LISA

Mission, status and science

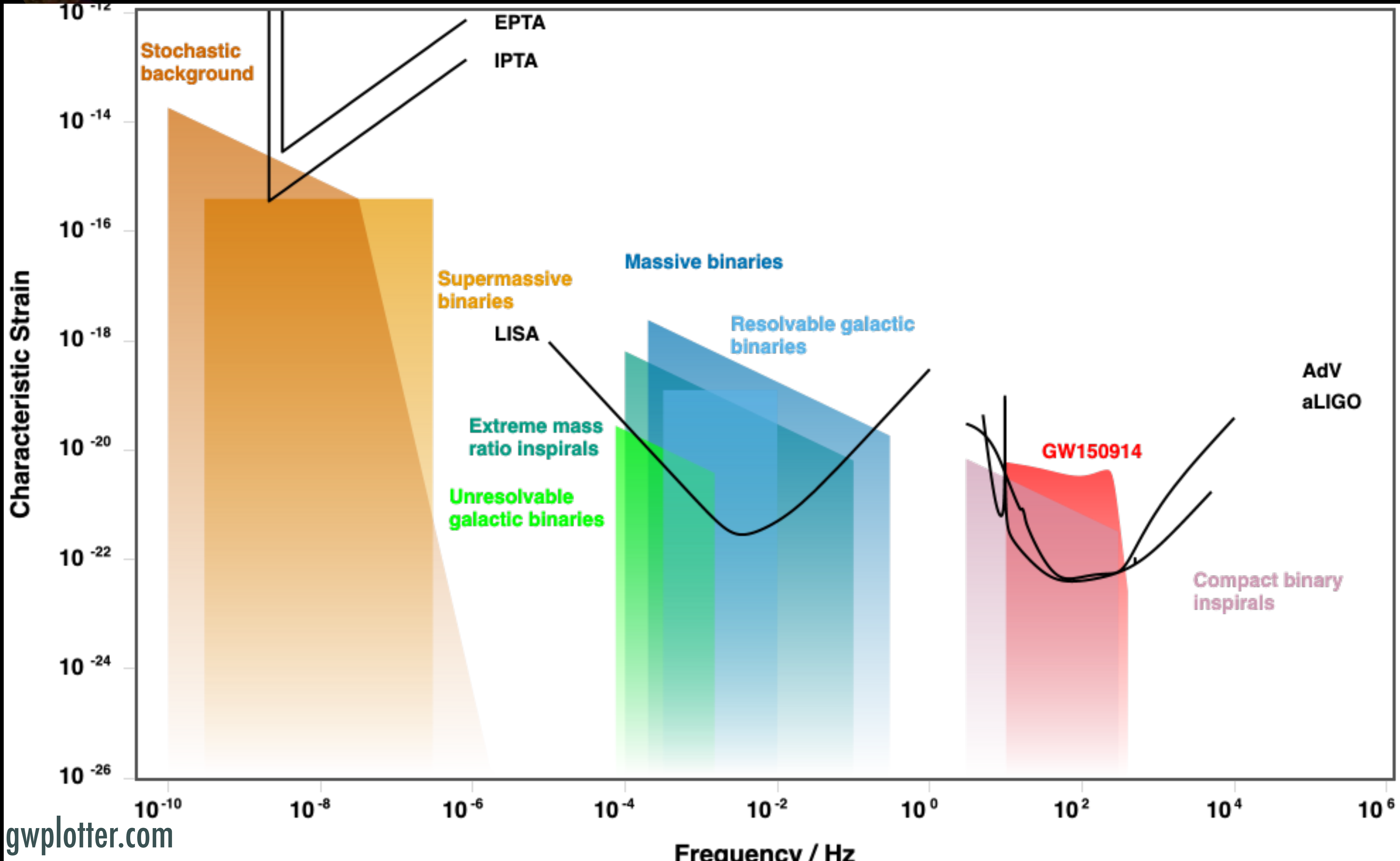
Antoine Petiteau (CEA/IRFU/DPhP & APC)

for the LISA mission and LISA Consortium

EDSU-Tools

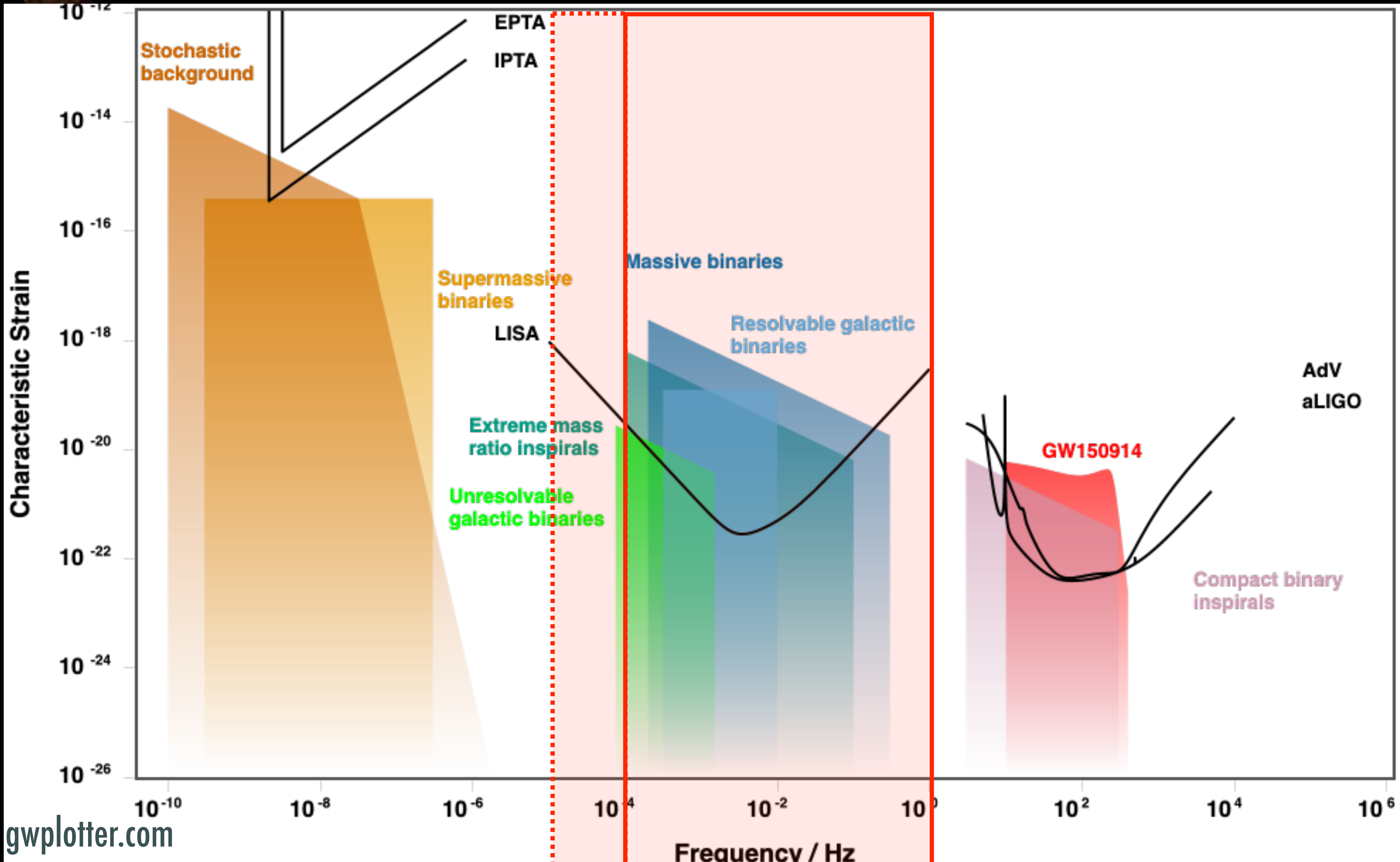
Noirmoutier - 6th June 2024

Sensitivity to GWs



gwplotter.com

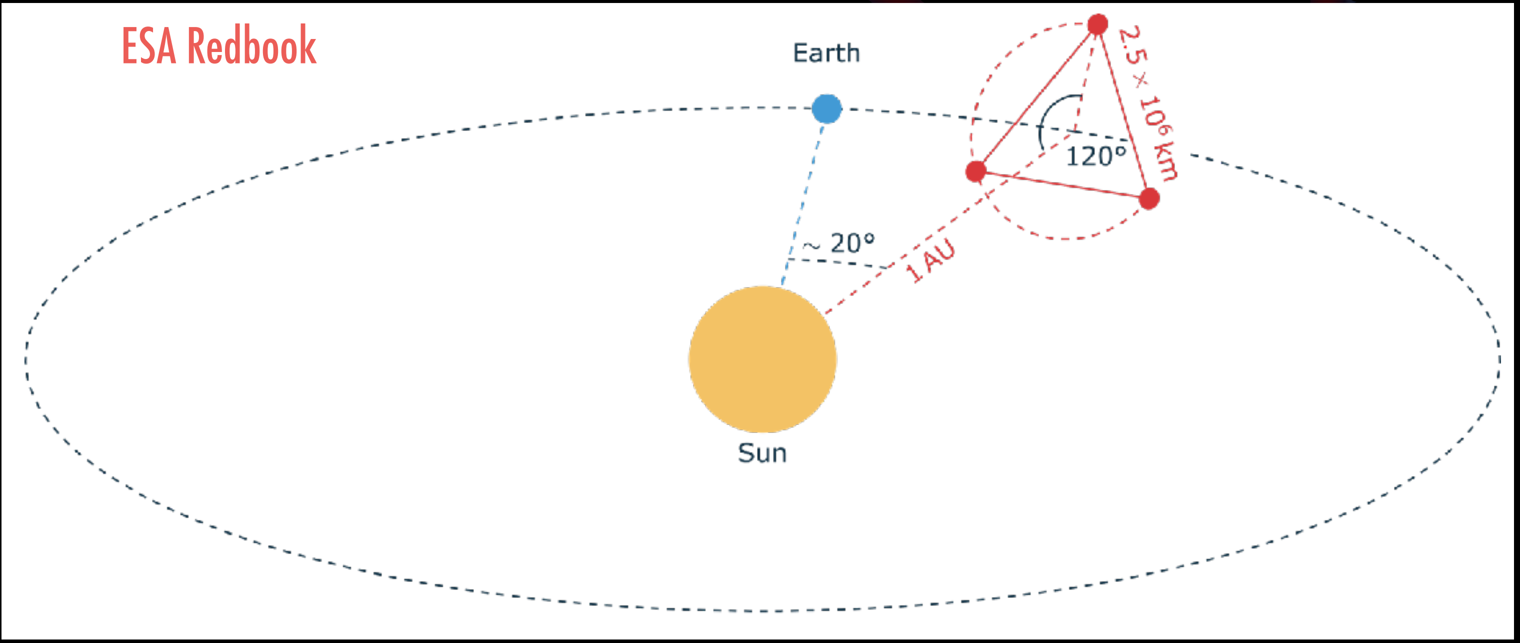
Sensitivity to GWs

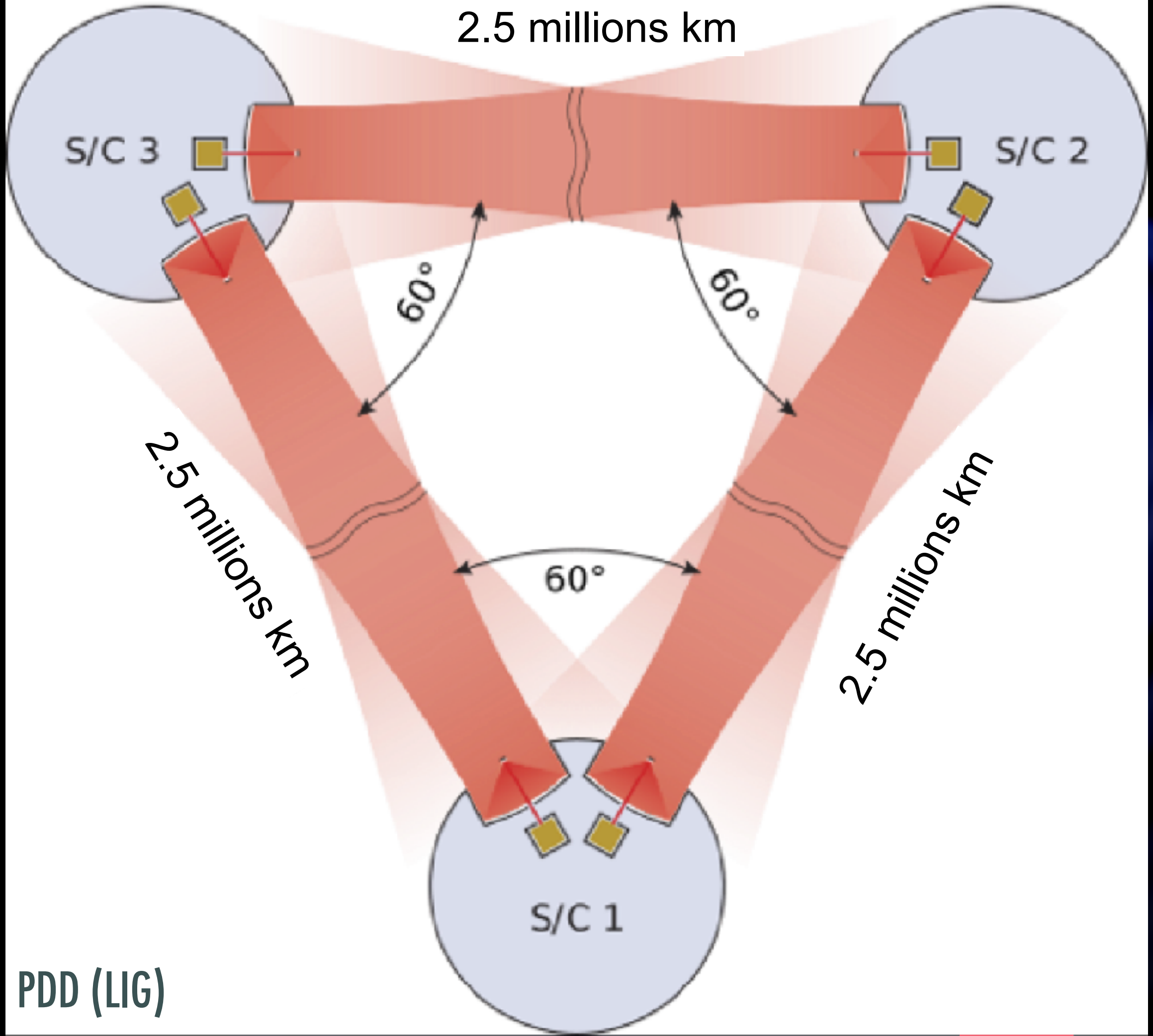


gwplotter.com

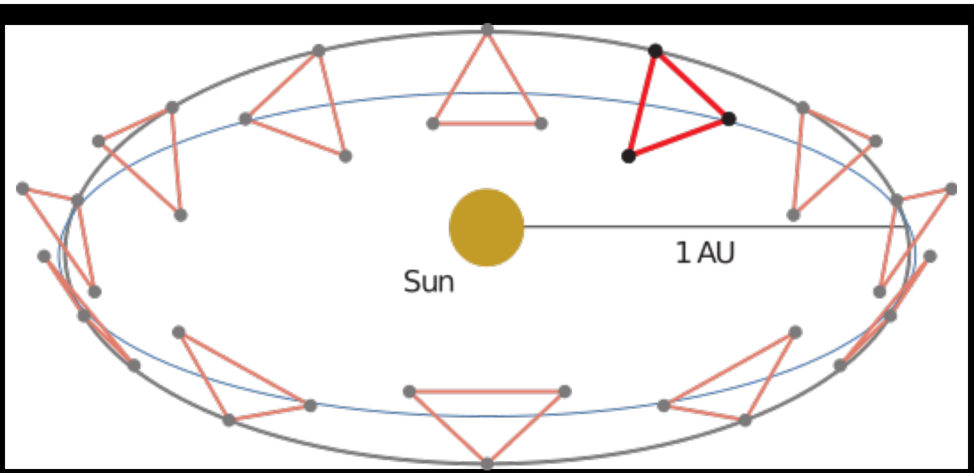
Mission design

- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits separated by 2.5 millions km
- Goal: detect strains of 10^{-21} by monitoring arm length changes at the few picometre level



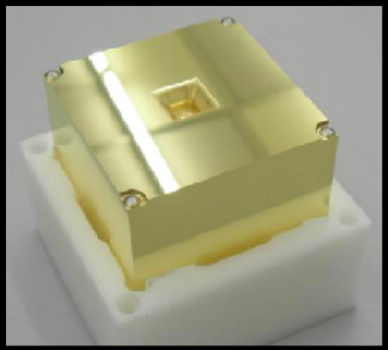


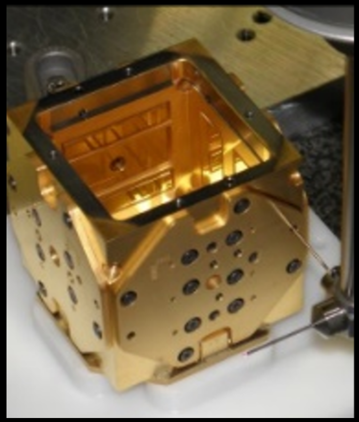
L3 proposal
(LISA Consortium)

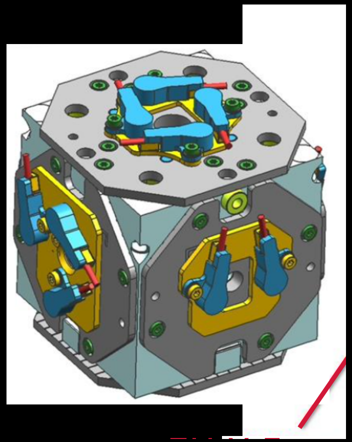


Mission design

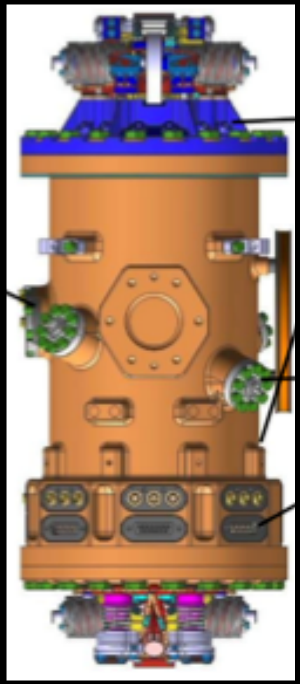
- Measurement points must be **shielded from fluctuating non-gravitational influences**:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing

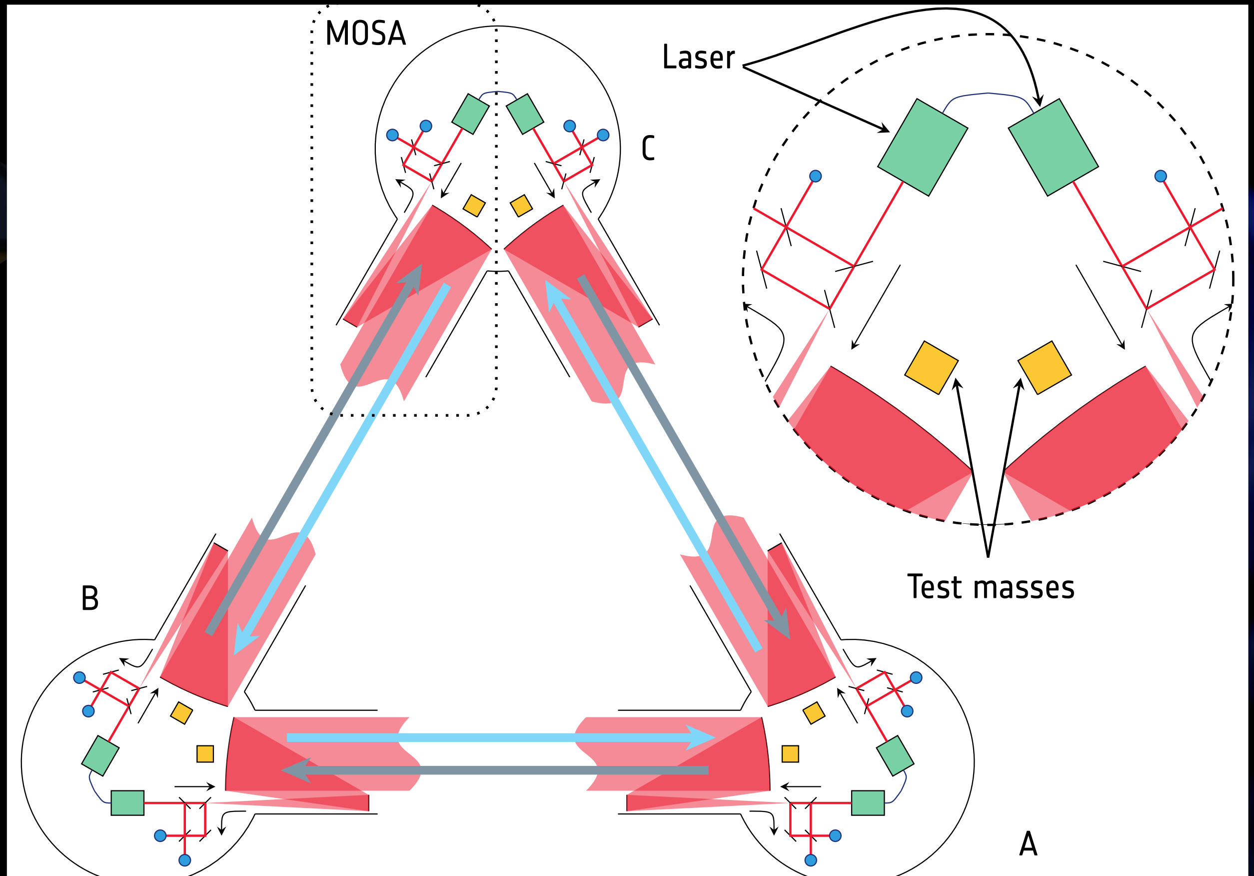






ESA Redbook - OHB Italia

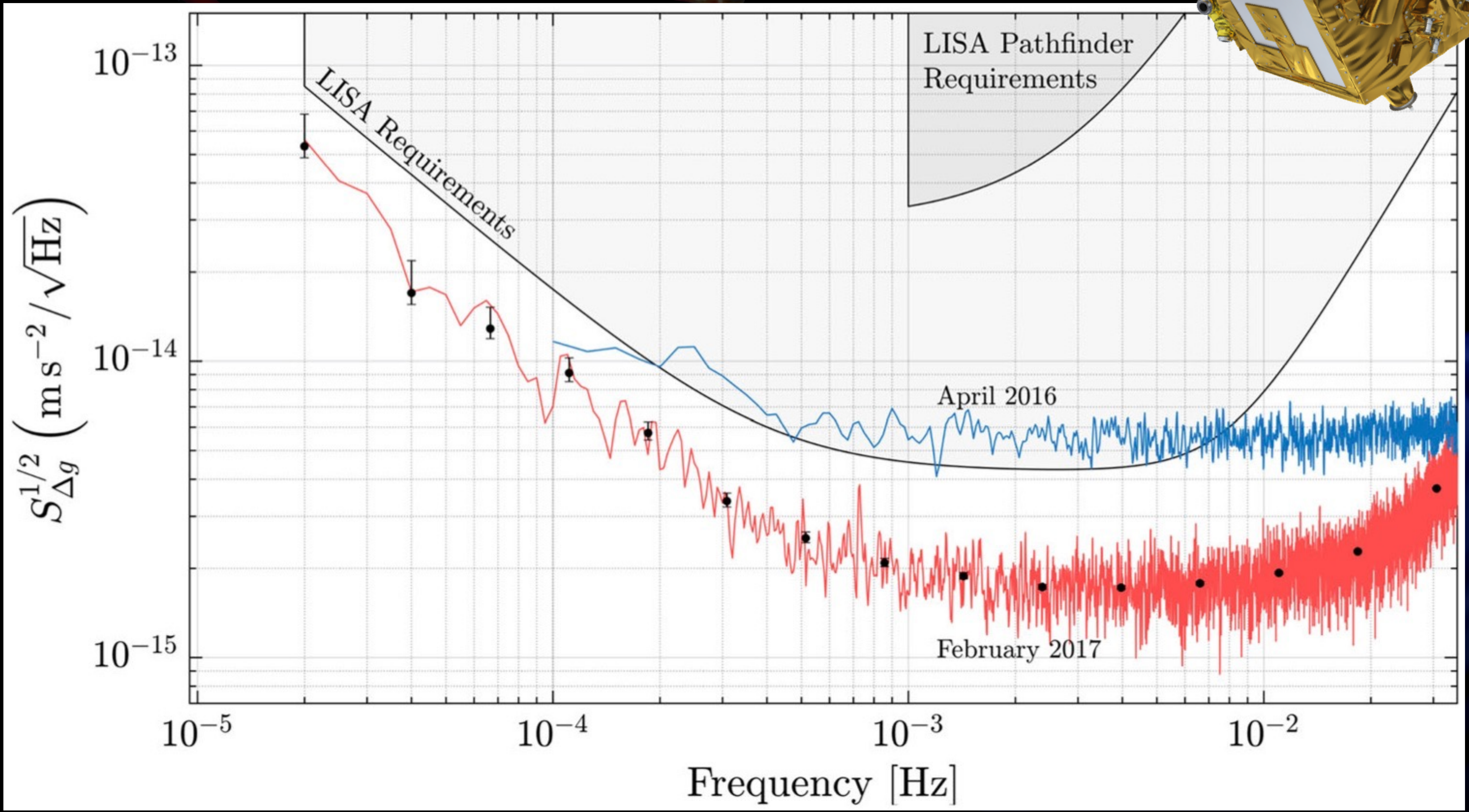




ESA Redbook

LISAPathfinder final main results

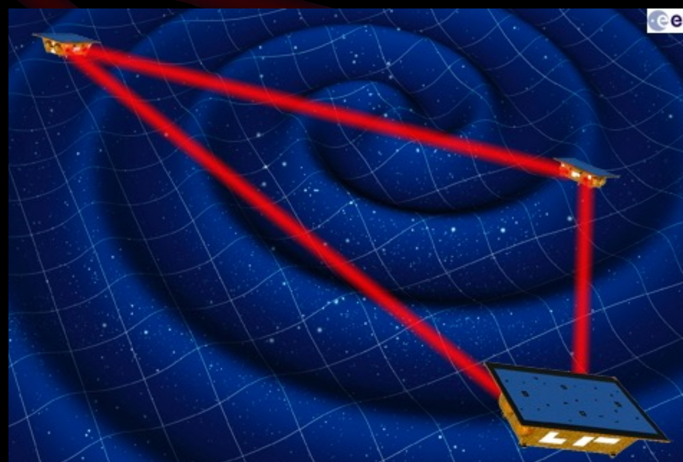
- Successful demonstration of the ability to shield from fluctuating non-gravitational influences



M. Armano et al. PRL 120, 061101 (2018)

Mission design

- Several steps towards the required precision of measurement



Mission design

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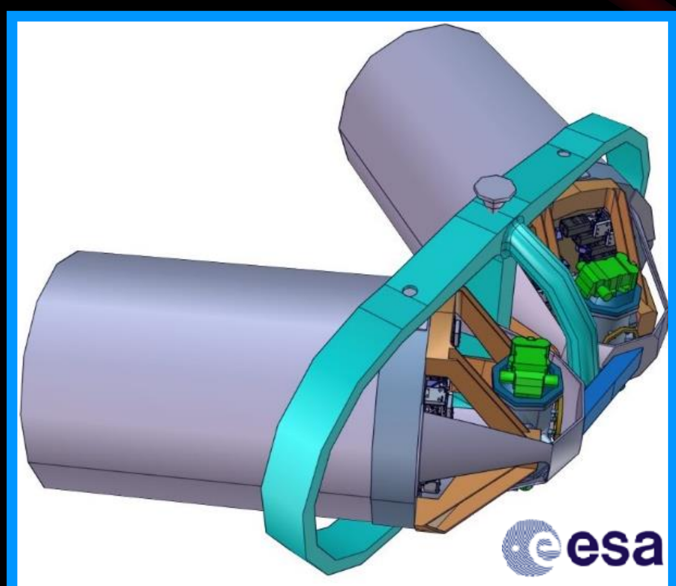

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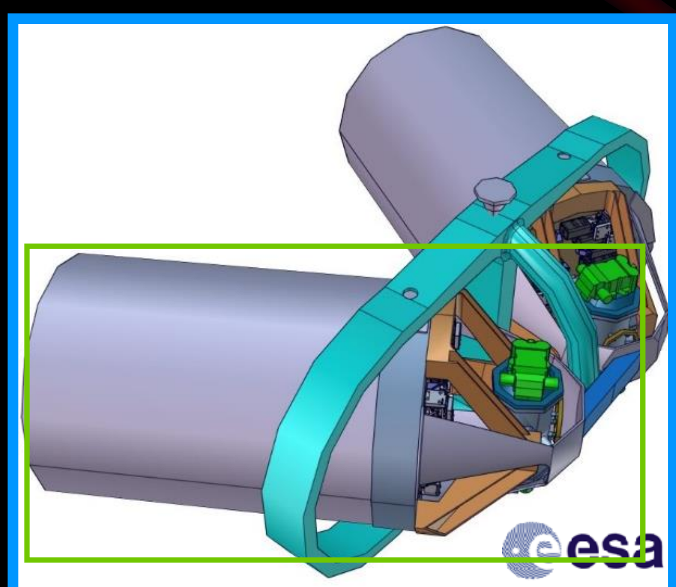

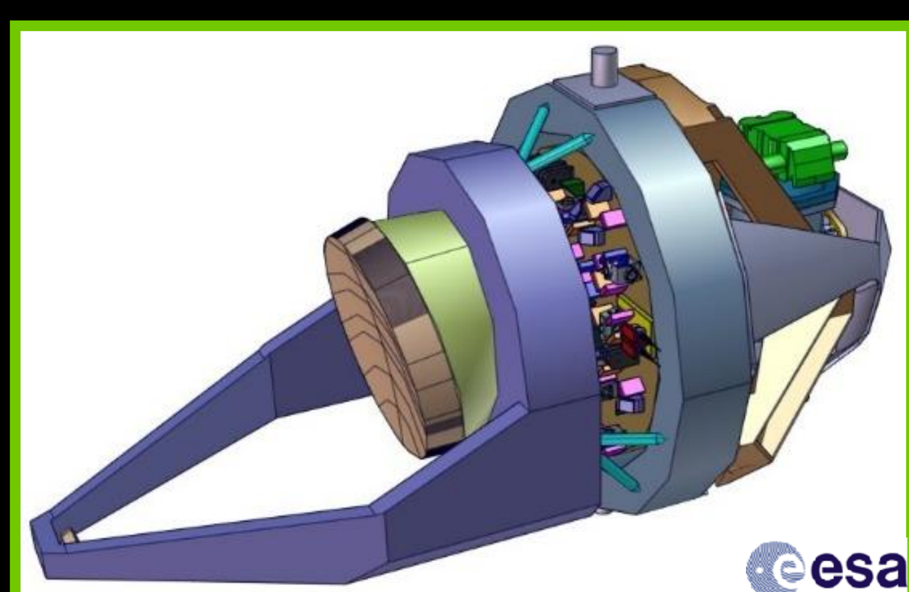

Mission design

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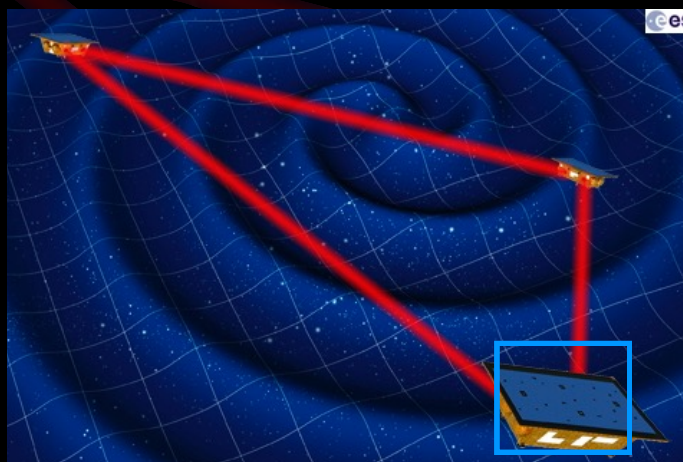

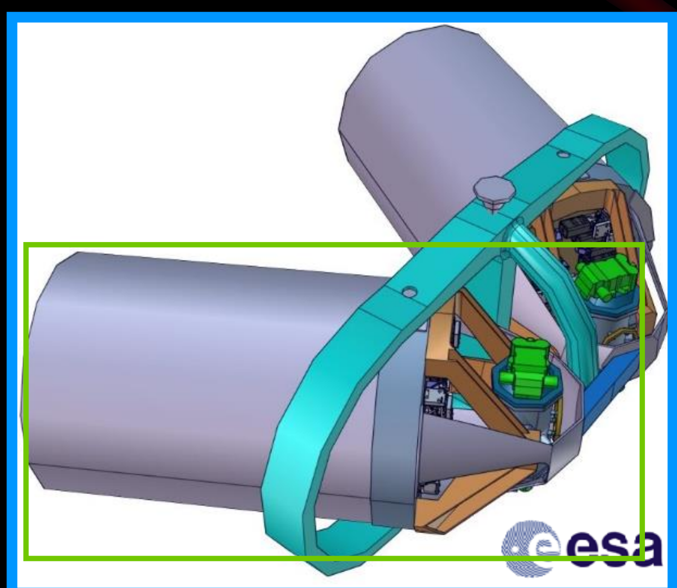

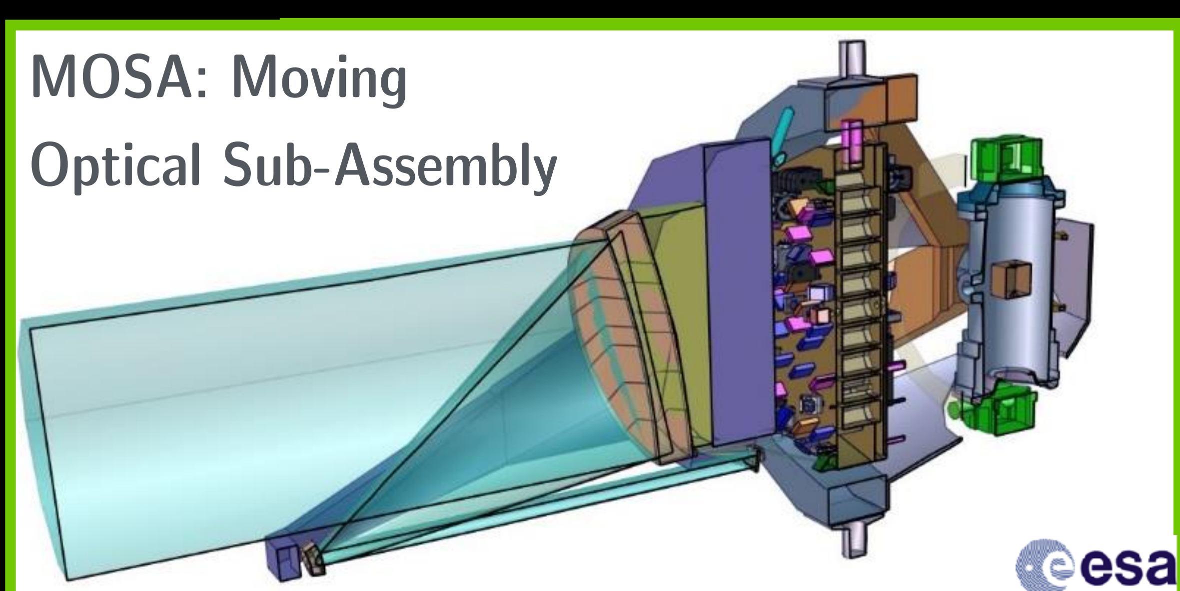

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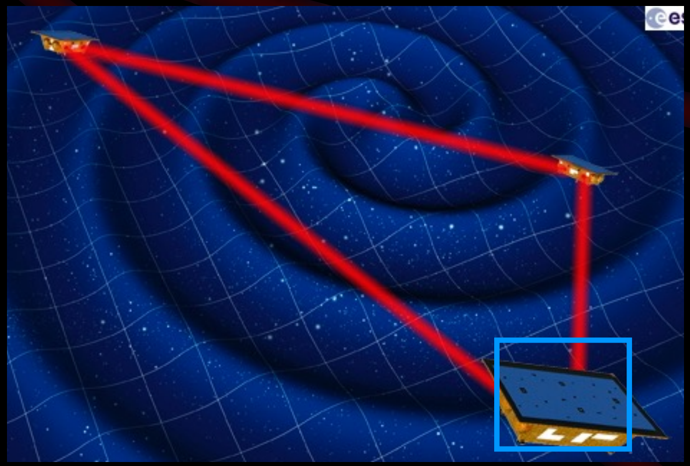
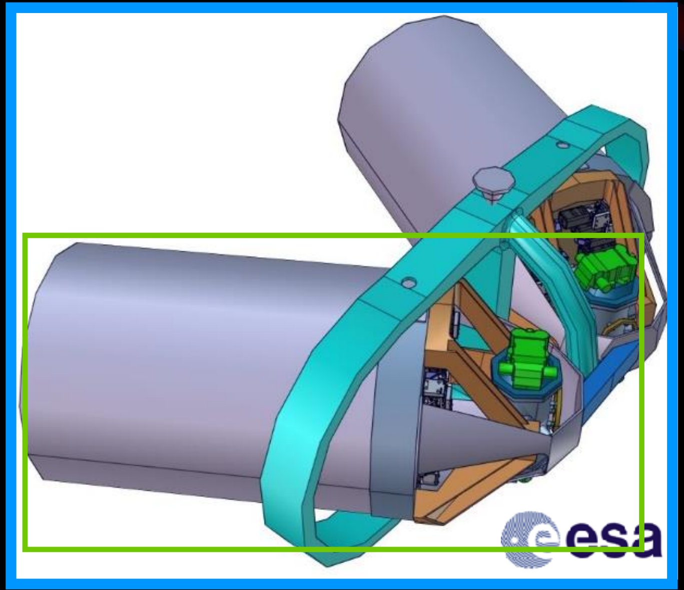
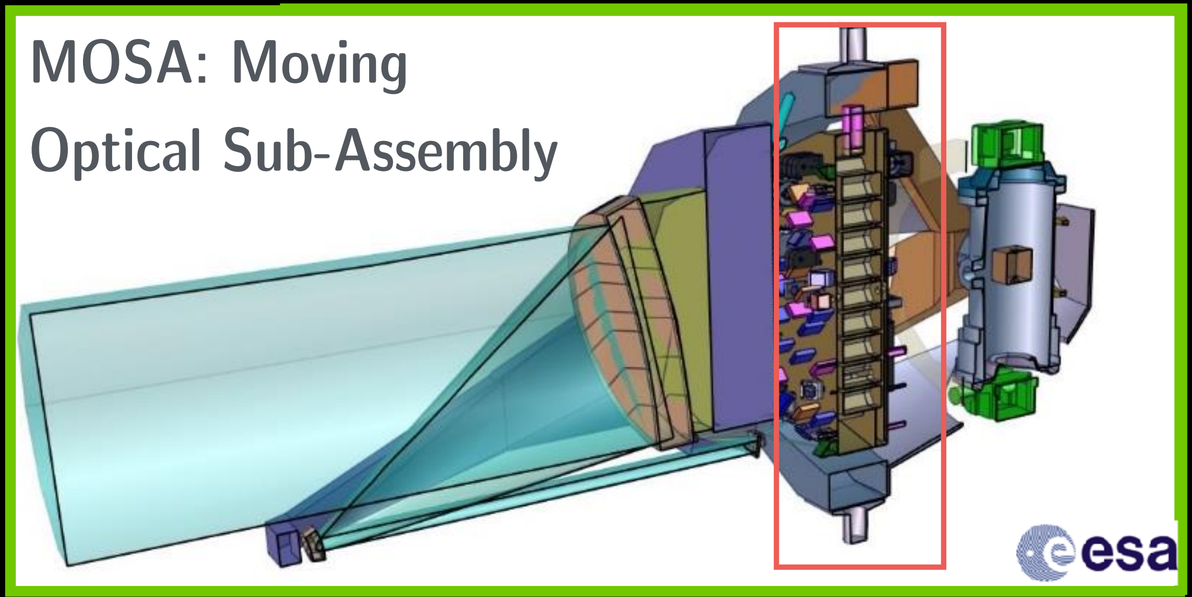
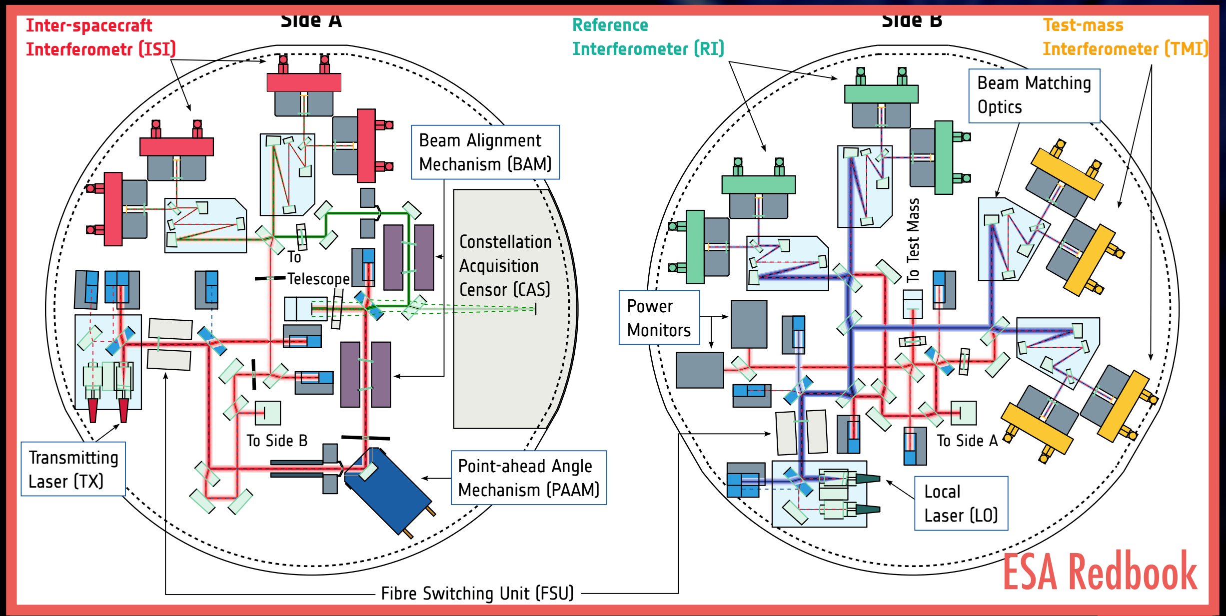






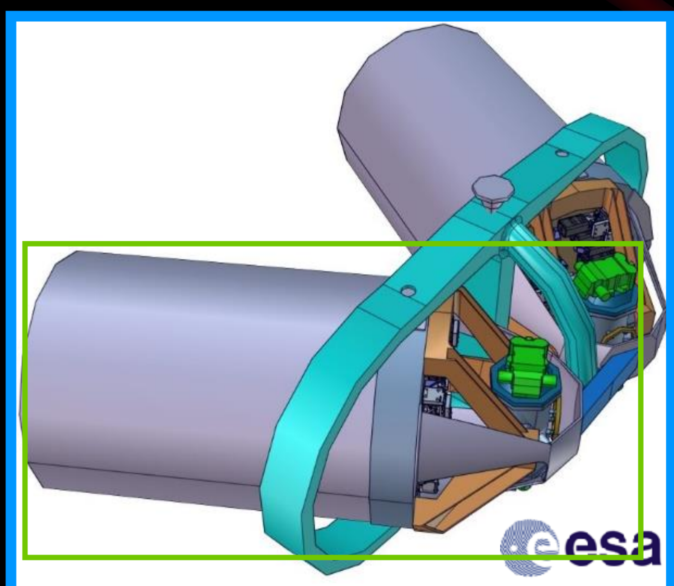


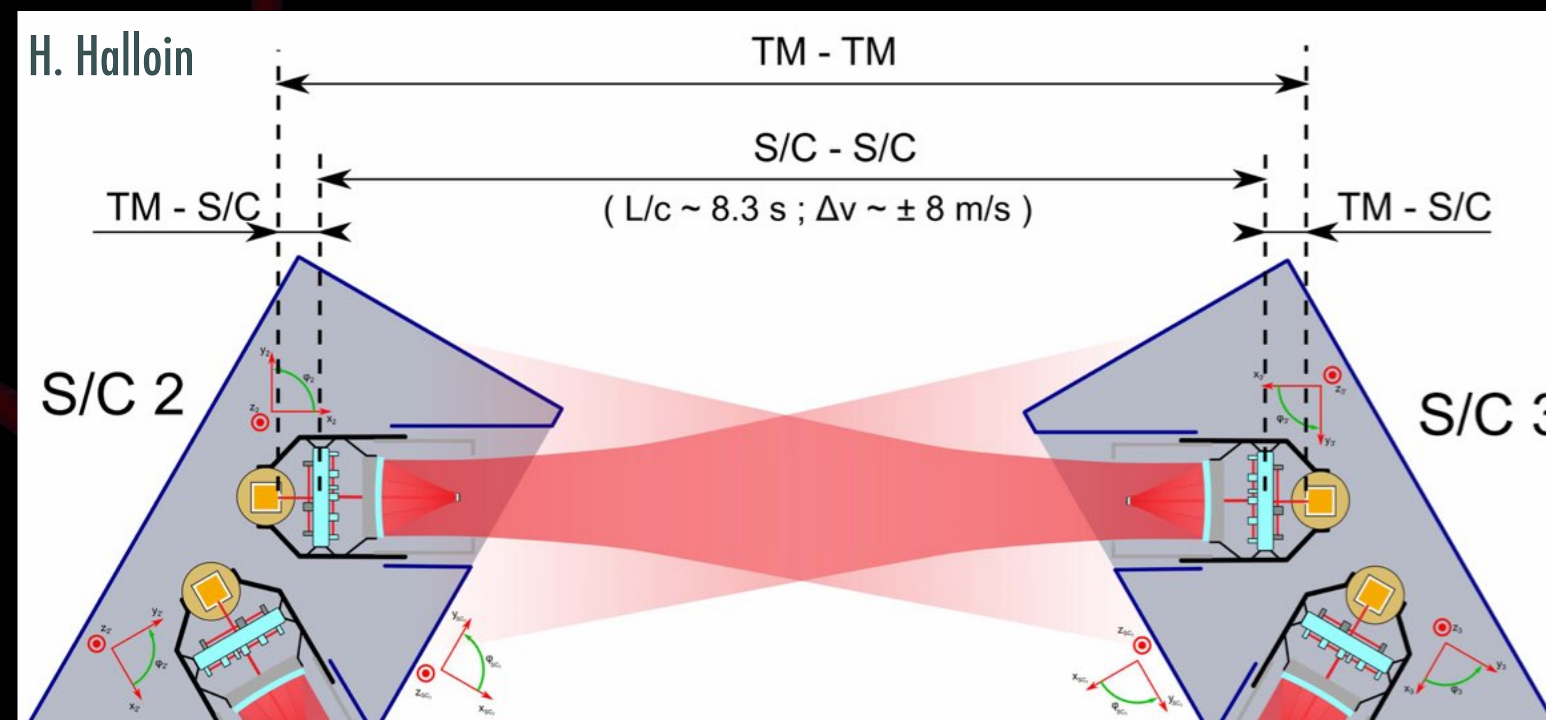
irfu

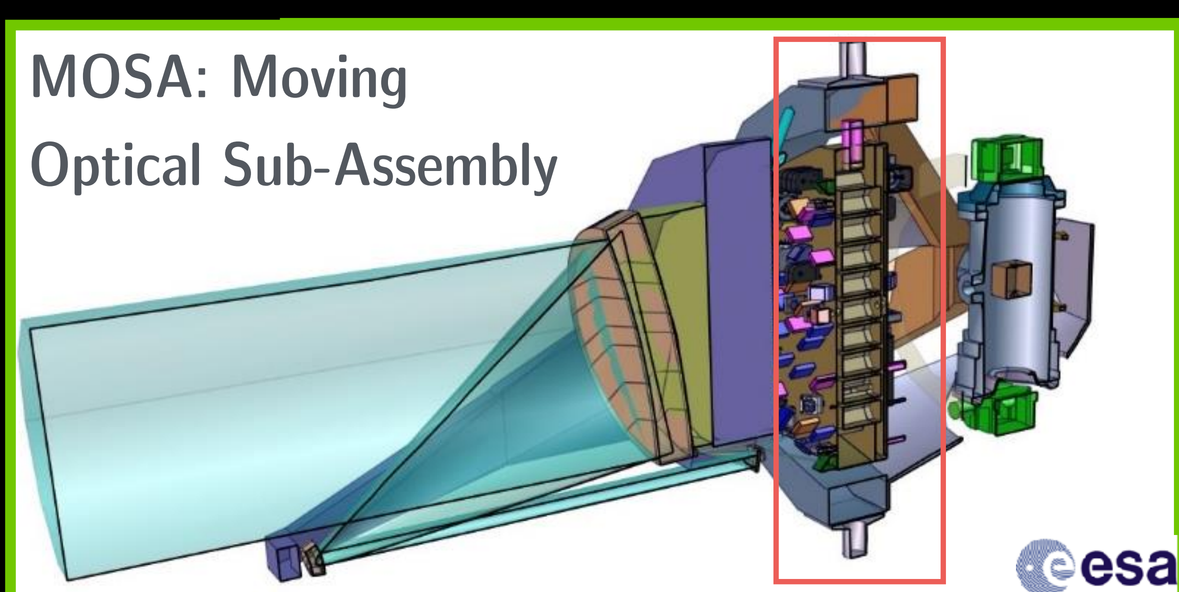
Mission design

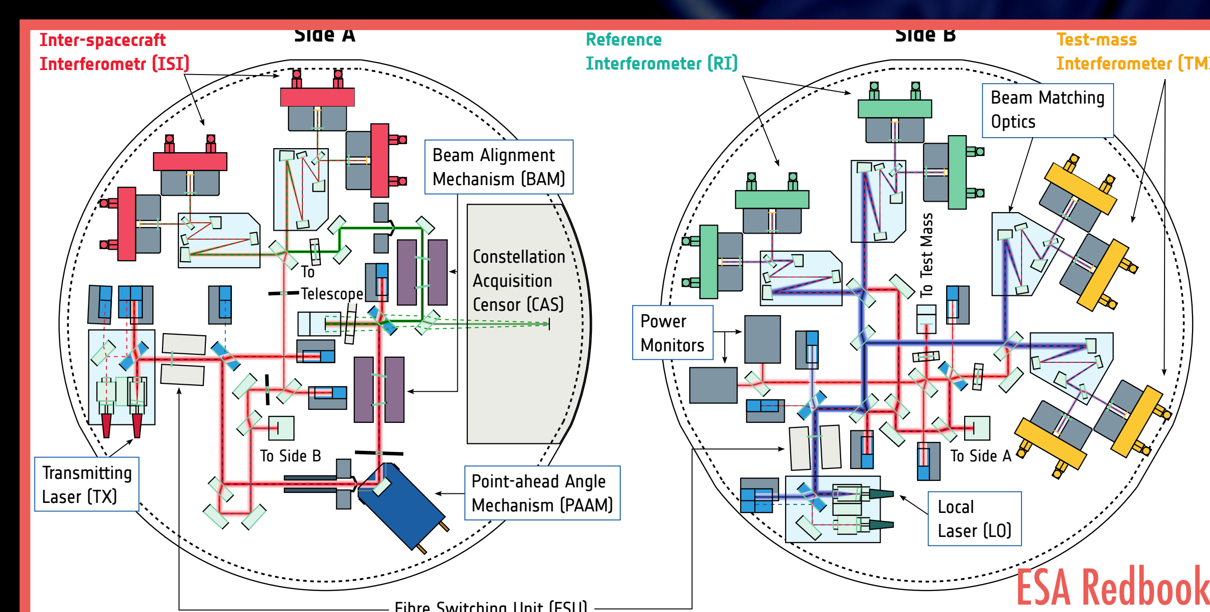
- Several steps towards the required precision of measurement

$$(TM2 \rightarrow SC2) + (SC2 \rightarrow SC3) + (SC3 \rightarrow TM3)$$



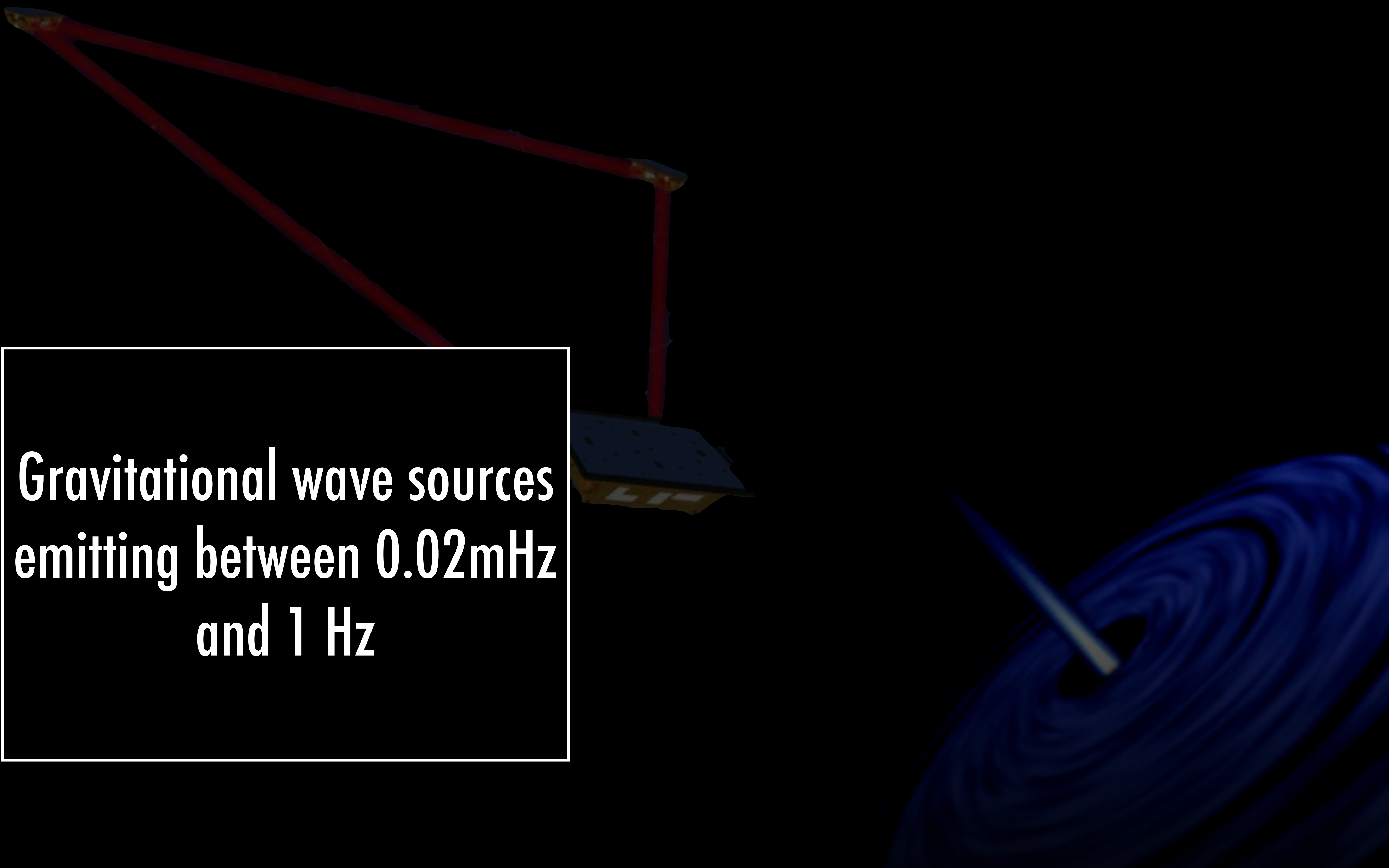






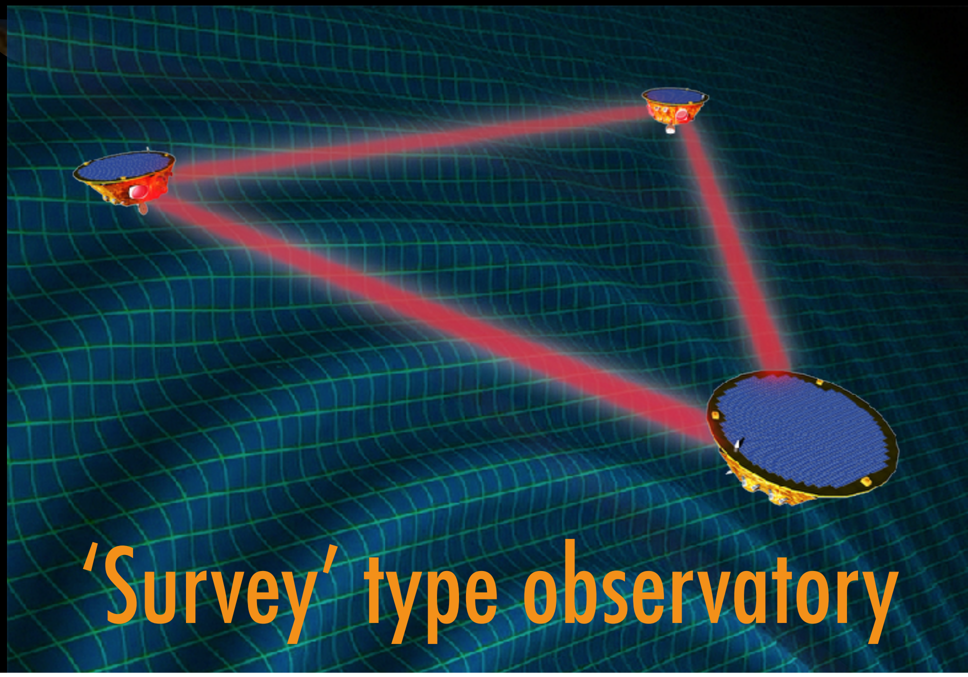
irfu

Data



Gravitational wave sources emitting between 0.02mHz and 1 Hz

Data



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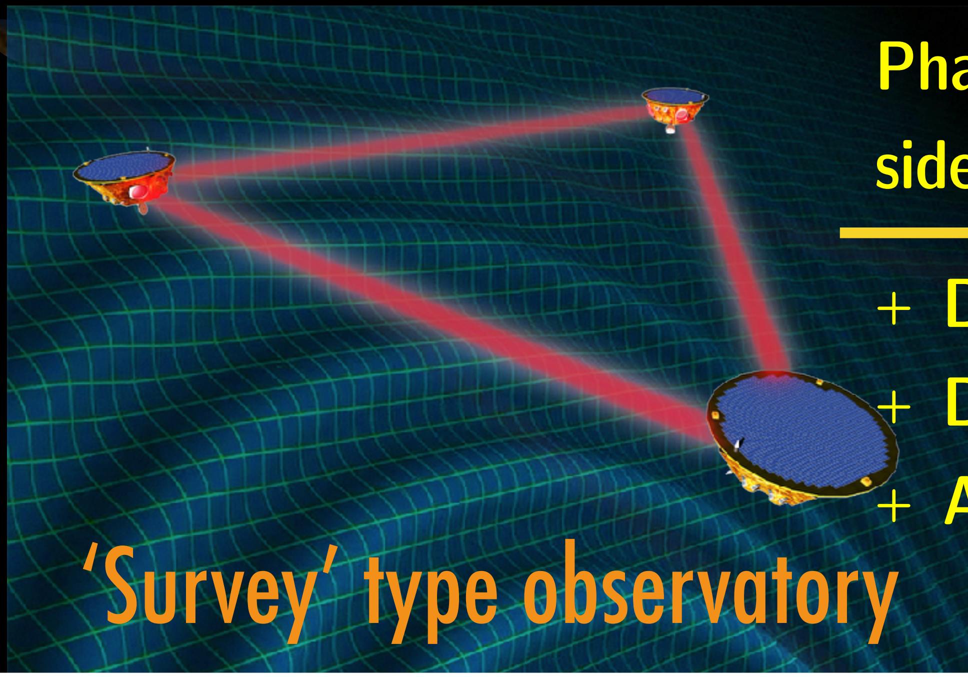


Phasemeters (carrier, sidebands, distance)

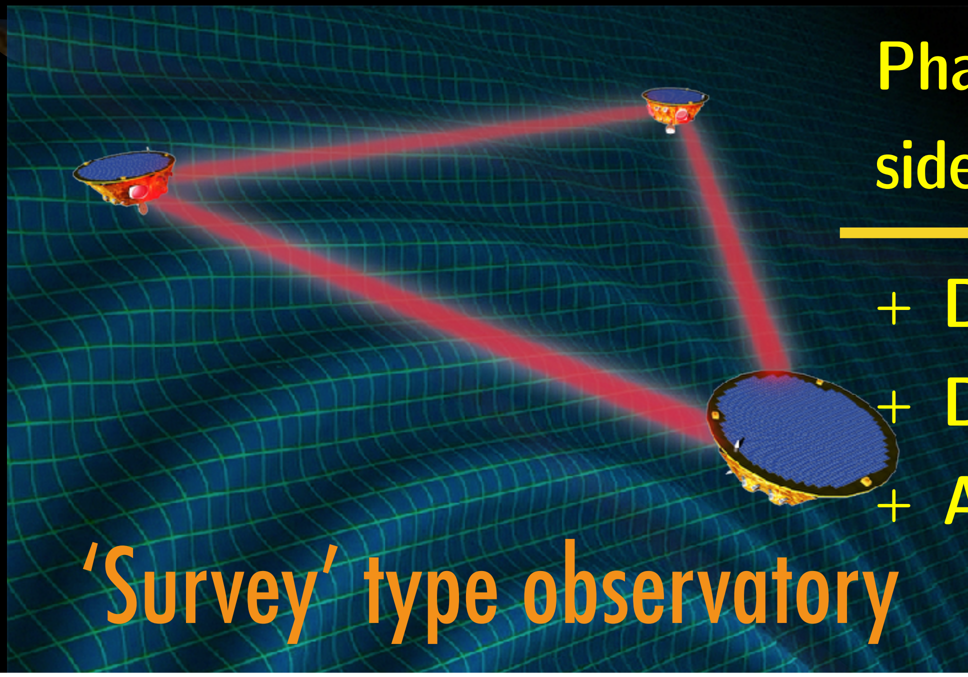
- + DFACS* & CMD**
- + Diagnostics
- + Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

Data



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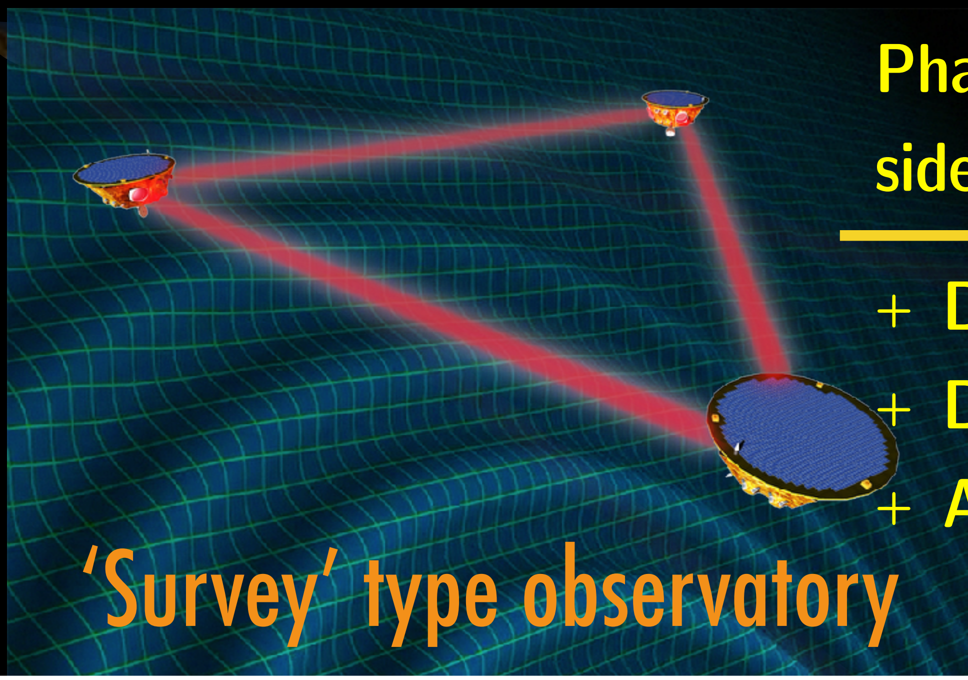

Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
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Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry reduction of laser noise

3 TDI channels with 2 "~independents"

Gravitational wave sources emitting between 0.02mHz and 1 Hz

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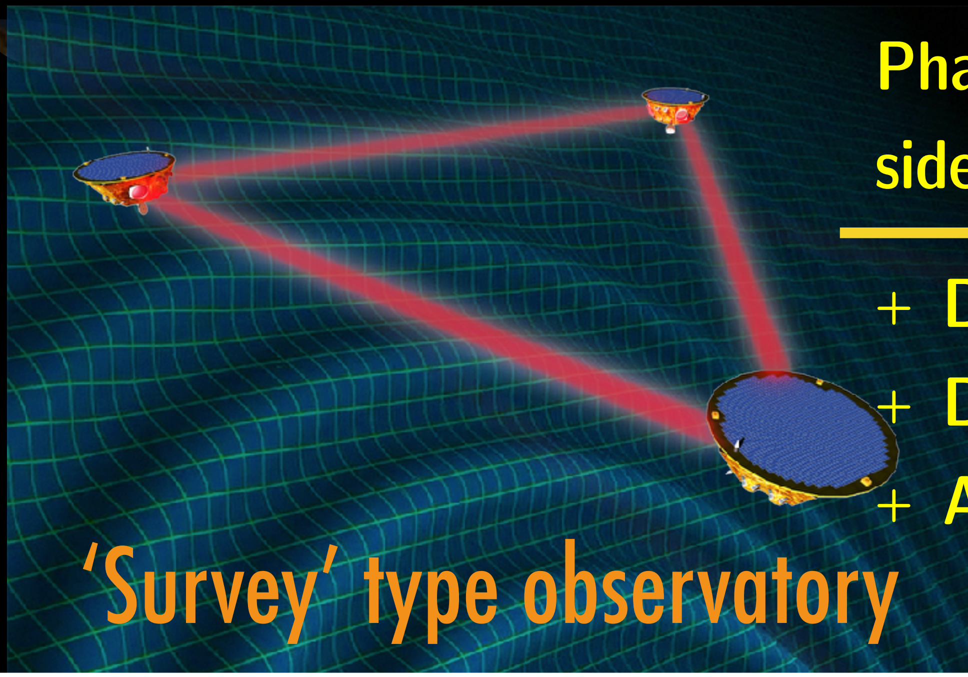

'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
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Data Analysis of GWs

Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

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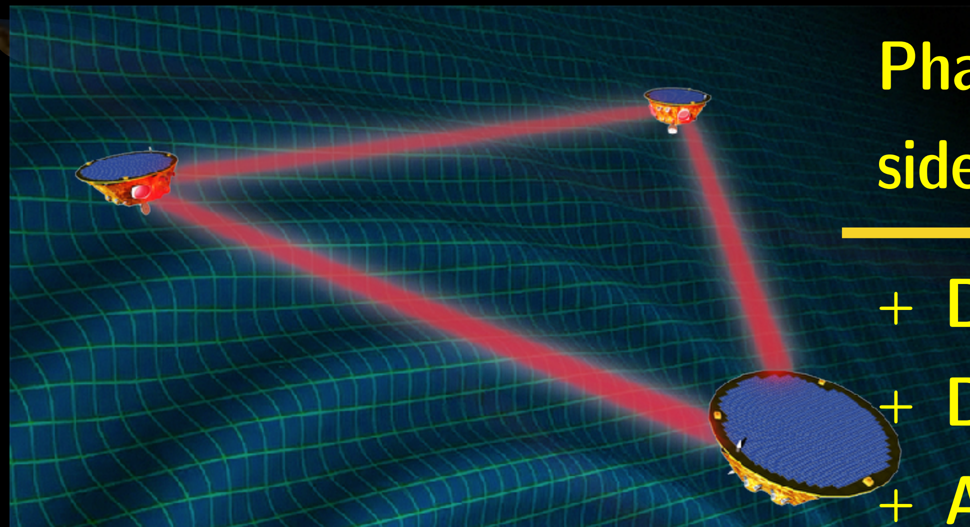
** Charge Management Device

Data



Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
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+ Auxiliary channels

'Survey' type observatory

L0

L0.5

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

Gravitational wave sources emitting between 0.02mHz and 1 Hz

L1 — 3 TDI channels with 2 "~independents"

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

* Drag-Free Attitude Control System

** Charge Management Device

Data

Phasemeters (carrier, ...ds, distance)

...CS* & CMD**

+ Diagnostics

+ Auxiliary channels

'Survey' type observatory

Gravitational wave sources

Mission Operation Center (ESA)

Science Operation Center (ESA)

DDPC: Distributed Data Processing Center (ESA Member States)

NASA Ground Segment

L0

L0.5

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

L1 — 3 TDI channels with 2 "~independents"

L2 — Data Analysis of GWs

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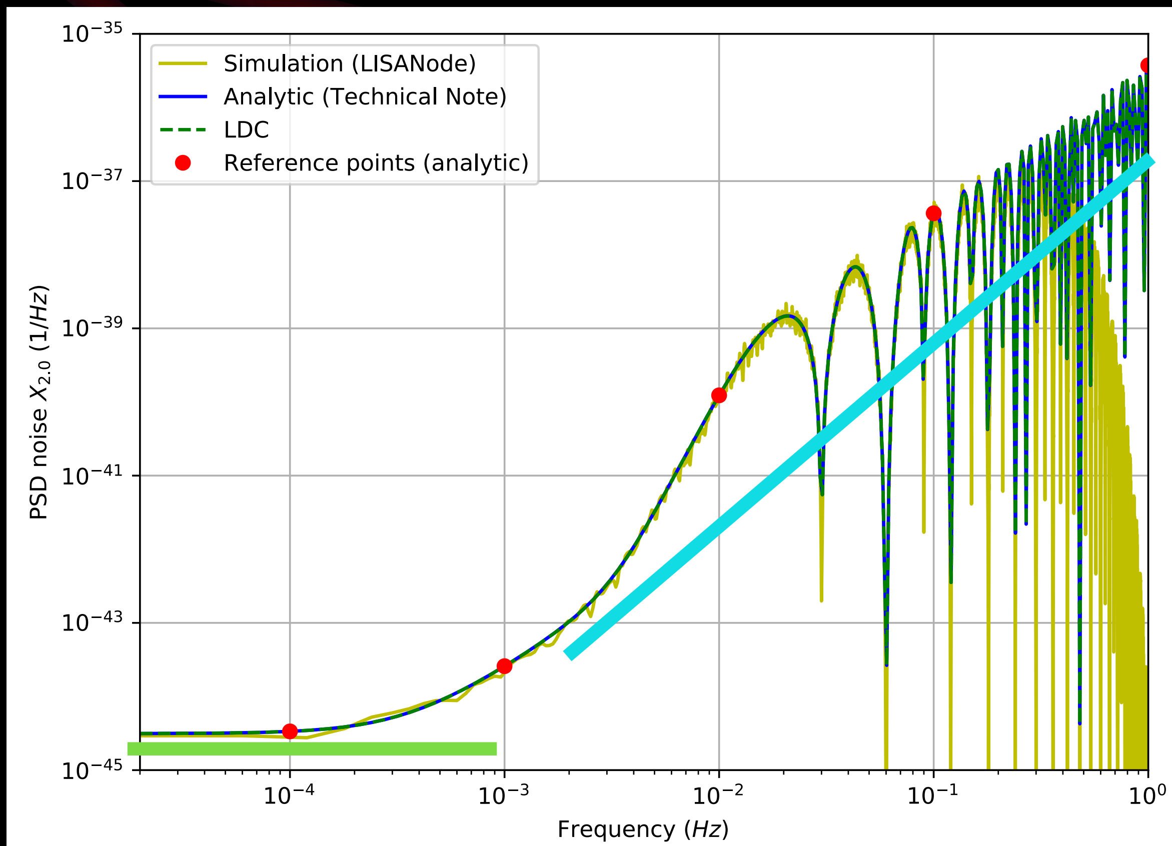
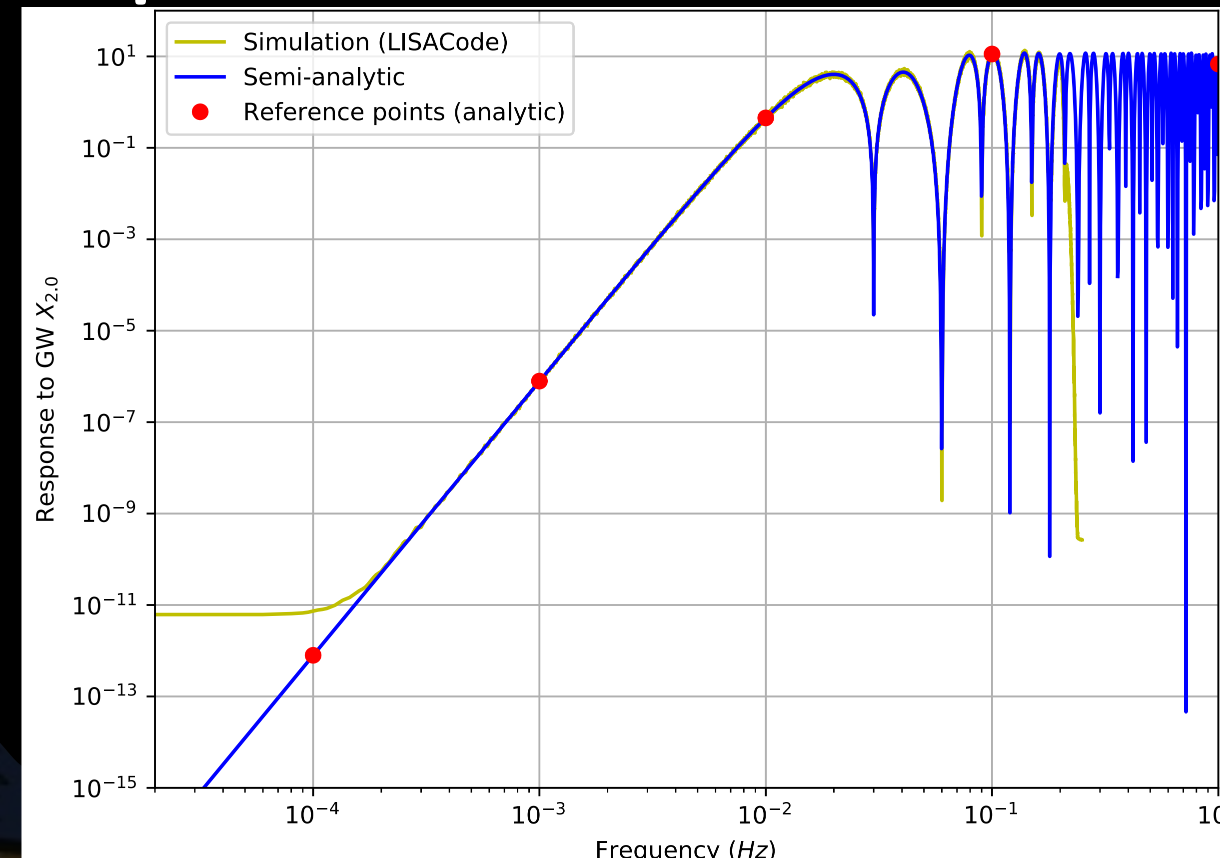
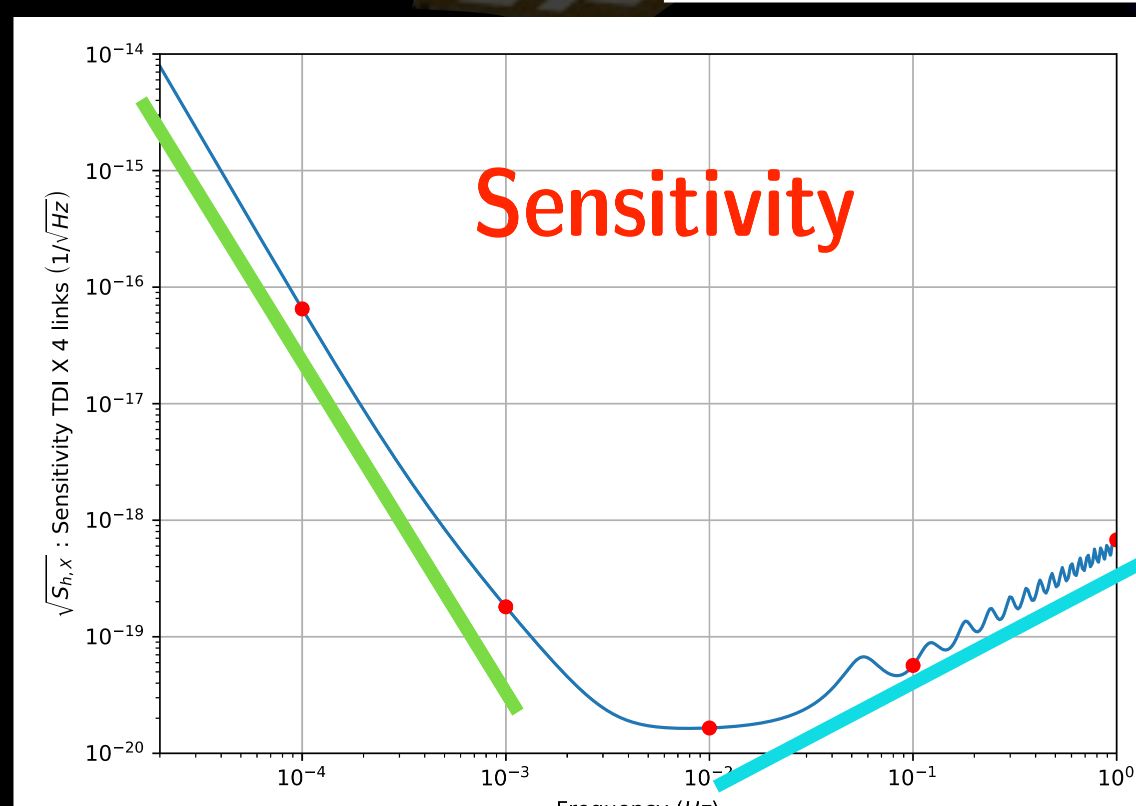
LISA sensitivity

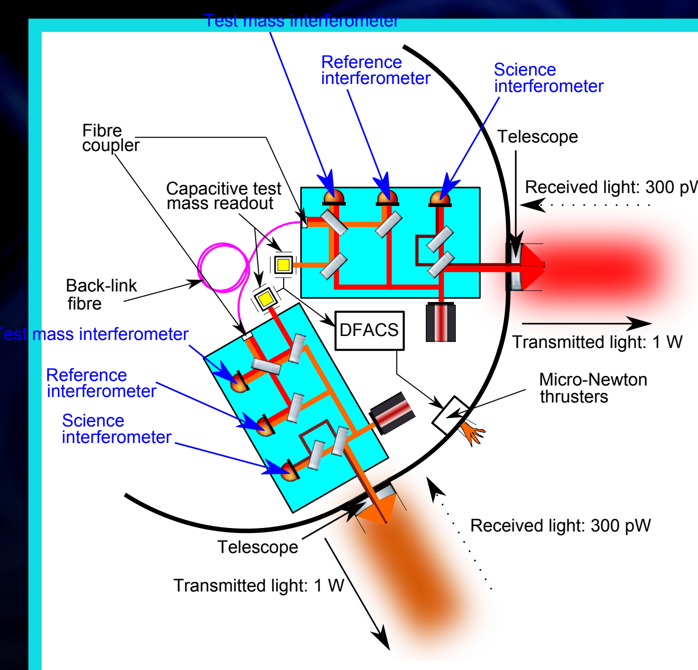
Noises



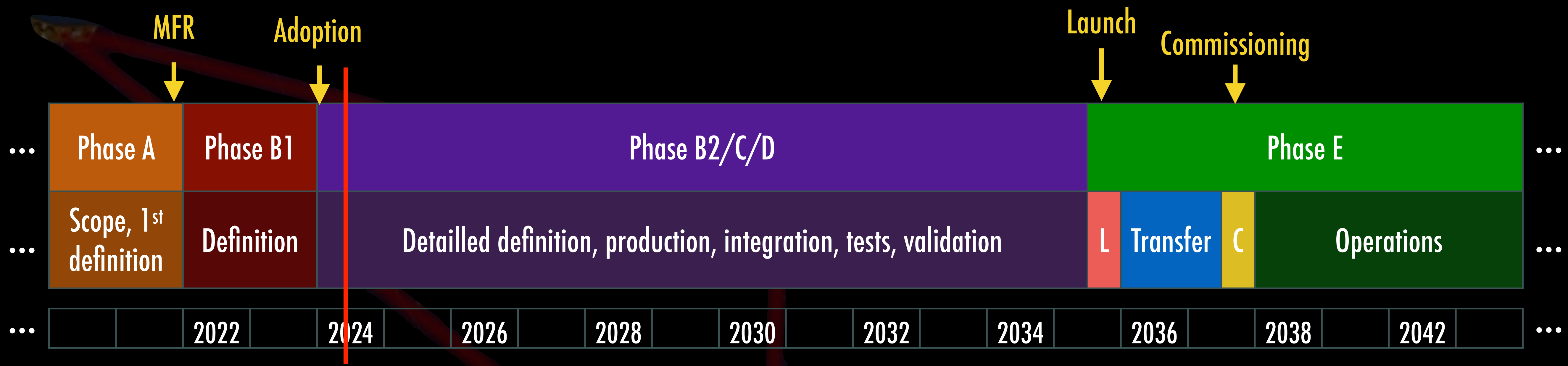
Response of the detector to GWs







Timeline and status

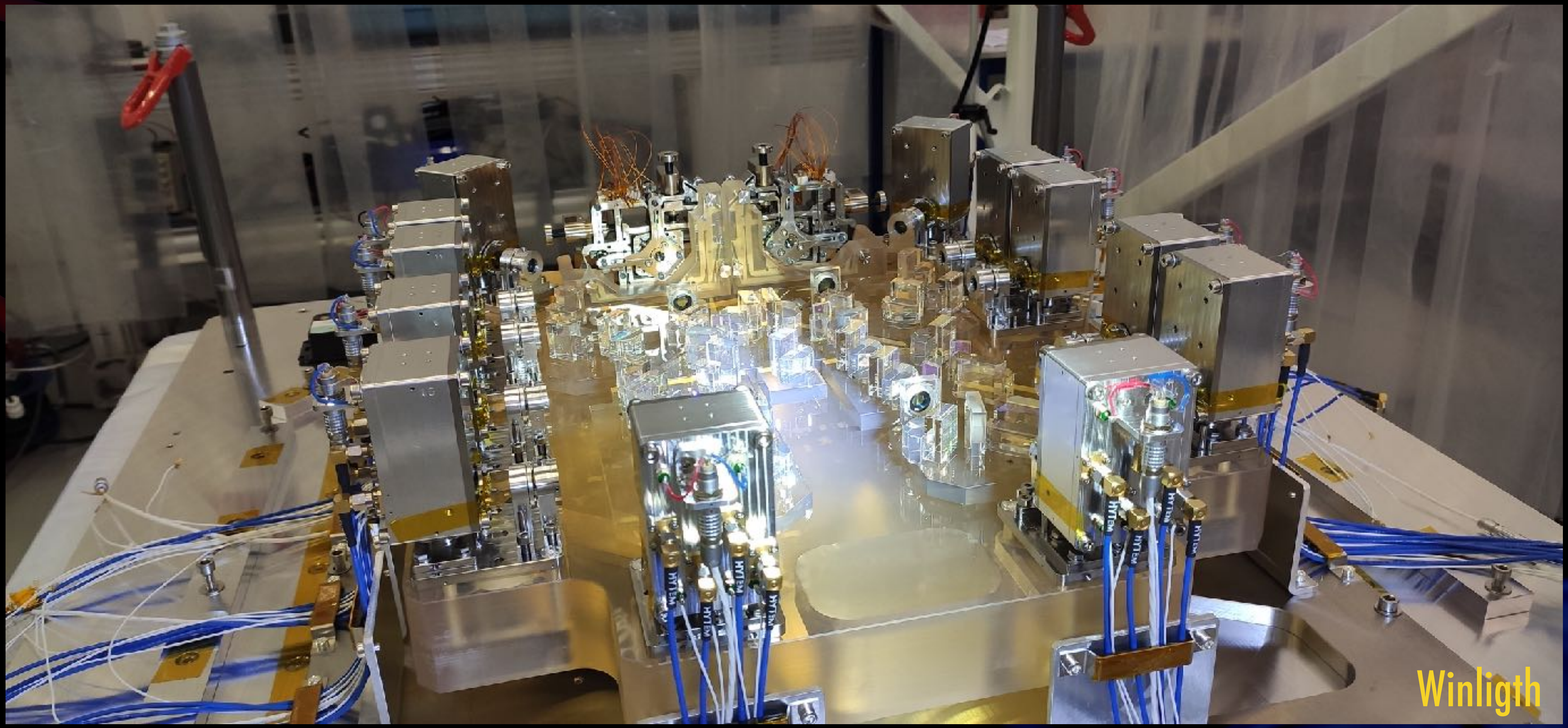


- 1993: first proposal ESA/NASA
- 20/06/2017: LISA mission approved by ESA Science Program Committee (SPC) after the success of LISAPathfinder and GW detection by LIGO-Virgo.
- End 2021: success of the ESA Mission Formulation Review
- 25/01/2024: success of the Mission Adoption Review and adoption by the SPC: design is fully validated and we have the ressource to build the instrument
- Long building phase of multiple MOSAs: 6 flight models + test models
- Launch 2035
- 1.5 years of transfer, 4.5 years nominal mission, 6.5 years extension

Timeline and status

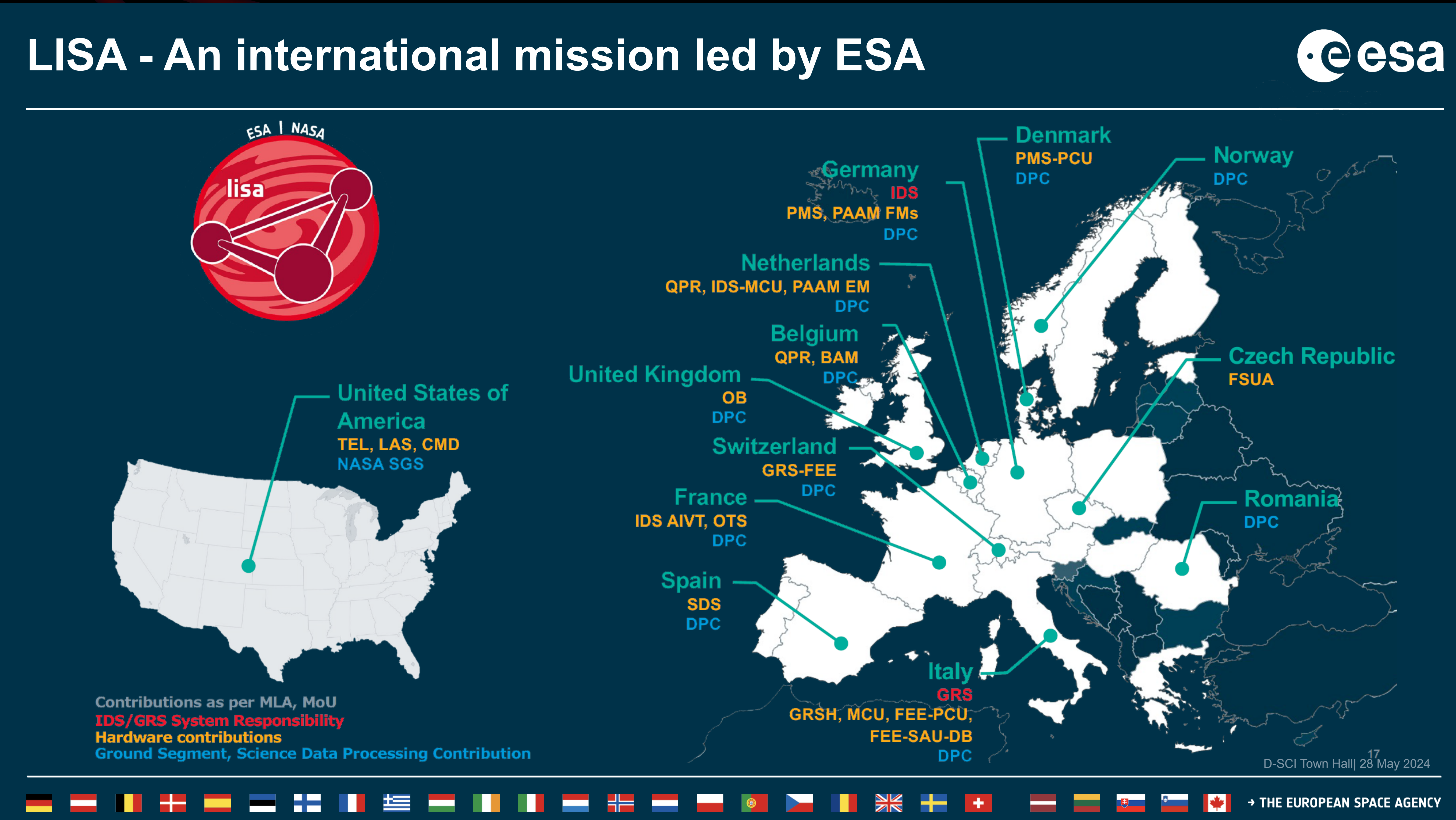
Building already started …

ZIFO (demonstration bench for high stability interferometry)



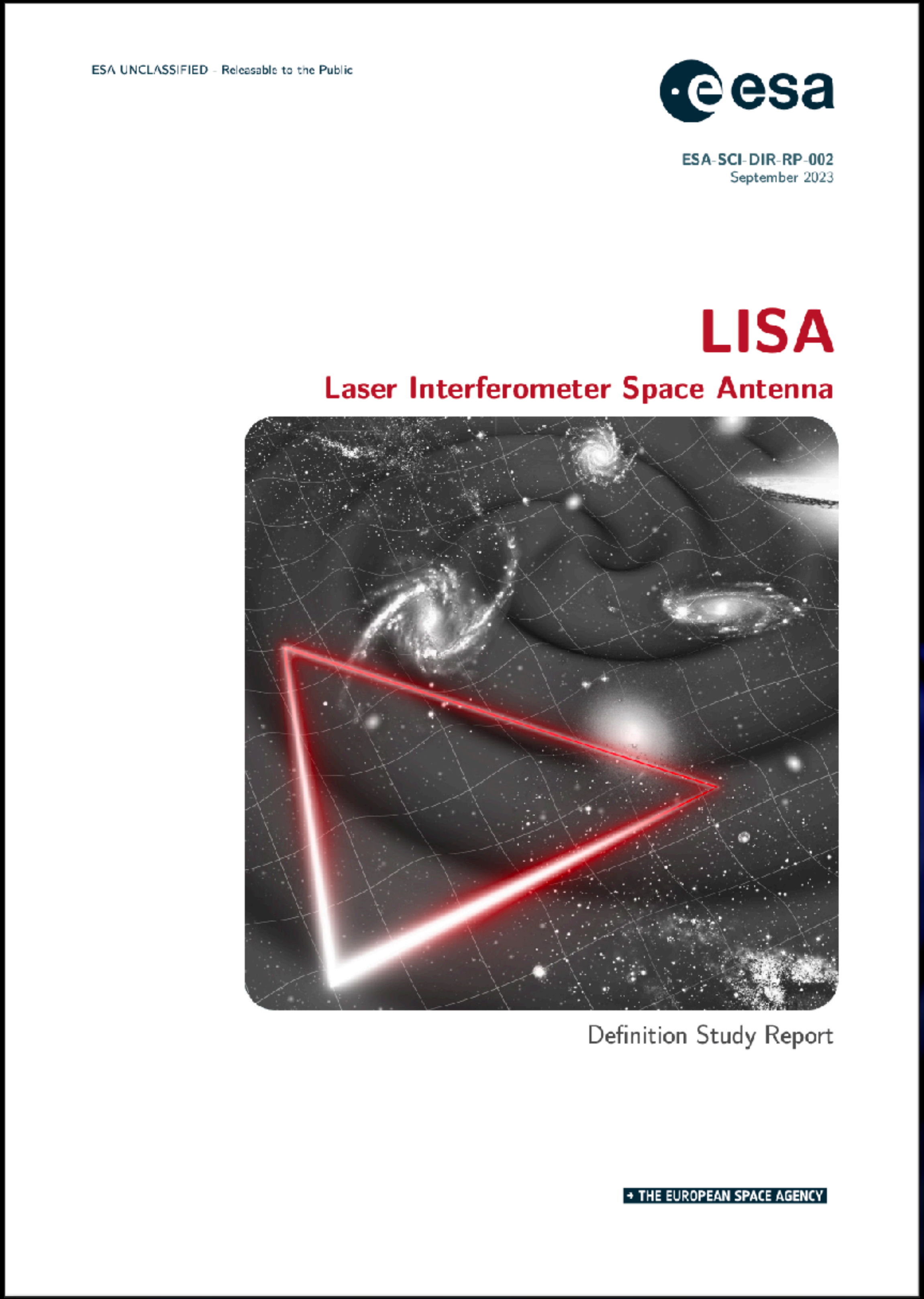
Telescope

LISA collaboration



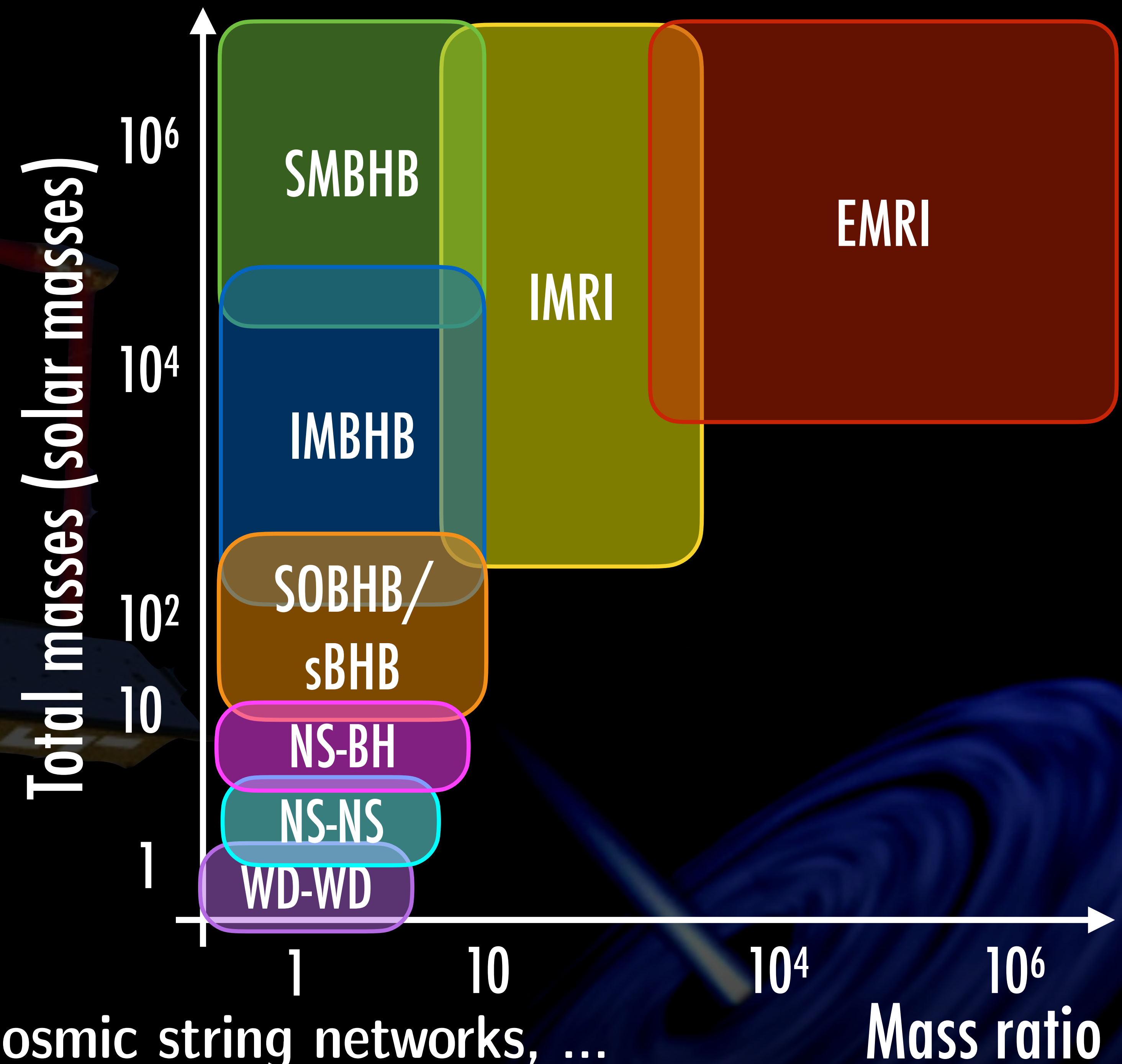
LISA RedBook

- LISA Definition Study Report (Redbook):
  - written by the LISA Science Study Team with the support of the LISA Consortium
  - submitted and validated at adoption
- Content:
  - Science of LISA
  - Instrument
  - Data processing
  - Organisation
- Available at :
  - arXiv:2402.07571
  - www.cosmos.esa.int/web/lisa/lisa-redbook



GW sources in the mHz band

- **Binaries**: large range of masses and mass ratios:
  - SuperMassive BH Binaries
  - Extreme Mass Ratio Inspiral
  - Stellar mass BH Binaries
  - Double White Dwarfs
  - Double Neutron Stars
  - Intermediate Mass Ratio Inspiral
  - Intermediate Mass BH Binaries



- **Stochastic backgrounds**:
  - First order phase transitions, cosmic string networks, ...
- Bursts: cosmic strings, ...
- Unknown?

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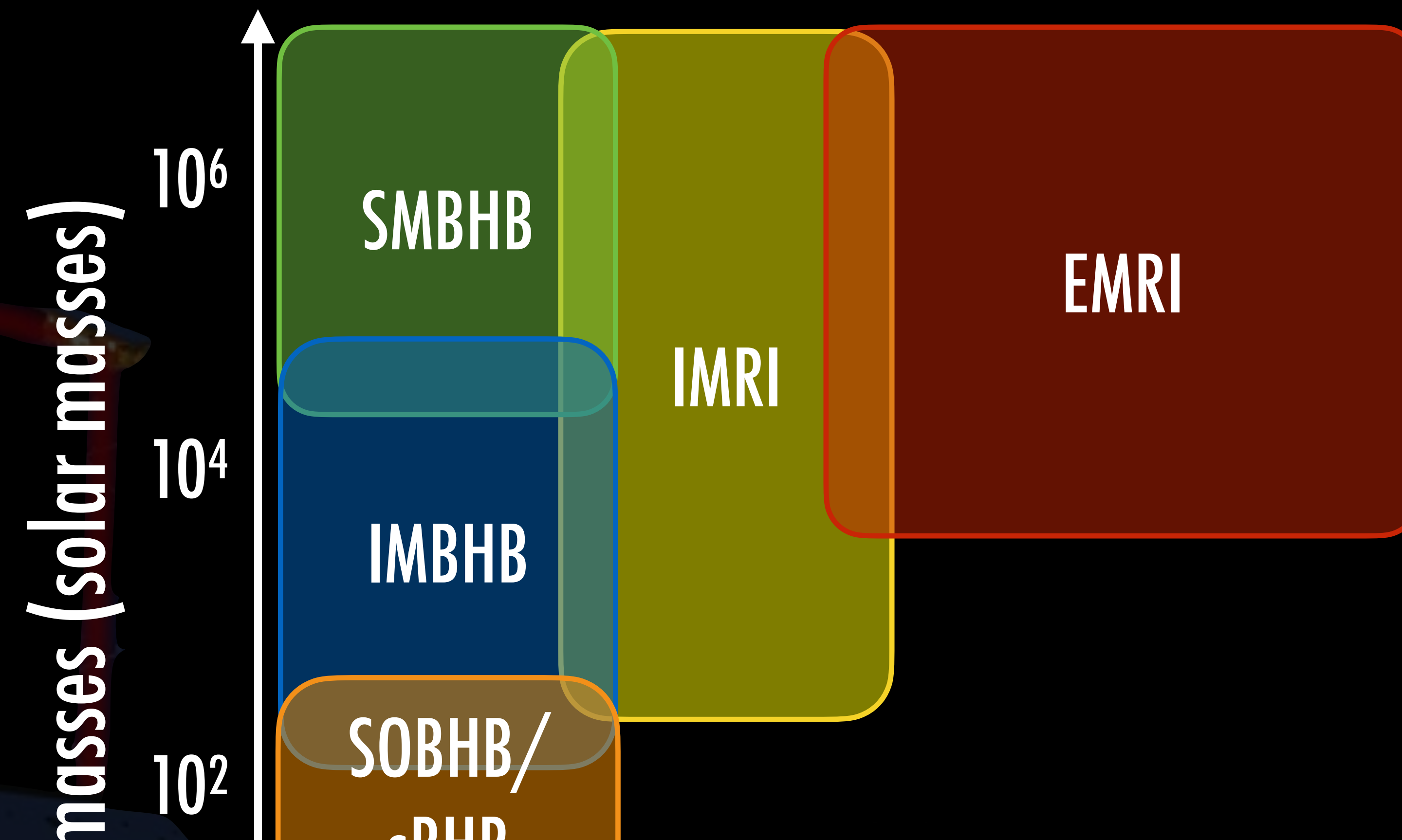
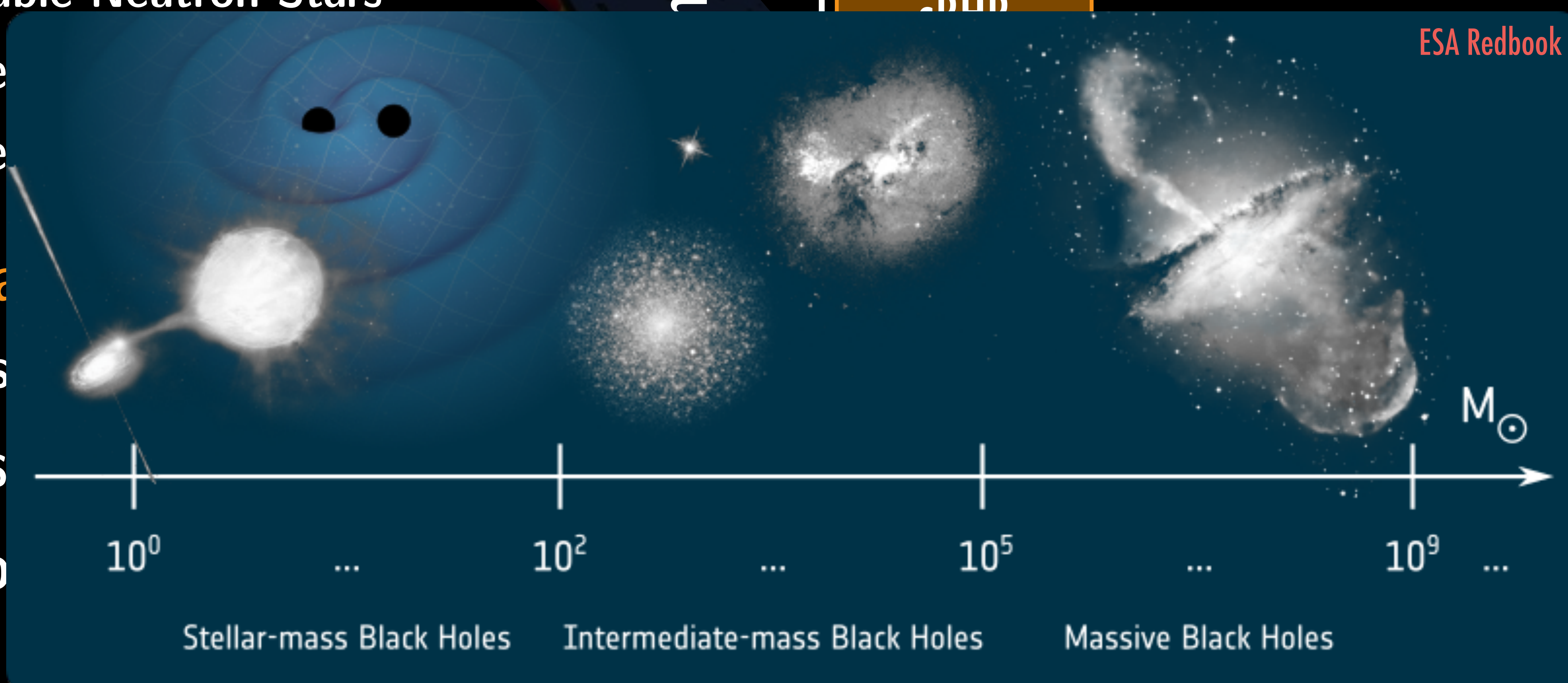
  - Inte
- **Stocha**
  - Firs
- Bursts
- Unkno





06
ratio

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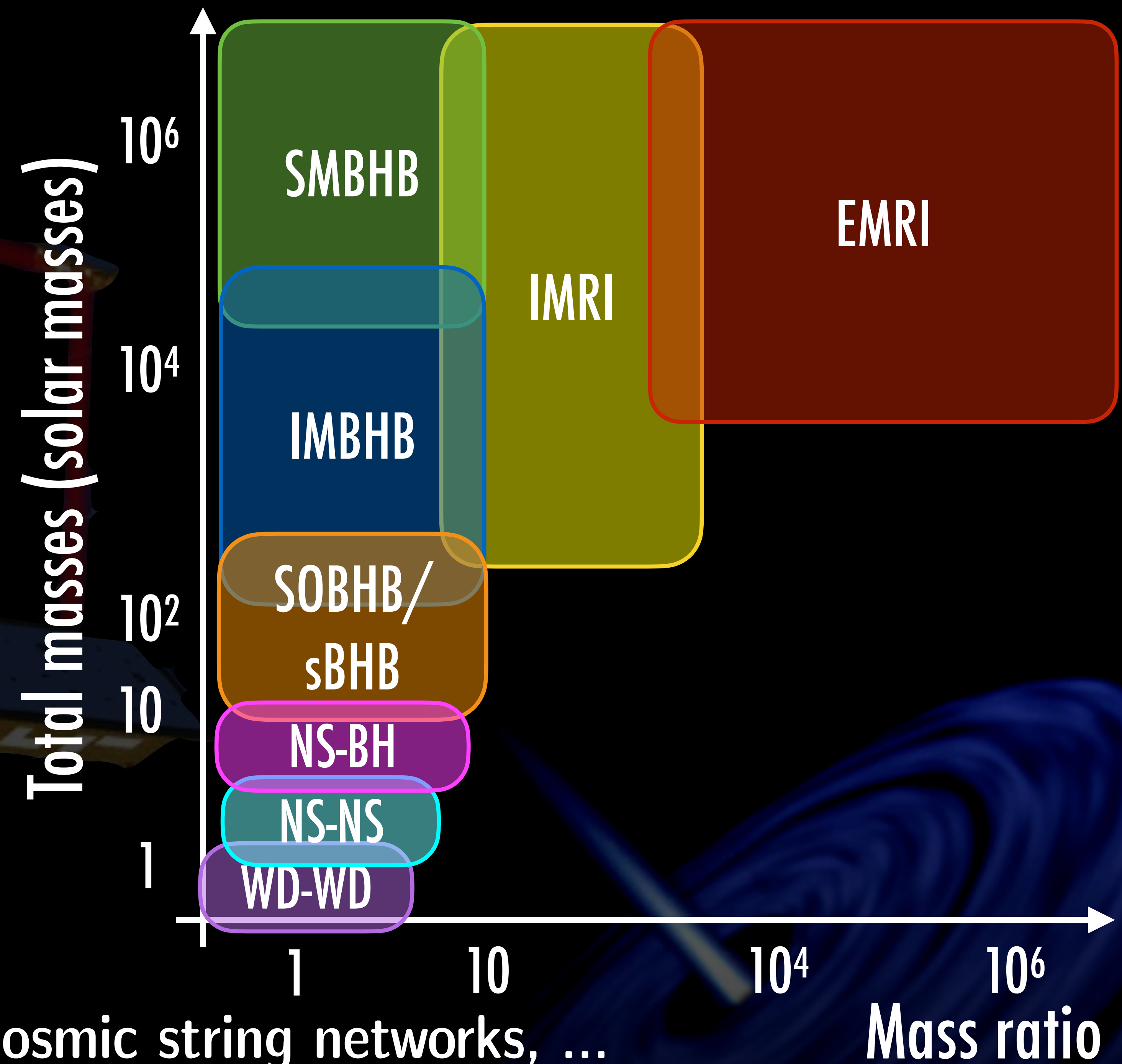

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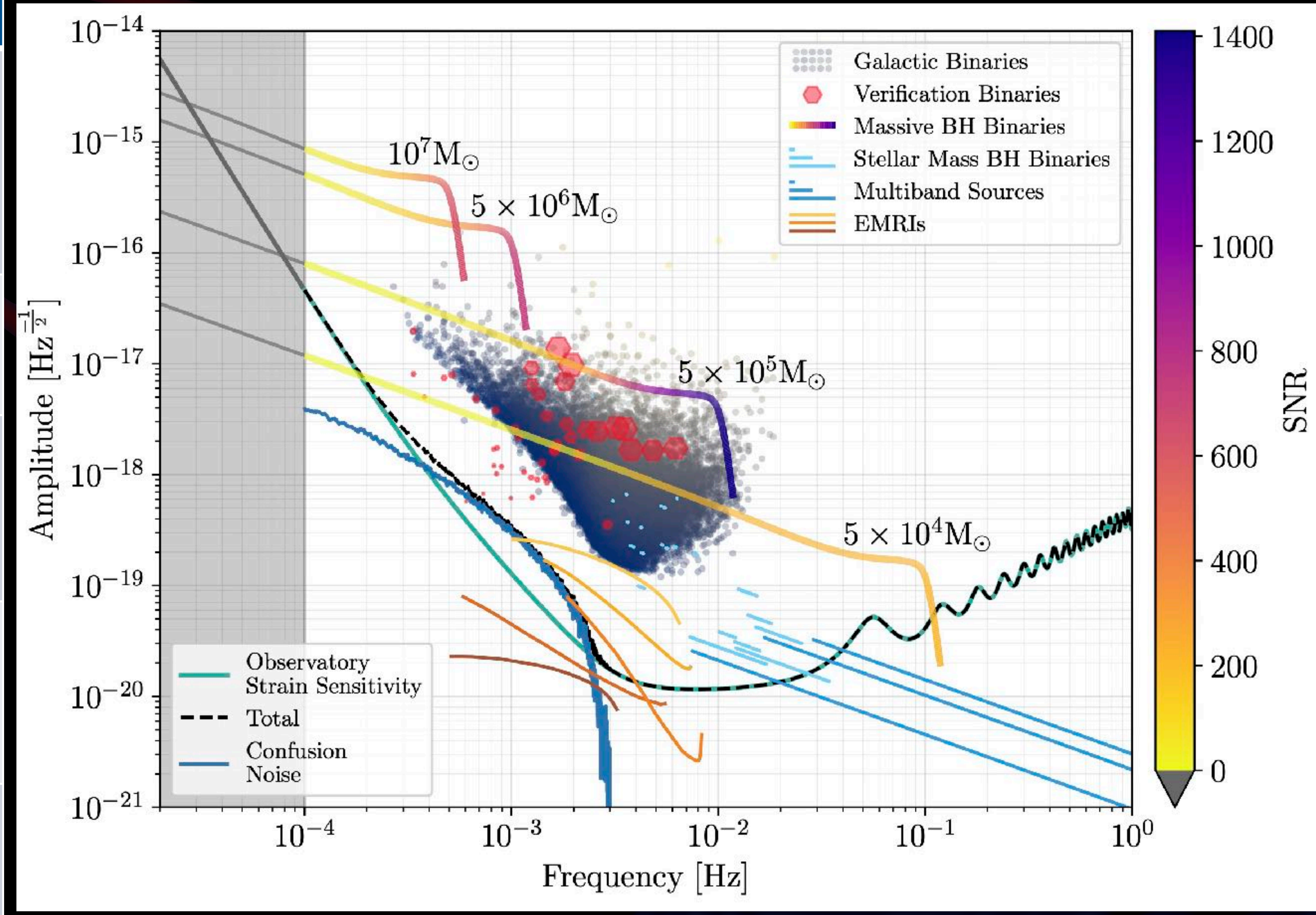
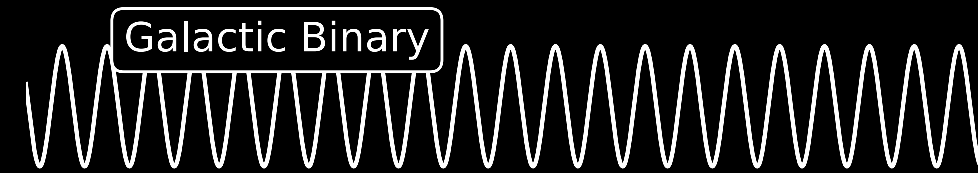
Binaries observed by LISA

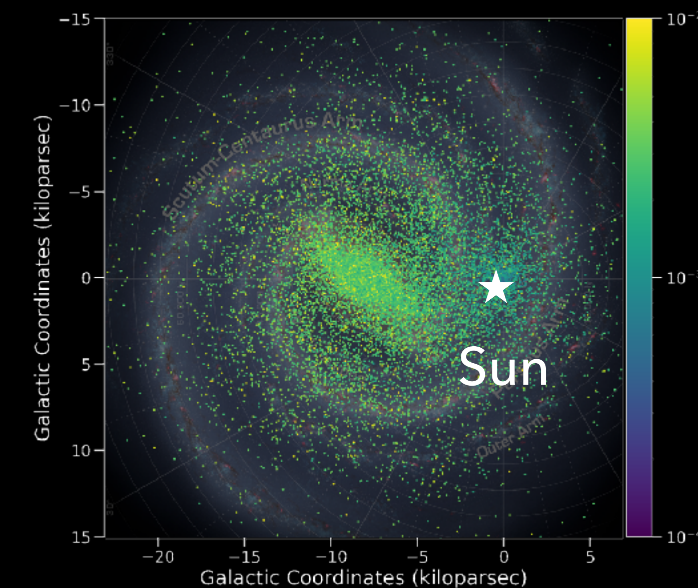
Sources	SNR	Duration	Event rate
Galactic binaries	10 – 500	permanent	10000 – 30000 detectables + background
Verification binaries	7 - 100	permanent	20 (today)
Stellar mass black hole binaries	7 - 30	1 à 10 years	1 to 20
Extreme Mass Ratio Inspirals	7 - 60	1 year	1 to 2000 / year
Massive Black Hole binaries	10 - 3000	Hours - months	10 to 100 / year



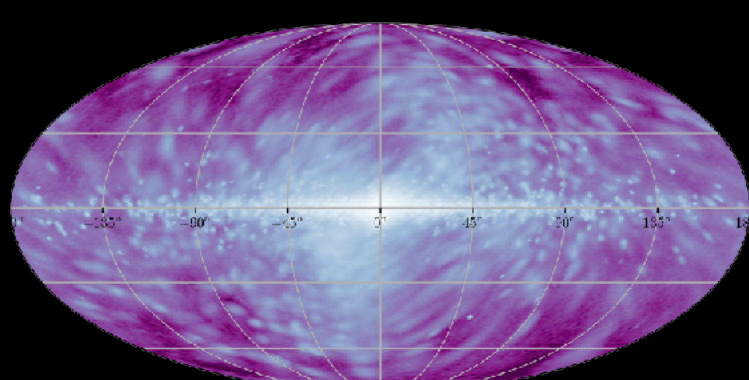
LISA Science

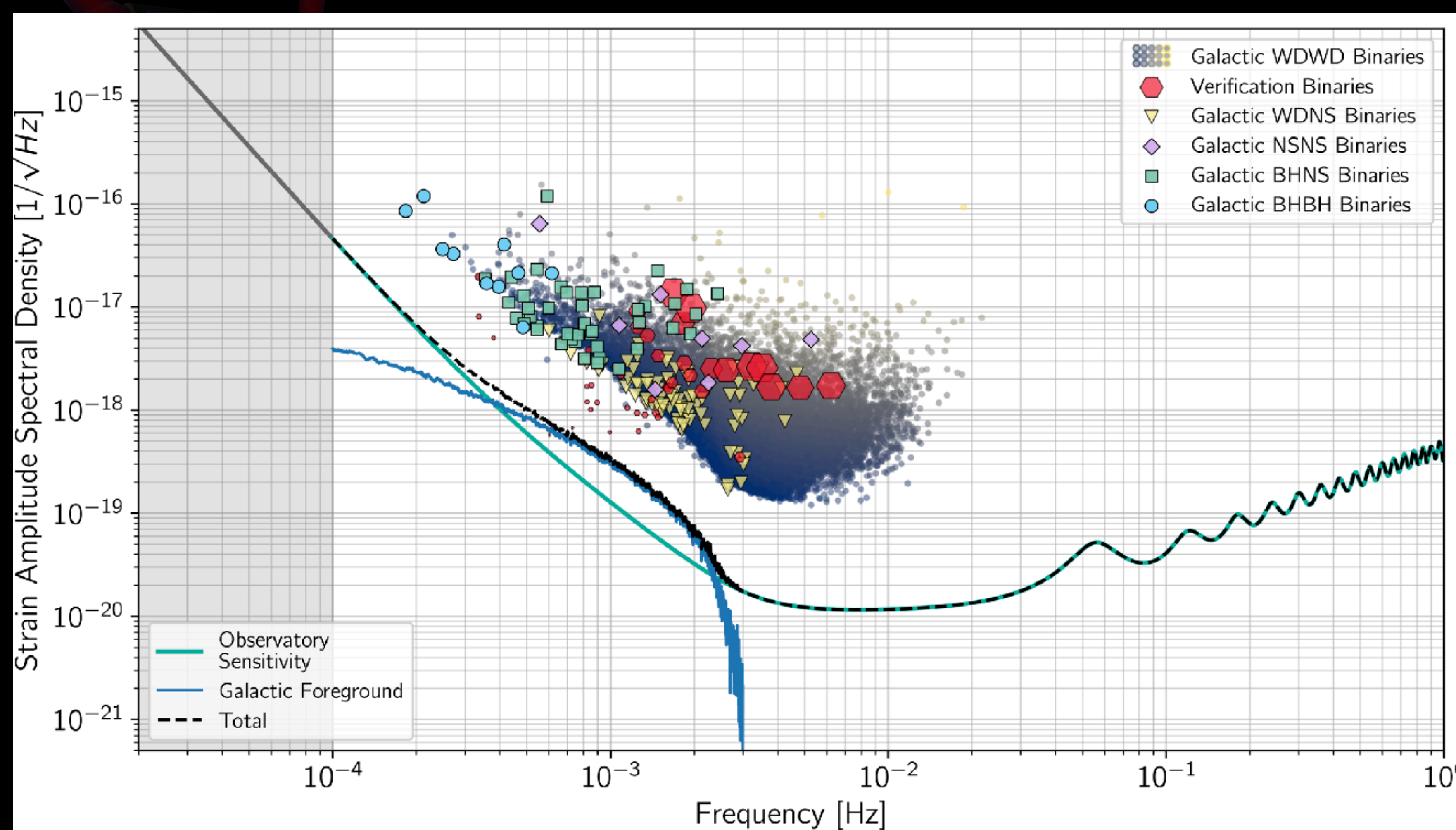


- **SO1:** Study the formation and evolution of compact binary stars in the Milky Way Galaxy:
  - Formation and evolution pathways of dark compact binary stars in the Milky Way and in neighbouring galaxies;
  - The Milky Way mass distribution;
  - The interplay between gravitational waves and tidal dissipation.



Precision:
- Distance: ∼ 30% - 1%
- Chirp mass: ∼10% - 0.0001%
- Sky position: ∼few deg^2

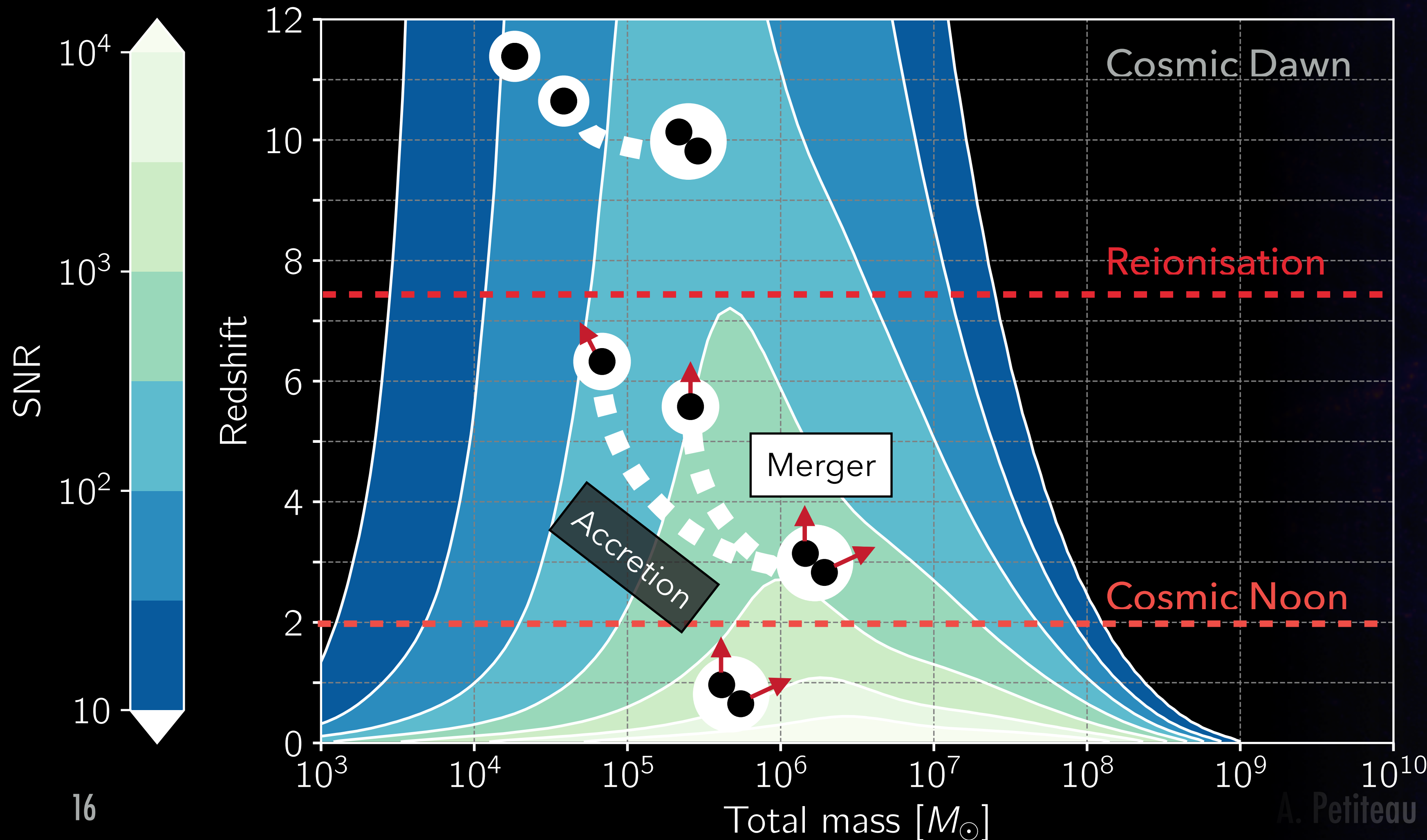


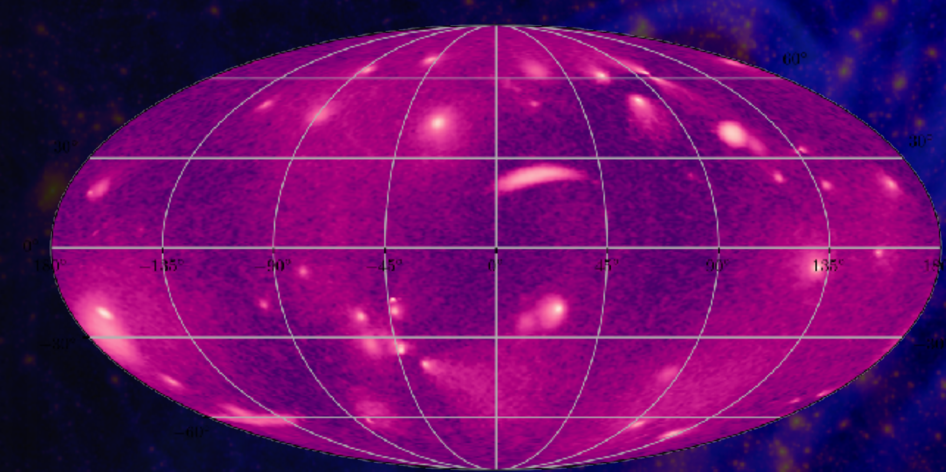


LISA Science

Massive BH Binary Merger

- **SO2:** Trace the origin, growth and merger history of massive black holes across cosmic ages:
  - Discover seed black holes at cosmic dawn;
  - Study the growth mechanism and merger history of massive black holes from the epoch of the earliest quasars;
  - ...





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LISA Science

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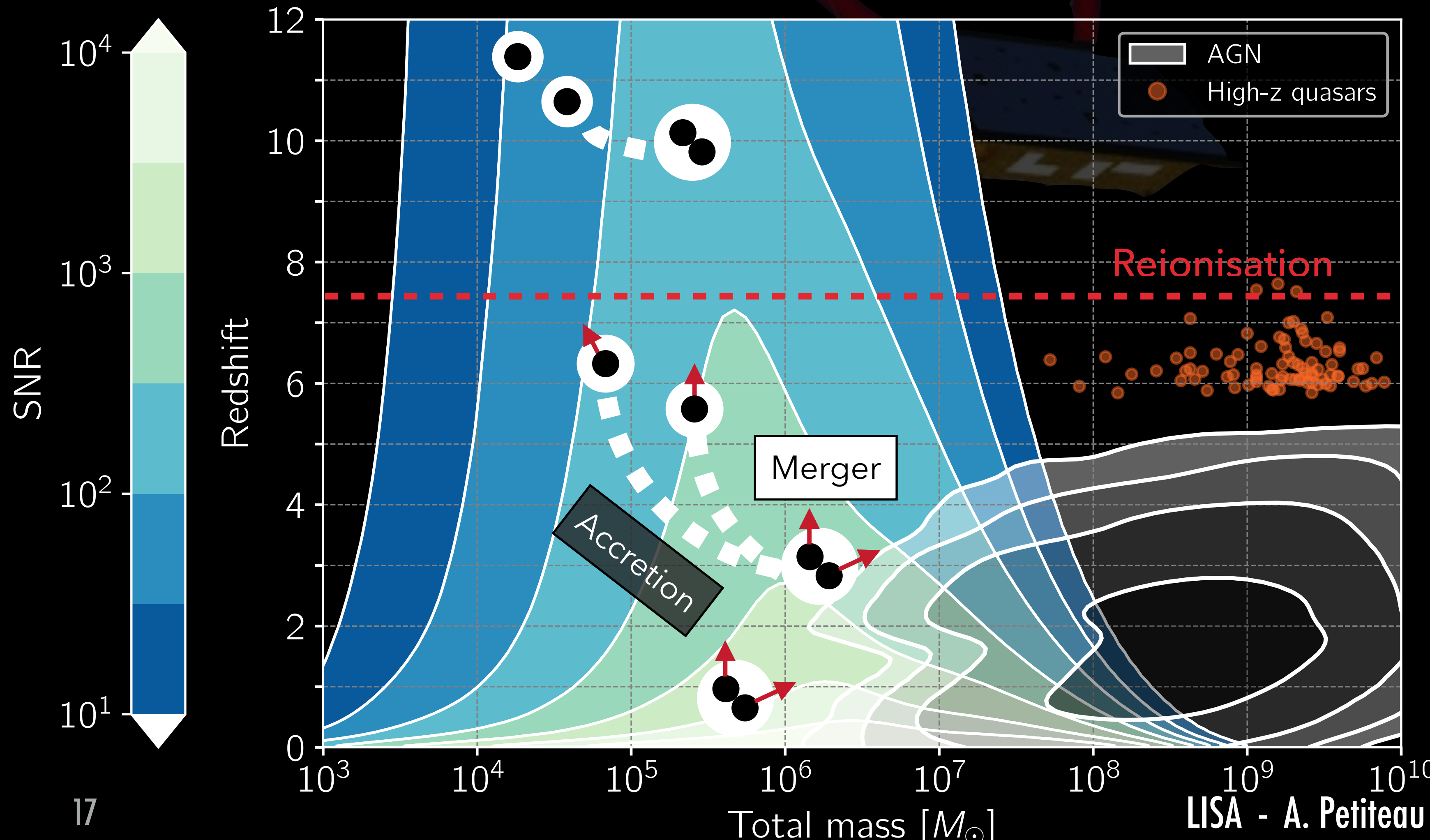
- **SO2:** Trace the origin, growth and merger history of massive black holes across cosmic ages:
  - ...
  - ...
  - Identify the electromagnetic counterparts of massive black hole binary coalescences.



LISA Science

LISA CONSORTIUM

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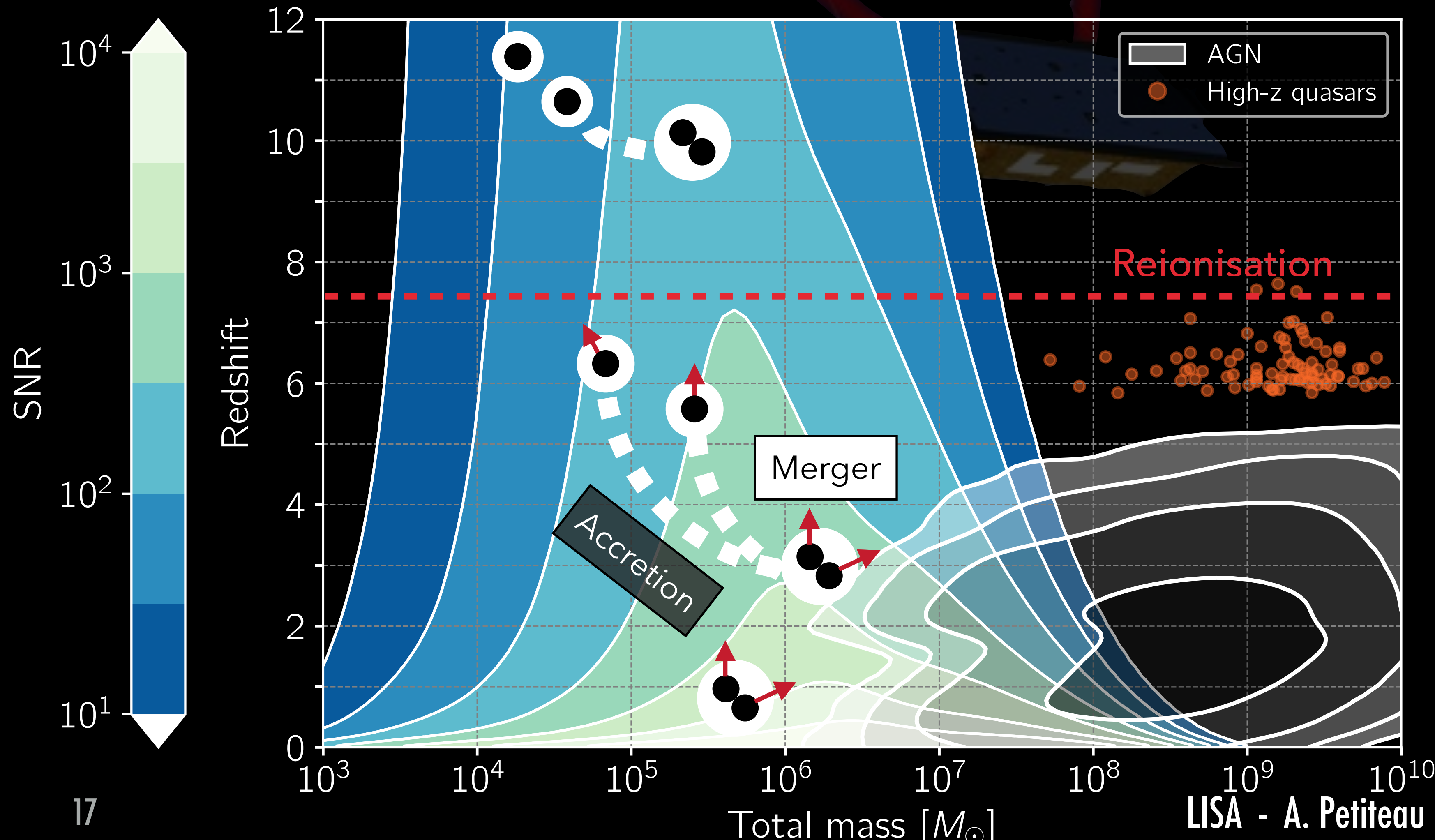

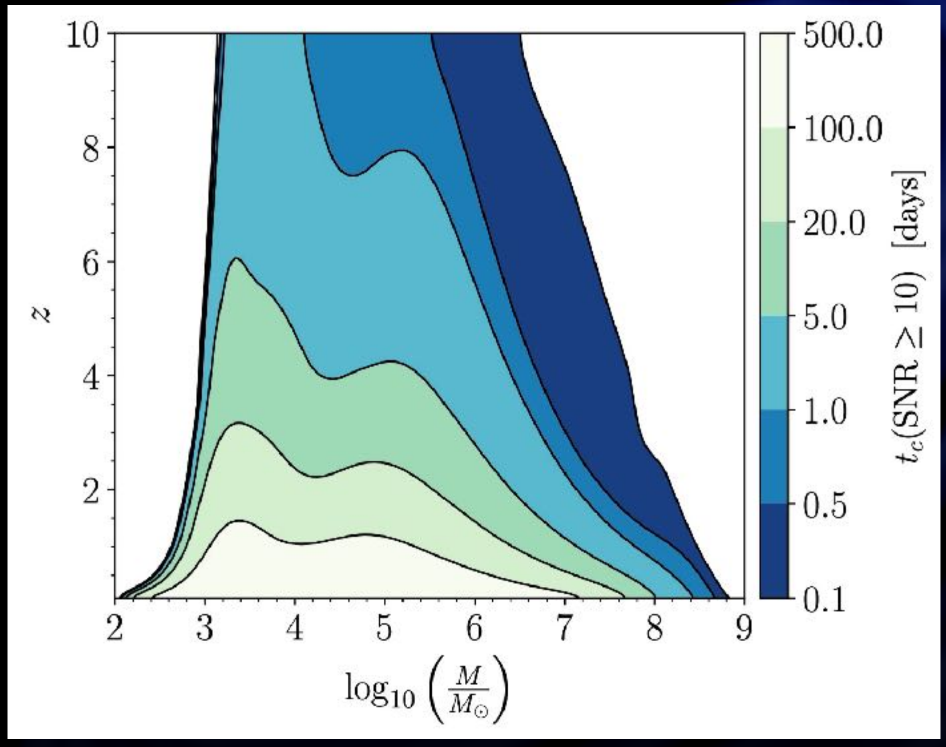

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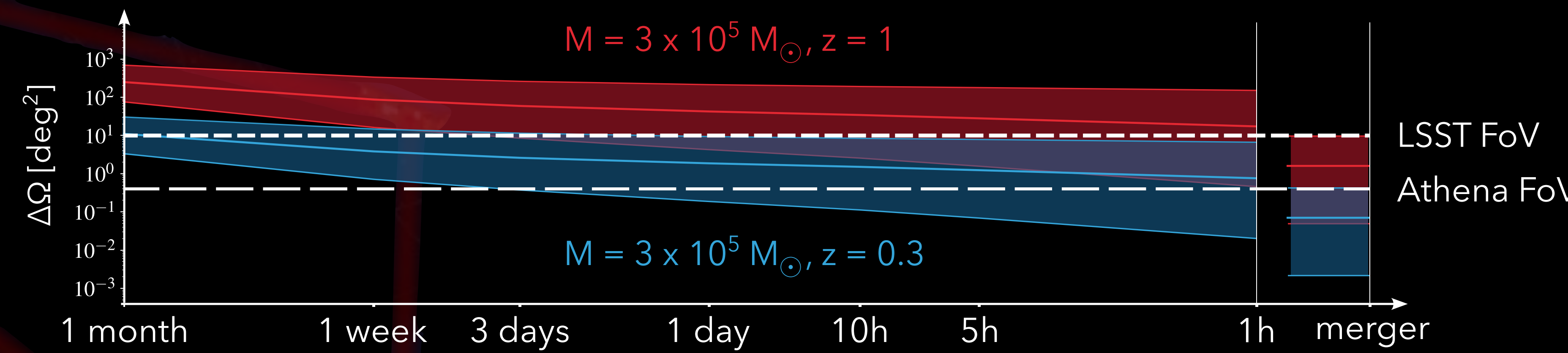
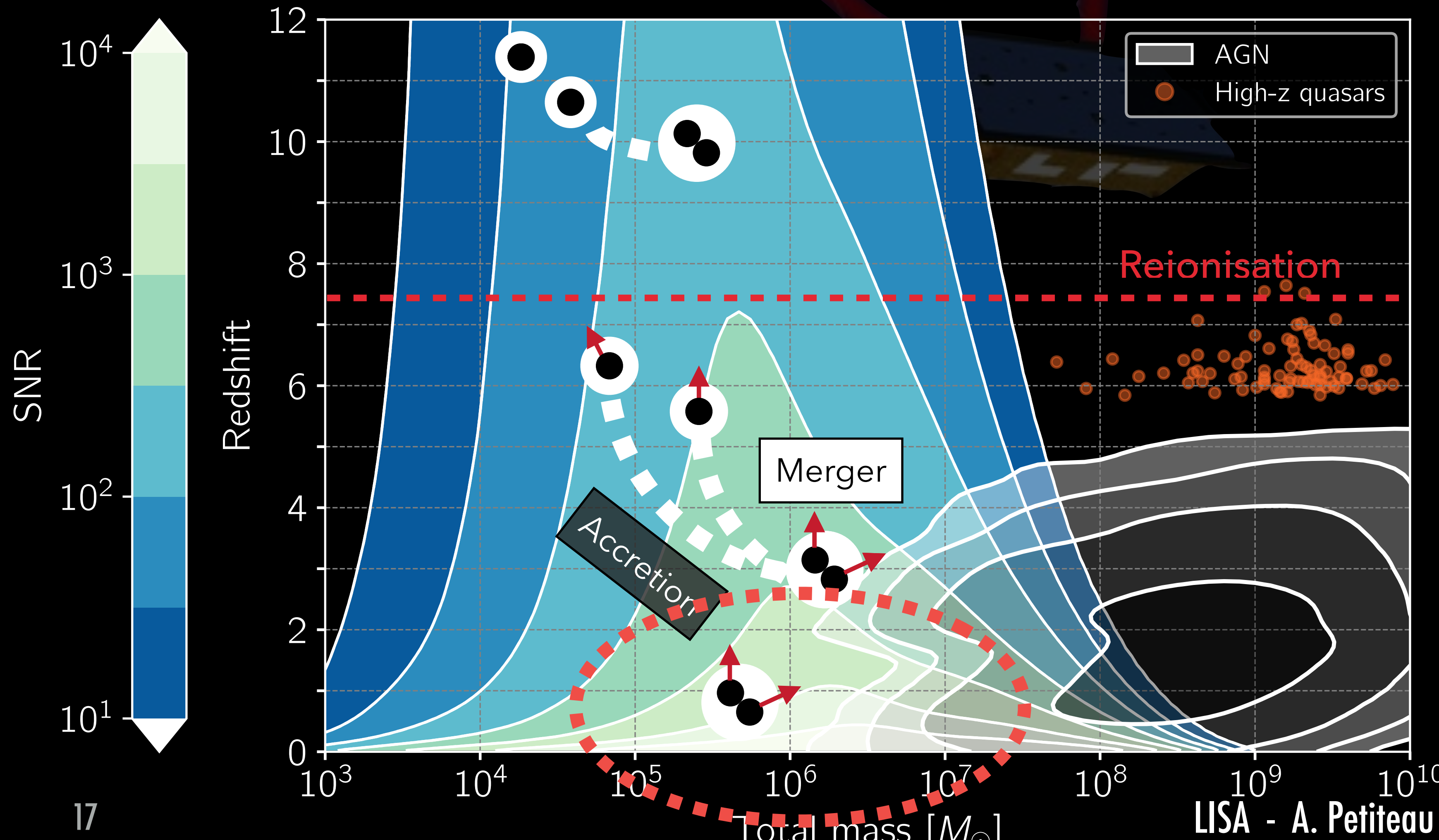
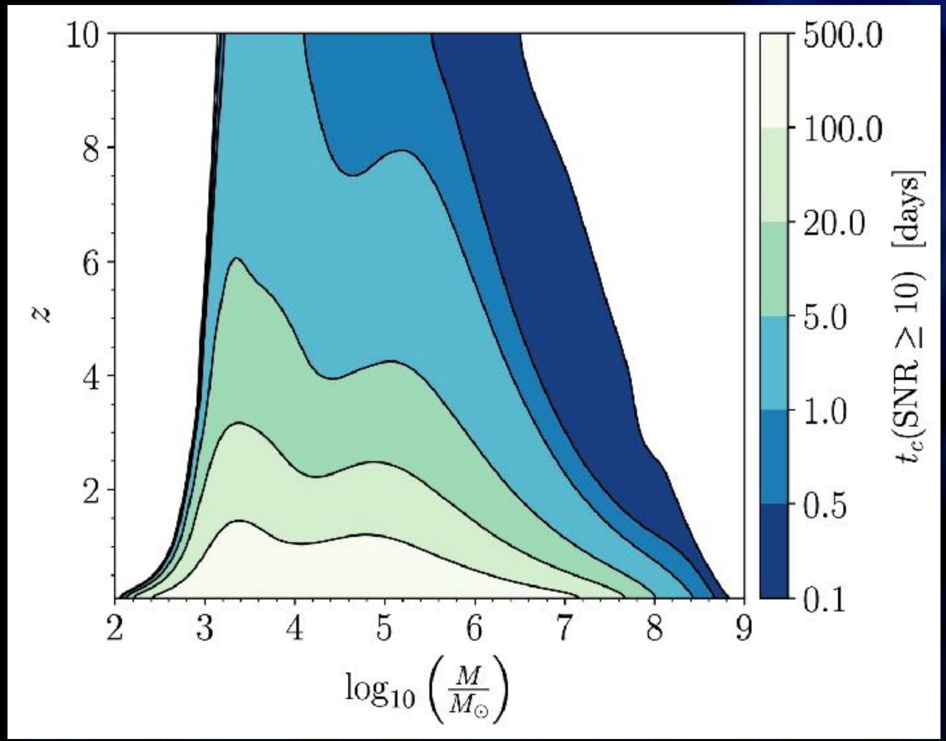
  - …
  - Identify the electromagnetic counterparts of massive black hole binary coalescences.





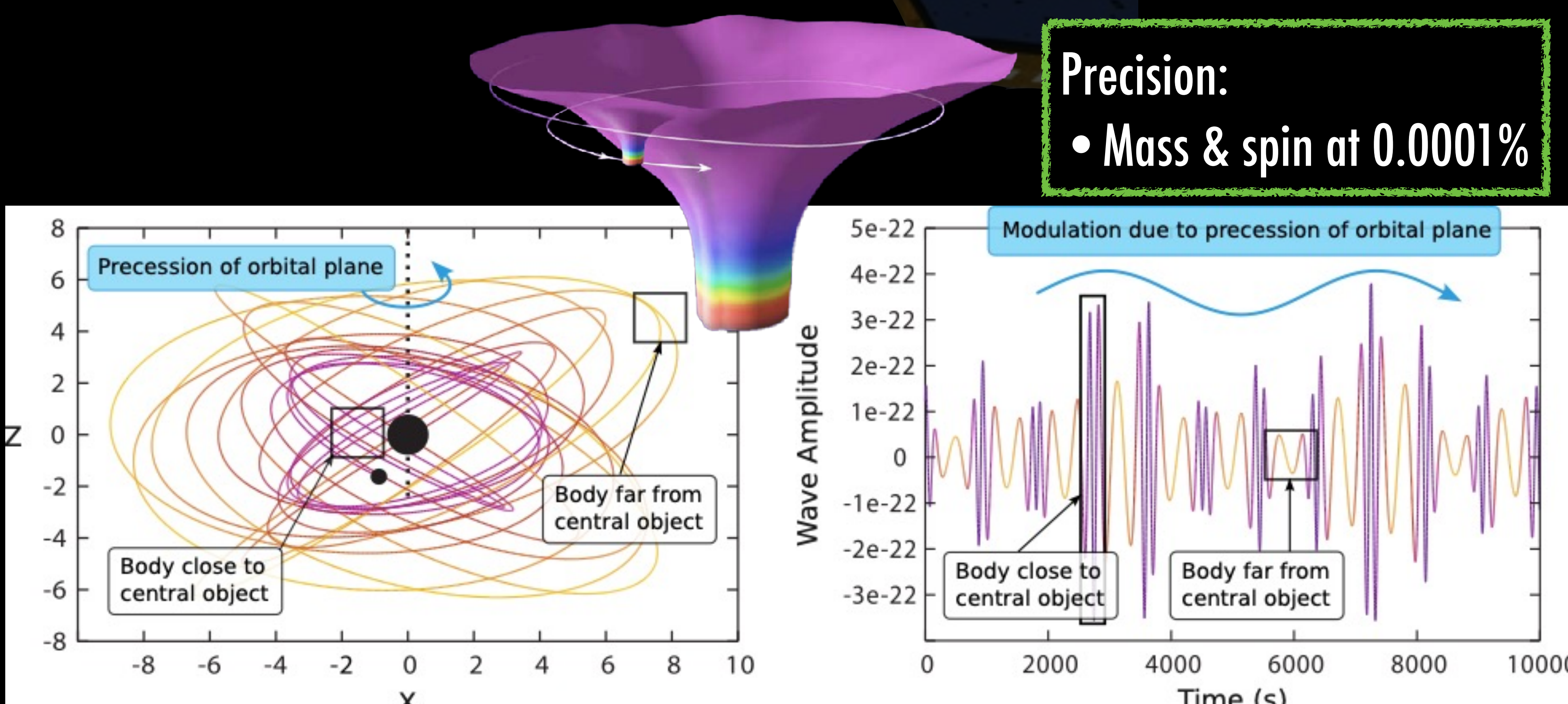


LISA Science

- <u>SO3:</u> Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs:

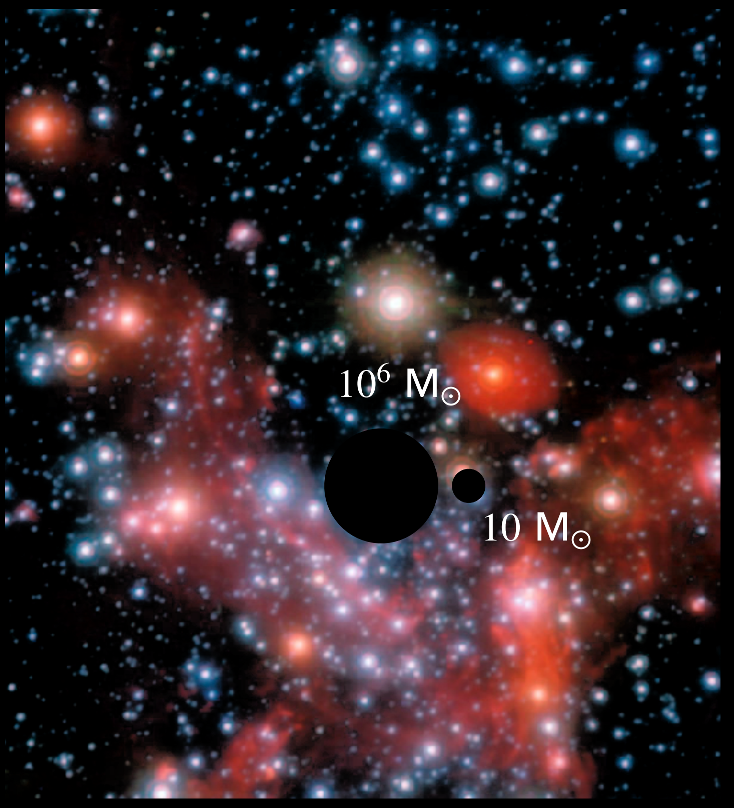
Precision:

- Mass & spin at 0.0001%



LISA Science

- <u>SO3:</u> Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs:
  - Study the properties and immediate environment of Milky Way-like MBHs using EMRIs;



Precision:
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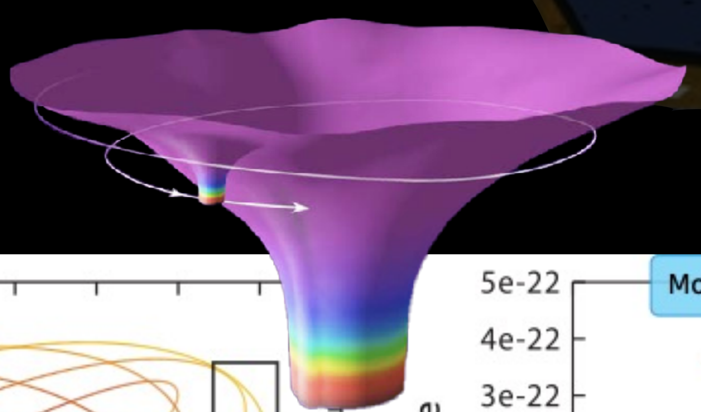
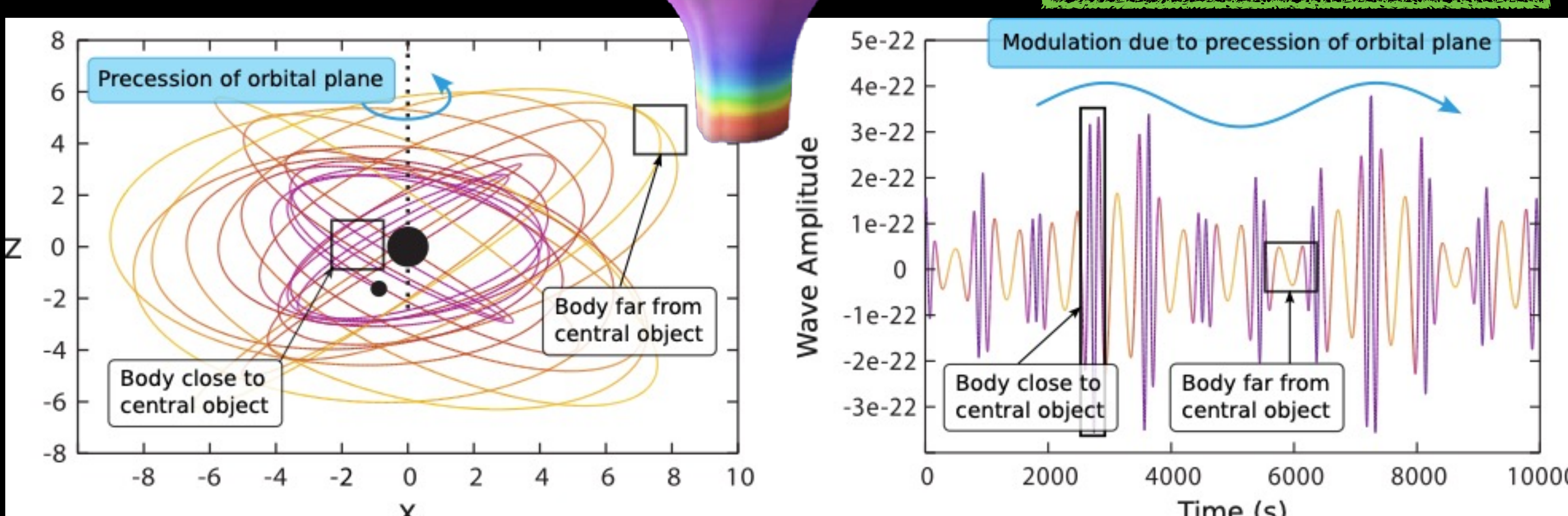
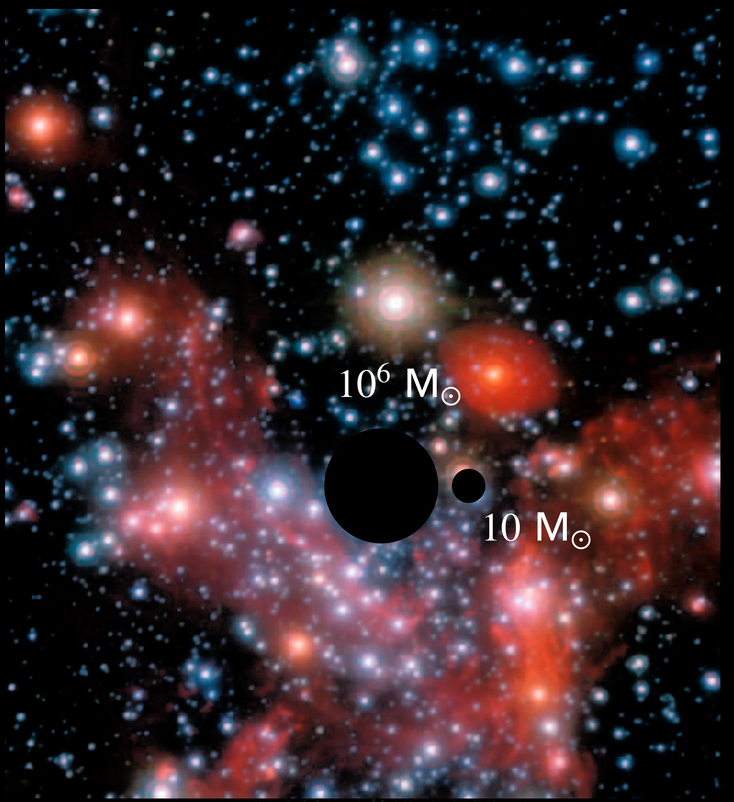
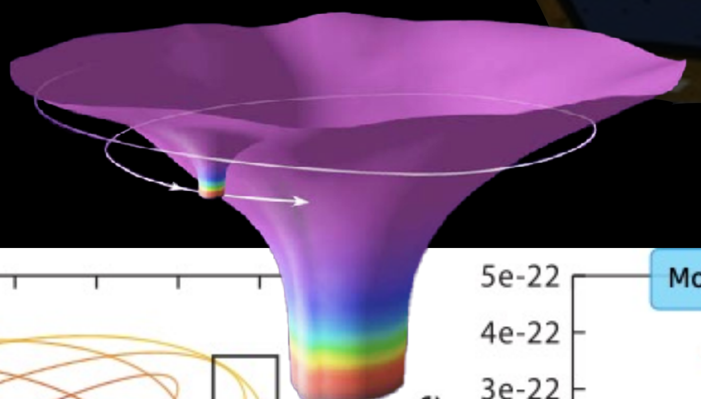




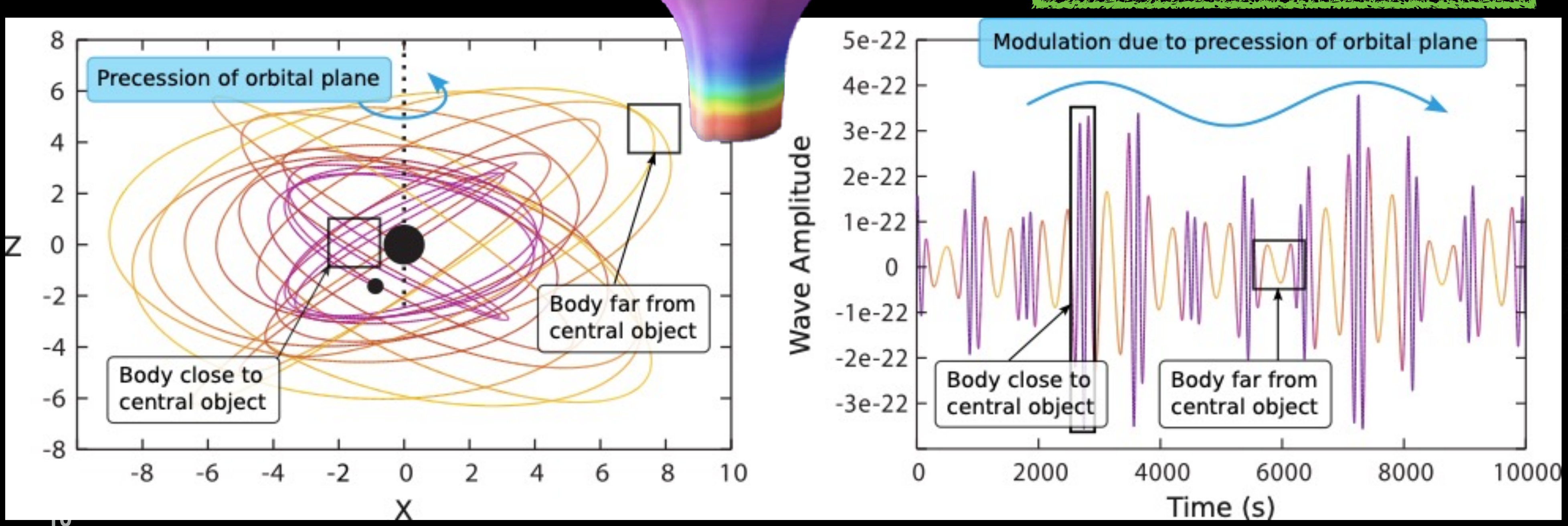
LISA Science

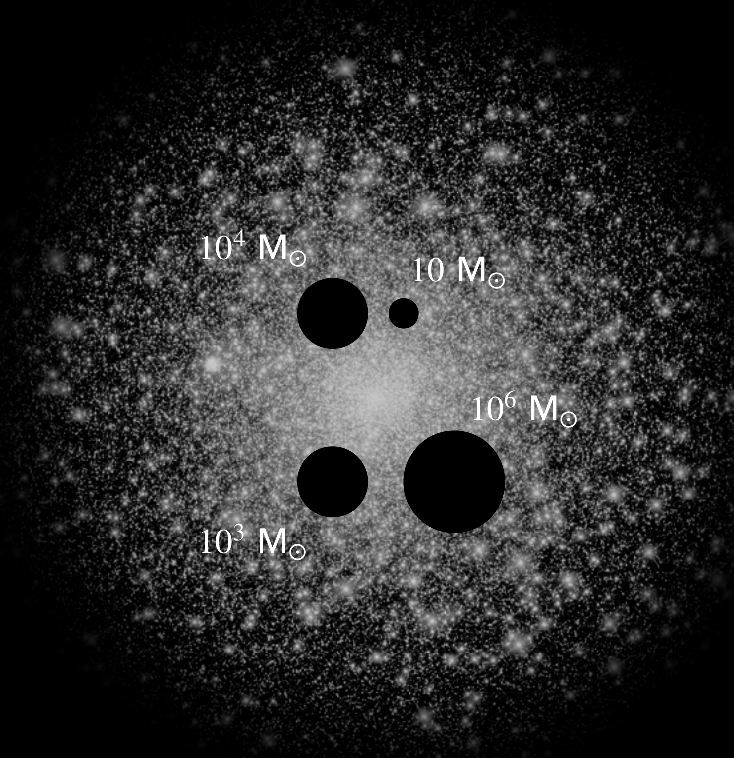
- **SO3:** Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs:
  - Study the properties and immediate environment of Milky Way-like MBHs using EMRIs;
  - Study the IMBH population using IMRI.





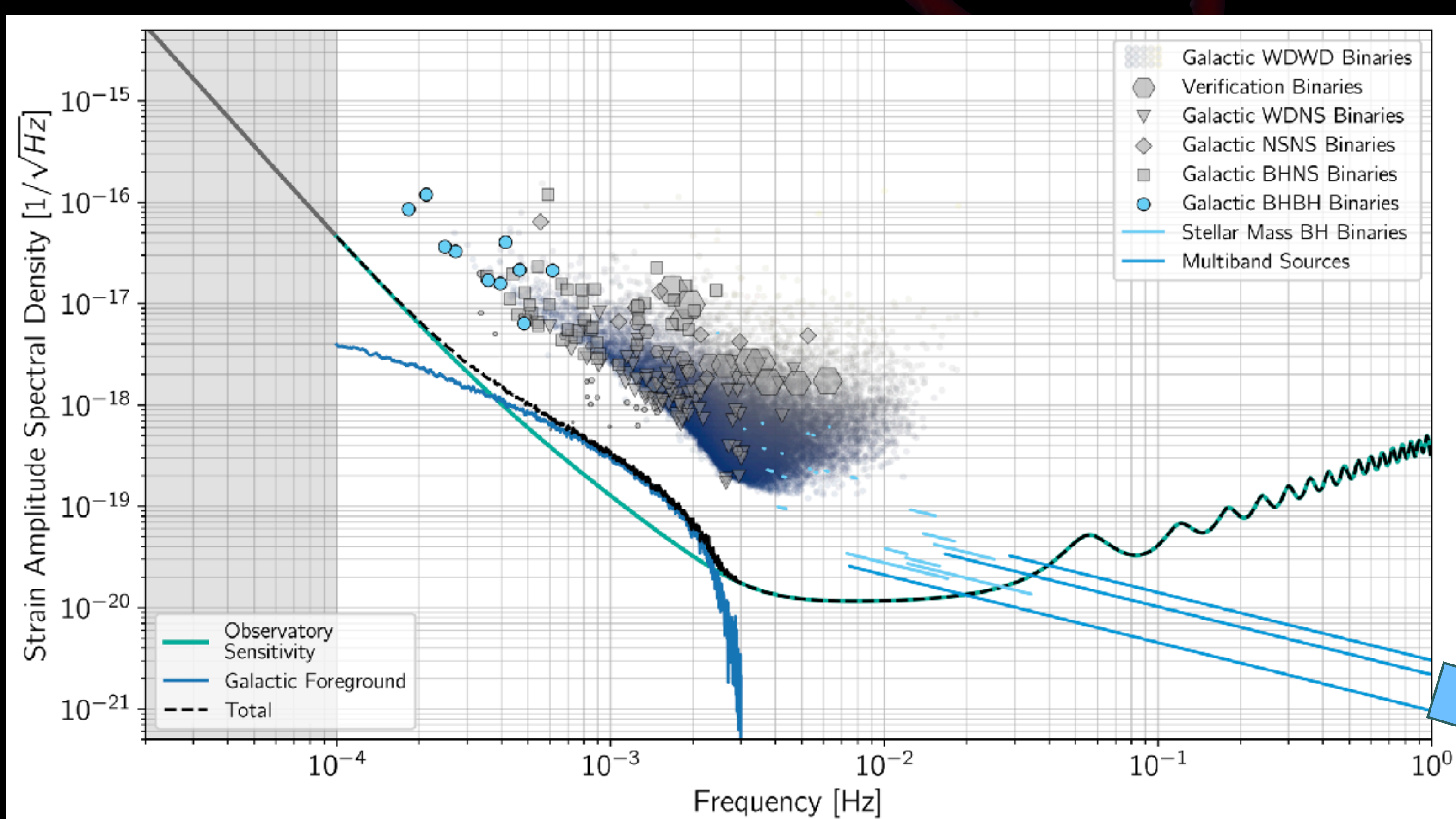
Precision:
- Mass & spin at 0.0001%





LISA Science

- **SO4:** Understand the astrophysics of stellar origin black holes :
  - Study the statistical properties of sBHs far from merger;
  - Detecting high mass sBHBs and probing their environment;
  - Enabling multiband and multimessenger observations at the time of coalescence.

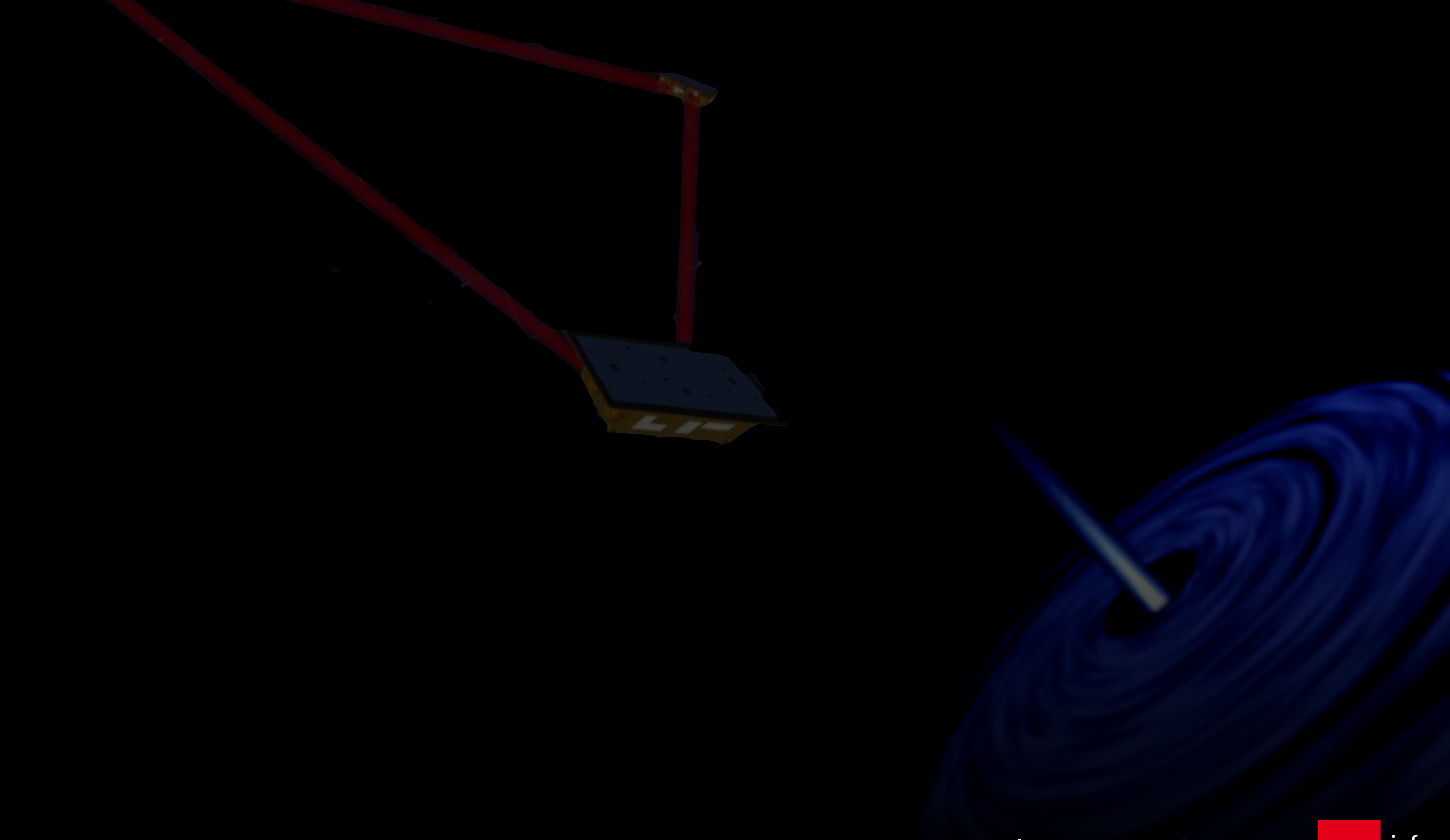


Precision:
- Eccentricity at 0.01%

Towards the band of ground based observatory

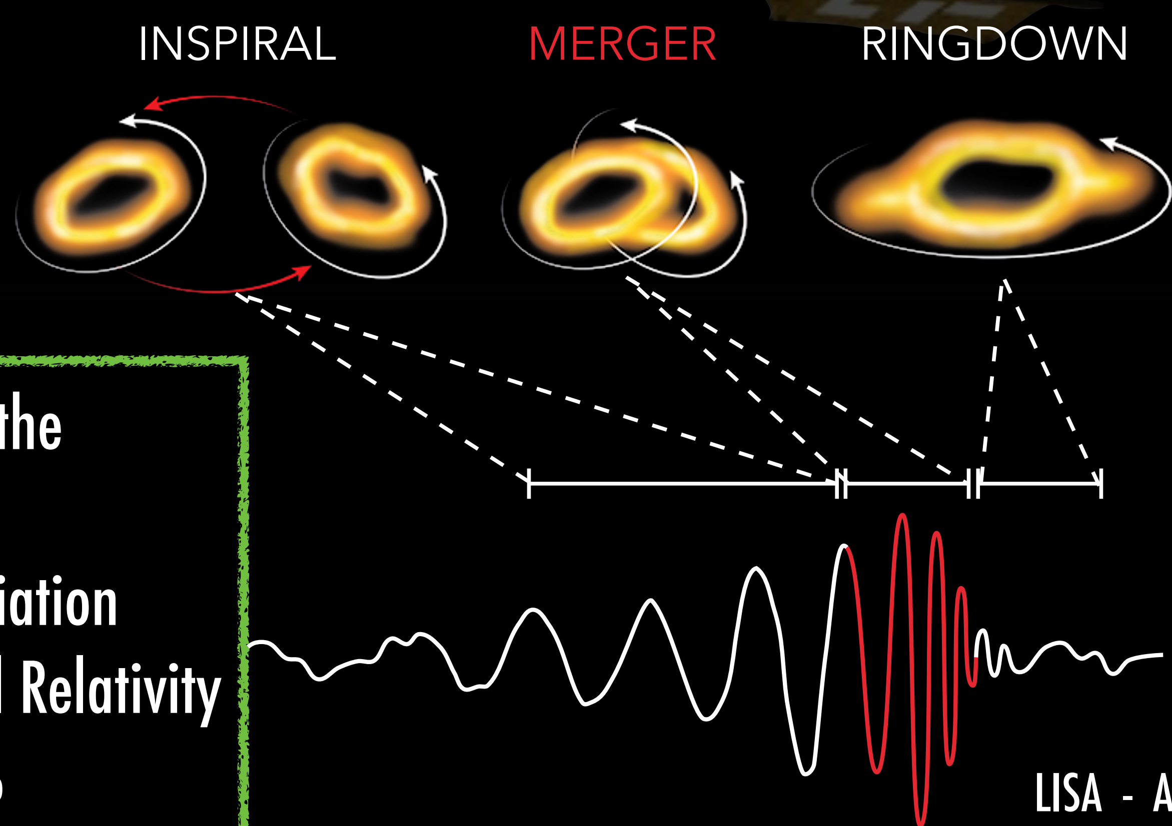
LISA Science

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



LISA Science

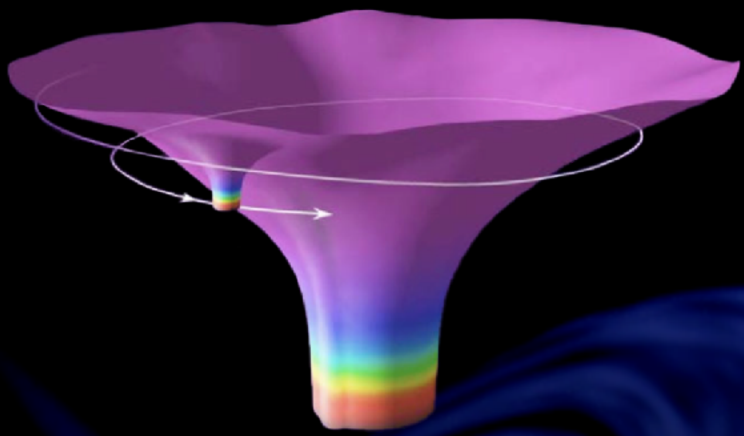
- **<u>SO5:</u> Explore the fundamental nature of gravity and black holes :**
  - Use ringdown characteristics observed in MBHB coalescences to test whether the post-merger objects are the MBHs predicted by GR;

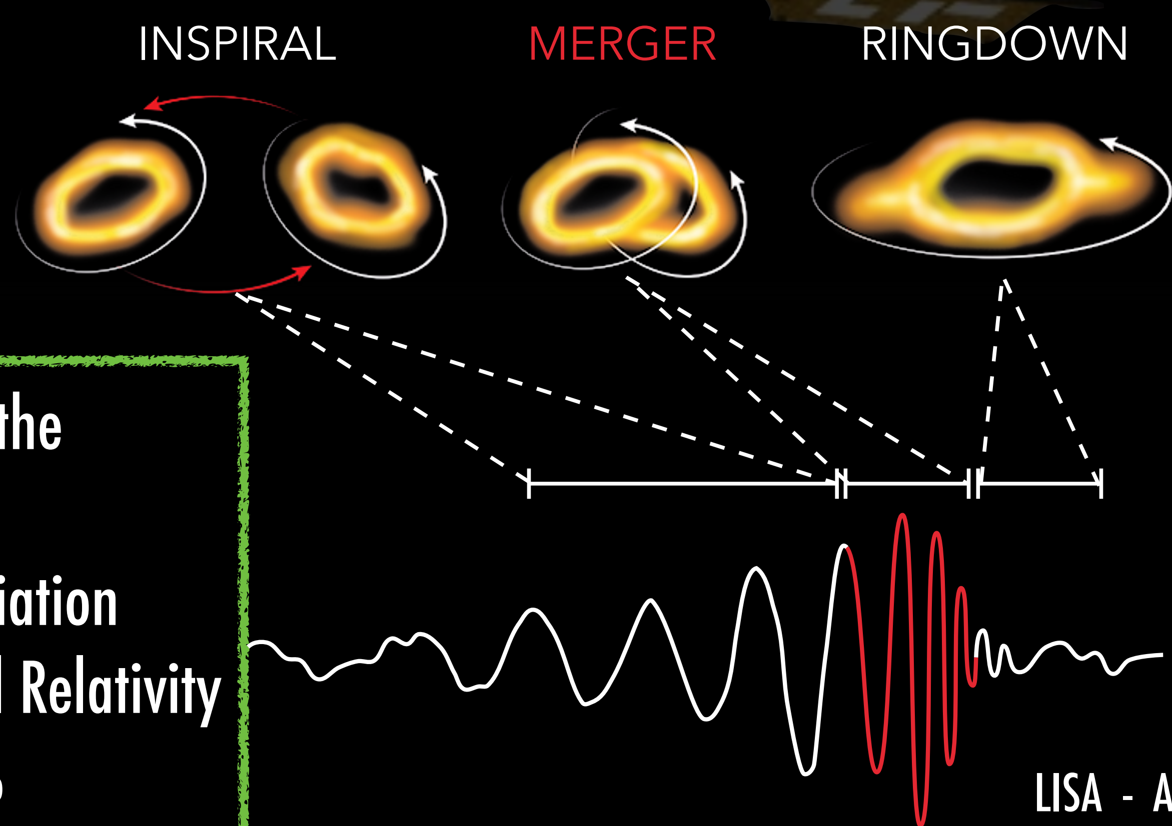


Precision from the ringdown:
- Measure deviation from General Relativity at 10% to 1%

LISA Science

- <u>SO5:</u> Explore the fundamental nature of gravity and black holes :
  - Use ringdown characteristics observed in MBHB coalescences to test whether the post-merger objects are the MBHs predicted by GR;
  - Use EMRIs to explore the multipolar structure of MBHs and search for the presence of new light fields;



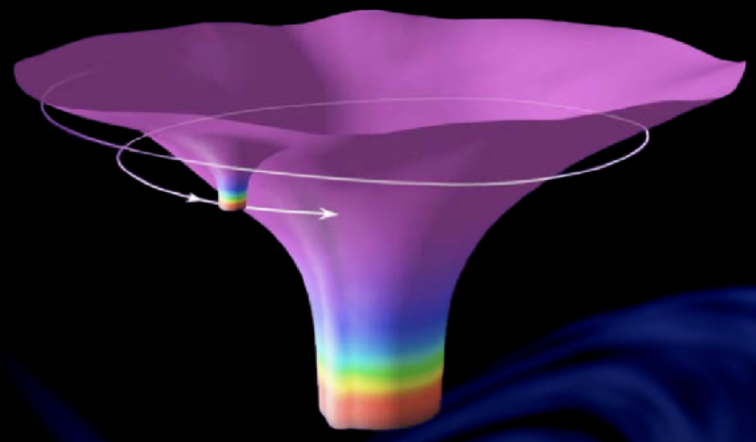


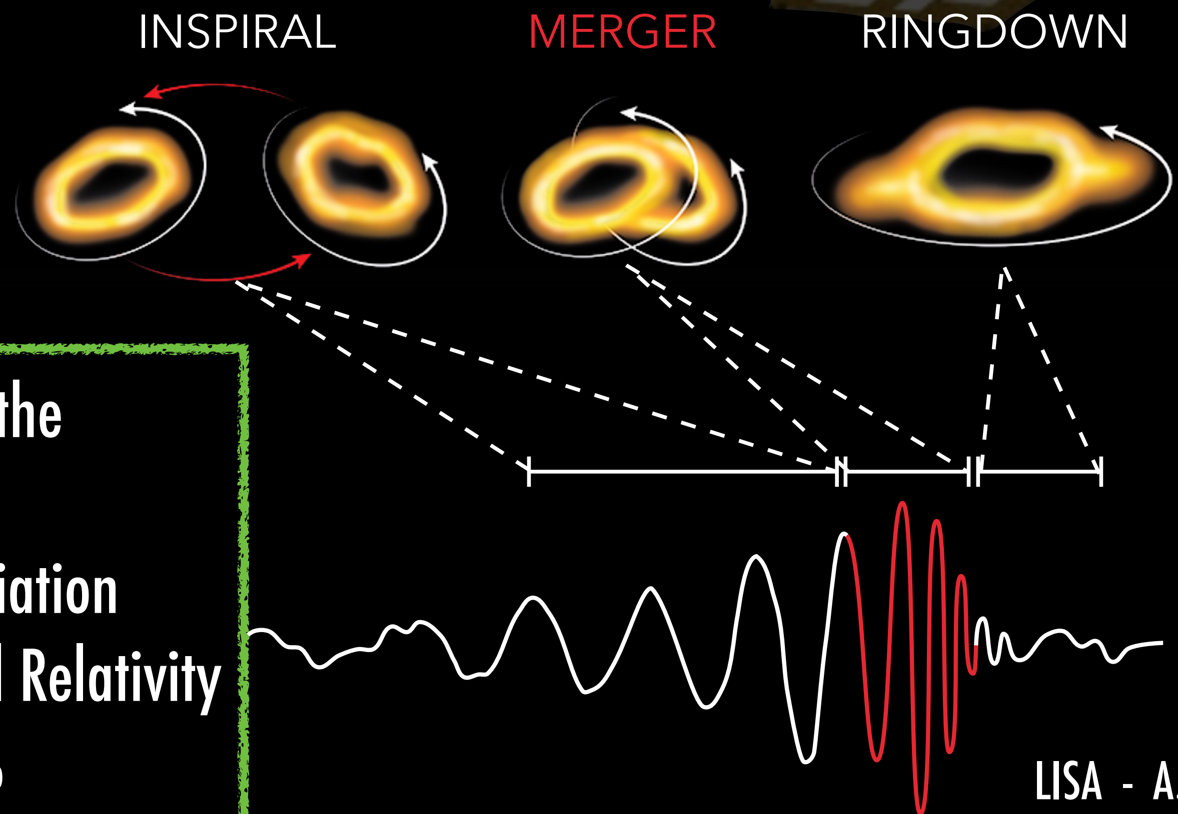
Precision from the ringdown:
- Measure deviation from General Relativity at 10% to 1%

Precision for the "golden" EMRI :
- Mass of the big black hole at ~ 0.001%
- Spin of the big black hole 10^{-5} (absolute)
- Quadrupolar moment 10^{-3} %

LISA Science

- **SO5:** Explore the fundamental nature of gravity and black holes :
  - Use ringdown characteristics observed in MBHB coalescences to test whether the post-merger objects are the MBHs predicted by GR;
  - Use EMRIs to explore the multipolar structure of MBHs and search for the presence of new light fields;
  - Test the presence of beyond-GR emission channels;
  - Test the propagation properties of GW.



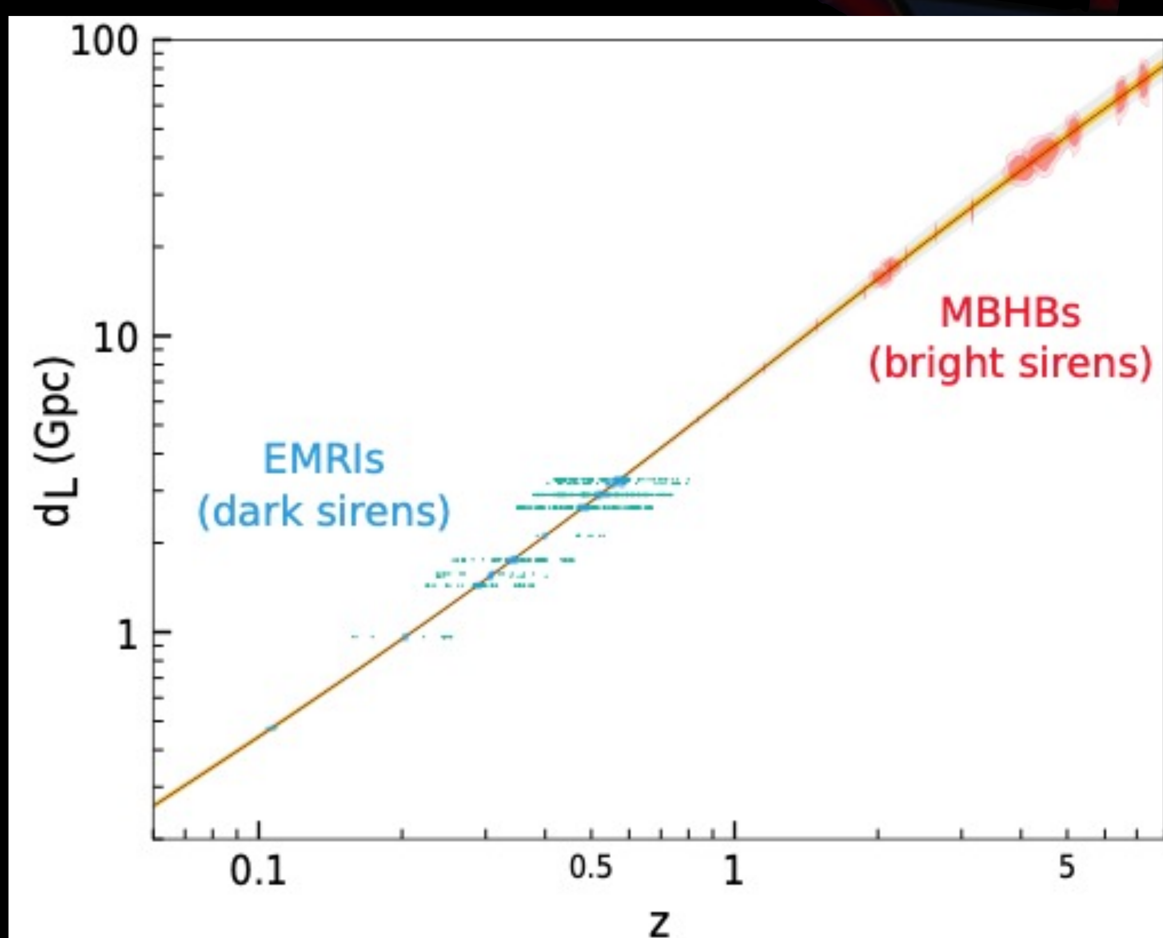


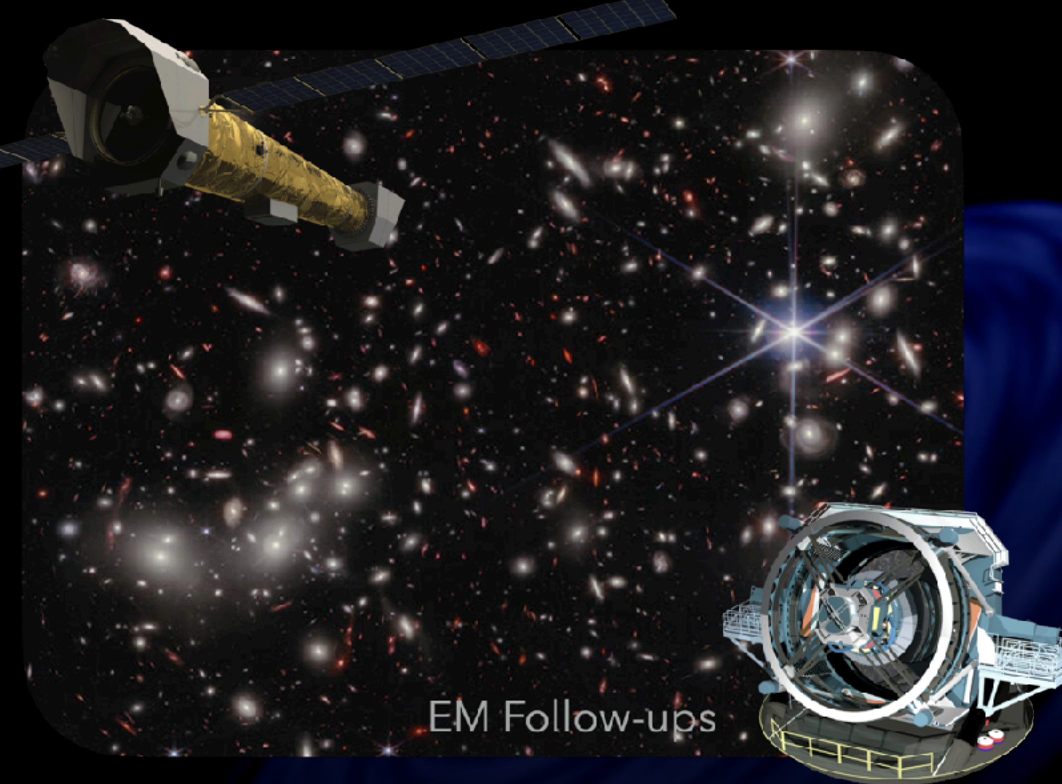
Precision from the ringdown:
- Measure deviation from General Relativity at 10% to 1%

Precision for the "golden" EMRI :
- Mass of the big black hole at $\sim 0.001\%$
- Spin of the big black hole 10^{-5} (absolute)
- Quadrupolar moment 10^{-3} %

LISA Science

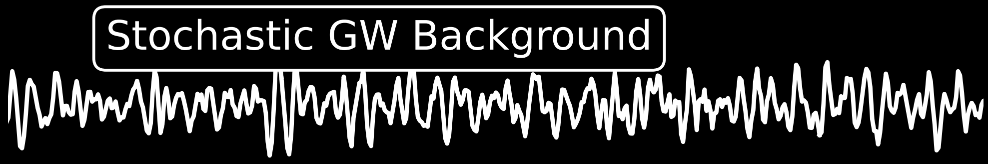
- <u>SO6:</u> Probe the rate of expansion of the Universe :
  - Cosmology from bright sirens: massive black hole binaries;
  - Cosmology from dark sirens: extreme mass ratio inspirals and stellar-origin black hole binaries;
  - Cosmology at all redshift: combining local and high-redshift LISA standard sirens measurements.



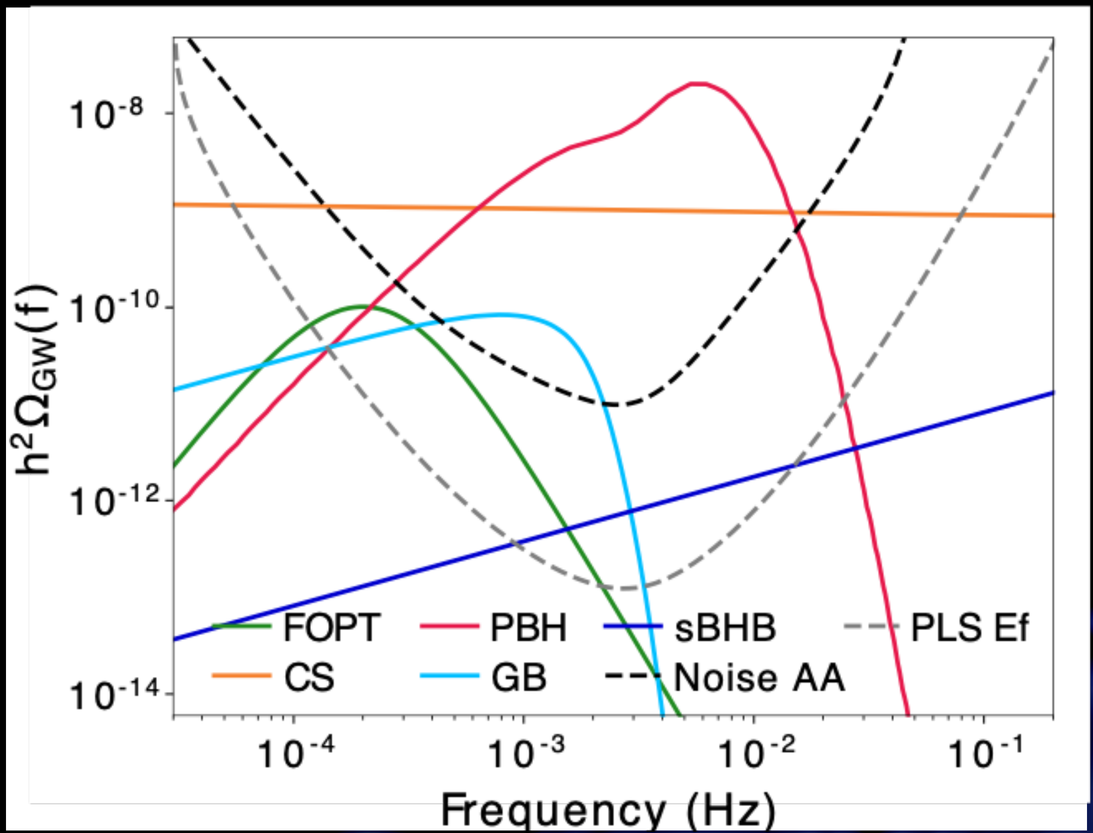


Constraint on the geometry of the Universe:
- No calibration needed
- H_0 to a few % with observations up to $z \sim 3$

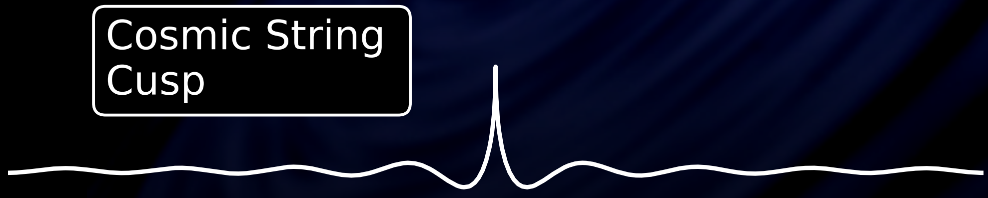
LISA Science



- SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics:
  - Characterise the astrophysical SGWB;
  - Measure, or set upper limits on, the spectral shape of the cosmological SGWB;
  - Characterise the large-scale anisotropy of the SGWB.



- SO8: Search for GW bursts and unforeseen sources :
  - Search for cusps and kinks of cosmic strings;
  - Search for unmodelled sources.



Science Objectives

LISA CONSORTIUM

- SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages.
- SO3: Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs.
- SO4: Understand the astrophysics of stellar origin black holes.
- 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.

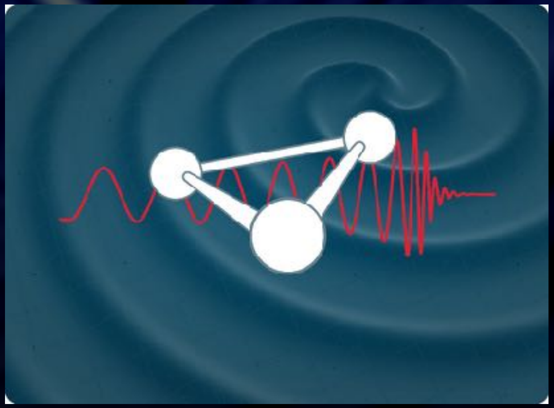
Astrophysics

Fundamental physics

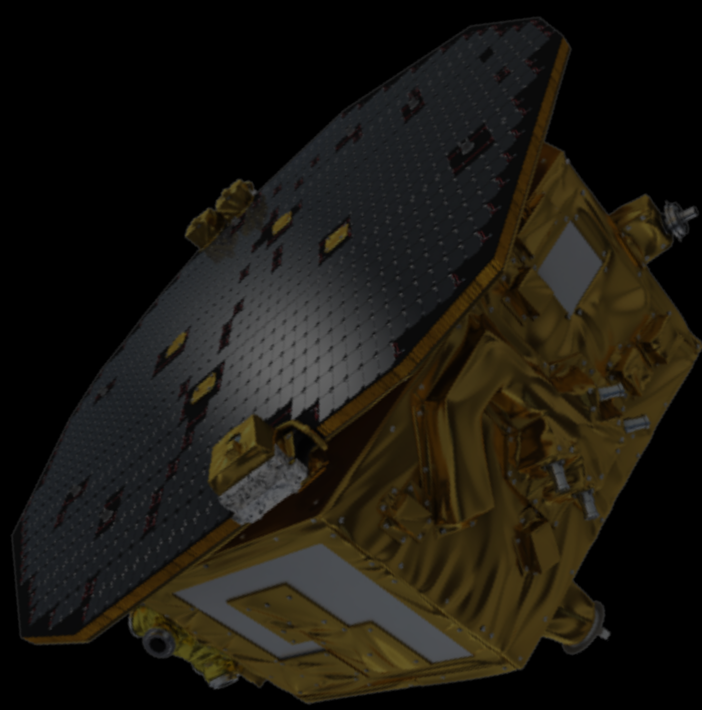
Cosmology

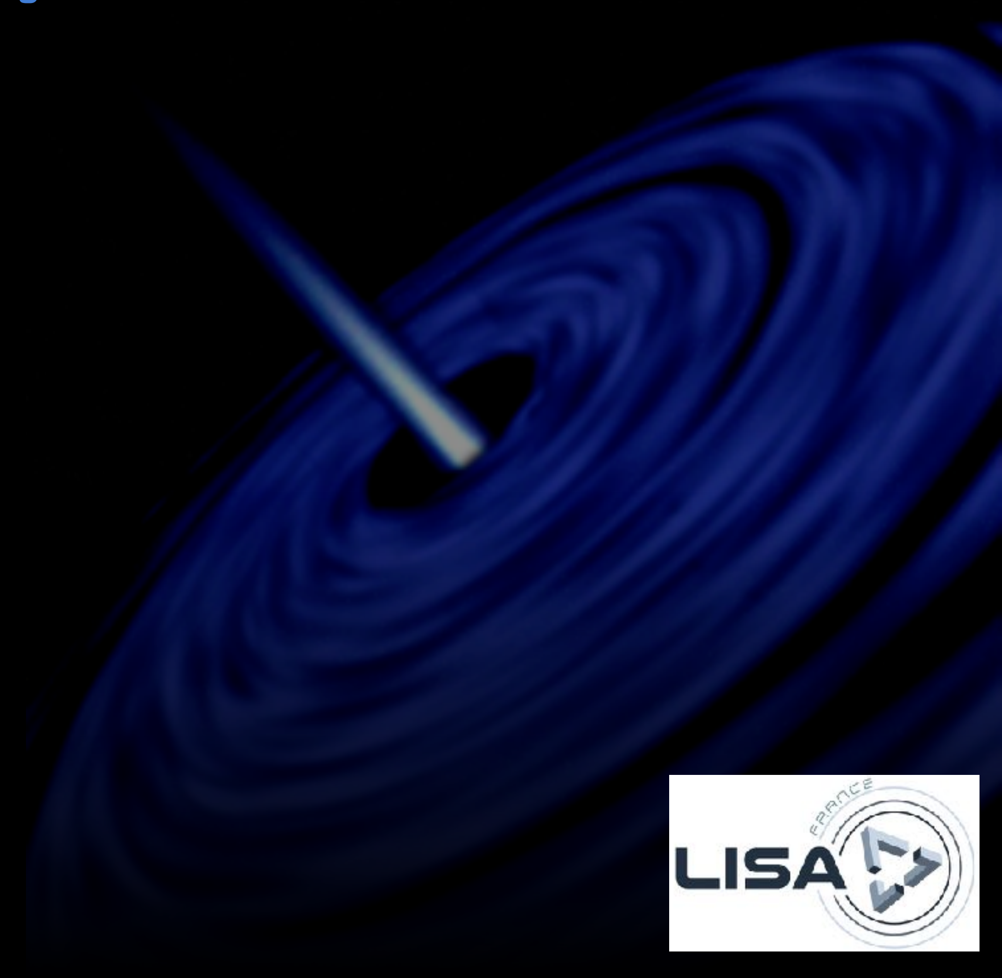
Conclusion

- LISA is a large mission led by ESA to explore the Universe with gravitational wave in the mHz band.
- LISA has been adopted in January by ESA, i.e. it is fully supported by ESA, its member states and NASA.
- It is now starting its development and building phase for a launch in 2035 for 4.5 to 10 years of operations.
- LISA in a large range of domains with a huge science case for astrophysics, cosmology and fundamental physics.
- LISA is a tool to explore the Dark Universe !



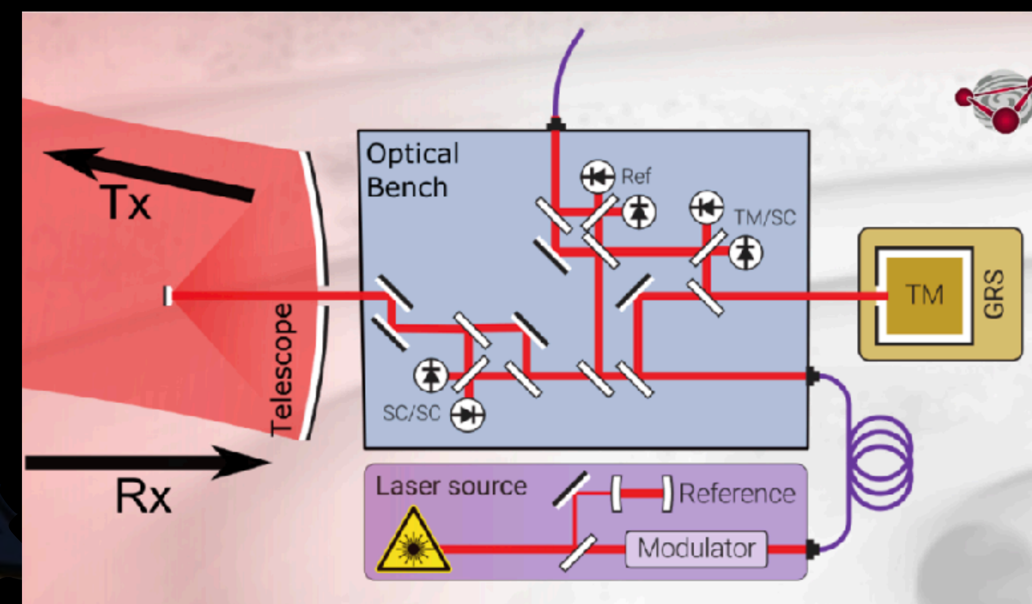
Thank you !

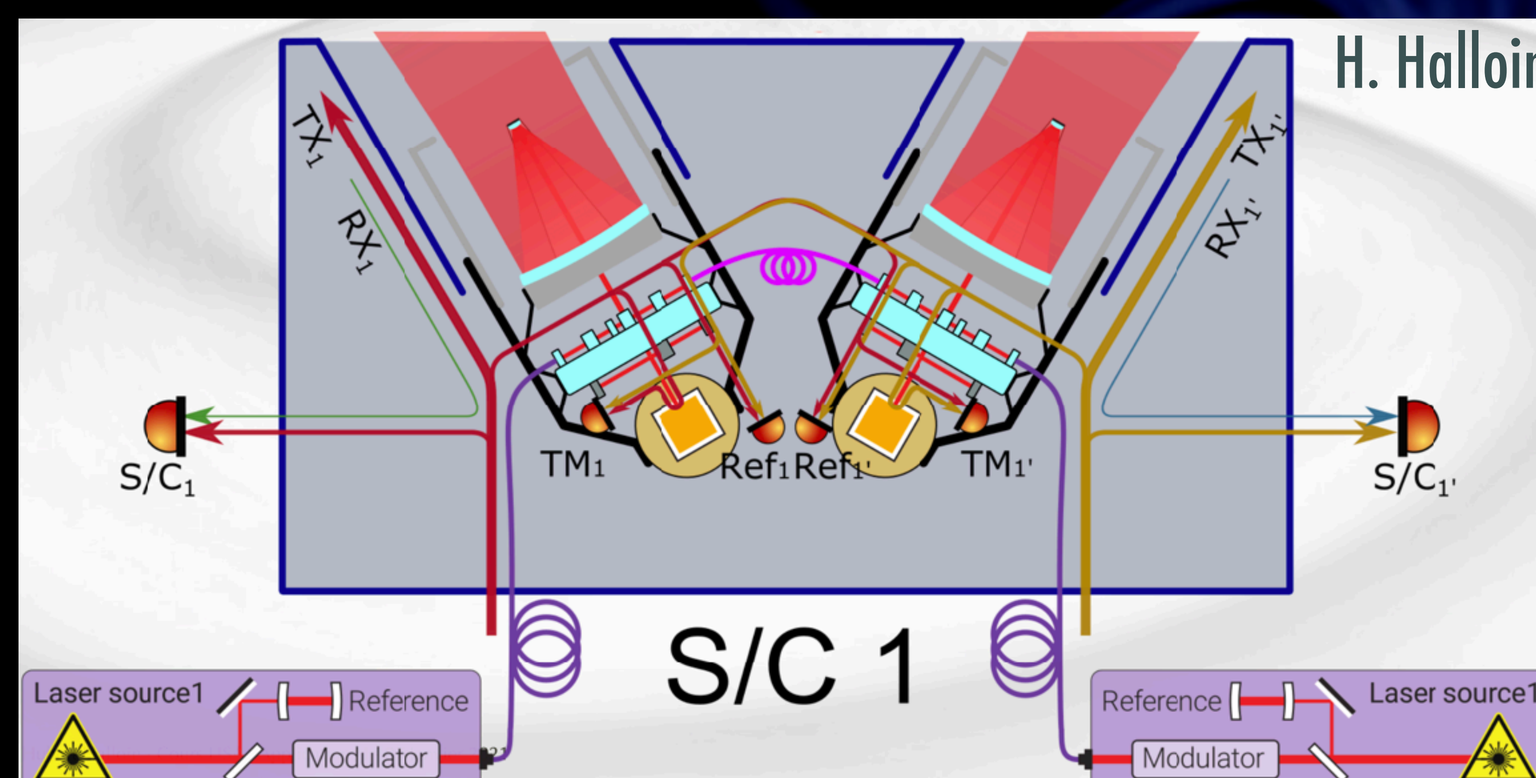




Interferometric measurements

- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts





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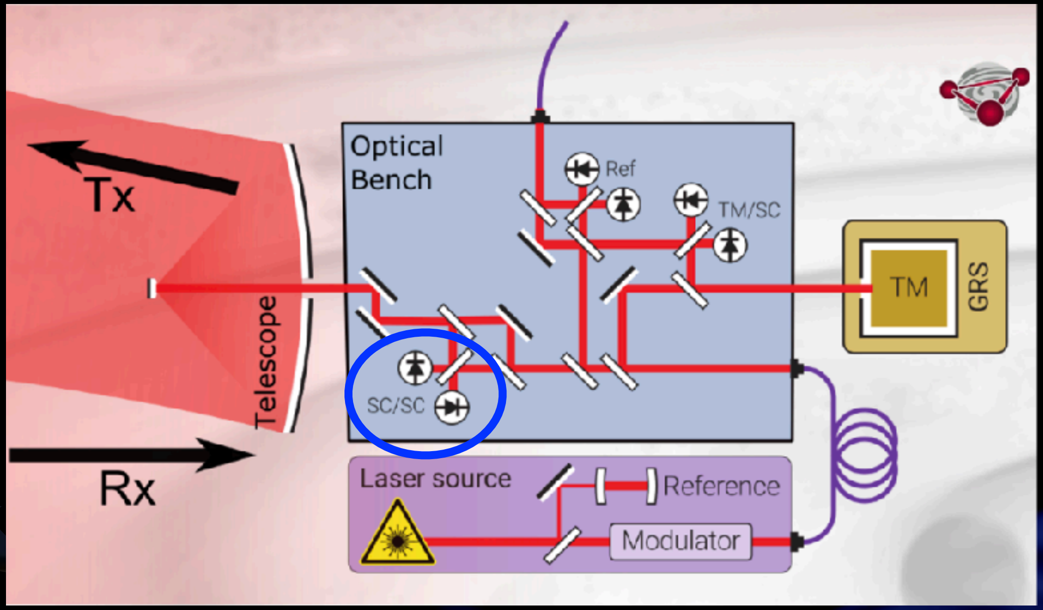

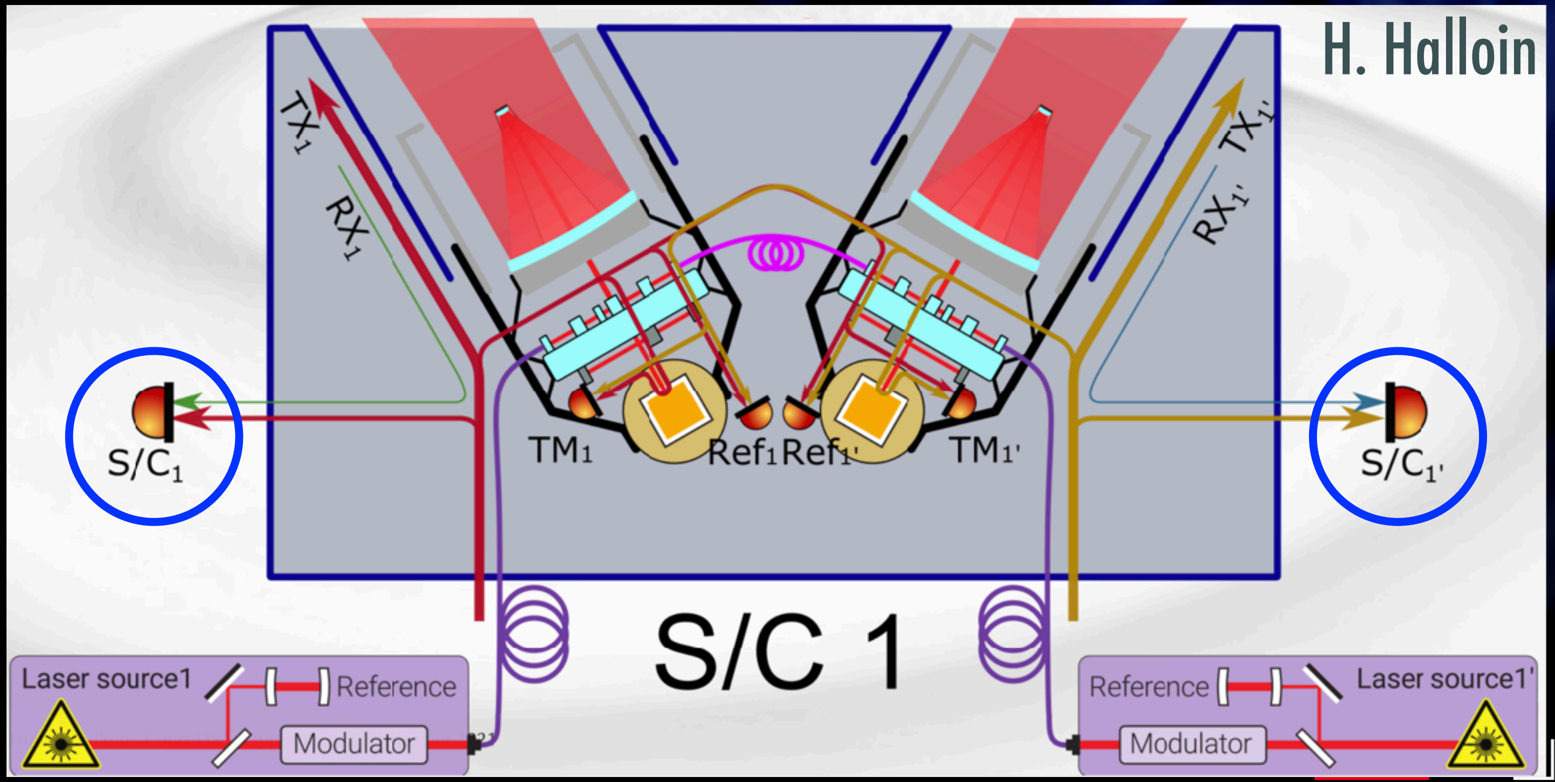

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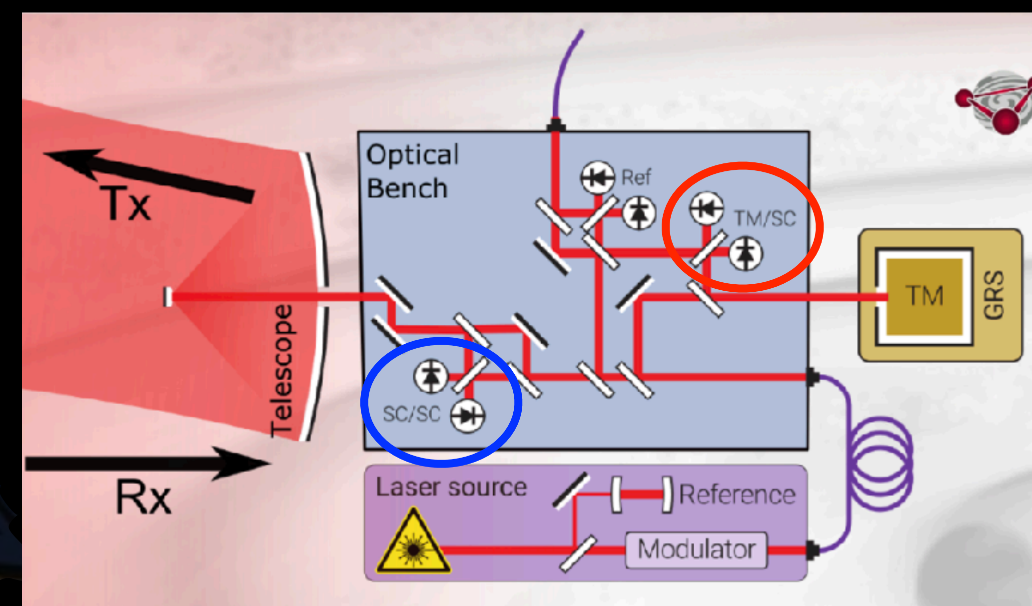

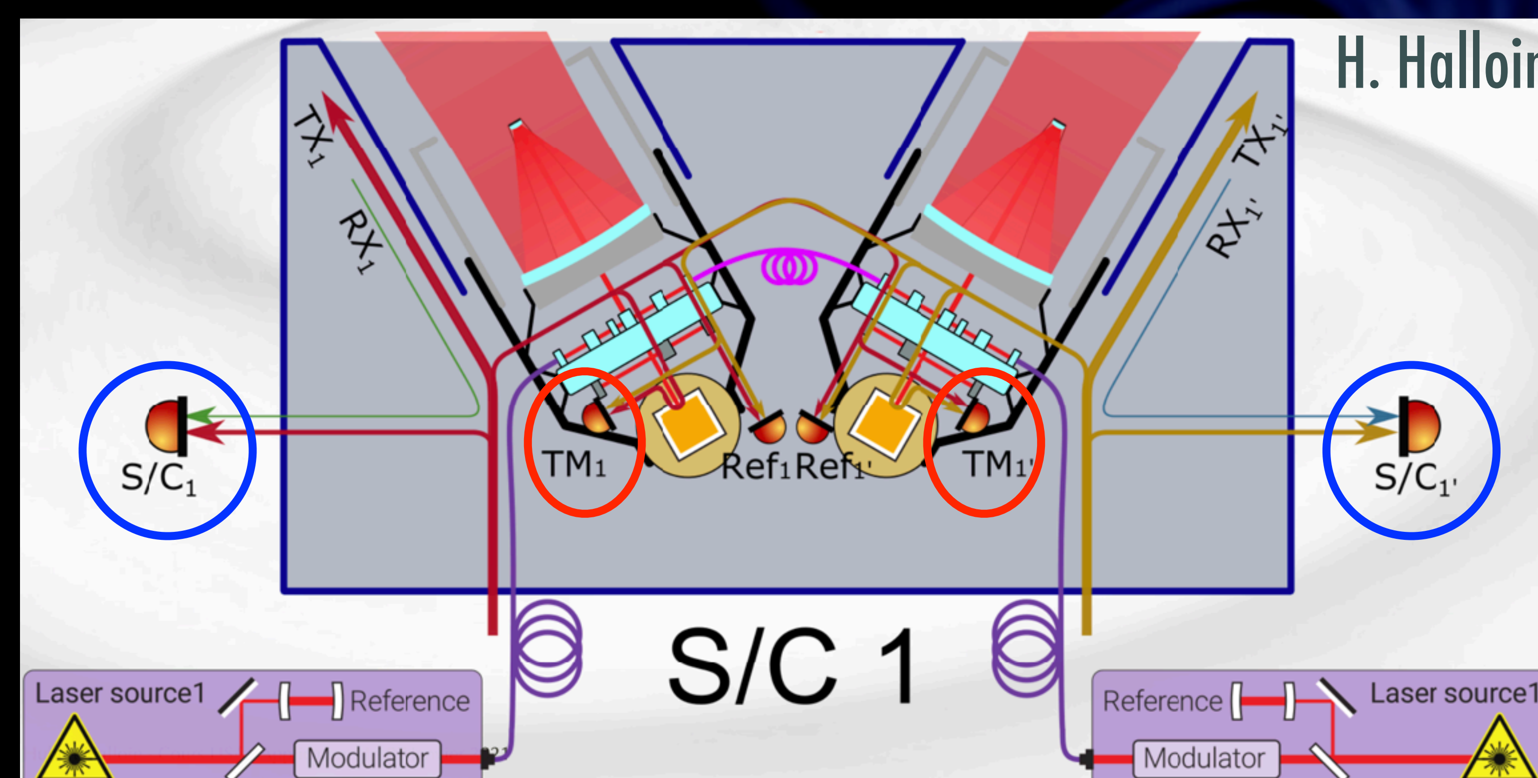

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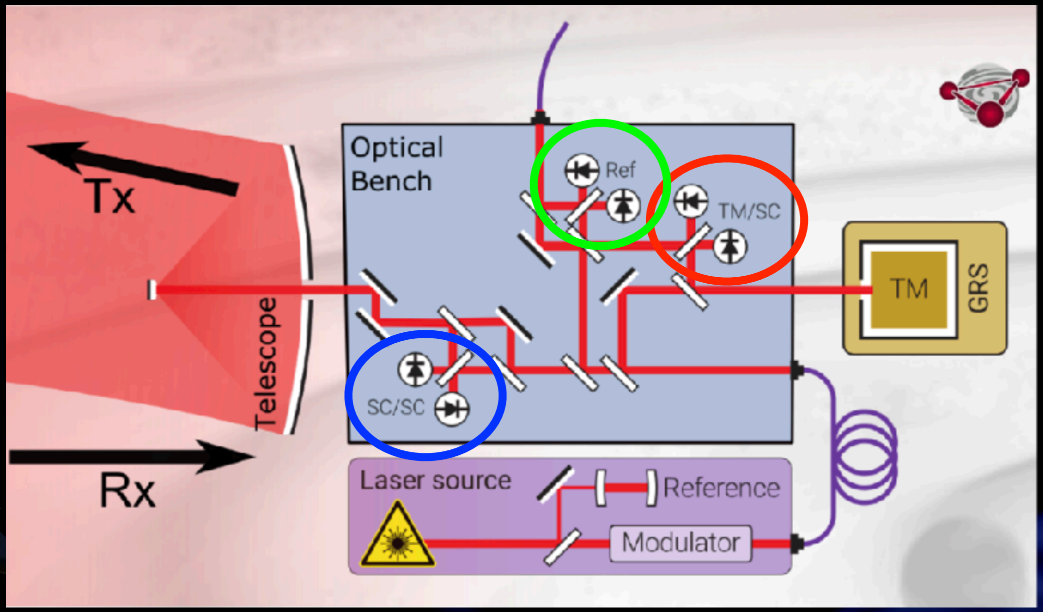

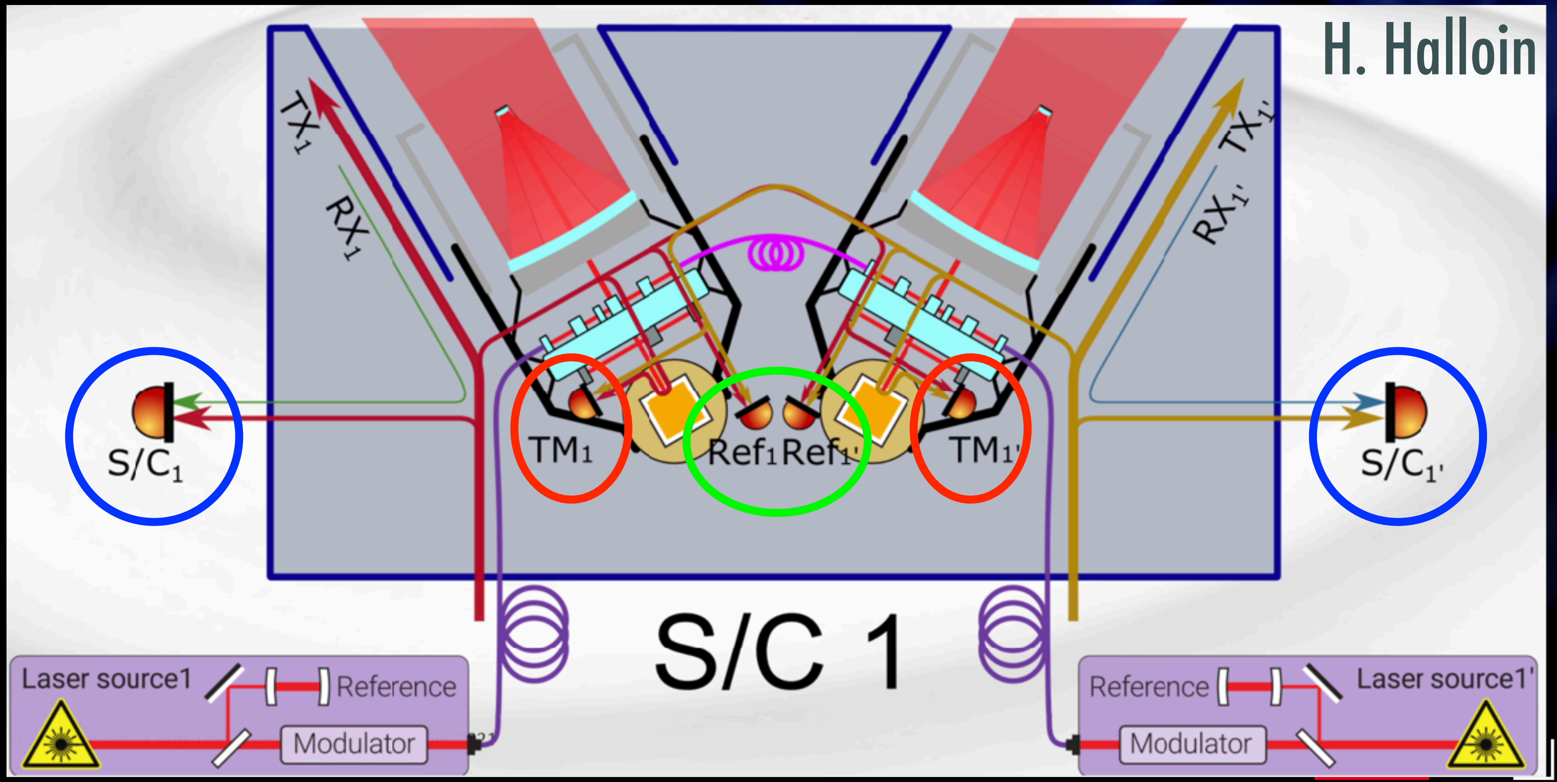

Interferometric measurements

- Measurements via exchange of beams:
  - Heterodyne interferometry with carrier for inter-spacecraft measurement => GWs
  - Sideband for transferring amplified clock jitter => correction of additional clock jitter
  - Pseudo-Random Noise => ranging (measure arm length)
  - Laser locking