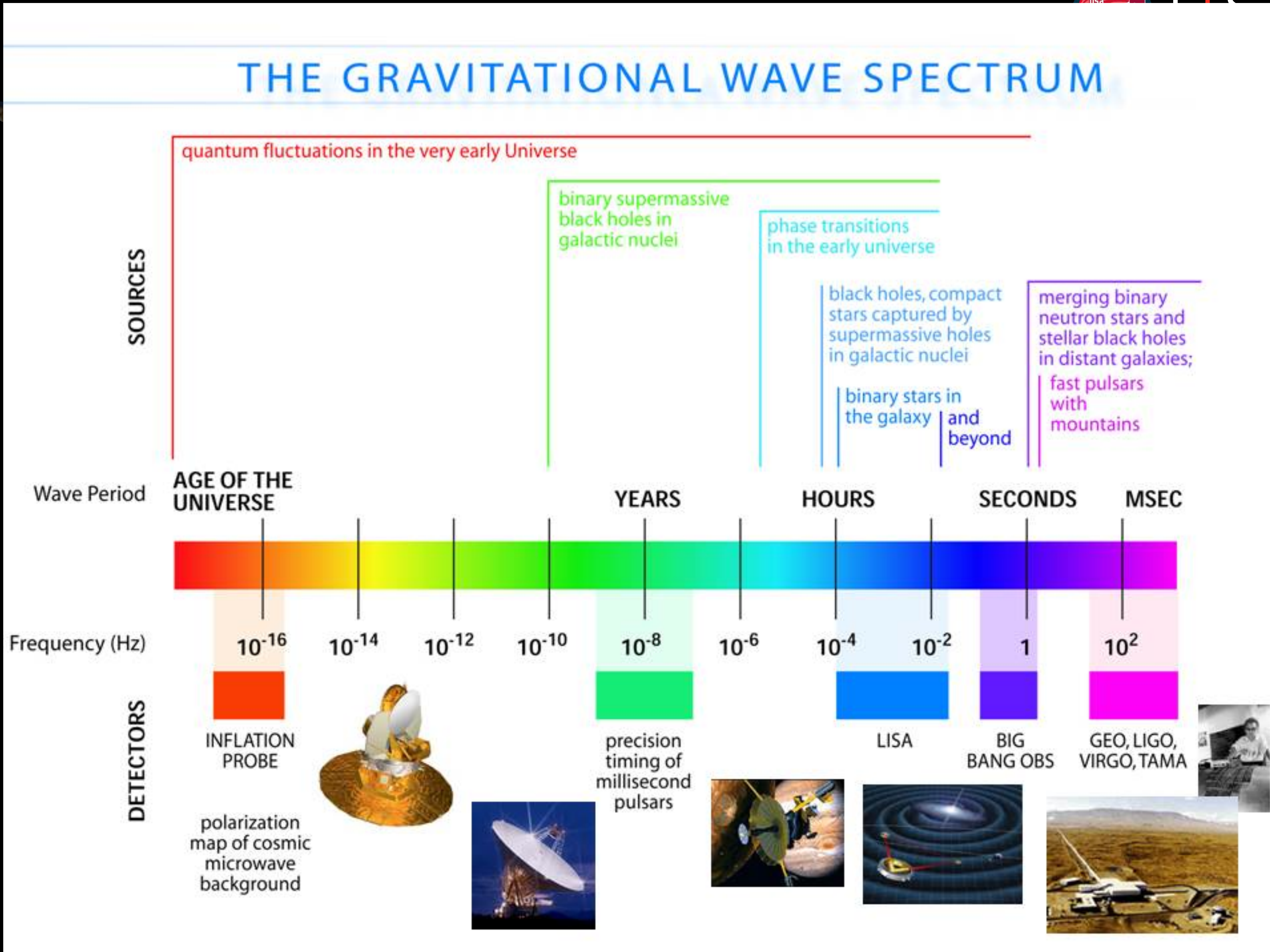
LISA Observing the Universe with GWs: Instrument, Data Analysis and Science

Antoine Petiteau (CEA/IRFU/DPhP & APC)

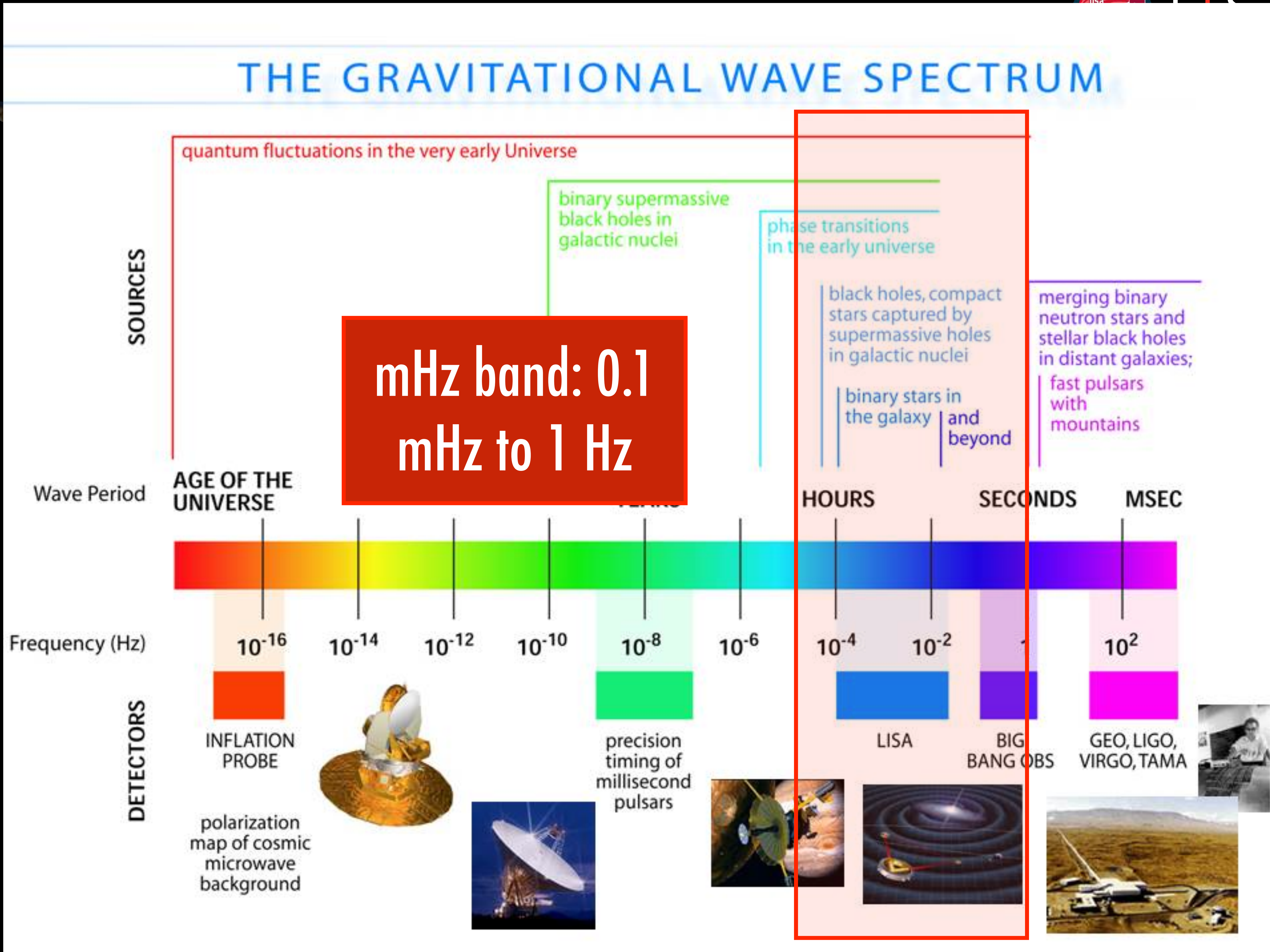
for the LISA mission and LISA Consortium

Fundamental physics and gravitational wave detectors

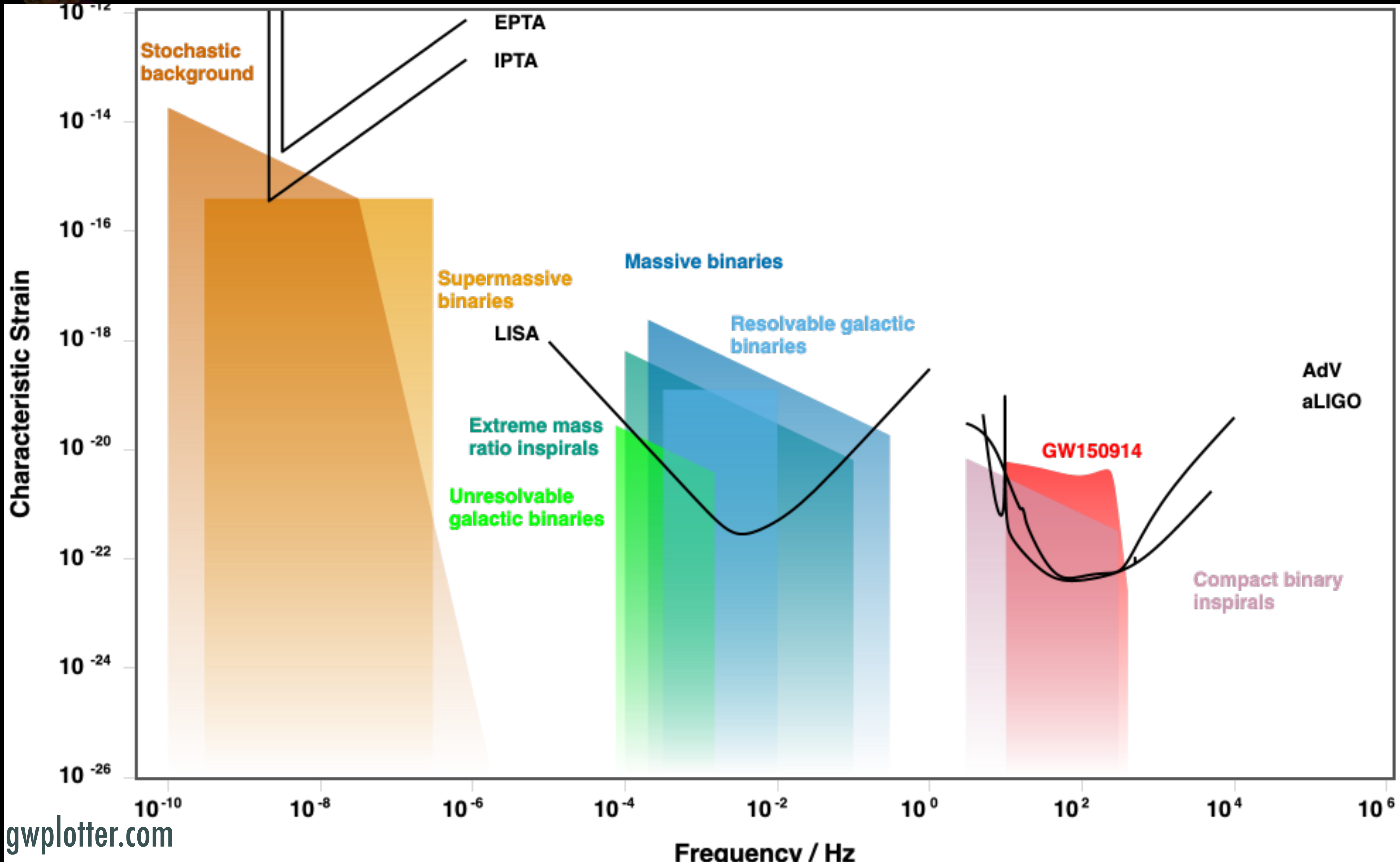
Pollica - 16th September 2024


THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10-16
10-14
10-12
10-10
10-8
10-6
10-4
10-2
1
102
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA

mHz band: 0.1 mHz to 1 Hz

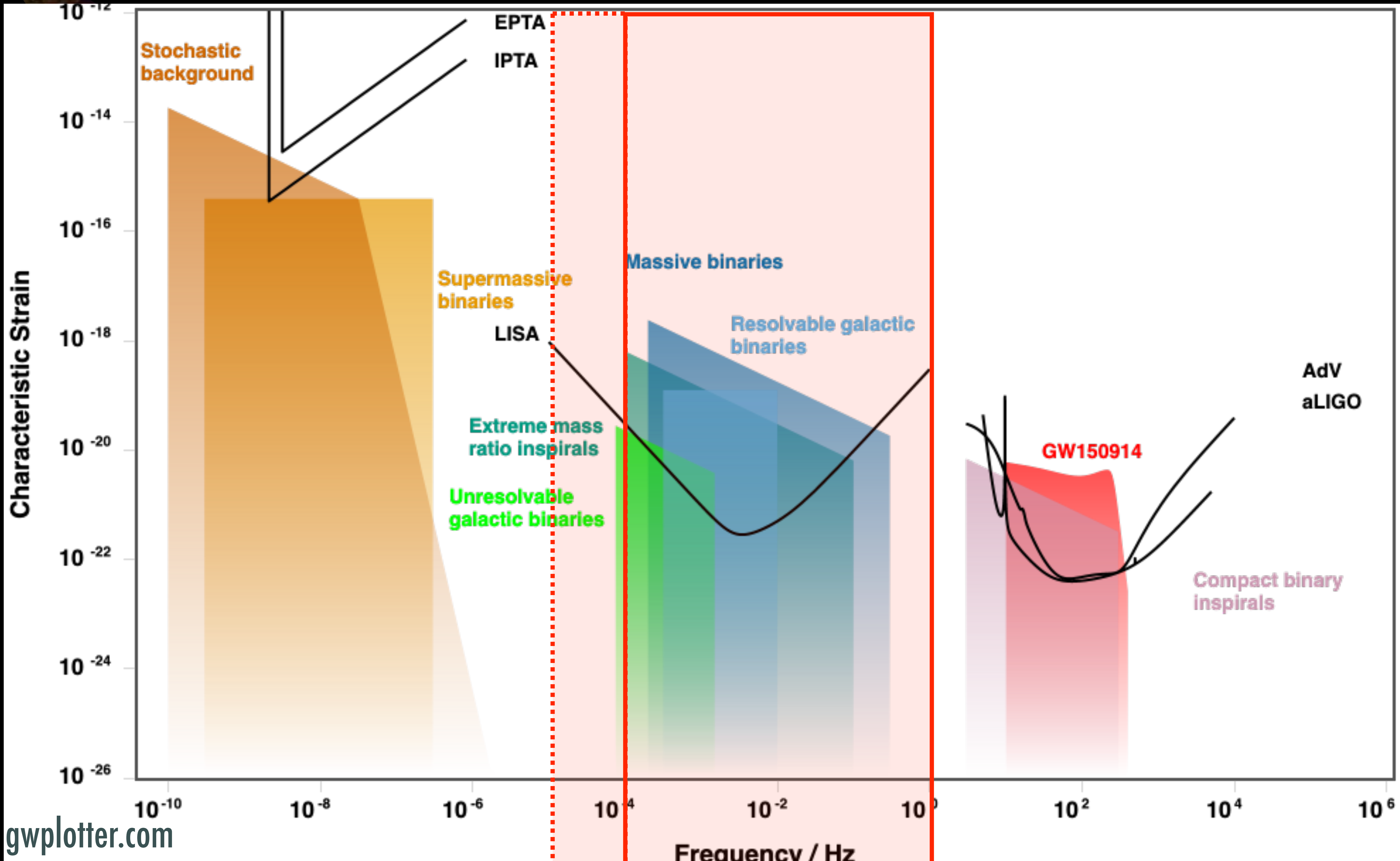


Sensitivity to GWs



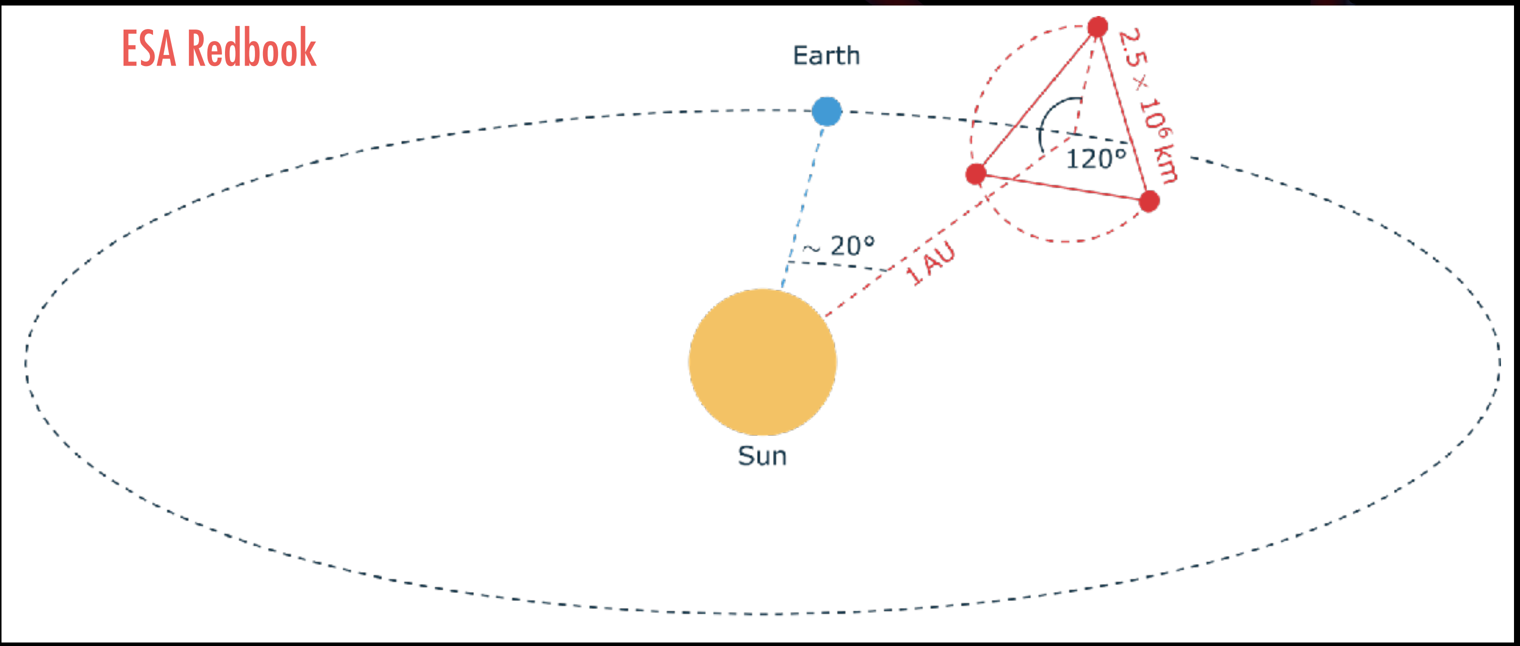
gwplotter.com

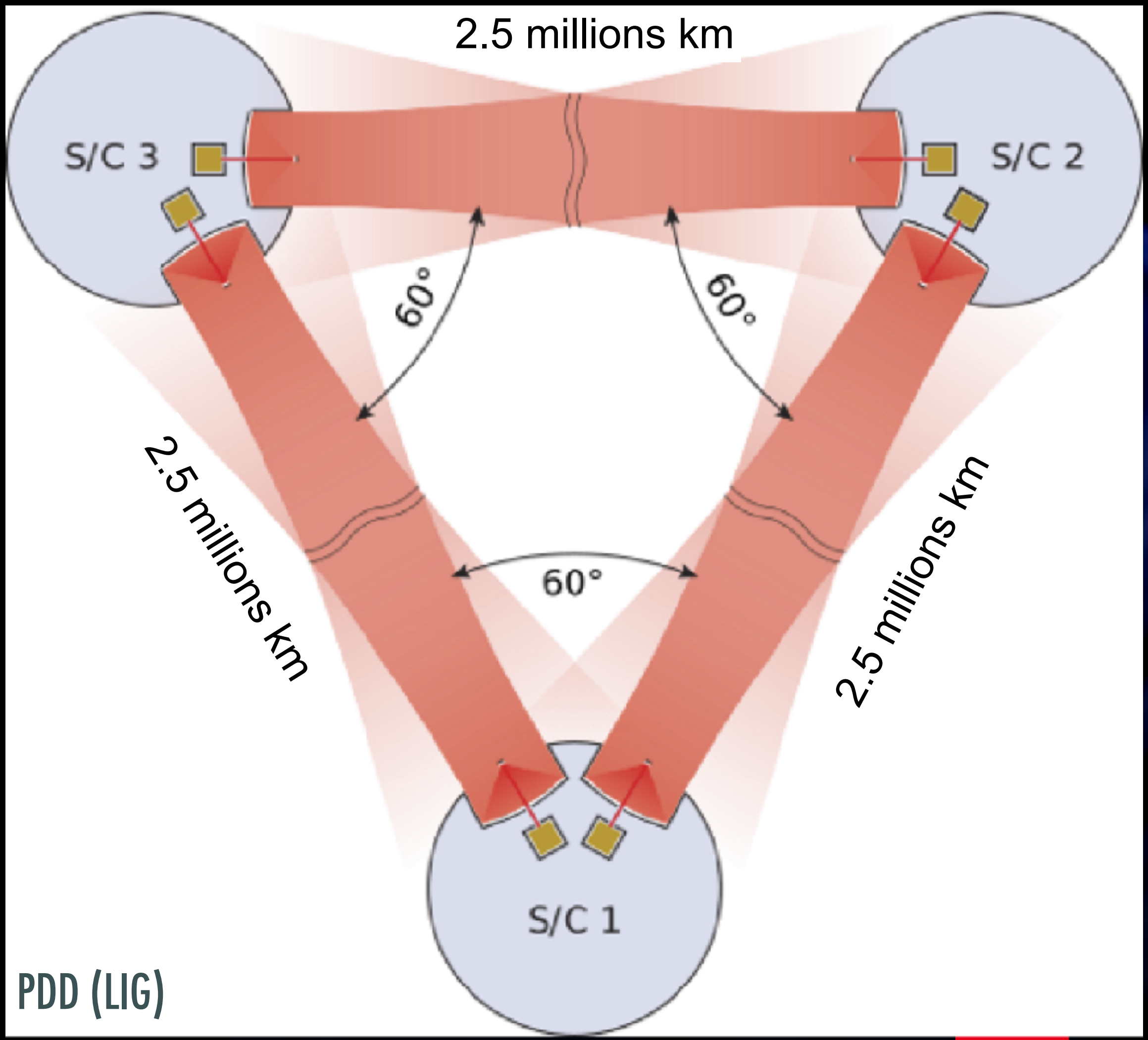
Sensitivity to GWs



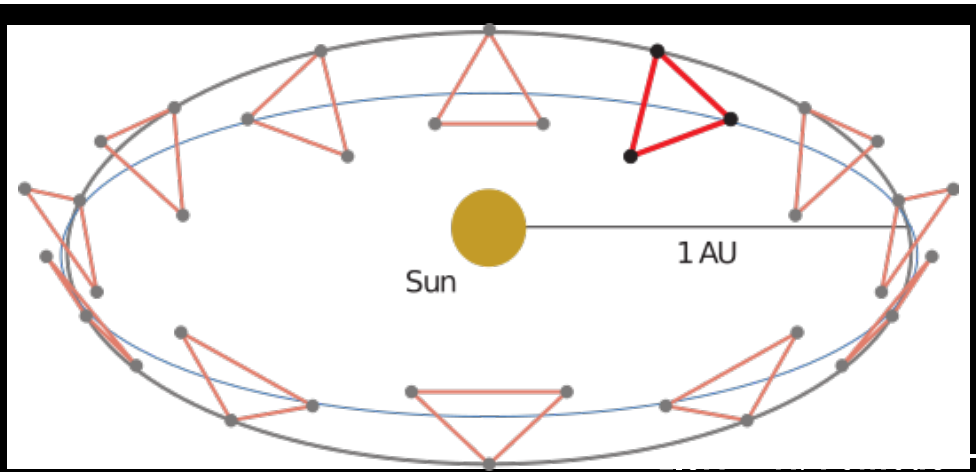
Mission design

- 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



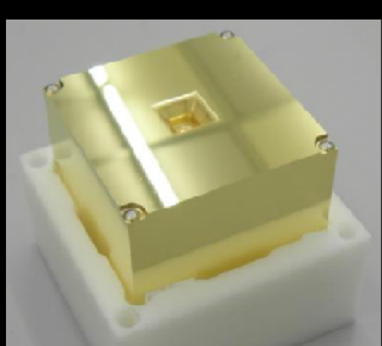


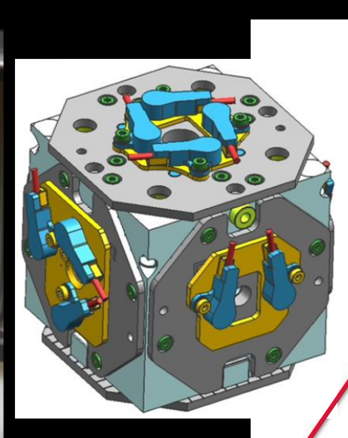
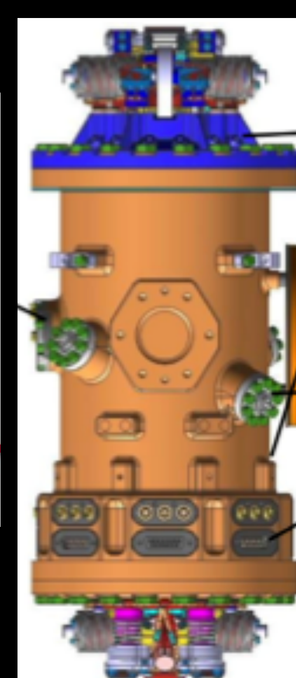
L3 proposal
(LISA Consortium)



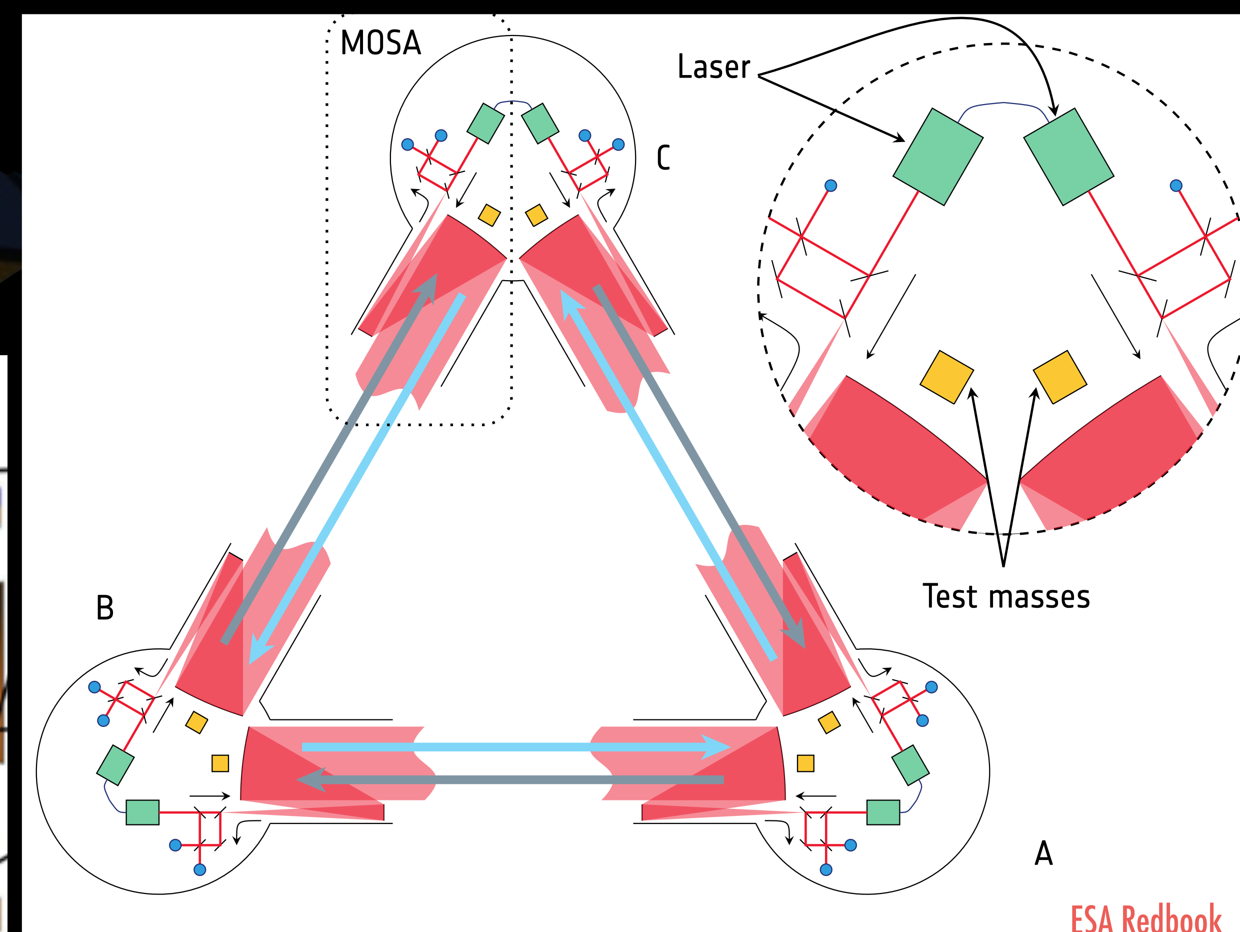
Mission design

- 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



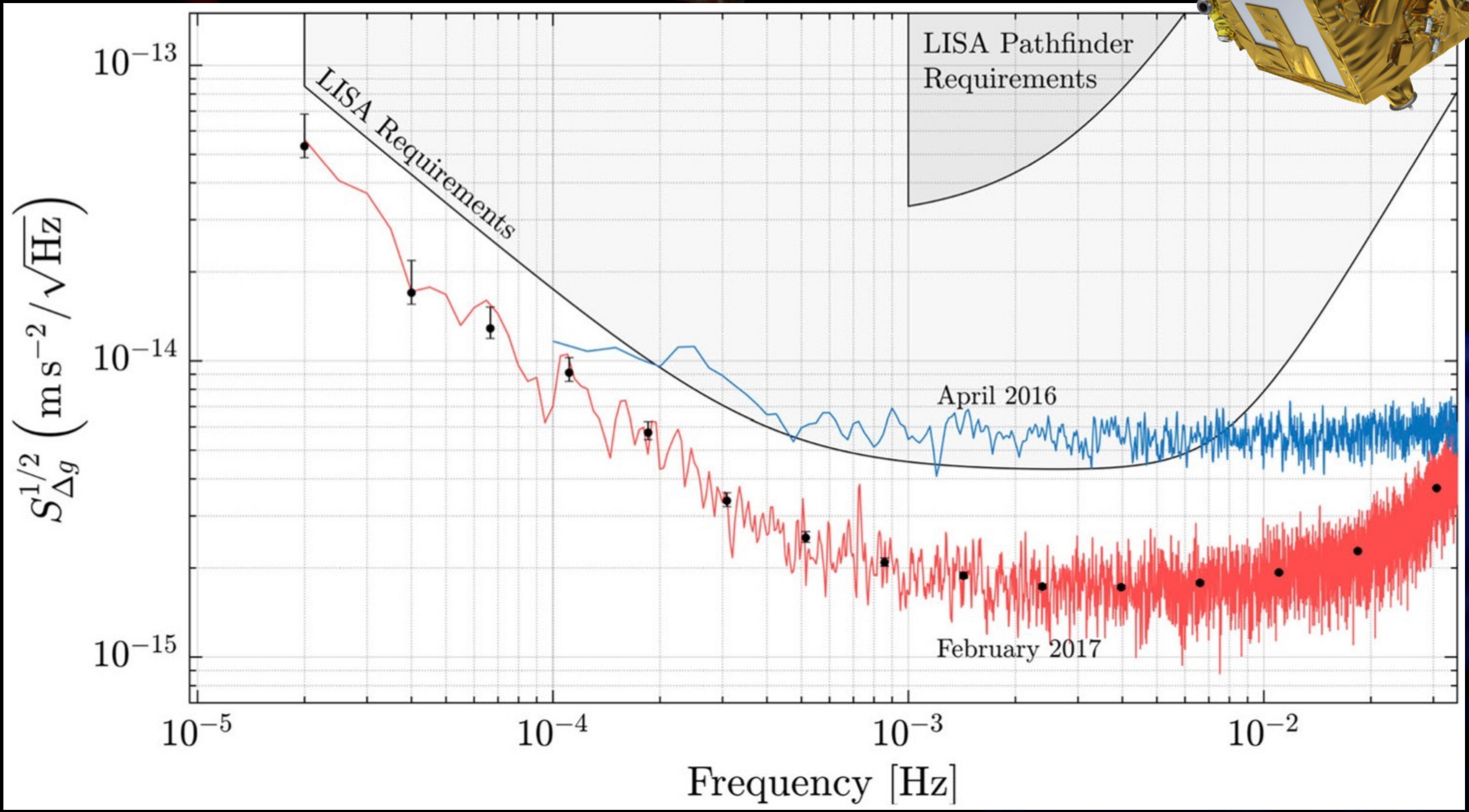
ESA Redbook - OHB Italia

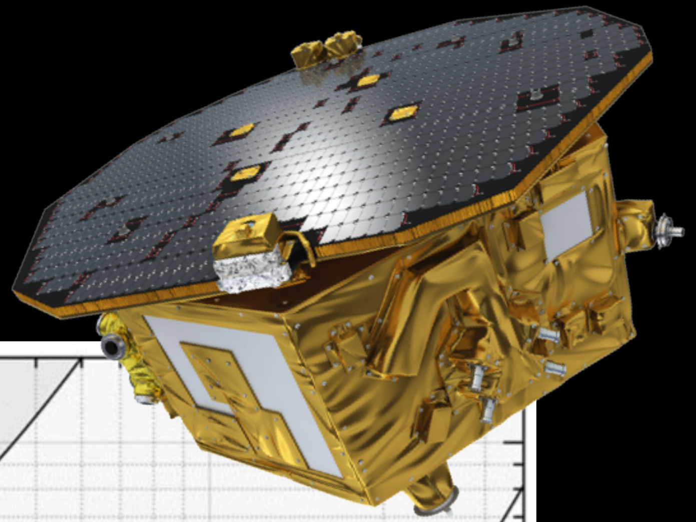


ESA Redbook

LISAPathfinder final main results

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

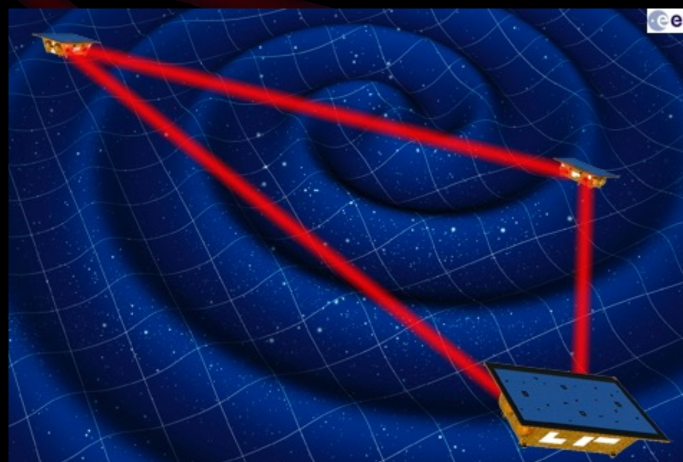


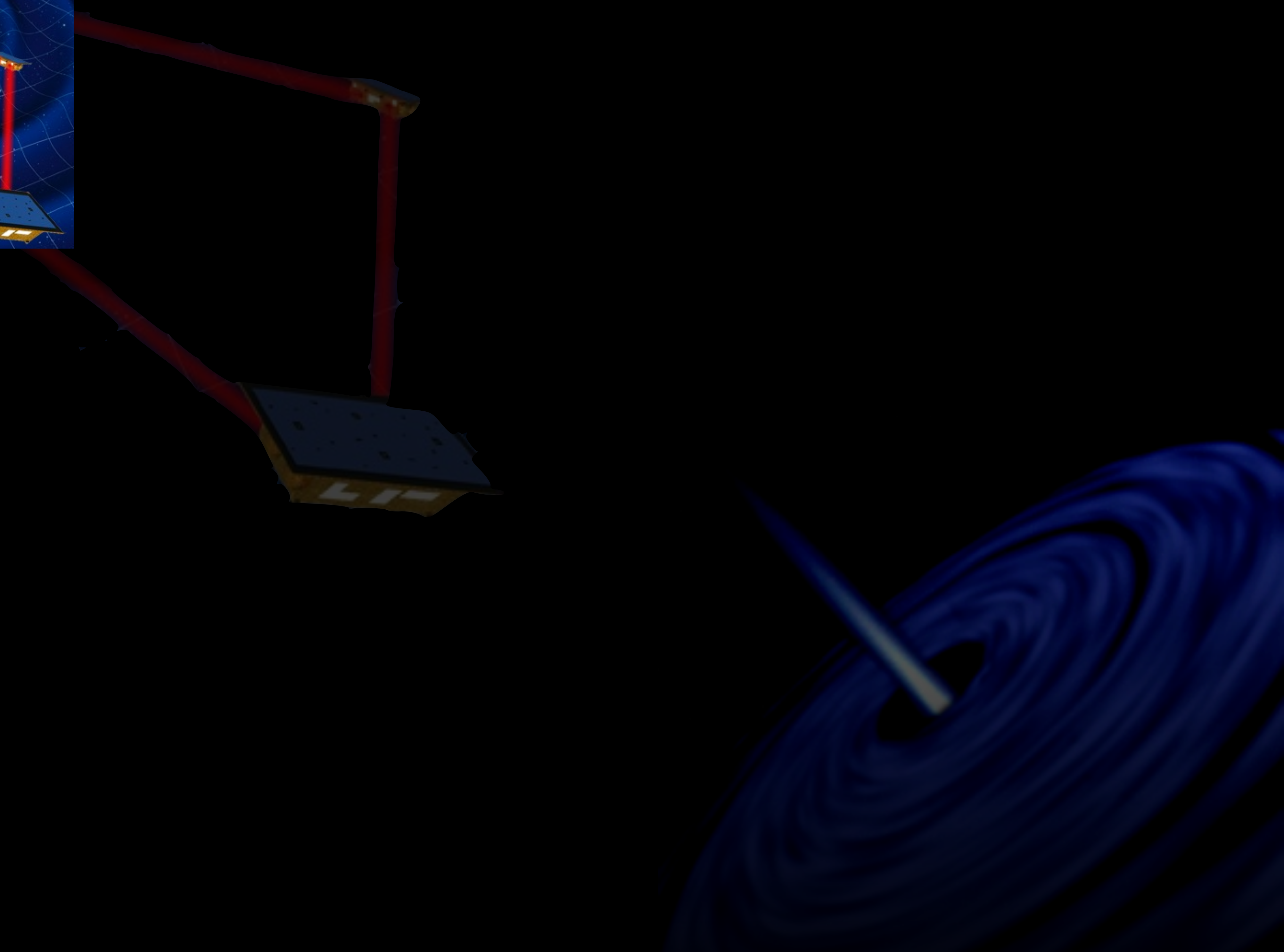


M. Armano et al. PRL 120, 061101 (2018)

Mission design

- Several steps towards the required precision of measurement





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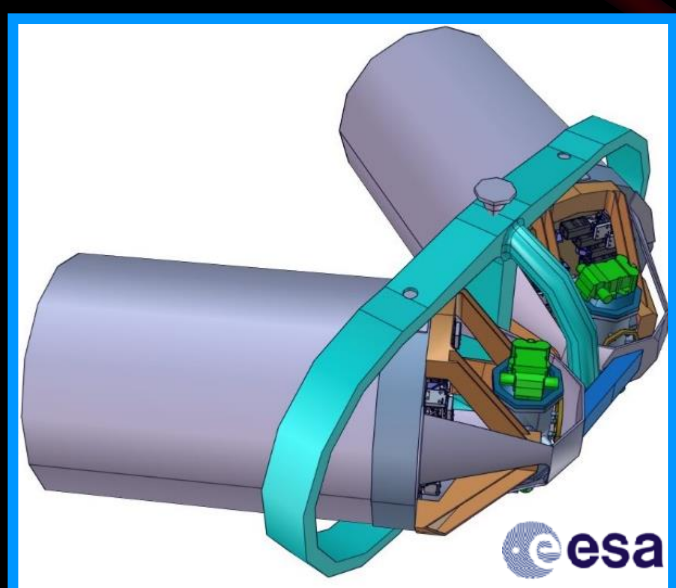

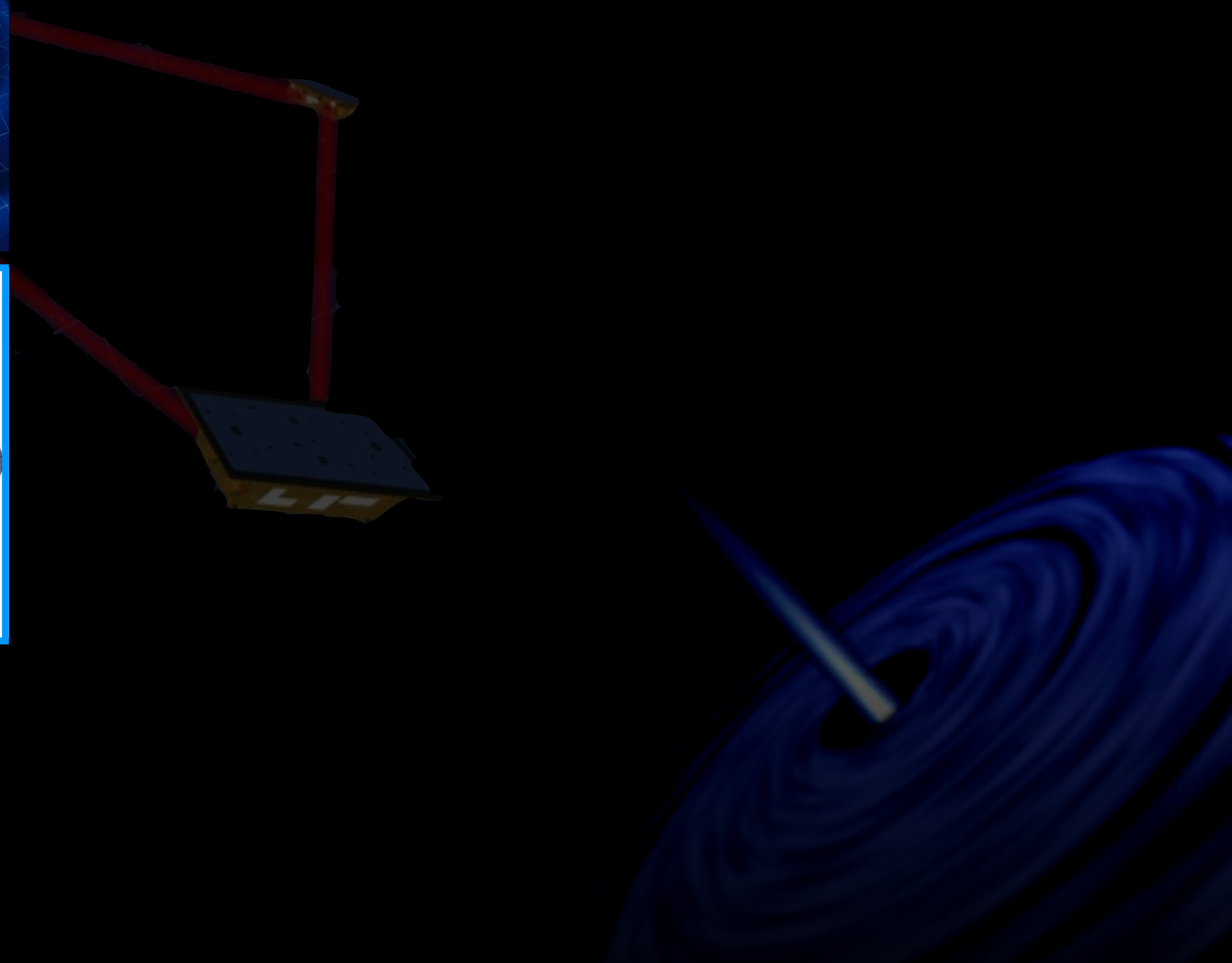

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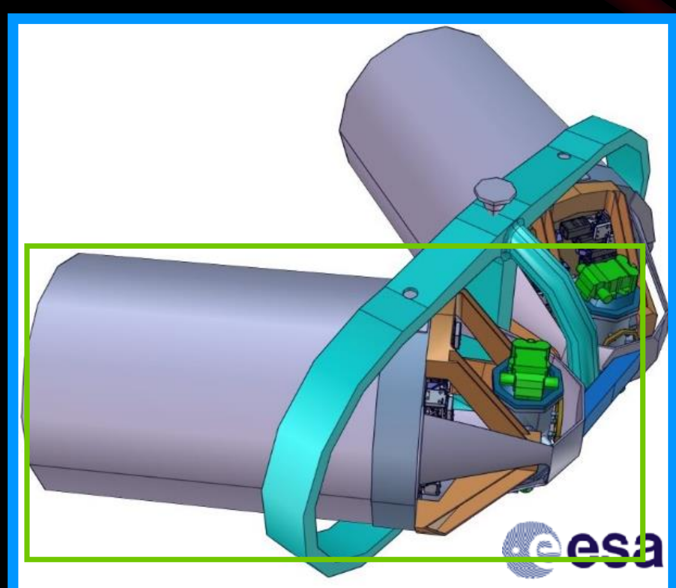

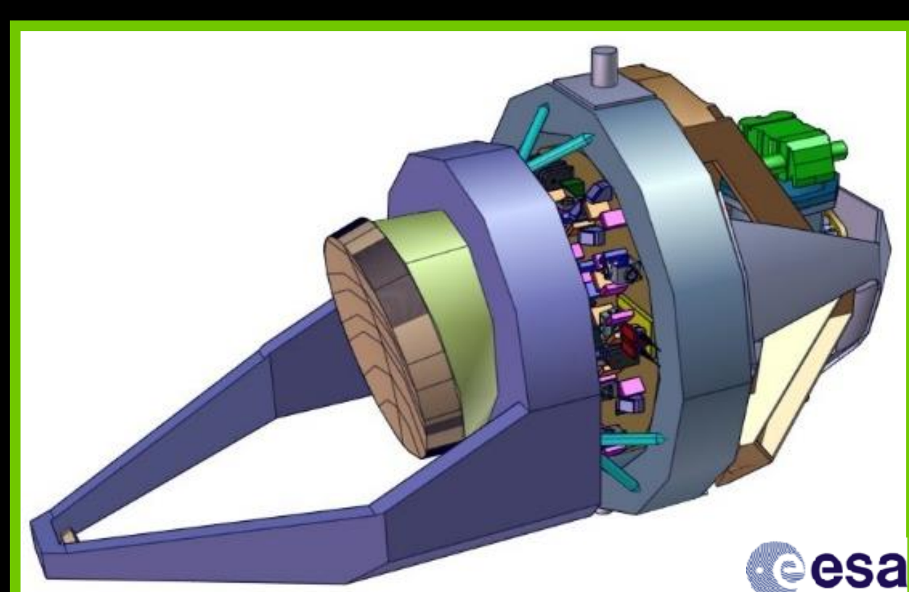

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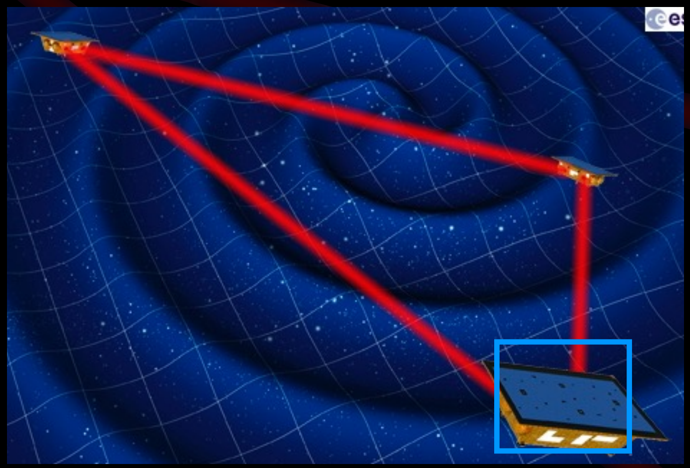

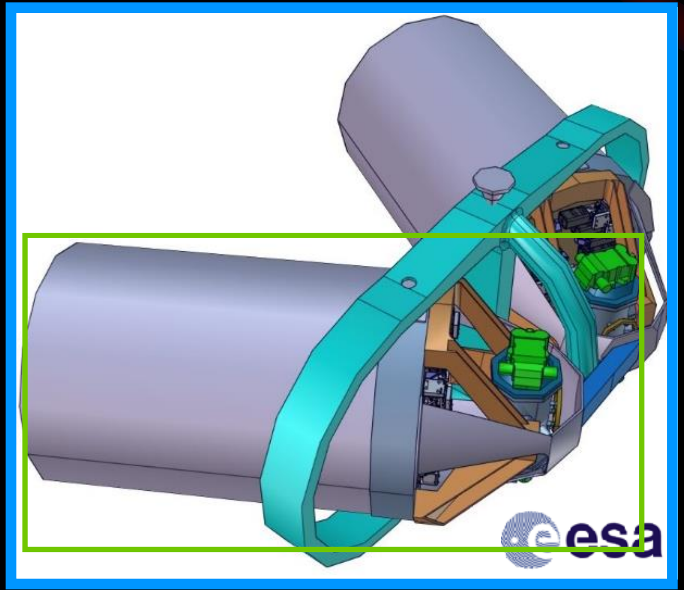

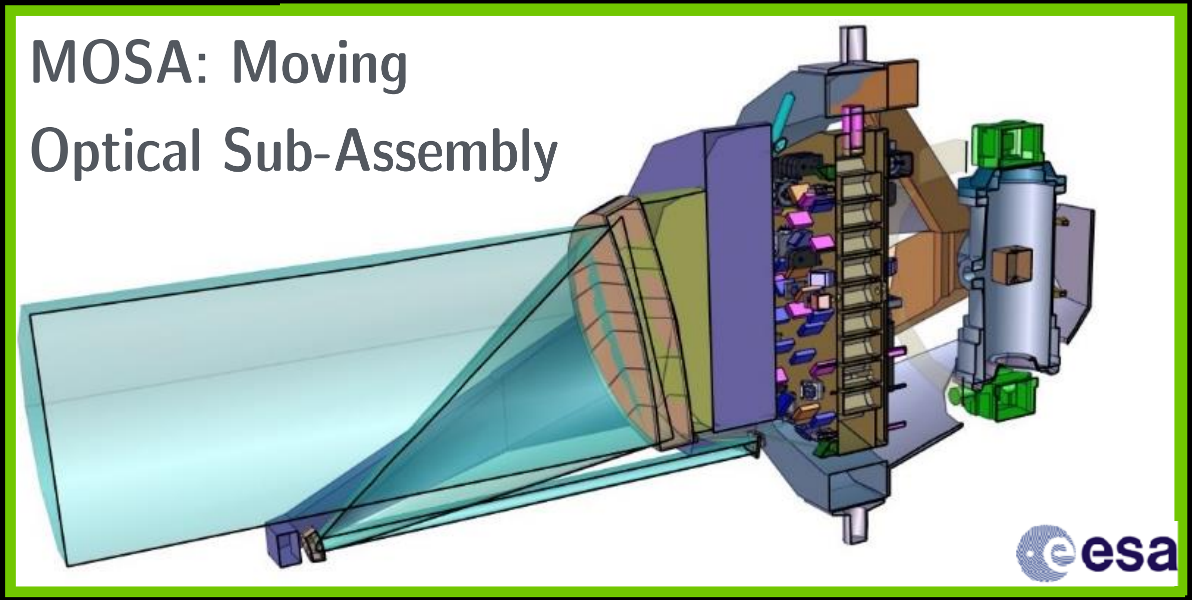

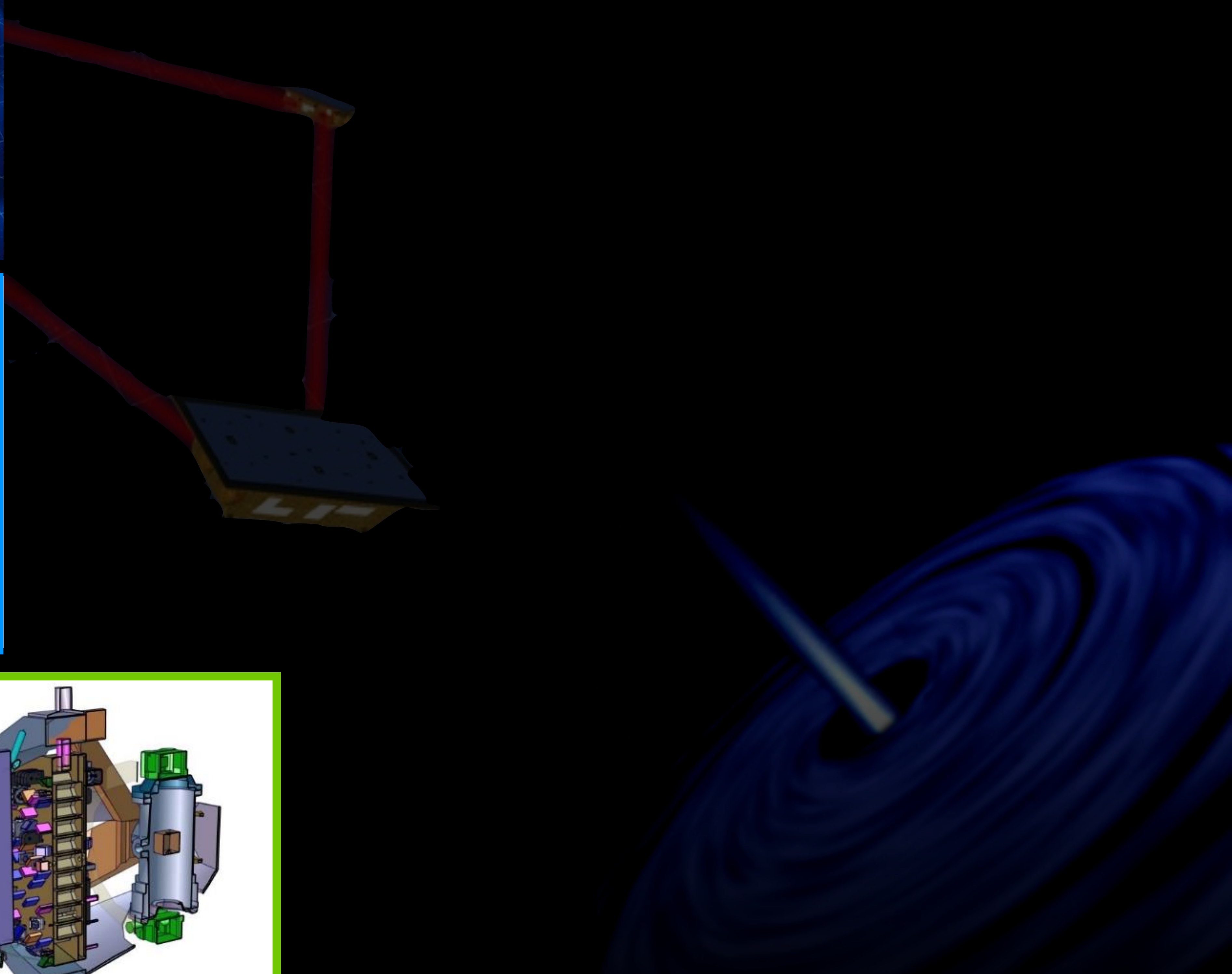

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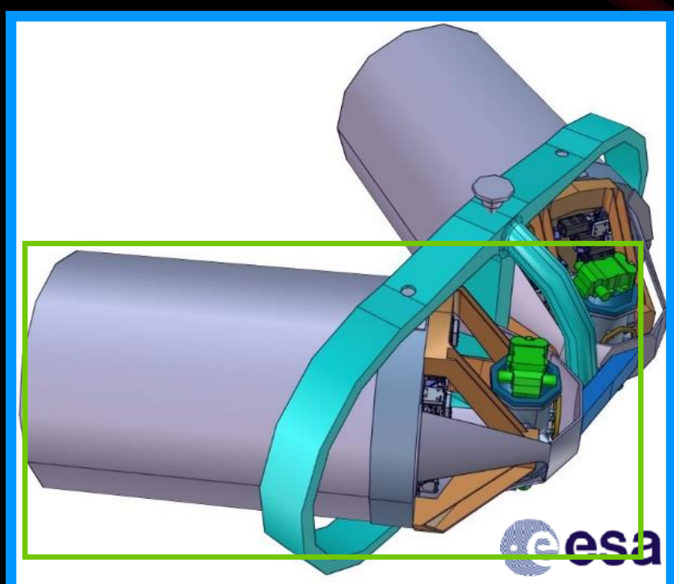
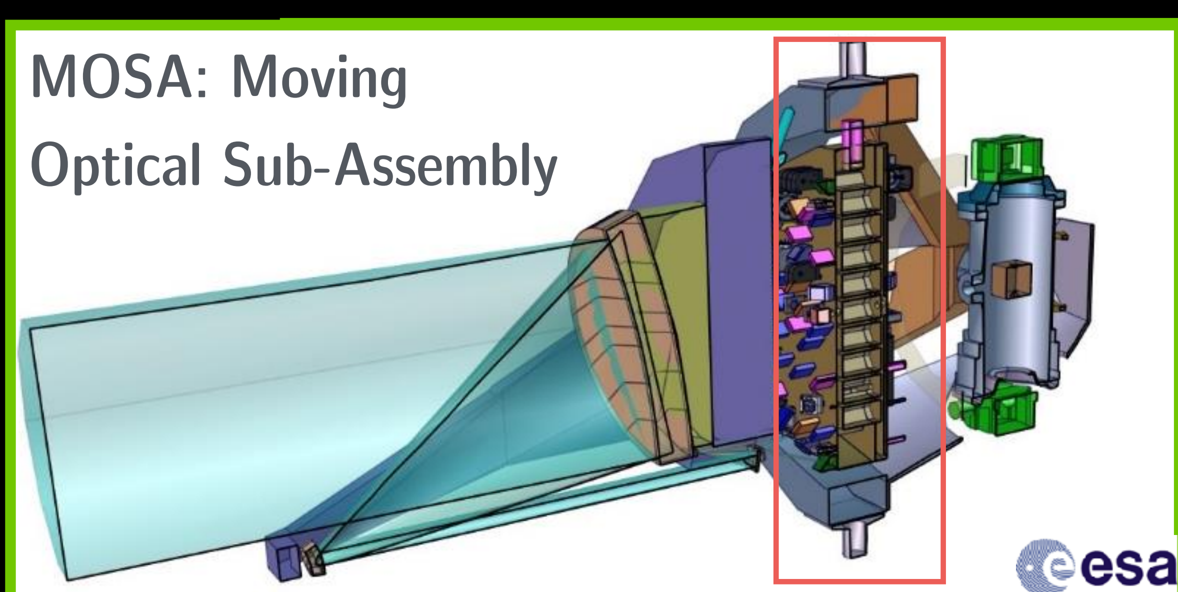
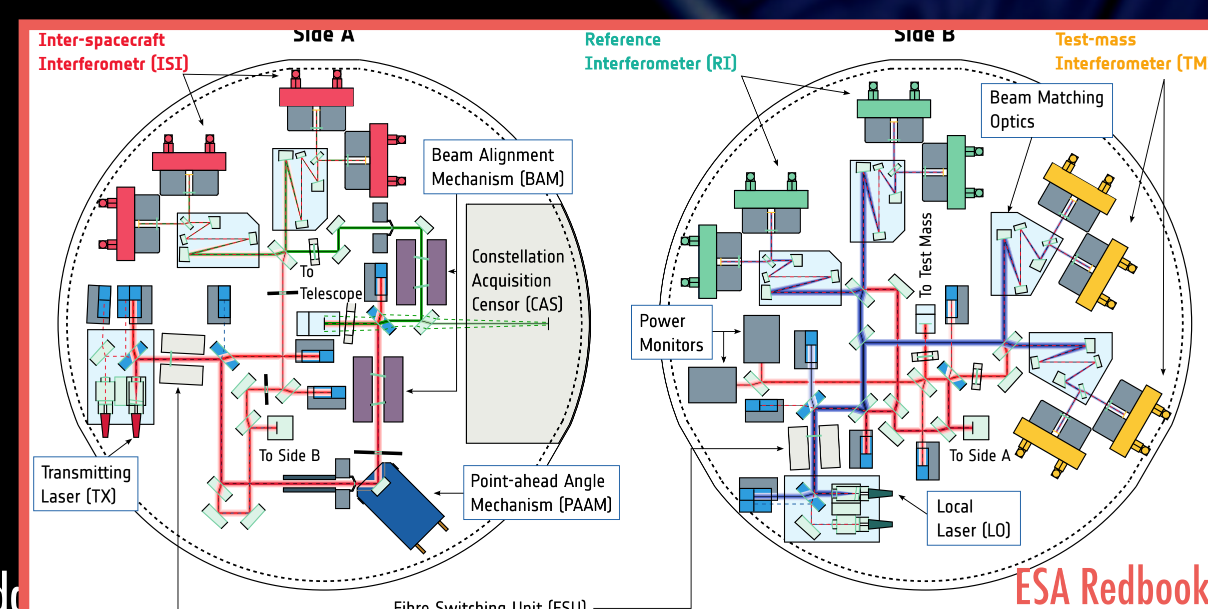


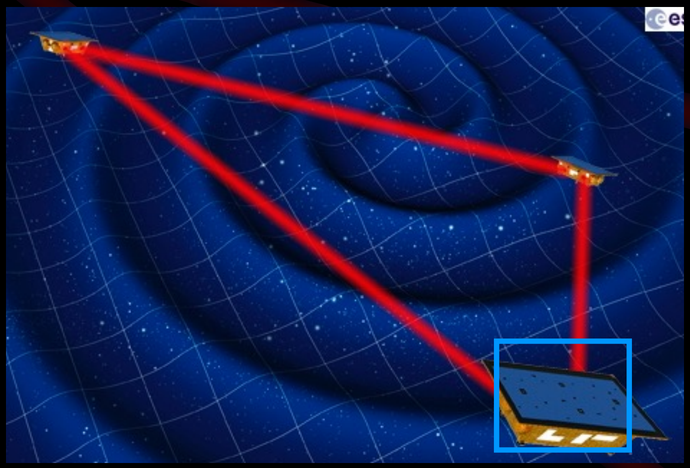


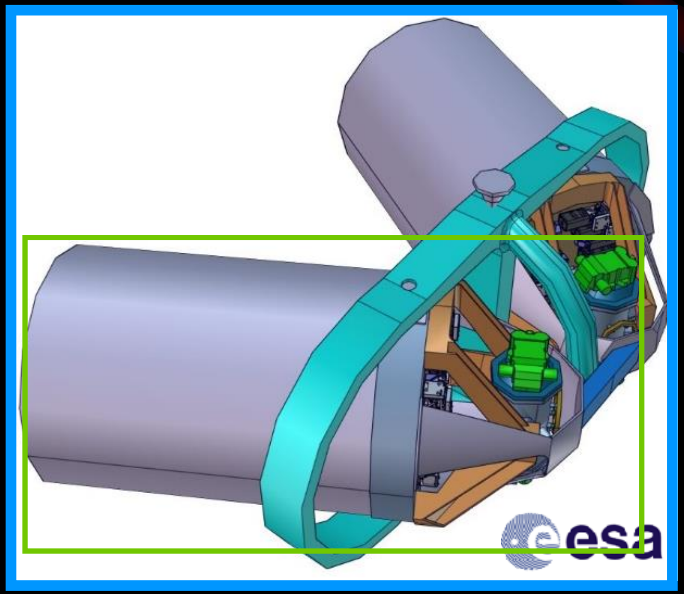


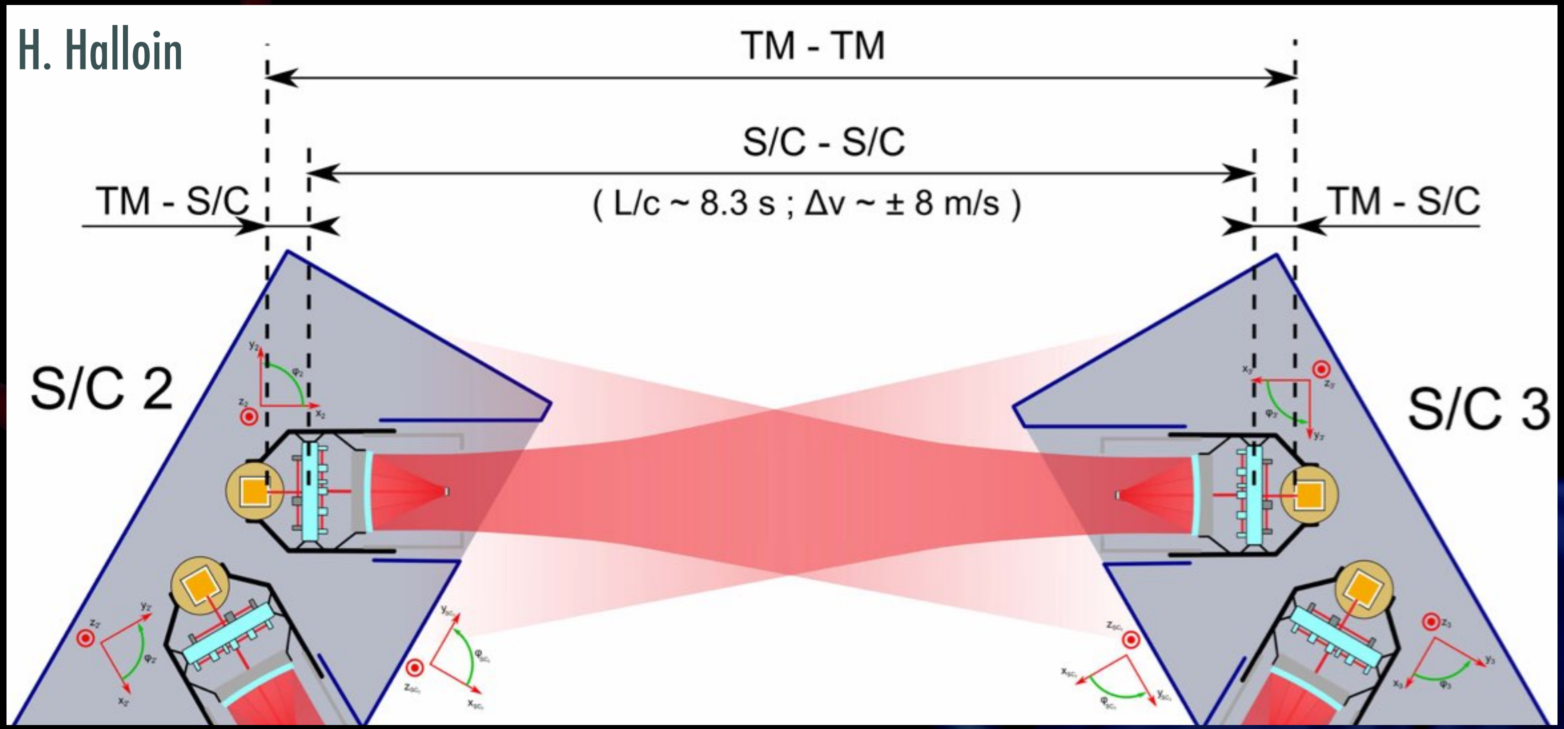
Mission design

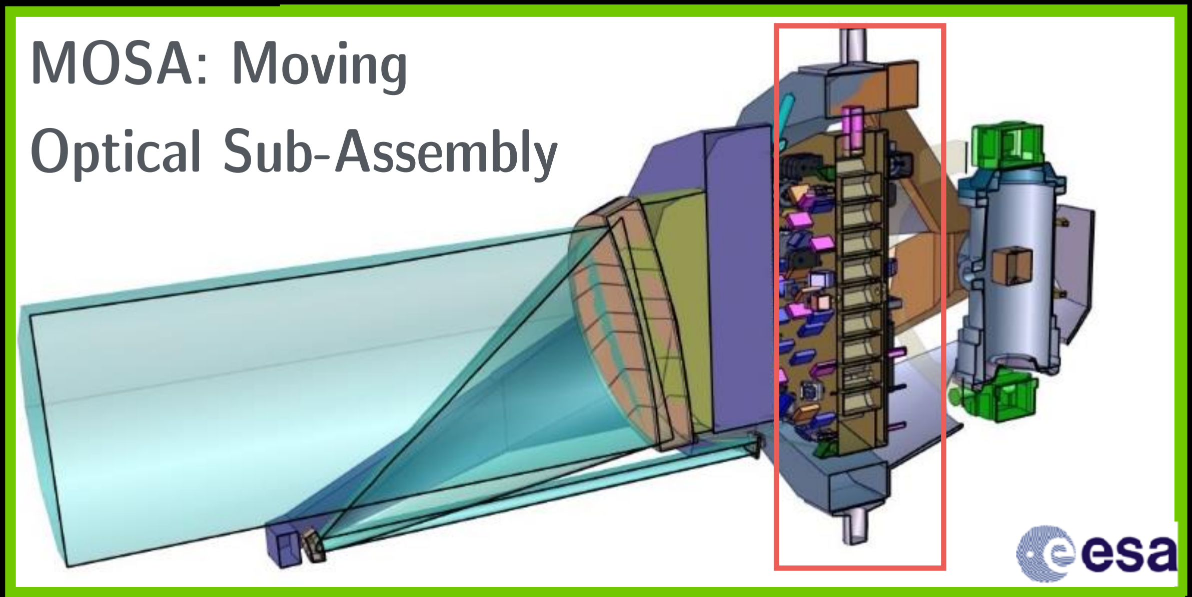
- Several steps towards the required precision of measurement

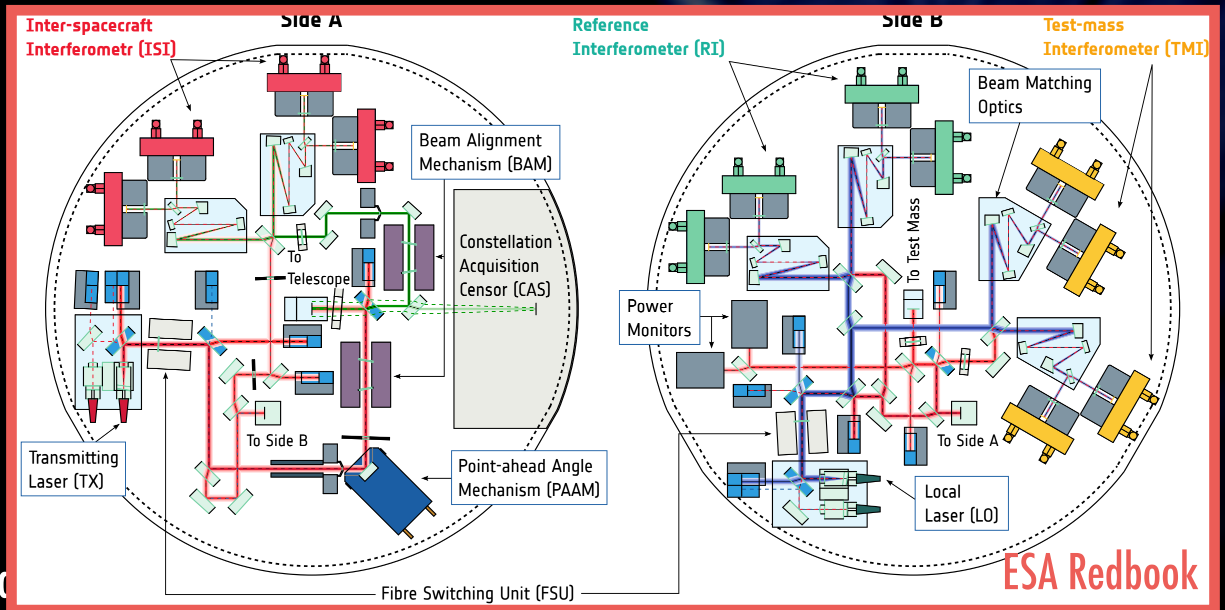
$$(TM2 \rightarrow SC2) + (SC2 \rightarrow SC3) + (SC3 \rightarrow TM3)$$





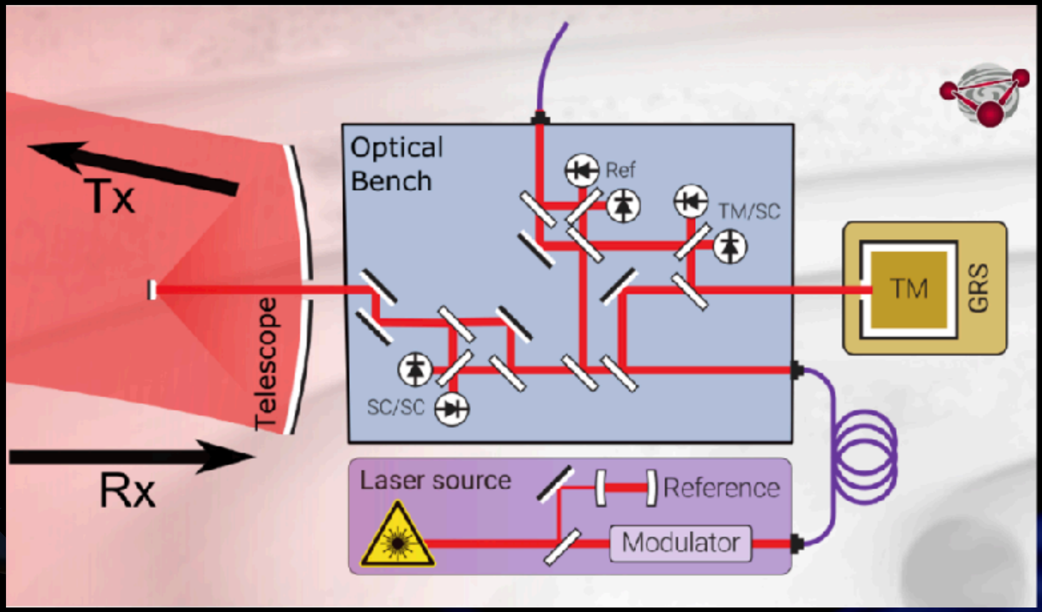


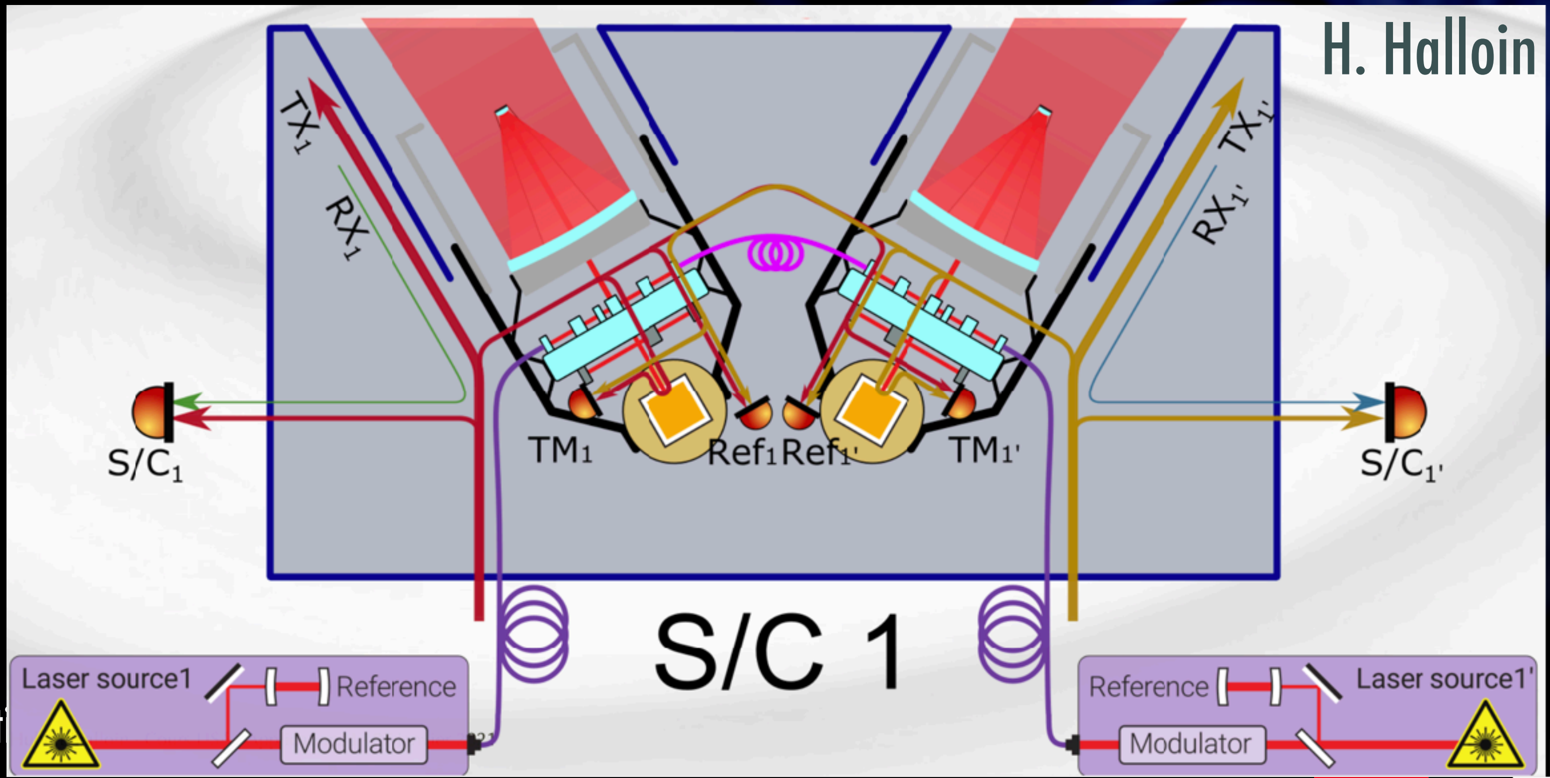




Interferometric measurements

- 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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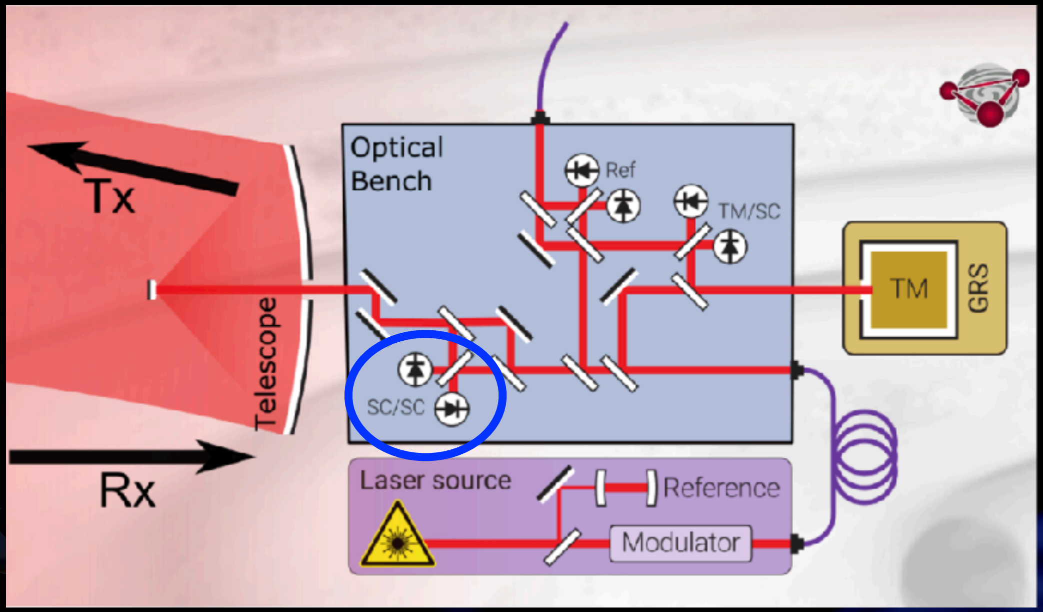

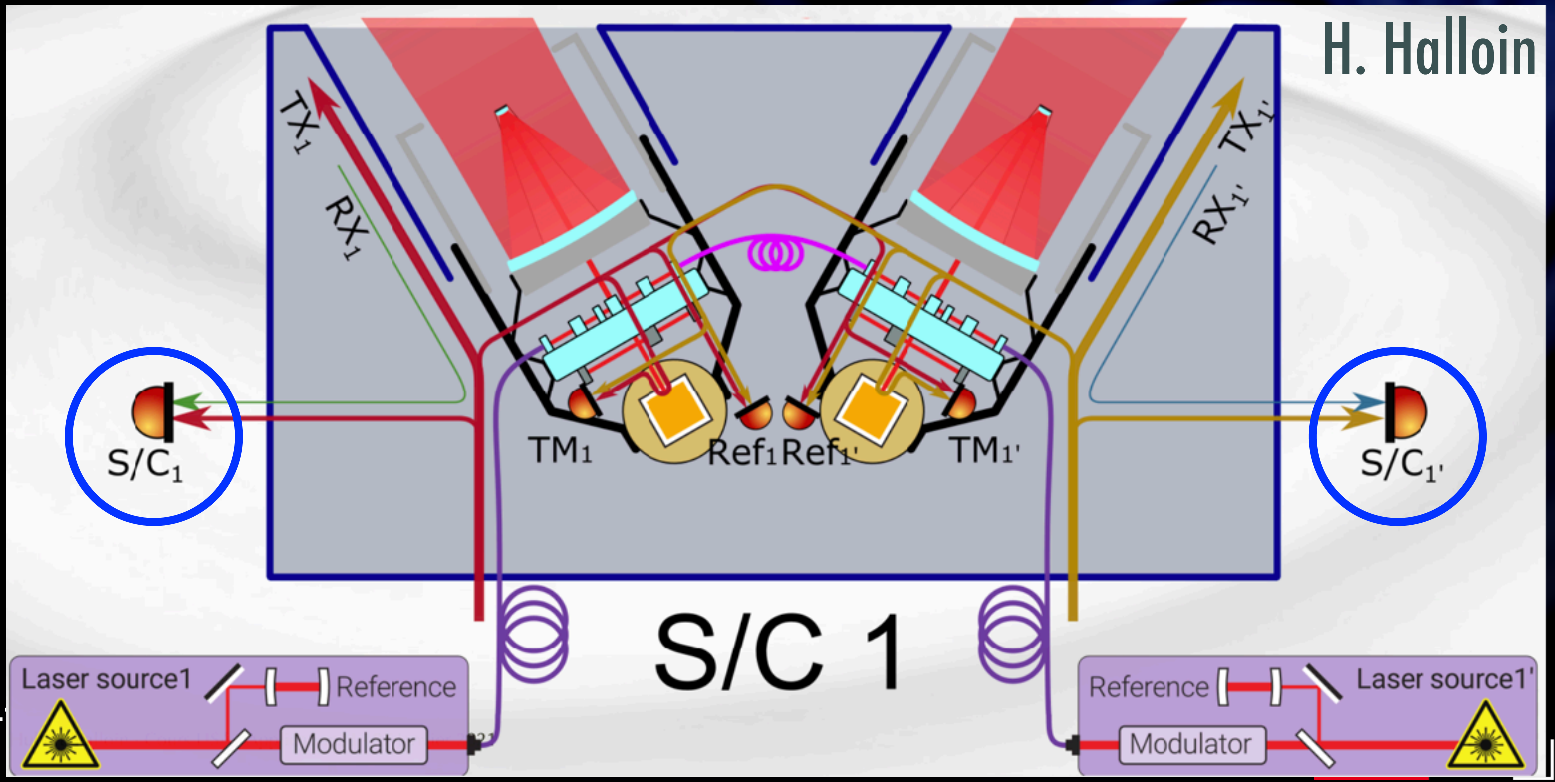

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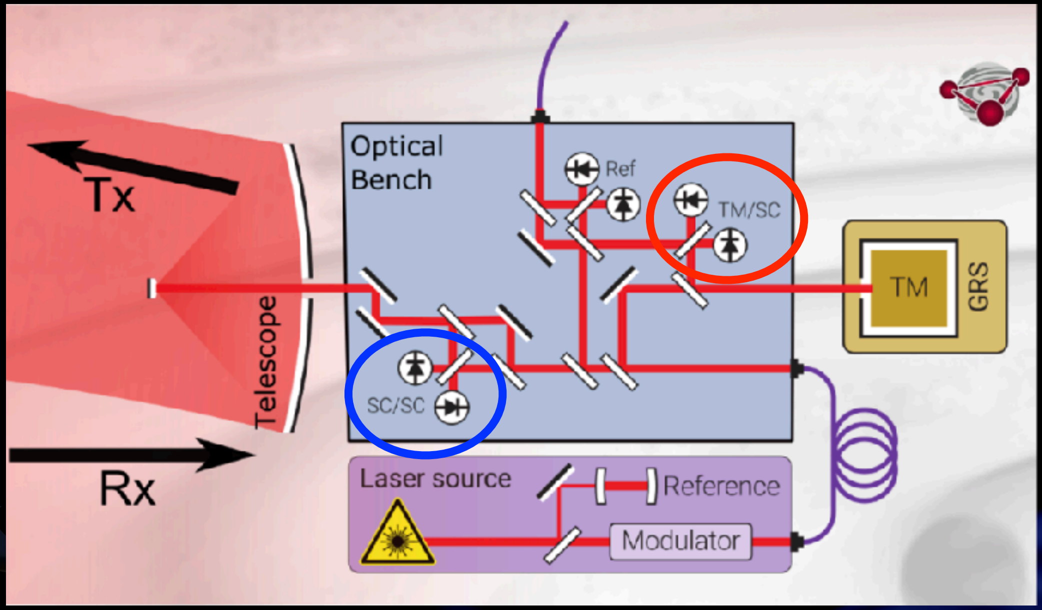

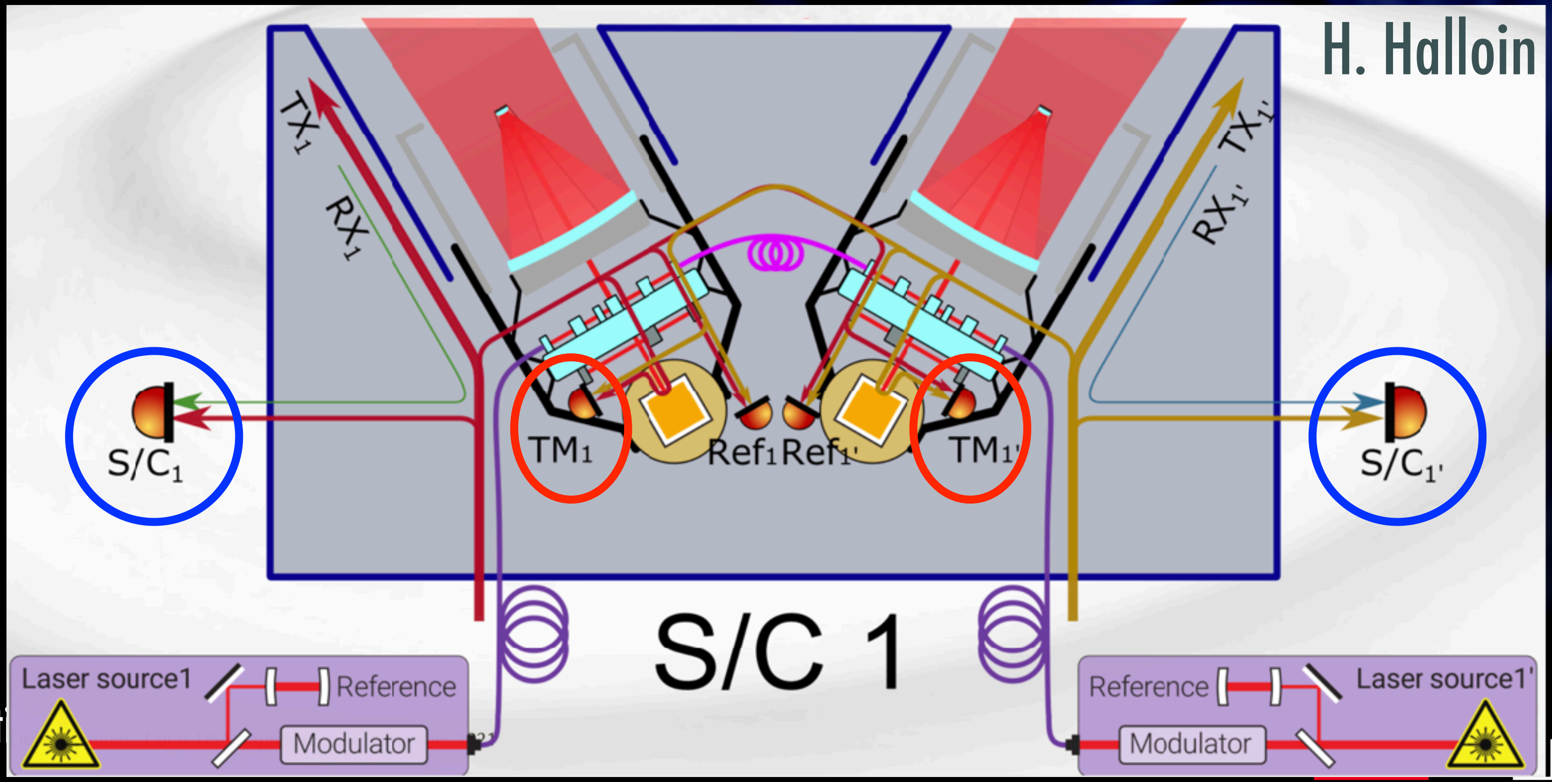

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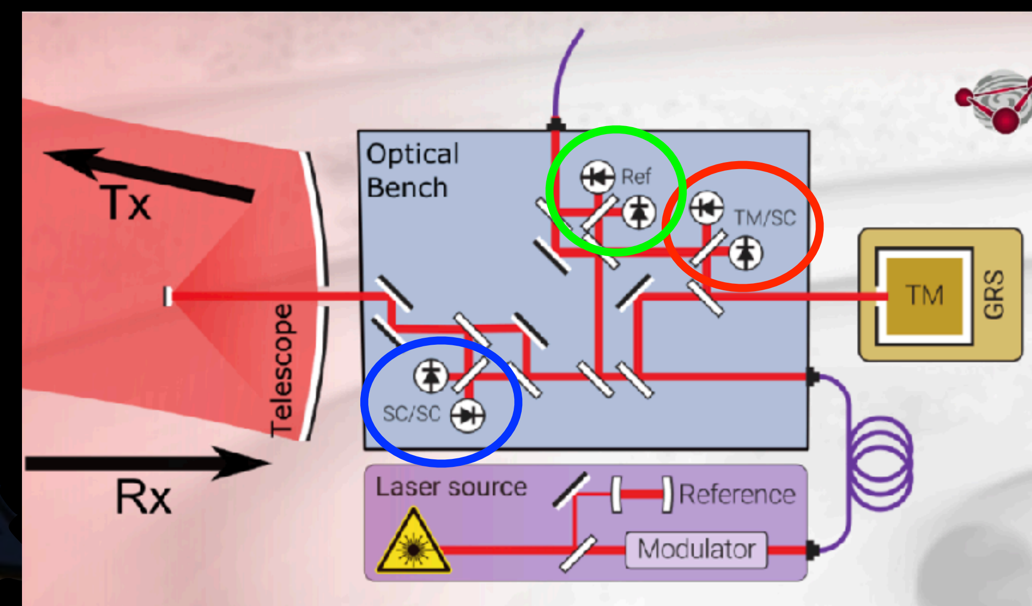
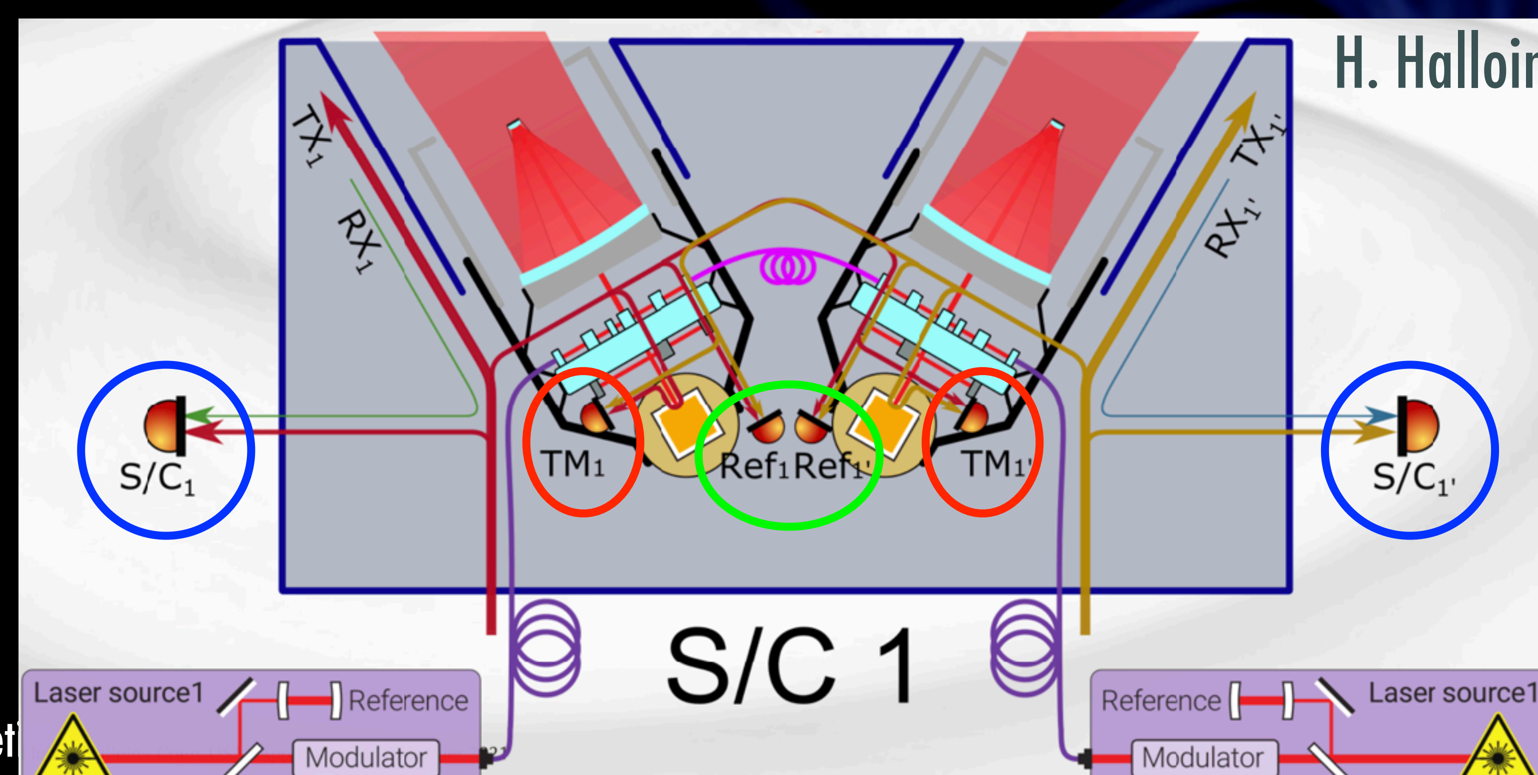
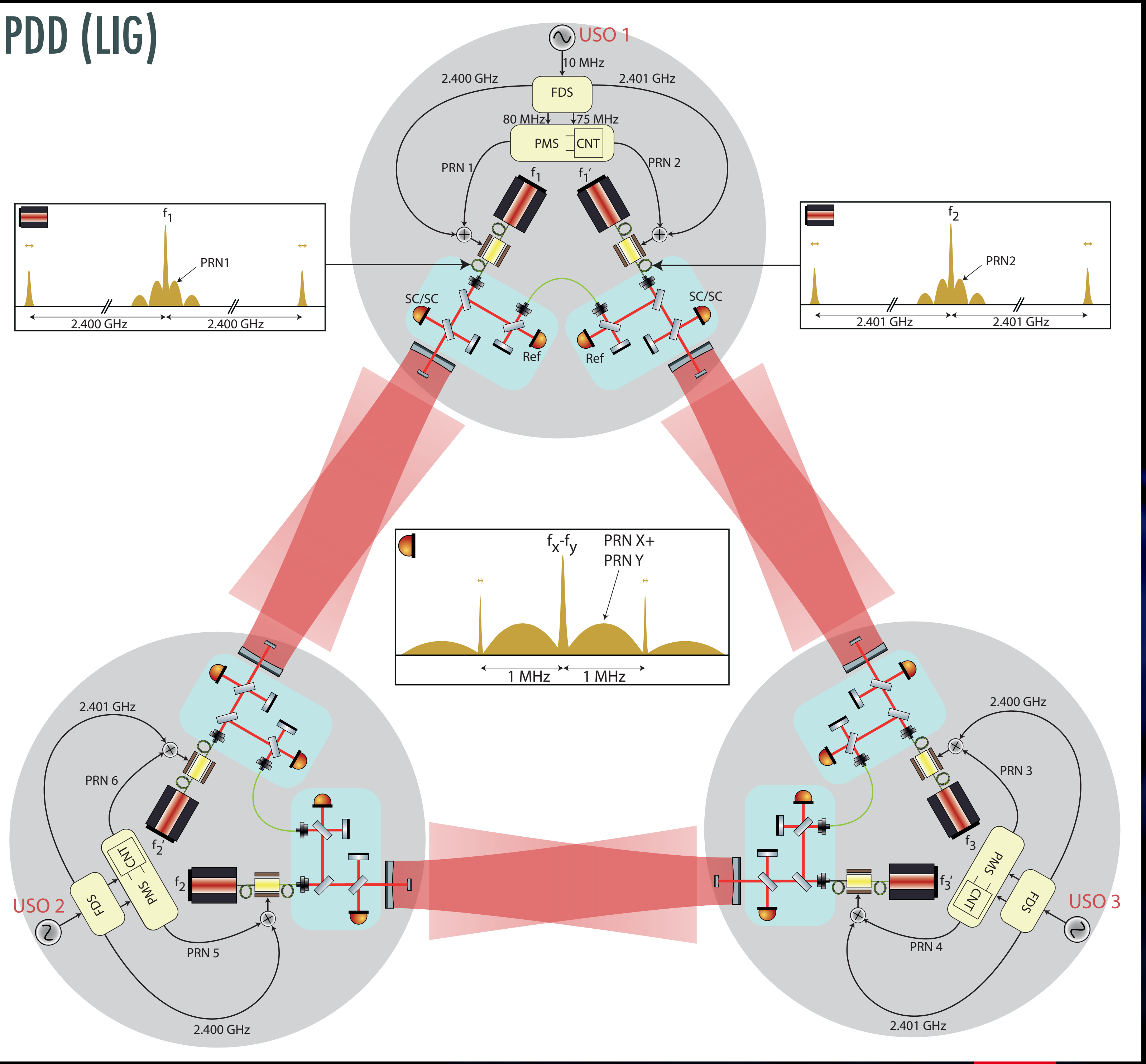


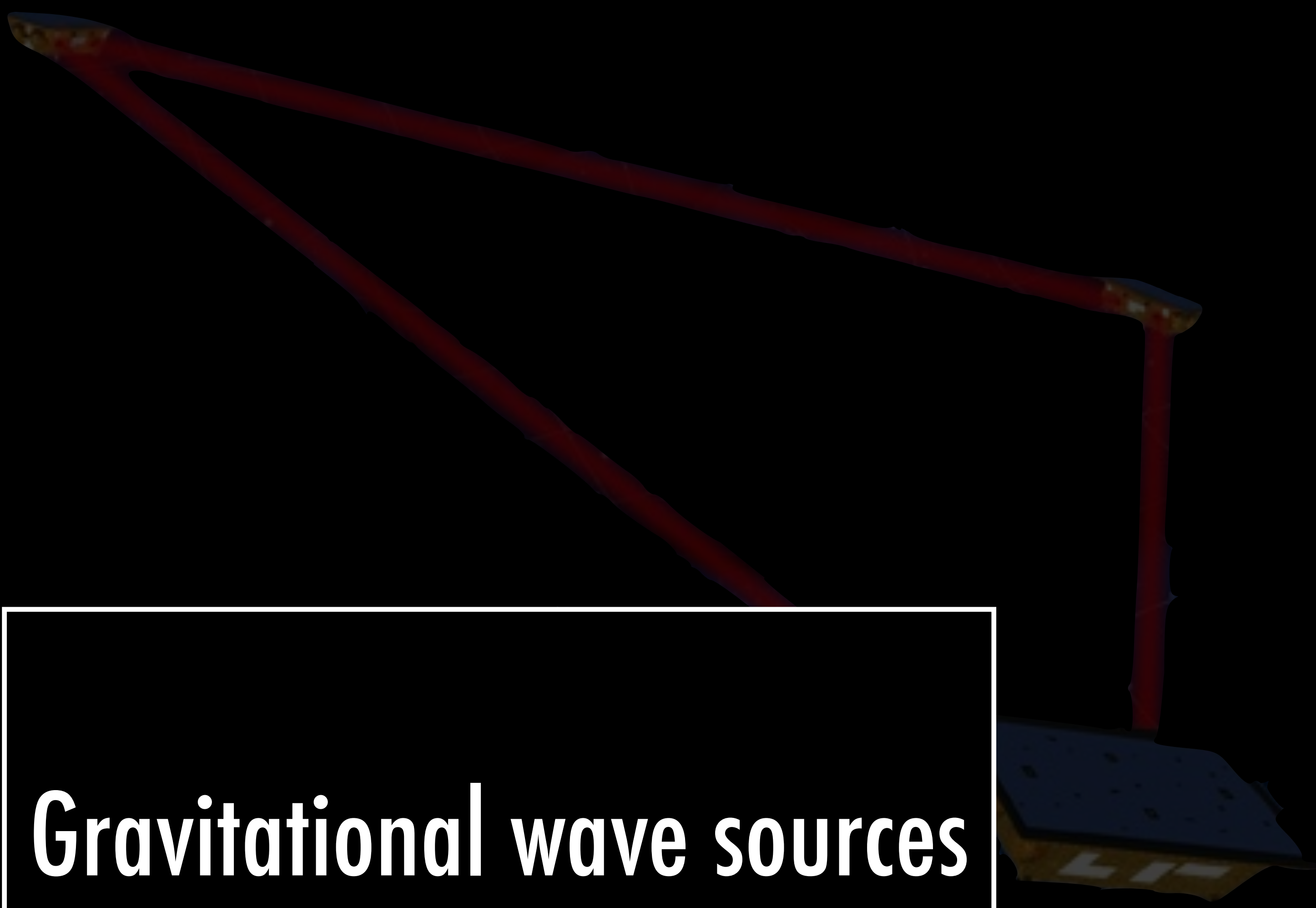


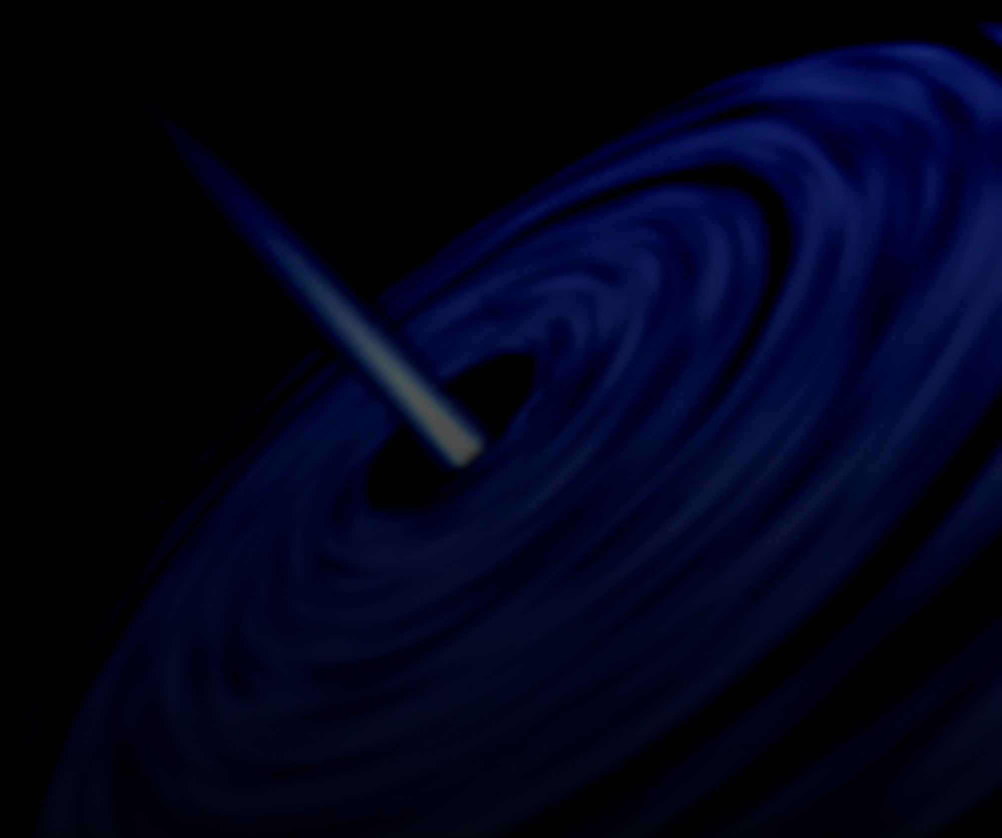
Interferometric measurements

- 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



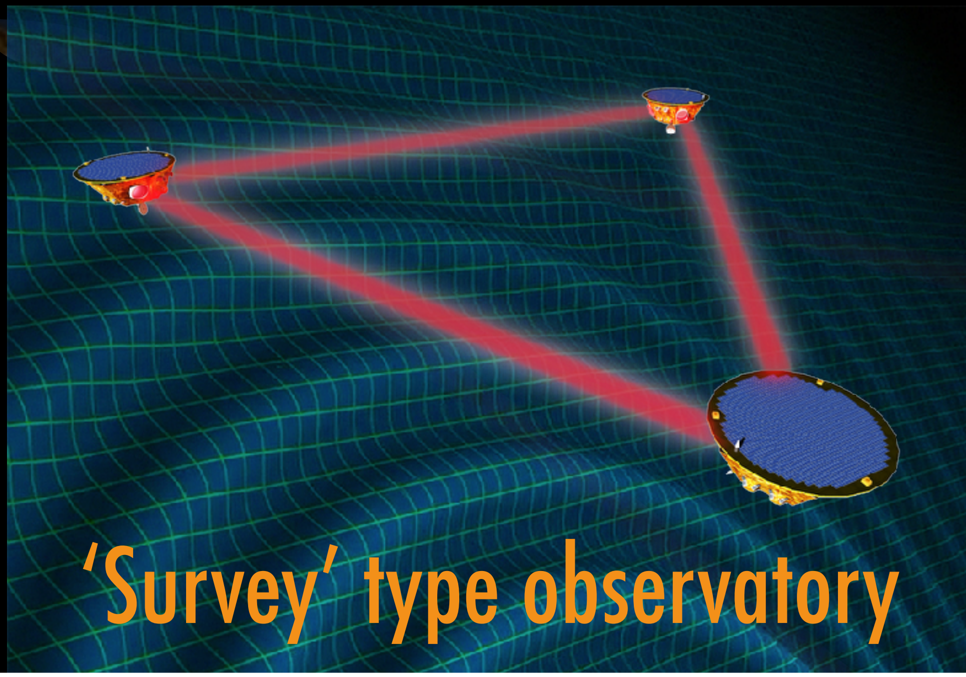
Data





Gravitational wave sources emitting between 0.02mHz and 1 Hz

Data



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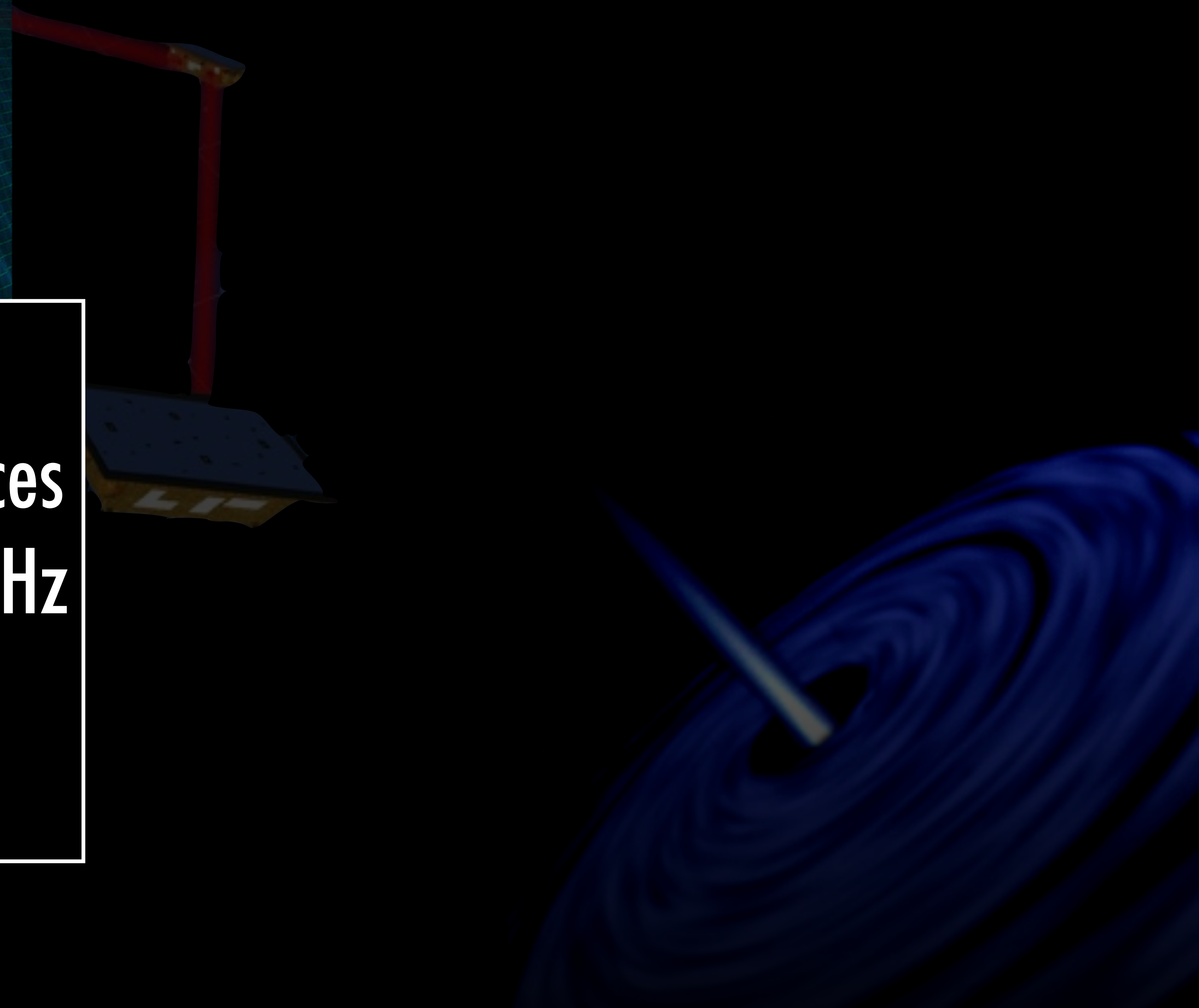

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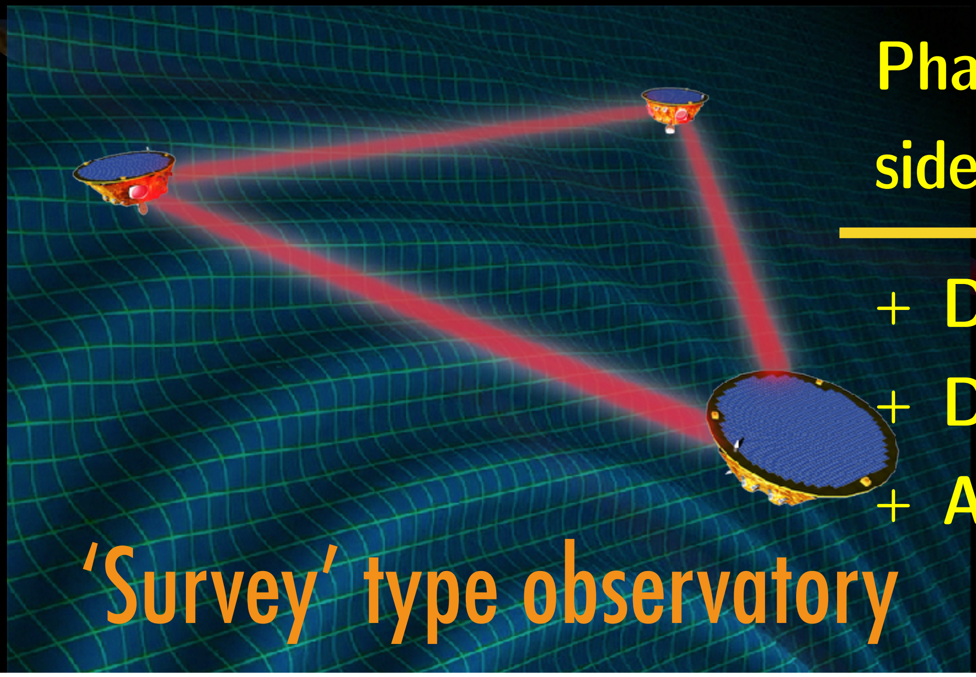

Phasemeters (carrier, sidebands, distance)

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

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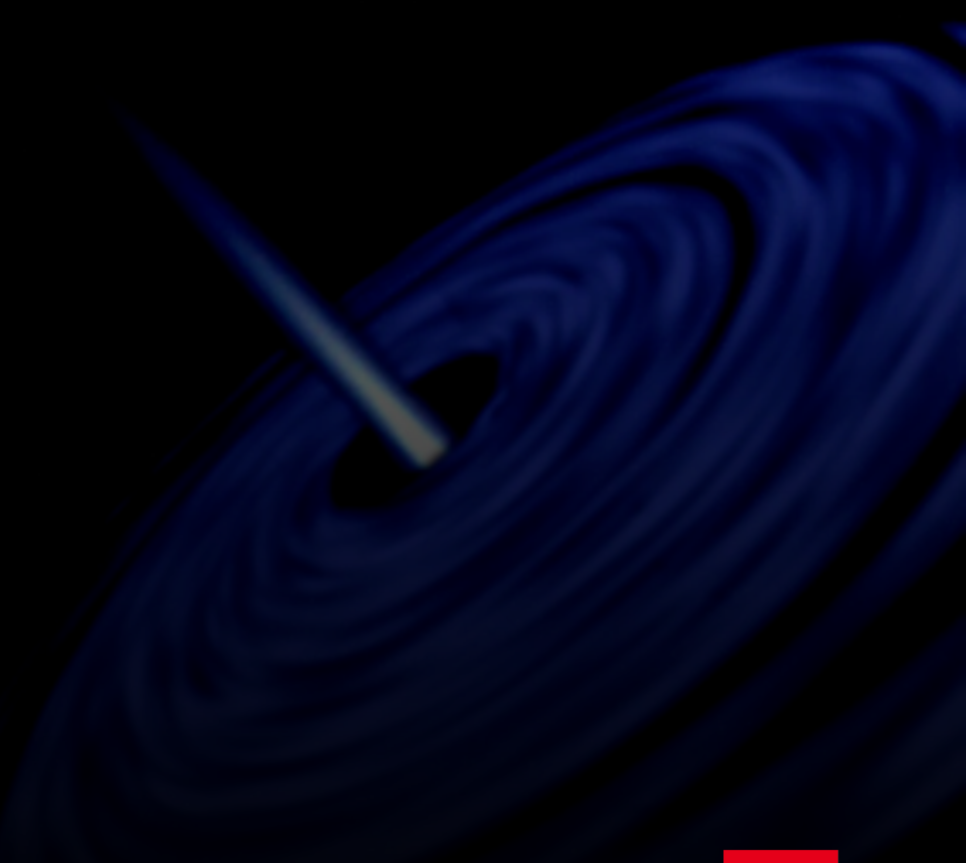
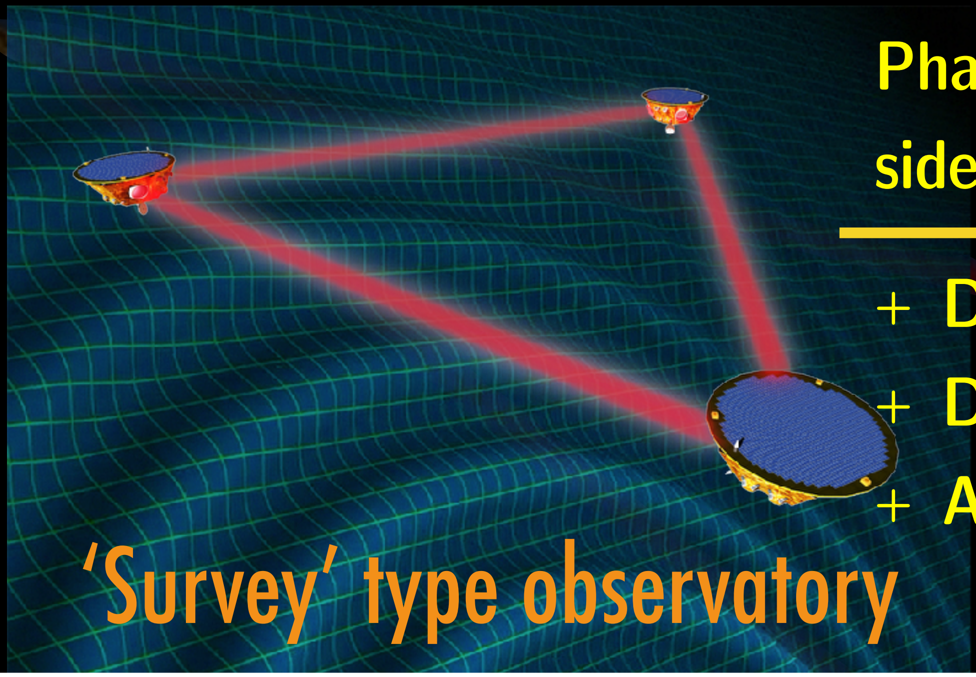


* Drag-Free Attitude Control System

** Charge Management Device

Data



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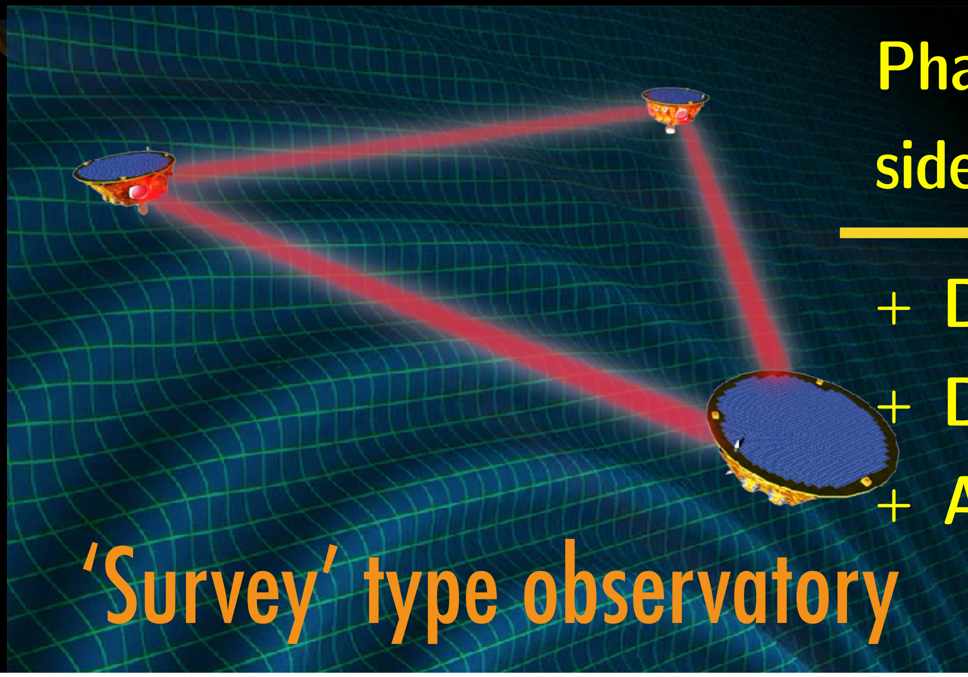

Phasemeters (carrier, sidebands, distance)

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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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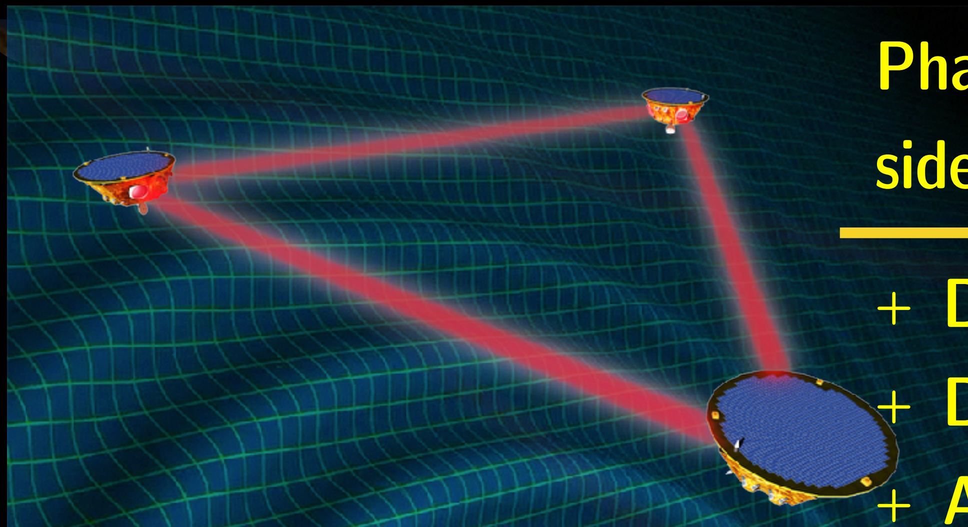

‘Survey’ type observatory

Phasemeters (carrier, sidebands, distance)

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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

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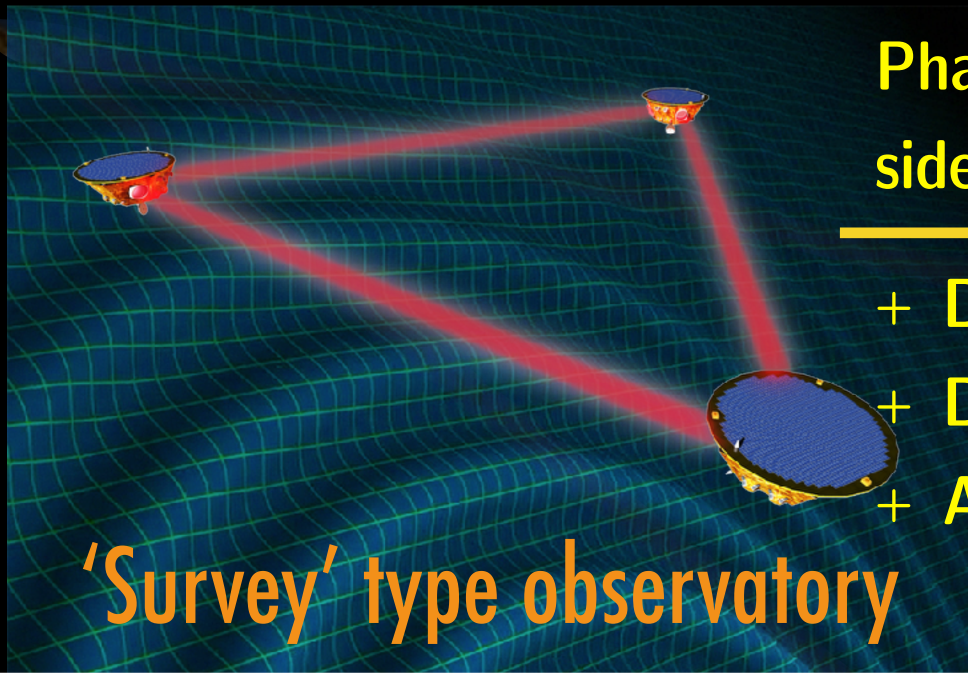

Phasemeters (carrier, sidebands, distance)

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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

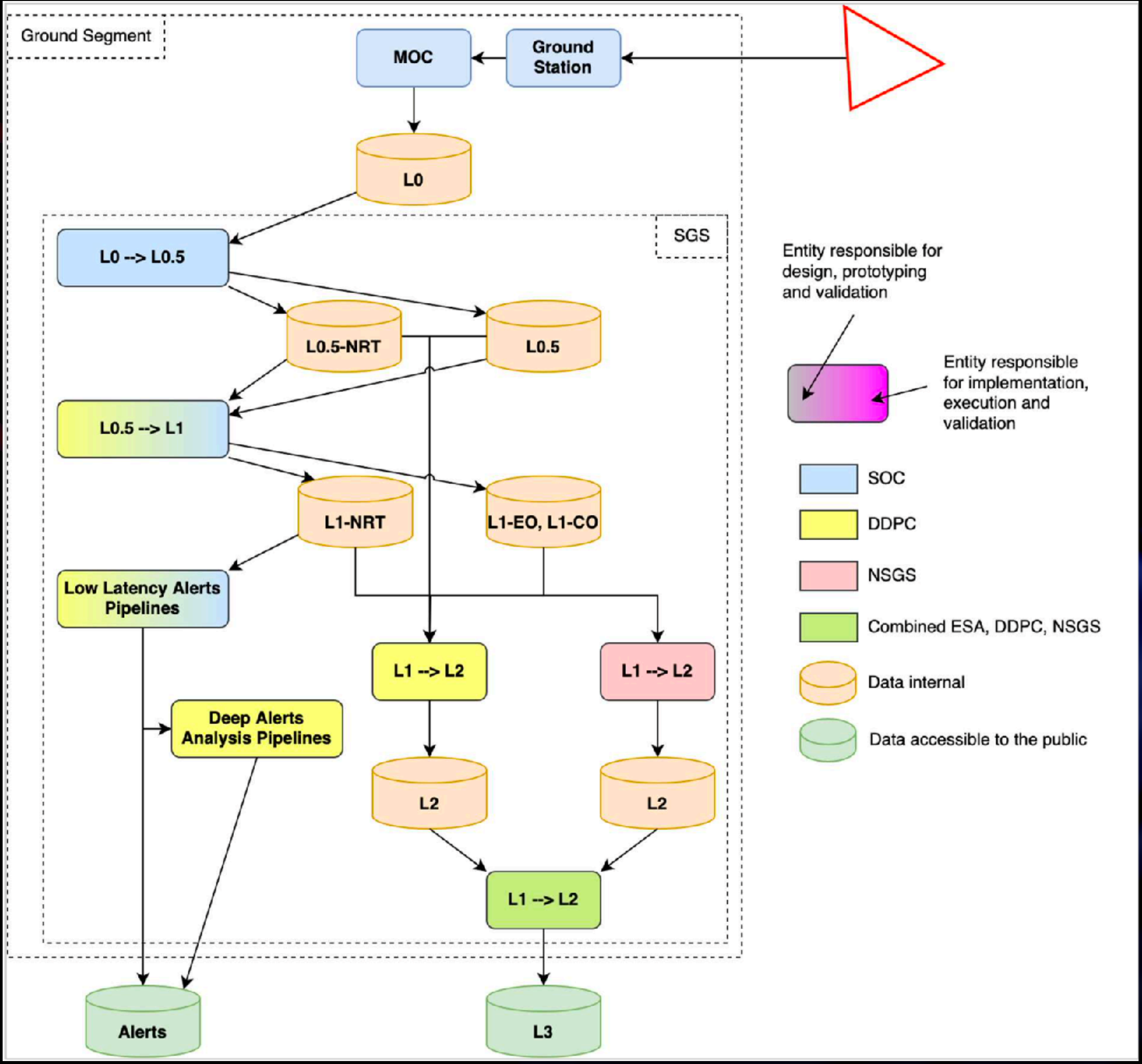
L1 — 3 TDI channels with 2 "~independents"

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

Ground segment

- Communication:
  - 8h per day
  - ~ 1 Bytes per day
- Availability :
  - Near-Real Time (NRT): near-real time data (segment of 5 minutes) for alerts generation with LLAP
  - L1 data daily consolidated: 2 versions depending on the used orbits (estimated or consolidated)
  - Several versions of L2 data on different time scale
- 2 pipelines designed and developed by the DDPC and integrated and operated by the SOC: L0.5-L1 pipeline and LLAP

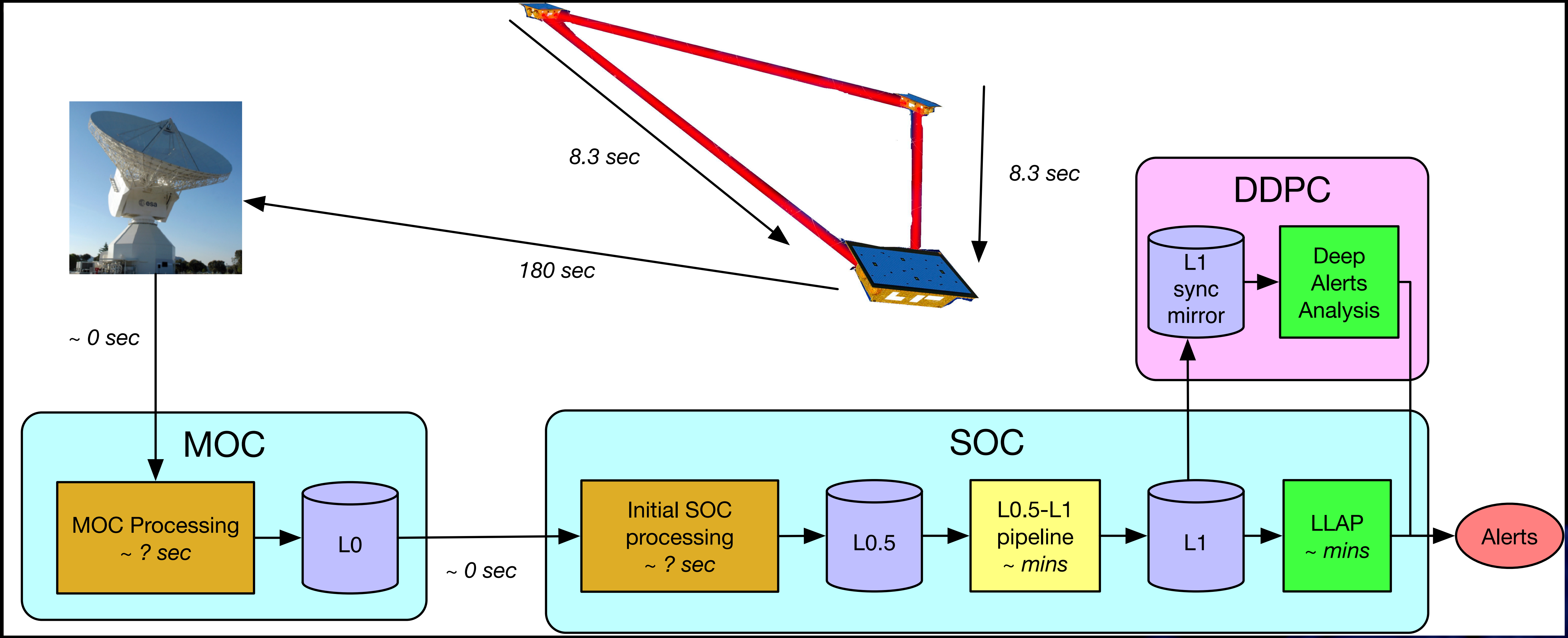


Data Analysis

- Analysis of all signals and noises together
  => global analysis
- Flexibility: first data of this kind
  => novel analysis challenge:
  - Multiple approaches, multiple pipelines
  - Quick development from prototyping to production

- Multiple pipelines with multiple approaches
- General approach with with multiple iterative steps (interconnection between products):
  1. Reduce dominant noises (Time Delay Interferometry) and partial correction on instrument artefacts => L1 data (TDI data)
  2. GLOBAL FITS: GW sources extraction + better understanding of noises and instrument with multiple pipelines => L2 data
  3. Cross-check, combination, merging of L2 data to produce catalogs + associated scientific products => L3 data
- All levels requires continuous scientific interactions: collaboration all over the mission

L1 to L2: alerts



- Low Latency Alerts Pipeline: automatic near-real time analysis to release an alert as fast as possible
- Deep Analysis Alerts Pipeline: when an alert has been detected, analysis to:
  - Confirm the nature of the events
  - Refine the parameters

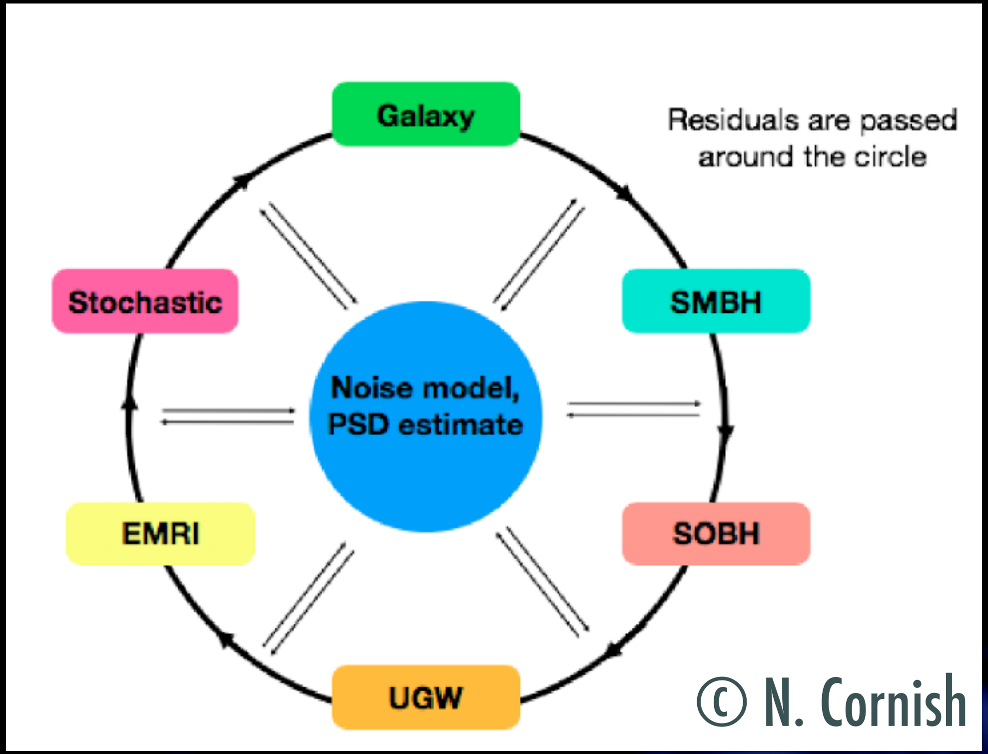
Low latency

- For "alerts", i.e. :
  - Detect new events
  - Update parameters of a known events (in the list of event to follow)
- During visibility phase 1 (0 to about 2h):
  - Low latency analysis on the Near Real Time Data:
    - 1) "Fast" L0-L1
    - 2.a) Low Latency for detection
    - 2.b) Low Latency for updating parameters
    - 3.a) If detection, issue of a new candidate alerts
    - 3.b) Update of parameters
  - Low latency analysis on the High Priority Data.
    - Idem as for Near Real Time Data
- During visibility phase 2 (about 2h to end of visibility):
  - Same as phase 1 but for Near Real Time Data only

Analysis on accumulated data

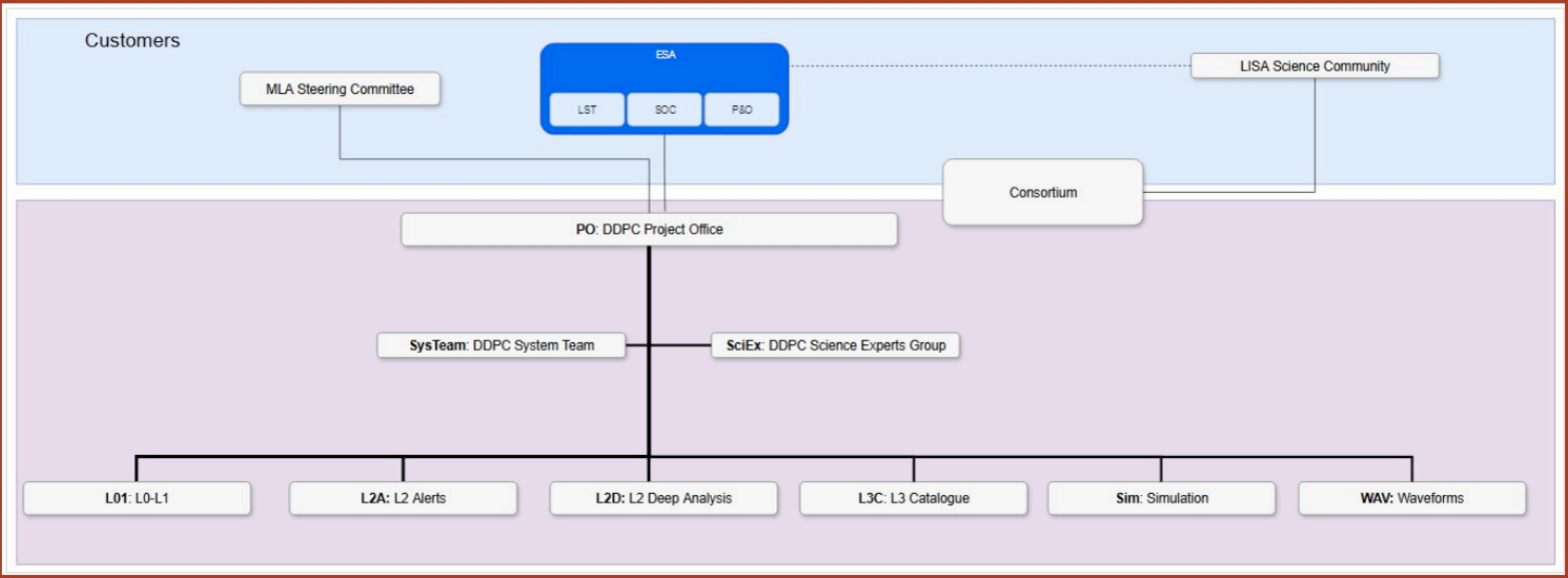
Global fit (deep analysis)

- Goal: GW sources extraction + better understanding of noises and instrument with multiple pipelines
- Challenge: large number of overlapping sources:
  - Multiple approaches
- Data
  - Available for the global fits:
    - Every day, 24h of new L1 data available
    - + every X days a refined version of L1 data
  - Data ingestions:
    - How to ingest this in the global fit? Depend on the global fit approaches ...
    - Few elements:
      - MBHBs: in order to provide alerts for low SNR sources probably need to ingest data daily,
      - For GBs, cadence of ingestion depends on the accumulated data,
      - ...



DDPC

- Distributed Data Processing Center
  - Project Office
  - 2 transverse groups: SysTeam and SciEx
  - 6 Coordination Units



DDPC timeline

- Kick-Off in June 2024
- Starting of the Coordination Units
- Goal:
  - Advanced prototypes by 2028
  - Implemented prototypes by 2032
- Next common dataset defined to be ready by end 2025:

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  - Populations

Source	Description of catalogue
Galactic Binaries	• Interacting binaries
Extra-galactic binaries (option?)	• *What is exactly ?* ∘ *Satellites to the MW* ∘ *"Extra-extra"*
MBHBs	• Mixture of models • Include few model outliers (ex: high mass ratio, ...) ; look at the distribution and see what to add
EMRIs	• Plan A: Model M1 from Babak+2017 • *(option) Plan B (if we can): populate Milan model with EMRIs*
xEMRIs	No
sBHB	• O3/O4-based empirical population • Mixture of field and dynamic formed (eccentricity) • *(option) Full O4 if available* • *(option?) Background like GB ?* ∘ *Ariana:* ▪ *sBHB should come from LVK O4 population* ▪ *Including eccentricity if possible* ∘ *open item*
SGWB	• Mainly as a noise component • Plausible models • We will see based on the result of the Stochastic Challenge (LEGO type, ongoing effort) → educated guess • For the components, see the ongoing activity • *(option) Background of EMRIs*

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  - Populations
  - Waveforms

Source	Description of waveform	Waveform
Galactic and Extra-Galactic Binaries	Circular	"Taylor expansion model"
	Eccentric	Peters & Mathews (Keplerian orbit)
MBHBs	• Precession ✔, higher modes ✔, eccentricity: **X** • > 2 models : debugging (ex: Phenom) vs production (ex: SEOB) • **CU**-WAV	NR surrogates
		PhenomXPHM
		SEOBNRv..PHM
EMRIs	• Kerr equatorial (not all the degree of freedom) • Diminish the complexity but large number of EMRIs	SF_0PA
sBHB	• 1.5PN inspiral eccentric	• Waveform and prescription exist (ex: A. Klein, Fourrier Domain)

DDPC timeline

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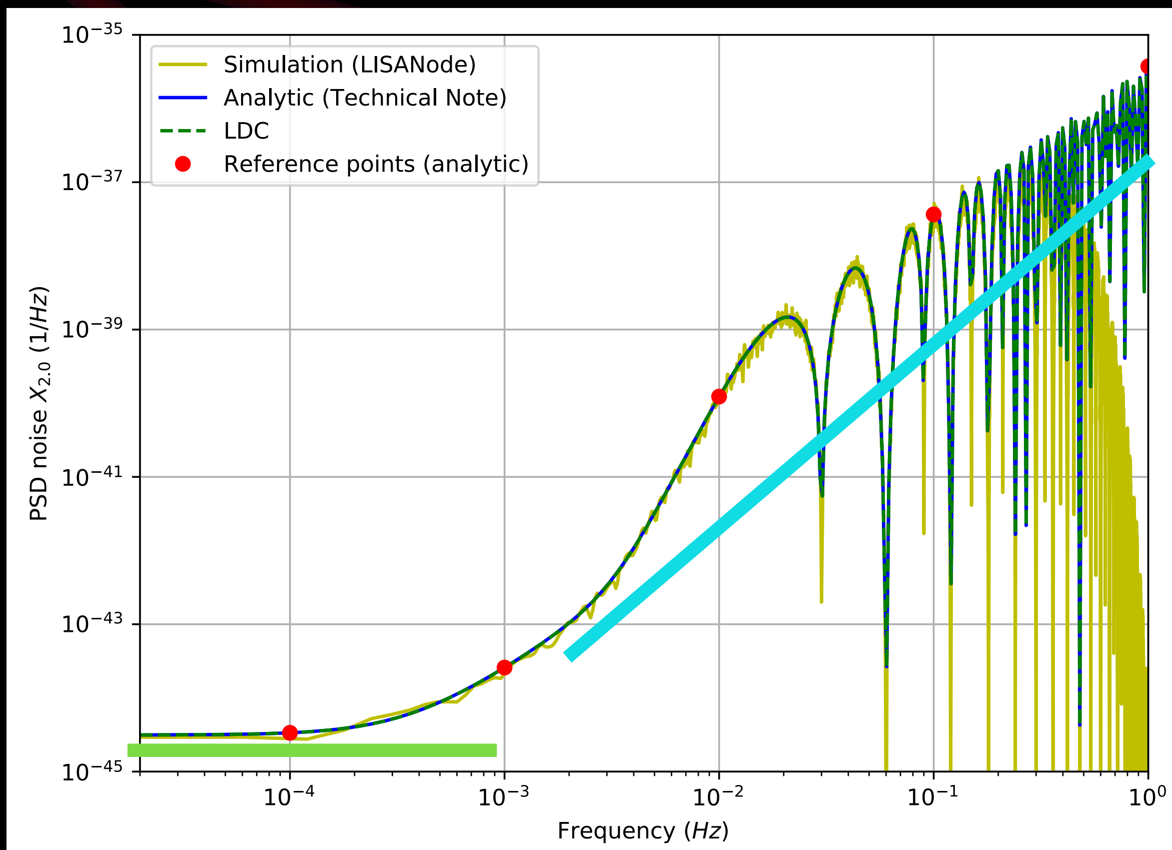
  - Populations
  - Waveforms
  - Instrument

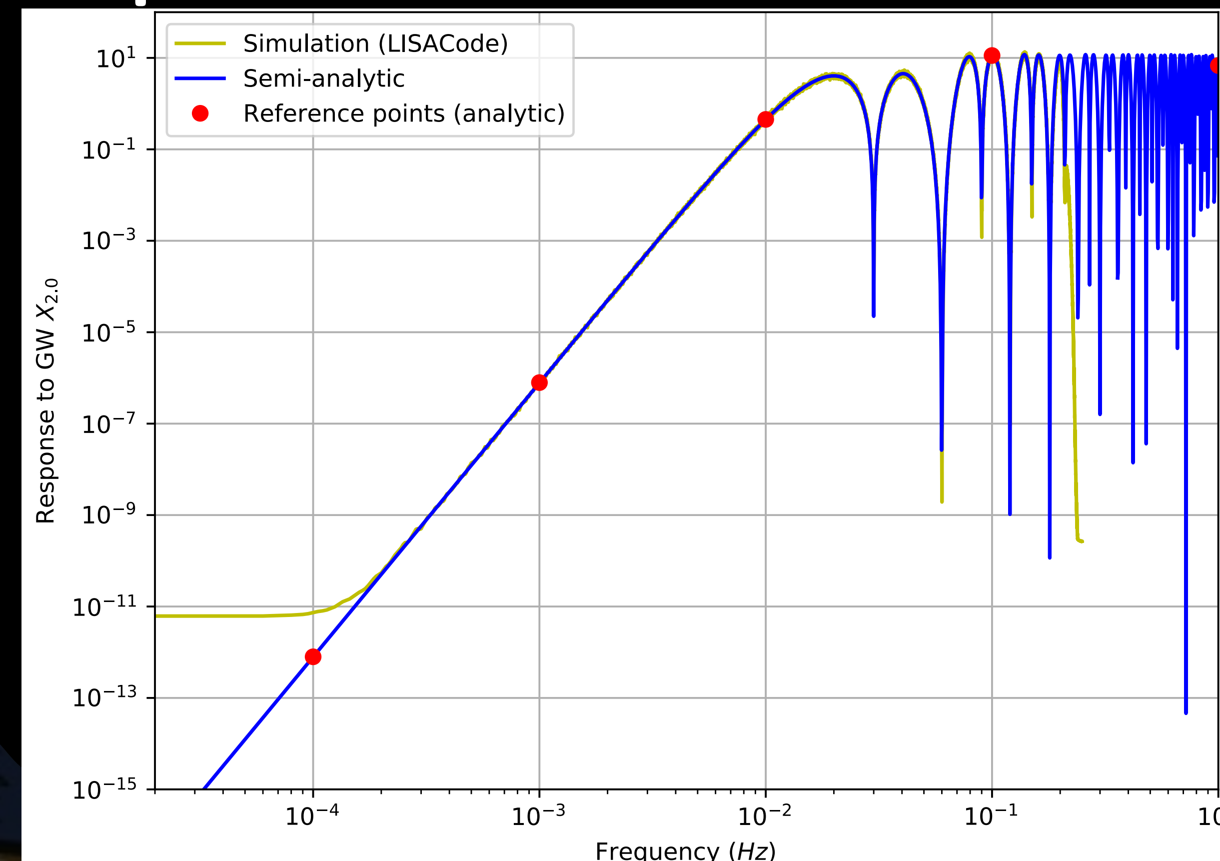
	Content
Real orbits	**ESA** provided (numerical)
Orbits reconstruction	Perfect orbit reconstruction
Frequency Plan	No and Yes
Laser frequency noise	Yes
Clock noise	No
Secondary noises	All available noises ... [specify => to be done by **CU**-SIM] All the noises at the same level on each unit ? yes and no 2 versions of the noise : • realistic armlength but same level and stationary • realistic armlength but same not the level and non-stationary, include also modulation noise, trend
Non-stationary noises	*(option)* *Use LPF as proxy* *Brownian?* *Two dataset*
TTL	No and Yes In the complex dataset, TTL correction assuming we know the coefficients, i.e. add DWS noises
Dynamics	No
Glitches	LPF+
Gaps	Model use in DA Robustness No loss of coherence across the gaps

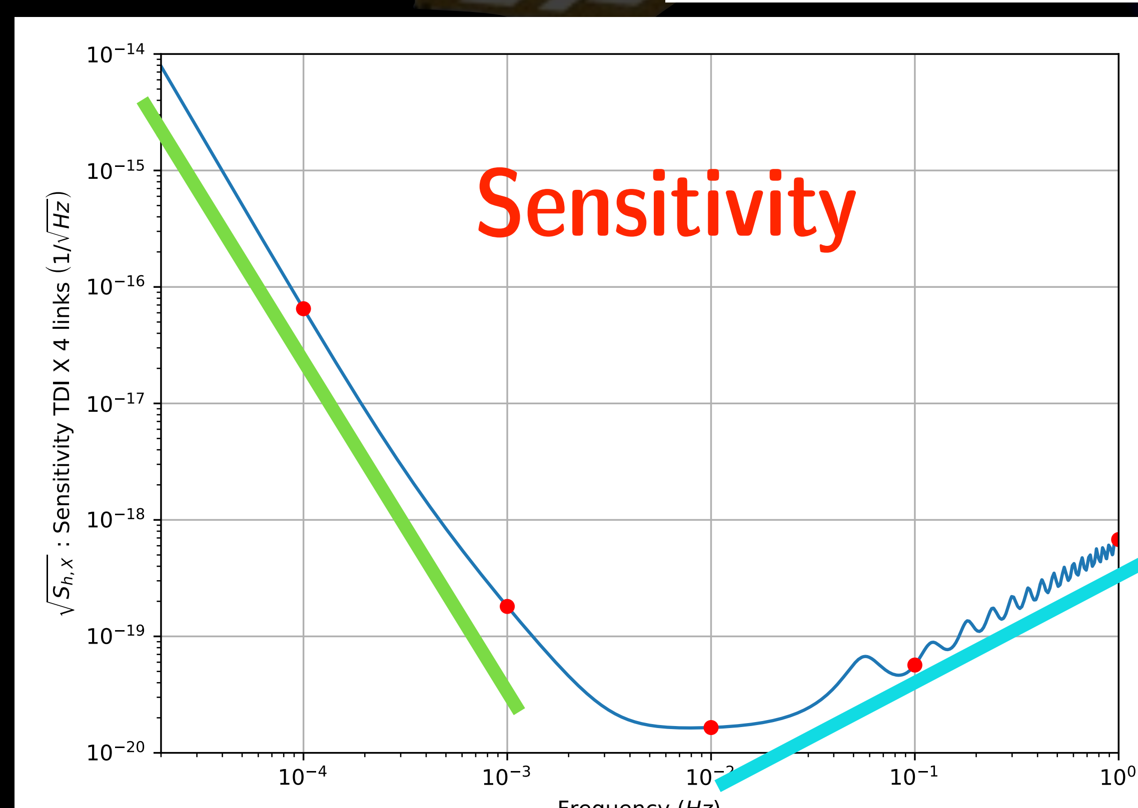
LISA sensitivity

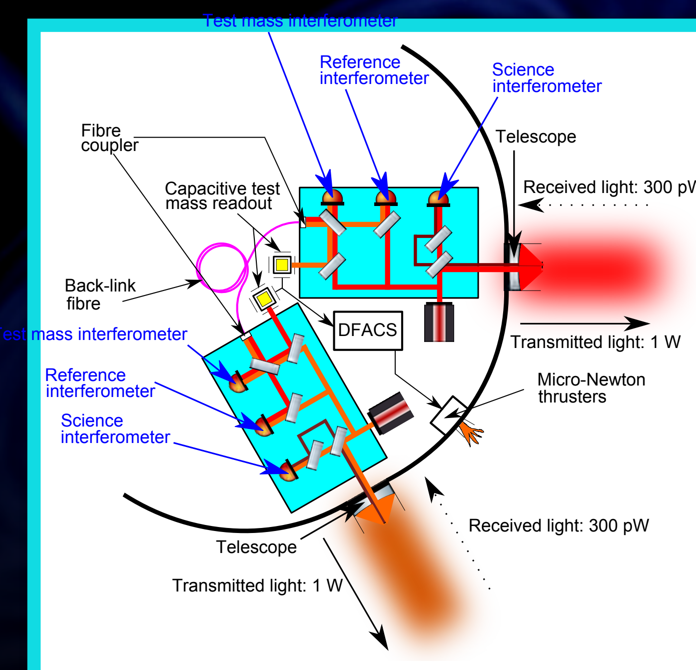
Noises



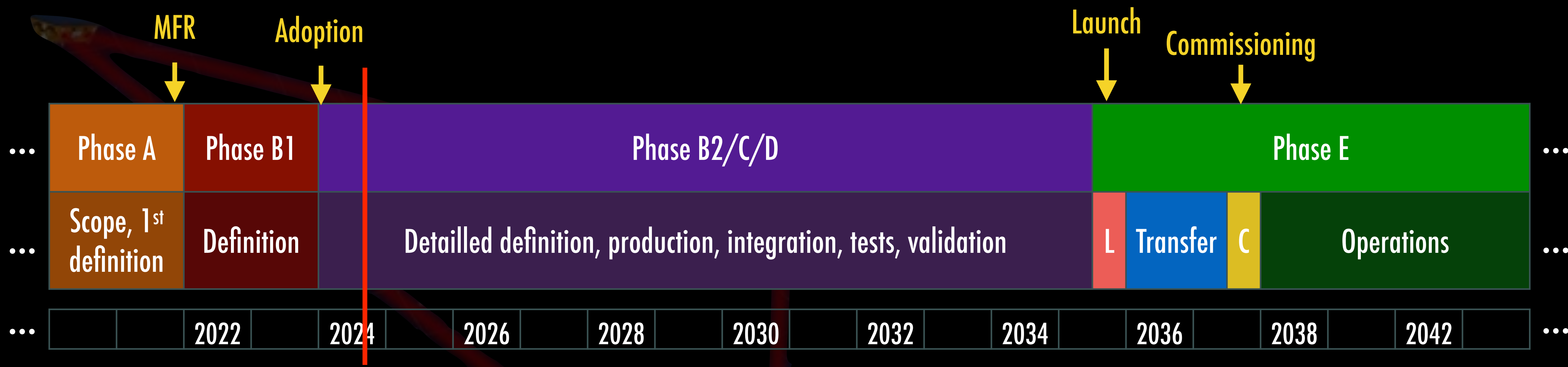
Response of the detector to GWs





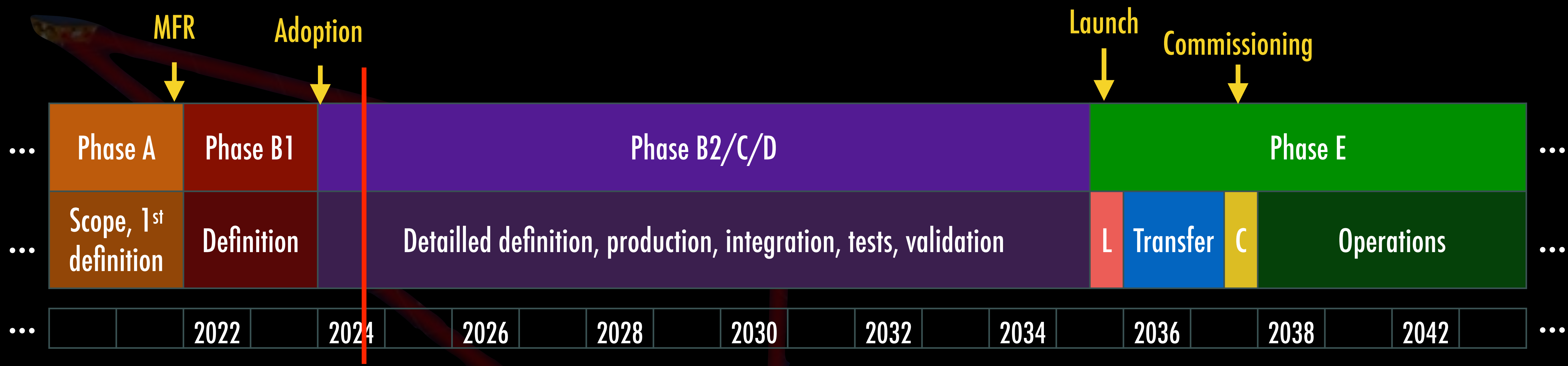


Timeline and status



- 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
- (New) LISA Science Team in place
- 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



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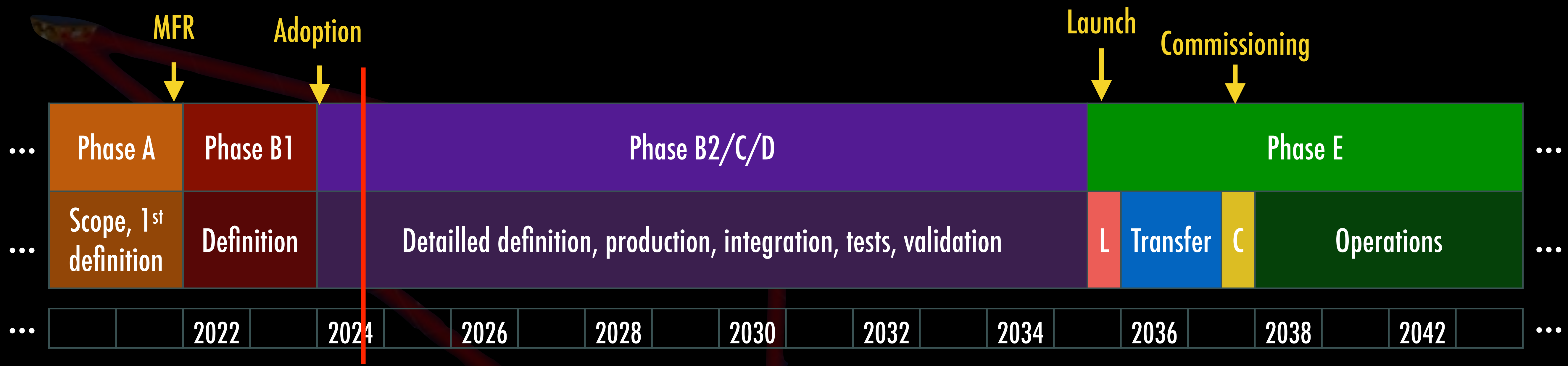

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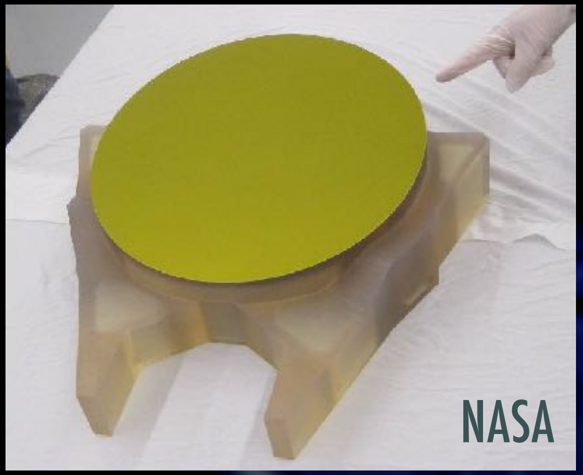
Timeline and status

- Long building phase of multiple MOSAs:
  6 flight models + test models:
  - Industrial prime:
    - March 2024: call
    - July 2024: 2 submissions: Airbus and OHB
    - November 2024: choice of the prime
    - Spring 2025: co-engineering phase ESA/ prime
  - Development and consolidation of performance model
  - Development and building of engineering models of the subsystem (optical benches, mechanics, phasemeters, Gravitational Reference System)
  - Building of the testing facilities

ZIFO (demonstration bench for high stability interferometry)

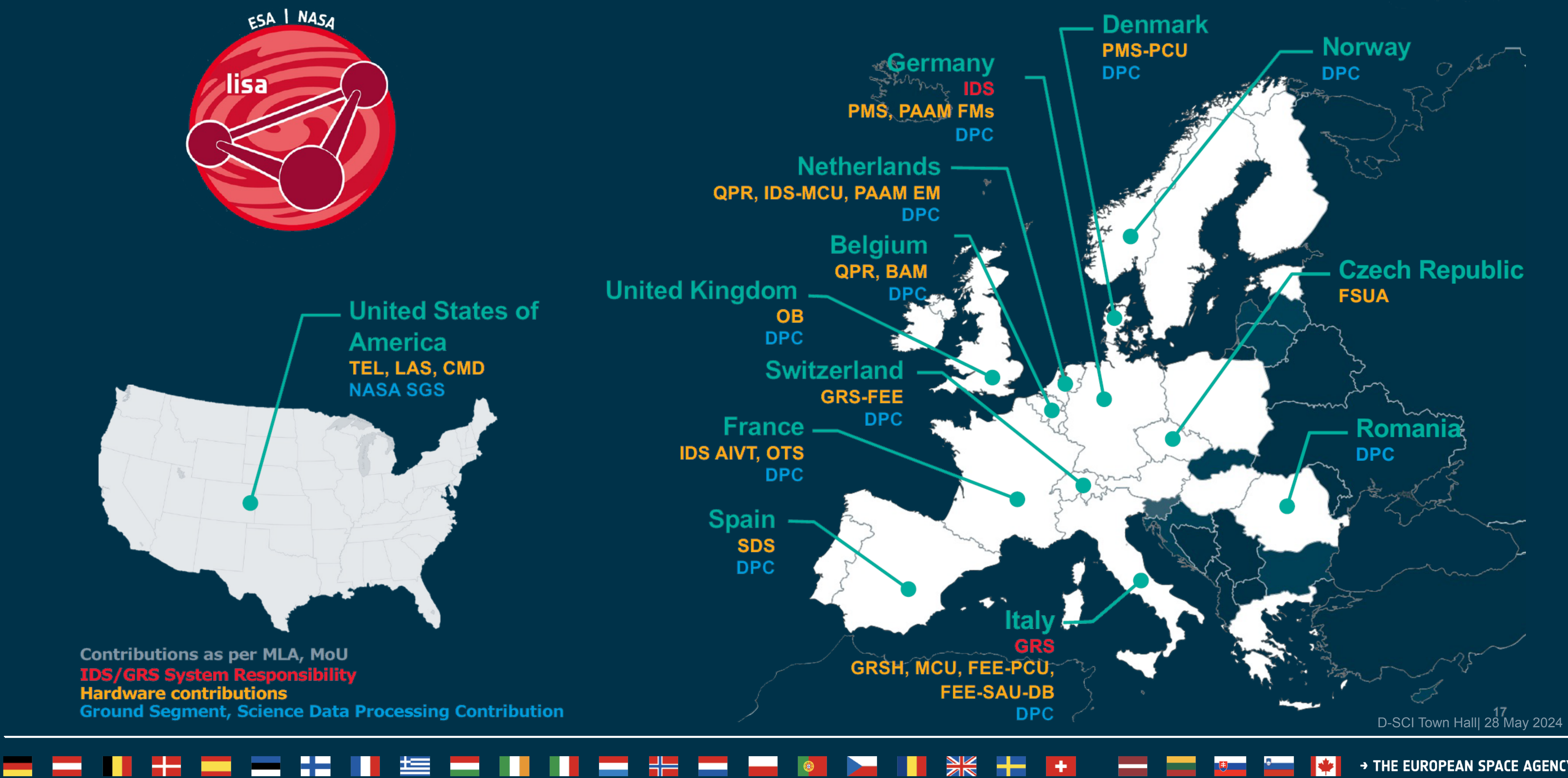


Telescope

LISA building at CNES for testing

LISA collaboration

LISA - An international mission led by ESA



LISA Consortium

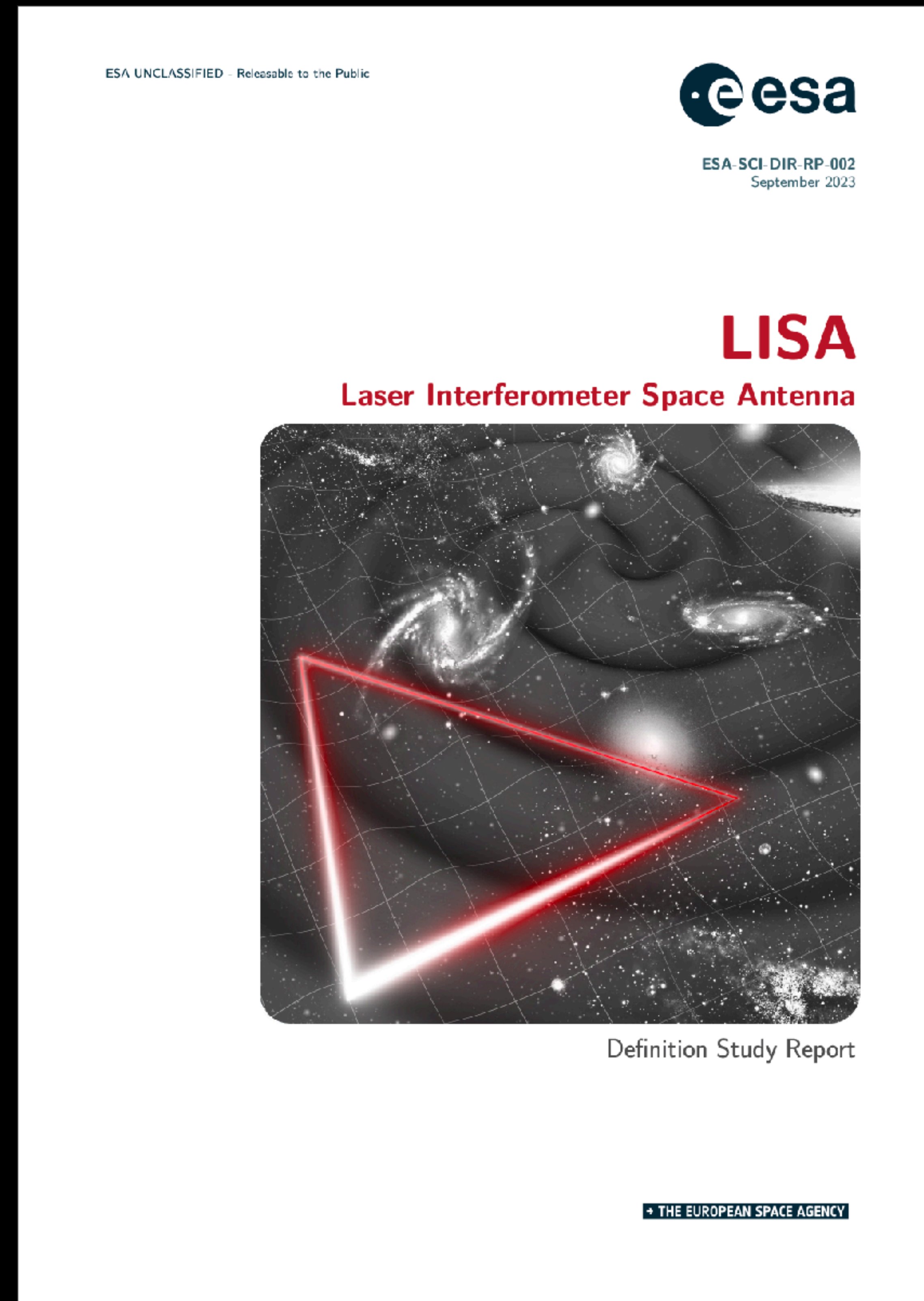
- LISA Consortium submitted the L3 LISA proposal to the ESA call in 2017
- It has many very active working groups
- It was organised for the formulation phases (0, A and B1)
- With the start of the development phase, a new organisation is necessary.

=> ongoing reorganisation:

- Consortium Constituent Committee is working since beginning 2024 to organise the new Consortium
- Goal: Apart the new Consortium in January 2025

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


ESA UNCLASSIFIED - Releasable to the Public

esa

ESA-SCI-DIR-RP-002
September 2023

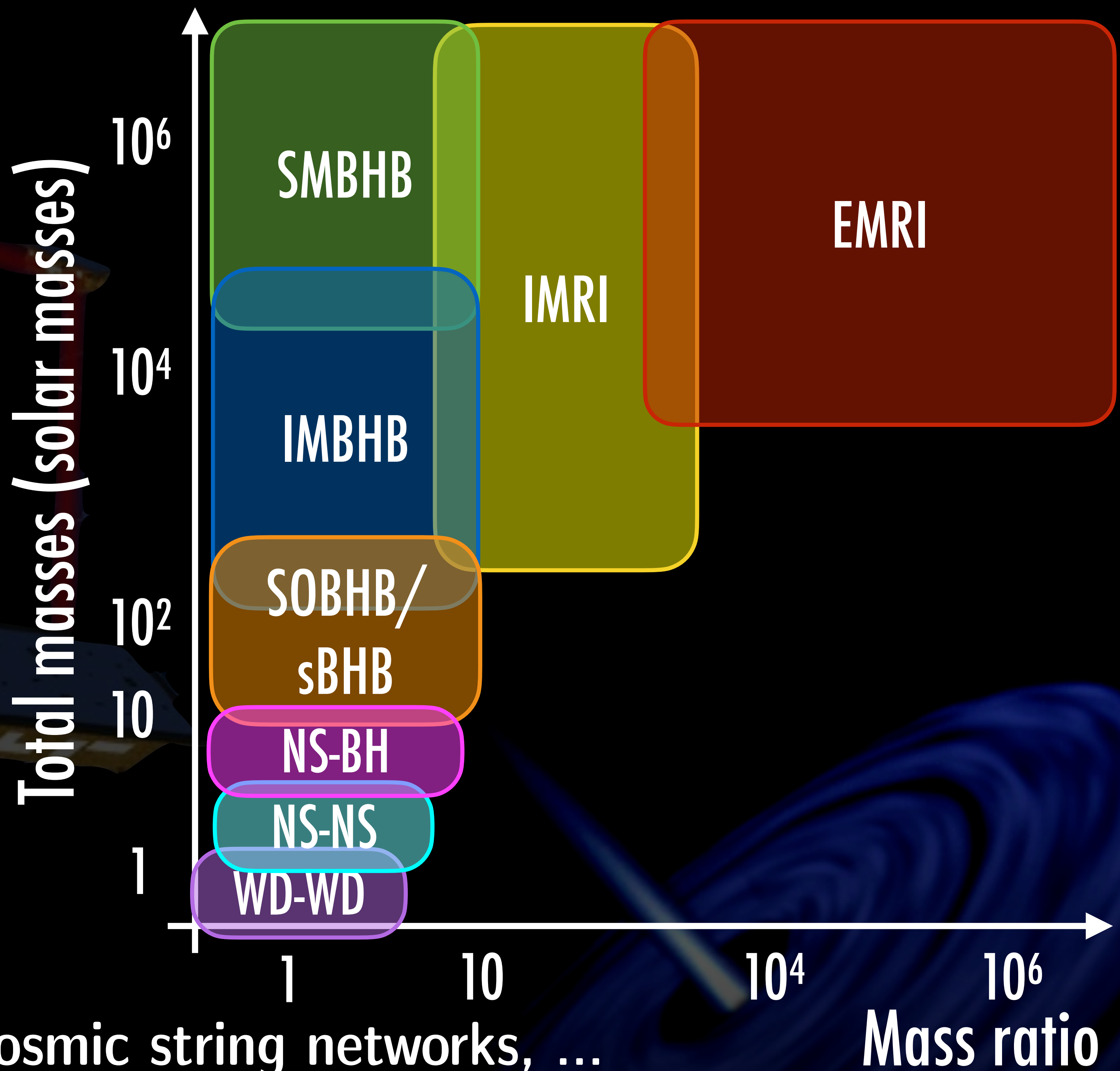
LISA
Laser Interferometer Space Antenna

Definition Study Report

THE EUROPEAN SPACE AGENCY

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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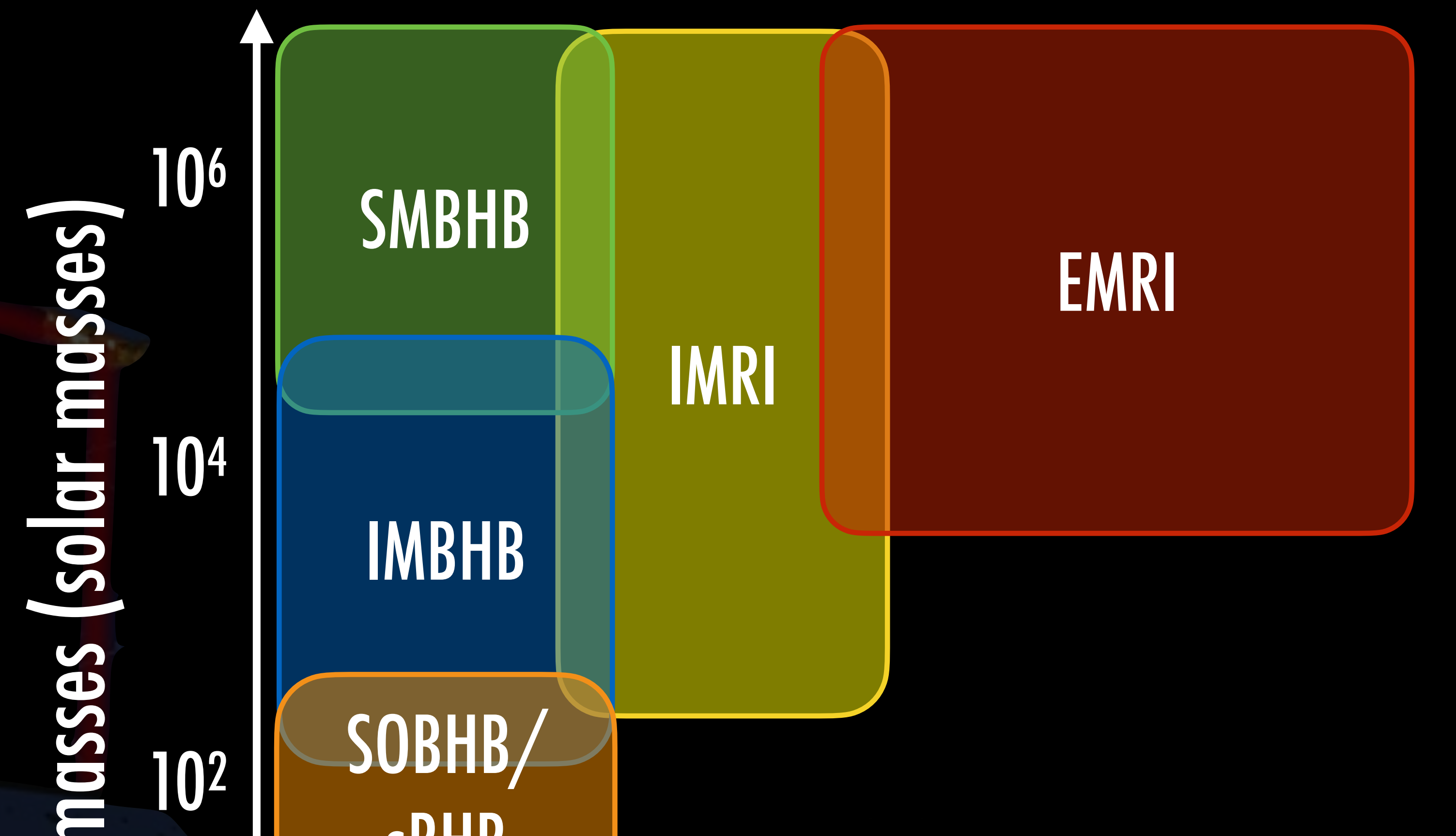
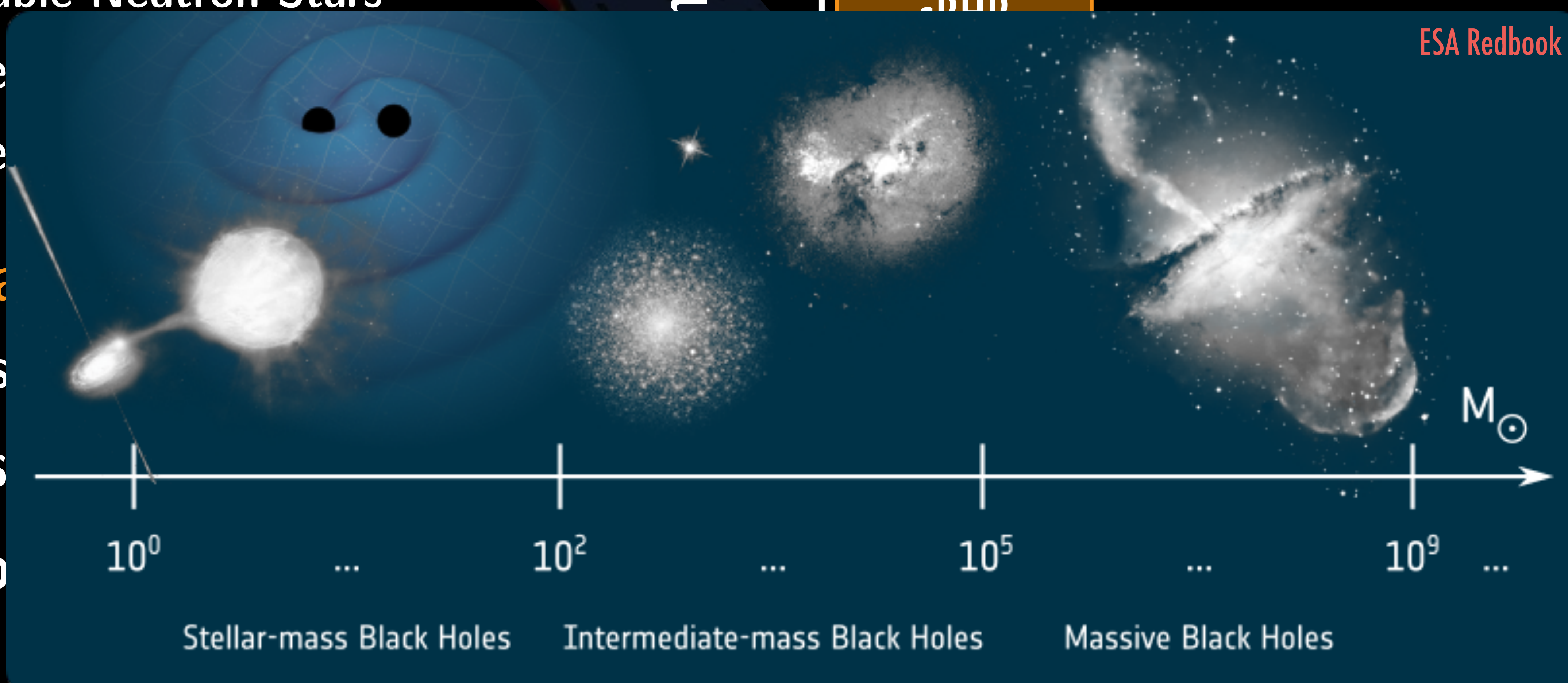
- Unkno





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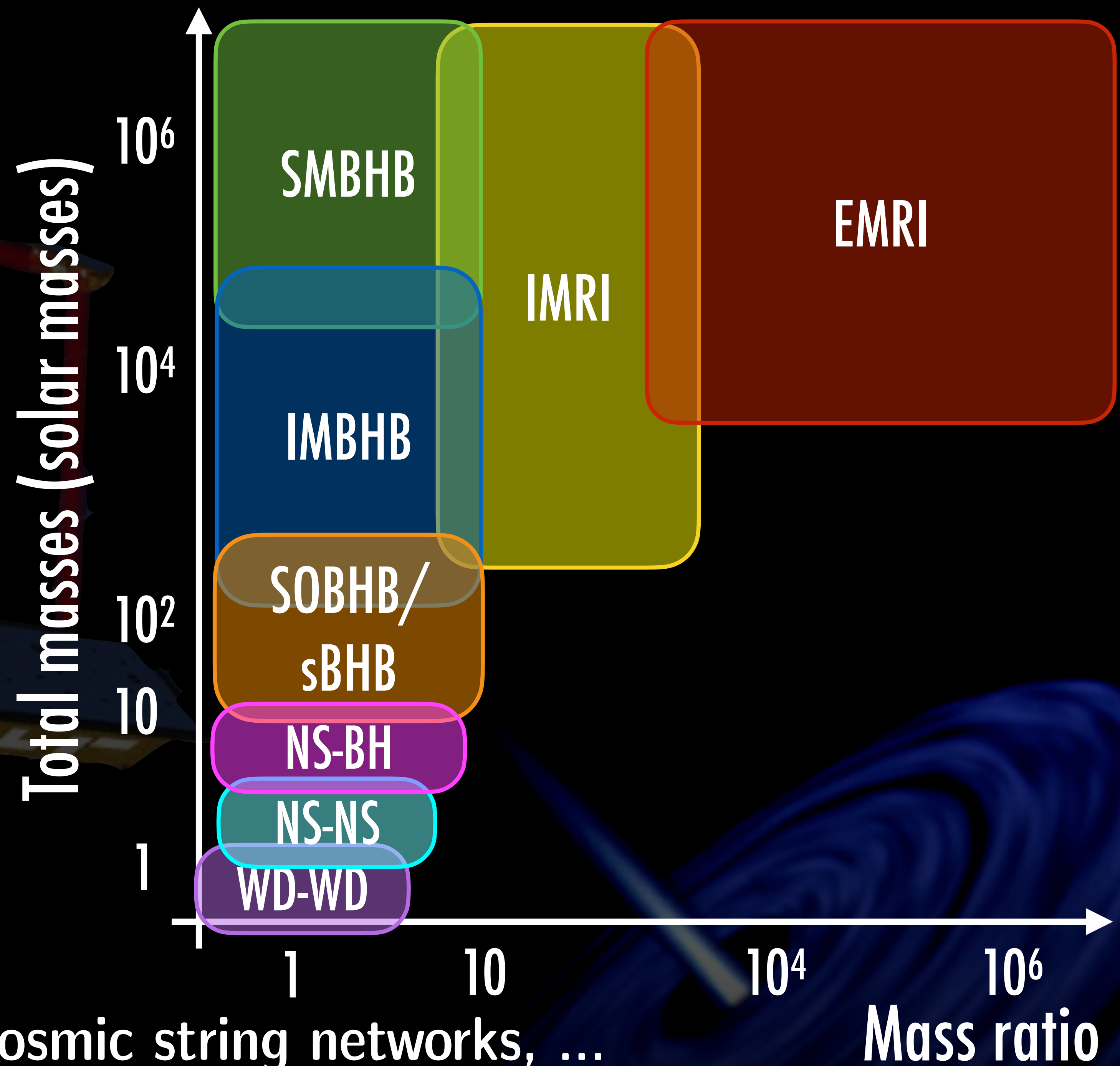
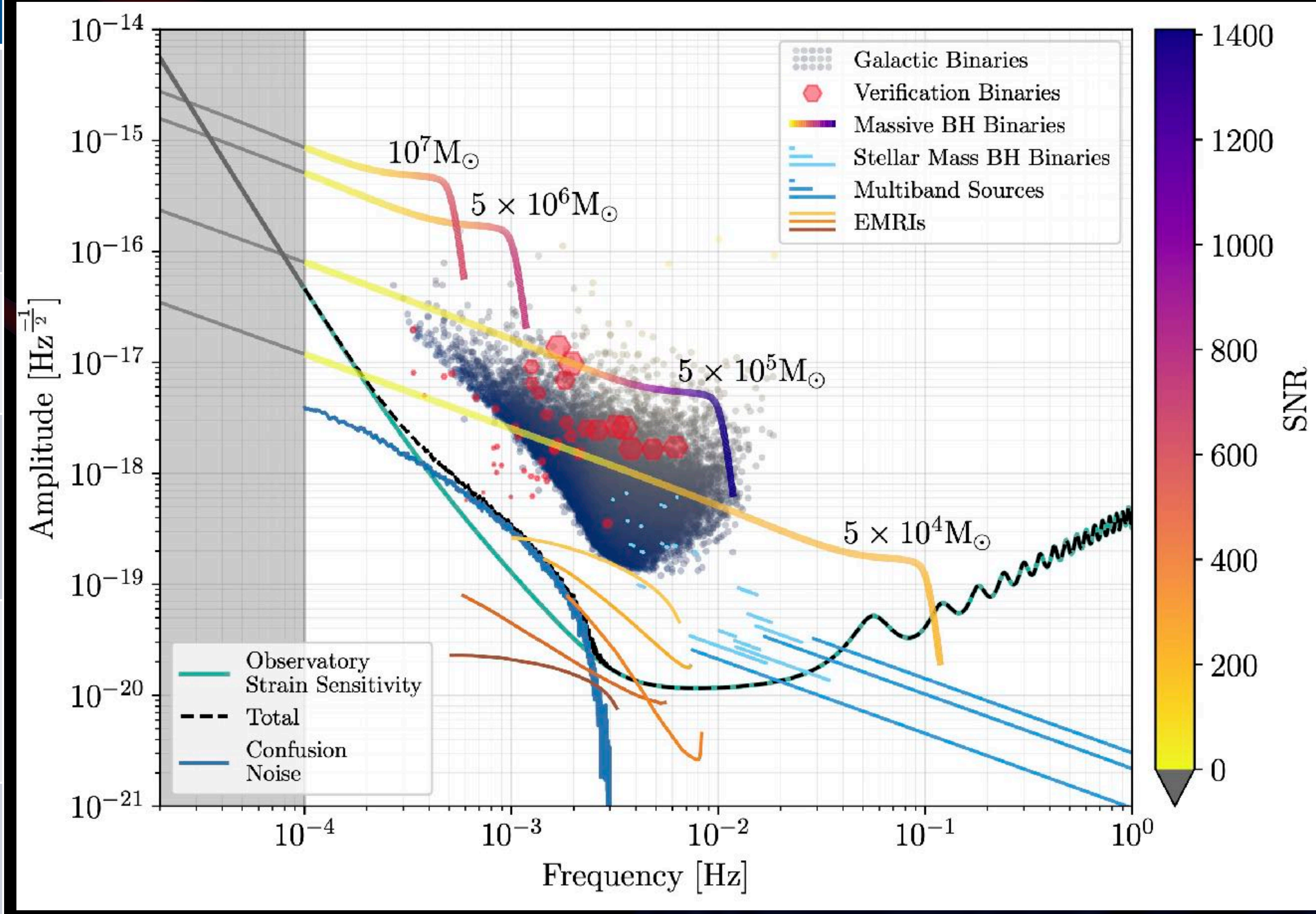


- **Stochastic backgrounds**:
  - First order phase transitions, cosmic string networks, …
- Bursts: cosmic strings, …
- Unknown?

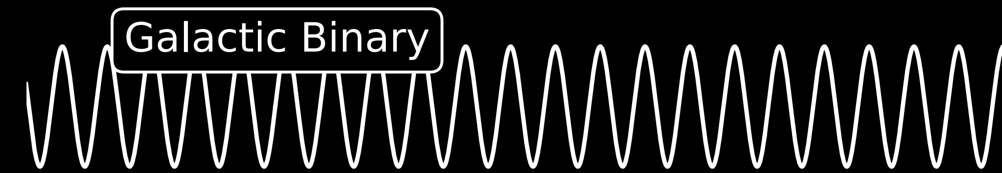
Binaries observed by LISA

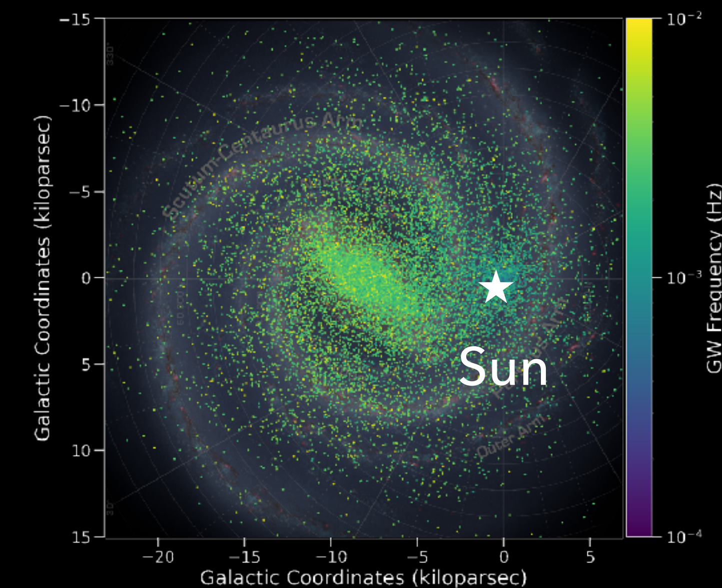
Sources	SNR	Duration	Event rate
Galactic binaries	10 – 500	permanent	10000 – 30000 detectables + background
Verification binaries	7 - 100	permanent	20 (today)
Stellar mass black hole binaries	7 - 30	1 à 10 years	1 to 20
Extreme Mass Ratio Inspirals	7 - 60	1 year	1 to 2000 / year
Massive Black Hole binaries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



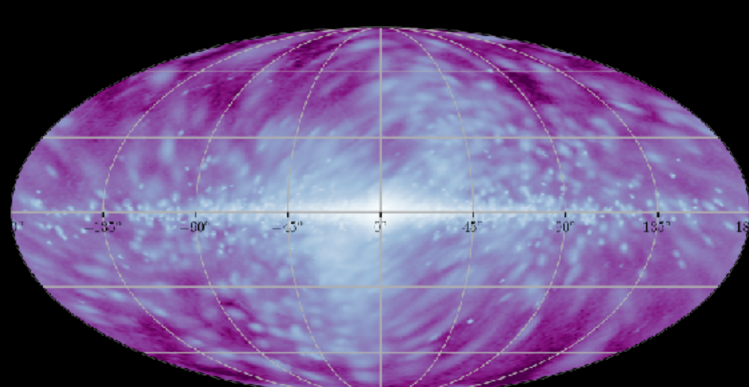
LISA Science

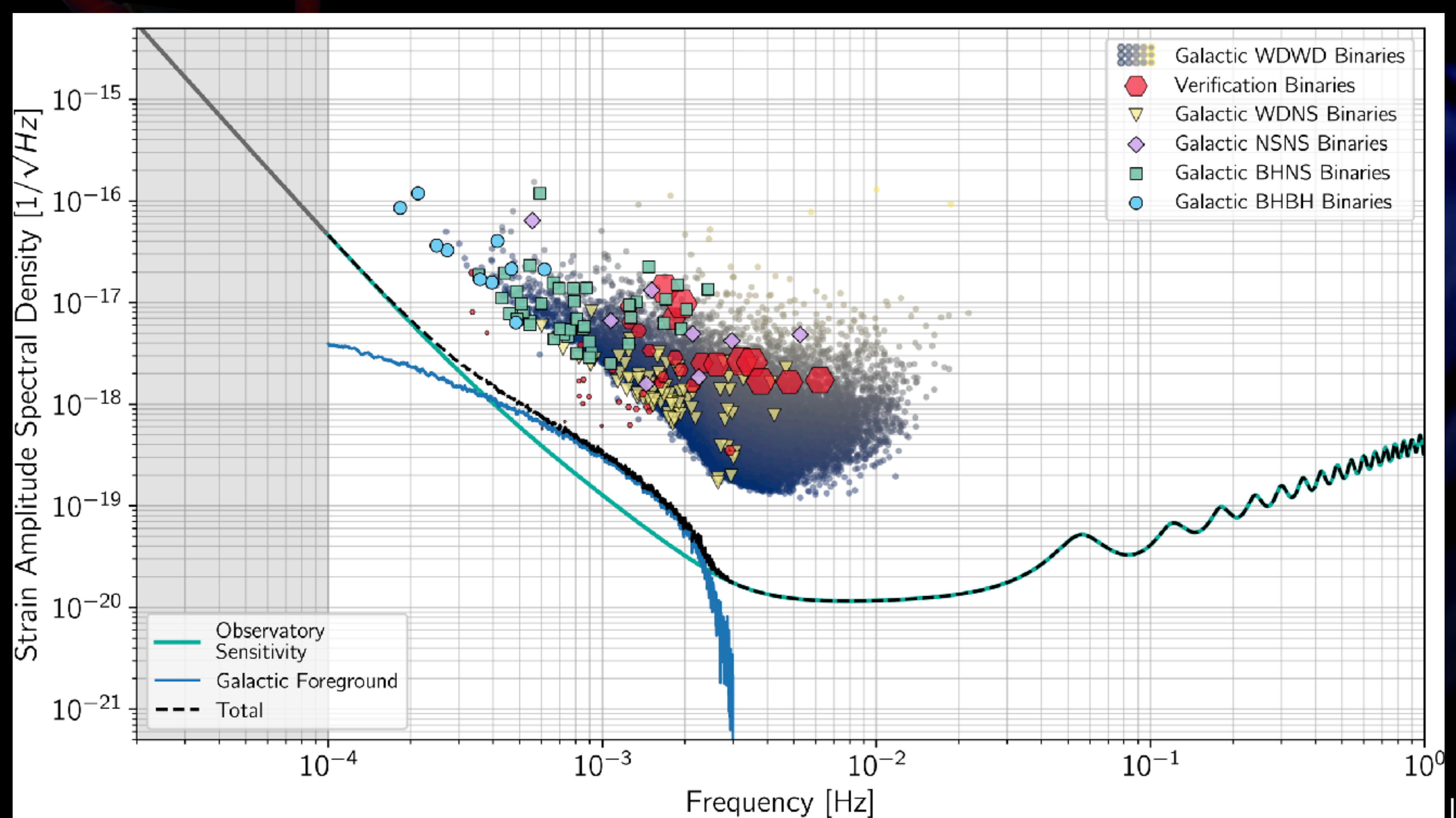
- <u>SO1:</u> Study the formation and evolution of compact binary stars in the Milky Way Galaxy:
  - Formation and evolution pathways of dark compact binary stars in the Milky Way and in neighbouring galaxies;
  - The Milky Way mass distribution;
  - The interplay between gravitational waves and tidal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





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

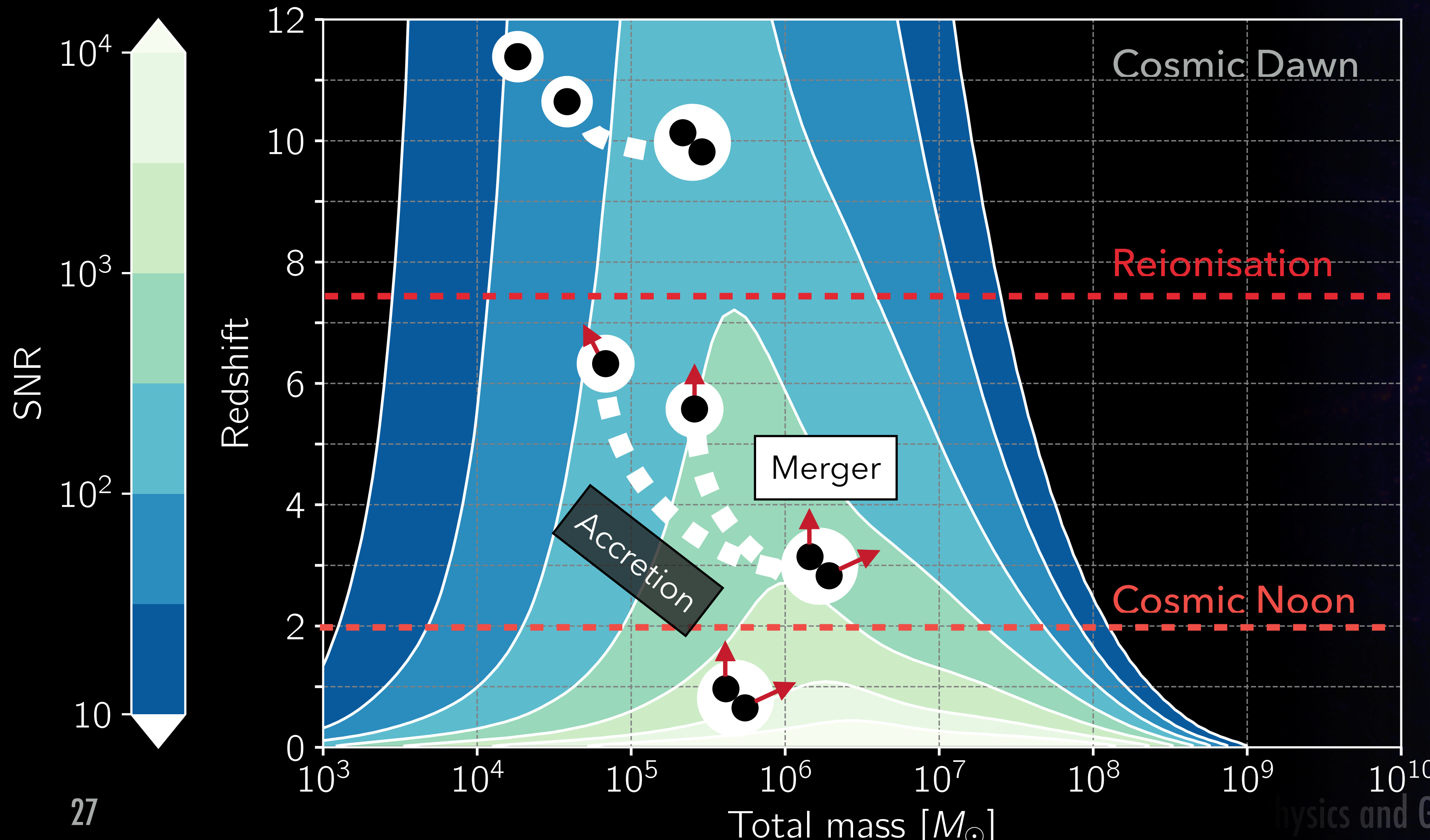


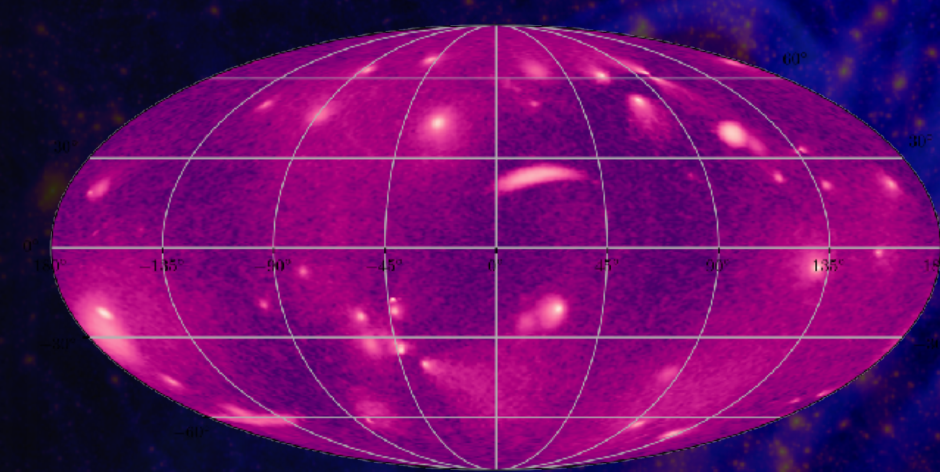


LISA Science

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;
  - ...

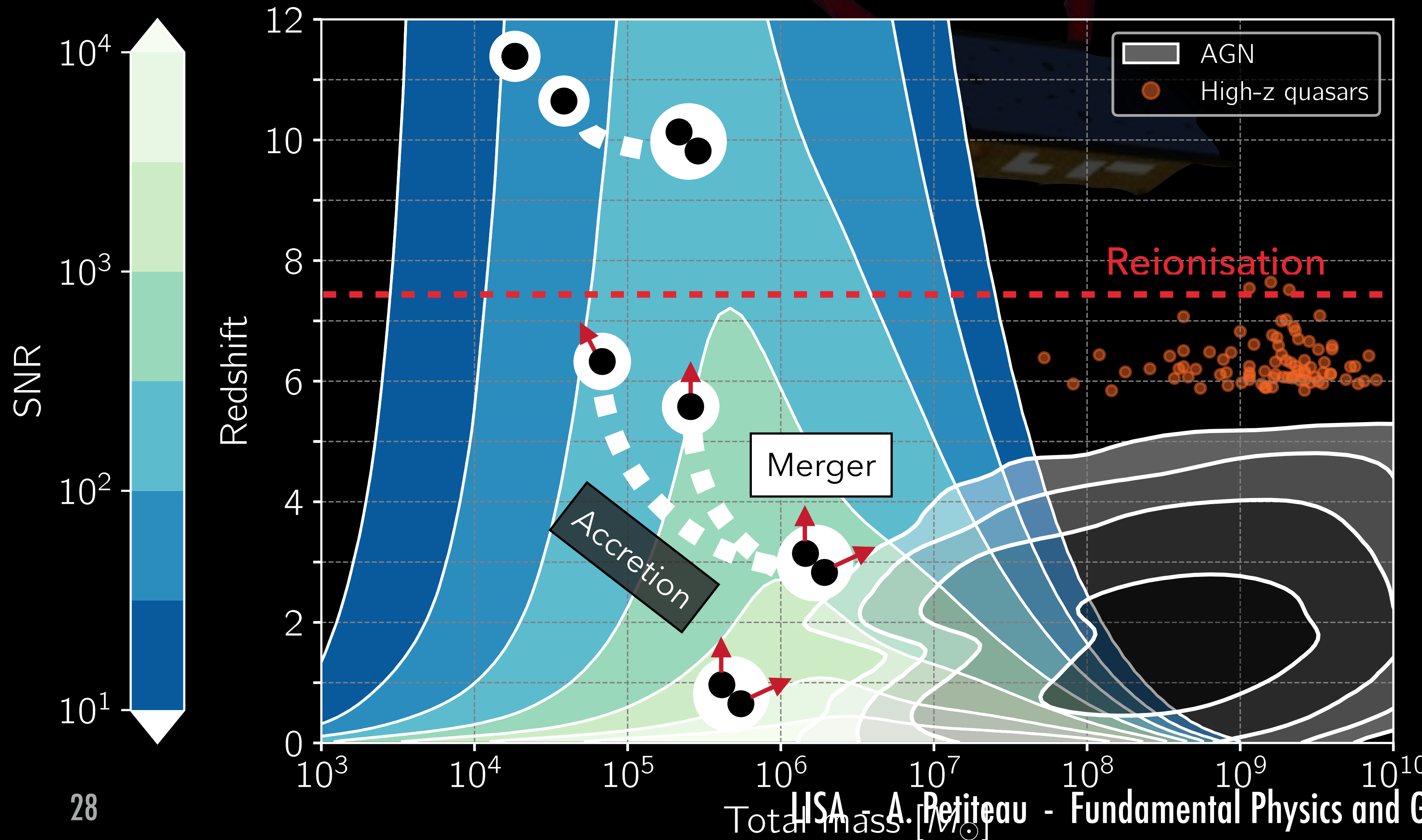




LISA Science

Massive BH Binary Merger

- **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.



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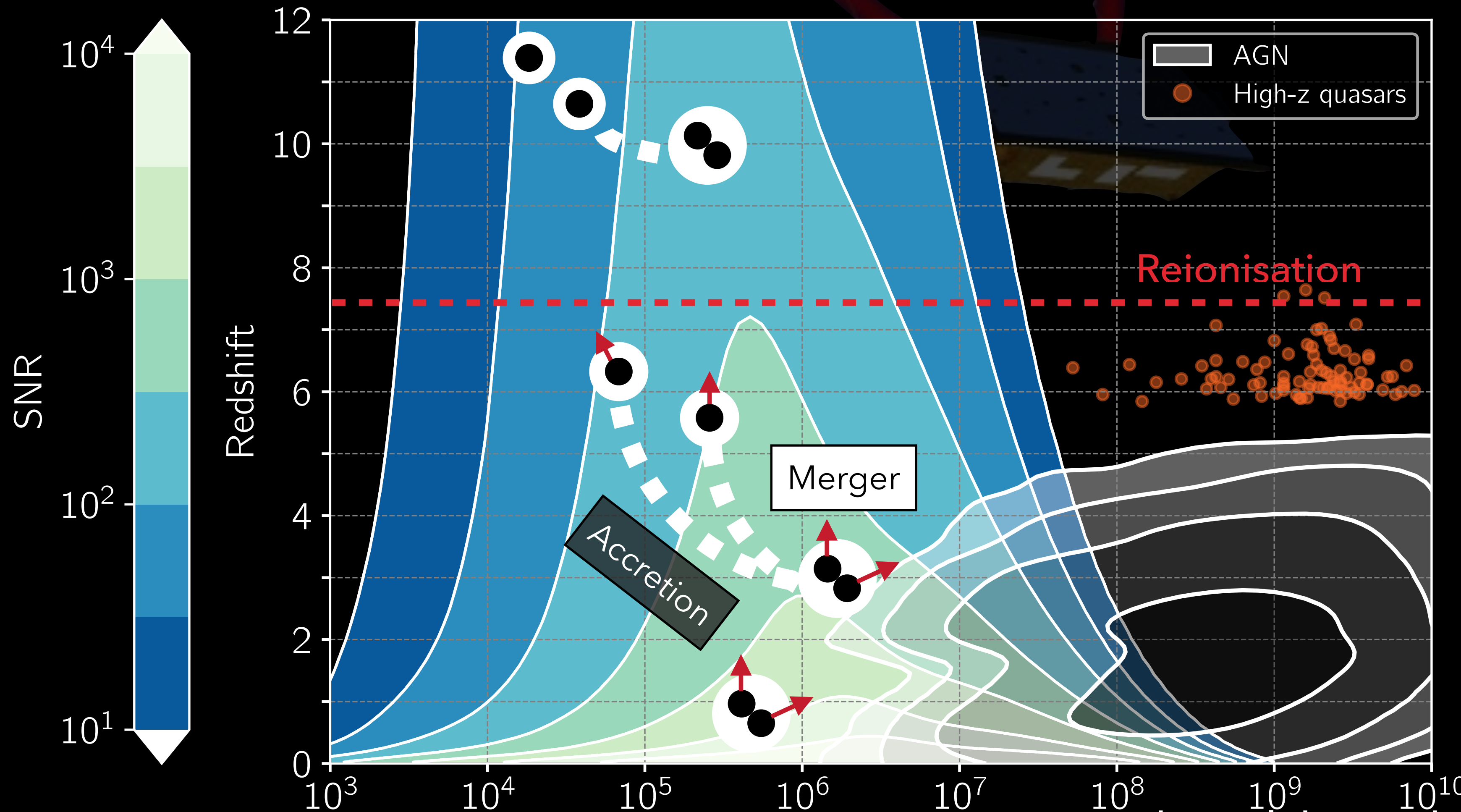

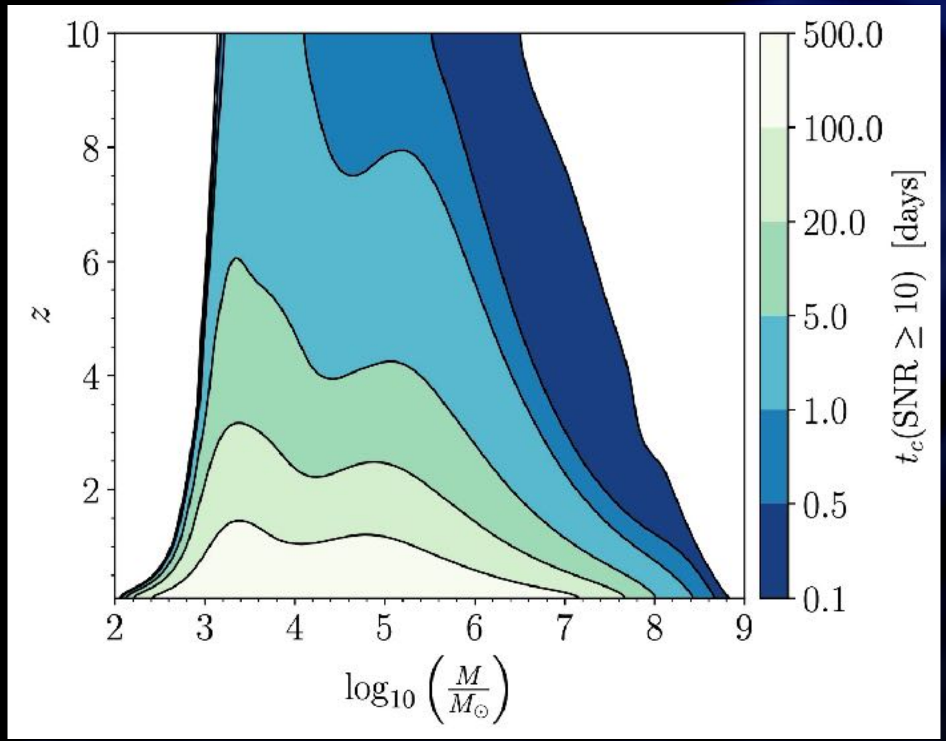

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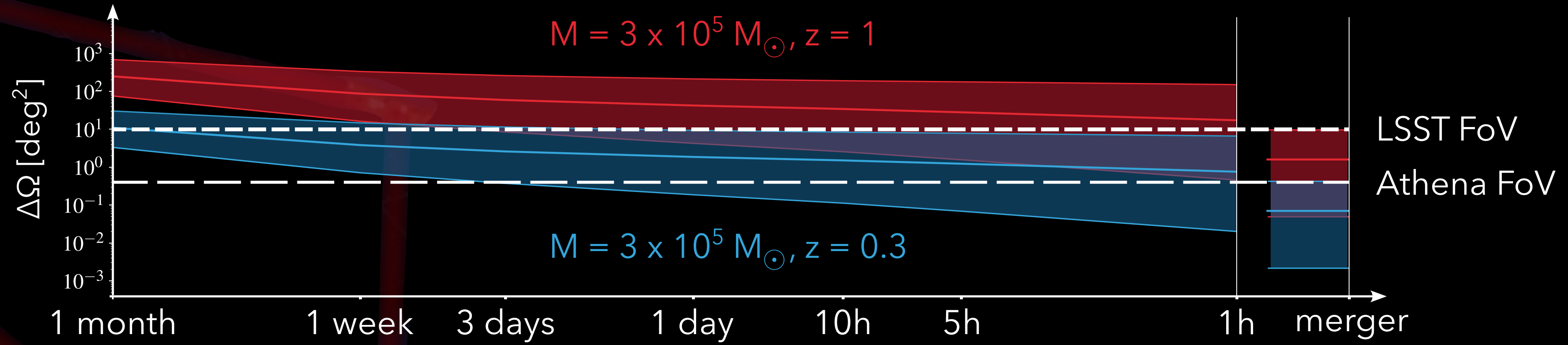

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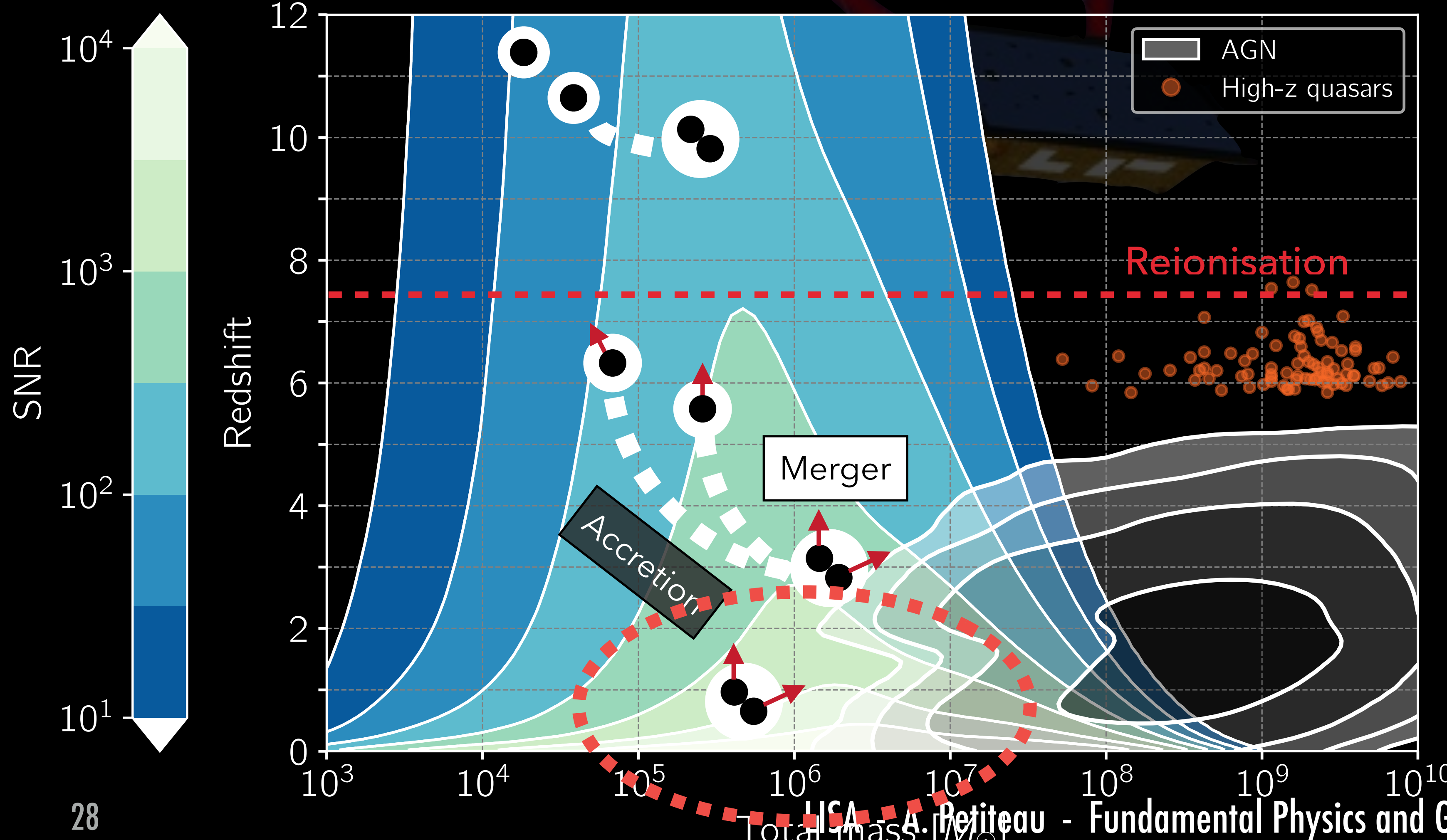
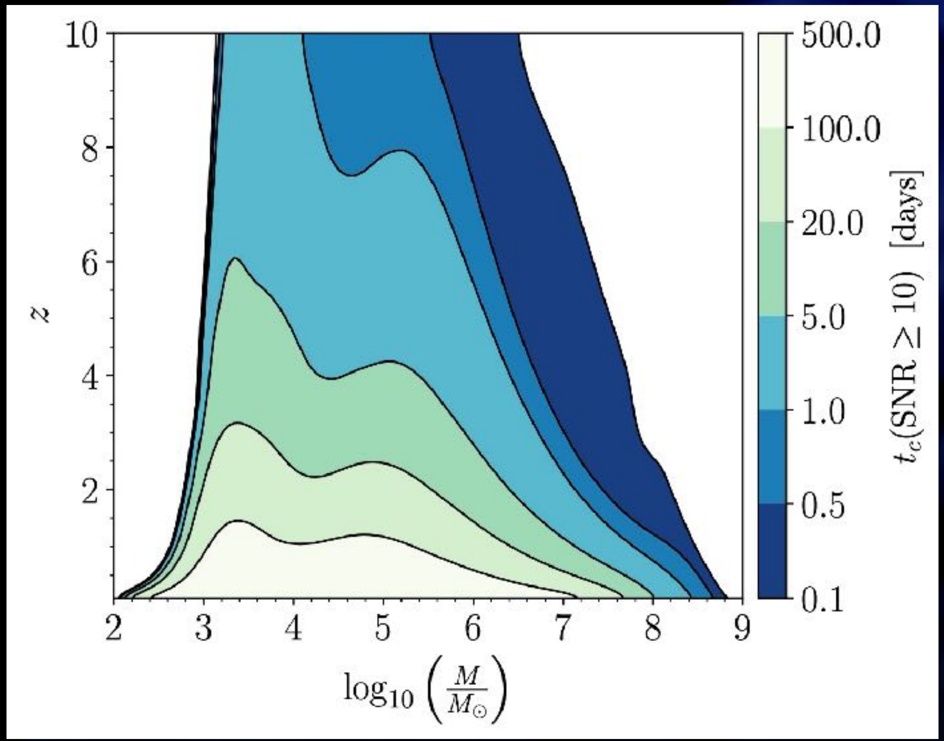
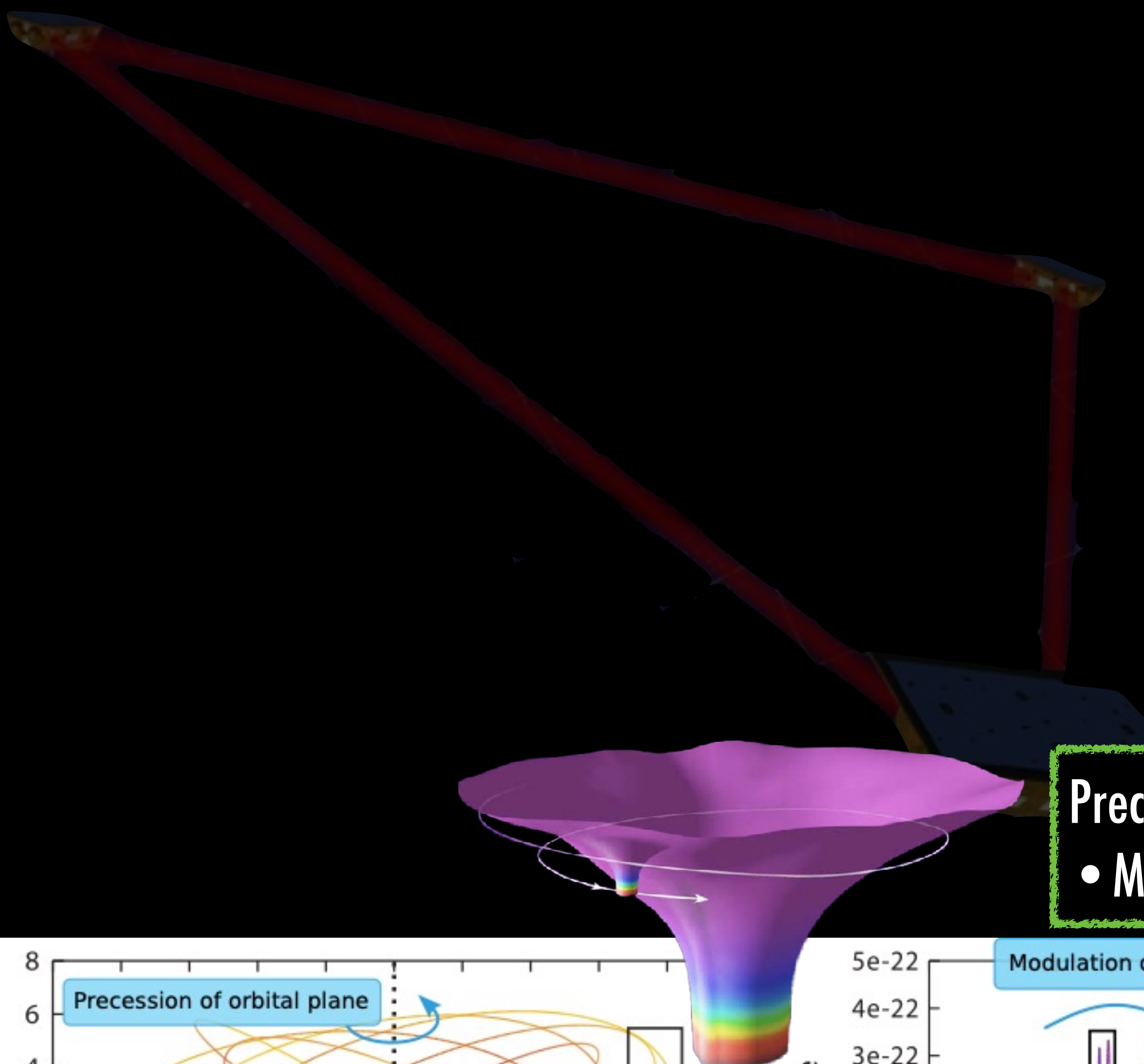




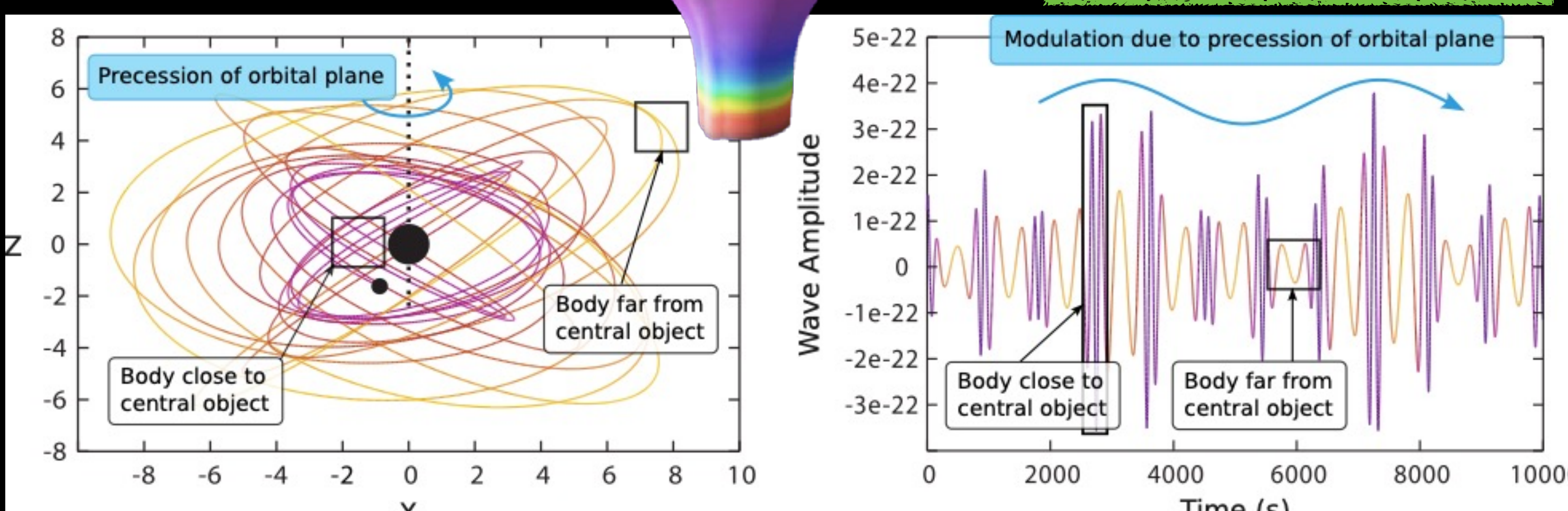
LISA Science

LISA CONSORTIUM



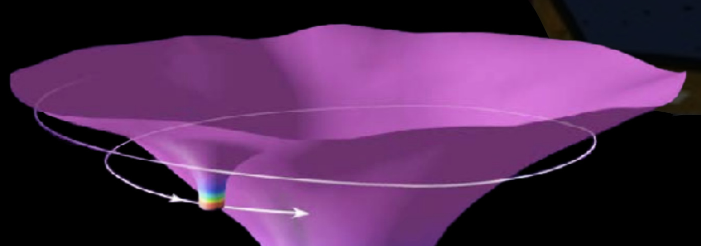
Precision:

- Mass & spin at 0.0001%



LISA Science

- **SO3:** Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs:



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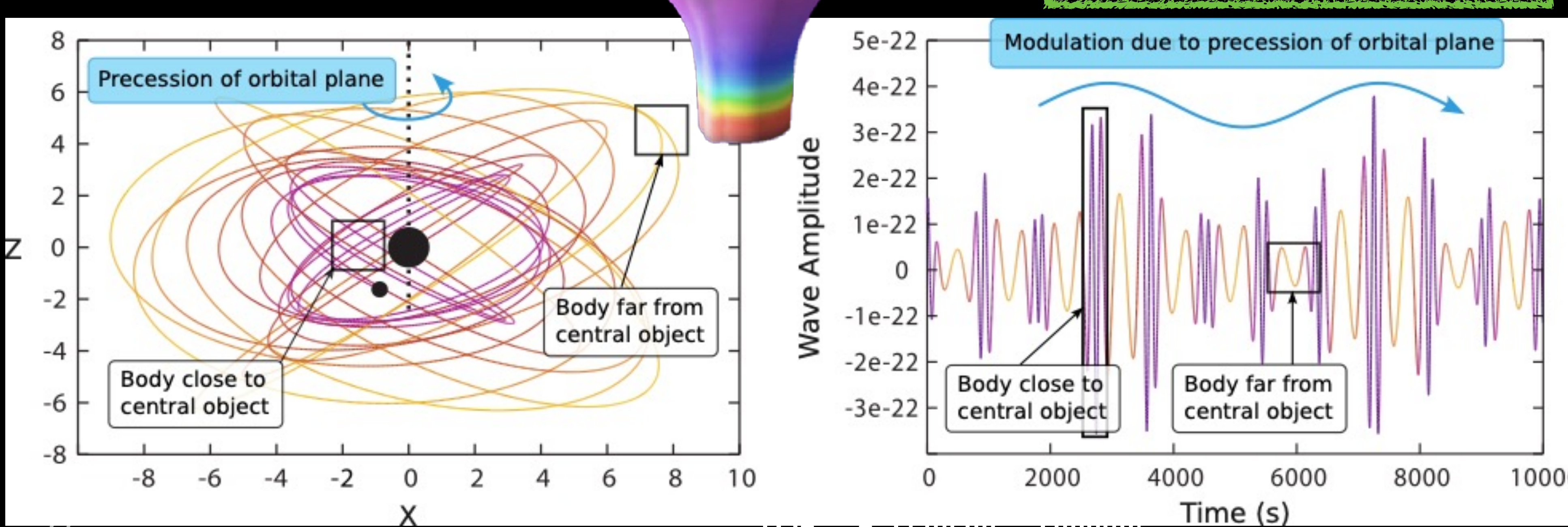

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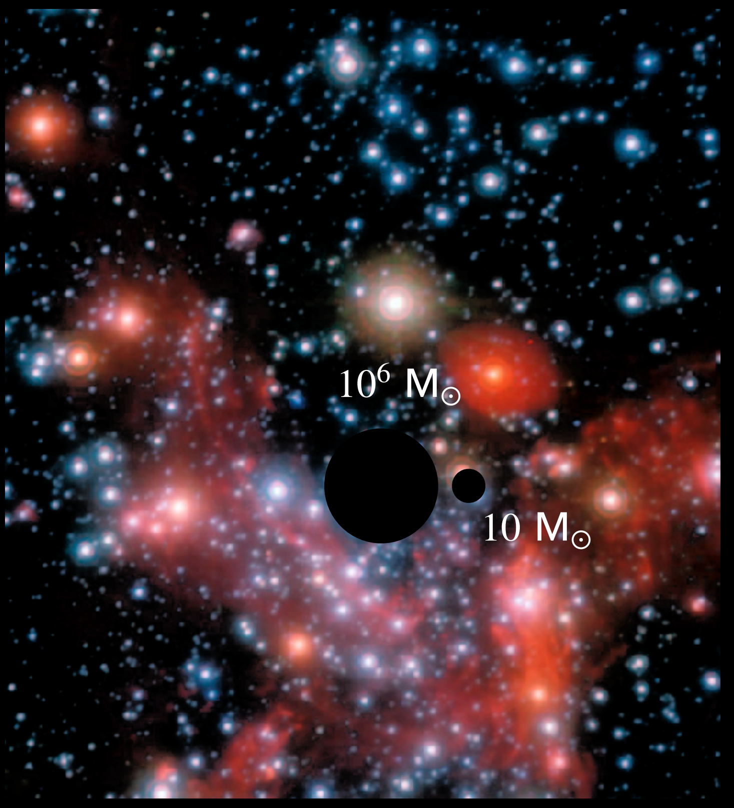
  - Study the properties and immediate environment of Milky Way-like MBHs using EMRIs;



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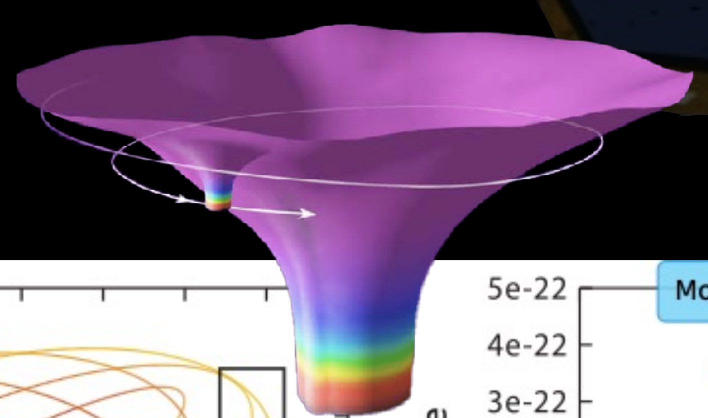

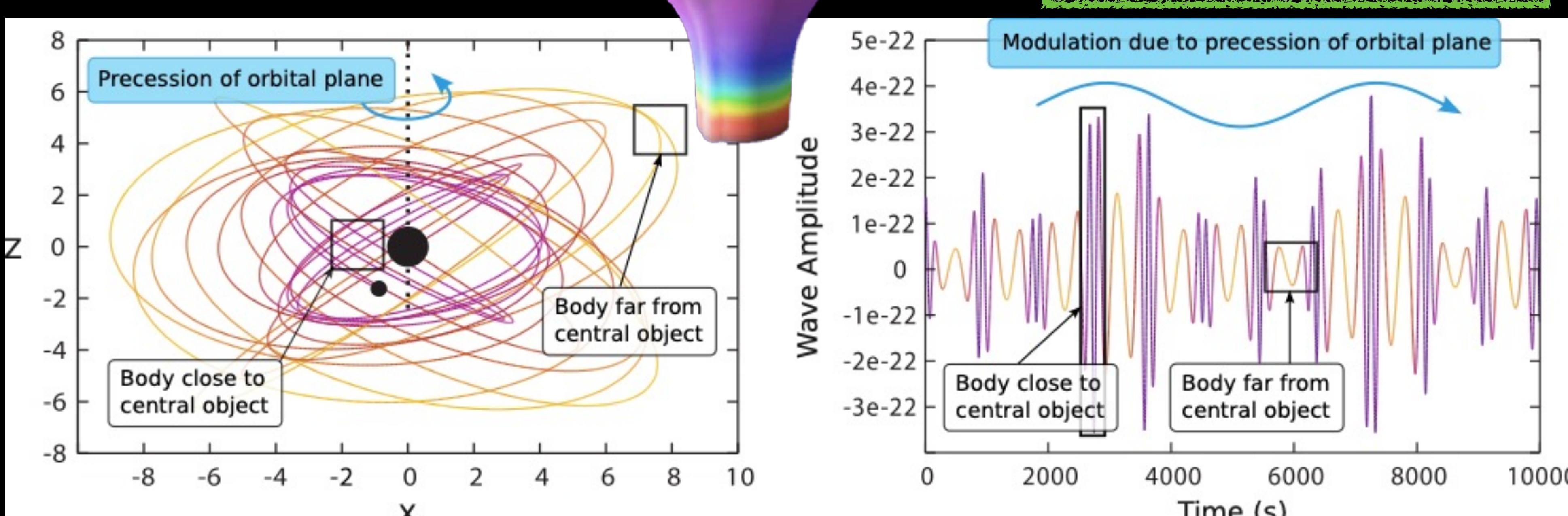

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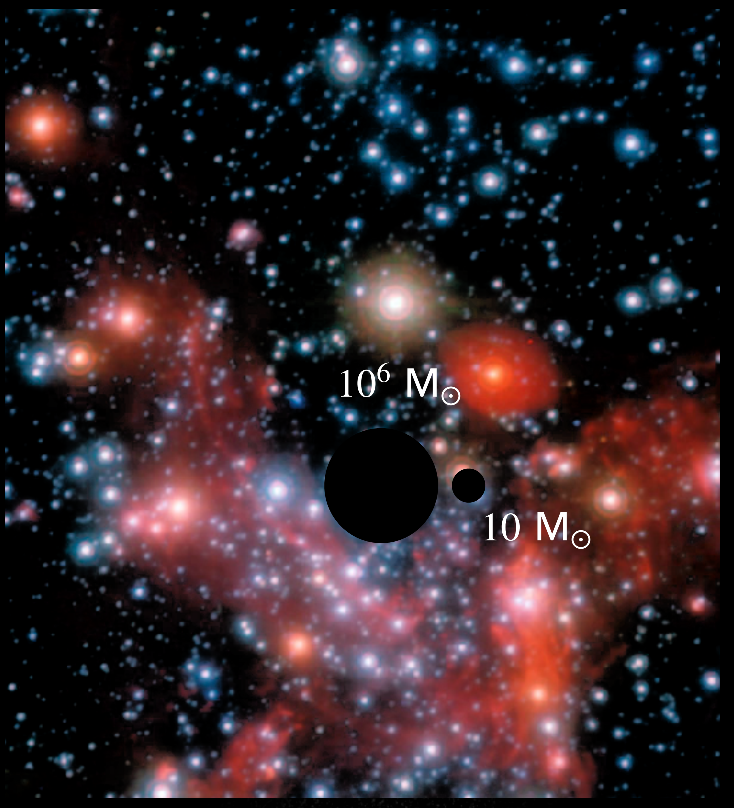

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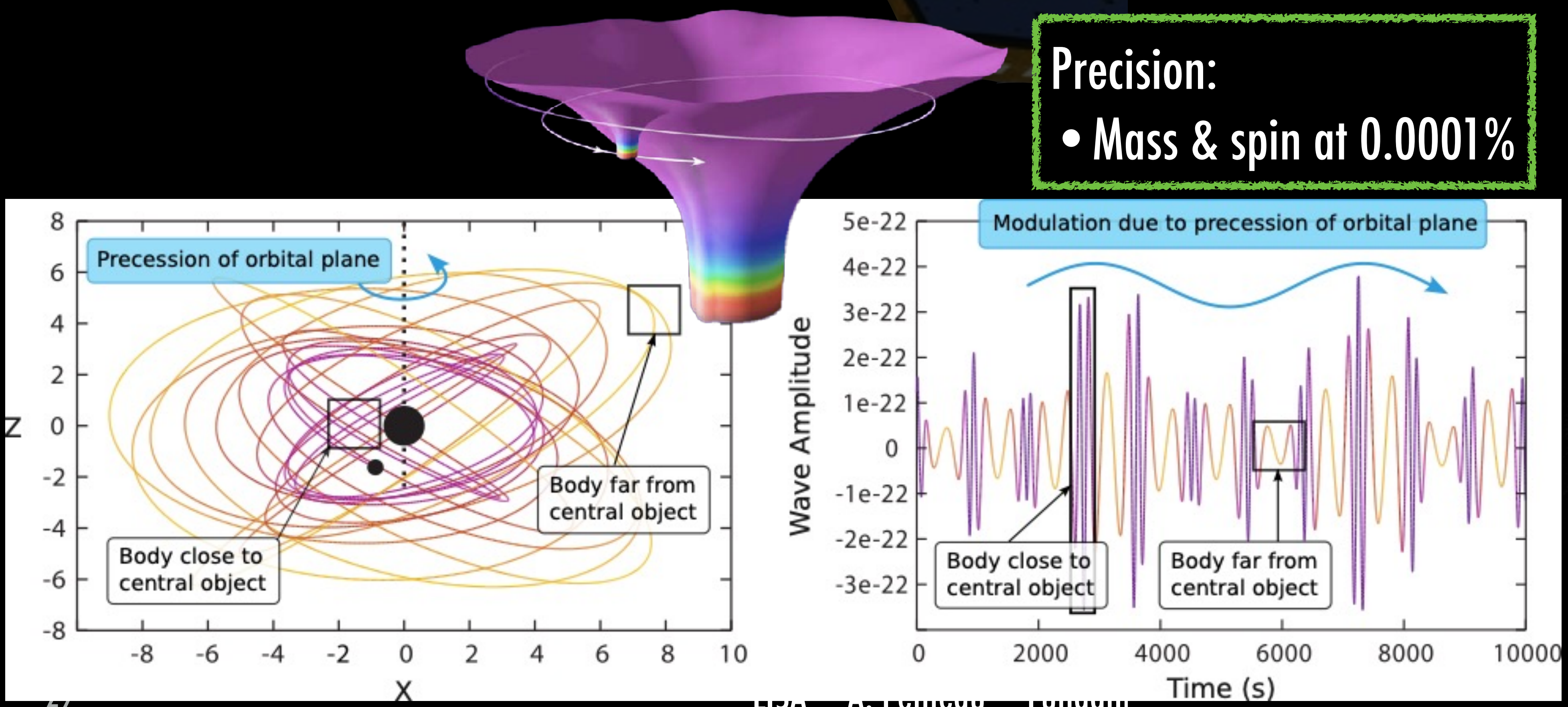
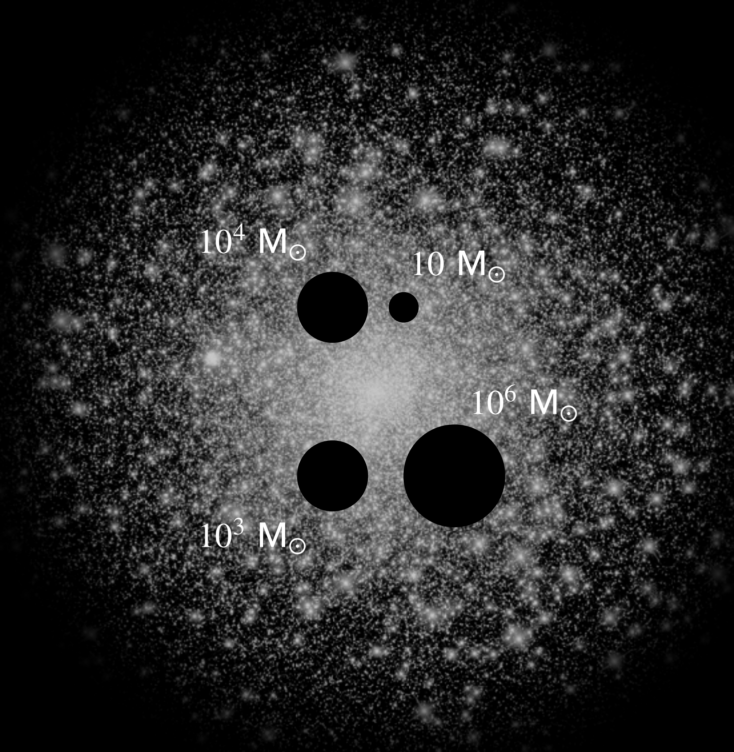
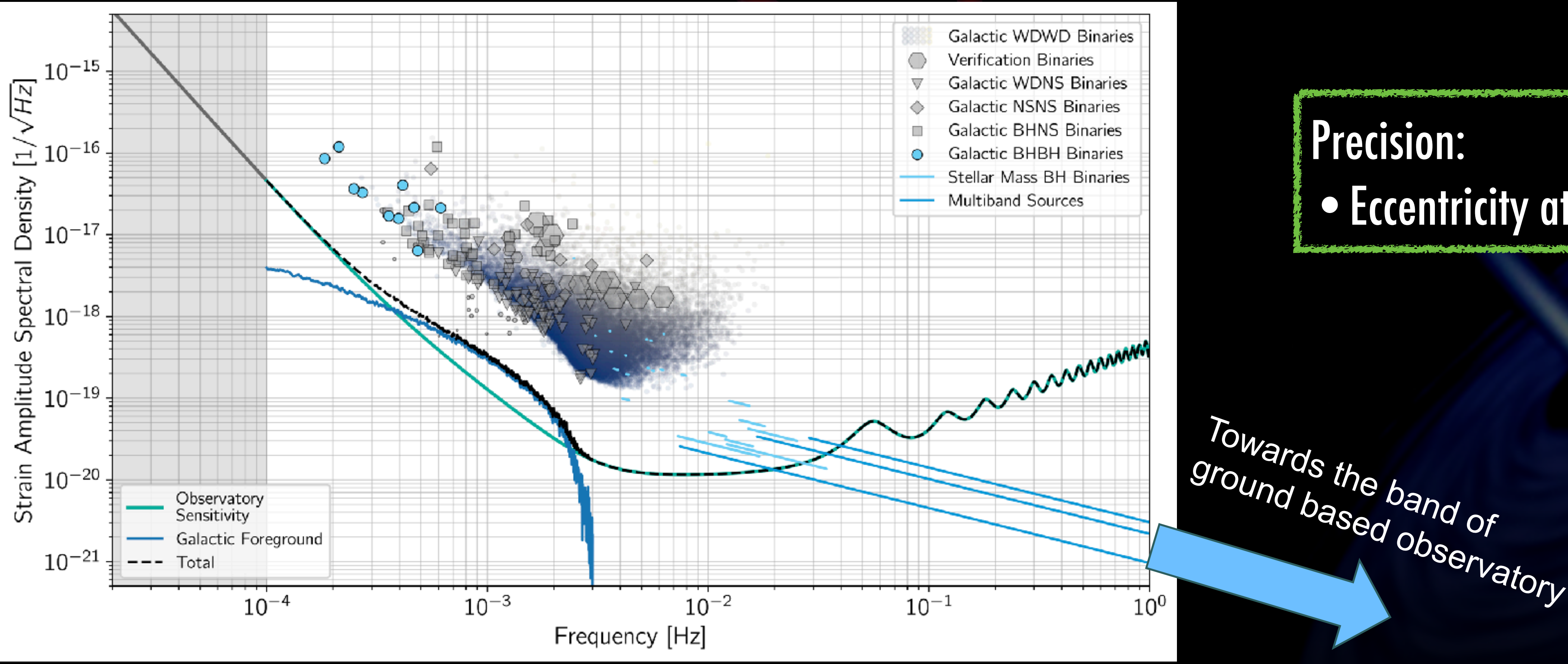




LISA Science

- **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.

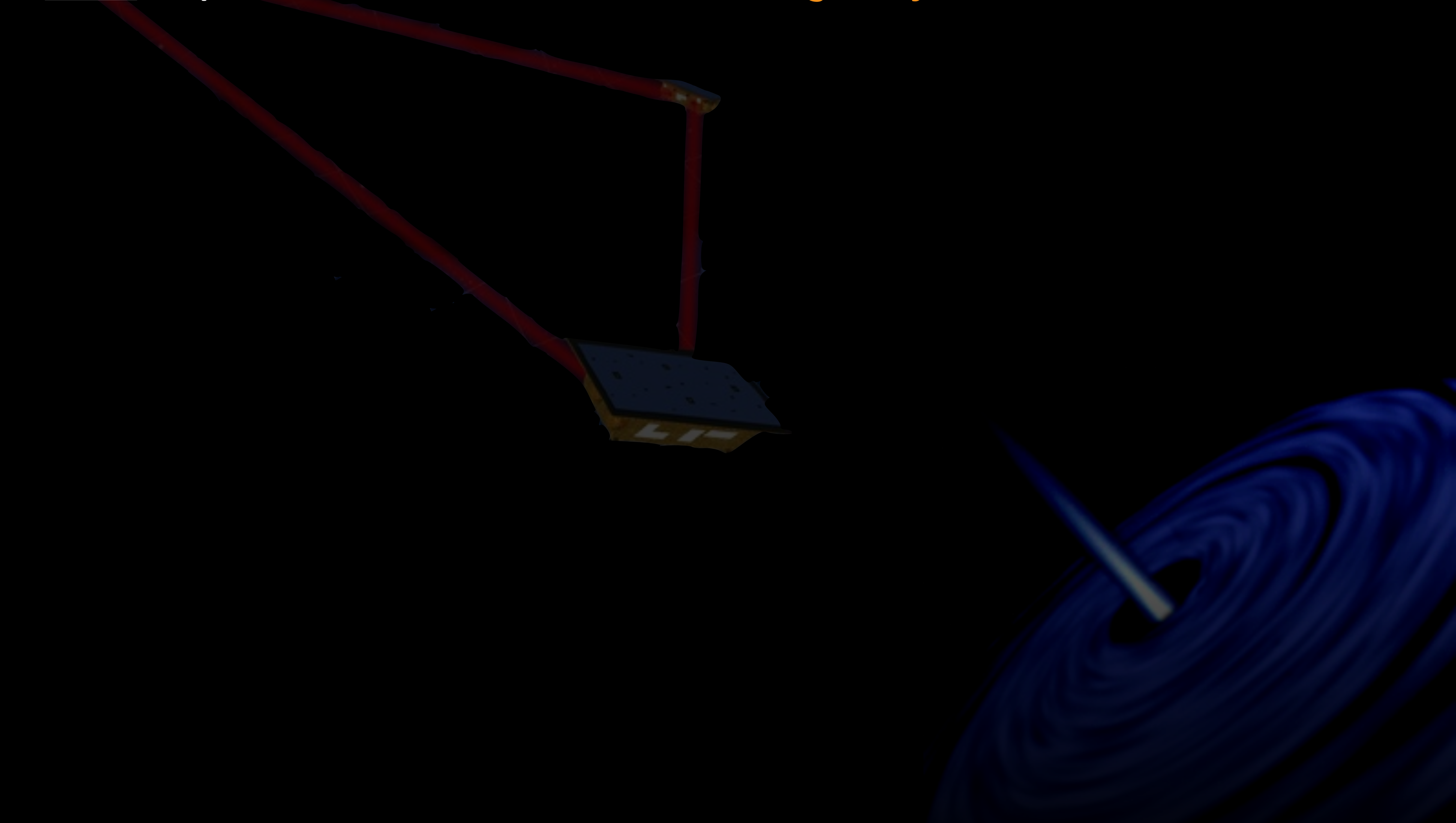


Precision:
- Eccentricity at 0.01%

LISA Science

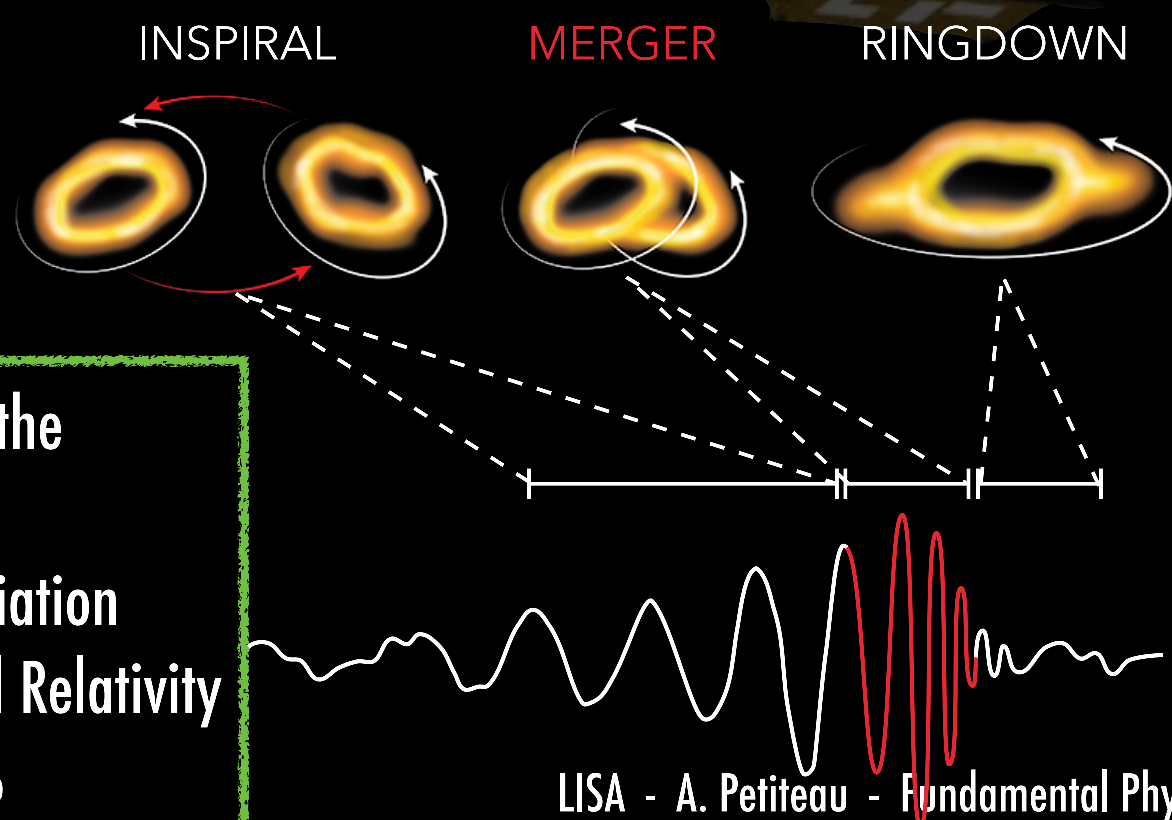
LISA Science

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



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;



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

LISA Science

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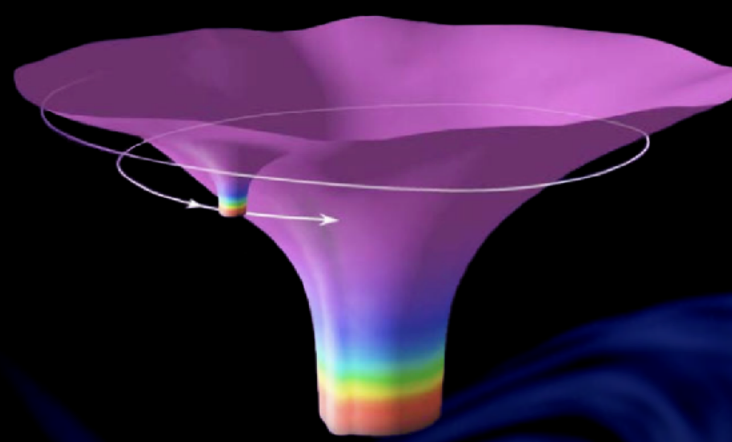
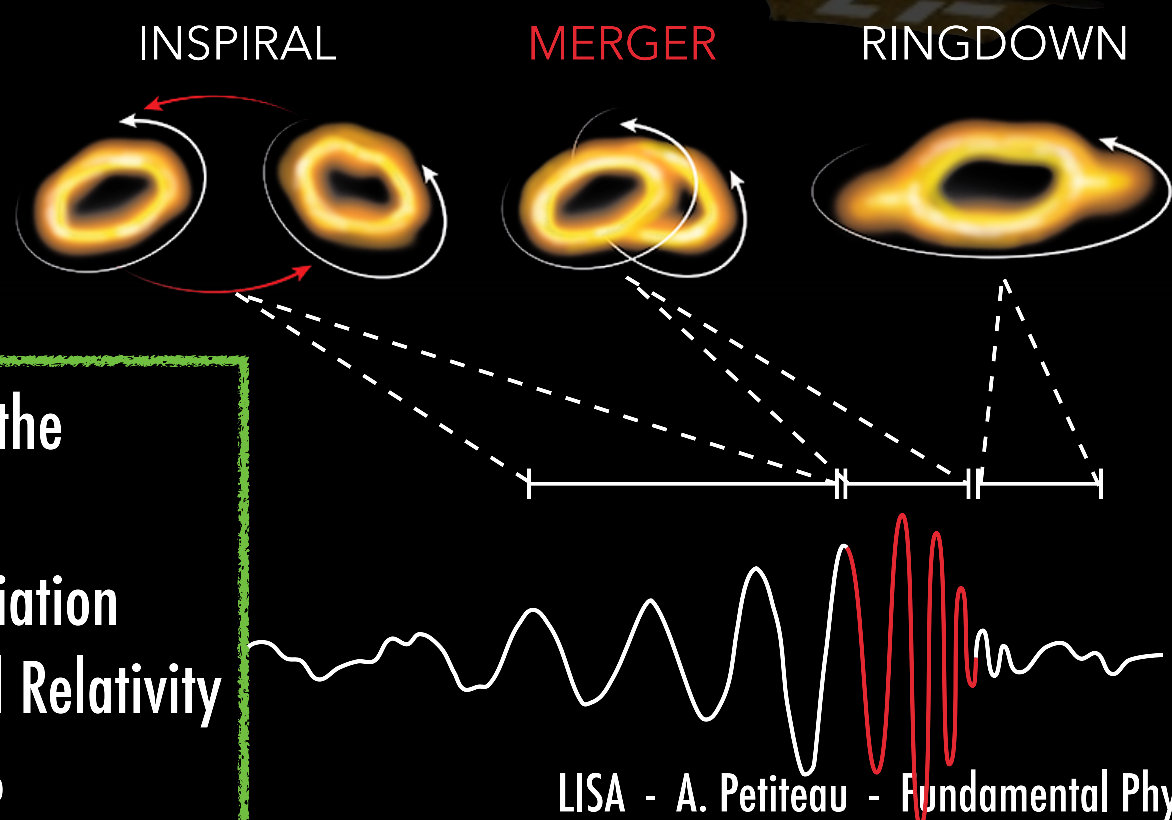
  - Use EMRIs to explore the multipolar structure of MBHs and search for the presence of new light fields;



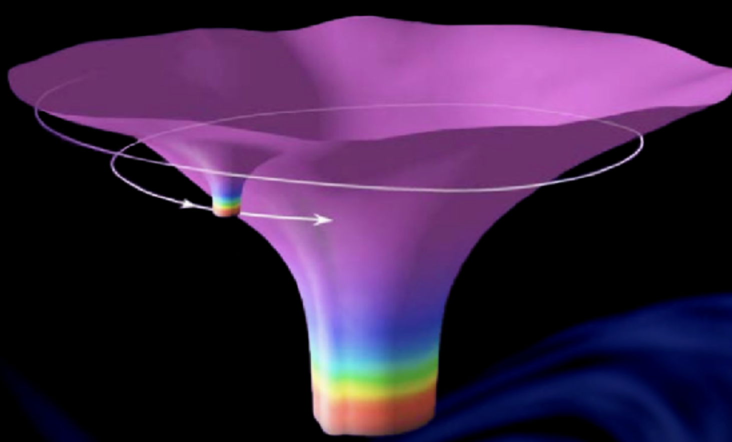


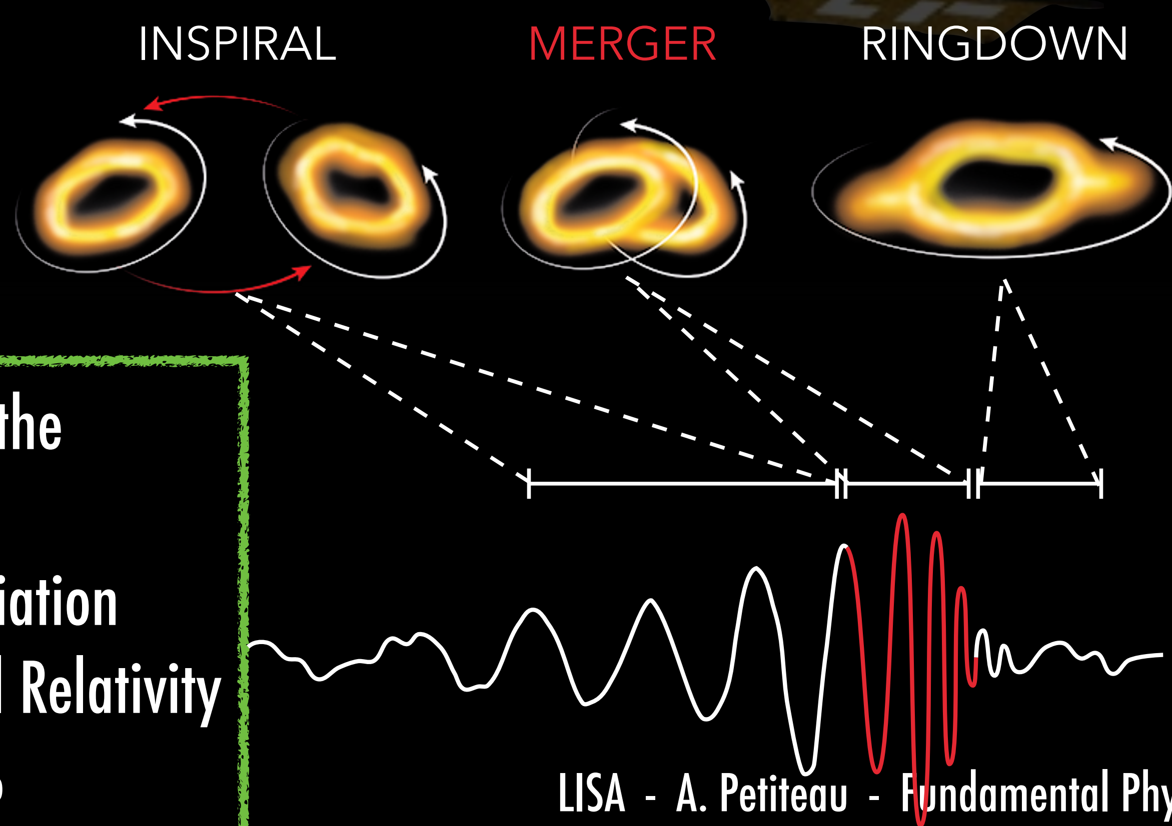
Precision from the ringdown:
- Measure deviation from General Relativity at 10% to 1%

Precision for the "golden" EMRI :
- Mass of the big black hole at $\sim$ 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.



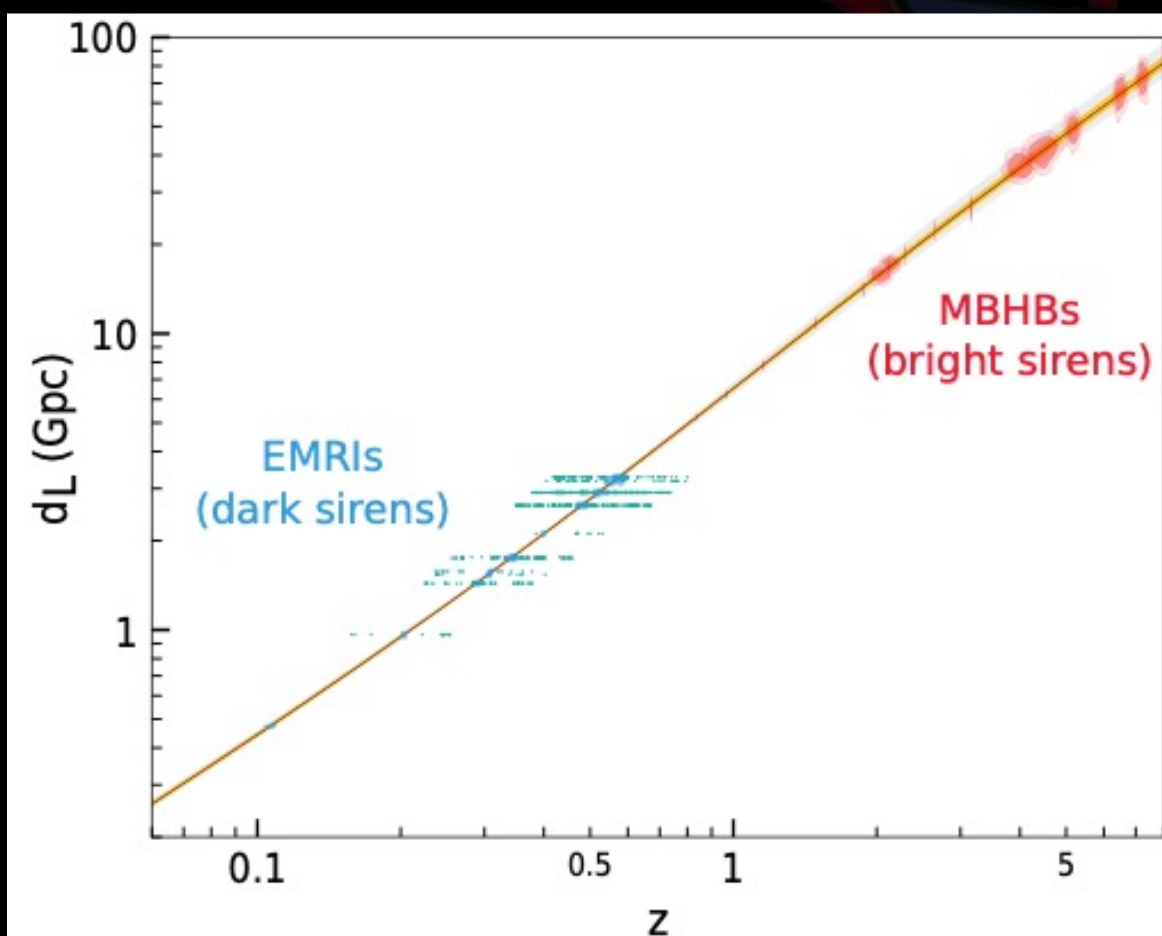


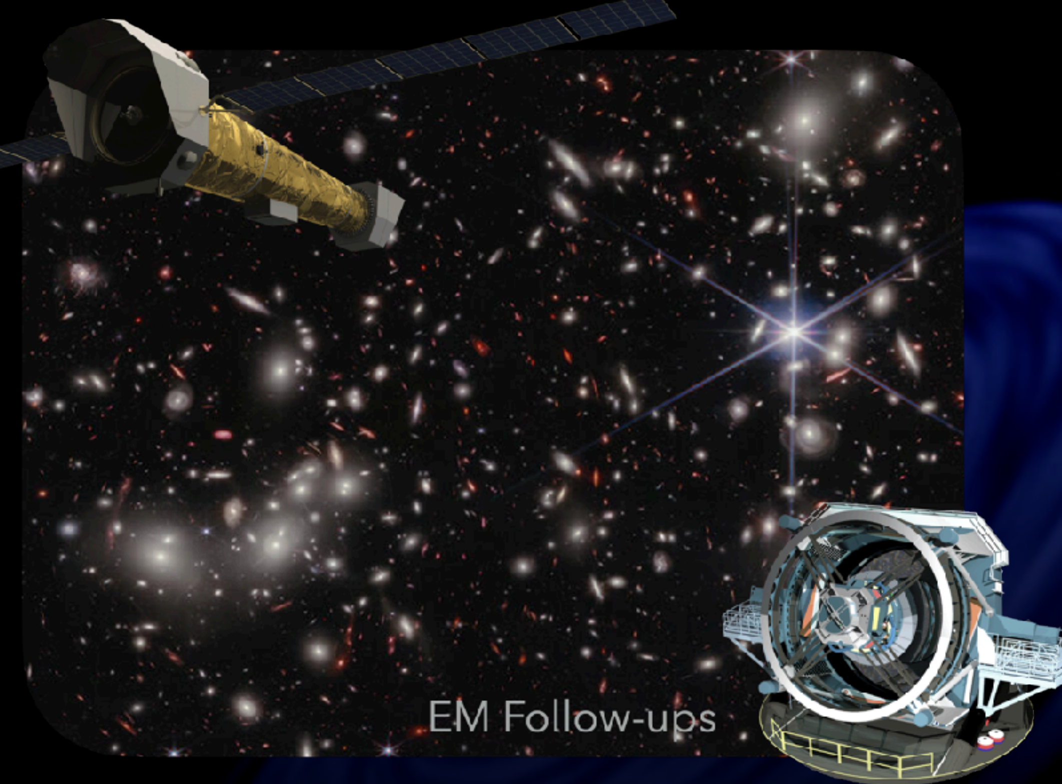
Precision from the ringdown:
- Measure deviation from General Relativity at 10% to 1%

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

- **SO6:** 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.



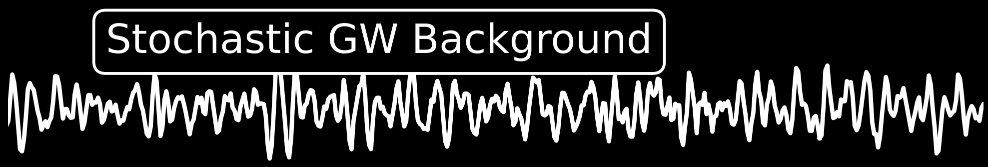


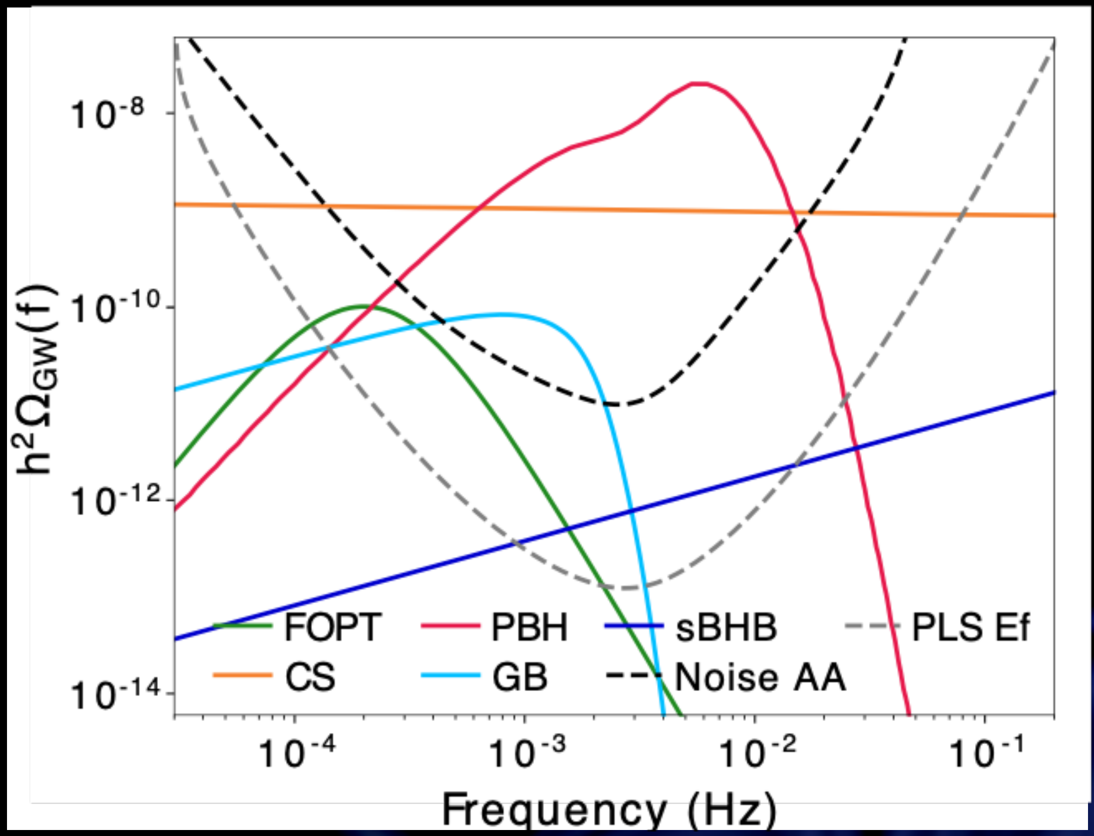
Constraint on the geometry of the Universe:

- No calibration needed
- H_0 to a few % with observations up to $z \sim 3$

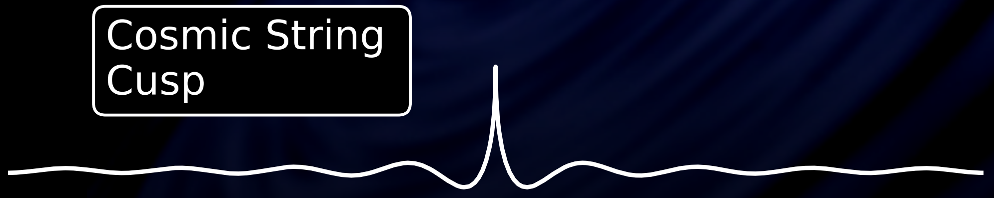
LISA Science

- 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

- 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

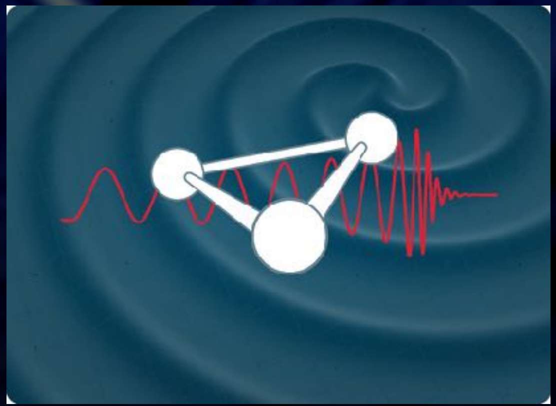
Cosmology

LISA and Fundamental Physics

- SO5: Explore the fundamental nature of gravity and black holes
  - But only a sub-part of what we could do with LISA for Fundamental Physics
  - LISA Fundamental Physics Working Group:
    - Several sub-groups with multiple projects:
      - Ringdown tests of the no-hair theorem with LISA:
        - Extend pyRing to allow for LISA use
        - Beyond GR
        - Multimode memory detectability
        - Ringdown tests with pSEOBNR
      - Effect of systematics on parametrized IMR tests
      - ...
- SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics
  - LISA Cosmology Working Group:
    - Active since 2015 with many projects and papers

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 in its development and building phase for a launch in 2035 for 4.5 to 10 years of operations.
- LISA will cover a large range of domains and has a huge science case for astrophysics, cosmology and fundamental physics.
- LISA is a one of the major upcoming instrument to explore Fundamental Physics in multiple ways!



Thank you !