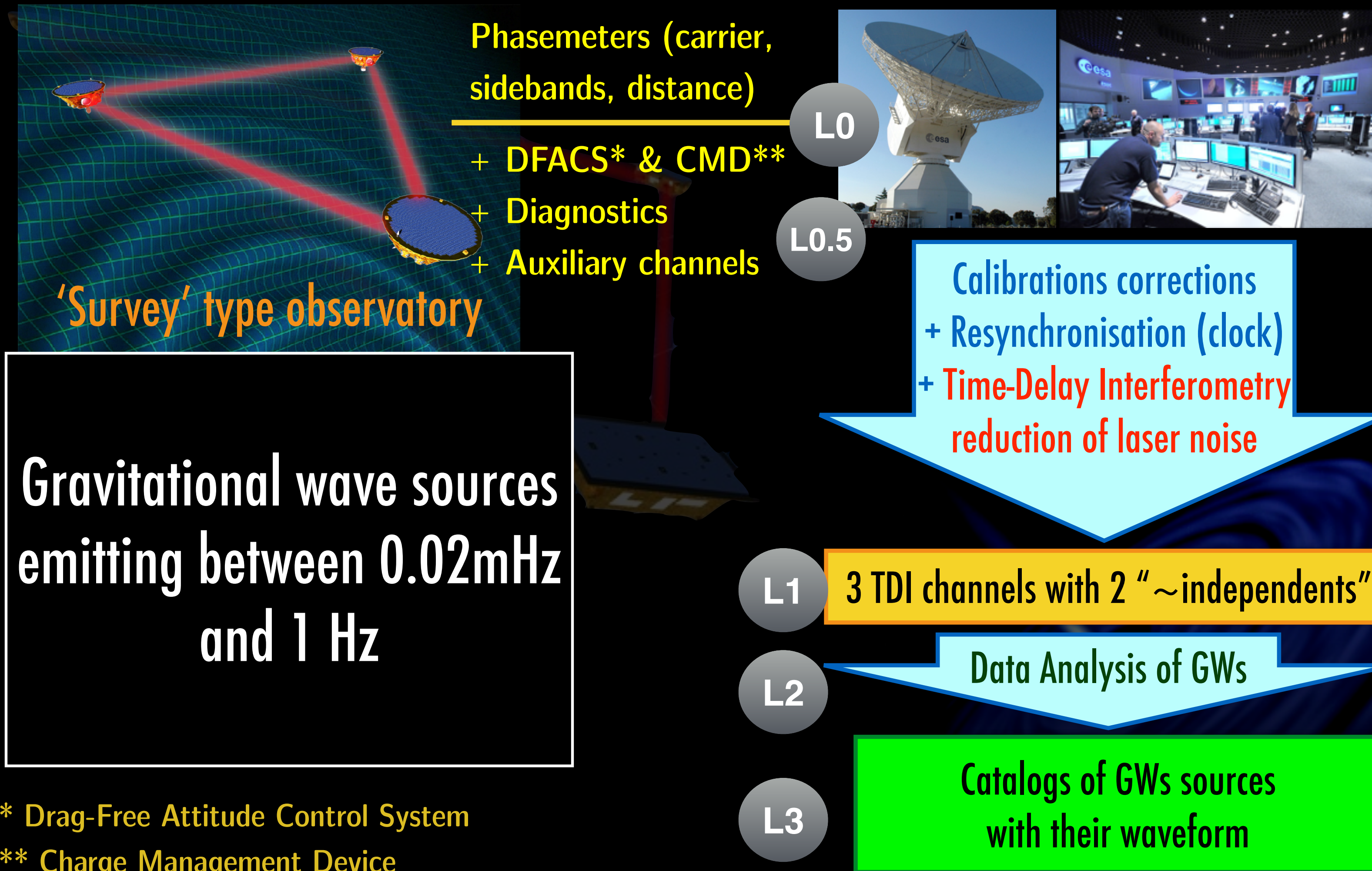
* Drag-Free Attitude Control System

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Processing LISA's Data



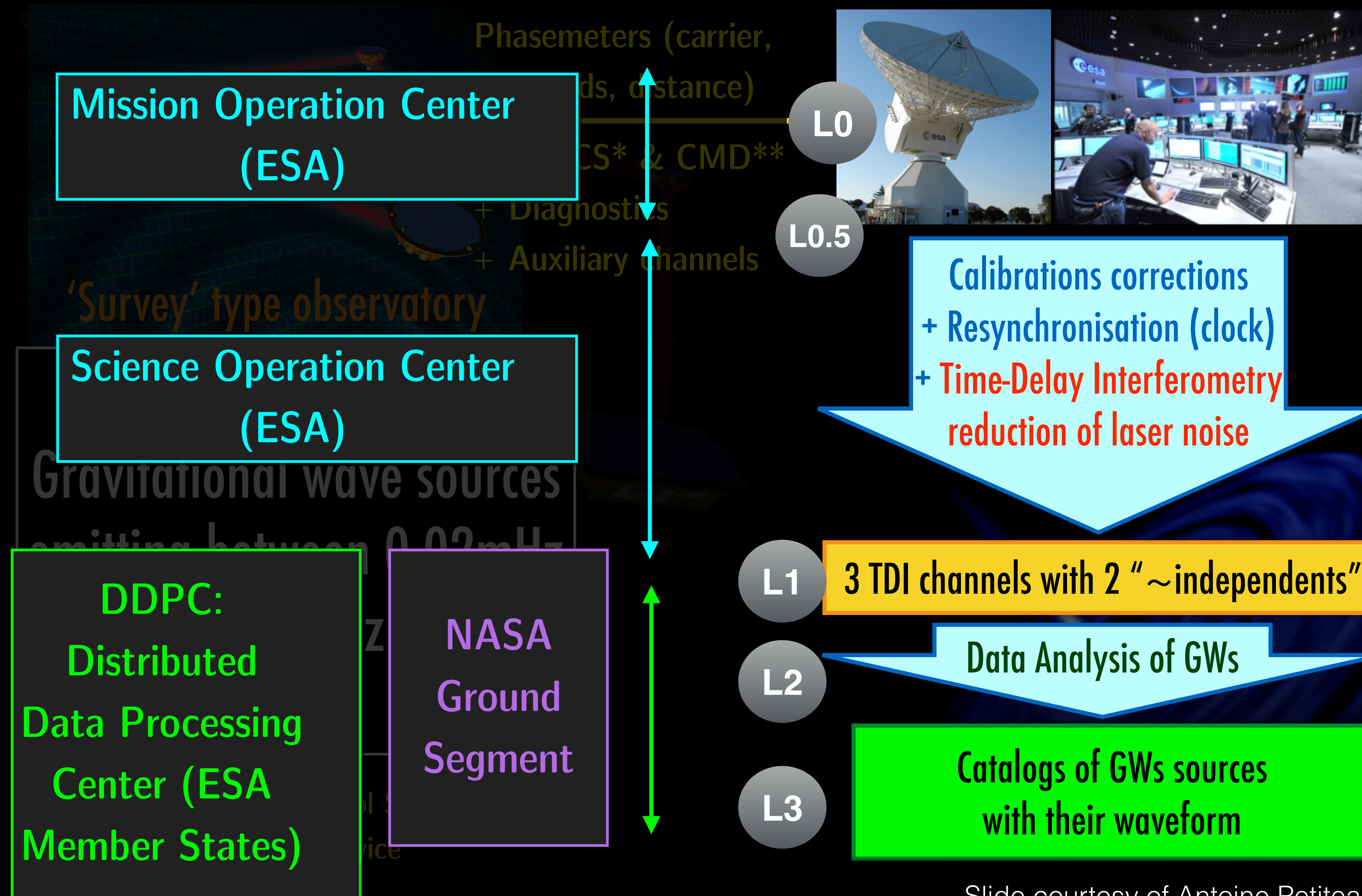
Data



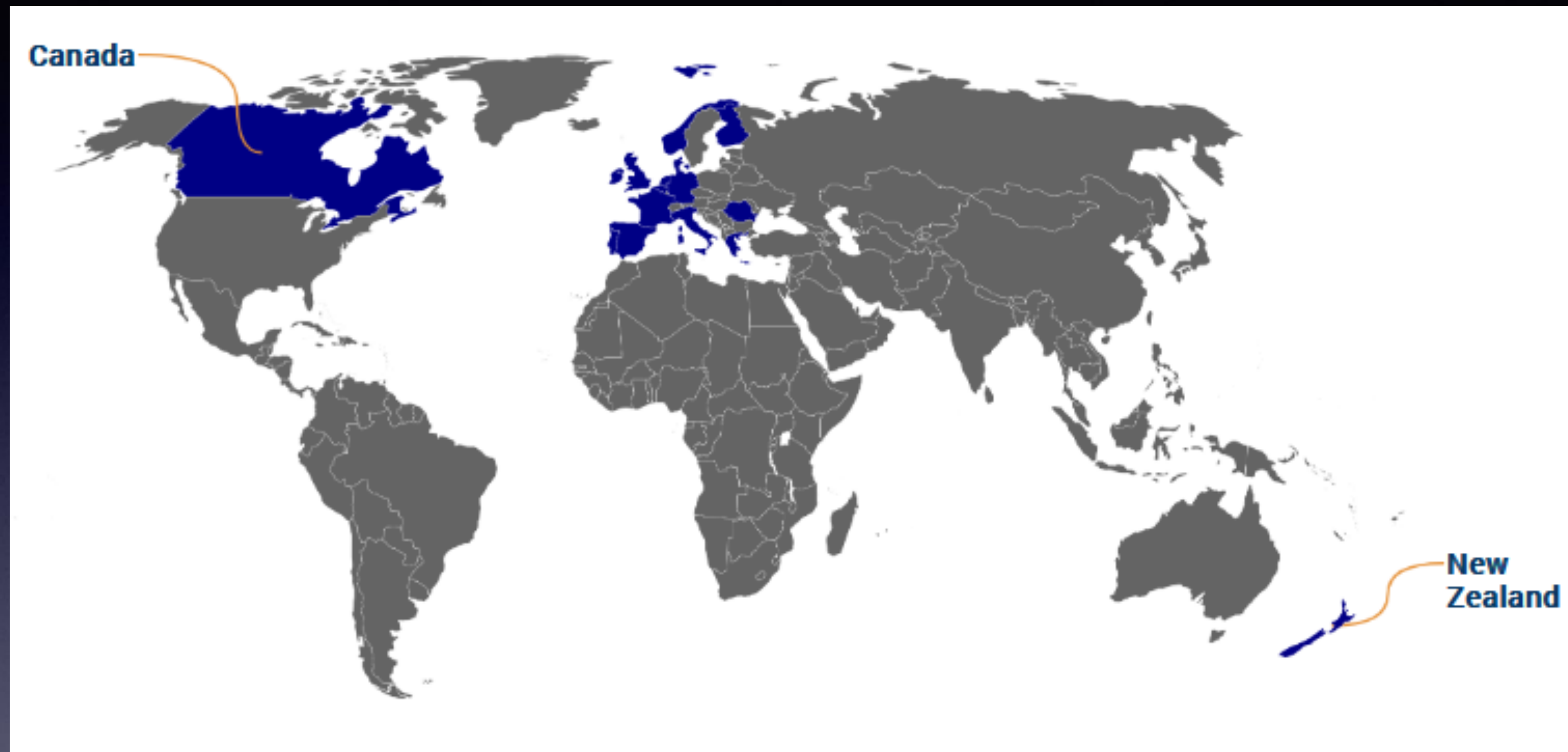
Processing LISA's Data



Data



LISA Distributed Data Processing Center (DDPC) Partners



Effort led by CNES

Pause

The LISA Science Community

The LISA Consortium

- A scientific collaboration
 - Maximize LISA science return
 - support the mission in all aspects
 - particular focus on scientific application of LISA data
 - Develop the LISA science community
 - provide supporting/inclusive environment
 - training/mentoring for all esp early career
 - engage the broader science community
- Membership:
 - Core members: Commit annually to roles in consortium projects
 - Community: Access to community and resources

The LISA Consortium (see: lisamission.org)

Governance

- [Consortium Council](#)
- [Management Team](#)

Committees

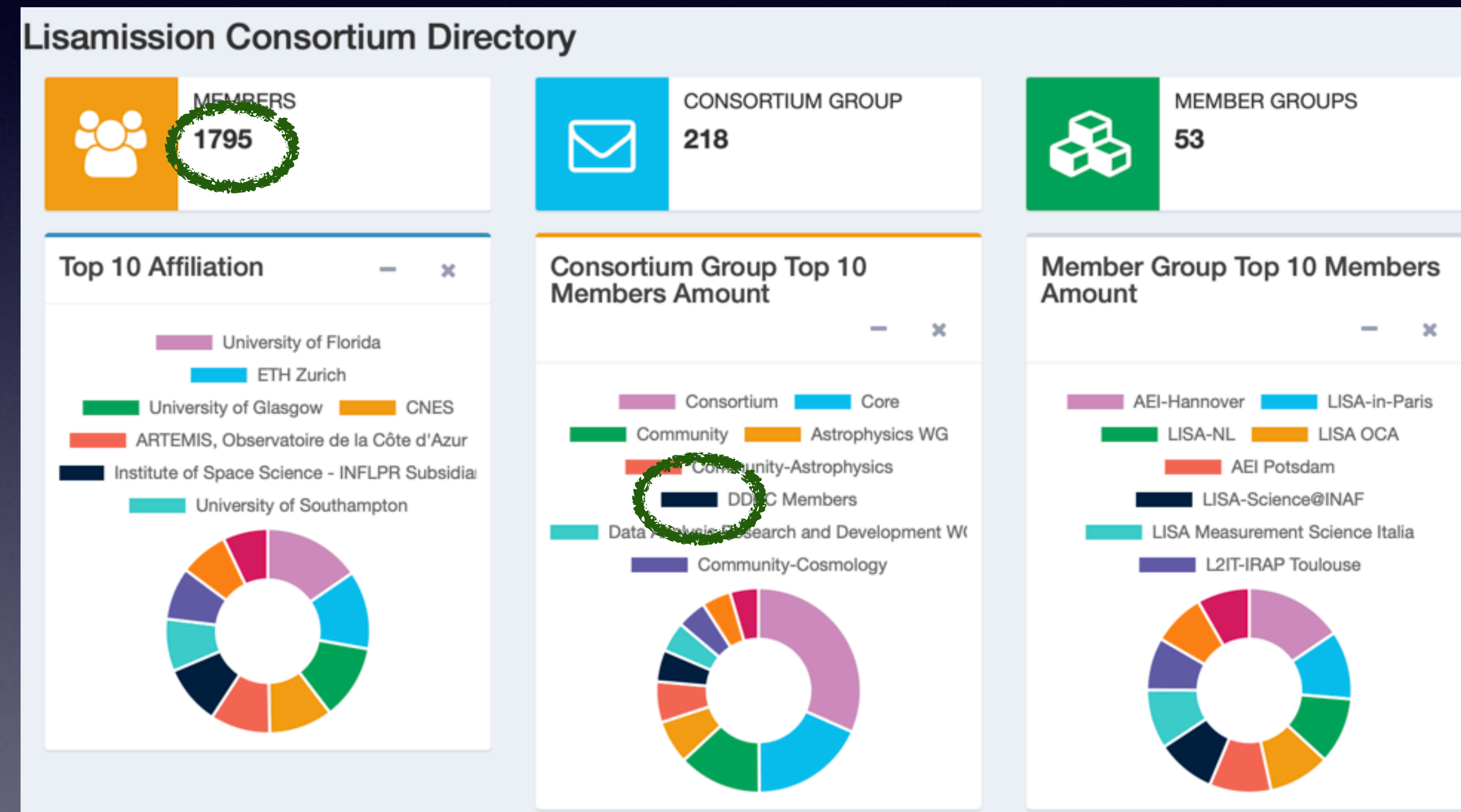
- [Appointments and Elections \(A&E\) Committee](#)
- [Bylaws Committee](#)
- [Publication and Presentation Committee](#)
- [Diversity, Equity and Inclusion Committee](#)
- [Membership committee](#)
- [Communications Committee](#)

Science working groups

- [Astrophysics Working Group](#)
- [Cosmology Working Group](#)
- [Fundamental Physics Working Group](#)
- [Instrumentation Working Group](#)
- [Waveform Working Group](#)
- [Data Analysis and Research Development Working Group](#)
- [Instrument Simulation and Processing Working Group](#)

Other working groups

- [Communications Implementation Working Group](#)
- [Early Career Scientist Working Group](#)



Summary

- The immense, quiet environment of space allows LISA to open a rich new band of GW astronomy in mHz
- After decades of science and technology development the mission is ready to push forward toward launch in 2035
- LISA data processing involves new challenges
- Much work remains to prepare to exploit LISA data
- A robust LISA science community is working on it
- You can too (see, e.g. lisamission.org)