Science prospects for LISA

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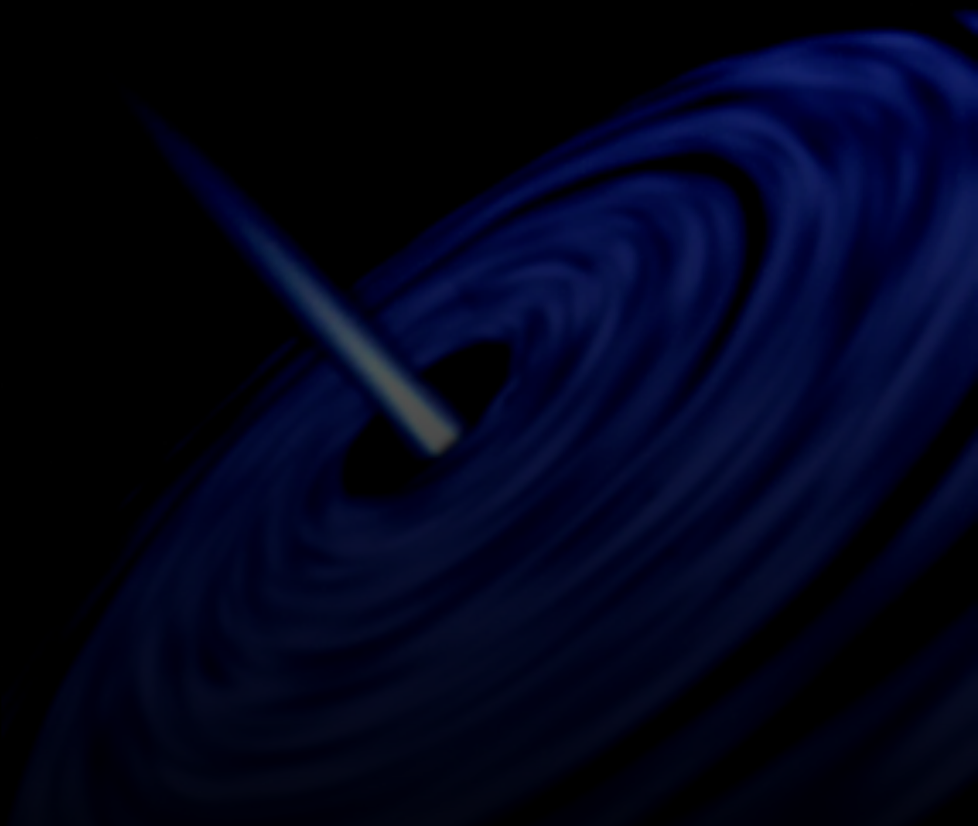
for the ESA LISA Science Study Team, the LISA Formulation Management Team and the LISA Consortium

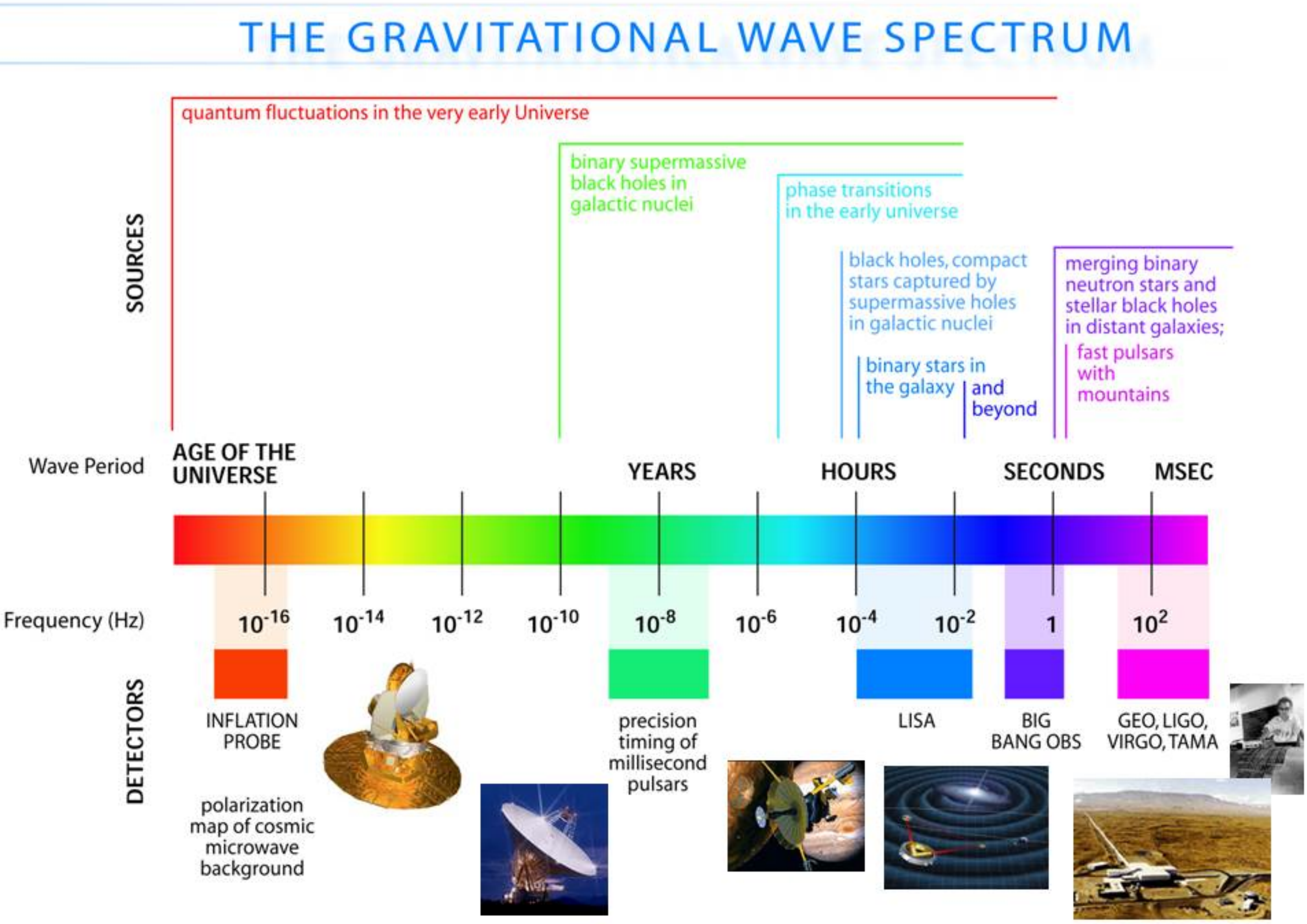
Seminar at CERN Theory Group

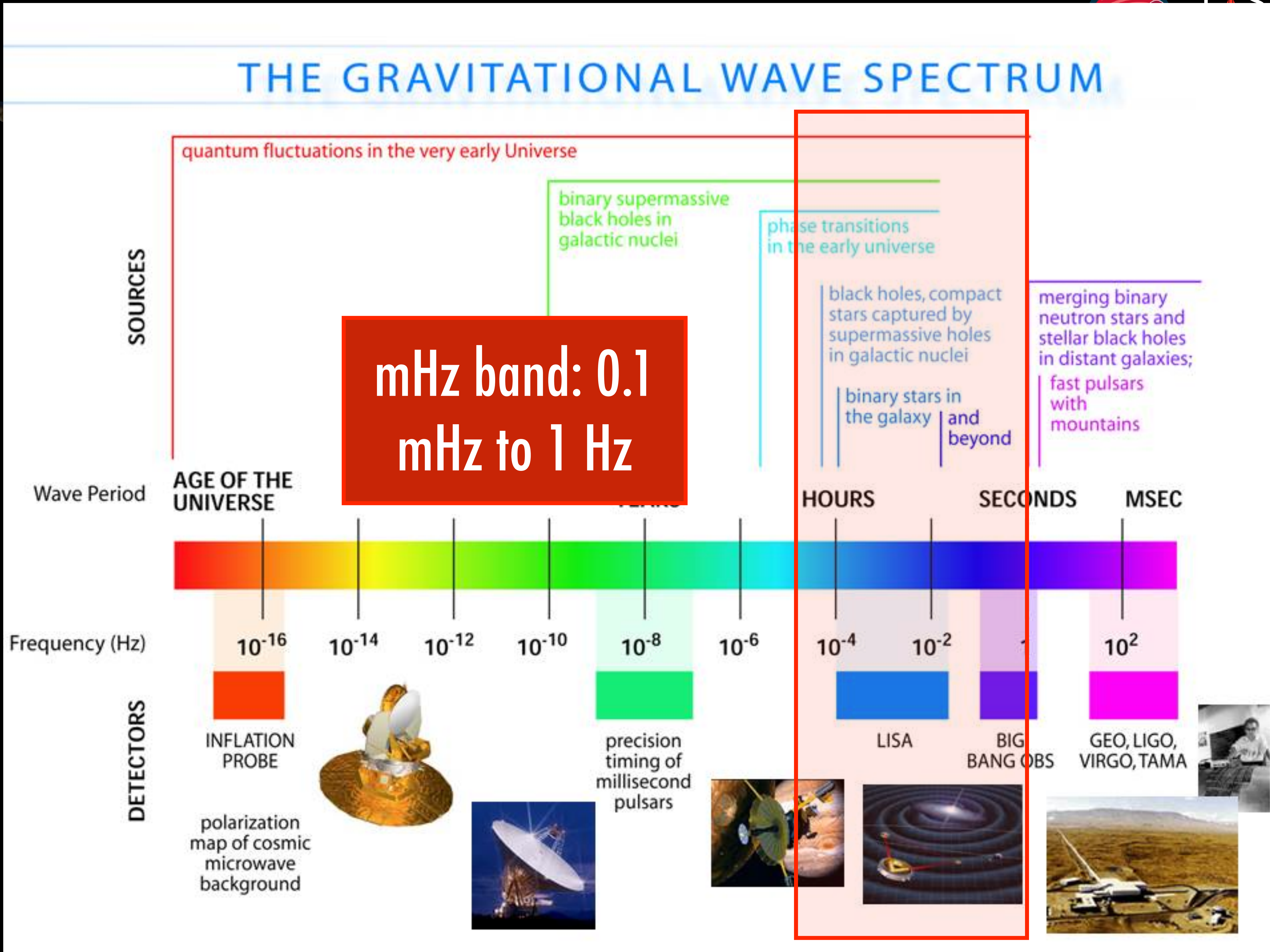
CERN - 19th July 2023

Talk outline

- LISA
  - Mission
  - Data analysis
  - Planning
  - Organisation
- Gravitational wave sources for LISA
- LISA science objectives




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
10^{2}
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA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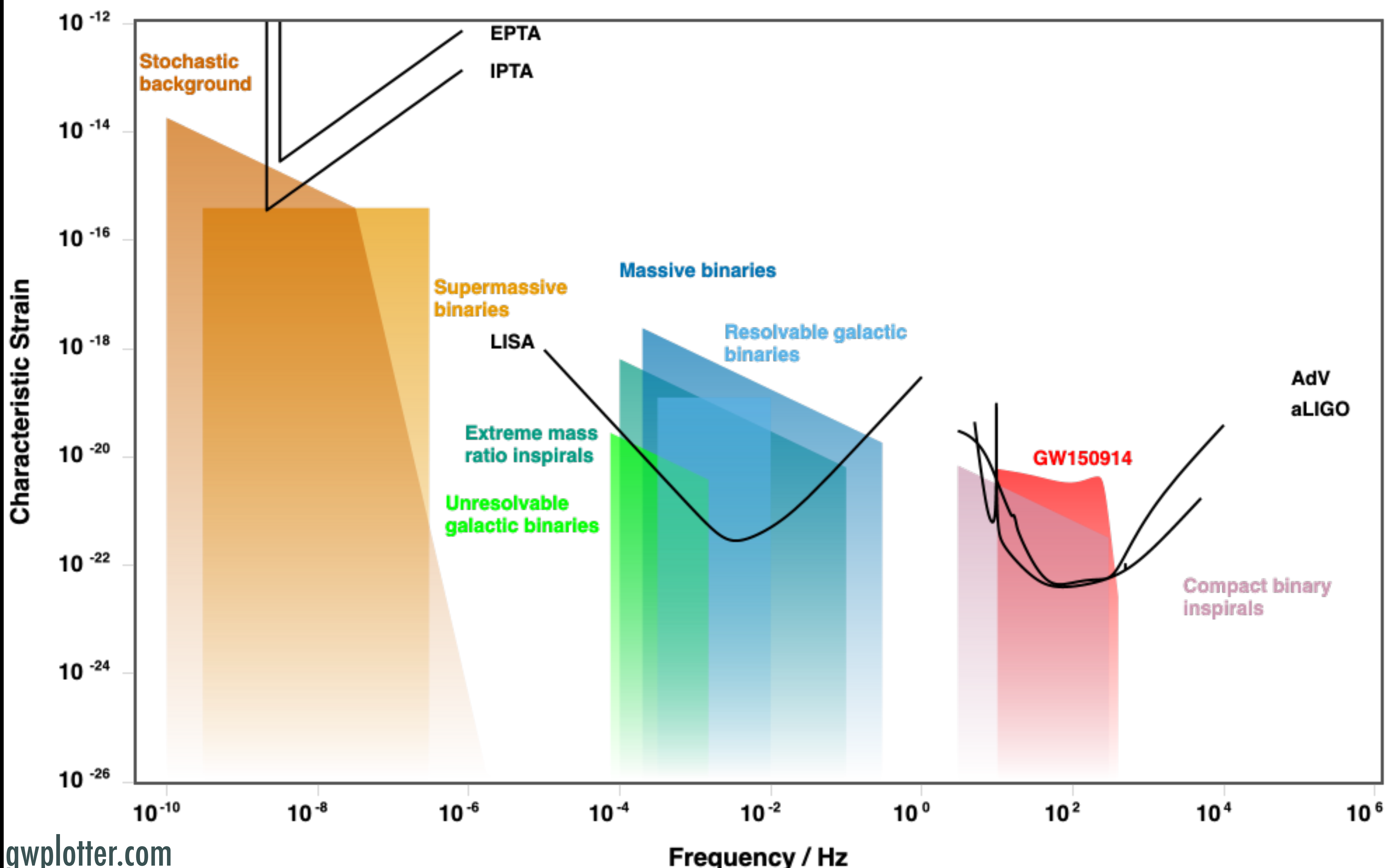
Sensitivity to GWs



gwplotter.com

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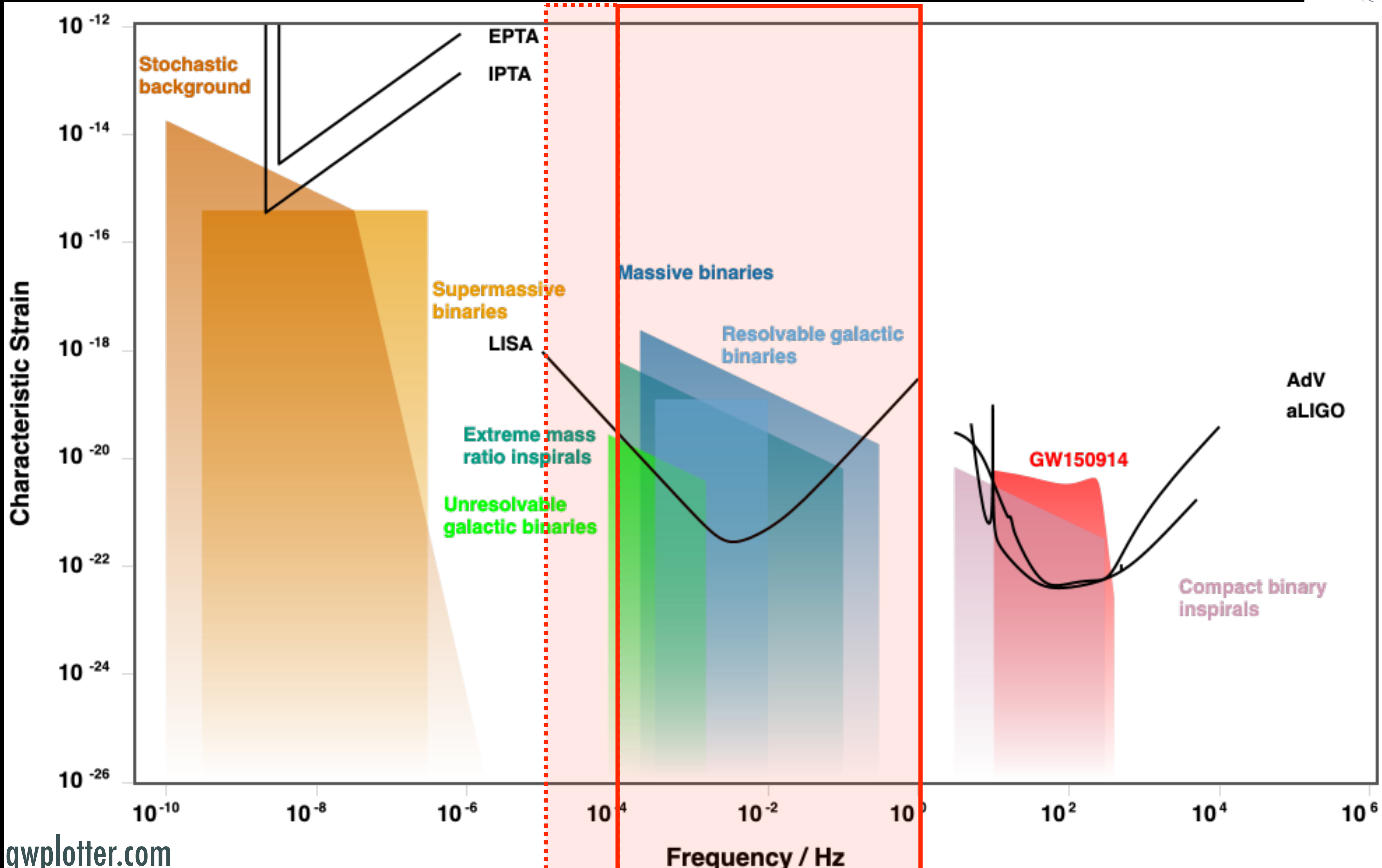
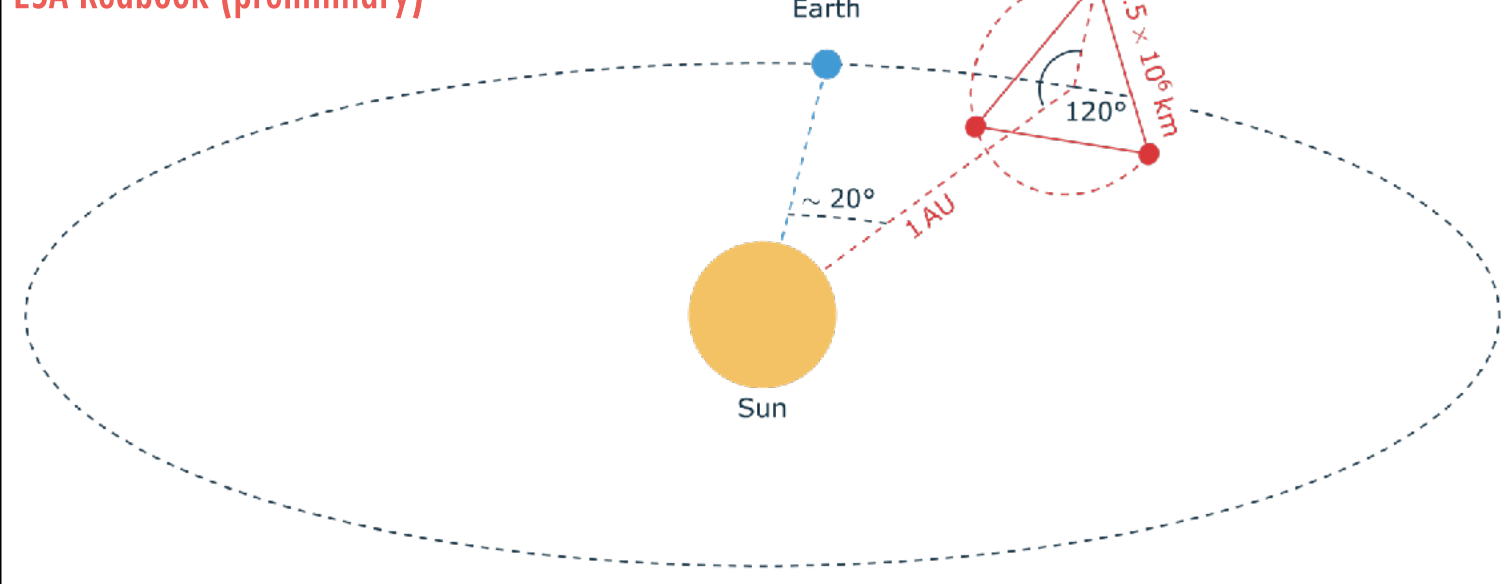


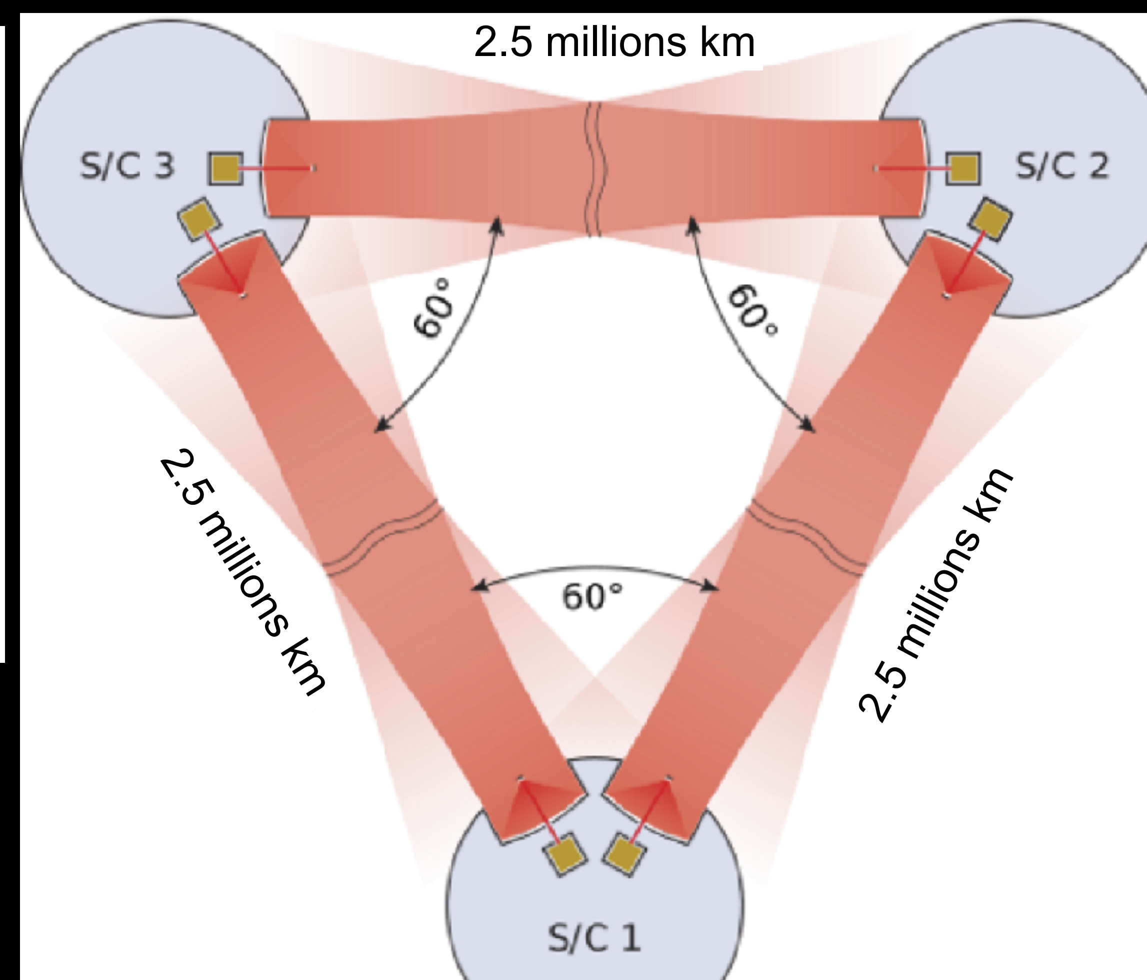
gwplotter.com

LISA mission

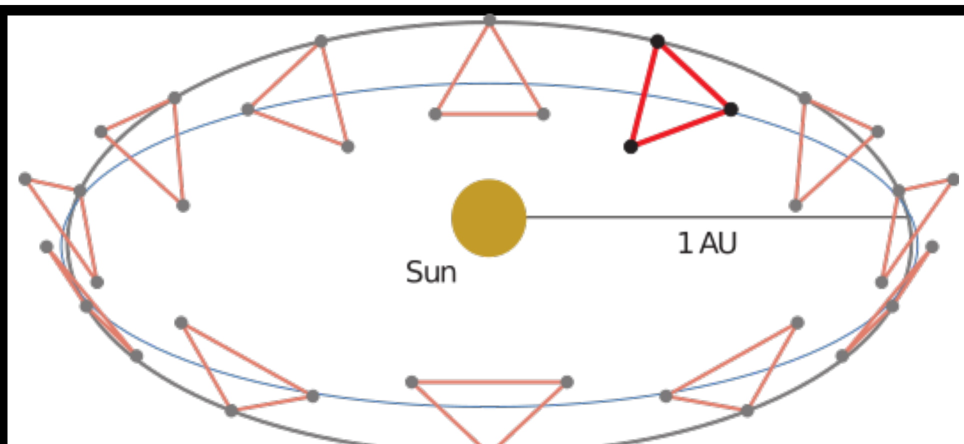
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits separated by 2.5 millions km
- Goal: detect strains of 10^{-21} by monitoring arm length changes at the few picometre level



ESA Redbook (preliminary)



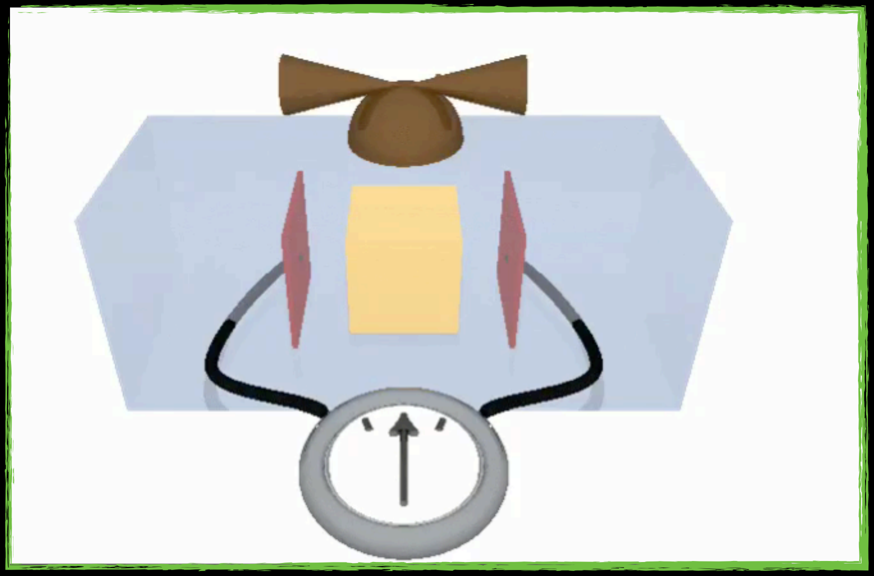
PDD (LIG)

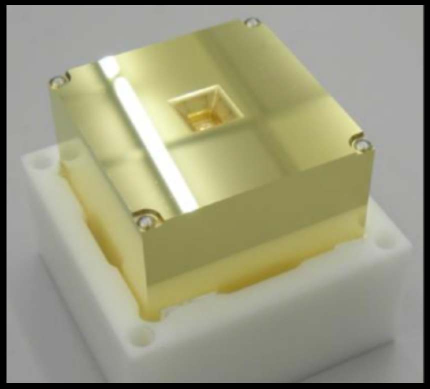


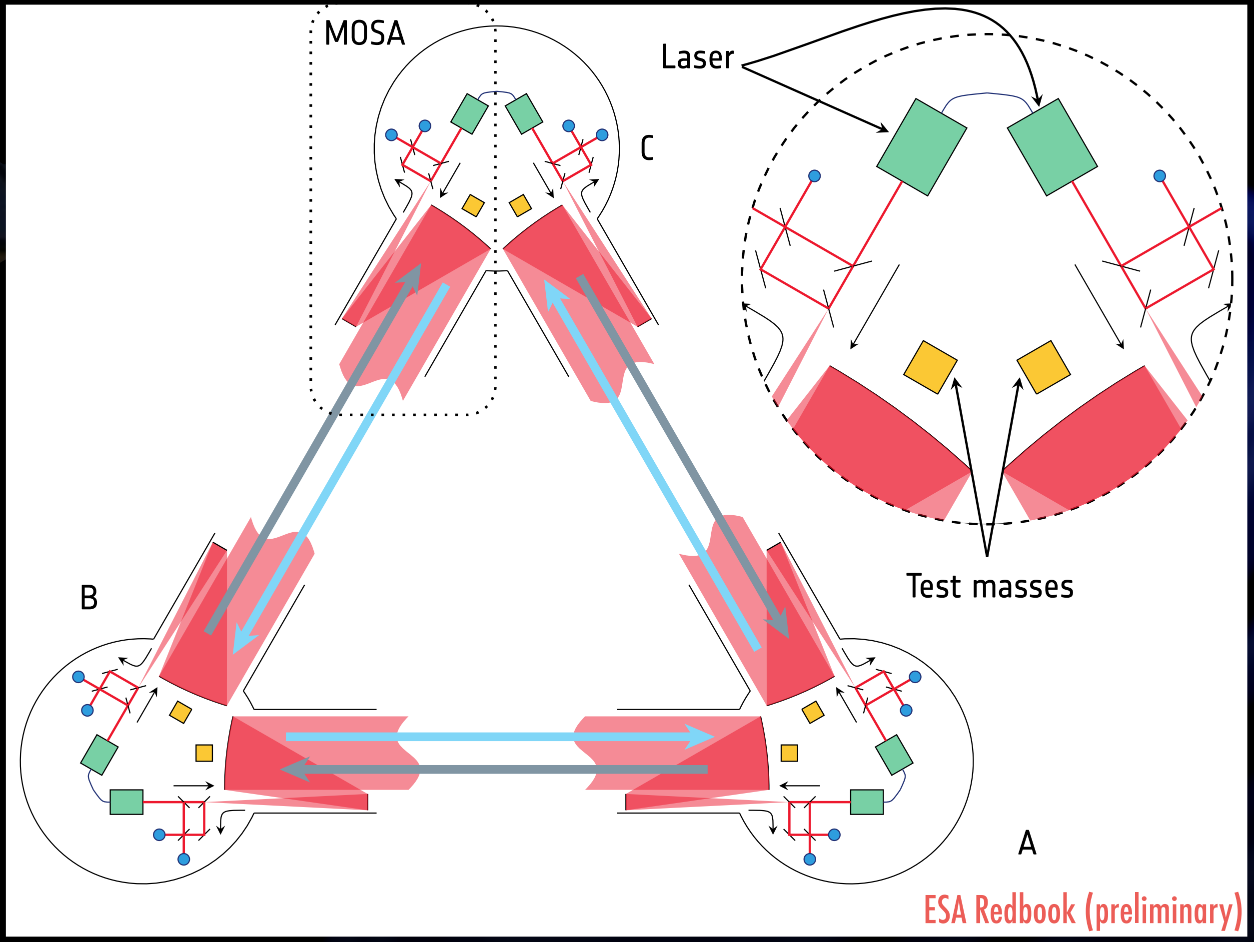
L3 proposal (LISA Consortium)

LISA mission

- 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







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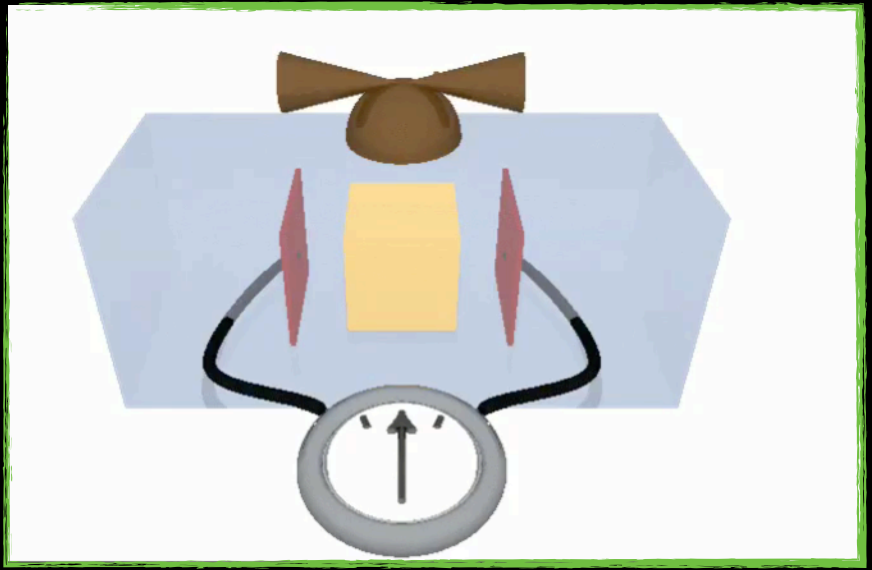
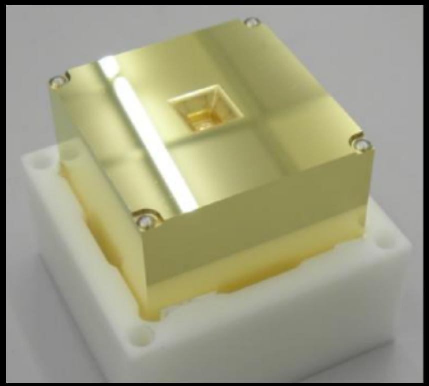
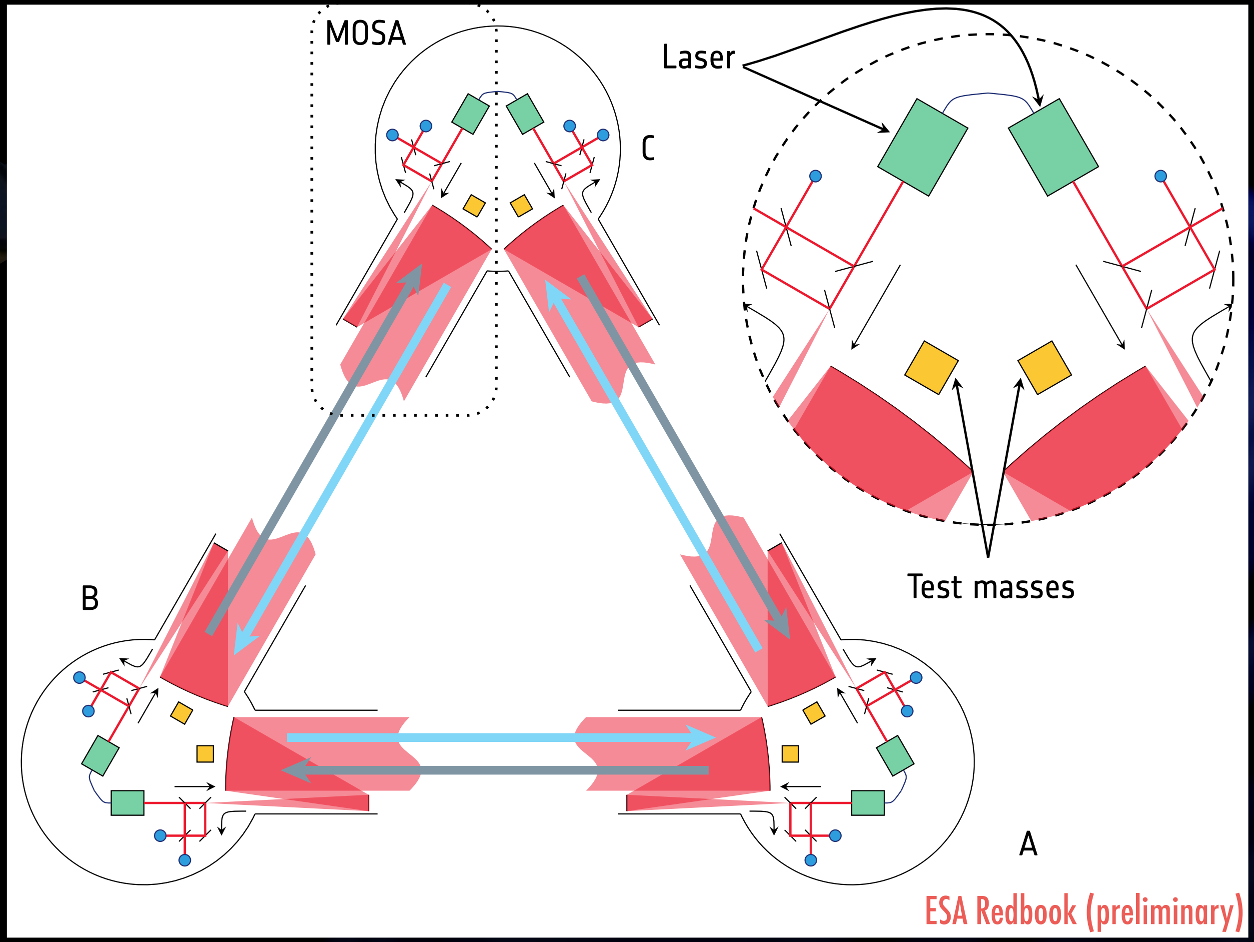
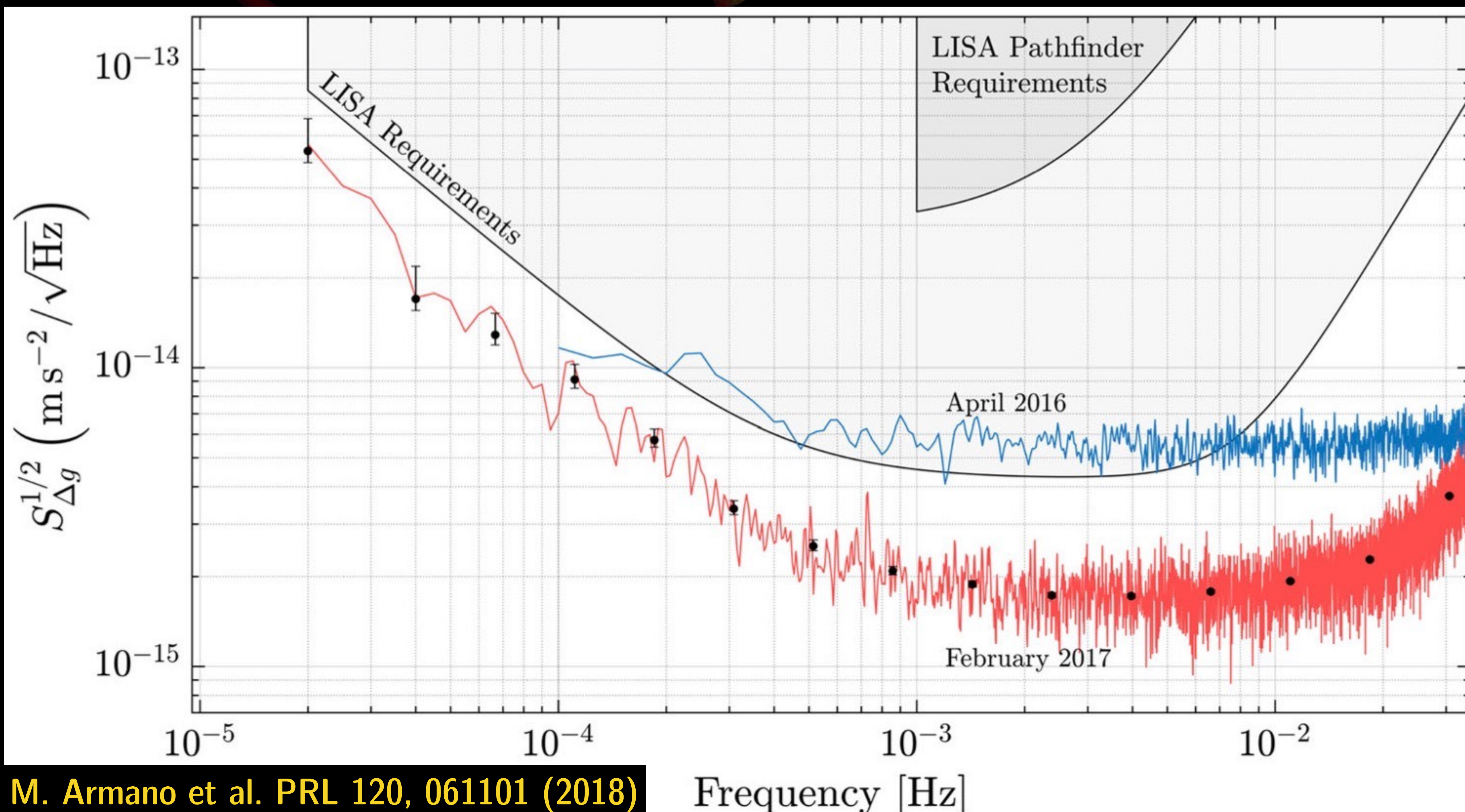






LISAPathfinder final main results

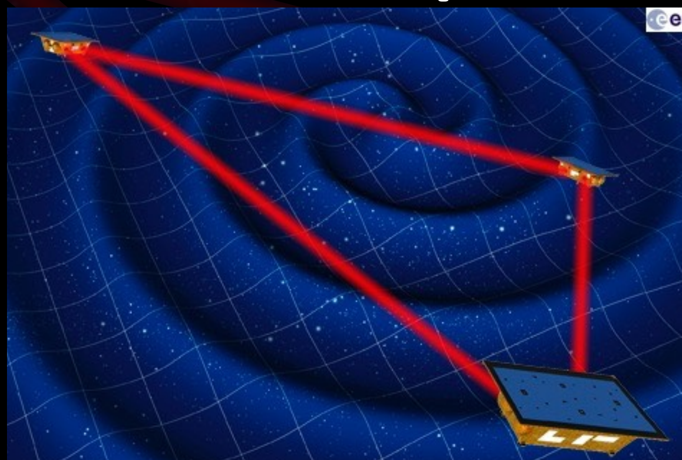
- Successful demonstration of the ability to shield from fluctuating non-gravitational influences

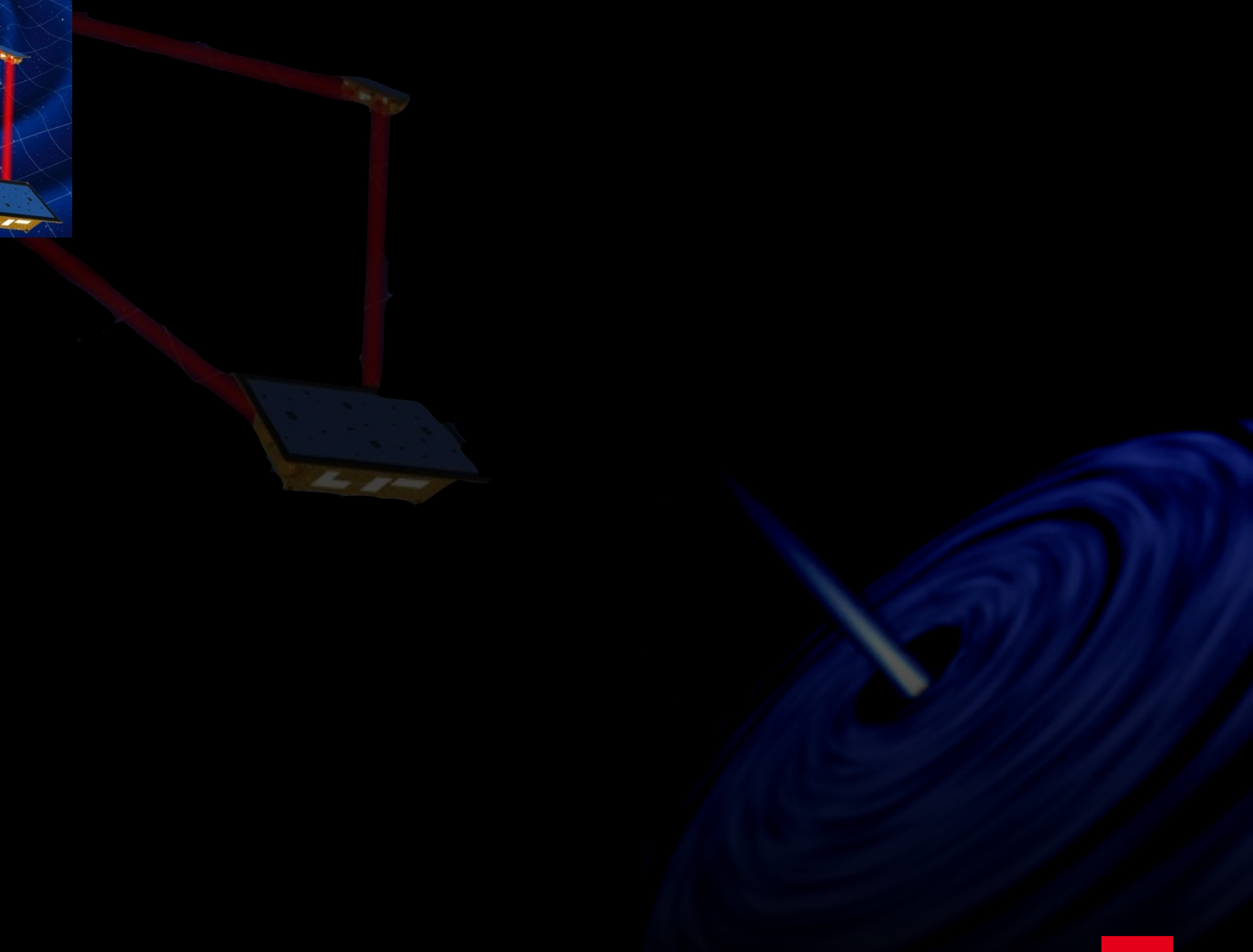


M. Armano et al. PRL 120, 061101 (2018)

LISA mission

- Several steps towards the required precision of measurement





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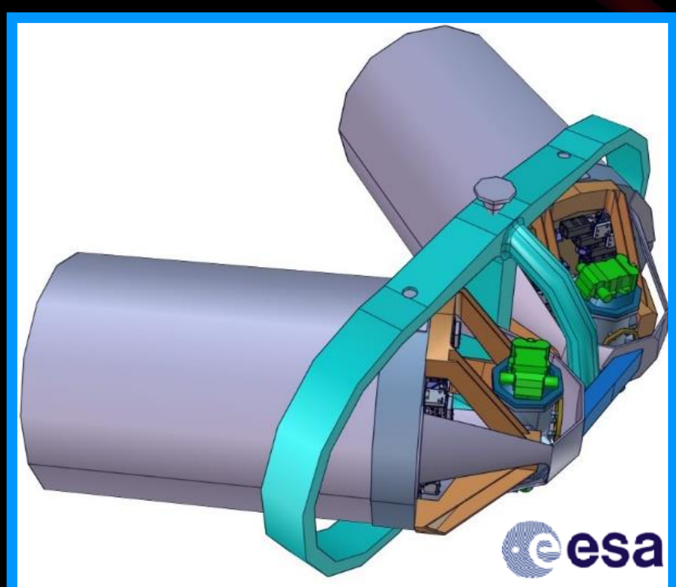

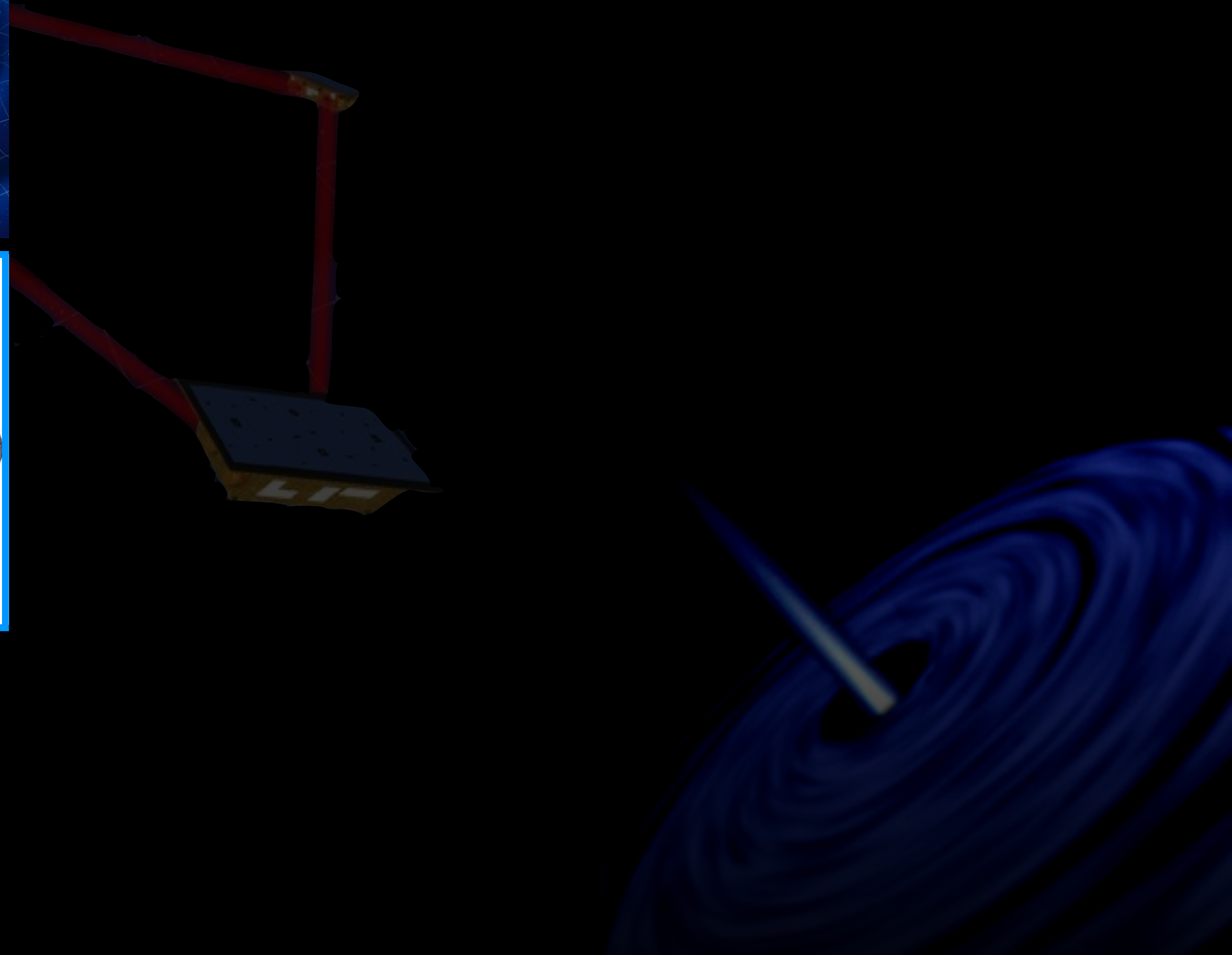

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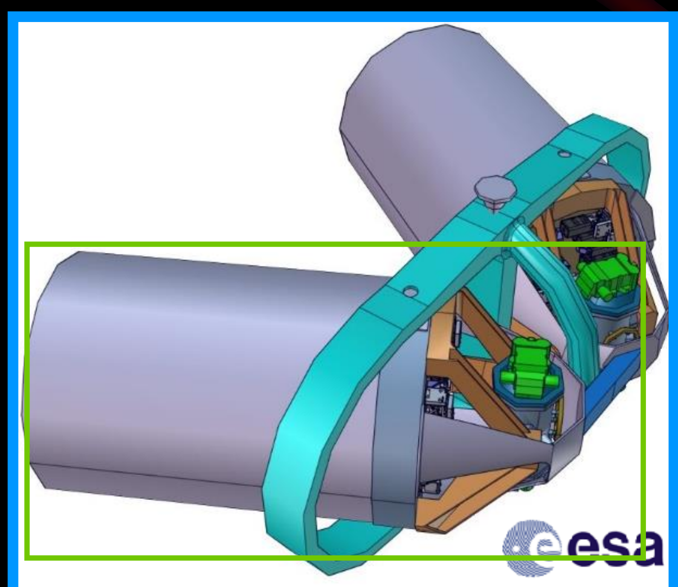

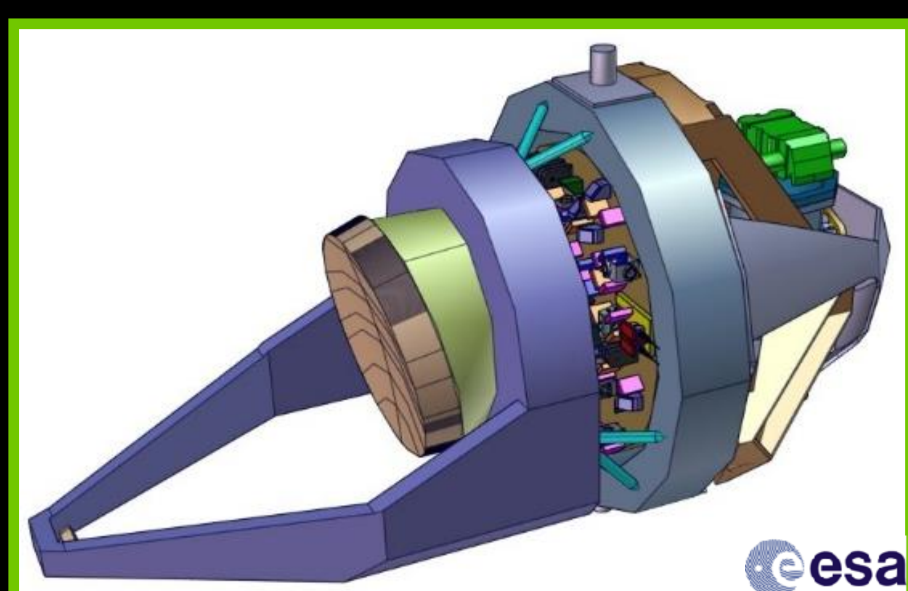

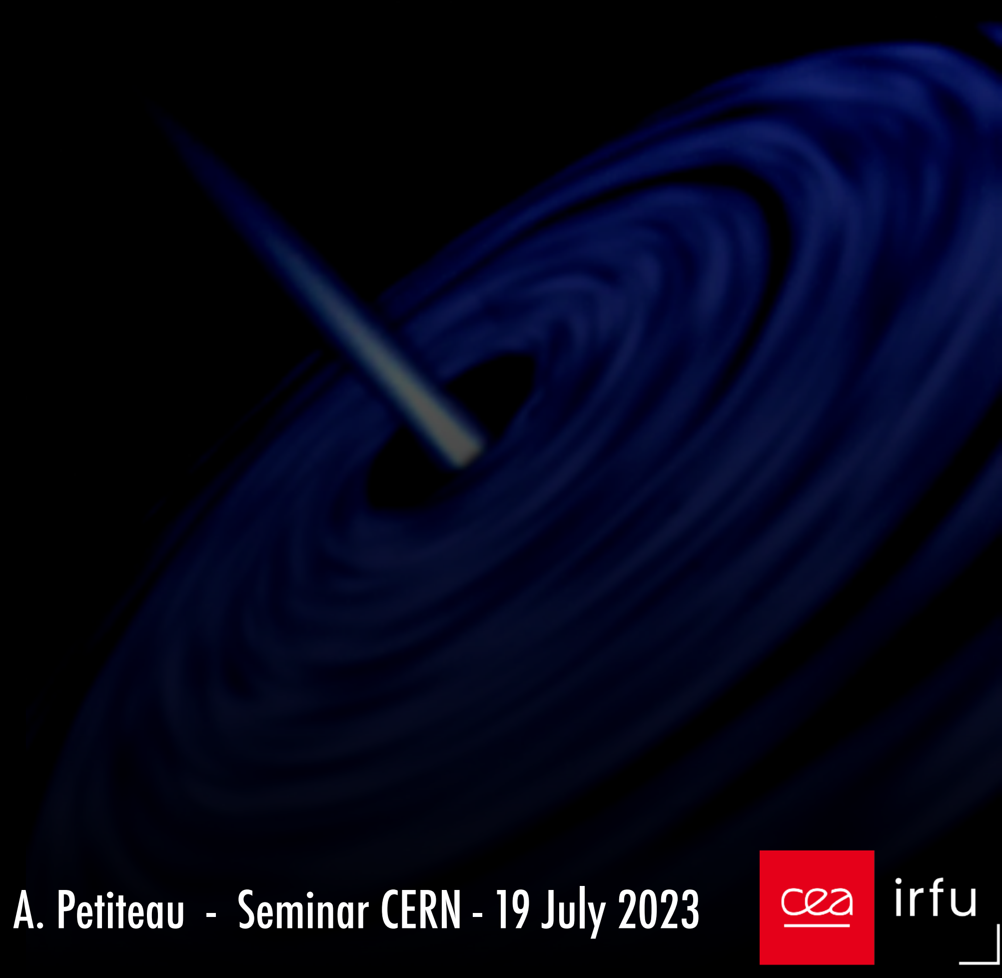

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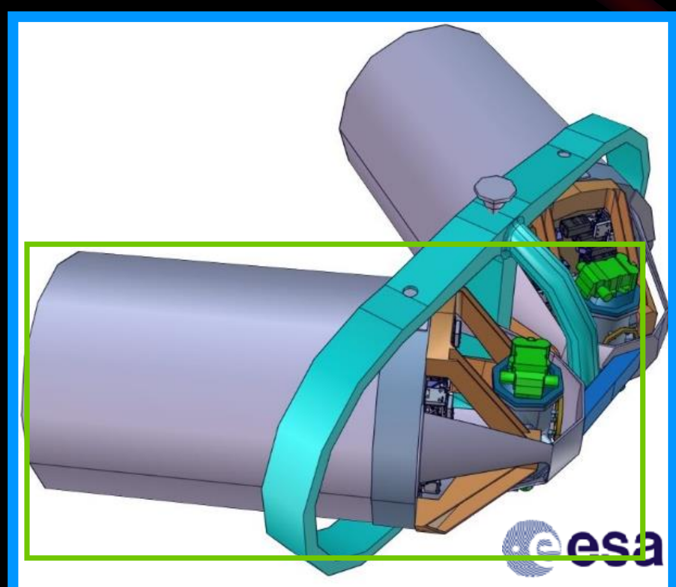

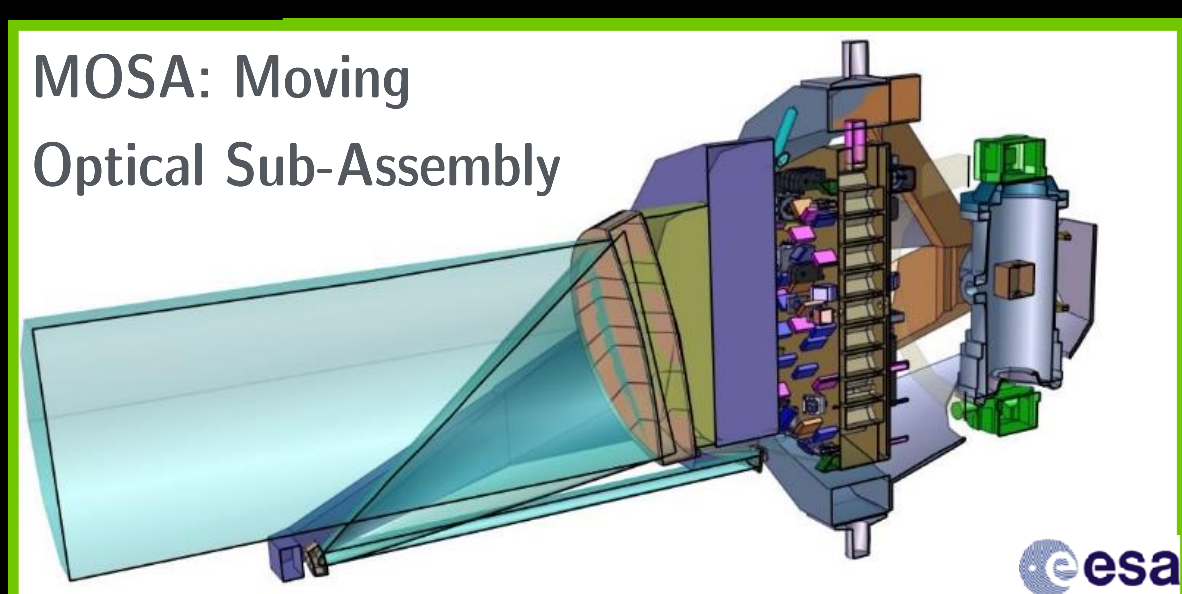

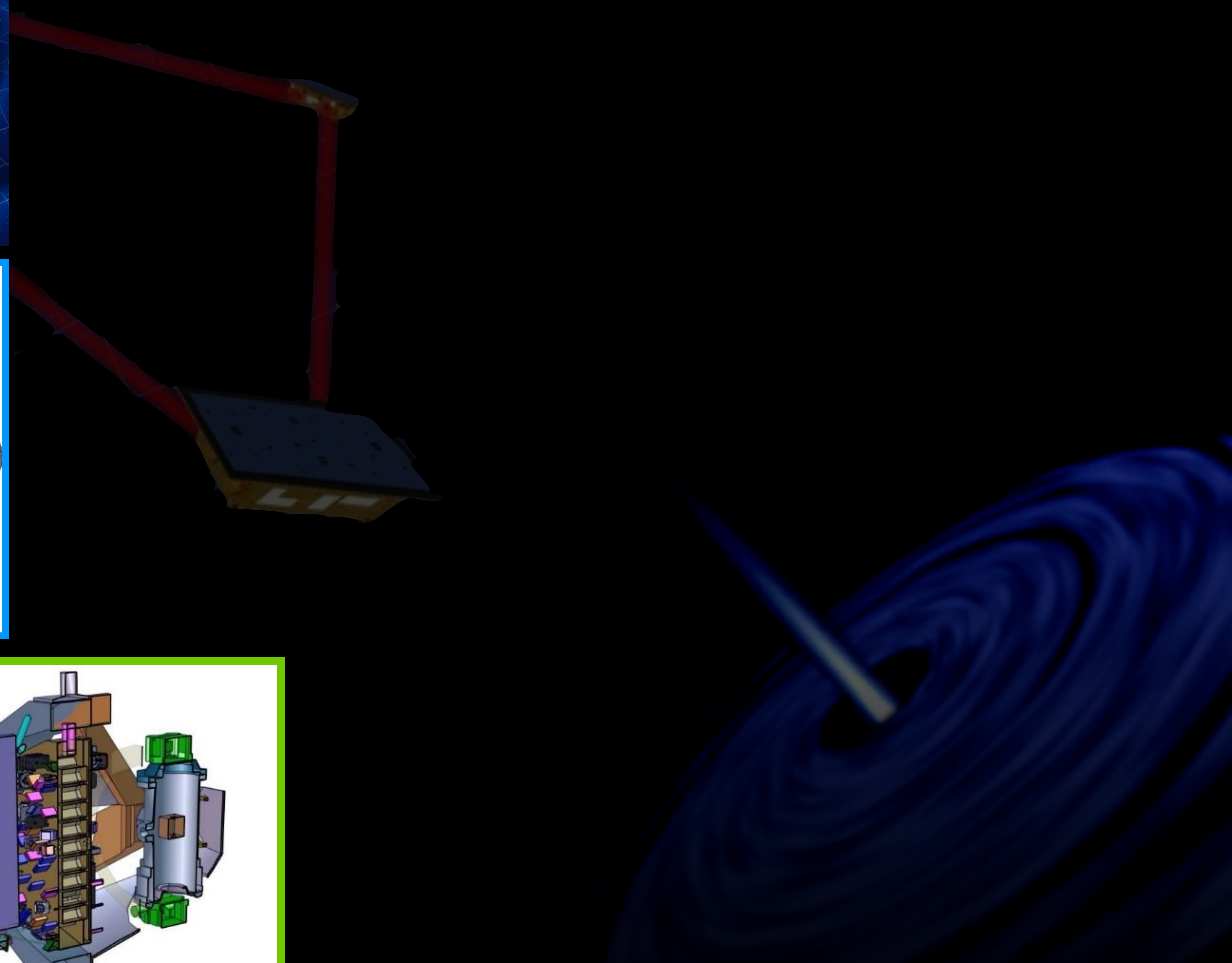

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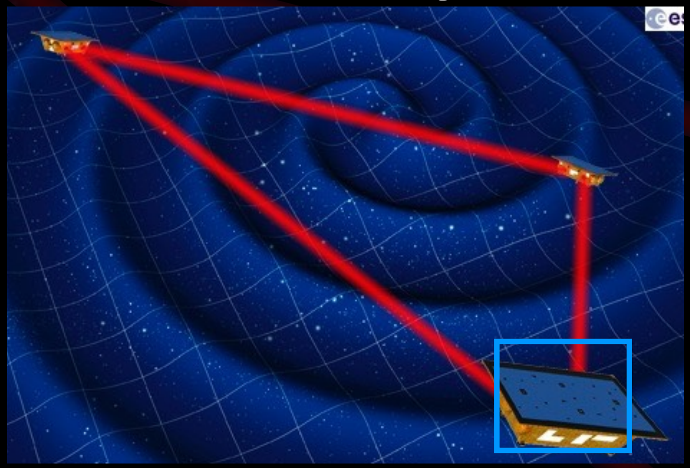
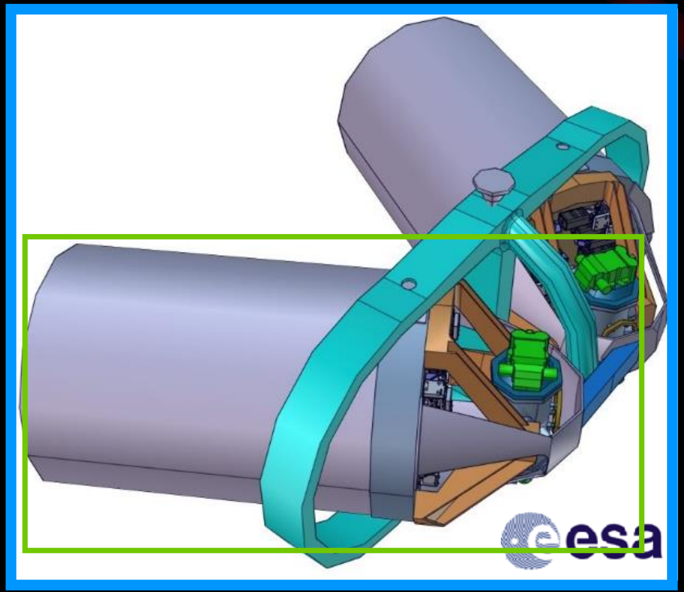
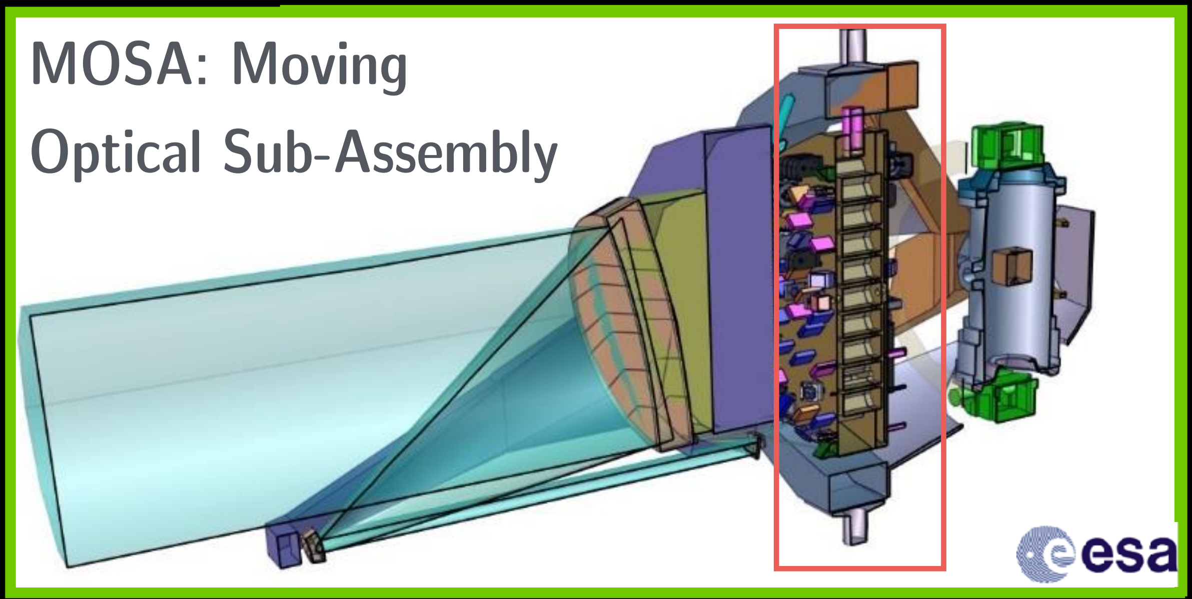
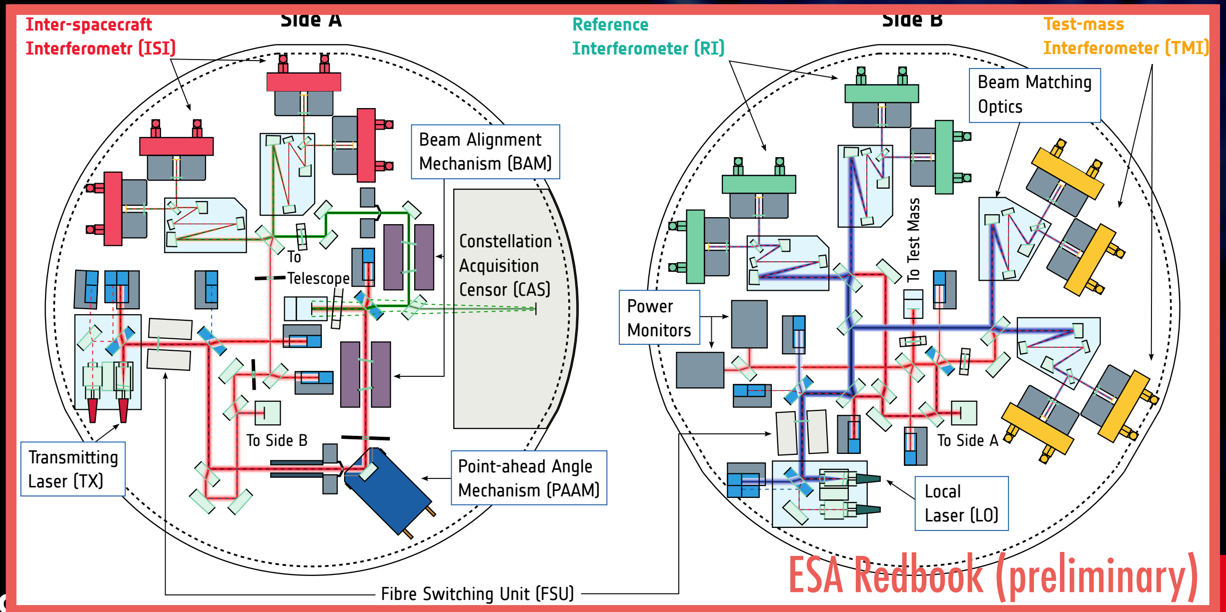




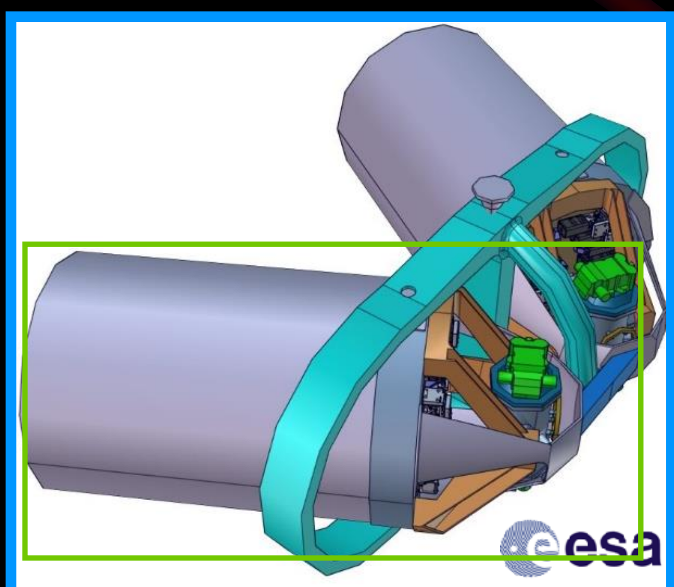


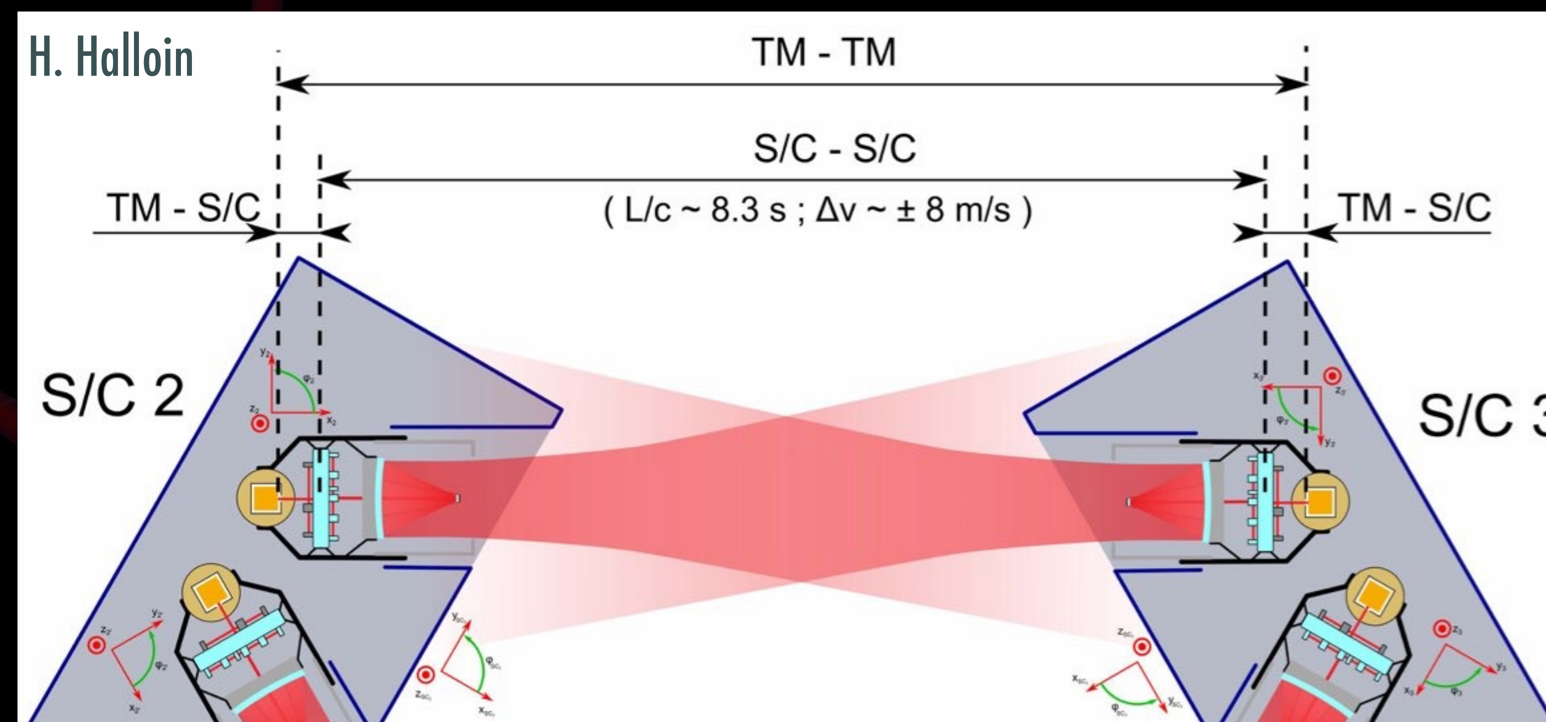


LISA mission

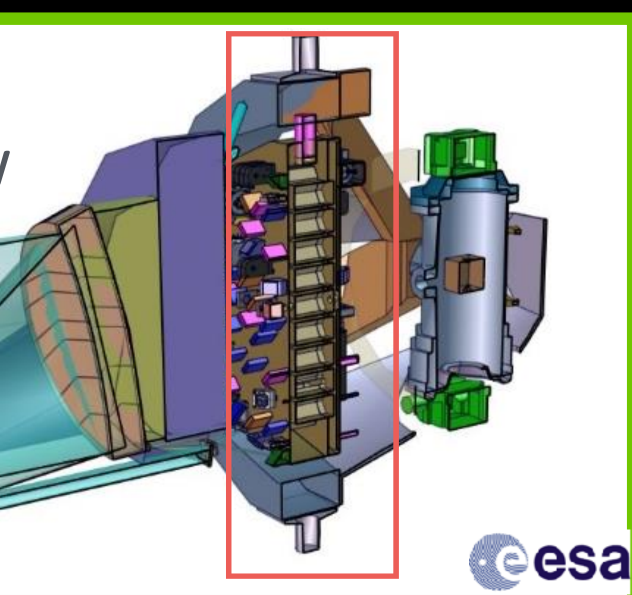
- Several steps towards the required precision of measurement

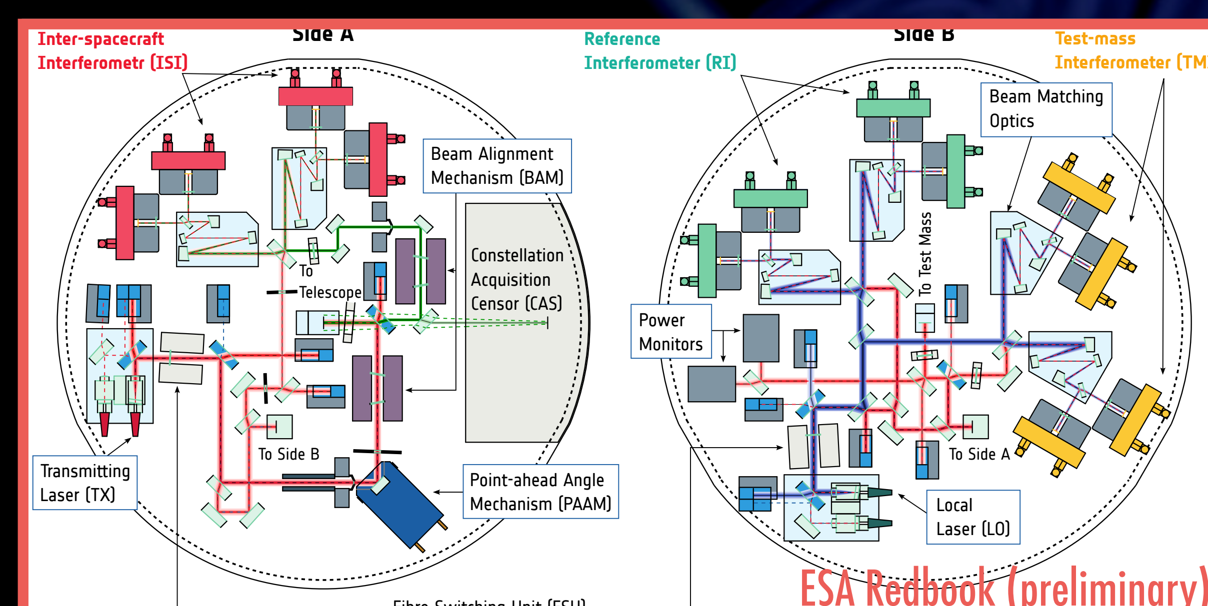
$$(TM2 \rightarrow SC2) + (SC2 \rightarrow SC3) + (SC3 \rightarrow TM3)$$





MOSA: Moving Optical Sub-Assembly

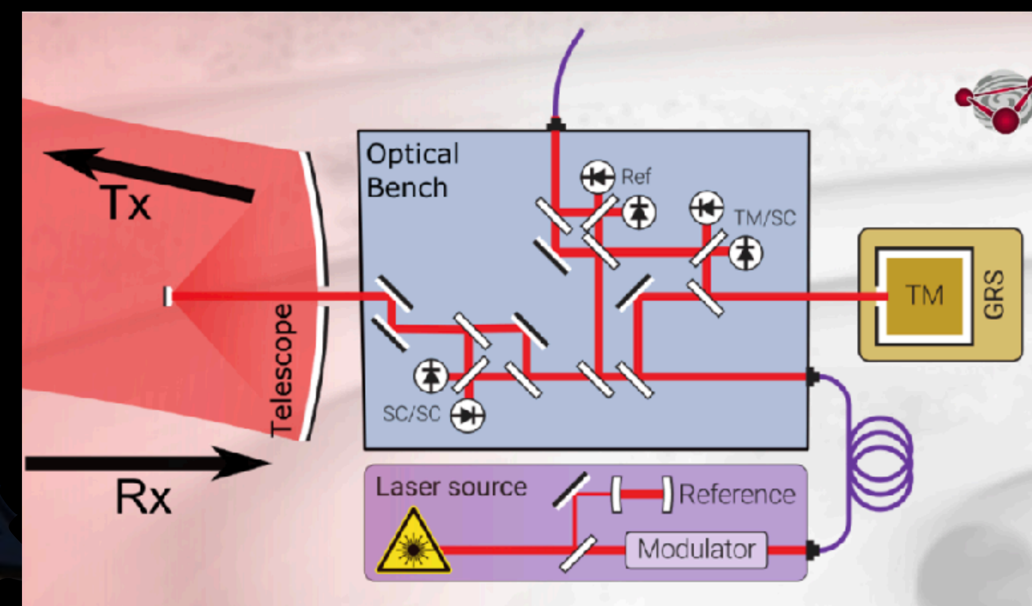


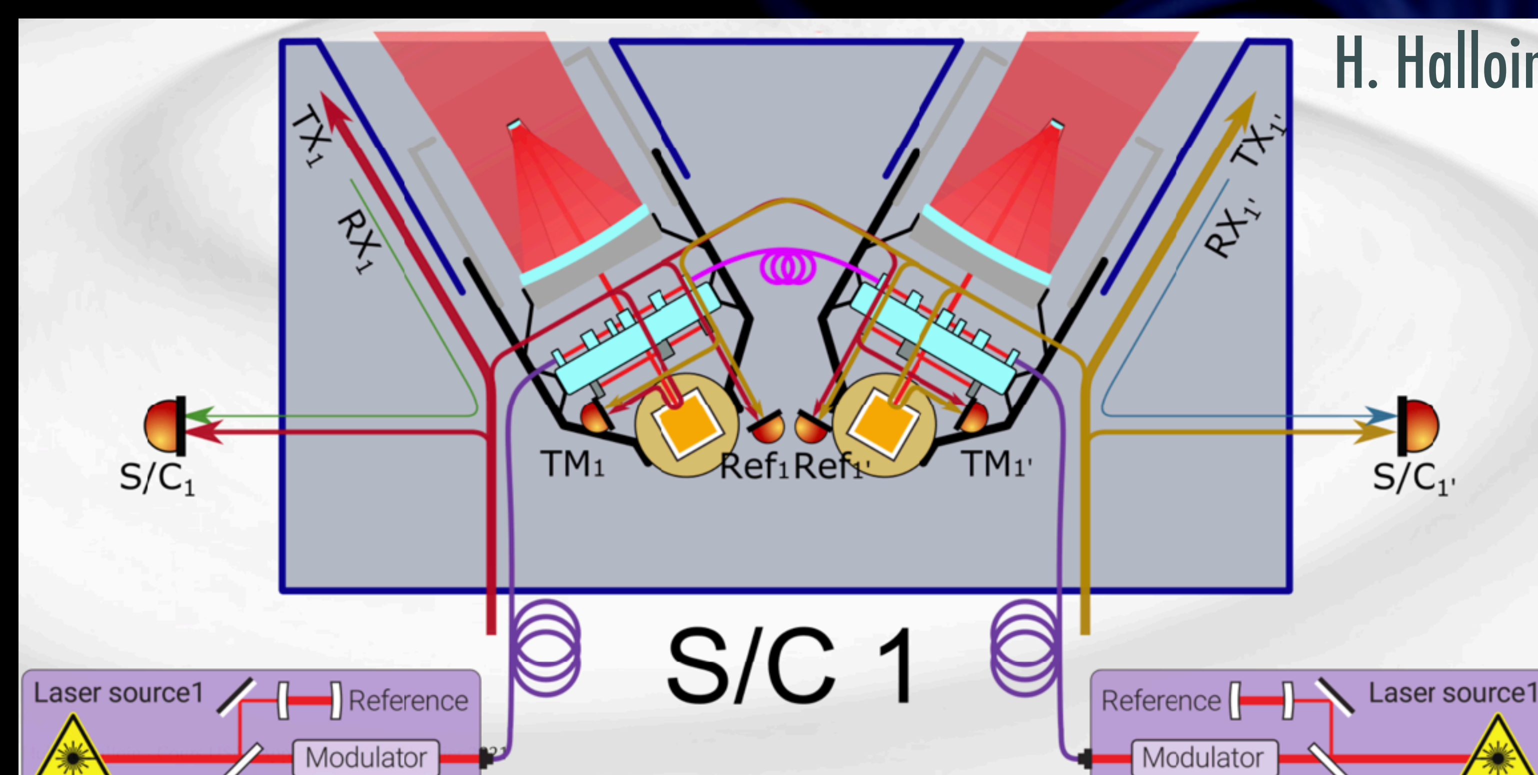


ESA Redbook (preliminary)

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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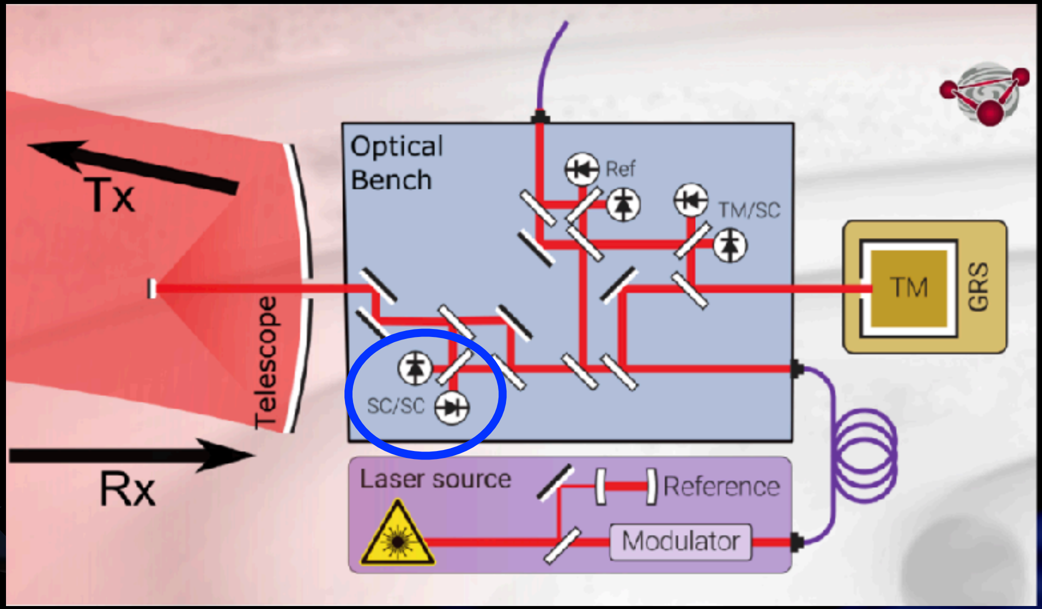

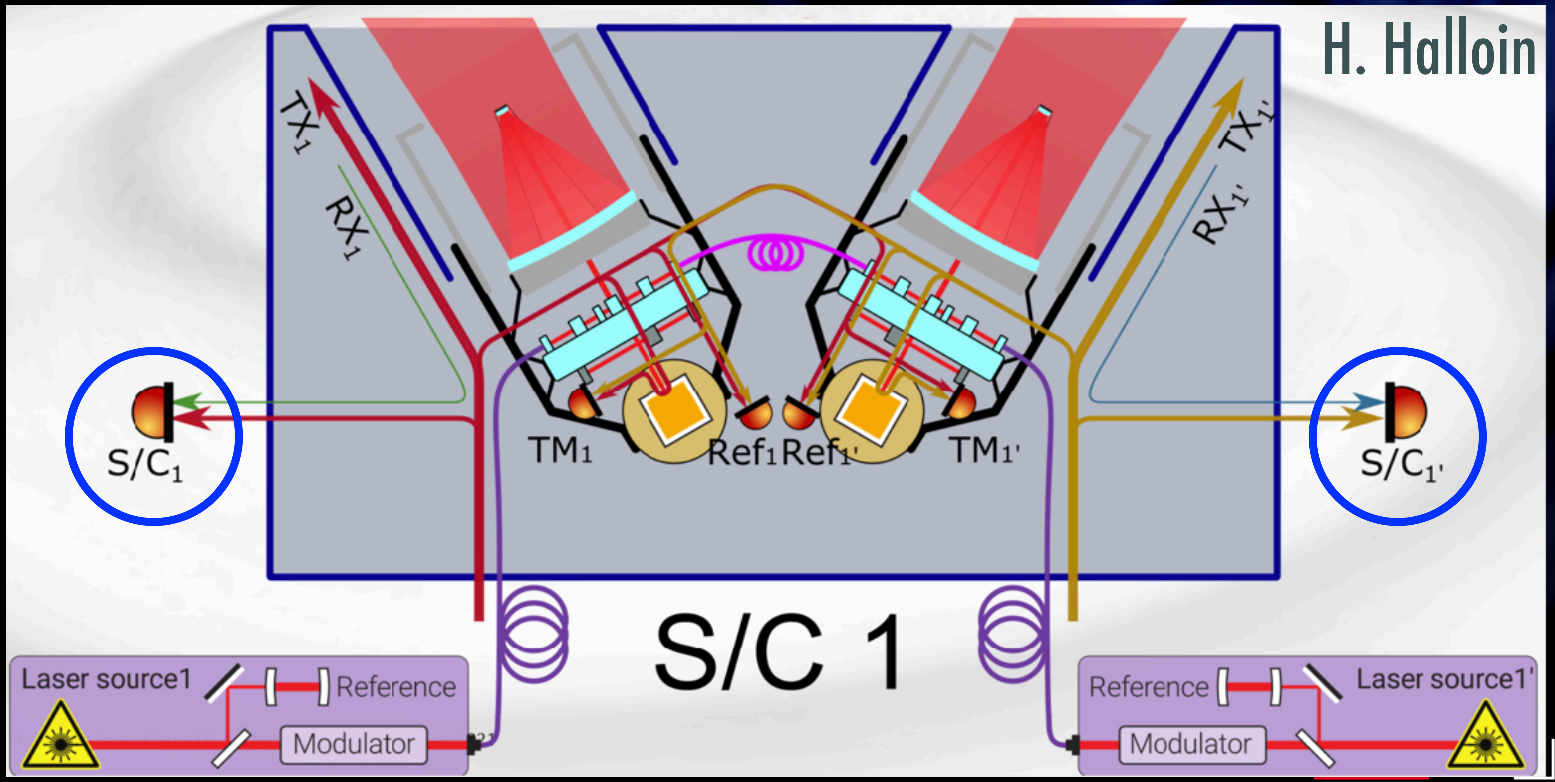

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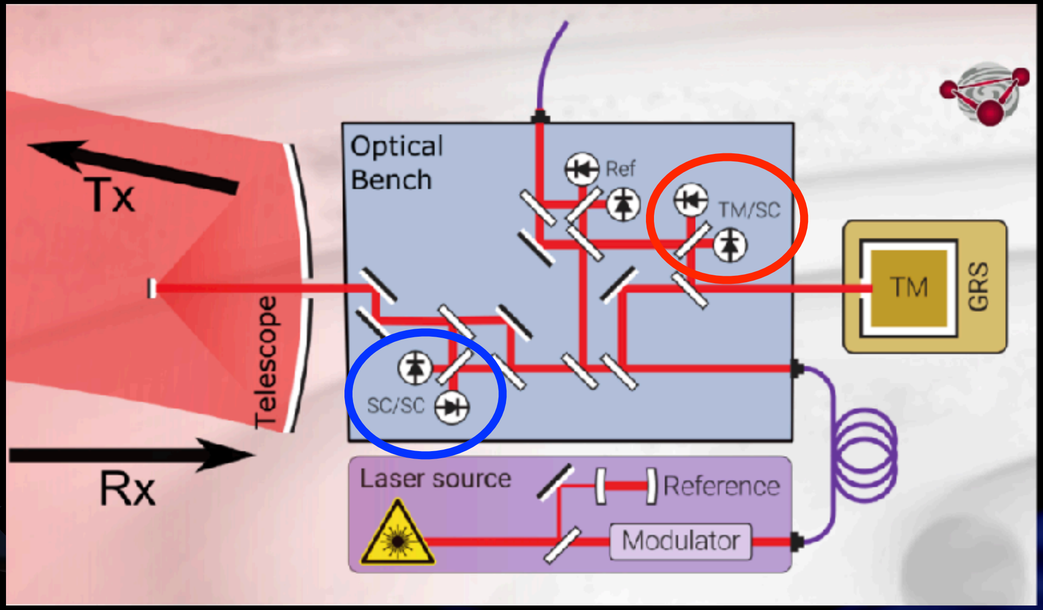

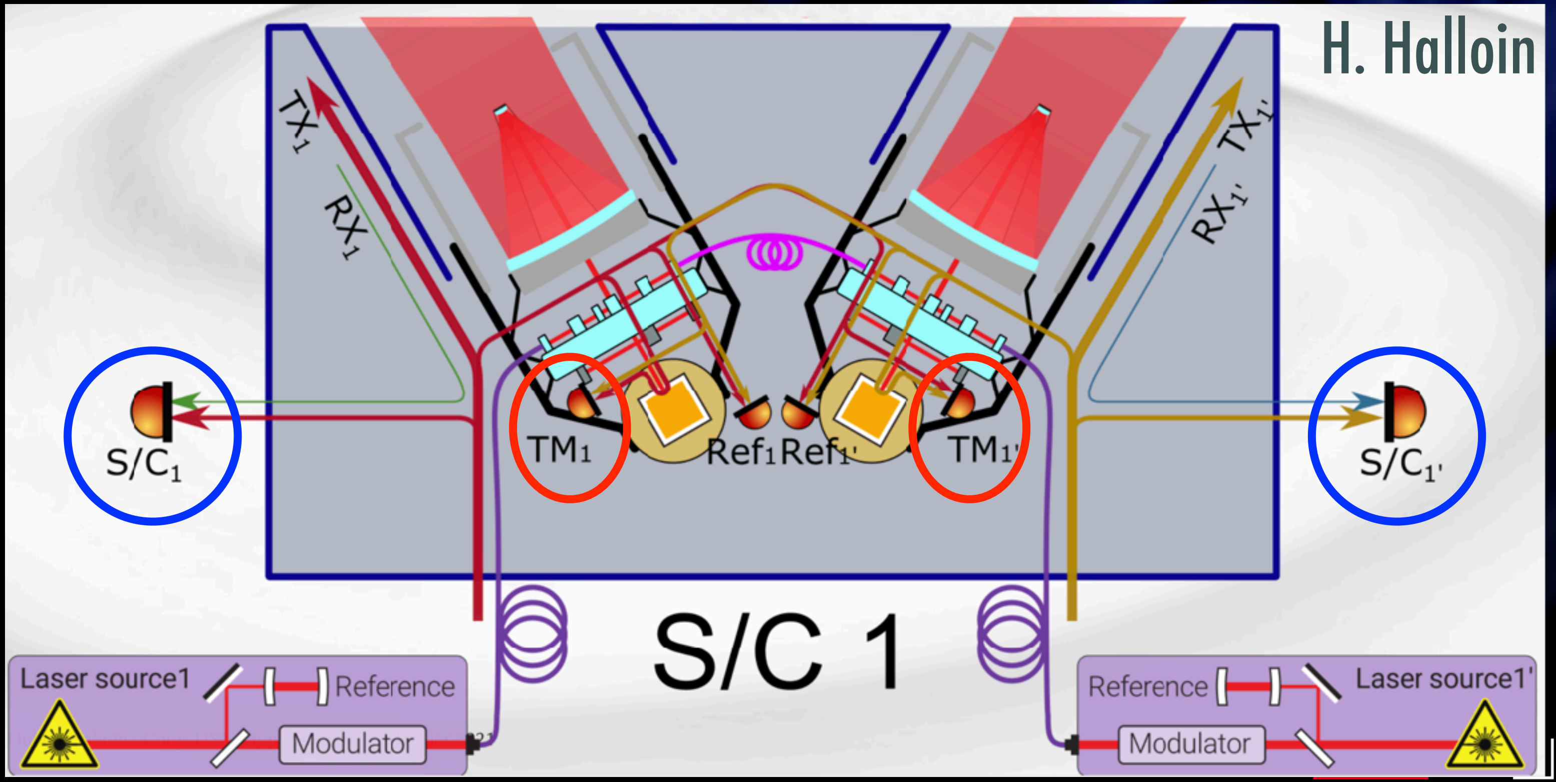

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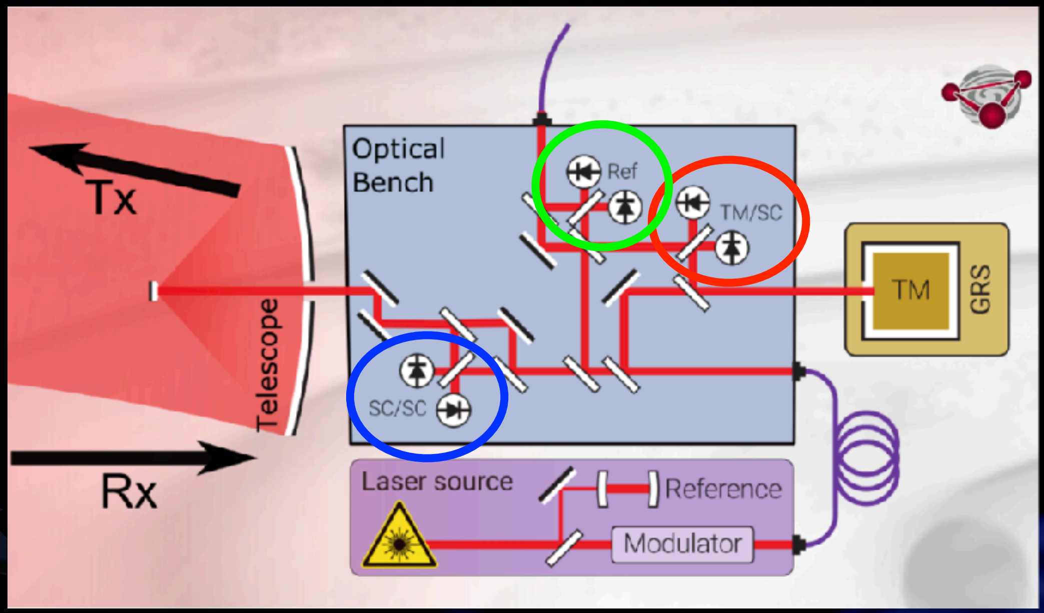
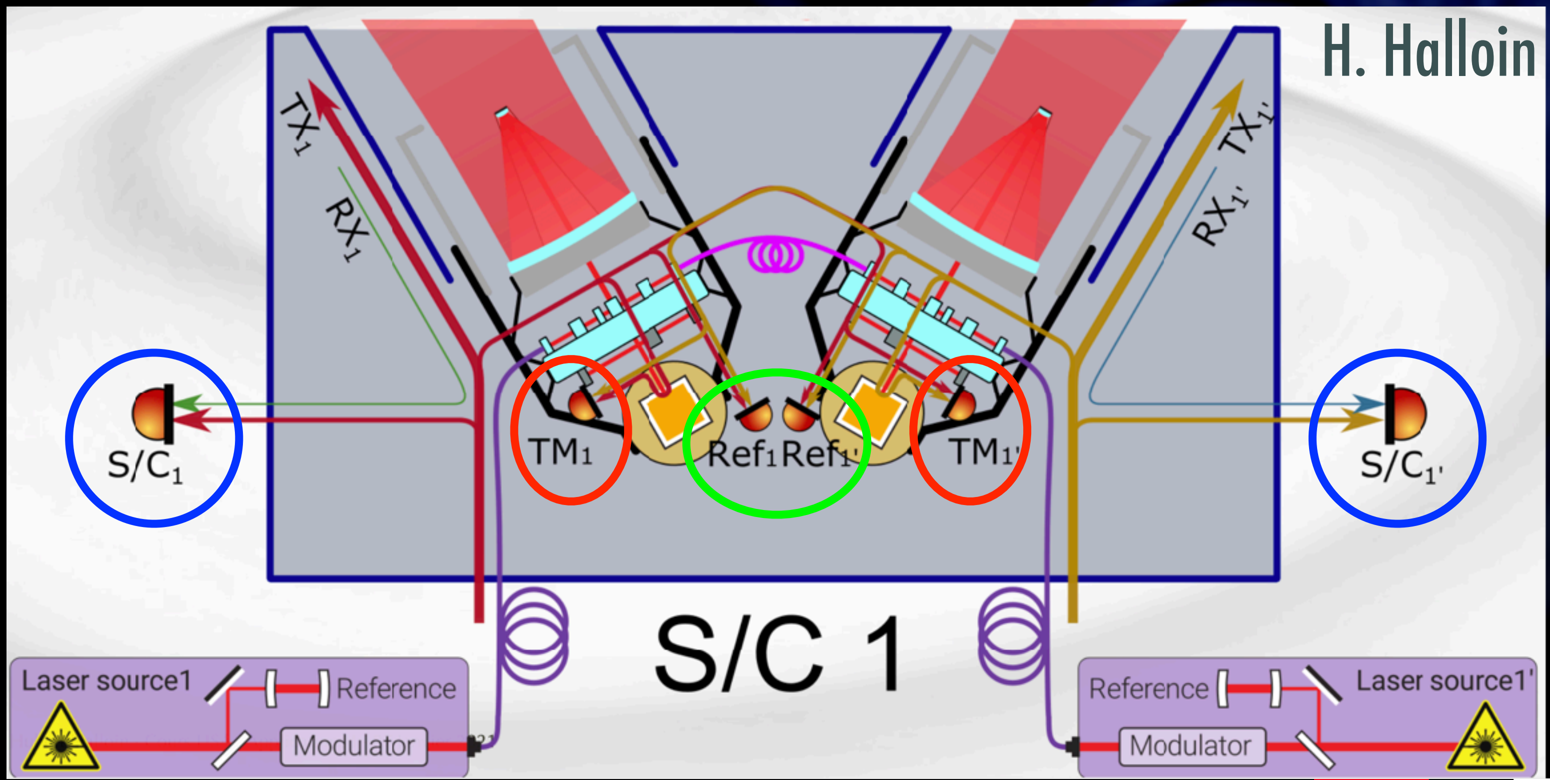
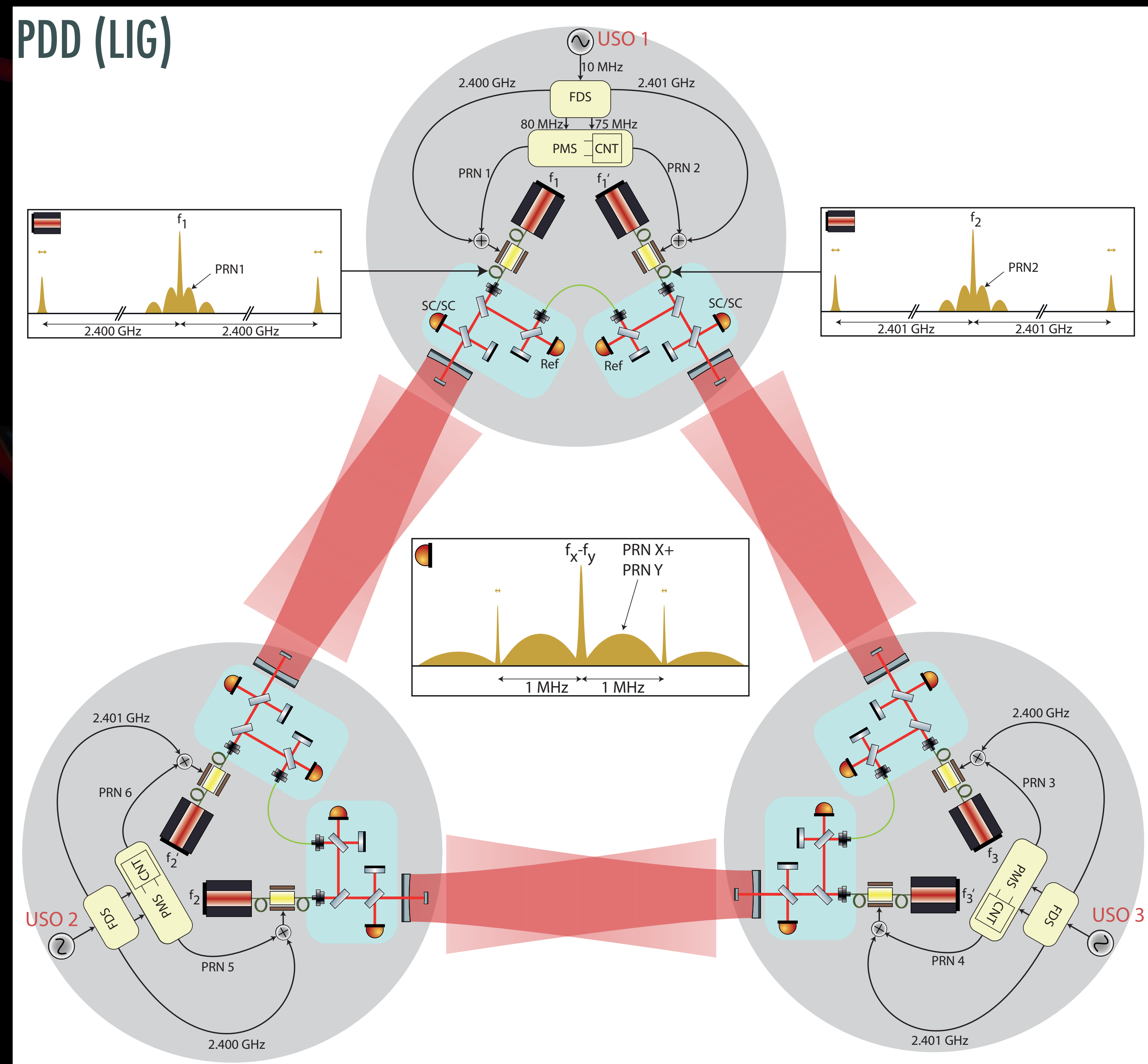


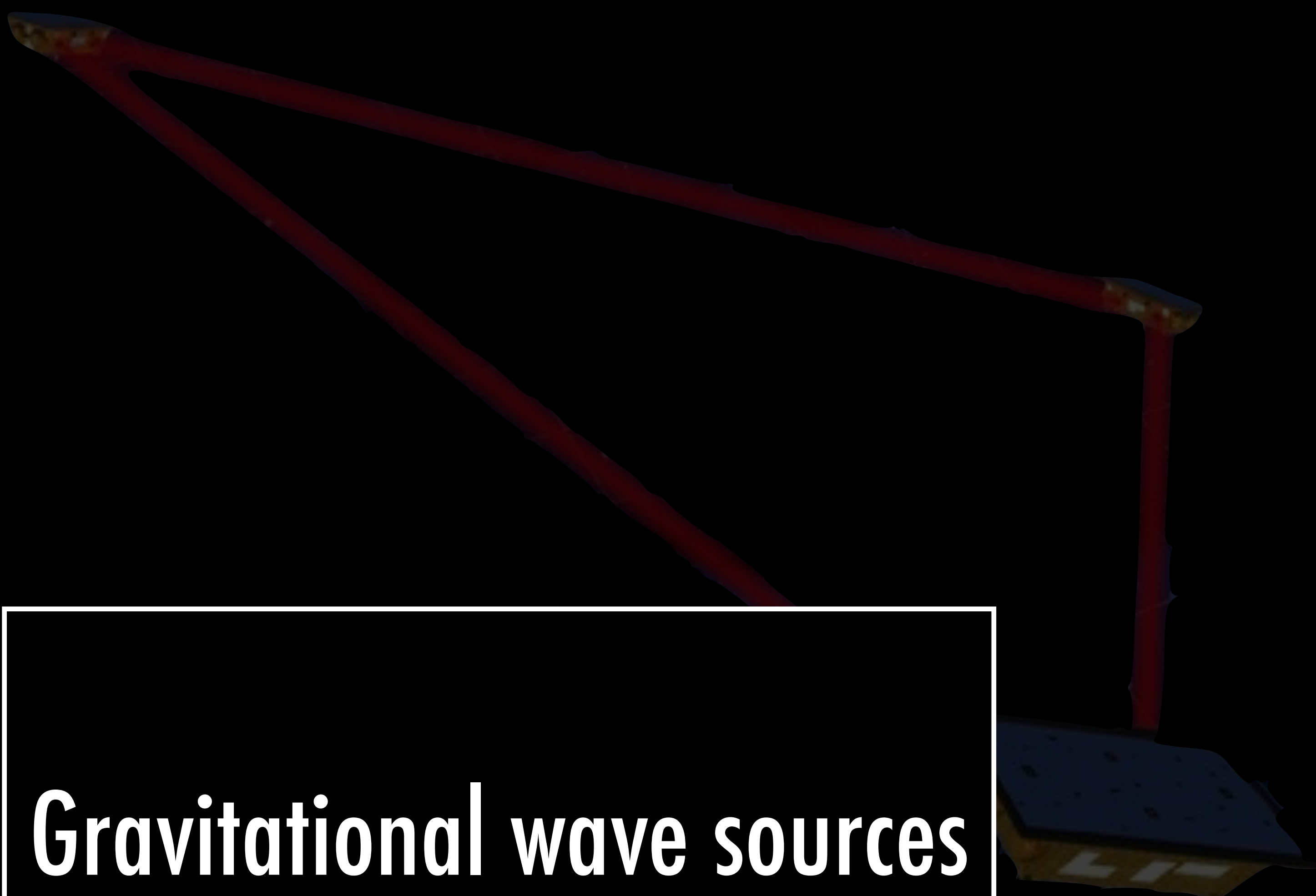


Interferometric measurements

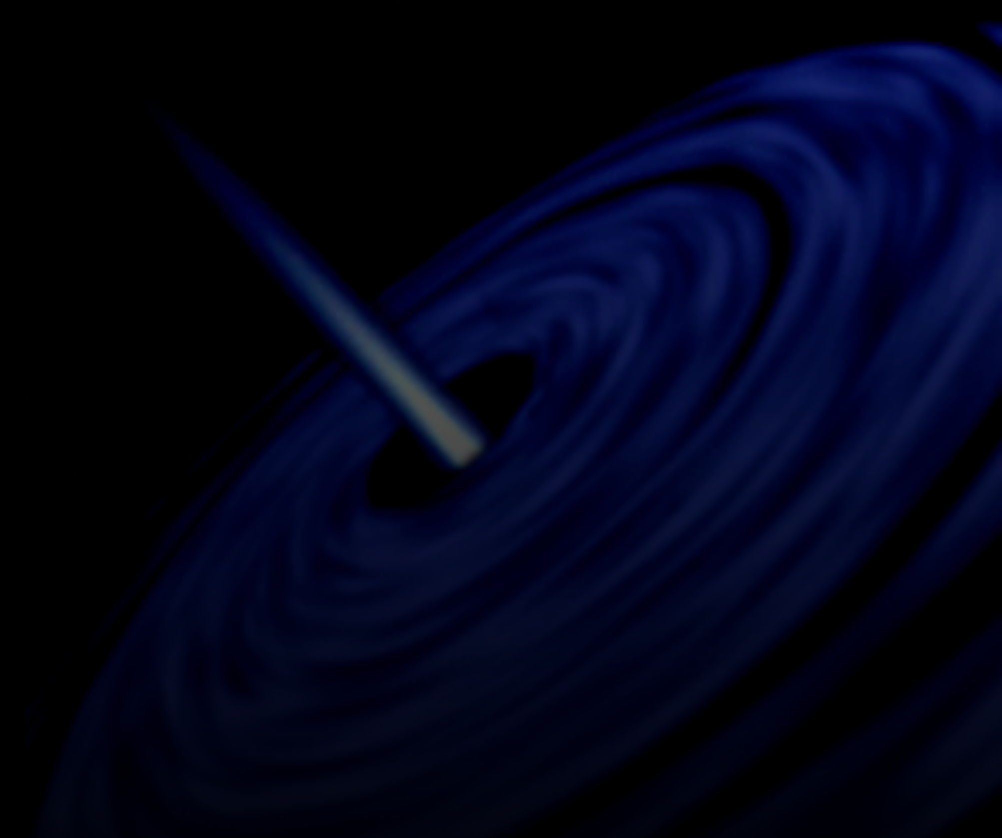
- Measurements via exchange of beams:
  - Heterodyne interferometry with carrier for inter-spacecraft measurement => GWs
  - Sideband for transferring amplified clock jitter => correction of additional clock jitter
  - Pseudo-Random Noise => ranging (measure arm length)
  - Laser locking



LISA data



Gravitational wave sources emitting between 0.02mHz and 1 Hz



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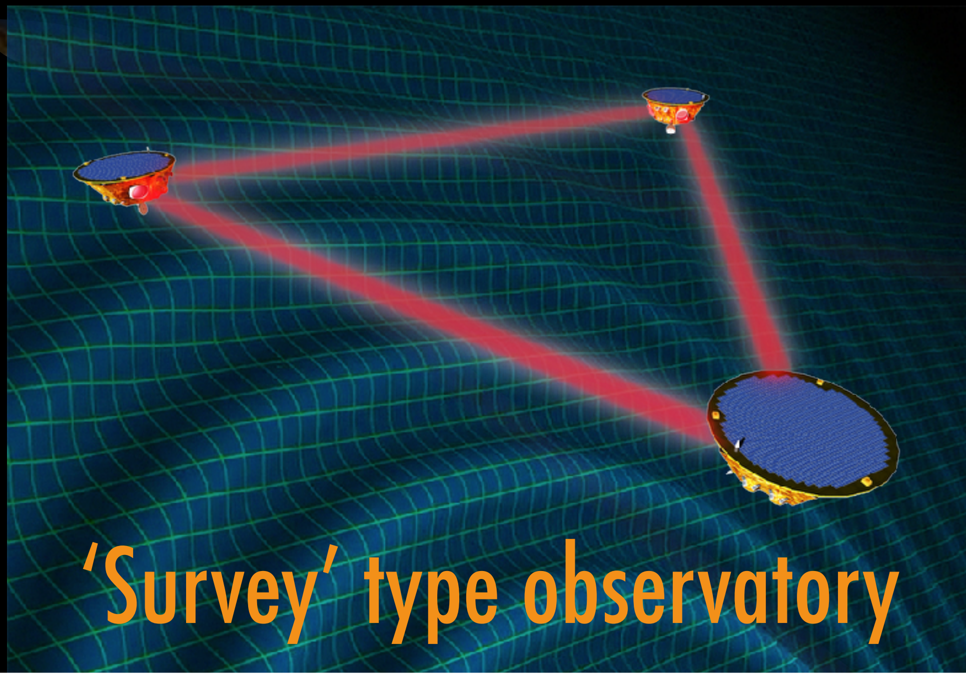

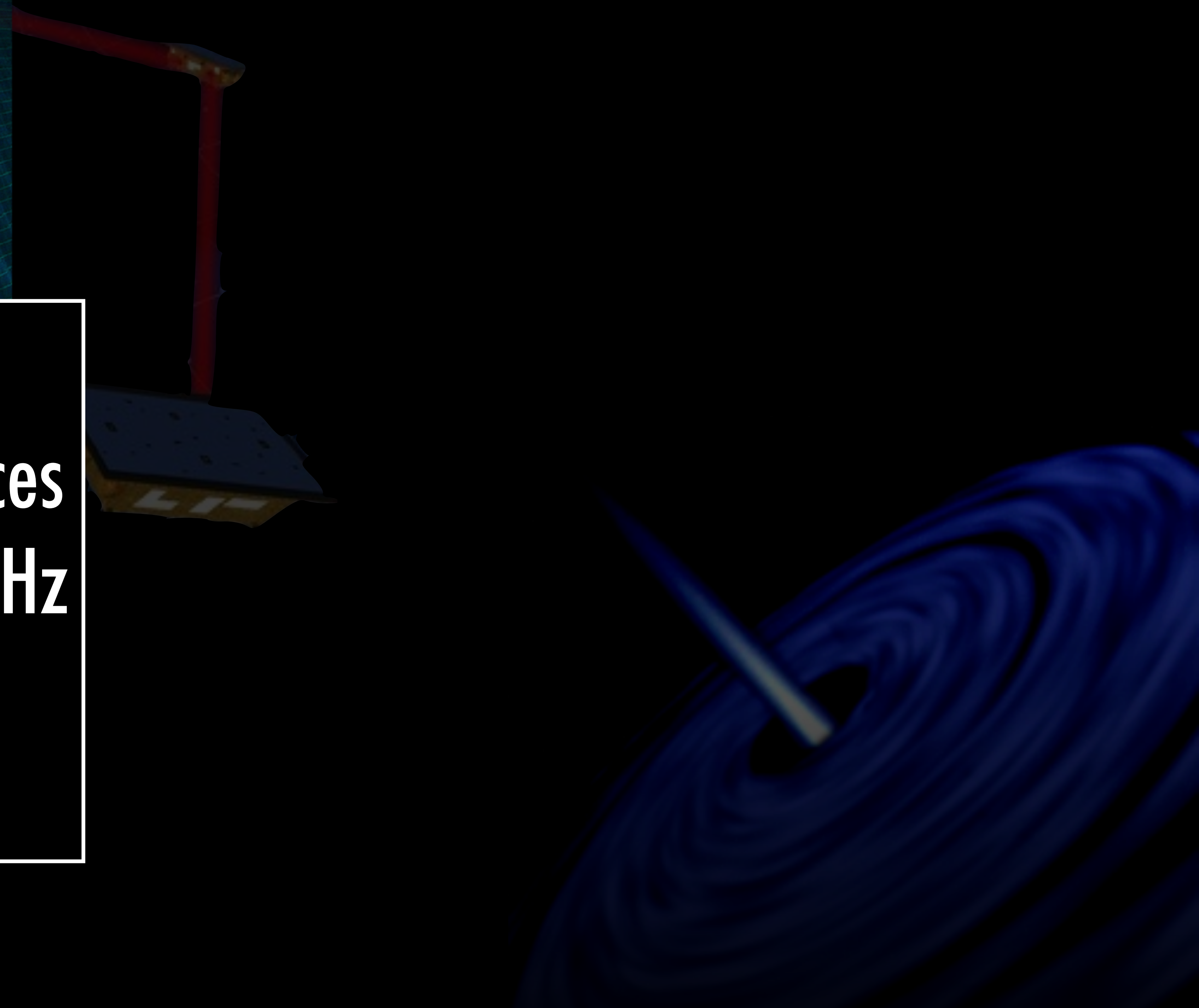

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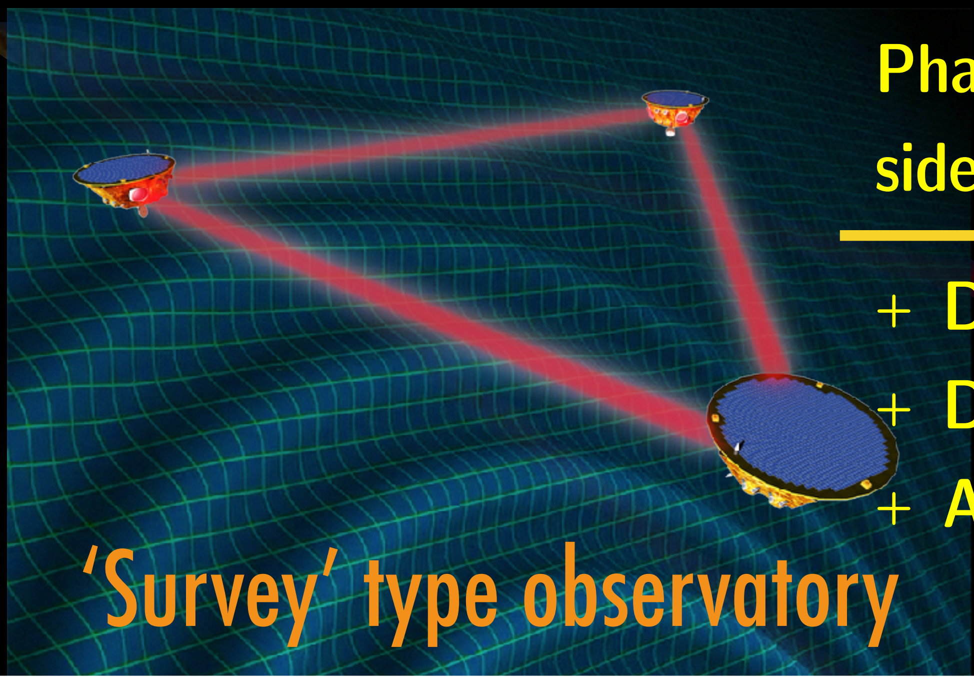
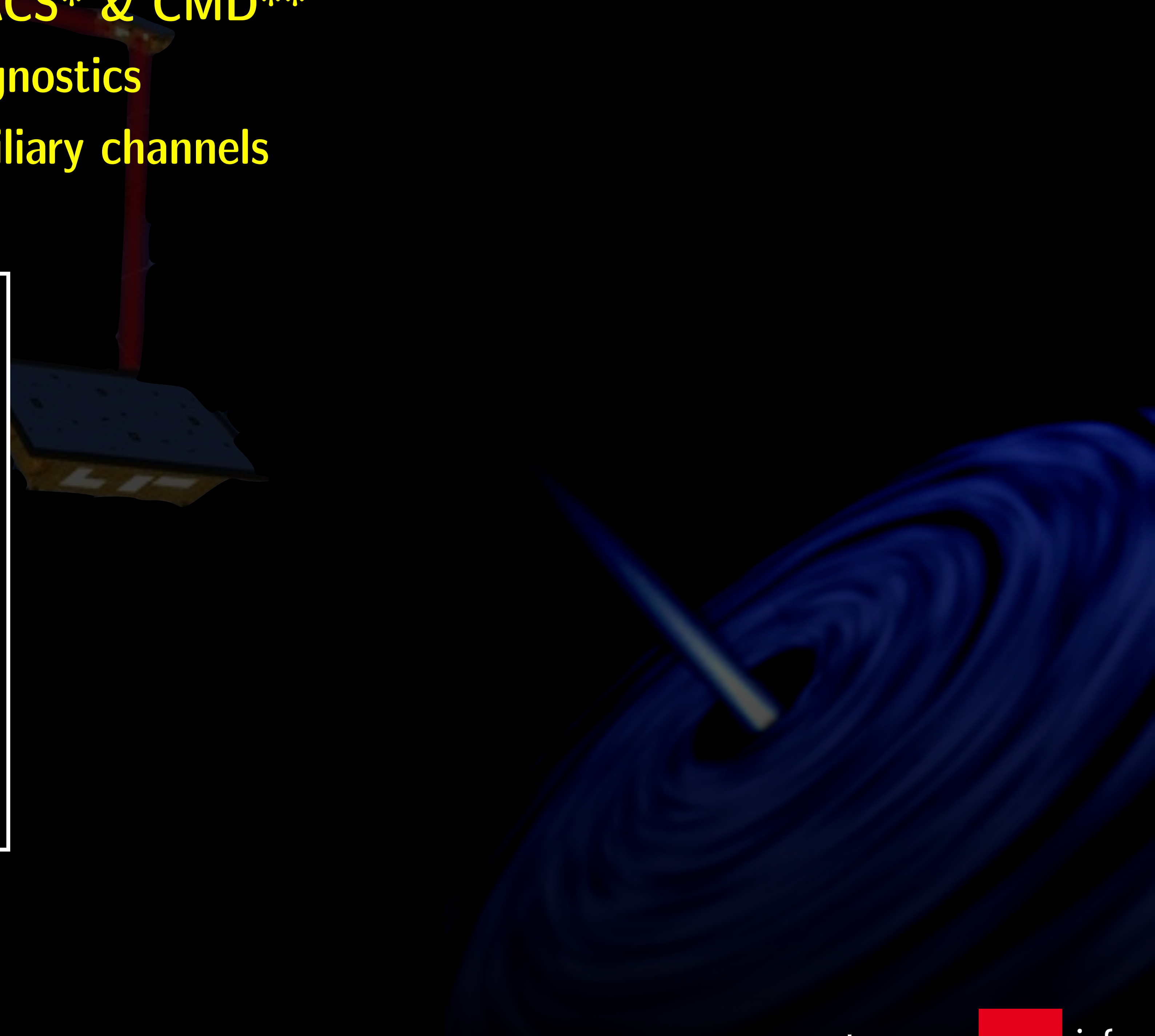


Phasemeters (carrier, sidebands, distance)

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

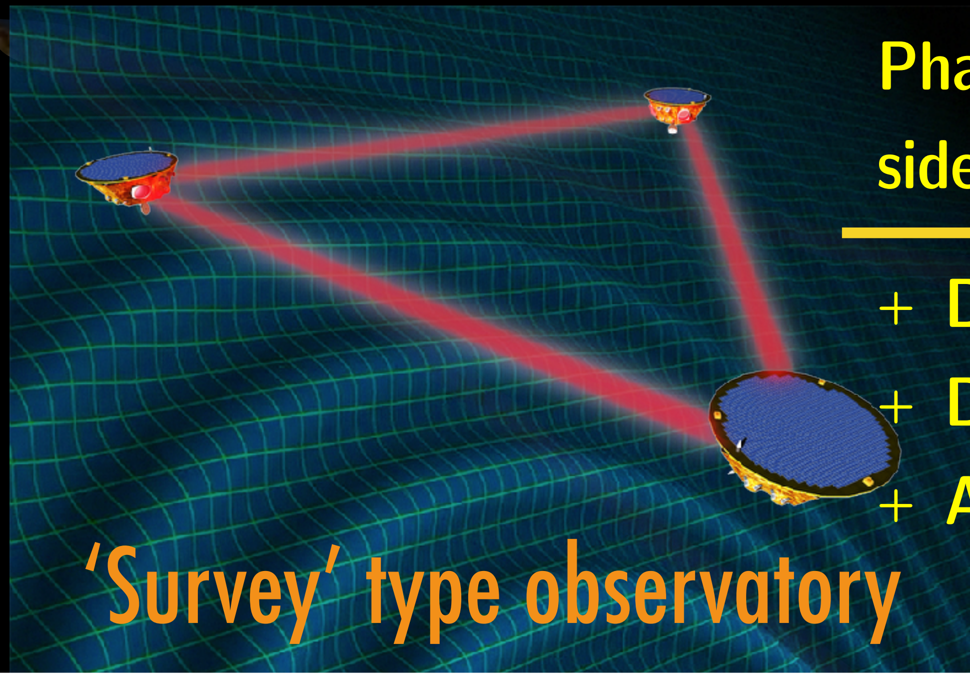


Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

LISA data



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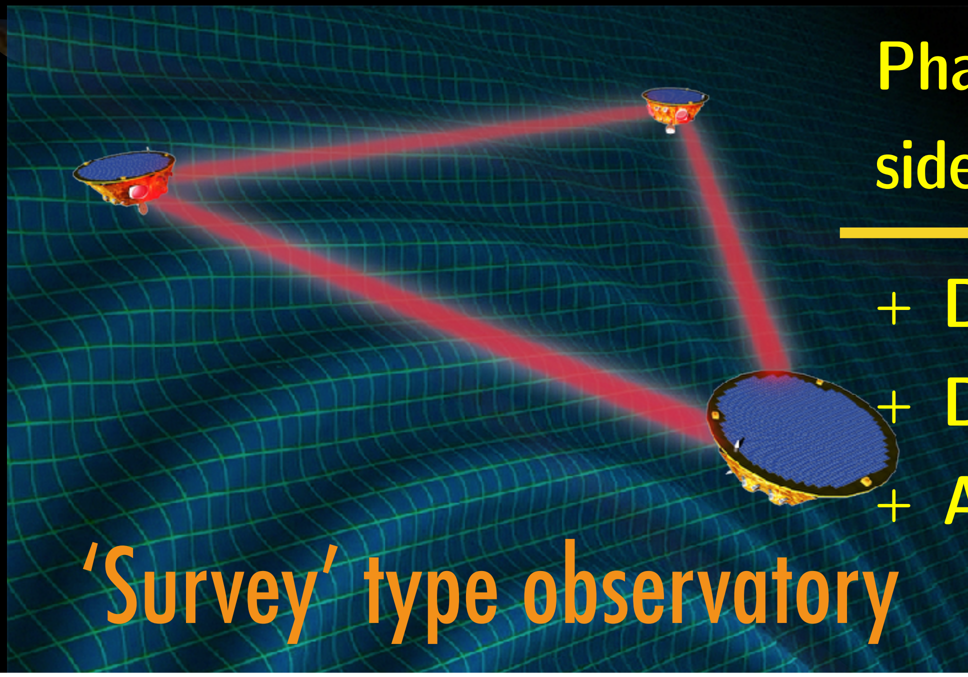

'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

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

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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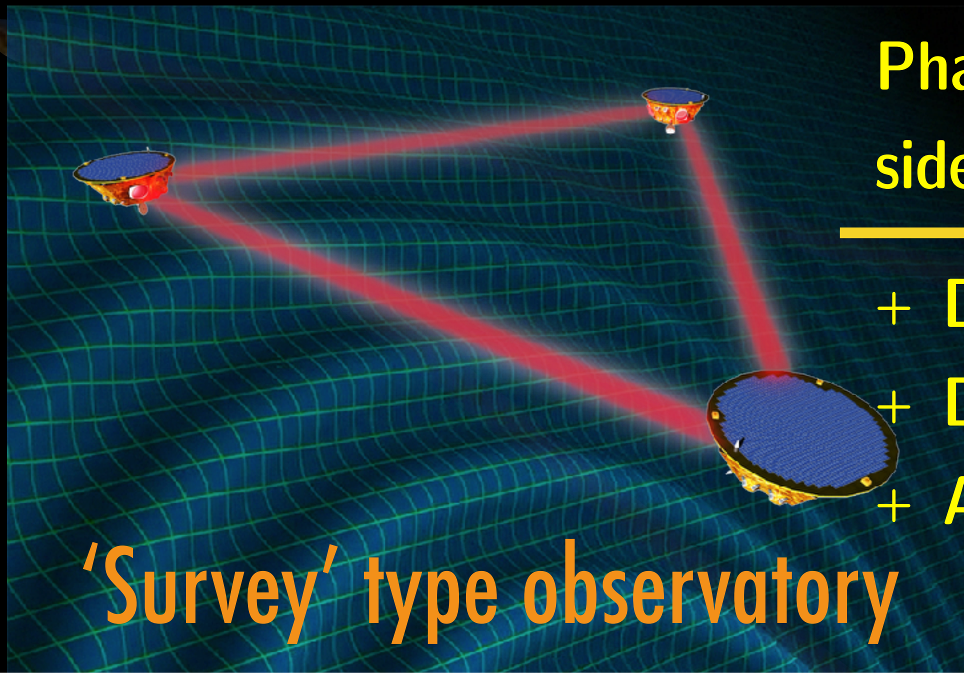

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Data Analysis of GWs

Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

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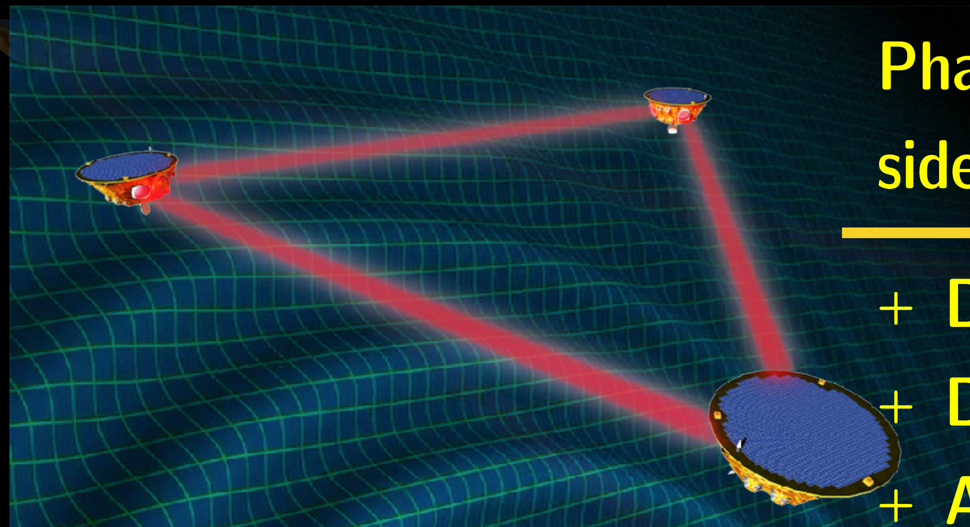

'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

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L0

L0.5

Calibrations corrections
+ Resynchronisation (clock)
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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

LISA data

Mission Operation Center (ESA)

L0

L0.5

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

Science Operation Center (ESA)

L1

3 TDI channels with 2 "~independents"

DDPC: Distributed Data Processing Center (ESA Member States)

NASA Ground Segment

L2

Data Analysis of GWs

L3

Catalogs of GWs sources with their waveform

LISA data

- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 82% duty cycle
  - Dominated by laser noise
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)

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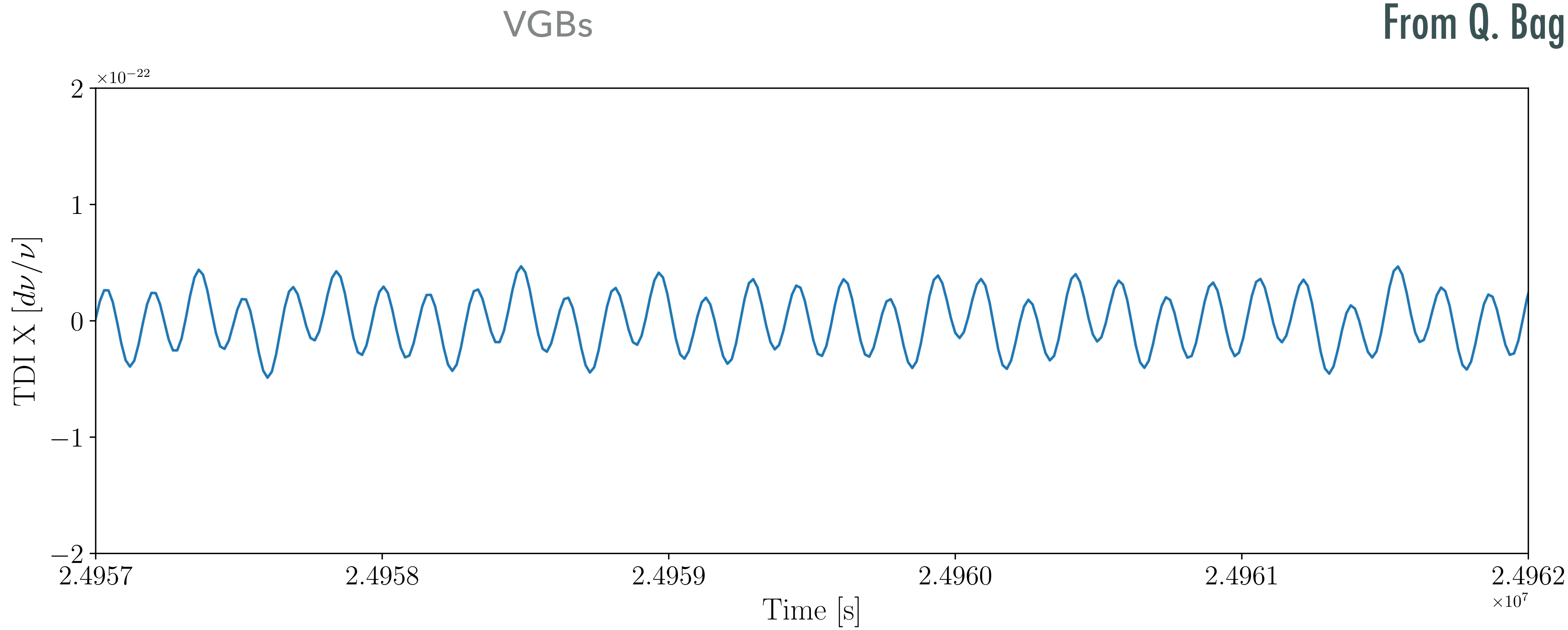

From Q. Baghi

LISA data

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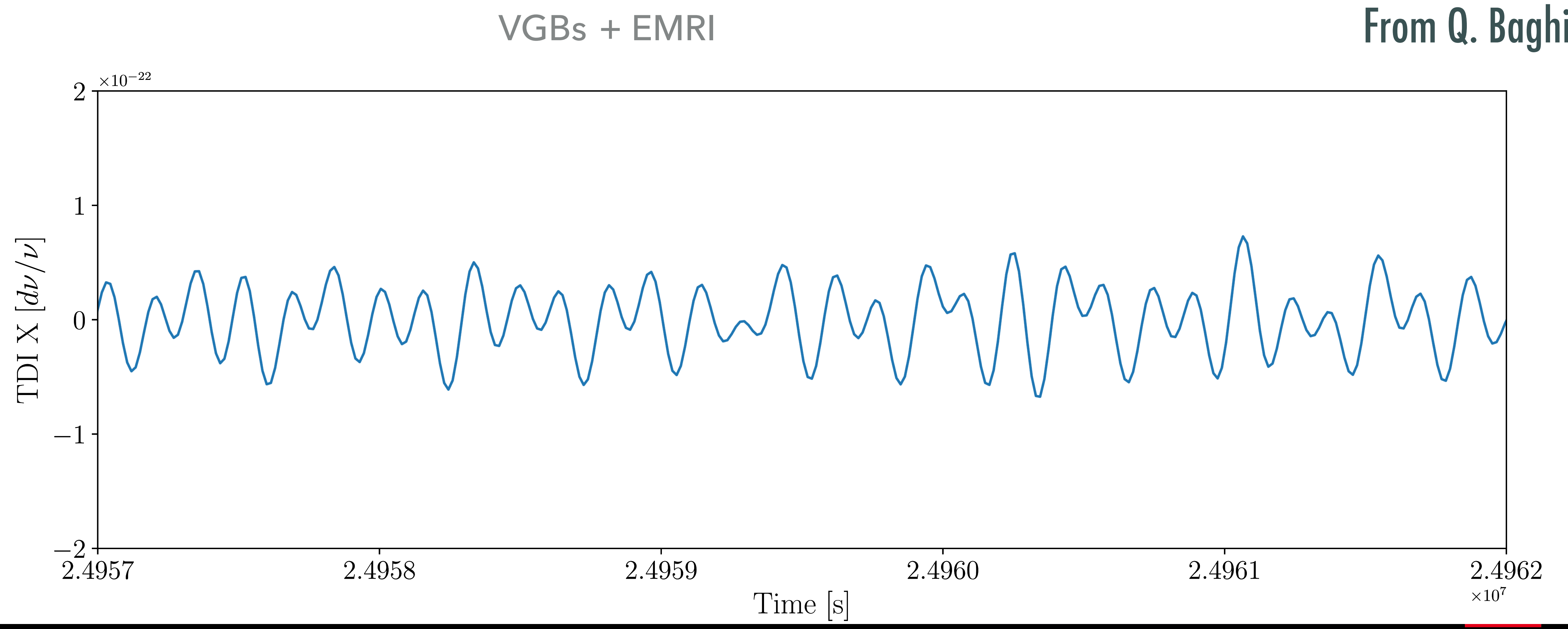

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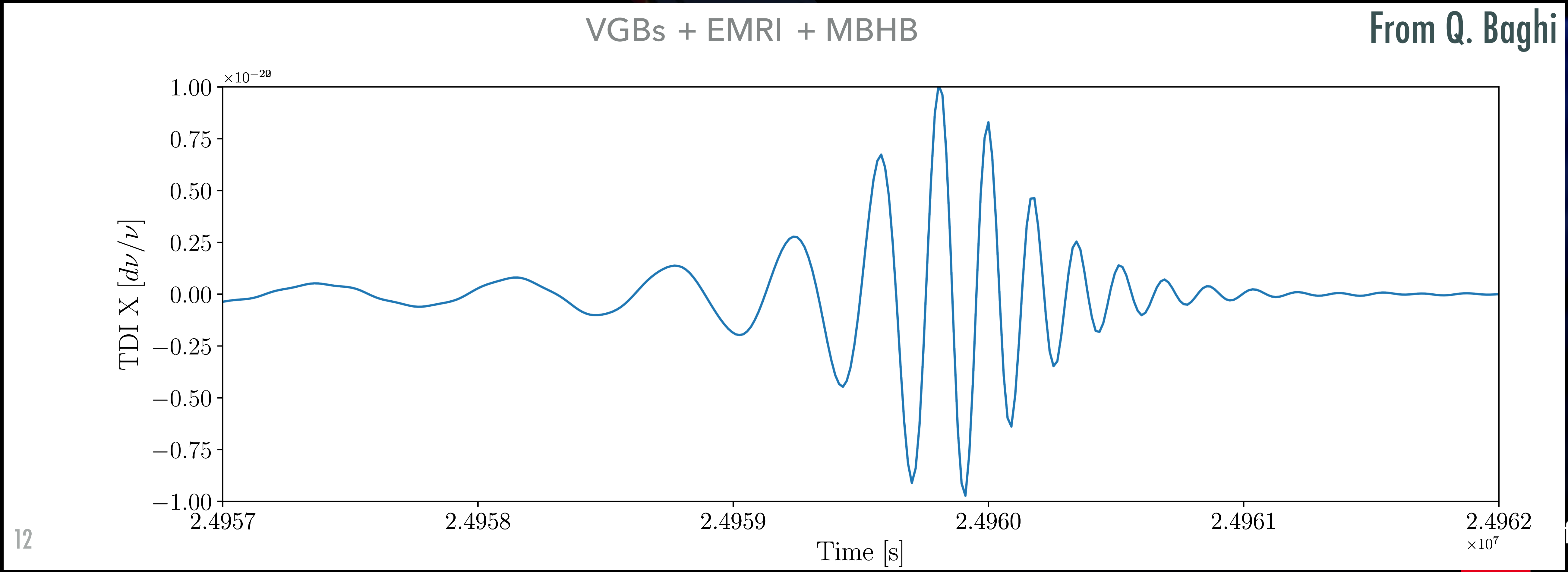
  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)



LISA data

- What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shits) from 27 interferometers
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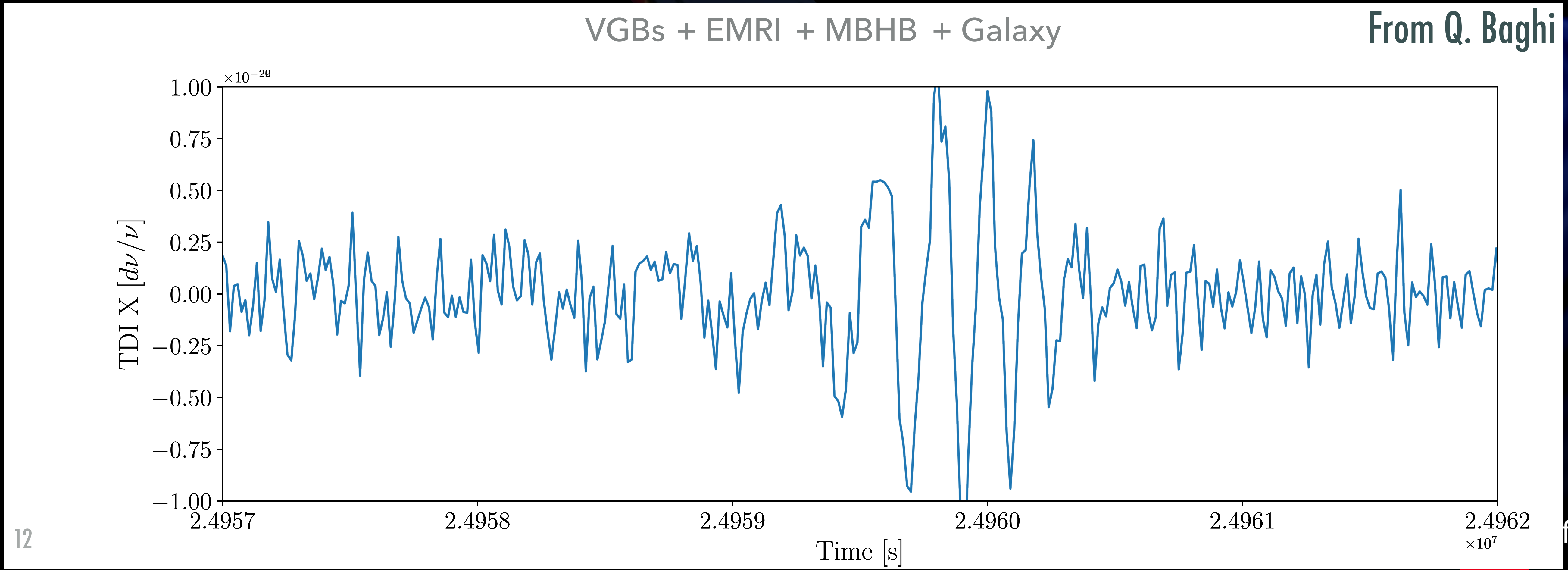

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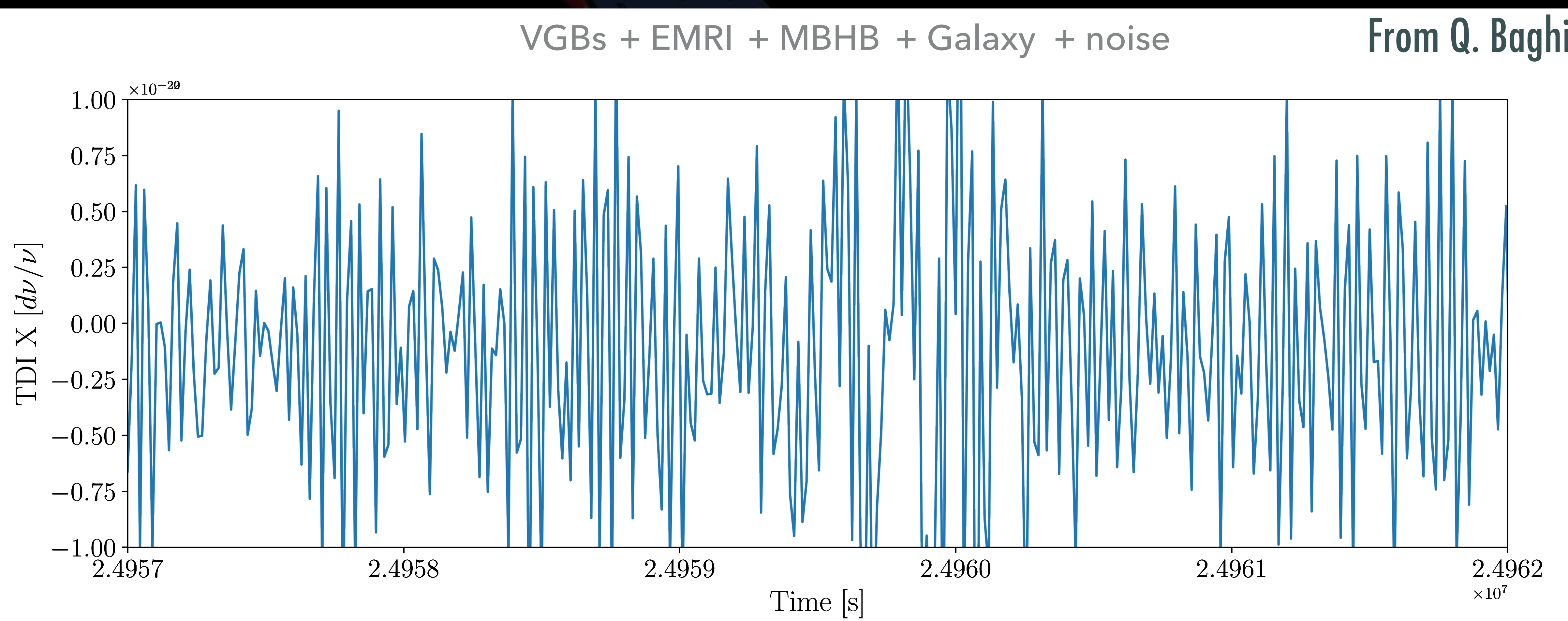

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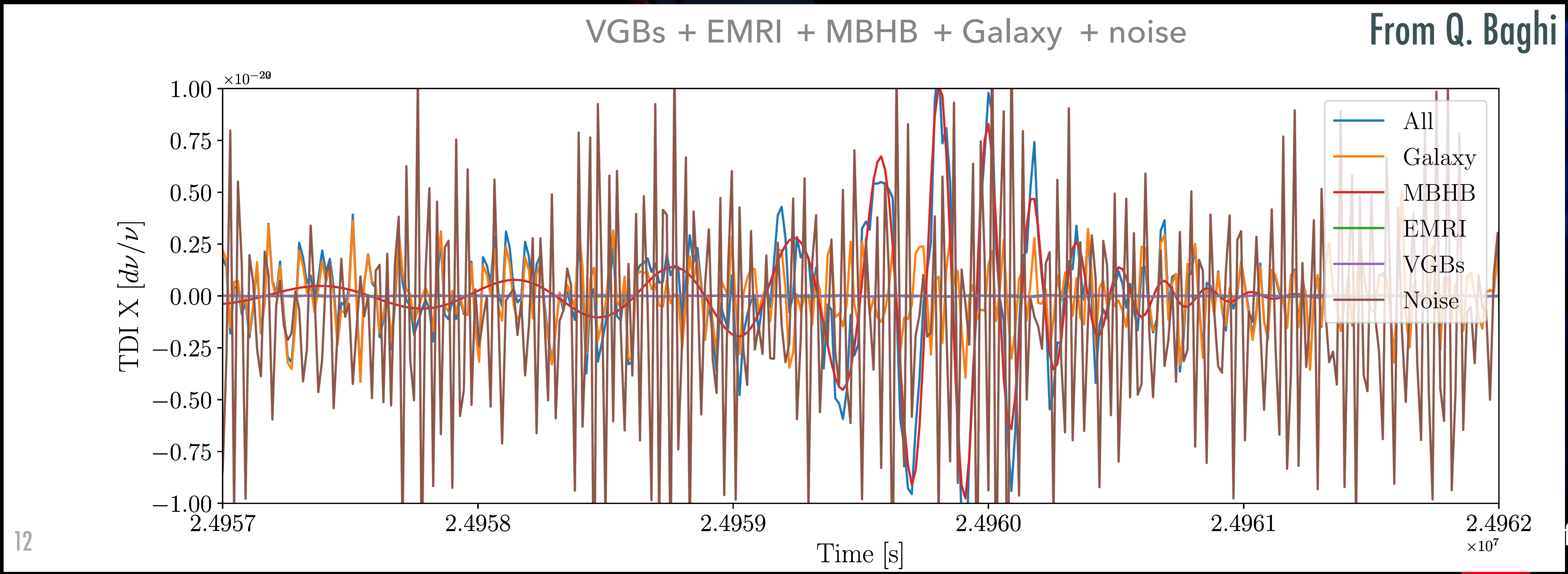

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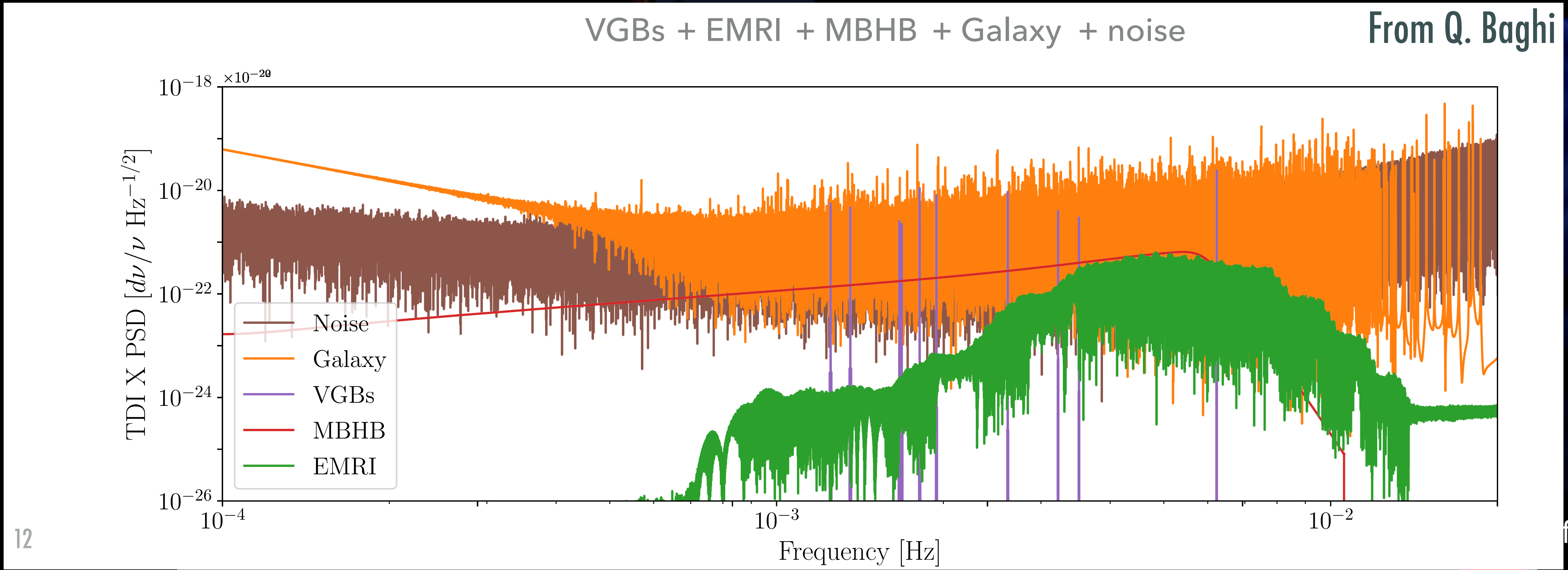
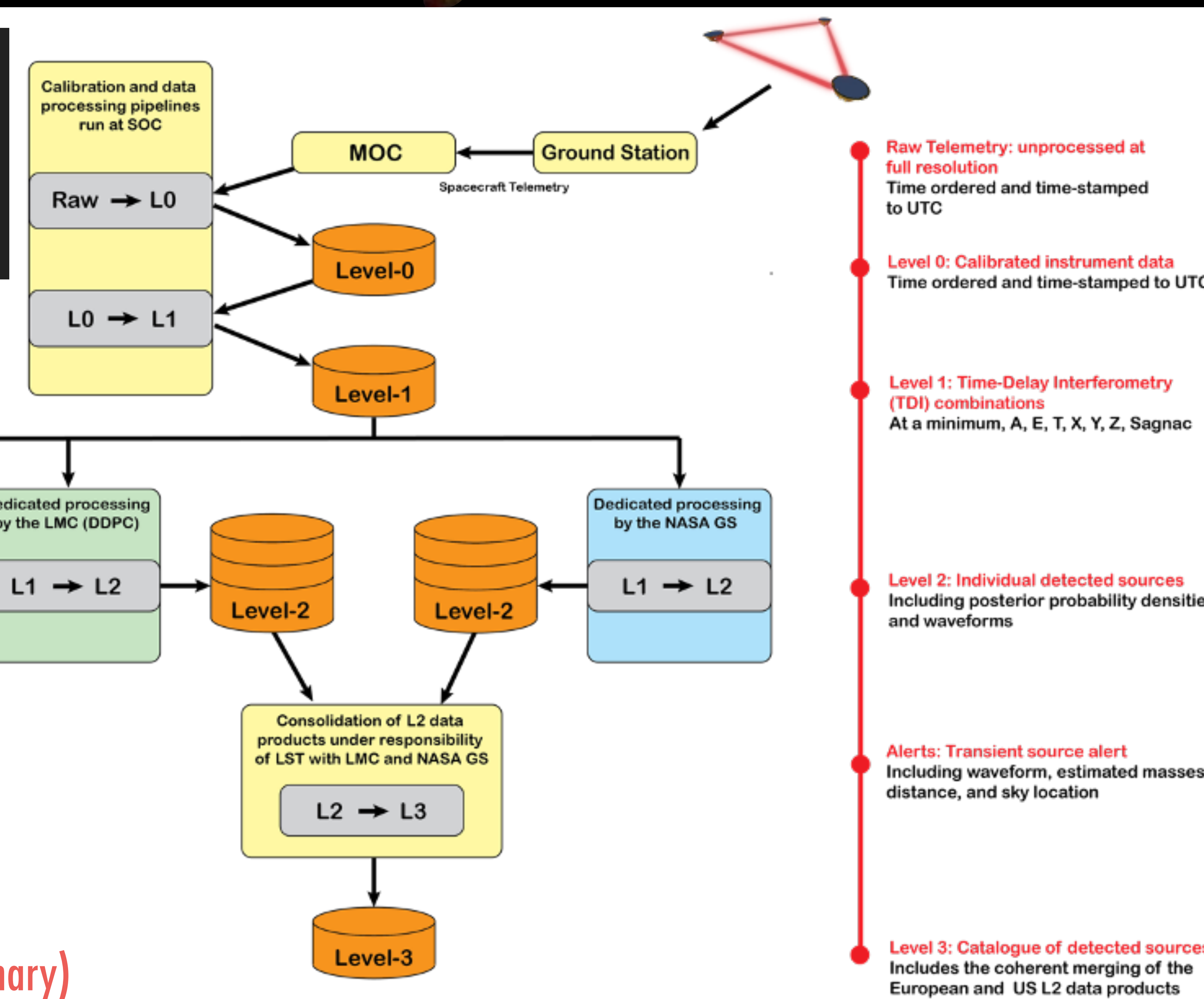


Ground Segment

- Draft schematic of the LISA science data processing and data flow form the preliminary SMP:

Communication:
- 8h per day
- ∼1 GBytes per day



ESA SMP (preliminary)

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

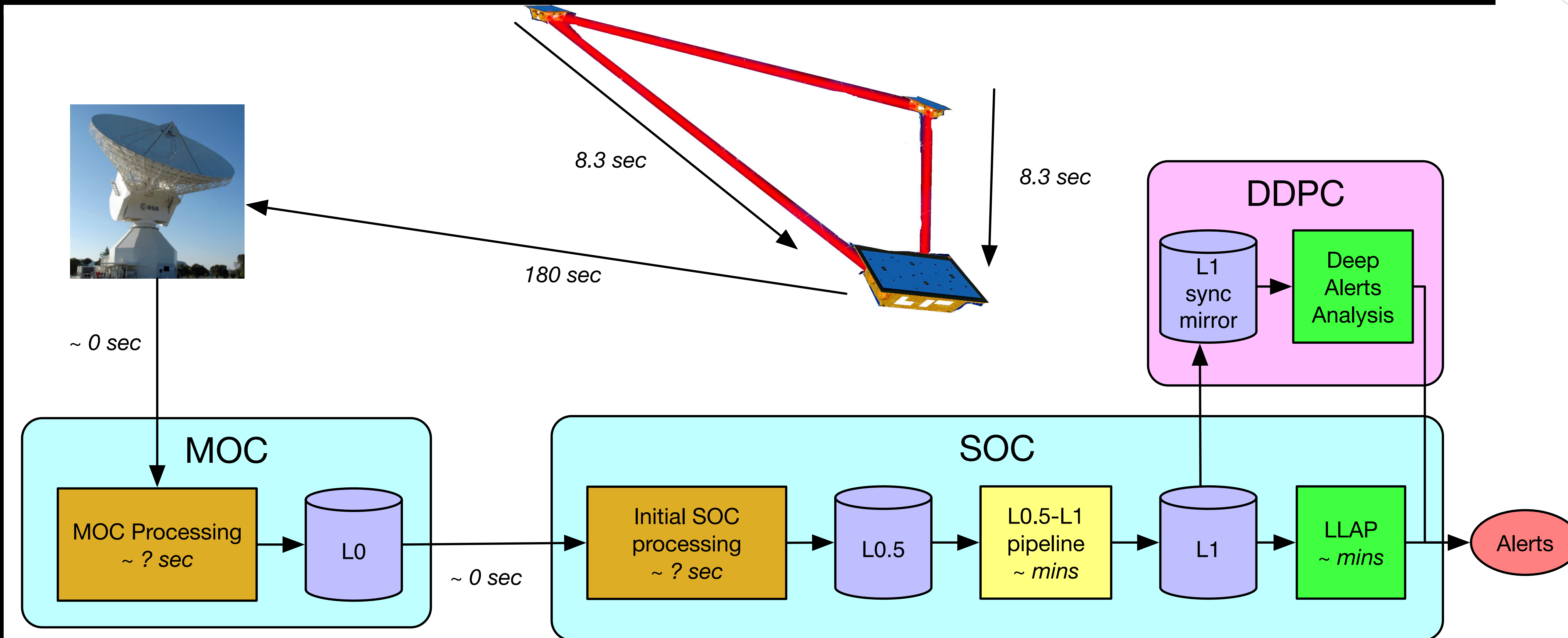
- Multiple pipelines with multiple approaches
- General approach with with multiple iterative steps (interconnection between products):
  1. Reduce dominant noises (Time Delay Interferometry) and partial correction on instrument artefacts => L1 data (TDI data)
  2. GLOBAL FITS: GW sources extraction + 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

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

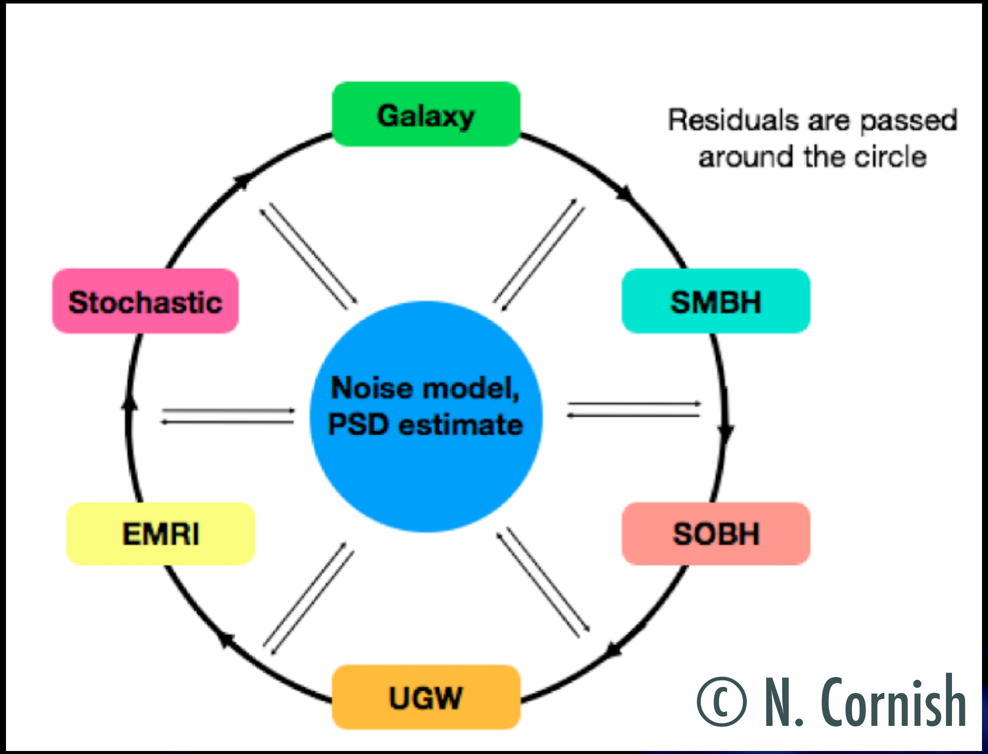
L1 to L2: alerts



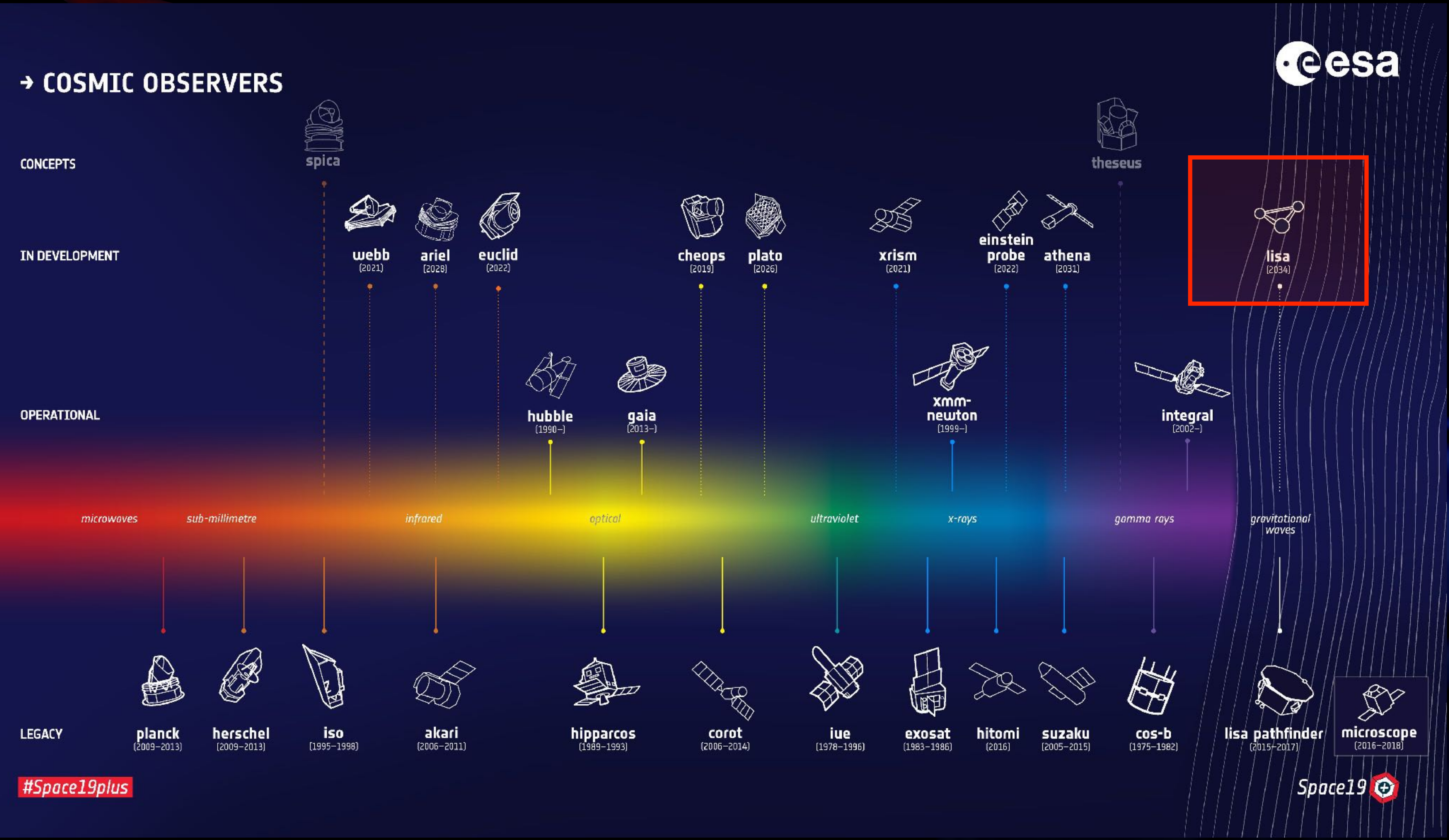
- Low Latency Alerts Pipeline: automatic near-real time analysis to release an alert as fast as possible
- Deep Analysis Alerts Pipeline: when an alert has been detected, analysis to:
  - Confirm the nature of the events
  - Refine the parameters

Global fit (deep analysis)

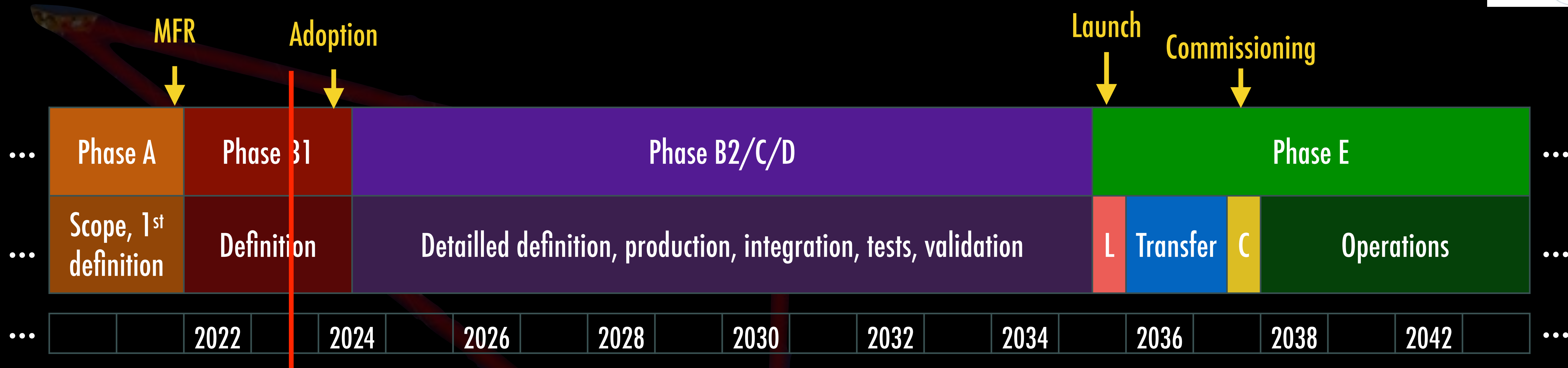
- Goal: GW sources extraction + better understanding of noises and instrument with multiple pipelines
- Challenge: large number of overlapping sources:
  - Multiple approaches
- Data
  - Available for the global fits:
    - Every day, 24h of new L1 data available
    - + every X days a refined version 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,
      - ...



Observing from space



Timeline

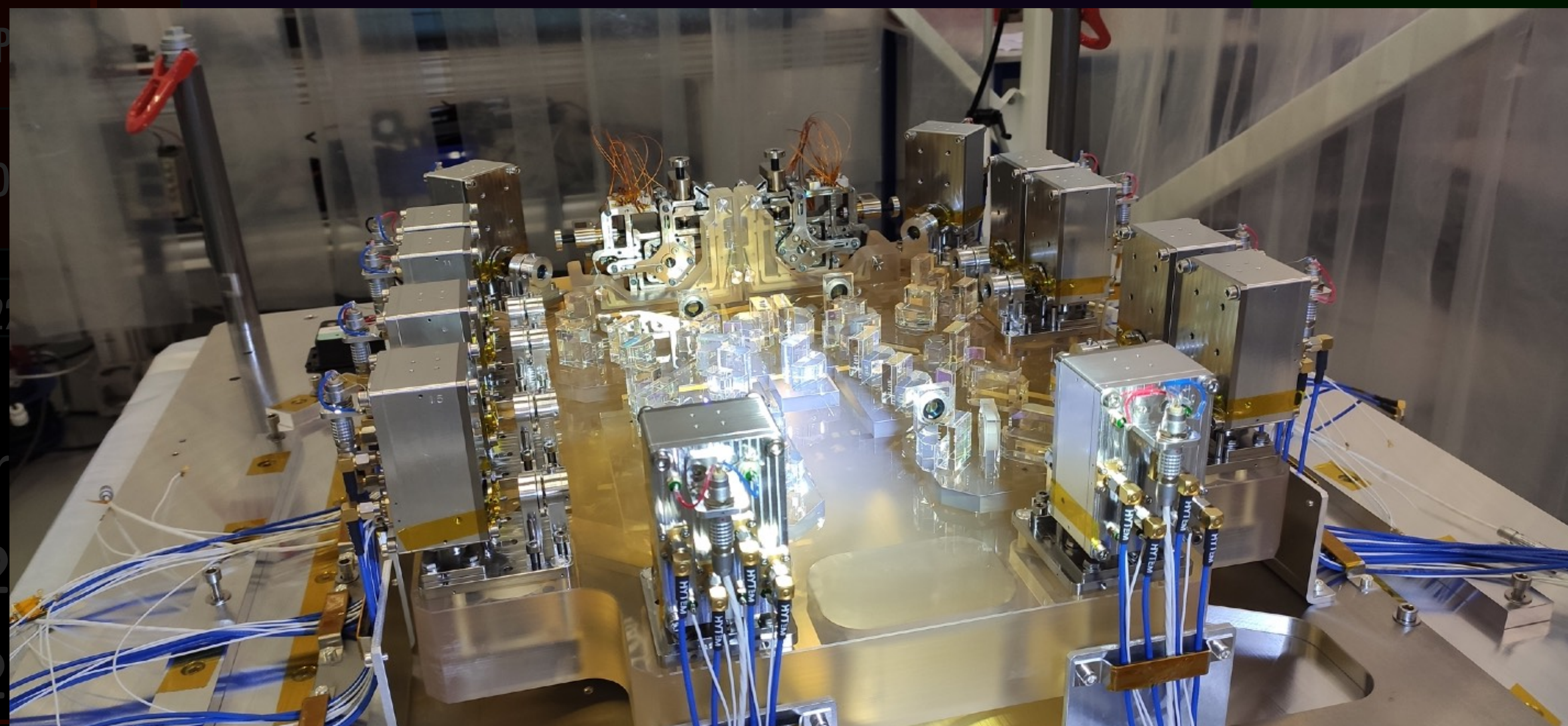


- 1993: first proposal ESA/NASA
- 20/06/2017: LISA mission approved by ESA Science Program Committee
- End 2021: success of the ESA Mission Formulation Review
- Now: accelerated phase B1 with ESA Adoption 25/01/2024
- Long building phase of multiple MOSAs: 6 flight models + test models
- Building of some subsystem models already started
- Launch 2035
- 1.5 years of transfer, 4.5 years nominal mission, 6.5 years extension

Timeline

MFR | Adoption | Launch | Commissioning

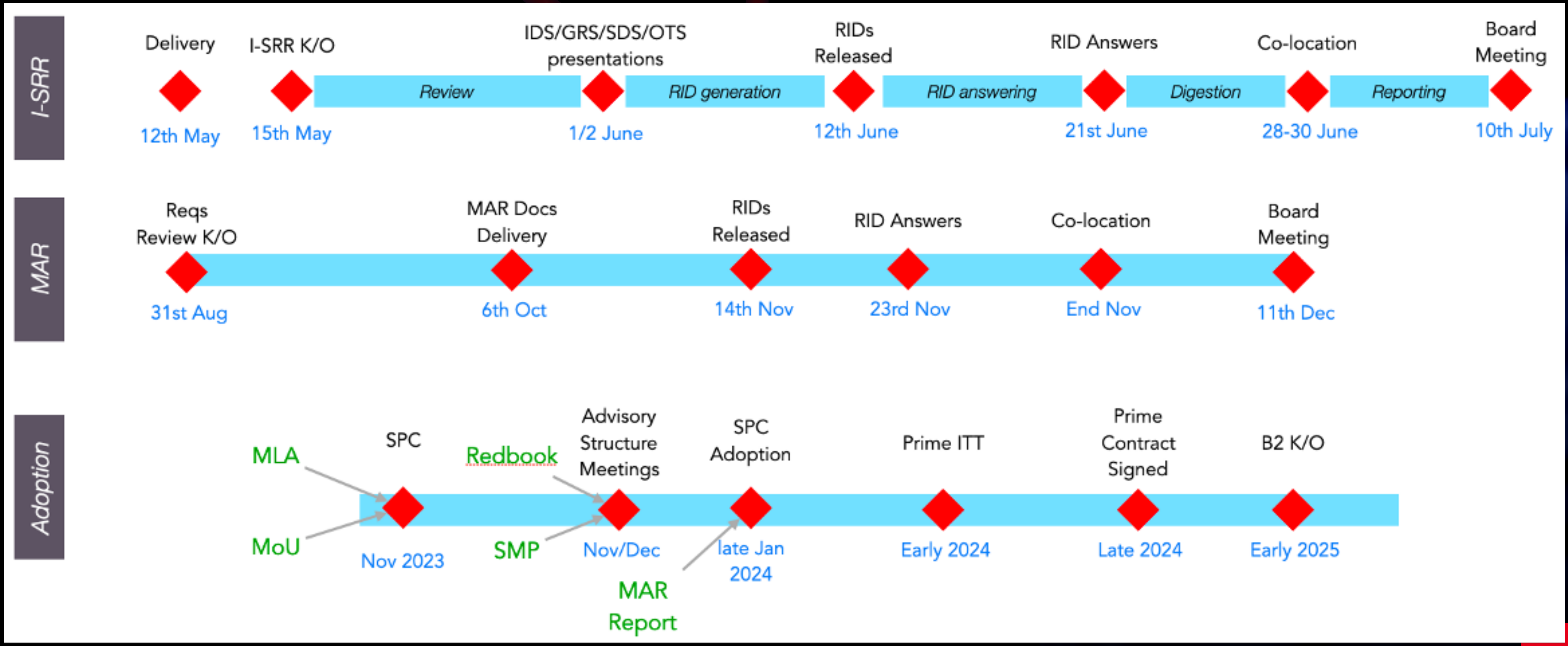
Phase A	P	e E
Scope, 1st definition	D	Operations
	202	2042



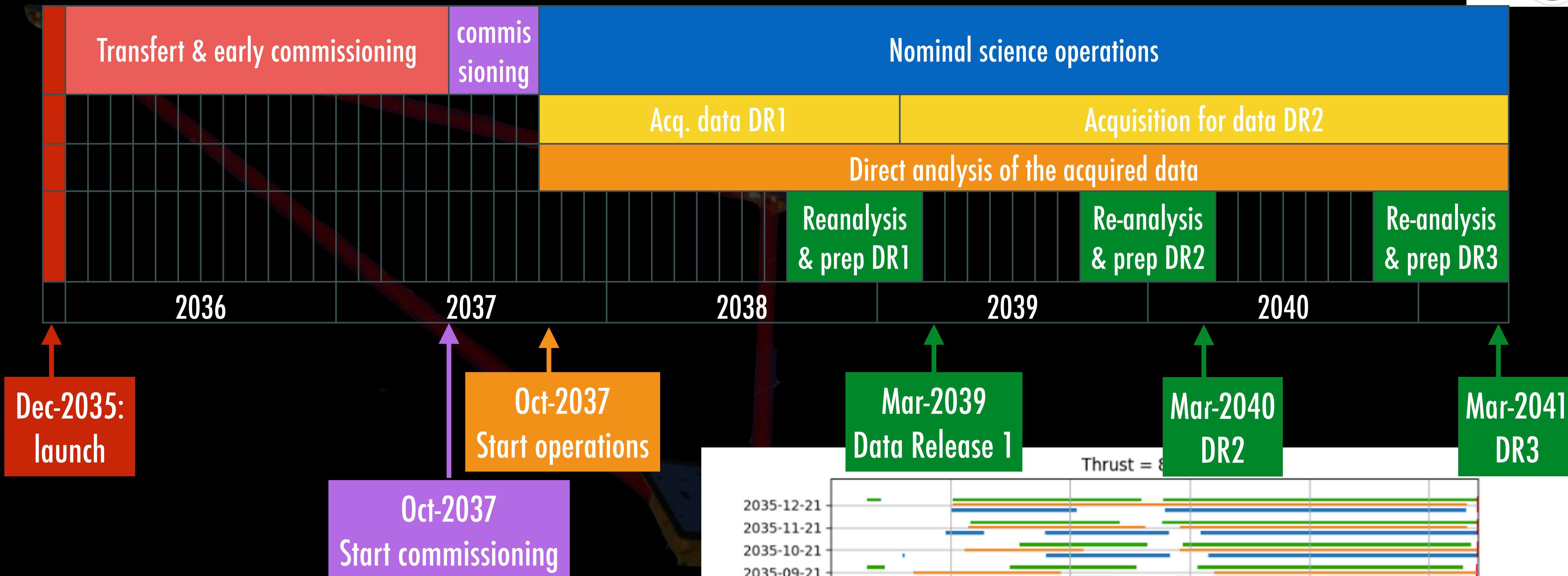
- 1993: fir
- 20/06/2 ... mittee
- End 202
- Now: accelerated phase ... /2024
- Long building phase of m ... els + test models
- Building of some subsyst
- Launch 2035
- 1.5 years of transfer, 4.5 ... ars extension

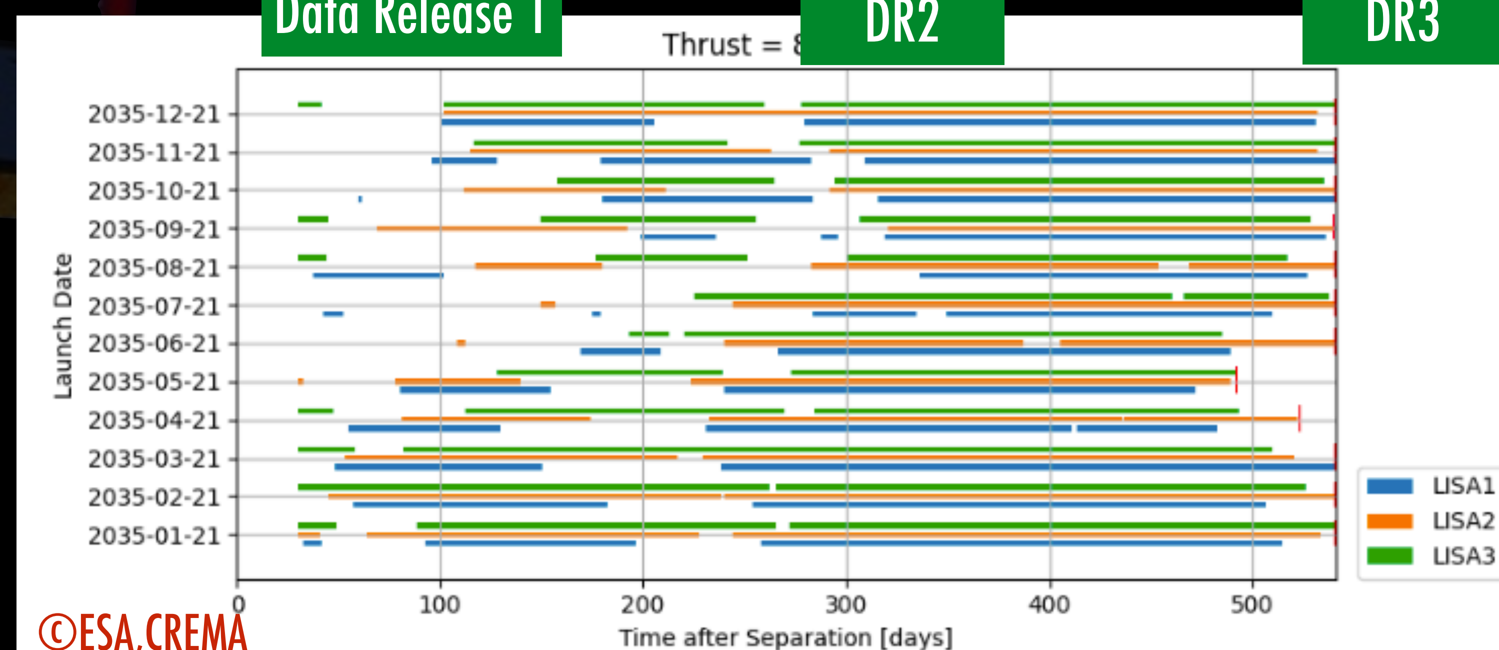
Timeline

- End of phase B1 and adoption:
  - I-SRR: Instrument System Requirement Review => passed
  - MAR: Mission Adoption Review
  - Adoption
  - Selection of the prime (ITT)

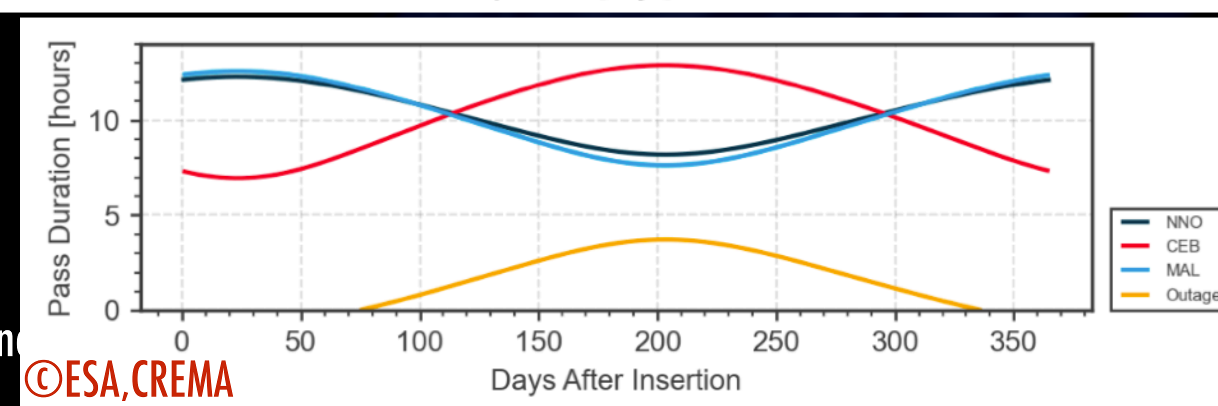


Example of Data Release Scenario





- Commissioning in 2 phases:
  - transfert
  - commissioning
- Current envisaged data policy:
  - DR1 (first data release) after 18 months for L0 to L3 of 6 months of data at least
  - Then Data Release every year

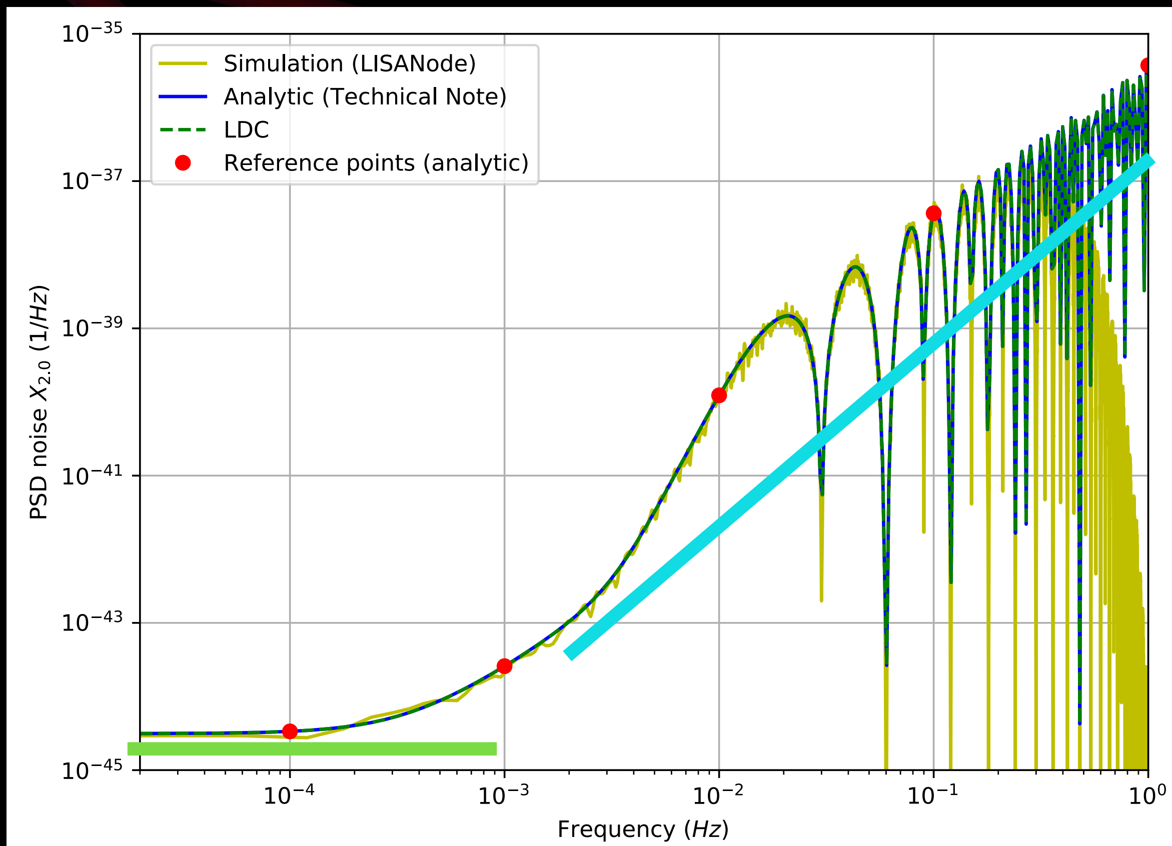


Mission configuration for adoption

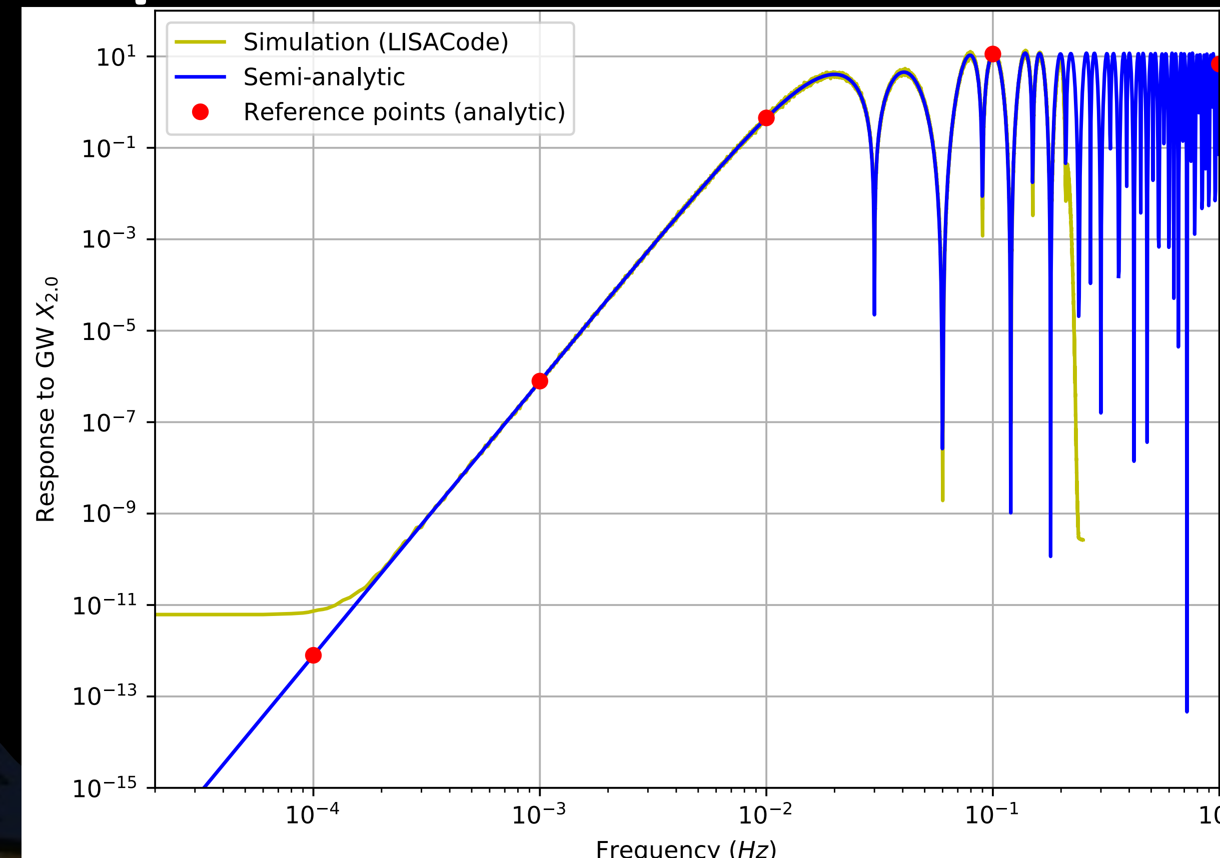
Payload		
Lasers	2 per spacecraft • 2 W ouput power at end-of-life • wavelength 1064 nm • frequency stability (pre-stabilised) 300 Hz/$\sqrt{\text{Hz}}$	
Optical Bench	2 per spacecraft • double-sided use• low thermal expansion (Zerodur)	
Interferometry	heterodyne interferometry • 15 pm/$\sqrt{\text{Hz}}$ requirement • Inter-spacecraft ranging to ~1 m	
Gravitational Reference System	46 mm × 46 mm × 46 mm test mass made from AuPt alloy • electrostatically controlled • optical readout • Faraday cage electrostatic shield housing • electrostatic actuation in 5 DOF	
Telescope	2 per spacecraft • 30 cm off-axis telescope	
Mission		
Duration	4.5 years science orbit • ~6.25 years including transfer and commissioning	
Orbits	Three drag-free satellites in heliocentric orbits • semimajor axis ~1 AU • eccentricity $e \approx 0.0096$ • inclination $i \approx 0.96°$	
Constellation	Equilateral triangle • 2.5×10^6 km armlength • trailing Earth by ~20° • inclined by 60° with respect to the ecliptic • armlength variation <1 % • angular variation ±0.8° • relative velocity between spacecraft <20 m/s	
Data Analysis		
Noise Reductions	Laser noise suppression with time-delay interferometry • Ranging processing and delay estimation • Spacecraft jitter suppression and reduction to 3 lasers • Tilt-to-length effect correction • Clock noise suppression • Clock synchronisation	
Data Levels	Level 0	Primary science telemetry, decommutated, time-stamped, unit-level calibrations applied
	Level 1	Time-Delay Interferometry (TDI) variables (GW strain)
	Level 2	Output from a global fit pipeline, posterior pdfs for all sources.
	Level 3	Catalogue of GW source candidates (detection confidence, estimated astrophys. parameters)

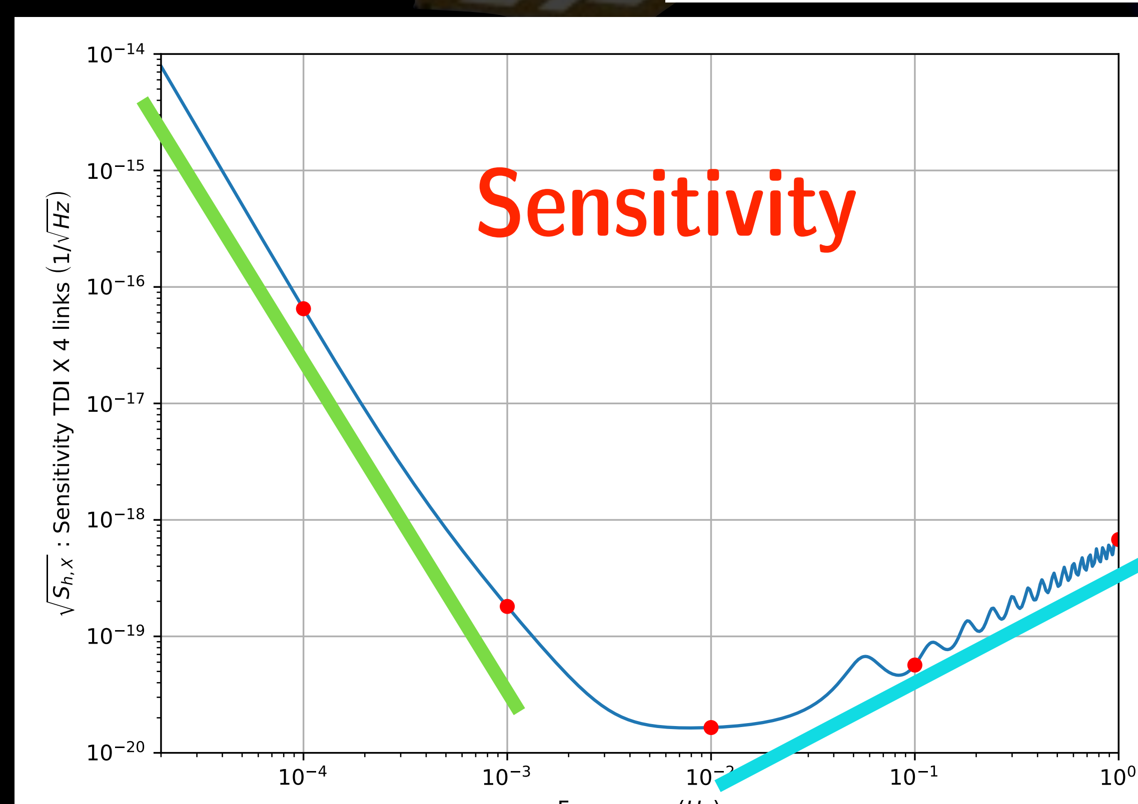
Sensitivity

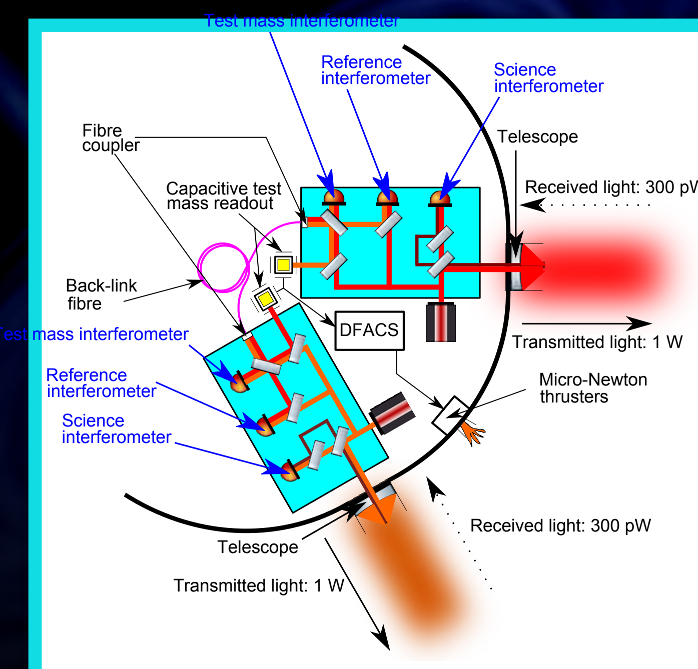
Noises



Response of the detector to GWs

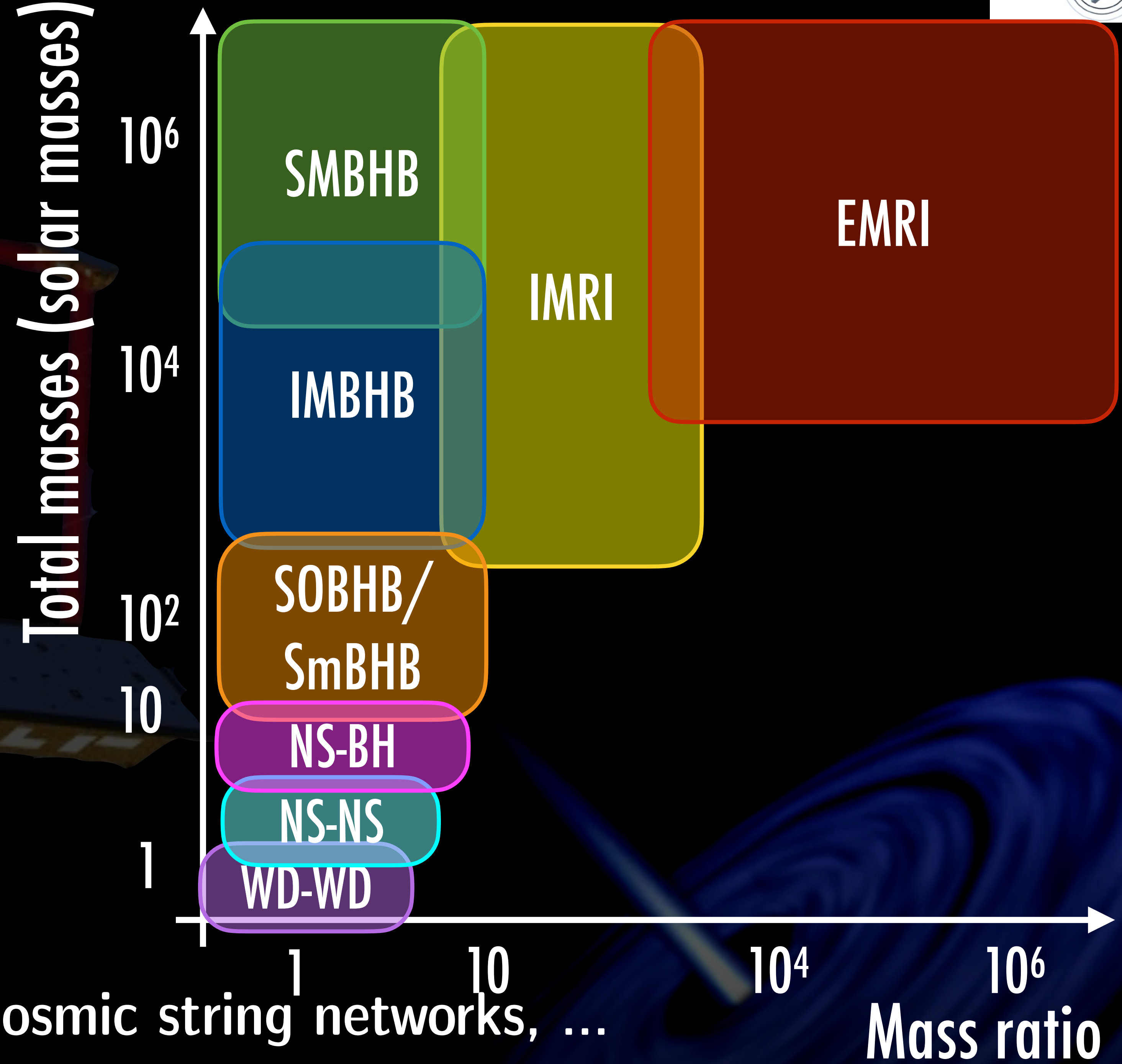






GW sources in the mHz band

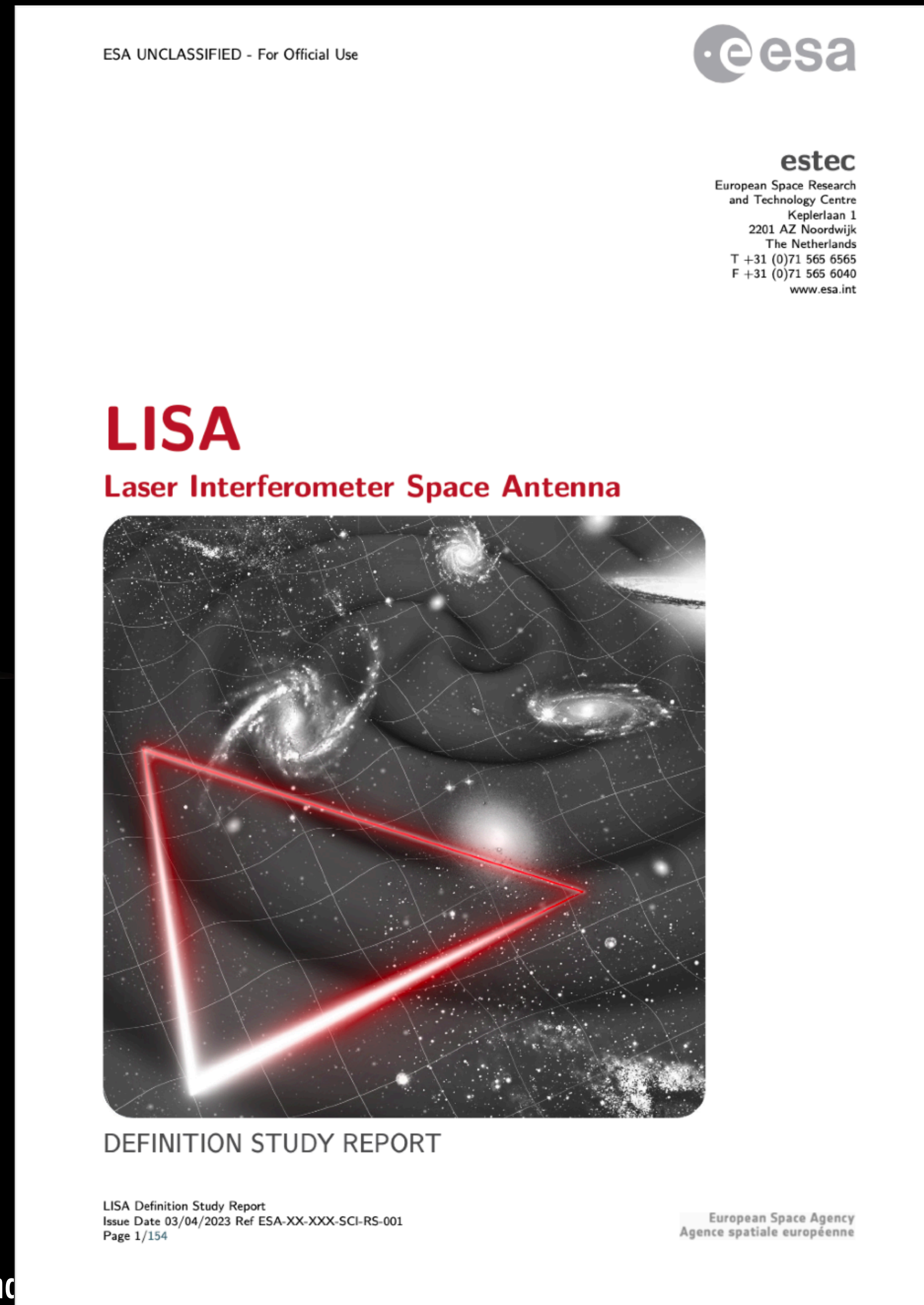
- **Binaries**: large range of masses and mass ratios:
  - SuperMassive BH Binaries
  - Extreme Mass Ratio Inspiral
  - Stellar mass BH Binaries
  - Double White Dwarfs
  - Double Neutron Stars
  - Intermediate Mass Ratio Inspiral
  - Intermediate Mass BH Binaries



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

RedBook

- The content shown in the next slides is based on the redbook, the main science document of the LISA mission which is almost finished.
- The Redbook is written by the LISA ESA Science Study Team with scientists of the Consortium.
- The document is in a advanced draft version so all content is preliminary.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LISA
Laser Interferometer Space Antenna

DEFINITION STUDY REPORT

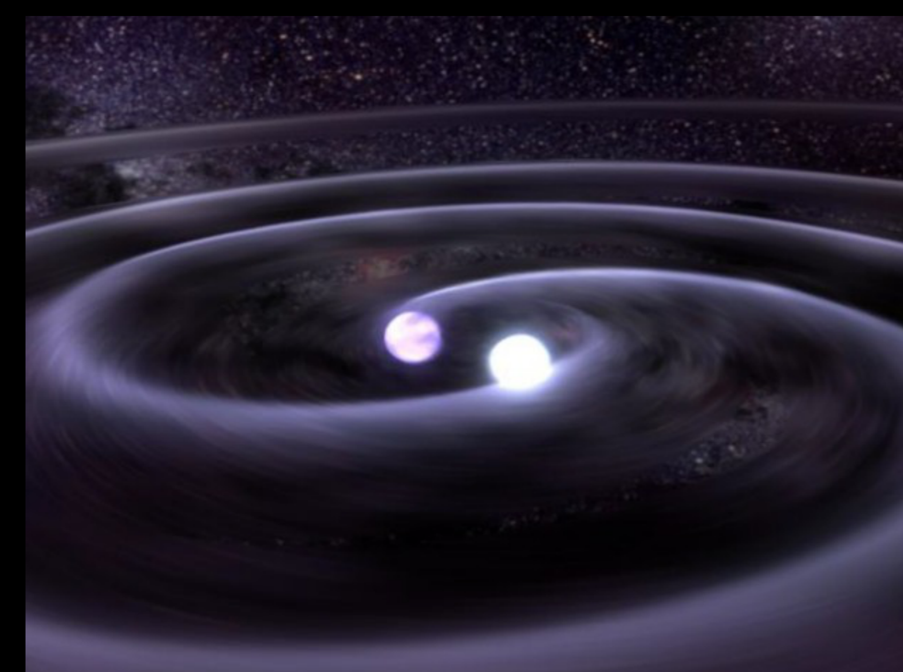
LISA Definition Study Report
Issue Date 03/04/2023 Ref ESA-XX-XXX-SCI-RS-001
Page 1/154

European Space Agency
Agence spatiale européenne

Compact solar mass binaries

- Large number of stars are in binary system.
- Evolution in white dwarf (WD) and neutron stars (NS).

  => existence of WD-WD, NS-WD and NS-NS binaries
- Estimation for the Galaxy: 30 millions.
- Gravitational waves:
  - most part in the slow inspiral regime (quasi-monochromatic): GW at mHz
  - coalescence at $f > 10$ Hz

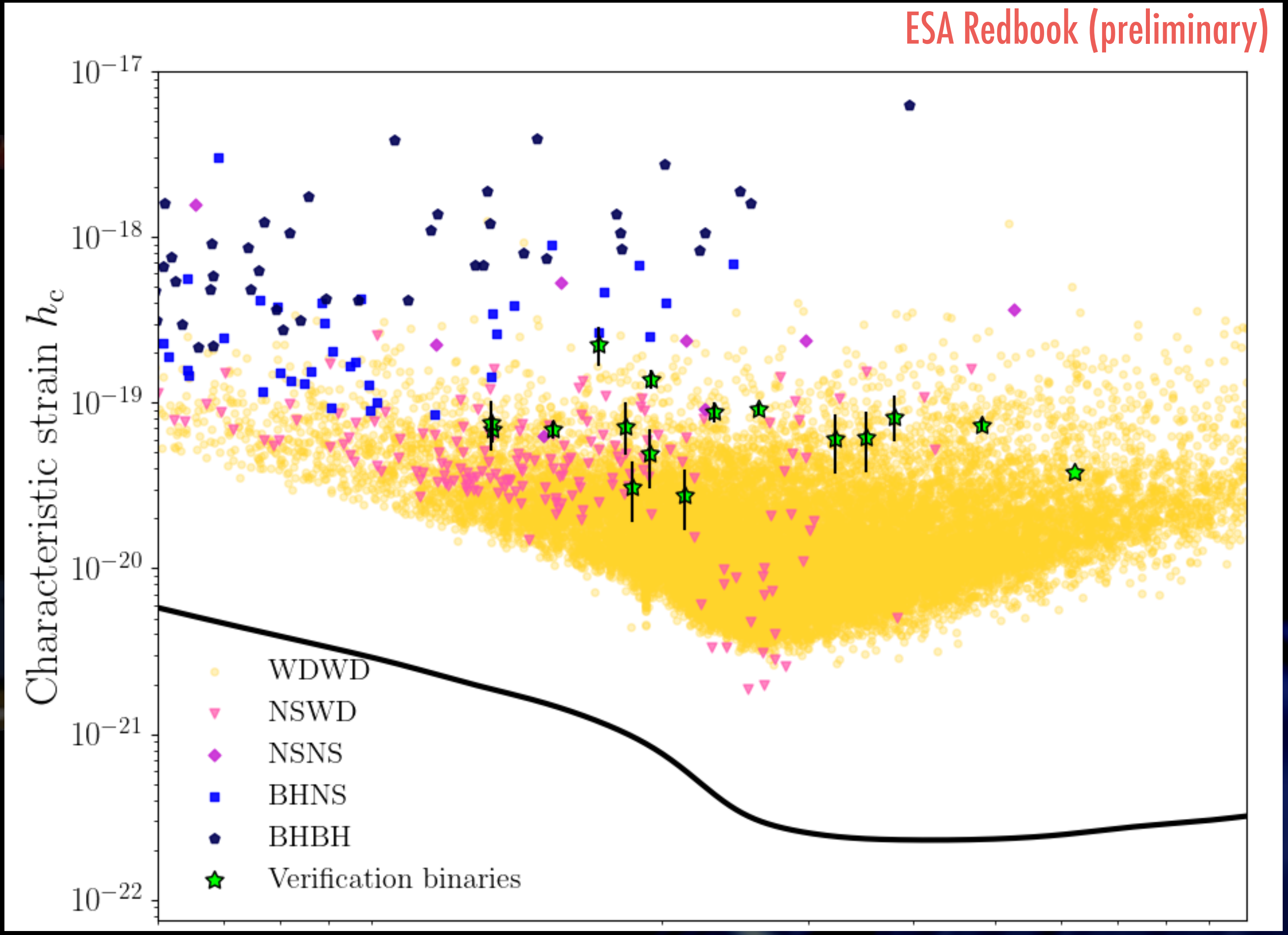


- Several known system emitting around the mHz

  => guaranteed sources

Galactic binaries

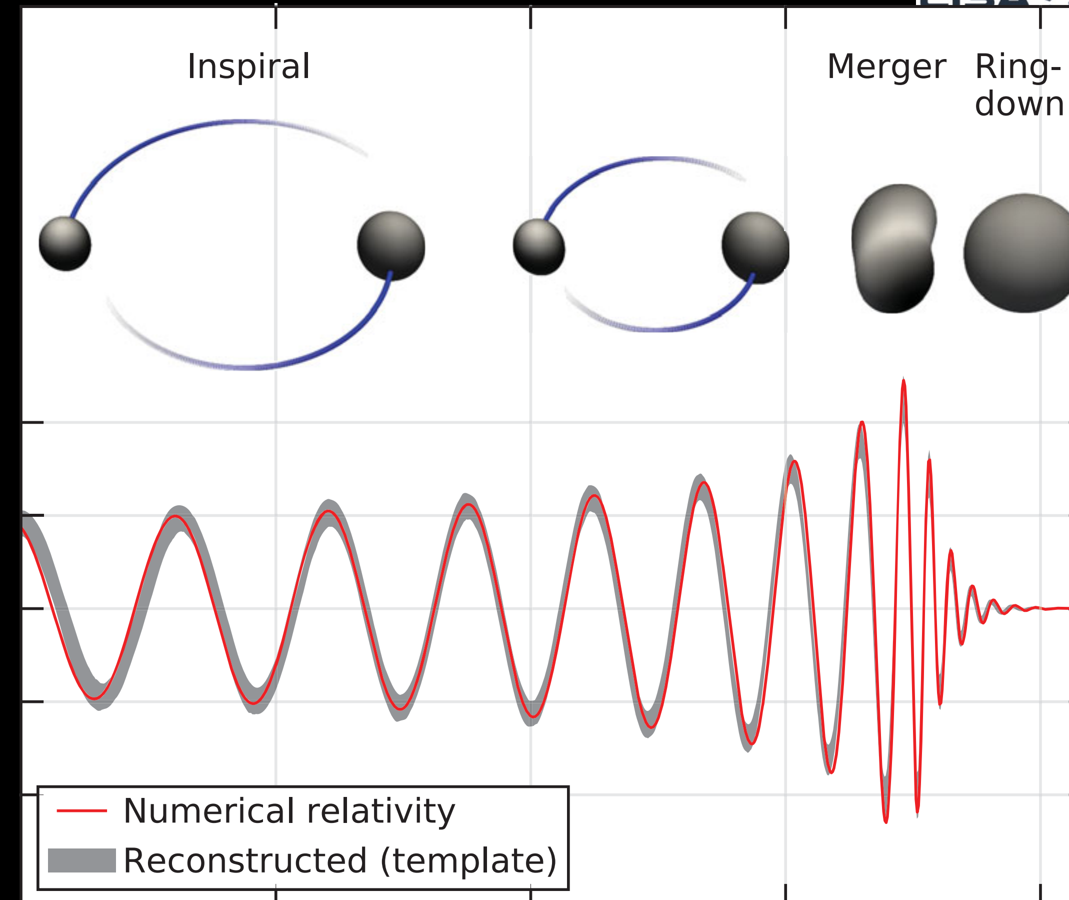
- GW waveform:
  - Approx.: quasi-monochromatic
- Duration: permanent
- Signal to noise ratio:
  - detected sources: 7 - 1000
  - confusion noise from non-detected sources

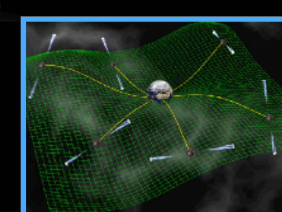


- Event rate:
  - 25 000 detected sources (over 30 millions sources)
  - more than 17 guarantied sources (verification binaries)

Super Massive Black Hole Binaries

- Mass > 10^5 M_{Sun}
- GW waveform:
  - Inspiral: Post-Newtonian
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.
- Inspiral at frequency < 10 mHz (depend on the mass)
- Merger and ringdown around mHz
- 10 - 100 events per year



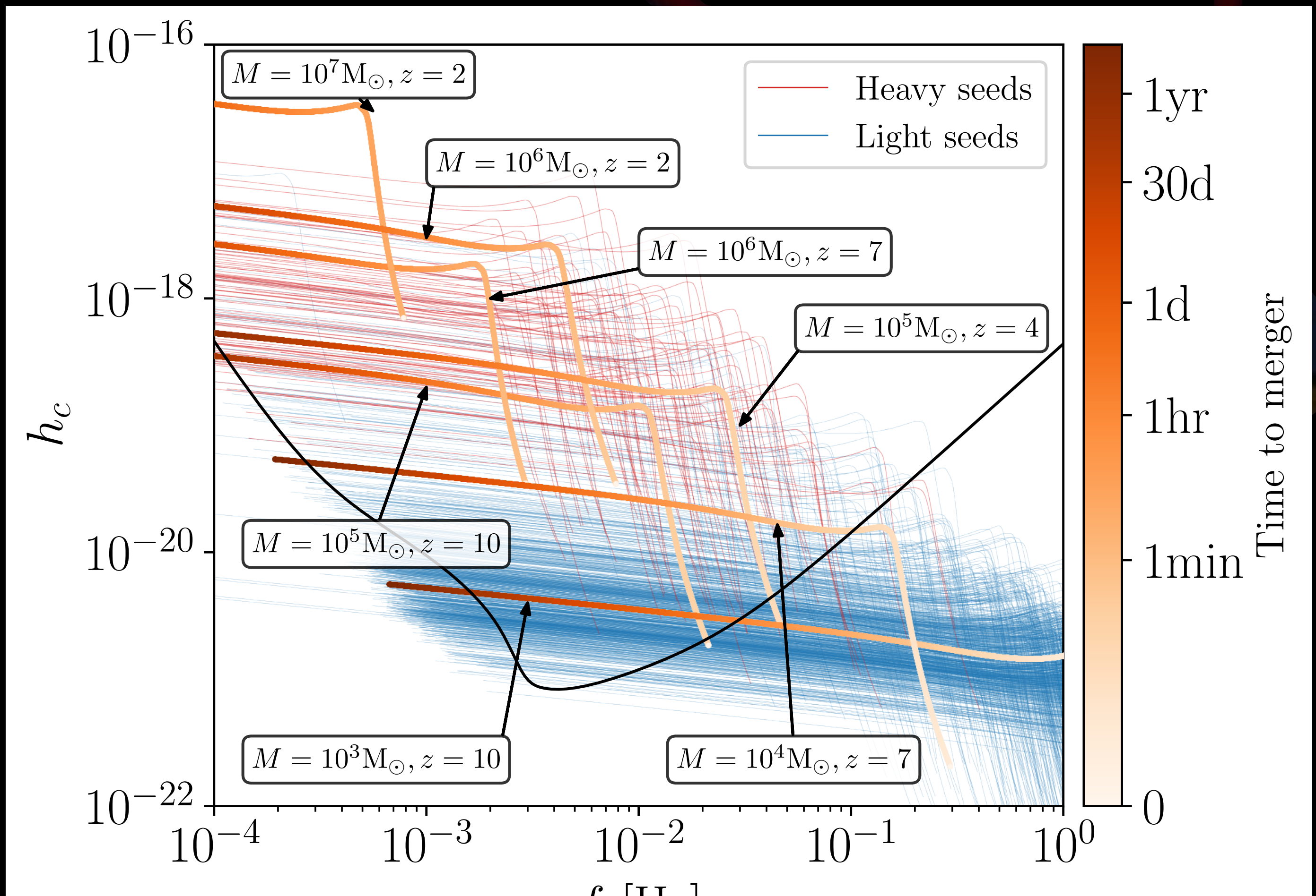



© Vincent, Paumard, Gourgoulhon, Perrin (2011)

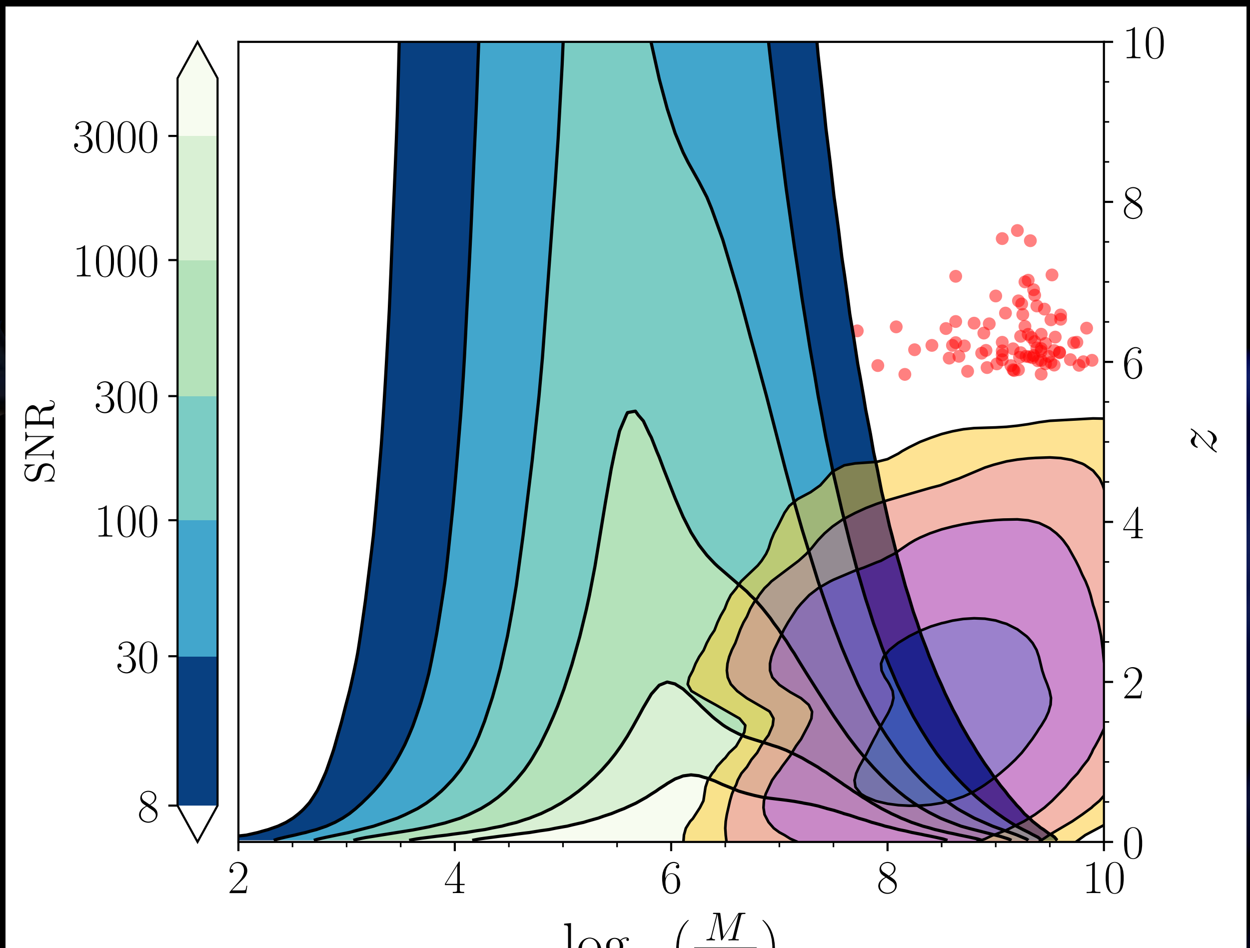

© EHT (2019)

Super Massive Black Hole Binaries

- Duration: hours to months
- SMBHB from 10^4 à 10^7 solar masses in "all" Universe



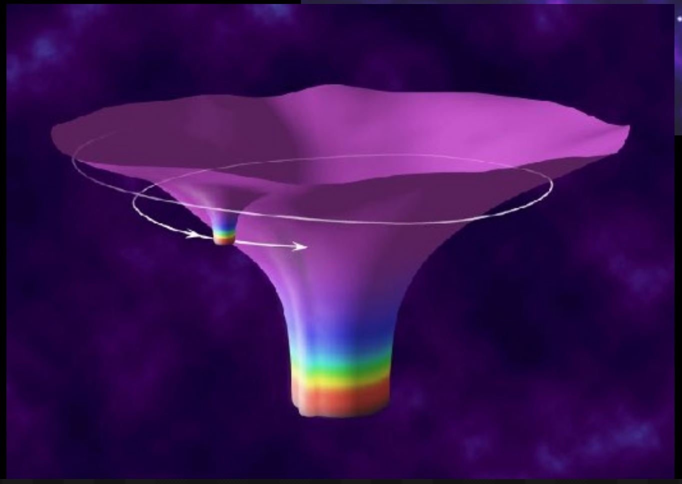
ESA Redbook (preliminary)

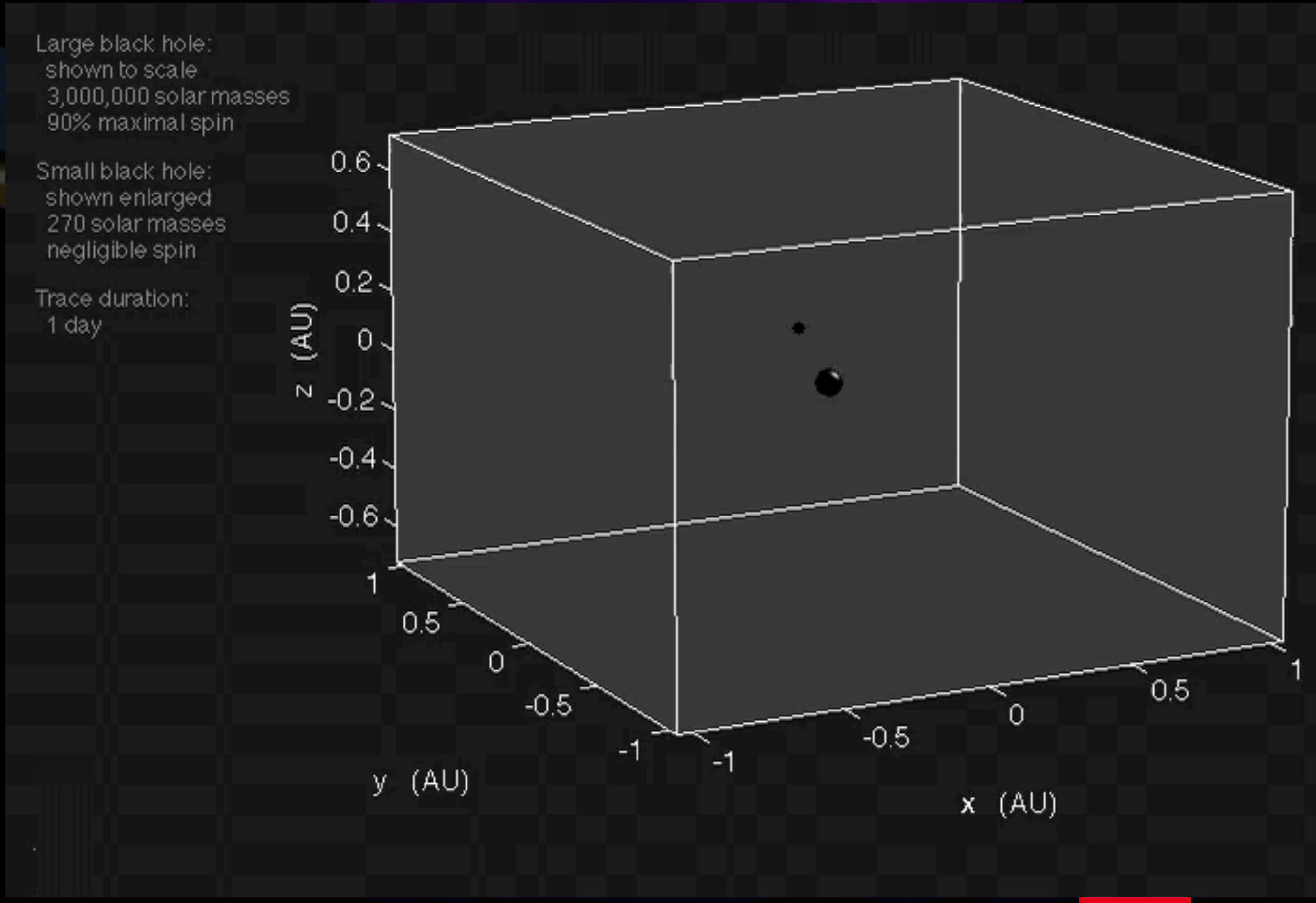


ESA Redbook (preliminary)

EMRIs

- Capture of a "small" object by massive black hole ($10 - 10^6\ M_{Sun}$): Extreme Mass Ratio Inspiral
  - Mass ratio > 1000
  - GW gives information on the geometry around the black hole.
  - Test General Relativity in strong field
  - Frequency : 0.1 mHz to 0.1 Hz
  - Large number of source could be observed by LISA





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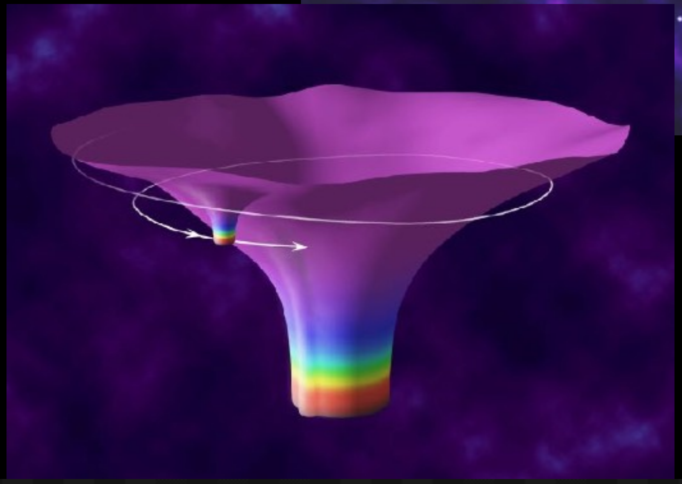
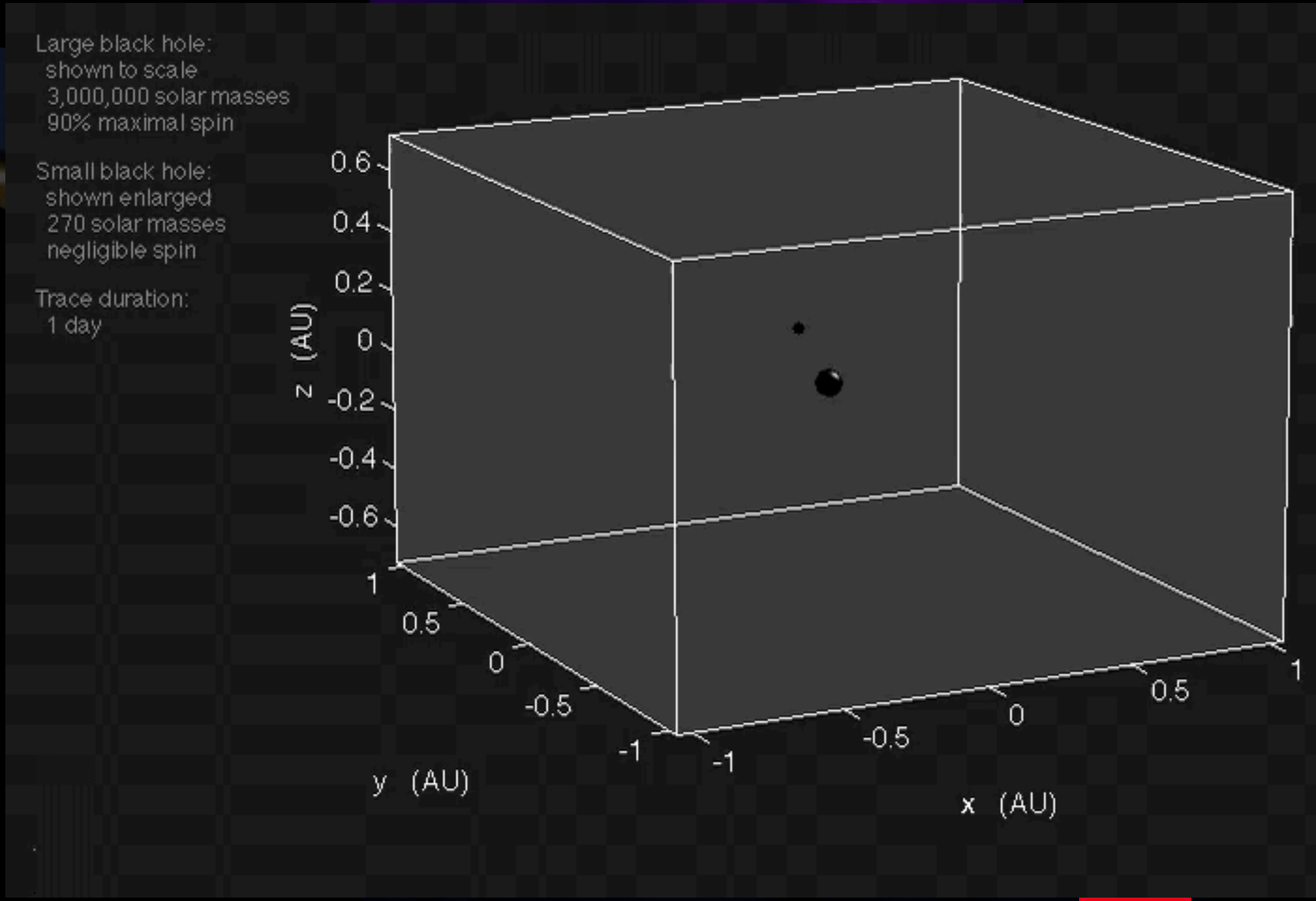
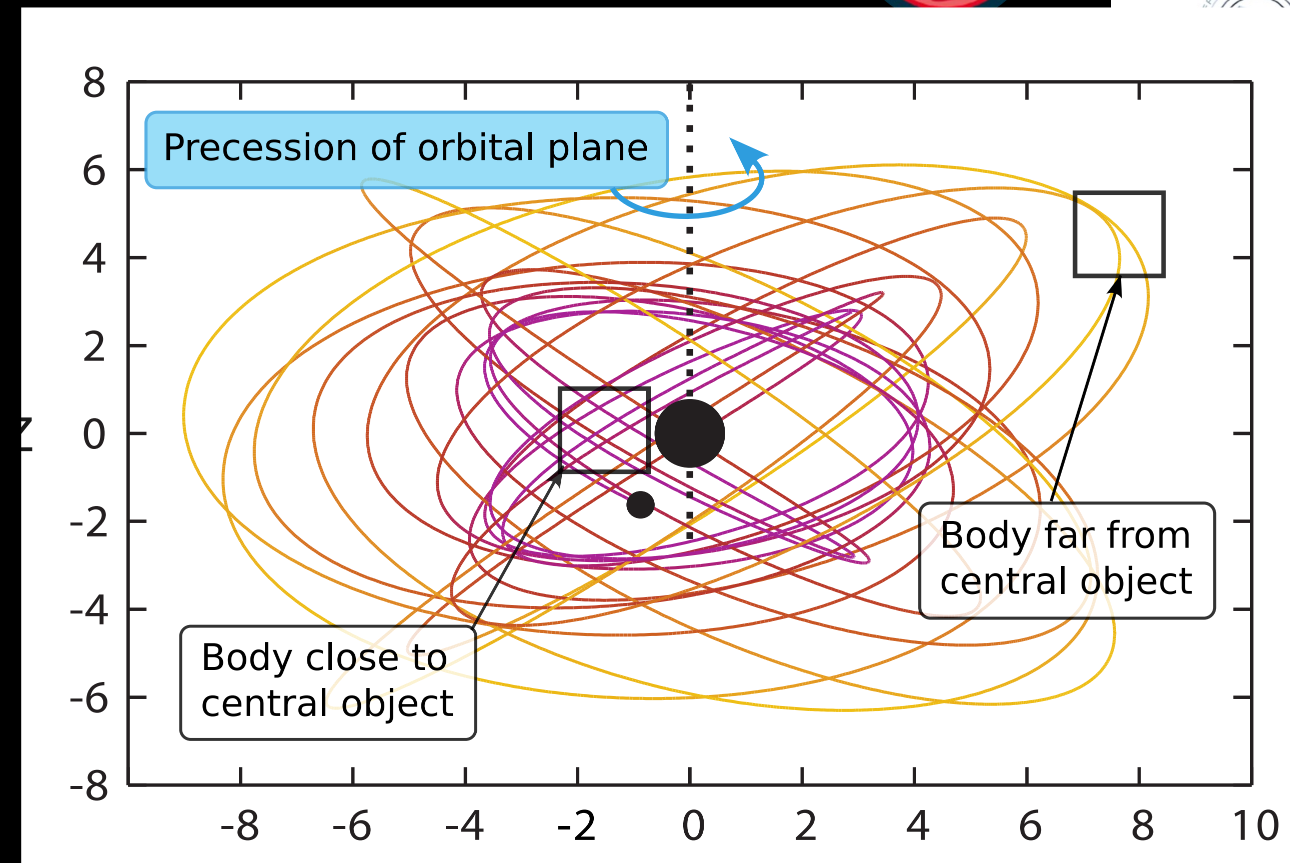
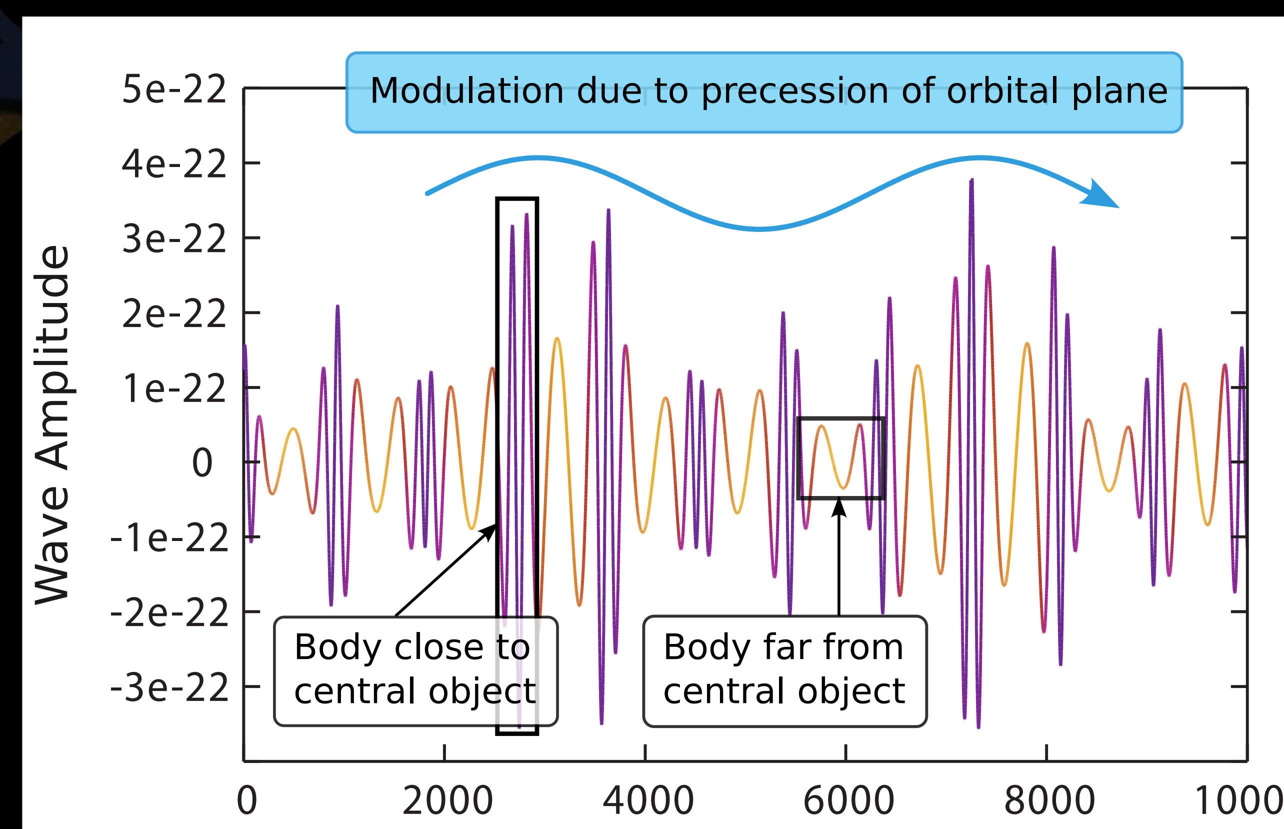




EMRIs

- GW waveform:
  - Very complex waveform
  - Multiple harmonics
  - No long & precise simulation at the moment
- Duration: about 1 year
- Signal to Noise Ratio: from tens to few hundreds
- Event rate: from few events per year to few hundreds



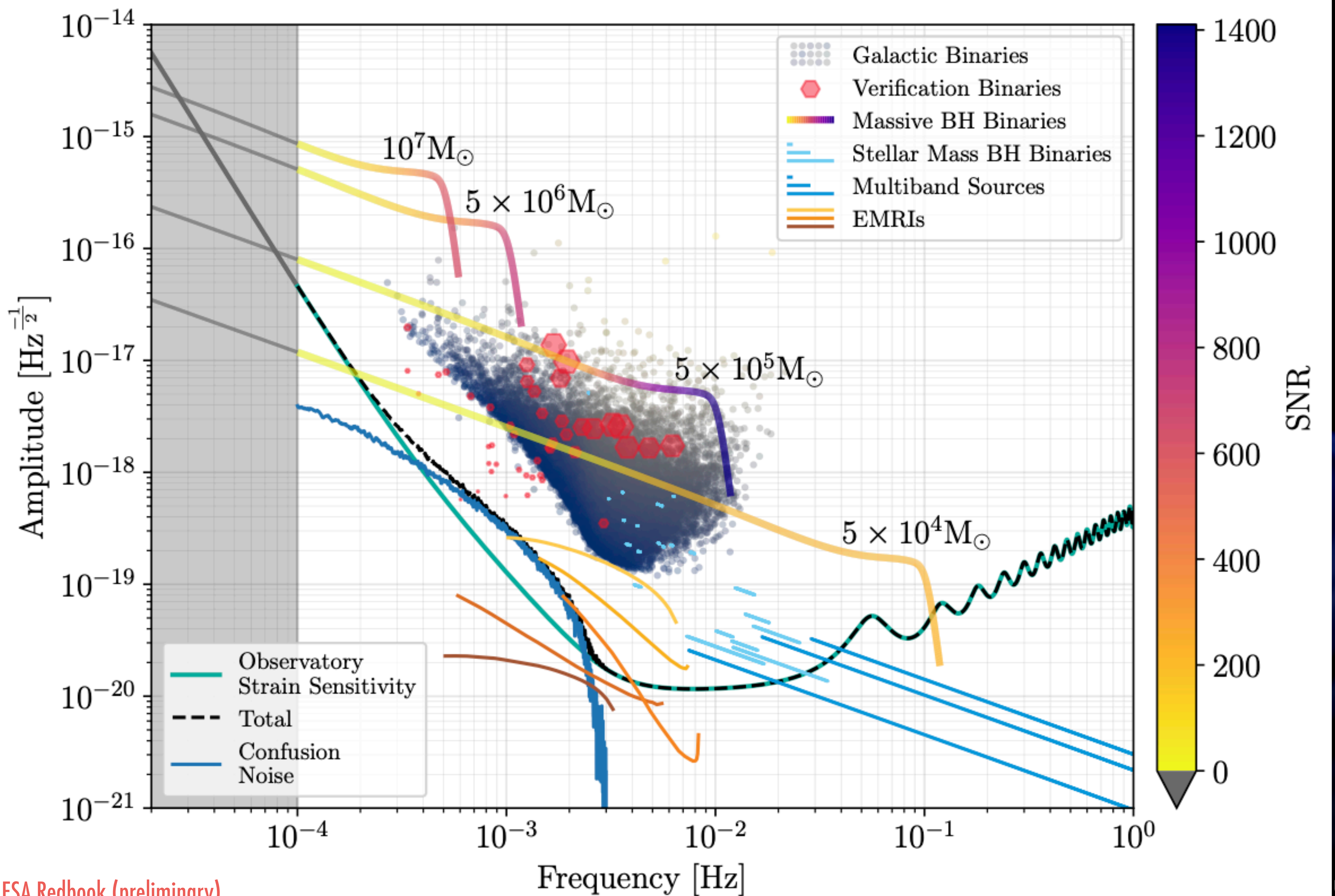


Stellar mass Black Hole Binaries

- Binaries with 2 black holes of masses between few M_{Sun} and 100 M_{Sun} , so called "Stellar mass BH Binaries"
- Inspiral: emission in the mHz band
- Merger: powerful emission around few tens Hz
  => many sources already observed

- Fast evolution: few years from tens mHz to tens Hz
  => multi-observatories observations

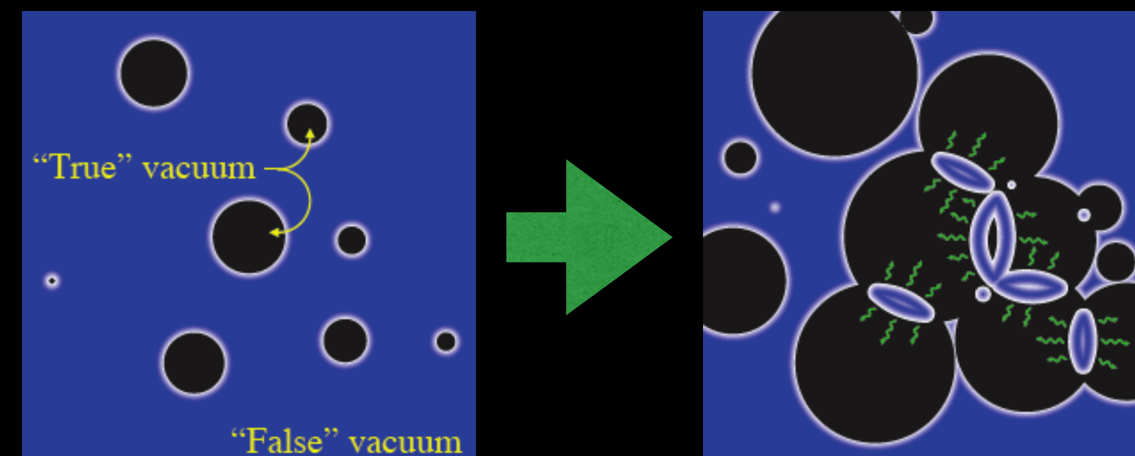
Binaries observed by LISA

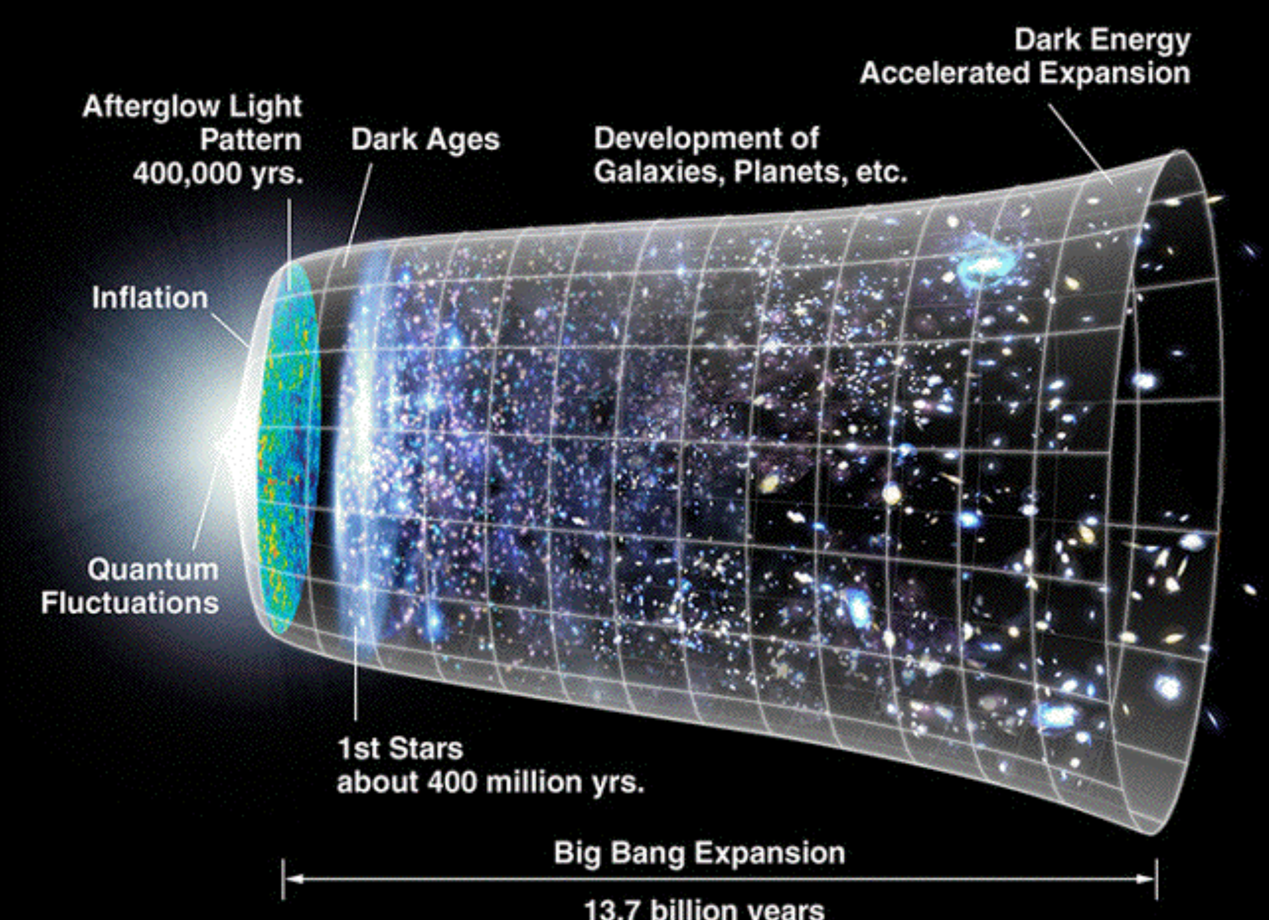


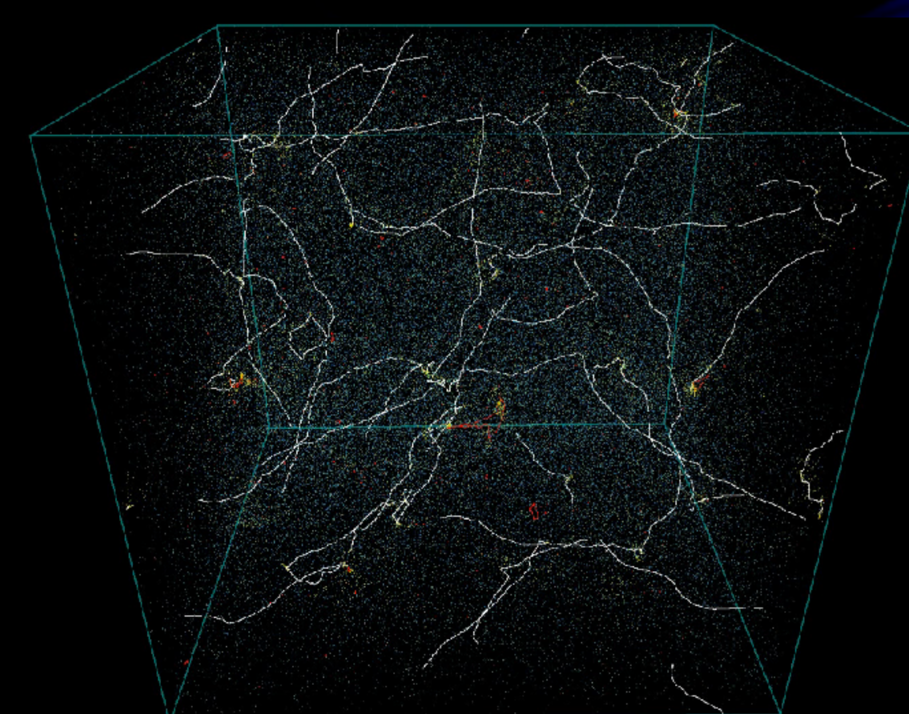
ESA Redbook (preliminary)

Cosmological backgrounds

- Variety of cosmological sources for stochastic backgrounds:
  - First order phase transition in the very early Universe;
  - Cosmic strings network;
  - Primordial Black Holes;
  - …

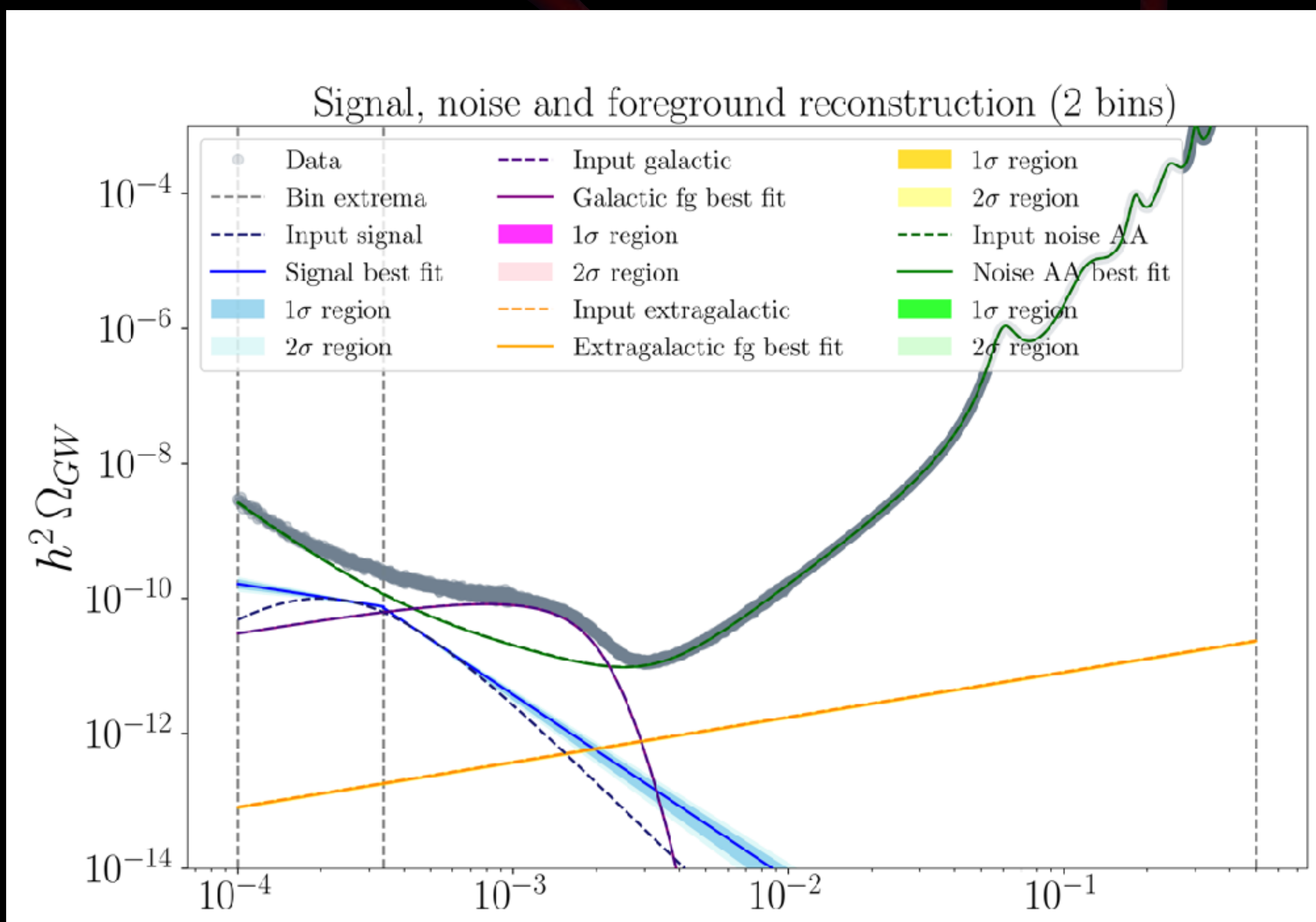




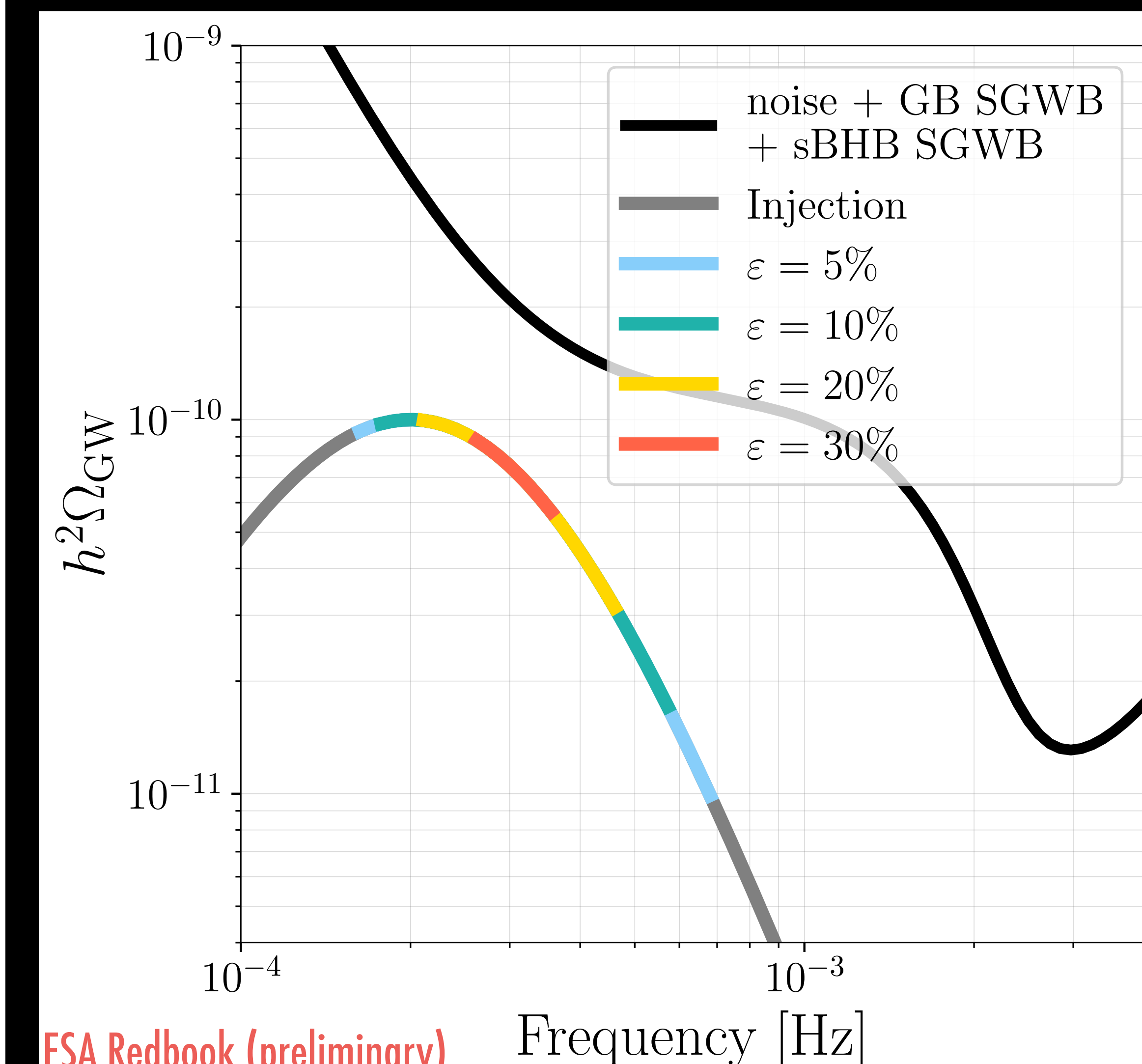


Stochastic backgrounds

- Large uncertainties on the prediction but huge potential of discovery



ESA Redbook (preliminary)

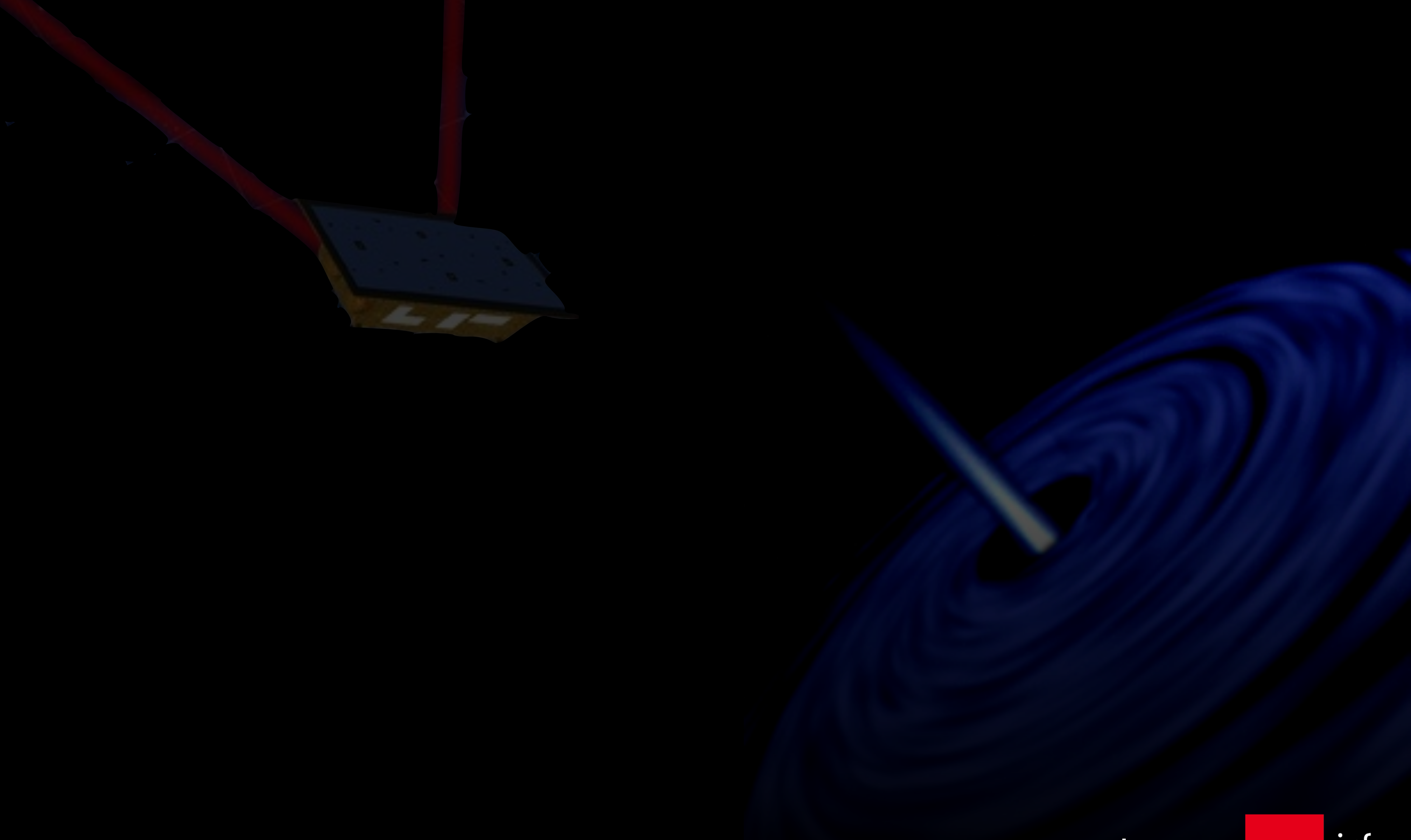


ESA Redbook (preliminary)

Science Objectives

Science Objectives

- SO1 : Study the formation and evolution of compact binary stars in the Milky Way Galaxy:



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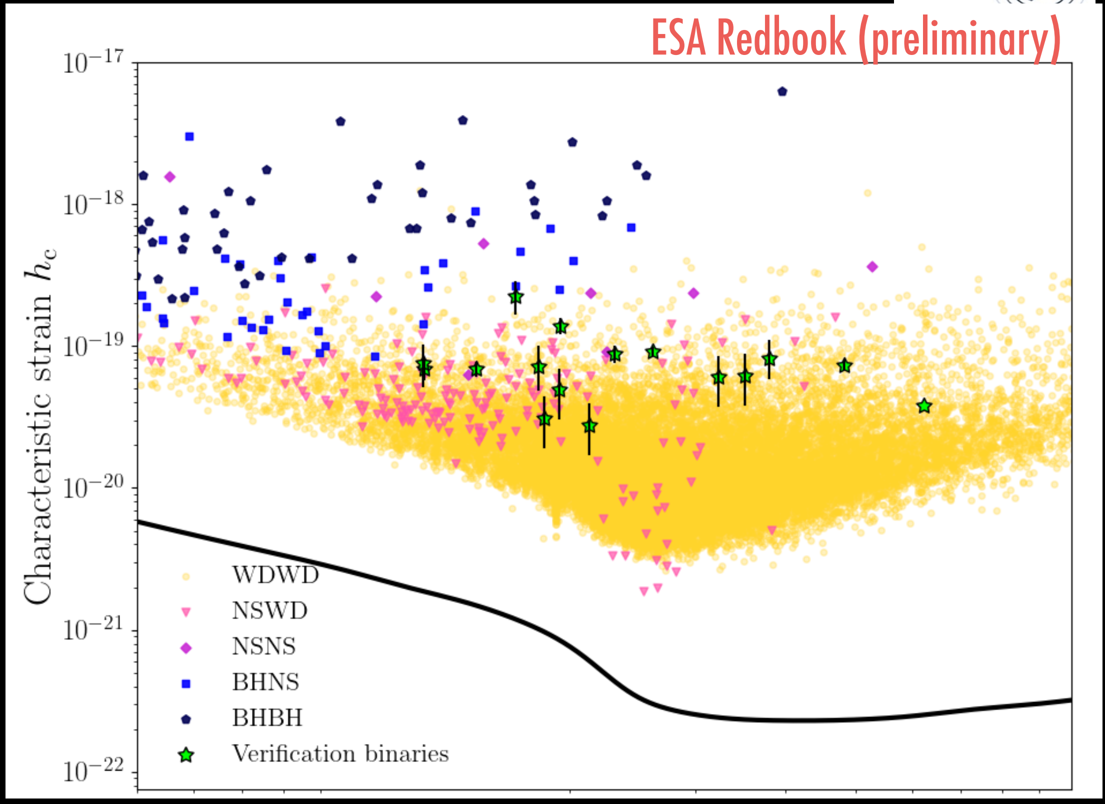
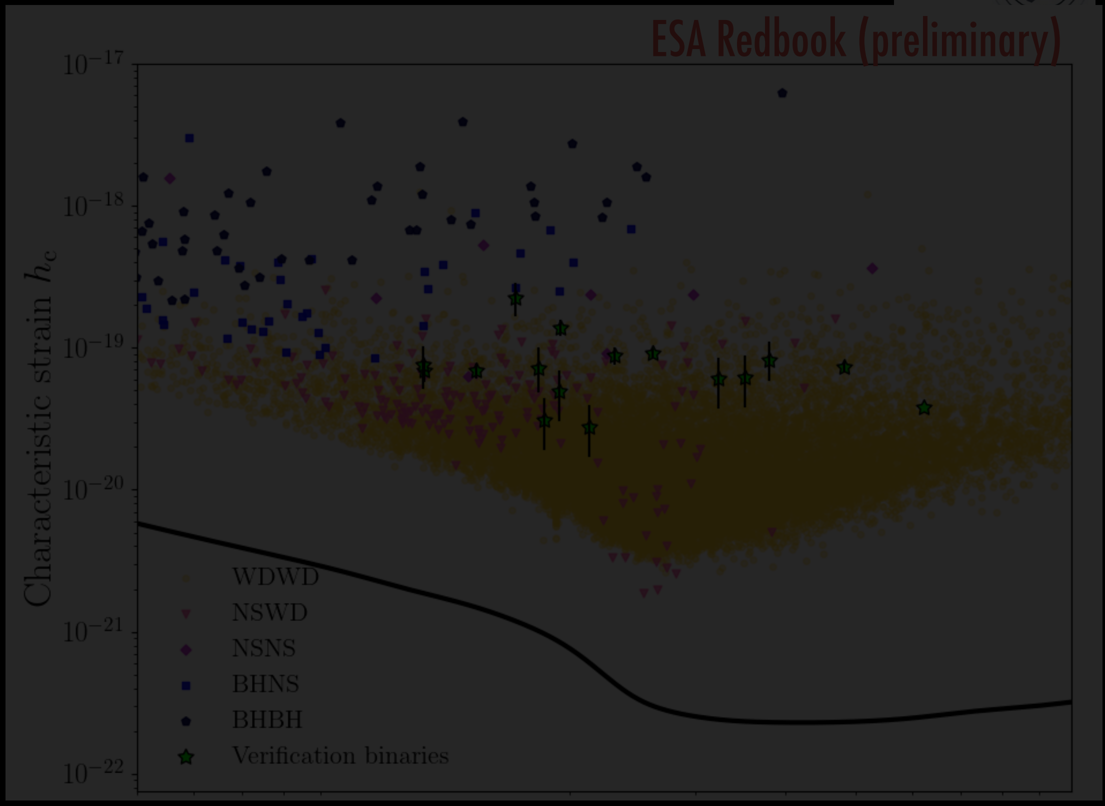


- How do binary stars evolve into close double compact systems?
- What is the current merger rate of white dwarfs, neutron stars and stellar-mass black holes in the Milky Way?

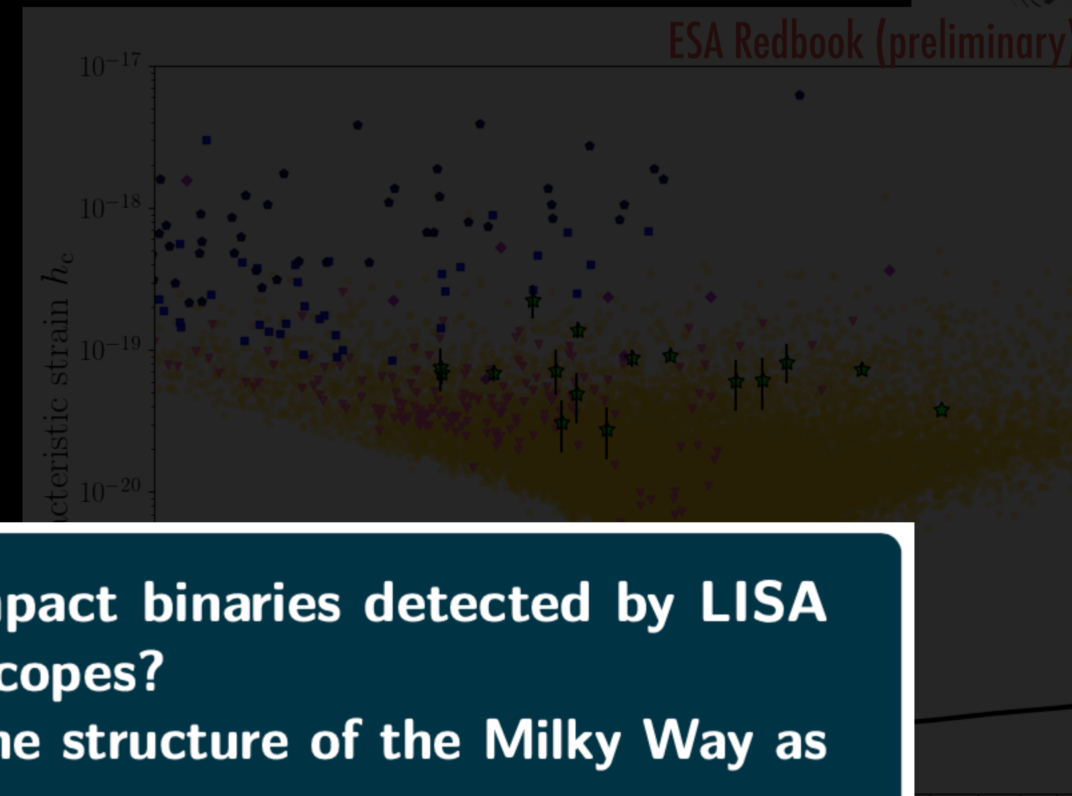
SI 1.1 aims at detecting GWs from the population of compact binaries in the Milky Way to study the evolution leading up to the formation of close double compact objects, including common envelopes, NS and BH formation and kicks. The measurements can be used to directly infer the merger rates of WDs, NSs and BHs in our Galaxy and thus better constrain the explosive events associated with these mergers.

Science Objectives

- **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;



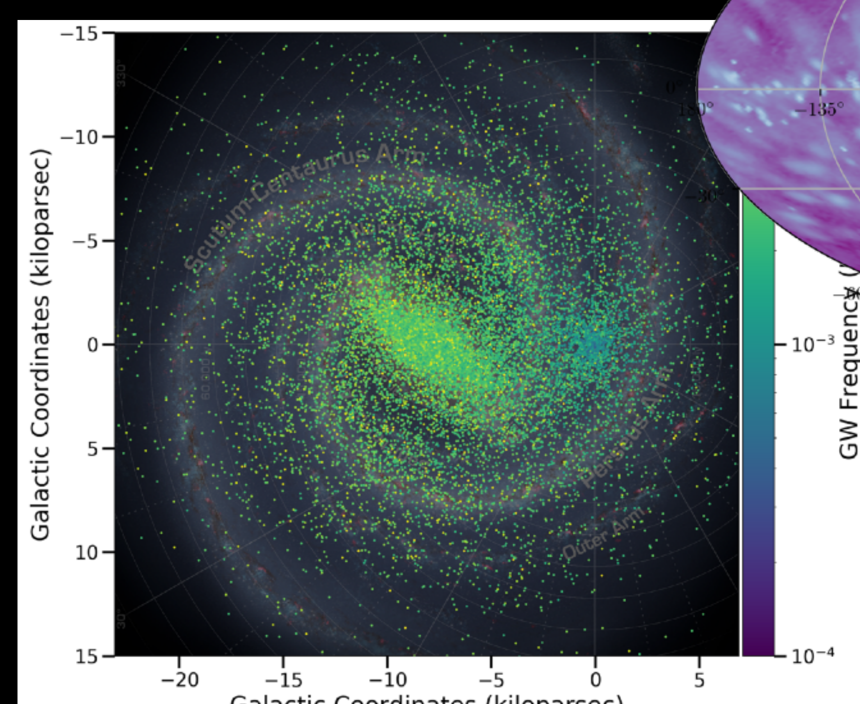
Science Objectives

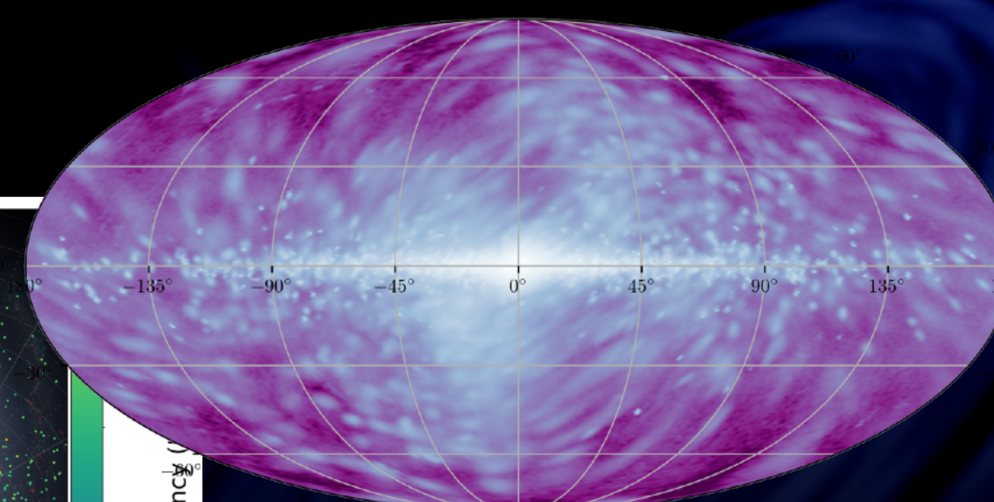


- SO1 : Study the formation and evolution of compact binary stars in the Milky Way Galaxy:

  - What is the spatial distribution of ultra-compact binaries detected by LISA that are too dim for detection with EM telescopes?
  - What can we learn from double WDs about the structure of the Milky Way as a whole?

- The Milky Way mass distribution;

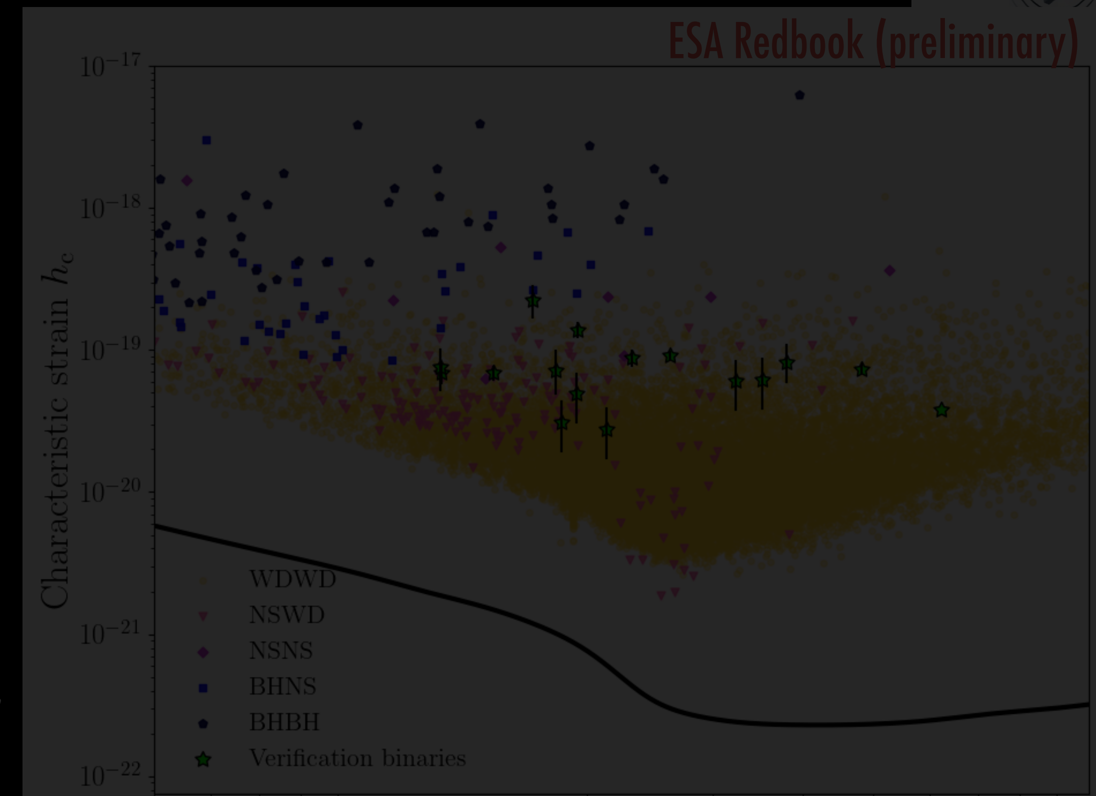


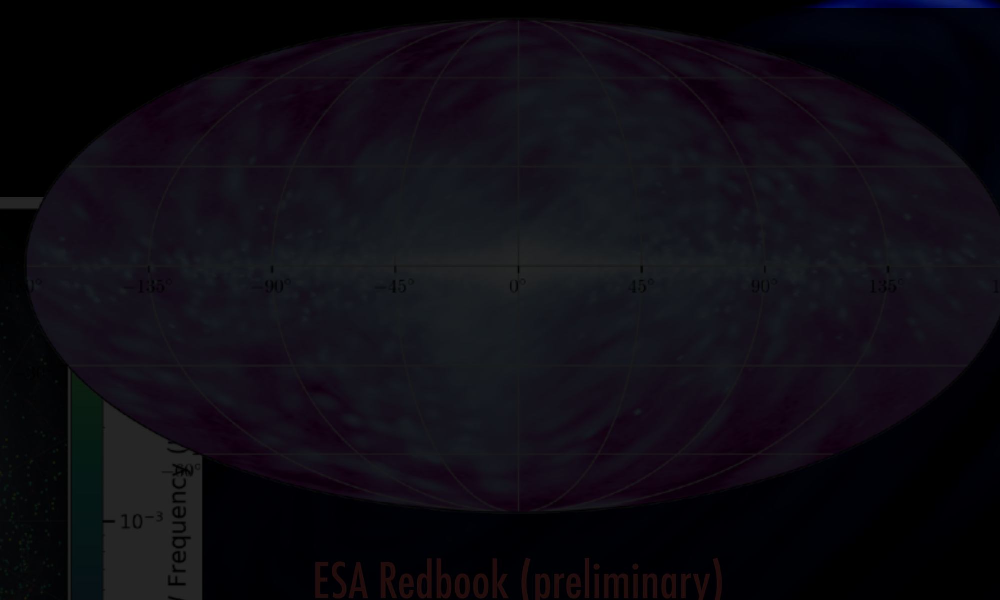


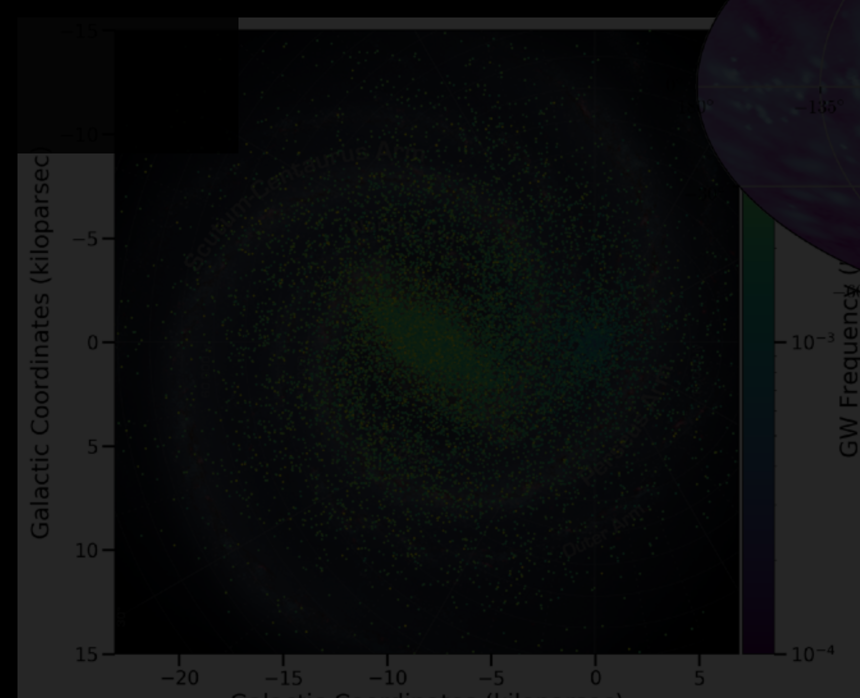
ESA Redbook (preliminary)

Science Objectives

- **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.







Science Objectives

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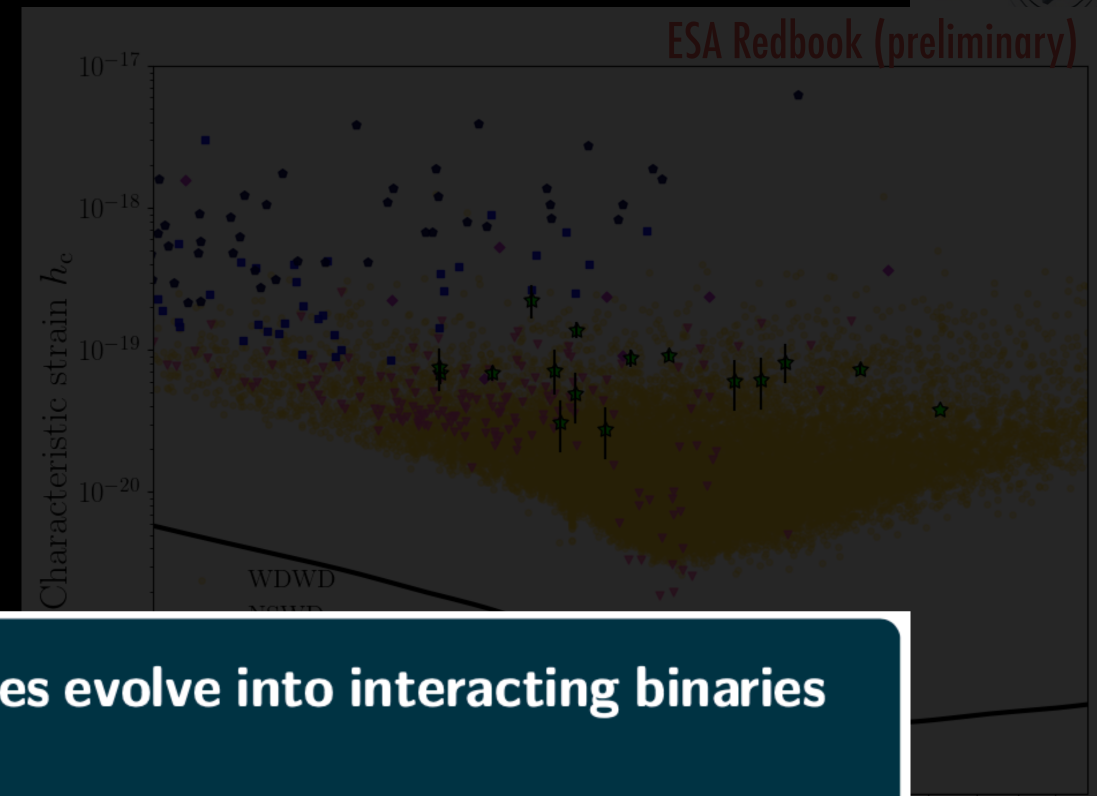
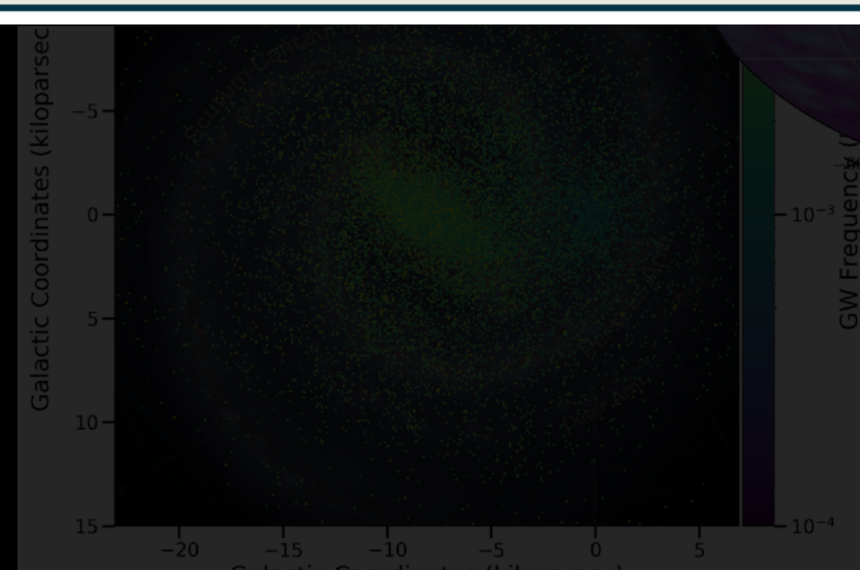
  - The interplay between gravitational waves and tidal dissipation.



- What fraction of detached ultra-compact binaries evolve into interacting binaries and avoid merger?
- What is the role of mass transfer, tides and GWs in the merger of systems, and what does it tell us about the explosion mechanism of type Ia supernovae?

SI 1.3 aims to determie the branching ratio between mergers and transition into stable mass transfer and at providing insight into the physics of tides in white dwarfs.



ESA Redbook (preliminary)

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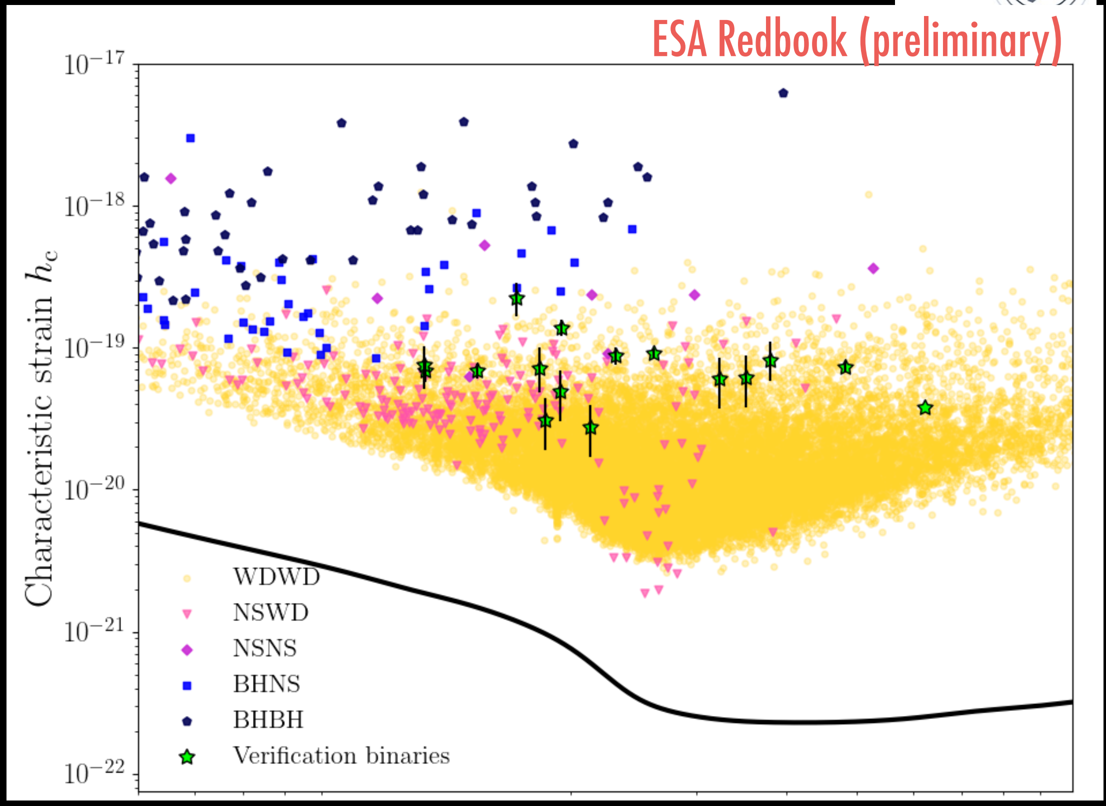
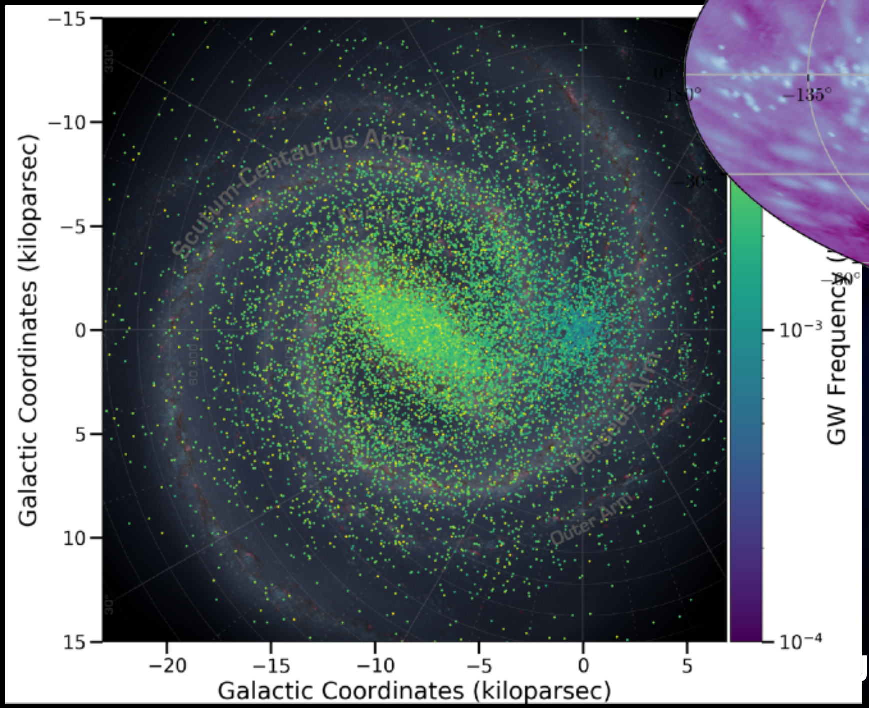
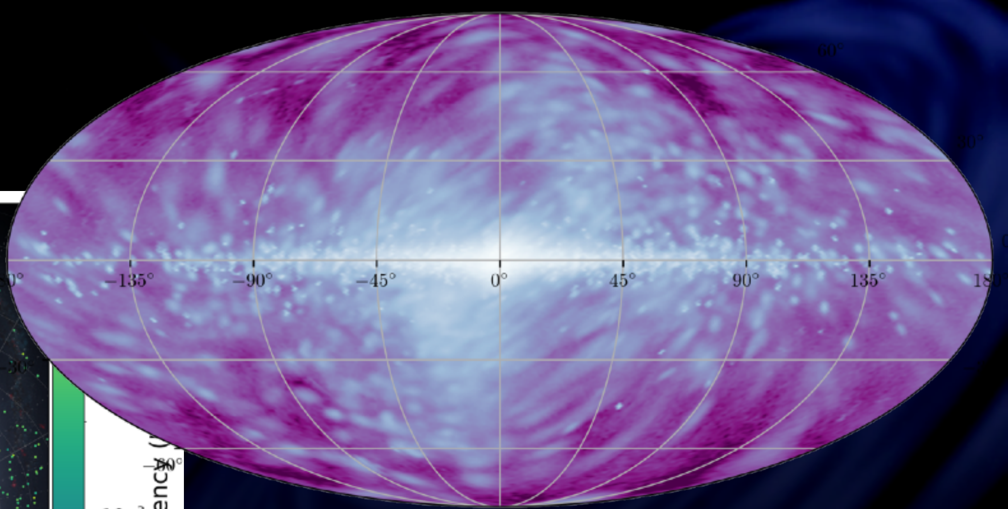
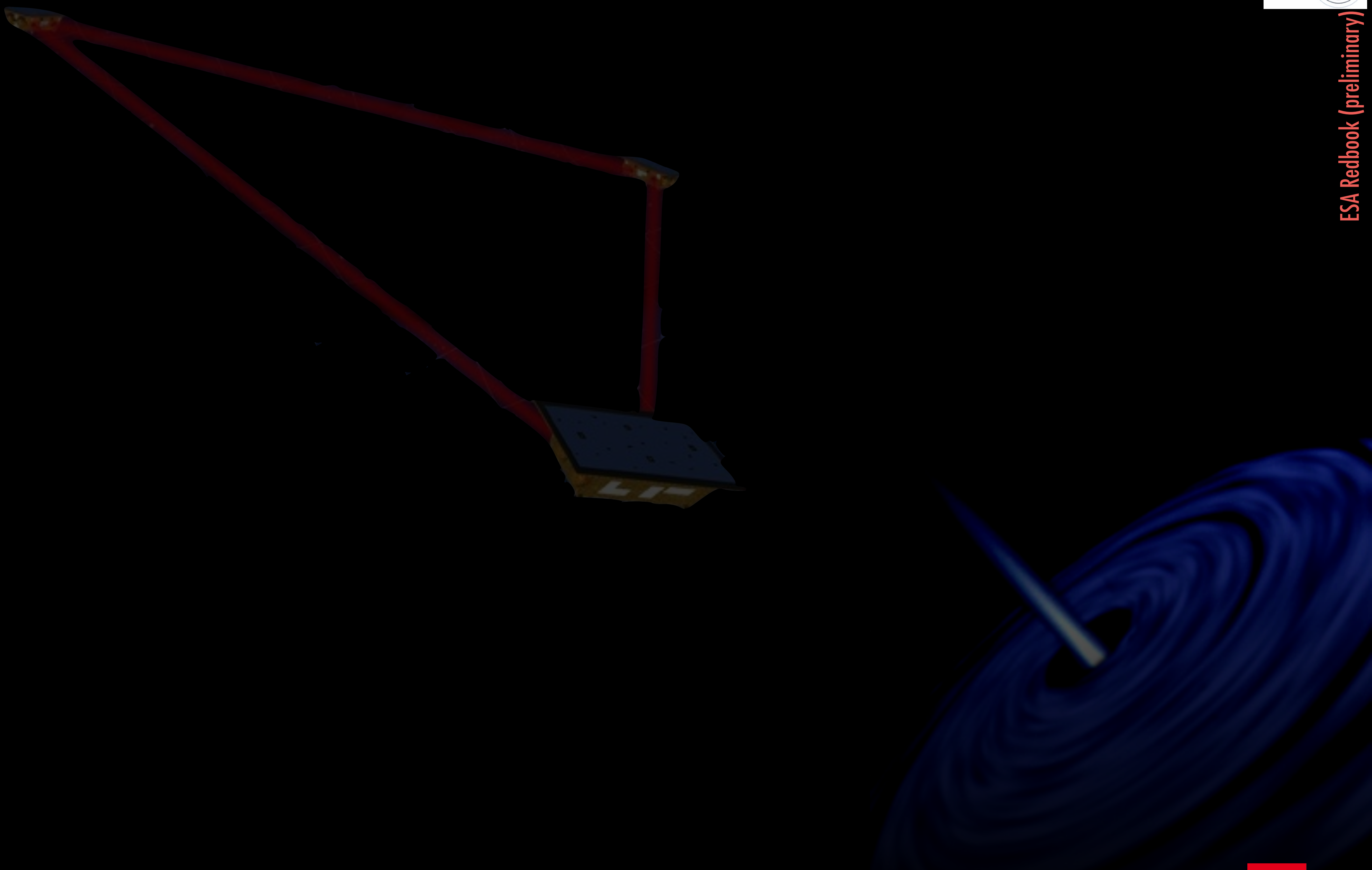






ESA Redbook (preliminary)

Science Objectives



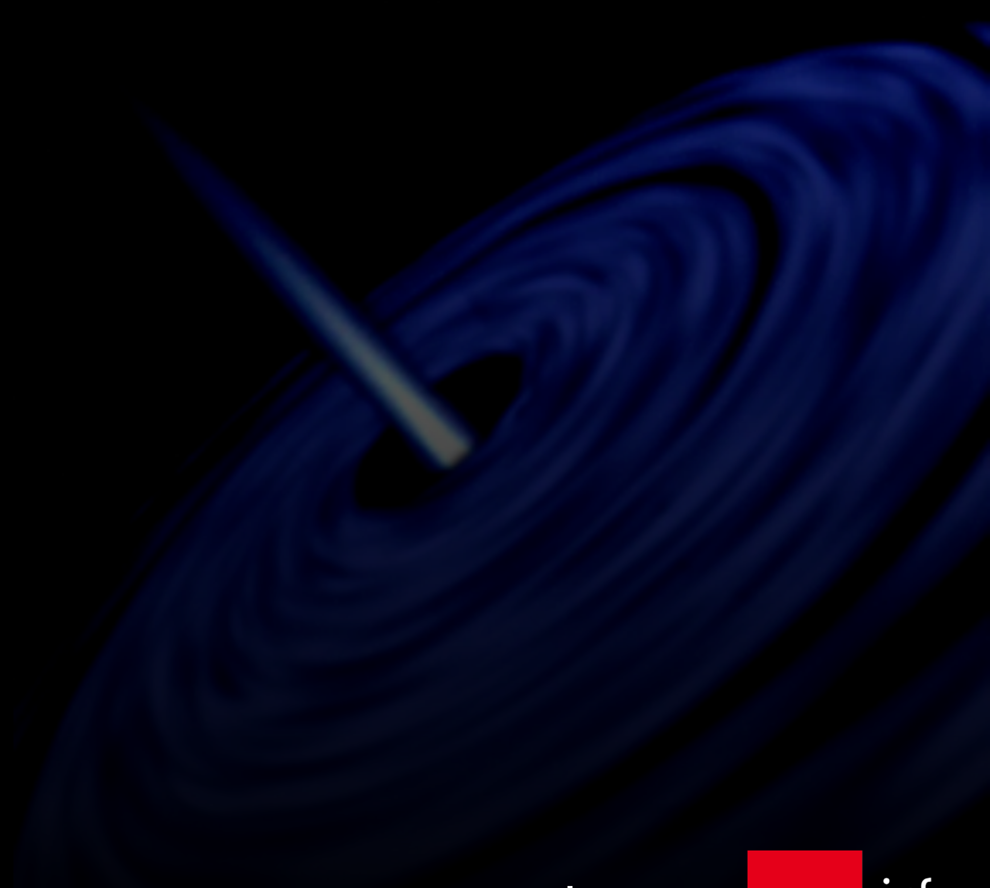
ESA Redbook (preliminary)

ESA Redbook (preliminary)

Science Objectives

ESA Redbook (preliminary)

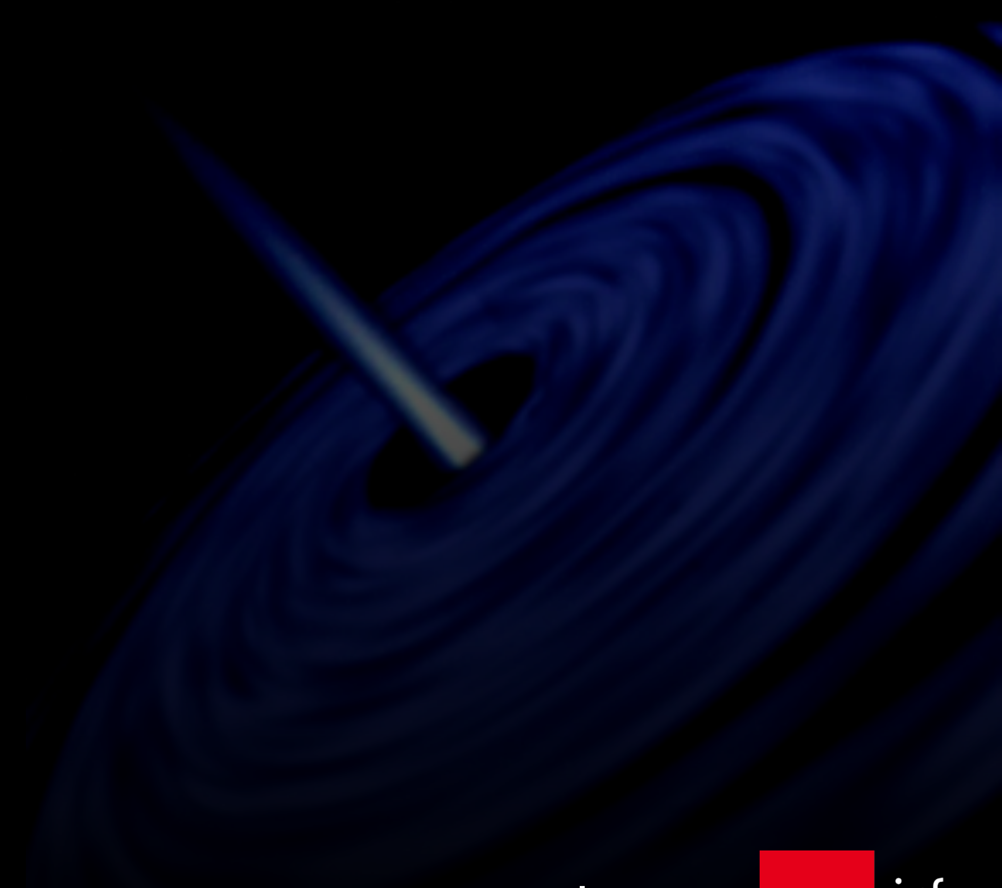
- SO2 : Trace the origin, growth and merger history of massive black holes across cosmic ages:



ESA Redbook (preliminary)

Science Objectives

- SO2 : Trace the origin, growth and merger history of massive black holes across cosmic ages:
  - Discover seed black holes at cosmic dawn;



ESA Redbook (preliminary)

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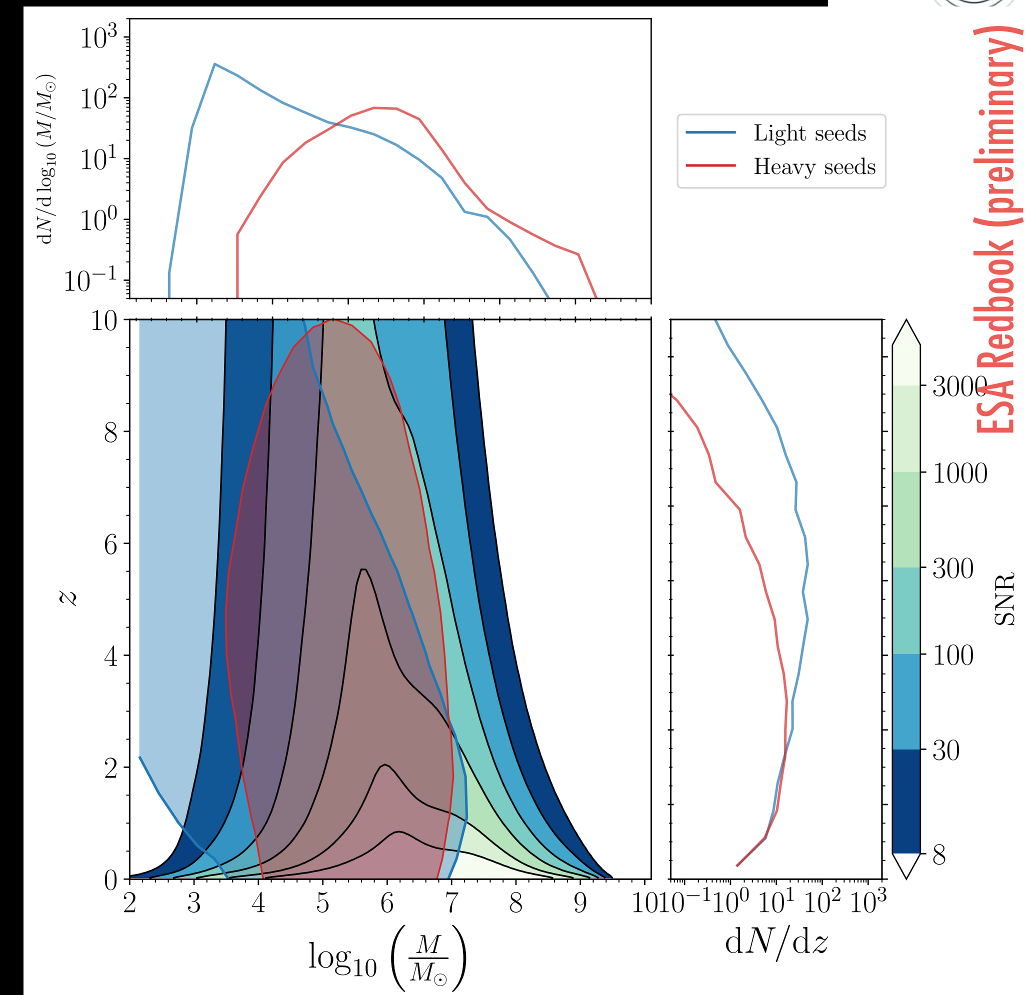


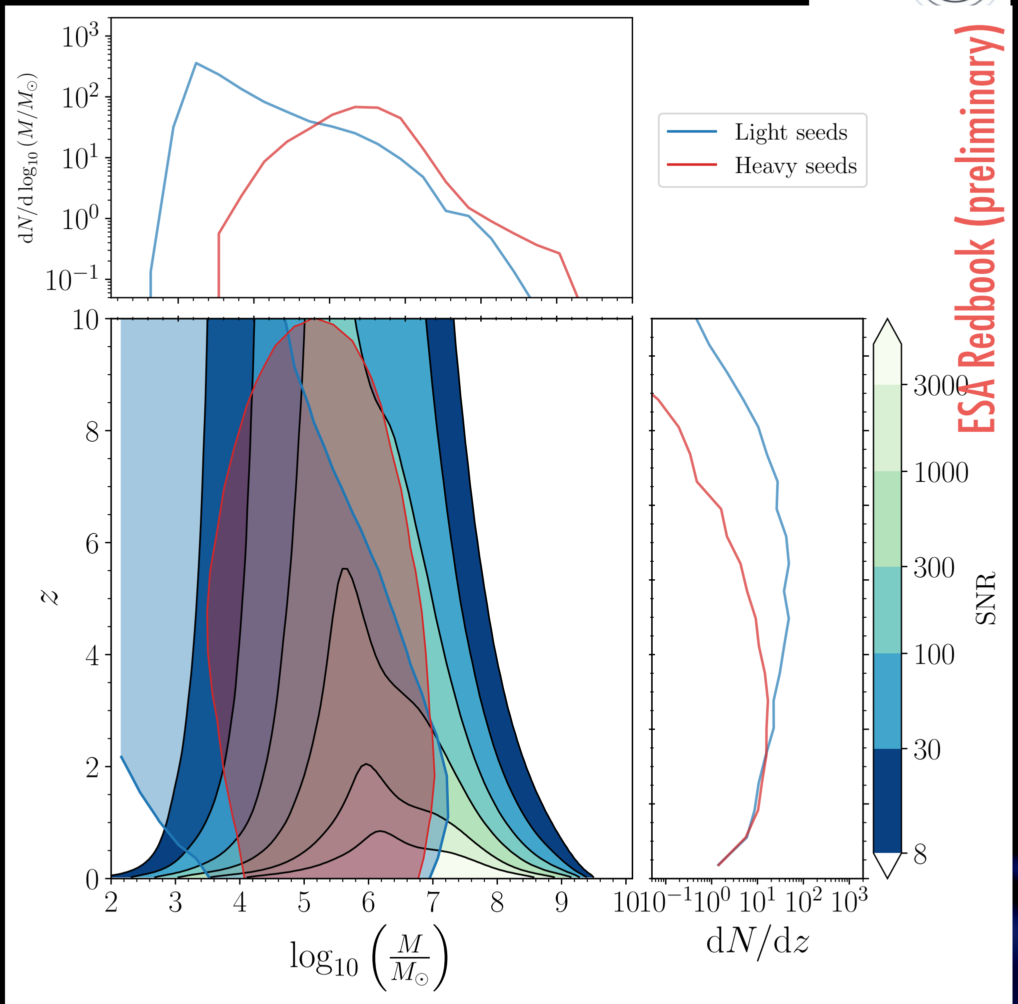
- How were MBHs born and how did they grow?
- What is the nature of the seed masses and how and when did they form?
- Are sBHs the only elementary building blocks of MBHs?

SI 2.1 aims to detect the GW signals from the earliest MBHBs in the mass interval between about $5 \times 10^3\ M_\odot$ and $5 \times 10^6\ M_\odot$, as measured in the source-frame, and at formation redshifts between $10 \lesssim z \lesssim 15$, to inform us about the physics producing the seeds and their early growth and assembly, providing knowledge of this pristine population that will anchor the initial conditions of MBH cosmic evolution.

ESA Redbook (preliminary)

Science Objectives

- 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;



ESA Redbook (preliminary)

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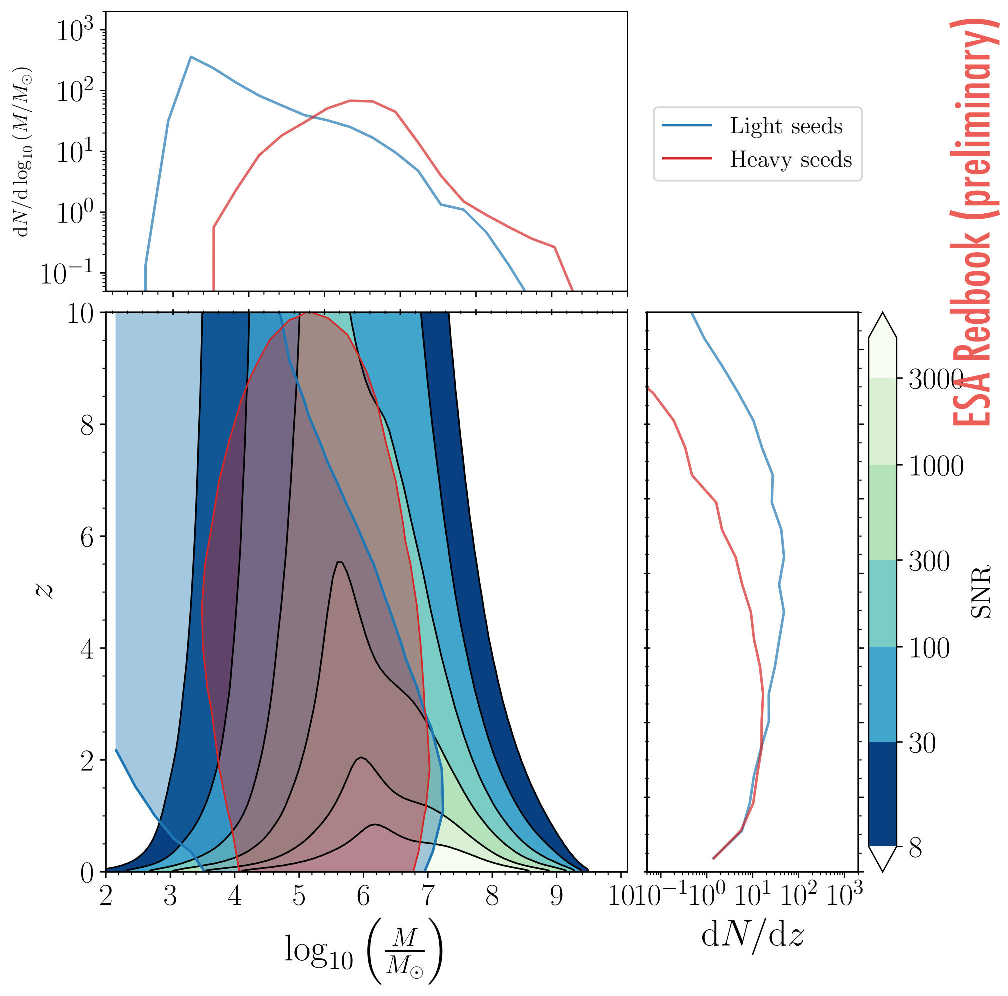
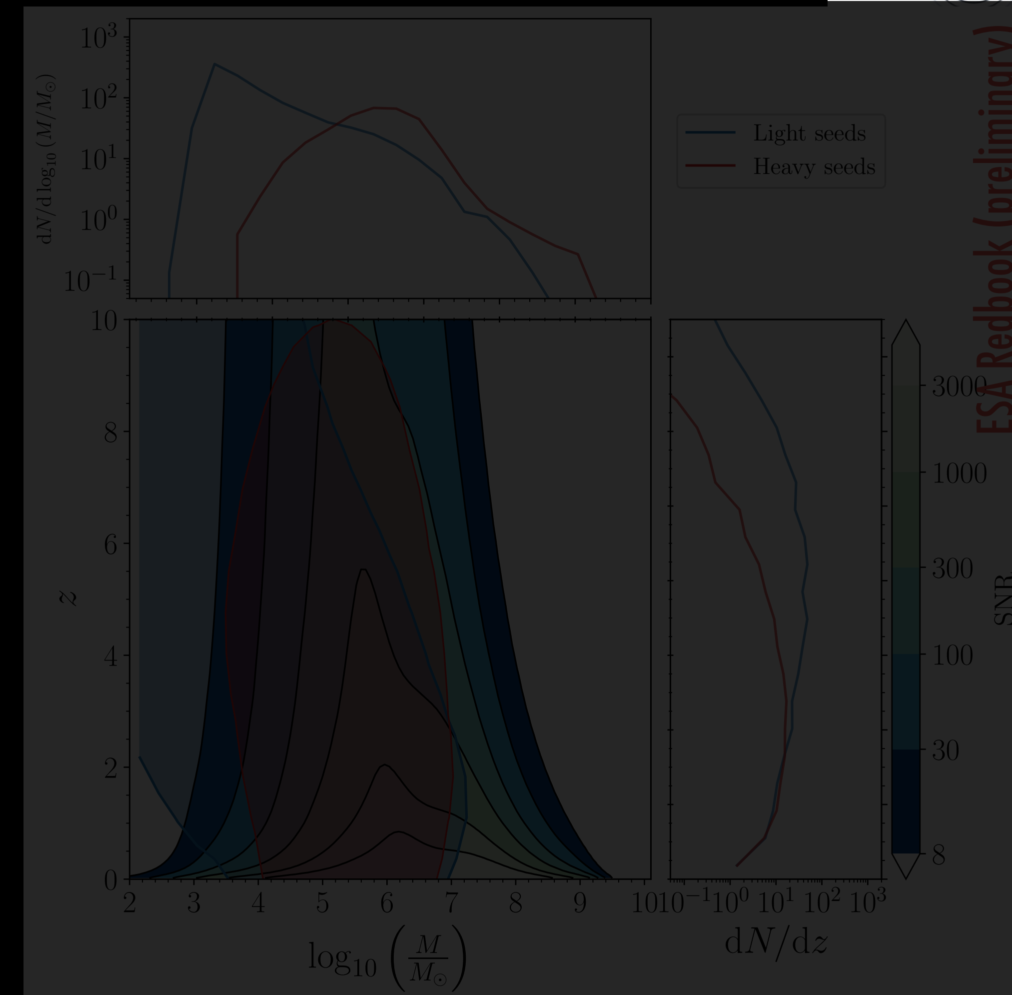


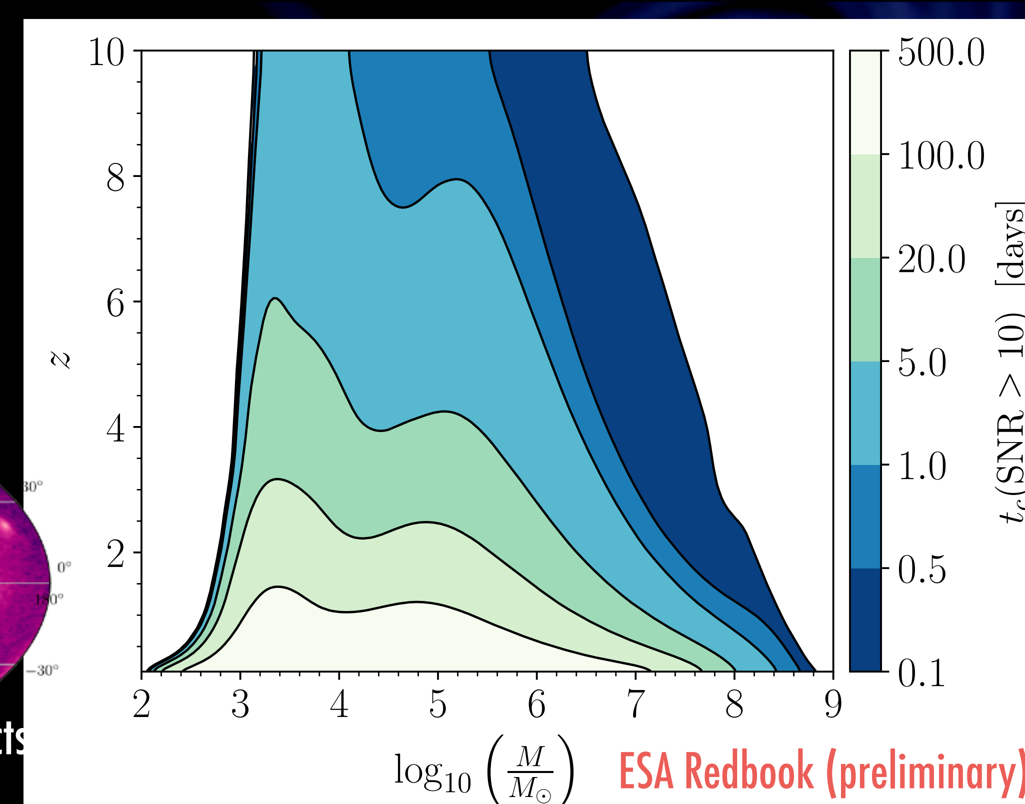
- How do MBHs grow in mass?
- How do MBH spins evolve?
- How do MBHs assemble inside the cosmic web?
- How efficiently do MBHs merge and when?

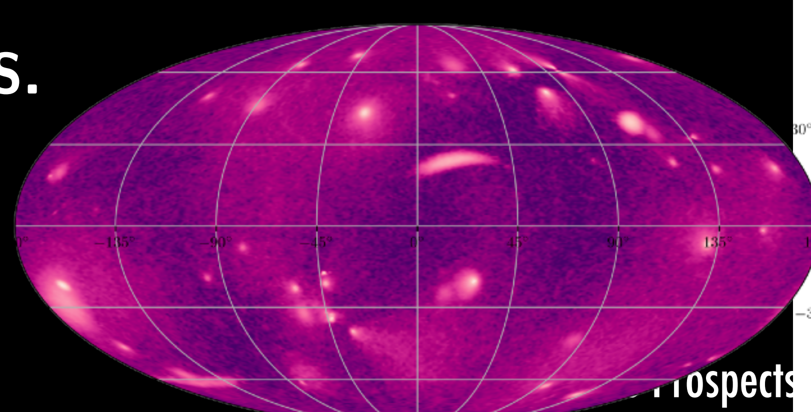
SI 2.2 aims to detect the inspiral, merger, and ringdown signal from MBHB between a few 10^4 $M_\odot$ up to $\sim 10^7$ $M_\odot$, at redshift $z \lesssim 8$.

Science Objectives

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

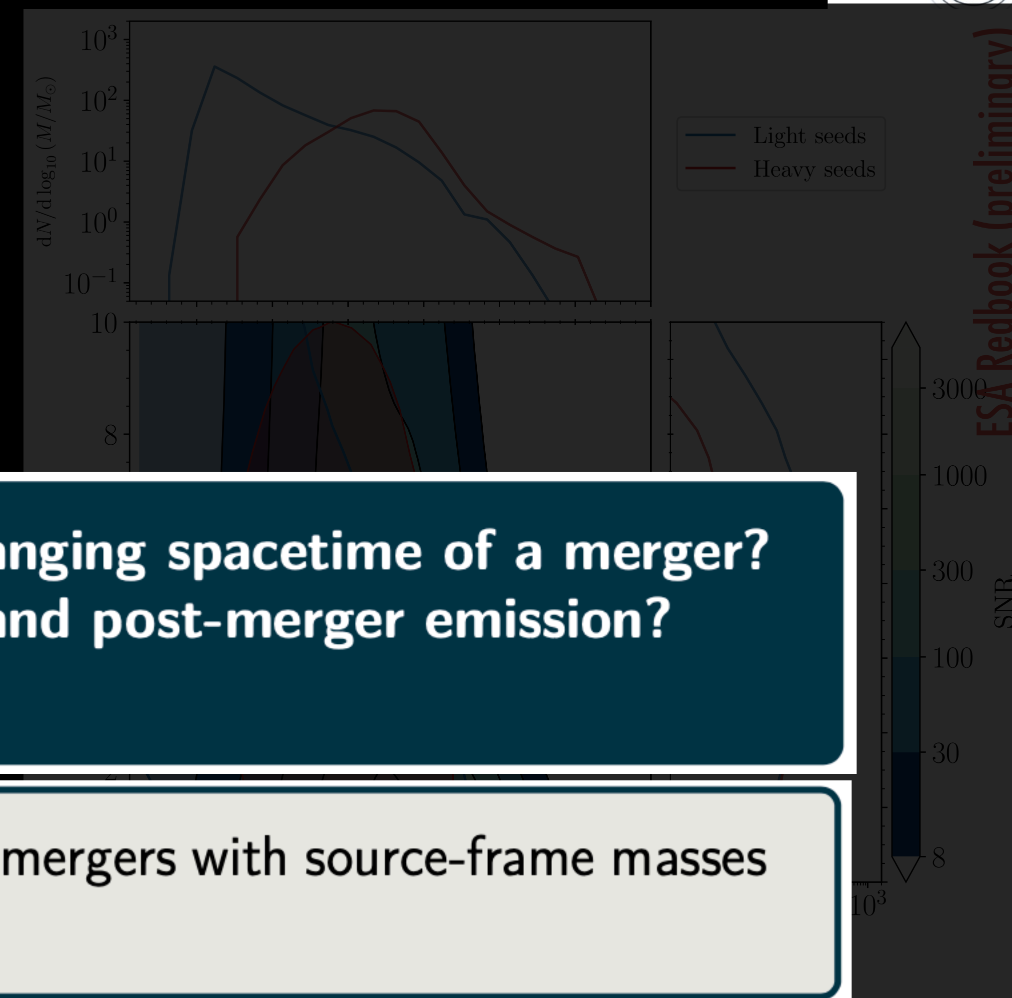






Science Objectives

- SO2 : Trace the origin, growth and merger history of massive black holes across cosmic ages:

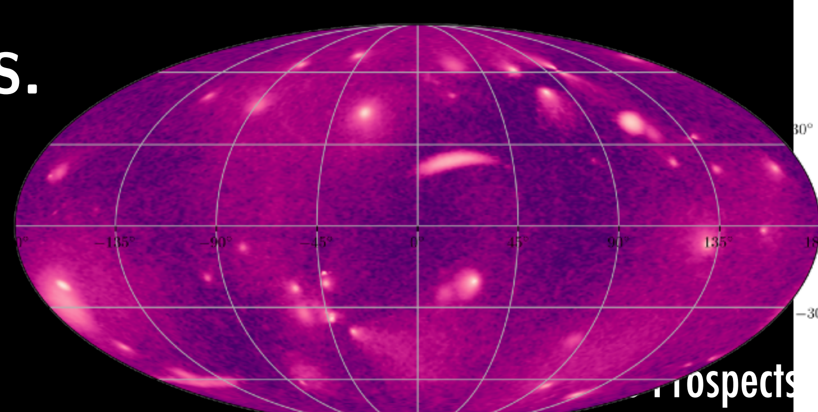


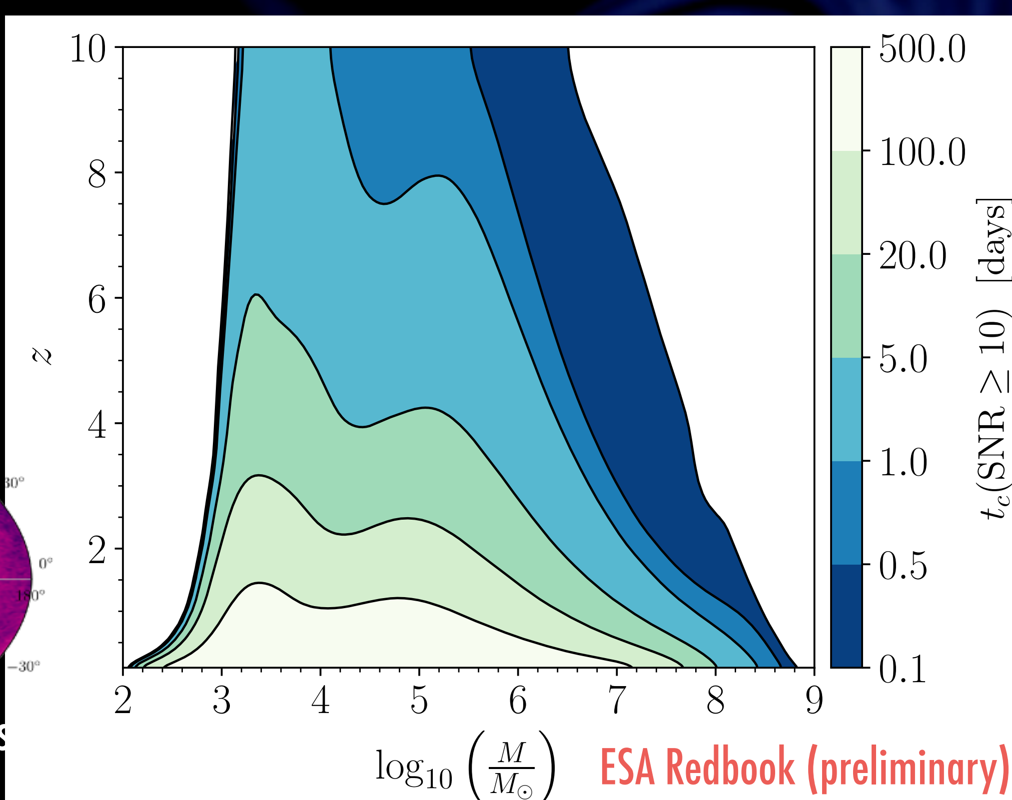
- How does accretion proceed in the violently changing spacetime of a merger?
- Which are the EM signatures of the precursor and post-merger emission?
- Can we identify the host galaxy?

SI 2.3 aims to detect joint GW and EM signals from MBHB mergers with source-frame masses between $10^5\ M_\odot$ and $\lesssim 10^7\ M_\odot$ below $z \lesssim 3$.

from the epoch of the earliest quasars;

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





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Science Objectives

- 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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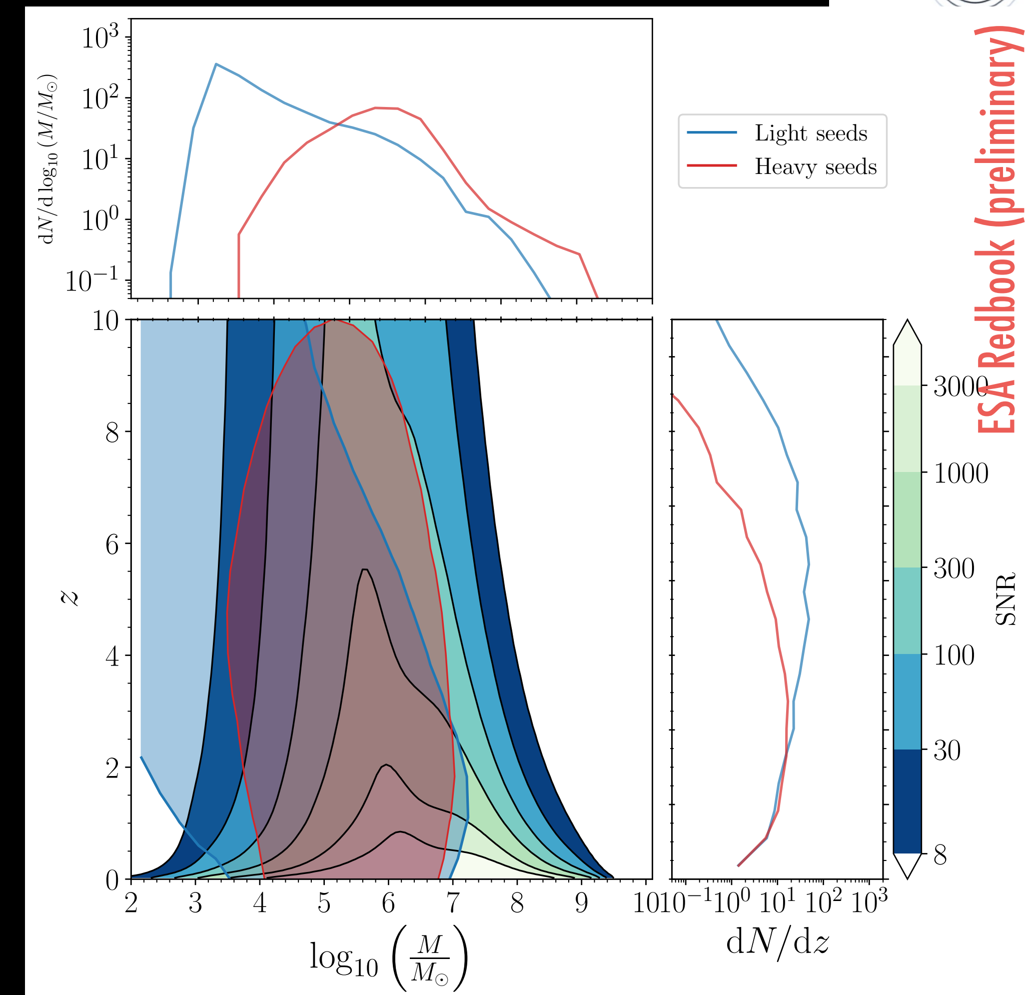
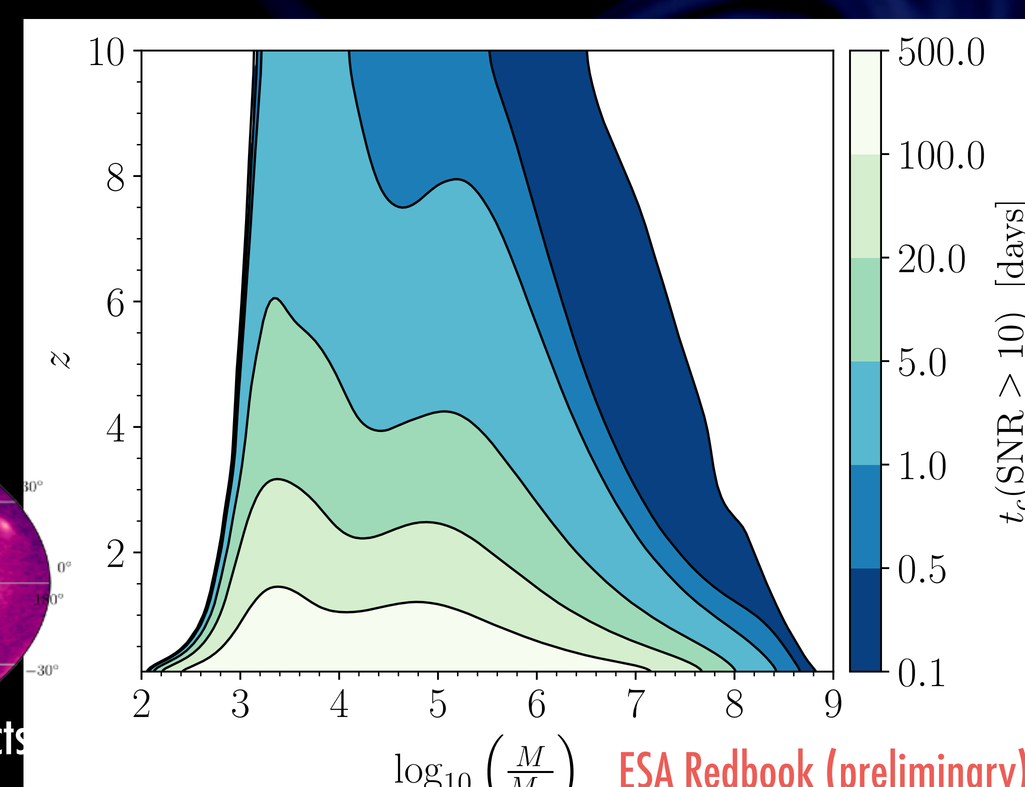
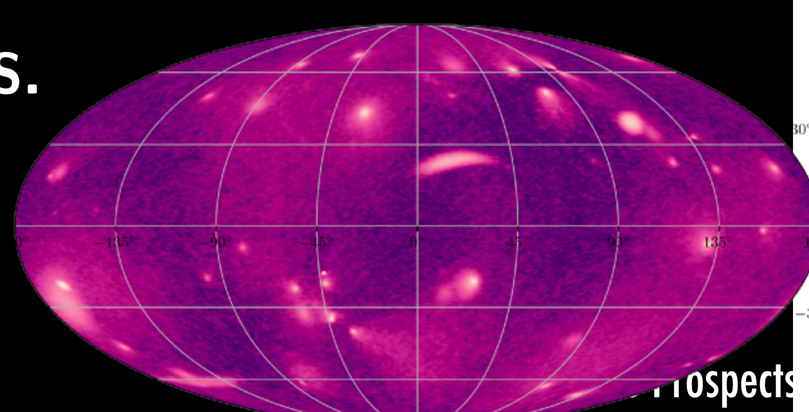
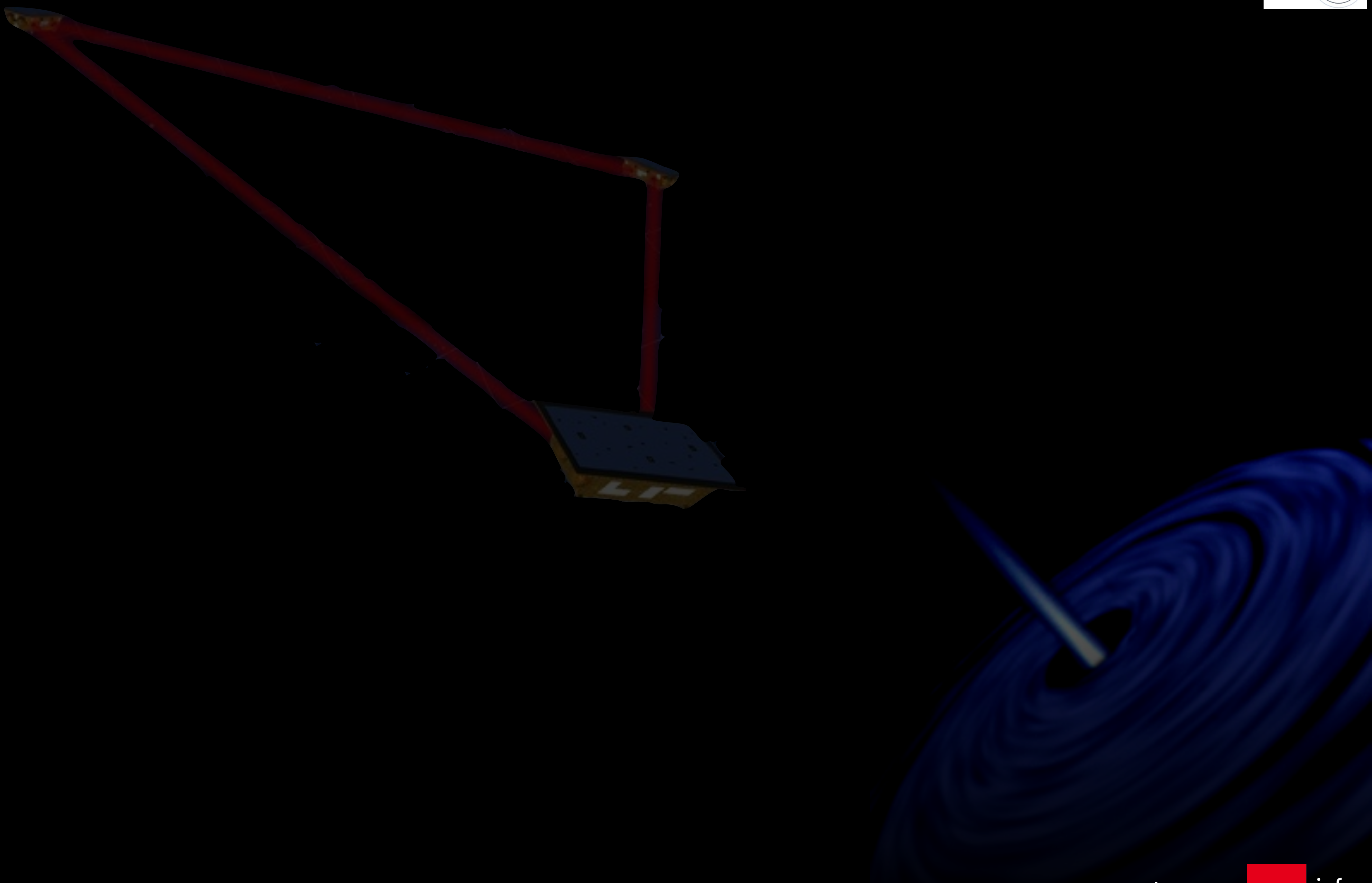




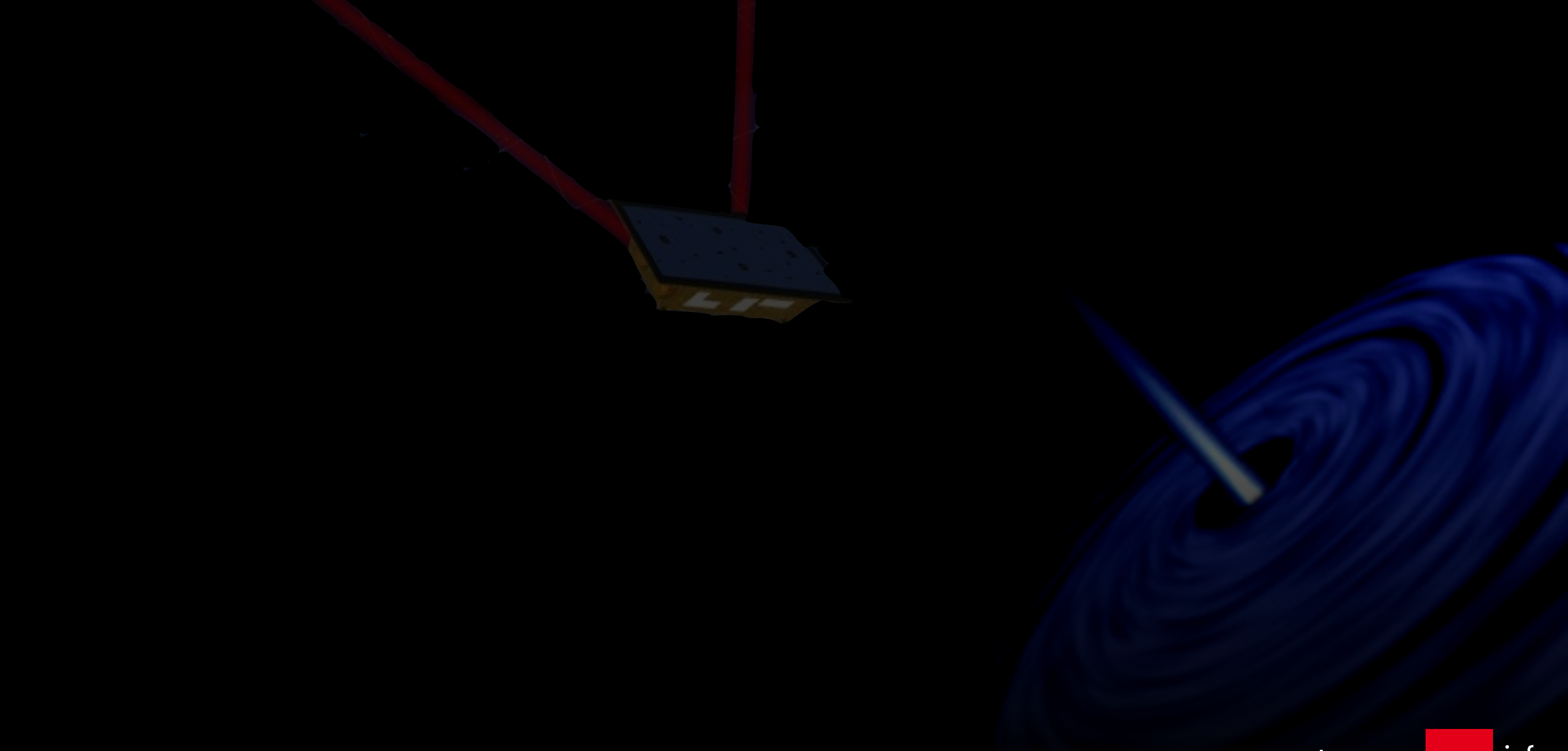


Science Objectives



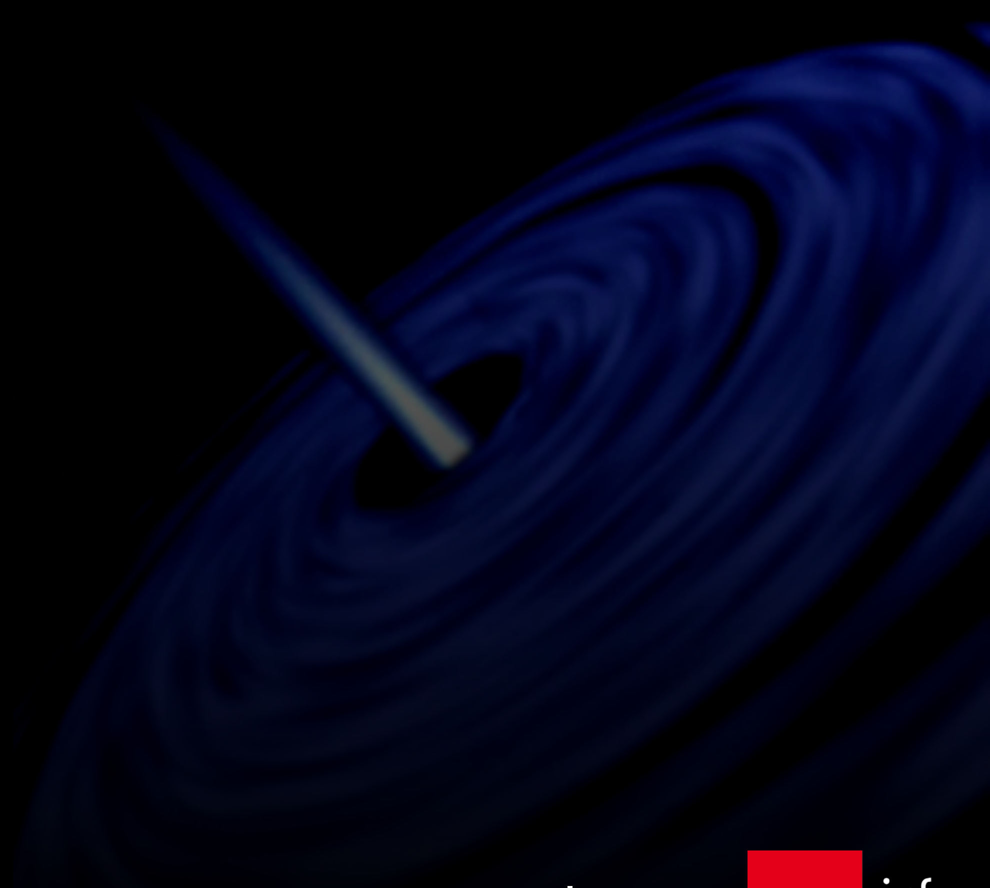
Science Objectives

- SO3 : Probe the dynamics of dense nuclear clusters using EMRIs:



Science Objectives

- **SO3 : Probe the dynamics of dense nuclear clusters using EMRIs:**
  - Study the properties and immediate environment of Milky Way-like MBHs using EMRIs;



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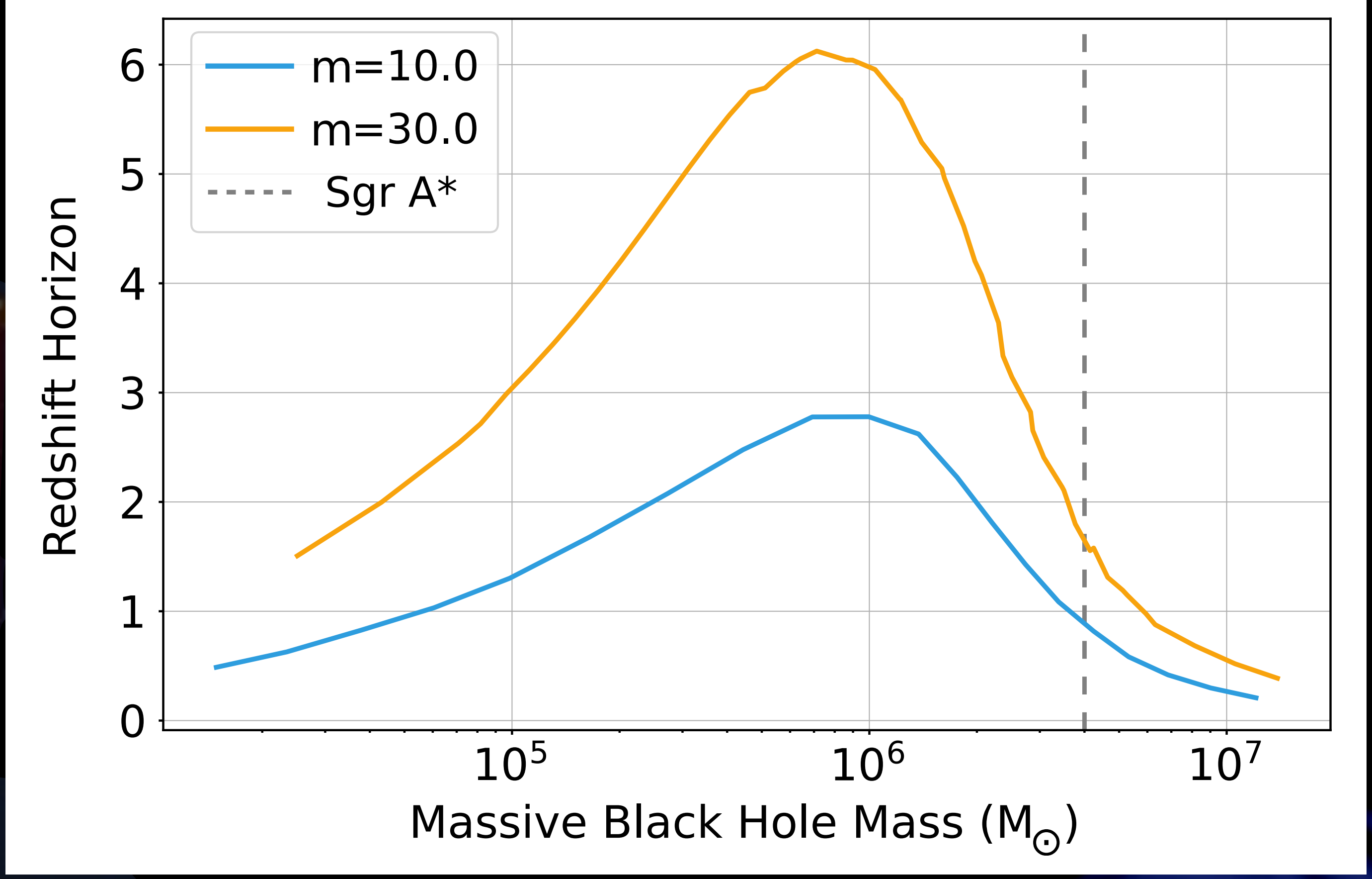
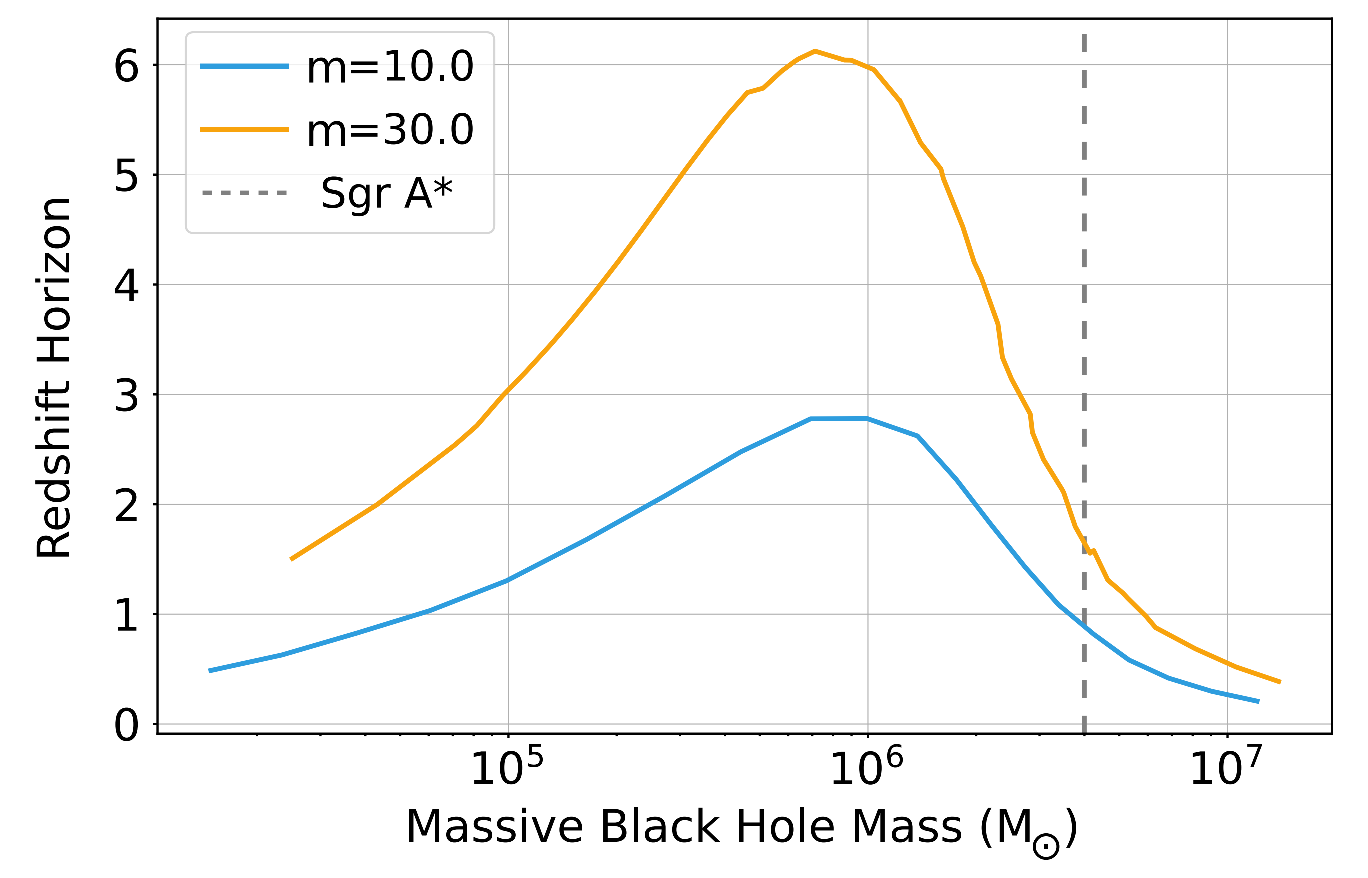


- What are the mass and spin distributions of MBHs?
- What stellar and gaseous environments do these MBHs live in?
- Which physical process dominate stellar dynamics near to these MBHs?

SI 3.1 aims at detecting the GW signals from EMRIs with MBH masses between a few times $10^4\,M_\odot$ and a few times $10^6\,M_\odot$ at redshifts up to $z \sim 3$ for inspiraling objects of $m \gtrsim 10\,M_\odot$.

Science Objectives

- SO3 : Probe the dynamics of dense nuclear clusters using EMRIs:
  - Study the properties and immediate environment of Milky Way-like MBHs using EMRIs;
  - Study the IMBH population using IMRI.



- How readily do IMBHs form in stellar clusters and galactic nuclei?
- How do these IMBHs subsequently grow and what are there properties?
- How often do these IMBHs merge with MBHs?

SI 3.2 aims at detecting gravitational waves from IMRIs at low redshift, $z \lesssim 2$, in which the IMBH has mass in the range $10^3\,M_\odot$ to $10^4\,M_\odot$.

Science Objectives

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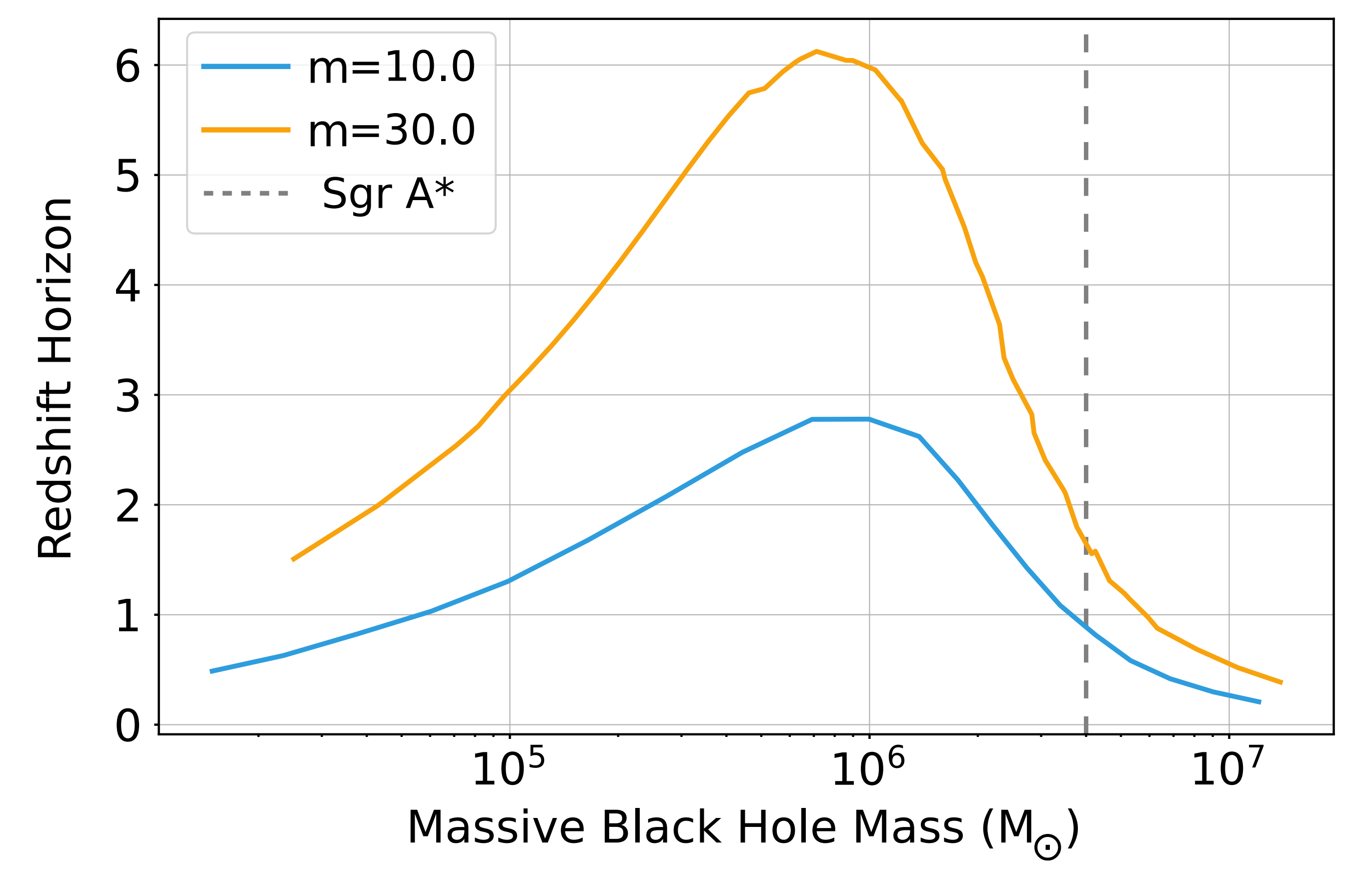
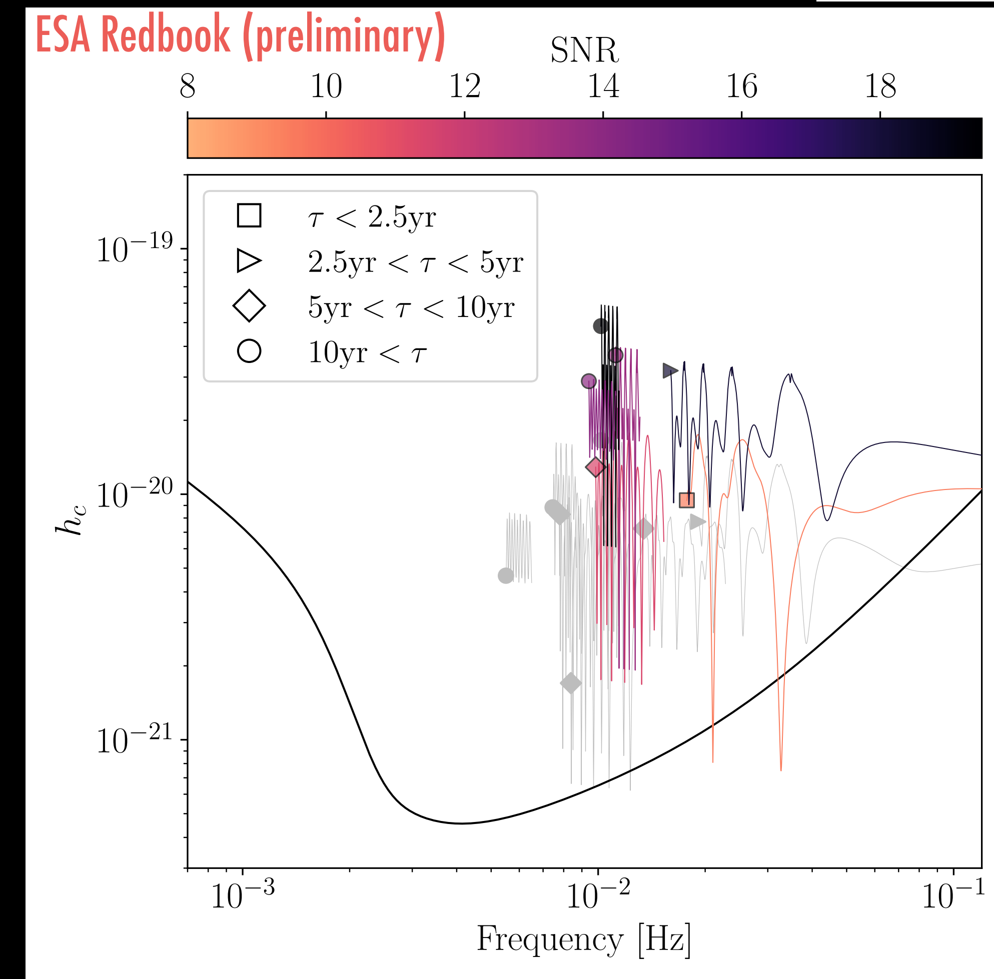
  - Study the properties and immediate environment of Milky Way-like MBHs using EMRIs;
  - Study the IMBH population using IMRI.

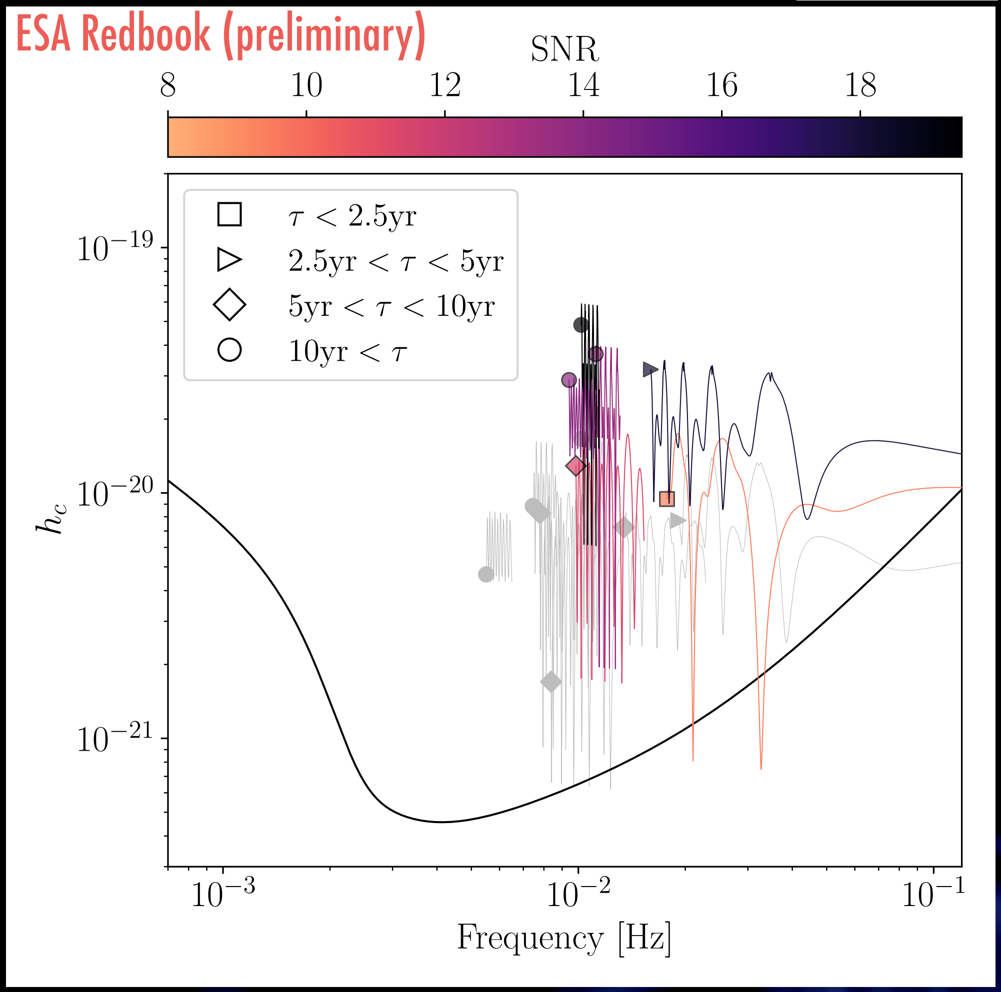


Science Objectives



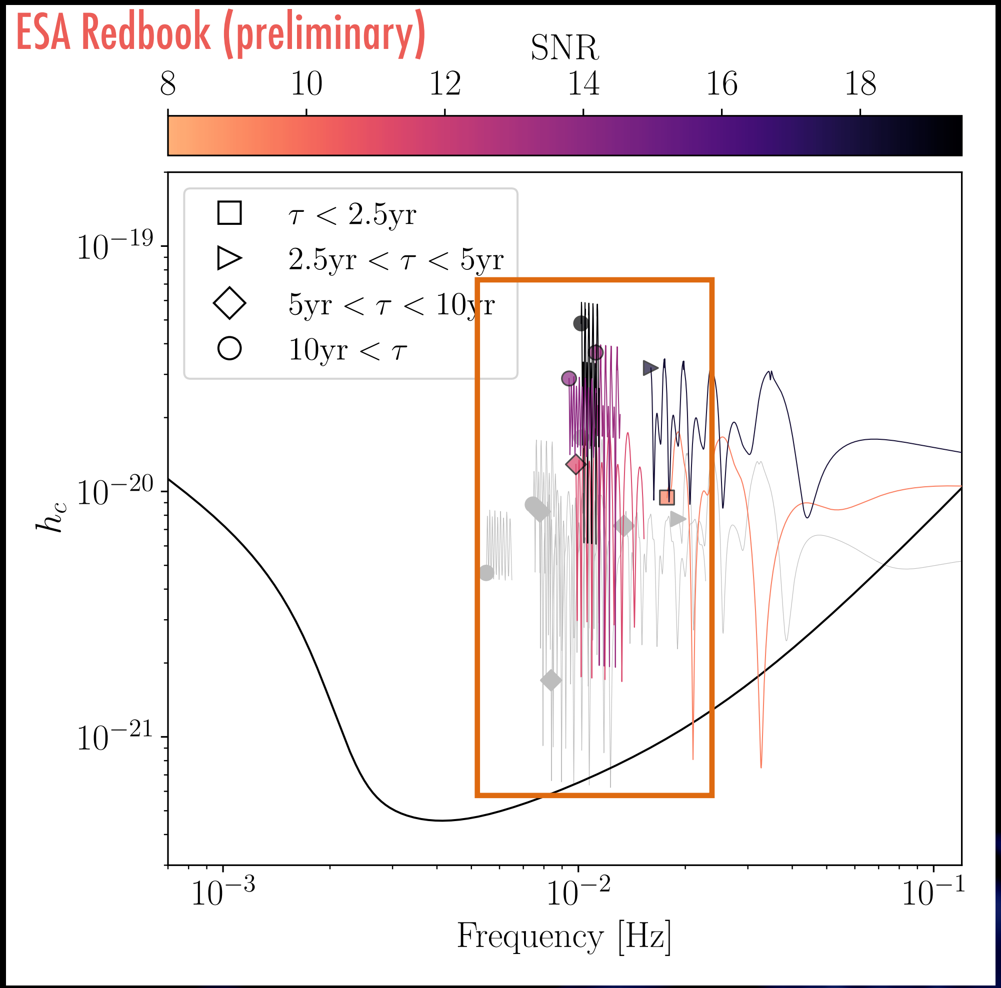
Science Objectives

- SO4 : Understand the astrophysics of stellar origin black holes :



Science Objectives

- SO4 : Understand the astrophysics of stellar origin black holes :
  - Study the statistical properties of sBHs far from merger;

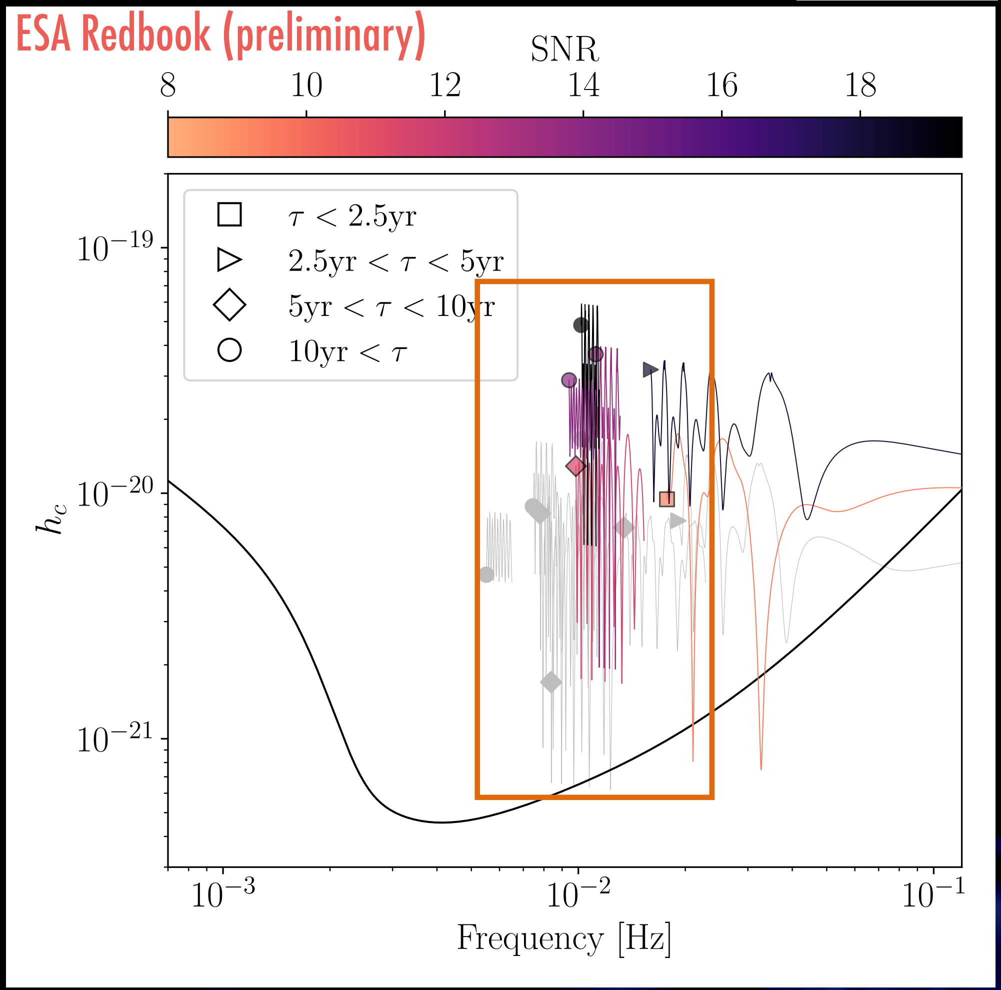


- **How are sBHB born?**
- **Are there multiple formation channels? To what extent does each channel contribute to the overall population?**

SI 4.1 aims at the individual detection of several sBHBs. The sub-percent measurement of their eccentricity will inform us about the physical mechanisms producing the bulk of their population, thus constraining the physics of binary stellar evolution and dynamics in dense environments.

Science Objectives

- 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;



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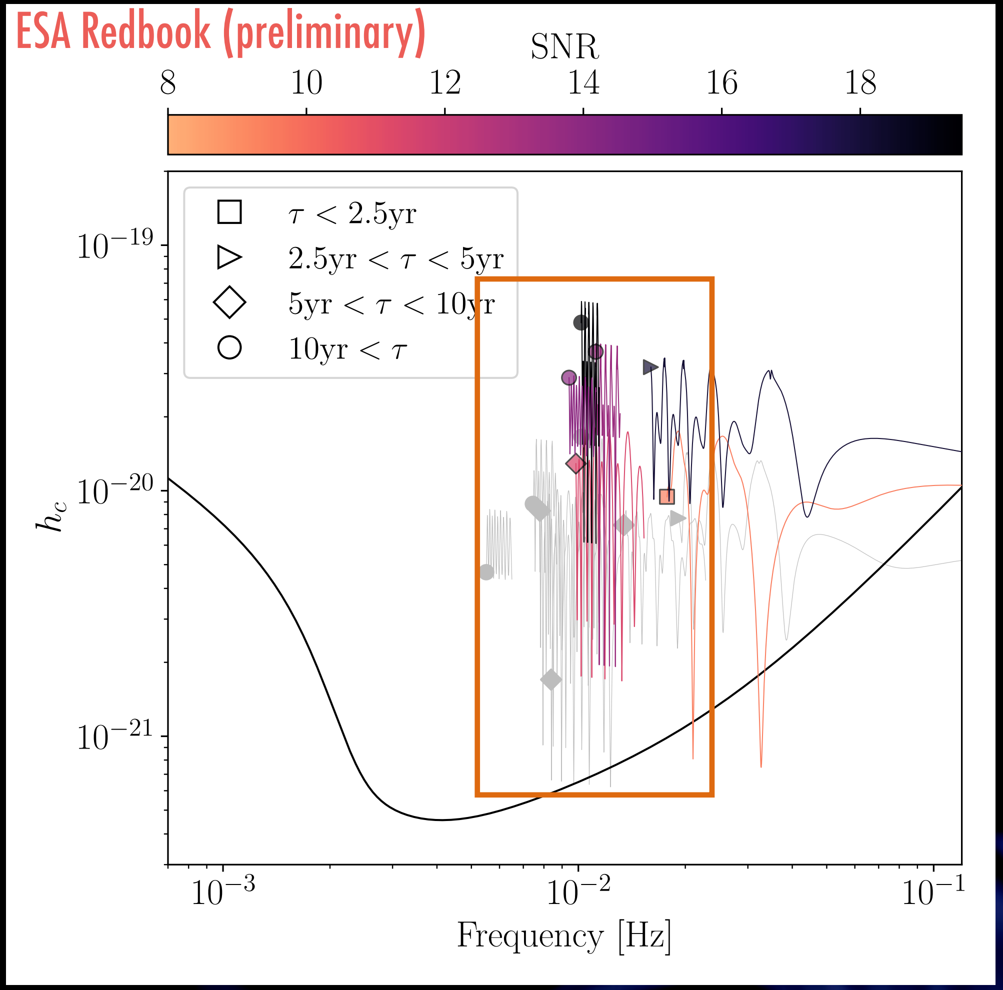
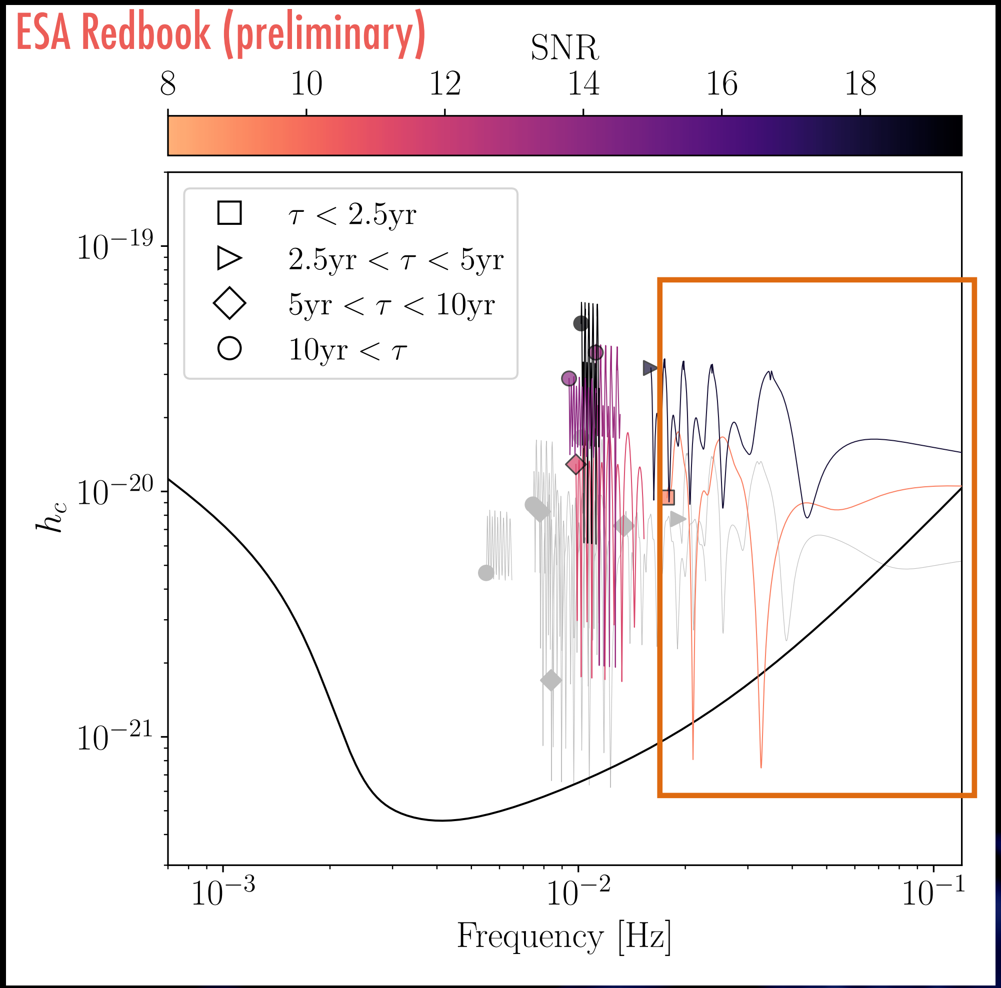


- How do BHs within and beyond the pair instability gap form?
- Do sBHBs efficiently form in AGN disks?
- Do hierarchical mergers of sBHBs occur in nature?

SI 4.2 aims at the detection of GW190521-like binaries. The measurement of their Center of Mass (CoM) acceleration and other environmental effects will help assessing their origin.

Science Objectives

- **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.



- **Are there any associated EM counterparts to merging sBHBs?**

SI 4.3 aims to detect GW150914-like binaries a few years prior to their coalescence. The inferred sky position and time to coalescence will inform ground-based GW detectors and EM observatories to enable the first GW multiband *and* multimessenger observations in astronomy.

Science Objectives

- 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;
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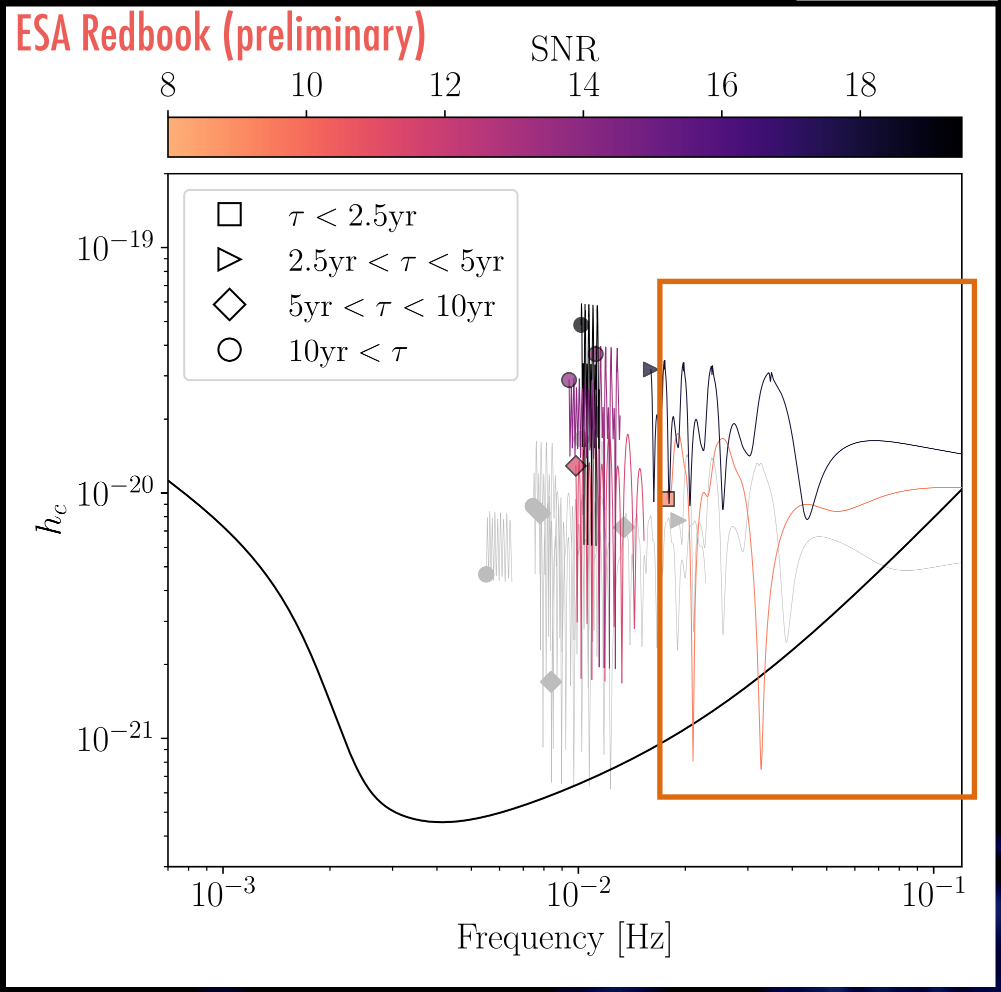

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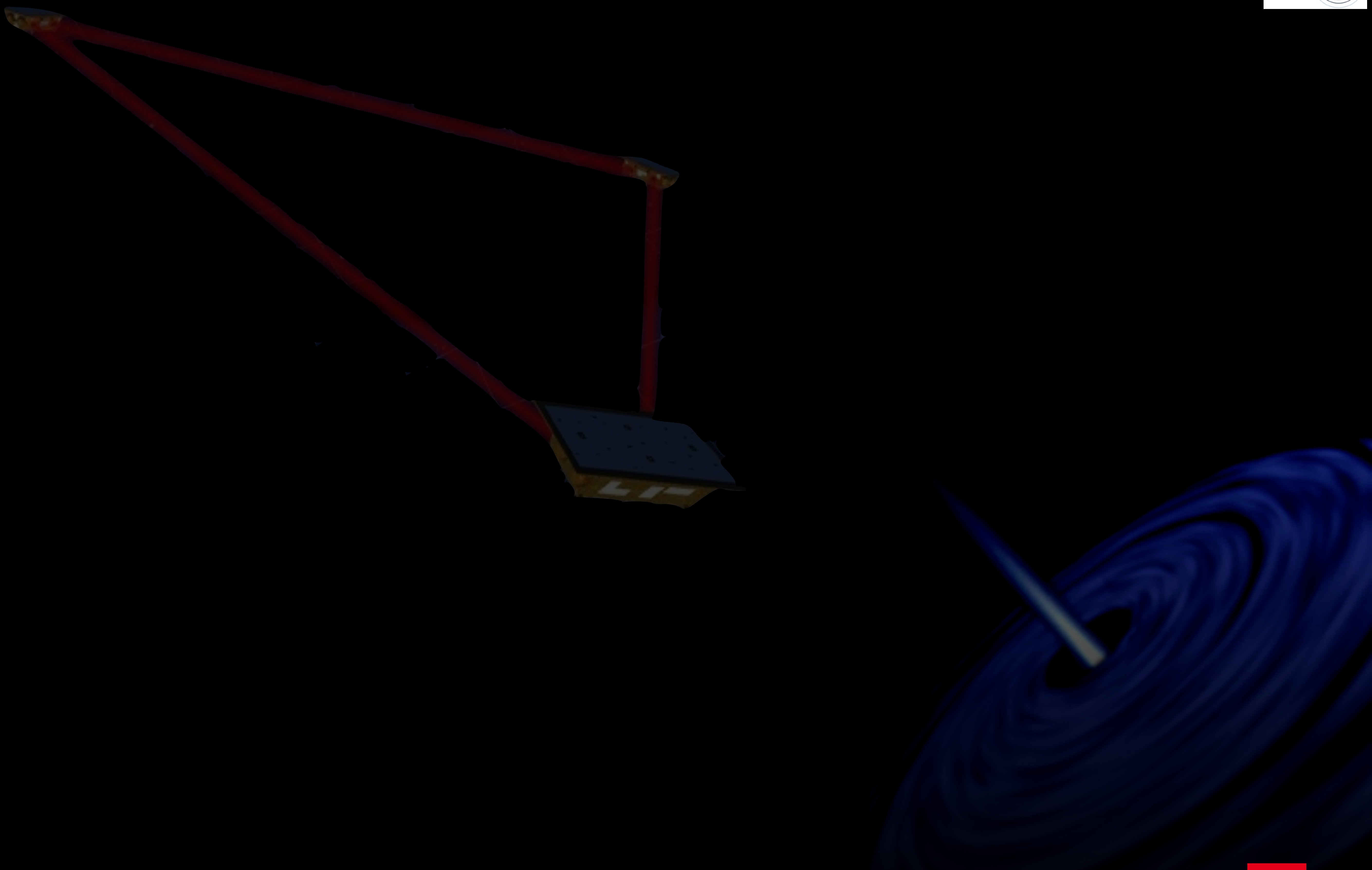


Science Objectives

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

> - Are the massive objects observed at centres of galaxies consistent with being rotating Kerr MBHs? Are they MBHs or horizonless ultracompact objects?
> - Are there new fundamental fields, extra gravitational degrees of freedom and extra polarisations, as predicted by some extensions of the standard model and of GR?
> - Does the fundamental theory of gravity respect Lorentz symmetry and parity invariance?
> - How do GWs propagate over cosmological scales?

Science Objectives

- 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;

SI 5.1 By detecting multiple ringdown "spectral lines" in the post-merger signal of MBHBs LISA can test if merger remnants are indeed Kerr BHs, and place constraints on modifications of GR and on the properties of horizonless massive compact objects.

Science Objectives

- **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;

SI 5.2 LISA aims to observe small objects spiralling into putative MBHs for thousands of cycles, with SNR in excess of 50, thus testing the structure of the spacetime around these objects, probing the presence of dark matter, and potentially measuring charges on the orbiting body associated with new fundamental fields.

Science Objectives

- 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;

SI 5.3 LISA aims to probe the existence of dynamical fields by searching for additional radiation channels and polarisations that would be a smoking gun for non-GR theories.

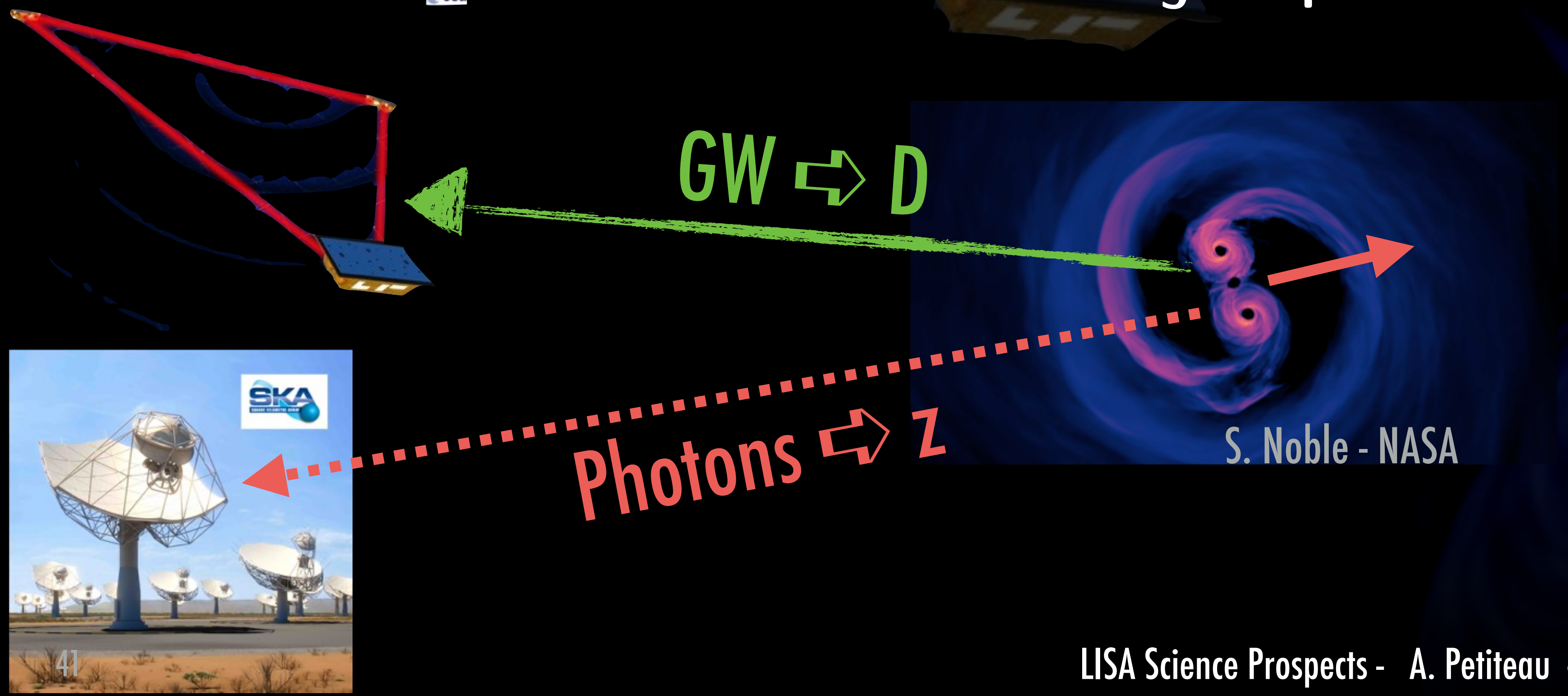
Science Objectives

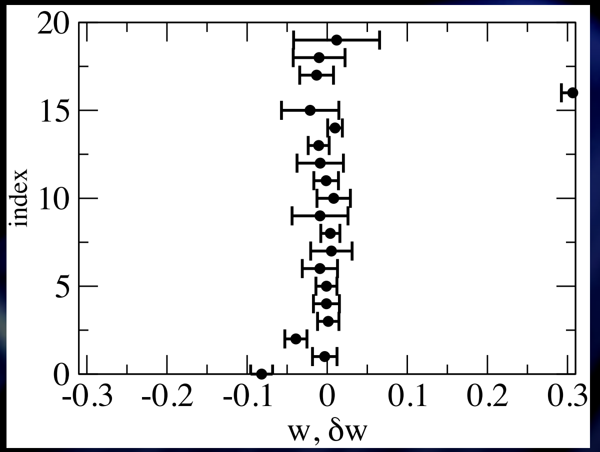
- SO5 : Explore the fundamental nature of gravity and black holes :
  - Use ringdown characteristics observed in MBHB coalescences to test whether the post-merger objects are the MBHs predicted by GR;
  - Use EMRIs to explore the multipolar structure of MBHs and search for the presence of new light fields;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

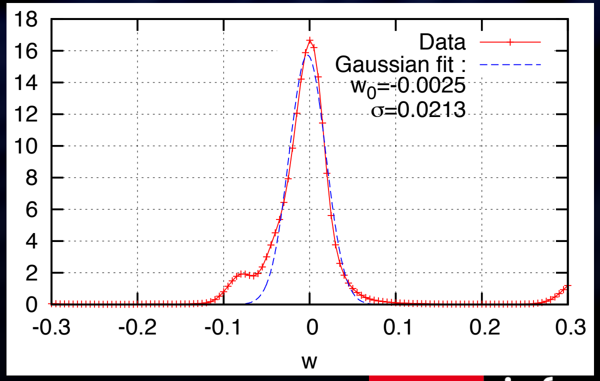
SI 5.4 By detecting GWs from coalescences of golden MBHBs coalescences or/and from EMRIs, all with SNR > 200, LISA can probe the propagation of GWs over very large distances by imposing new stringent constraints on dark energy models, modified graviton dispersion relations, and theories of gravity beyond GR.

Science Objectives

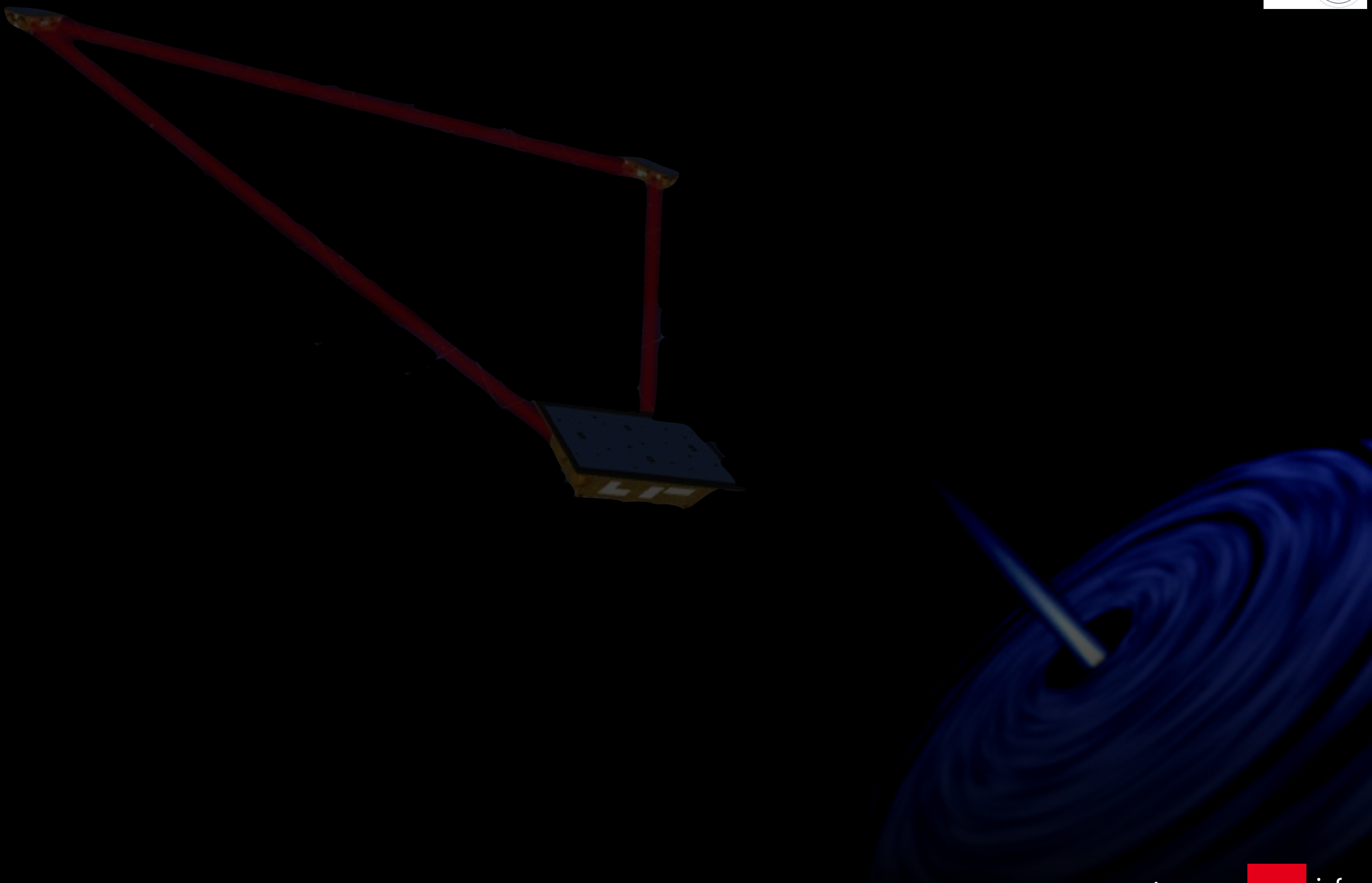
- SO6 : Probe the rate of expansion of the Universe :
  - Estimation of cosmological parameters via the observation of standard sirens: observations of binaries :
  - GWs ➪ "luminosity distance", D
  - Electromagnetic observations ➪ redshift, z
    ➪ constraint on the relation D(z) depending on the geometry of the Univers ➪ measurement of cosmological parameters







Science objectives



Science objectives

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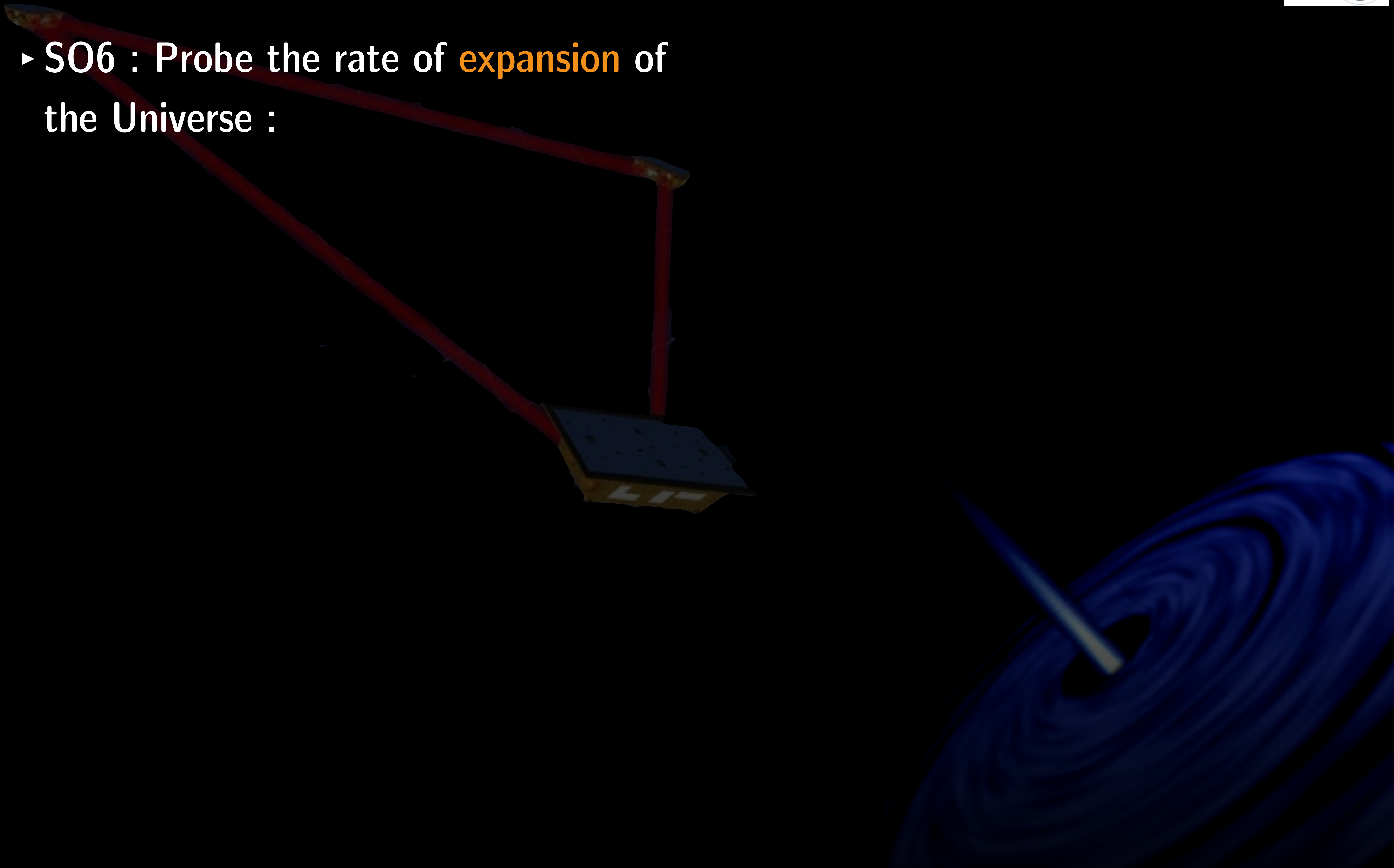

Science objectives

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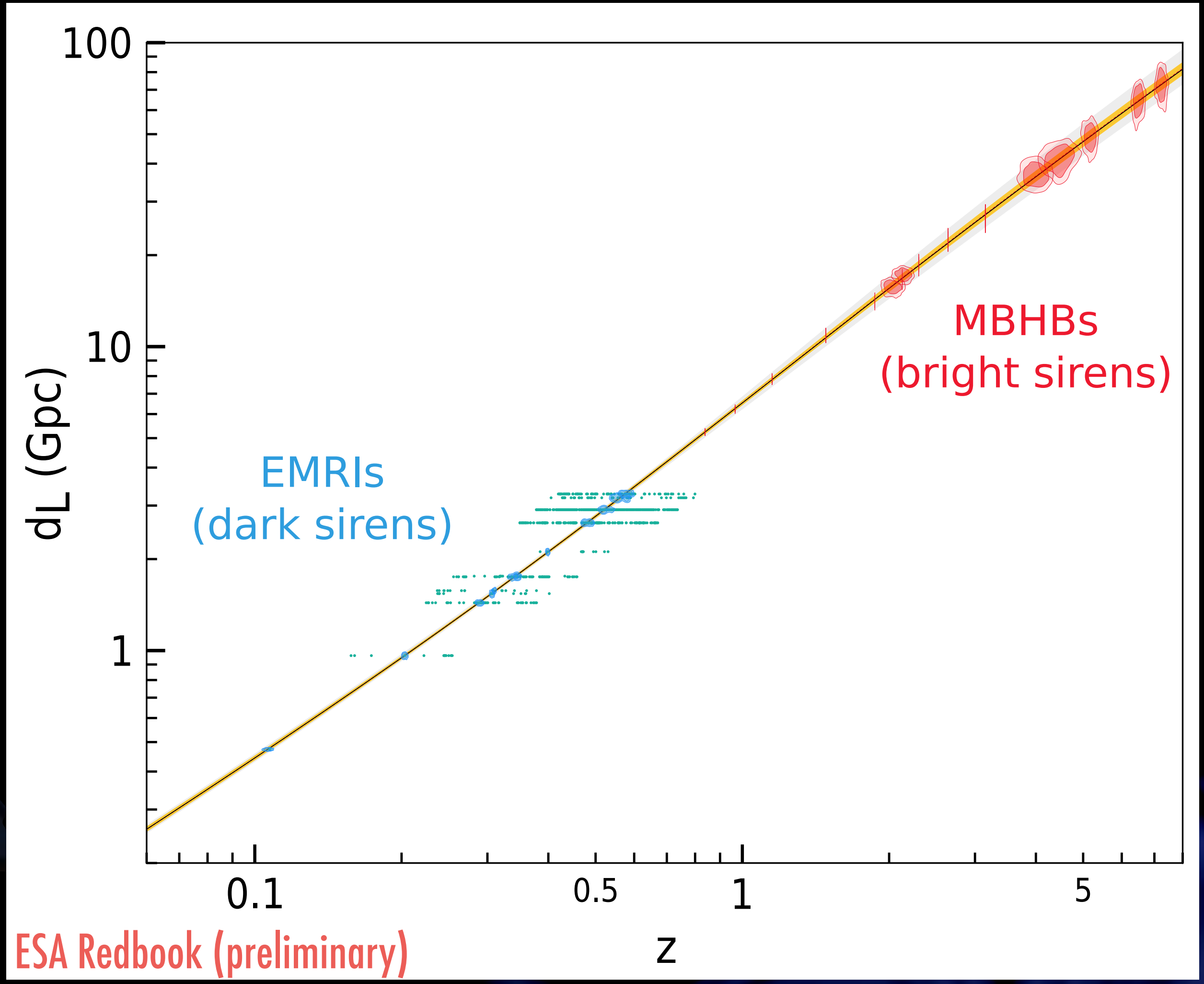
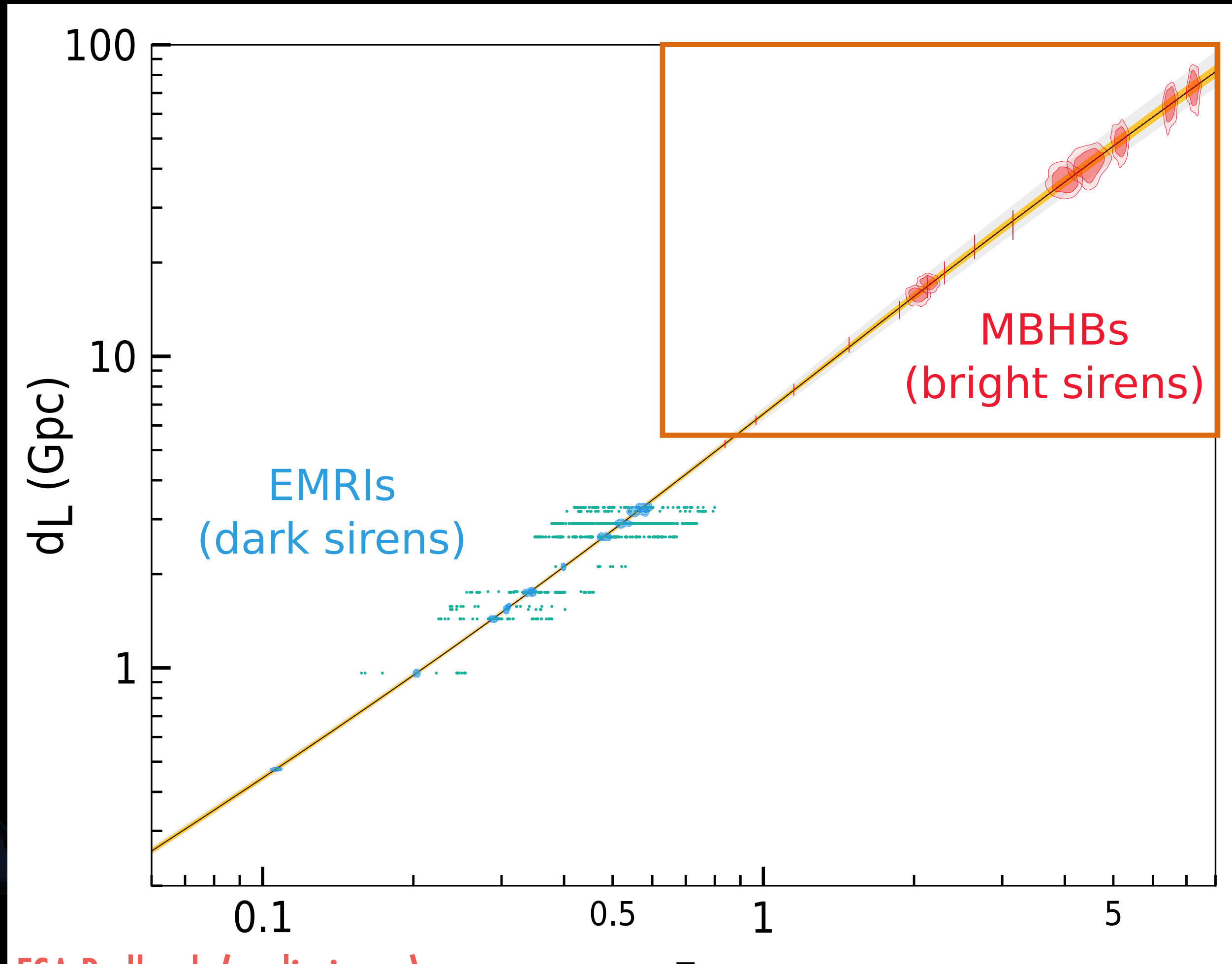


Science objectives

- SO6 : Probe the rate of expansion of the Universe :
  - Cosmology from bright sirens: massive black hole binaries;



ESA Redbook (preliminary)

Science objectives

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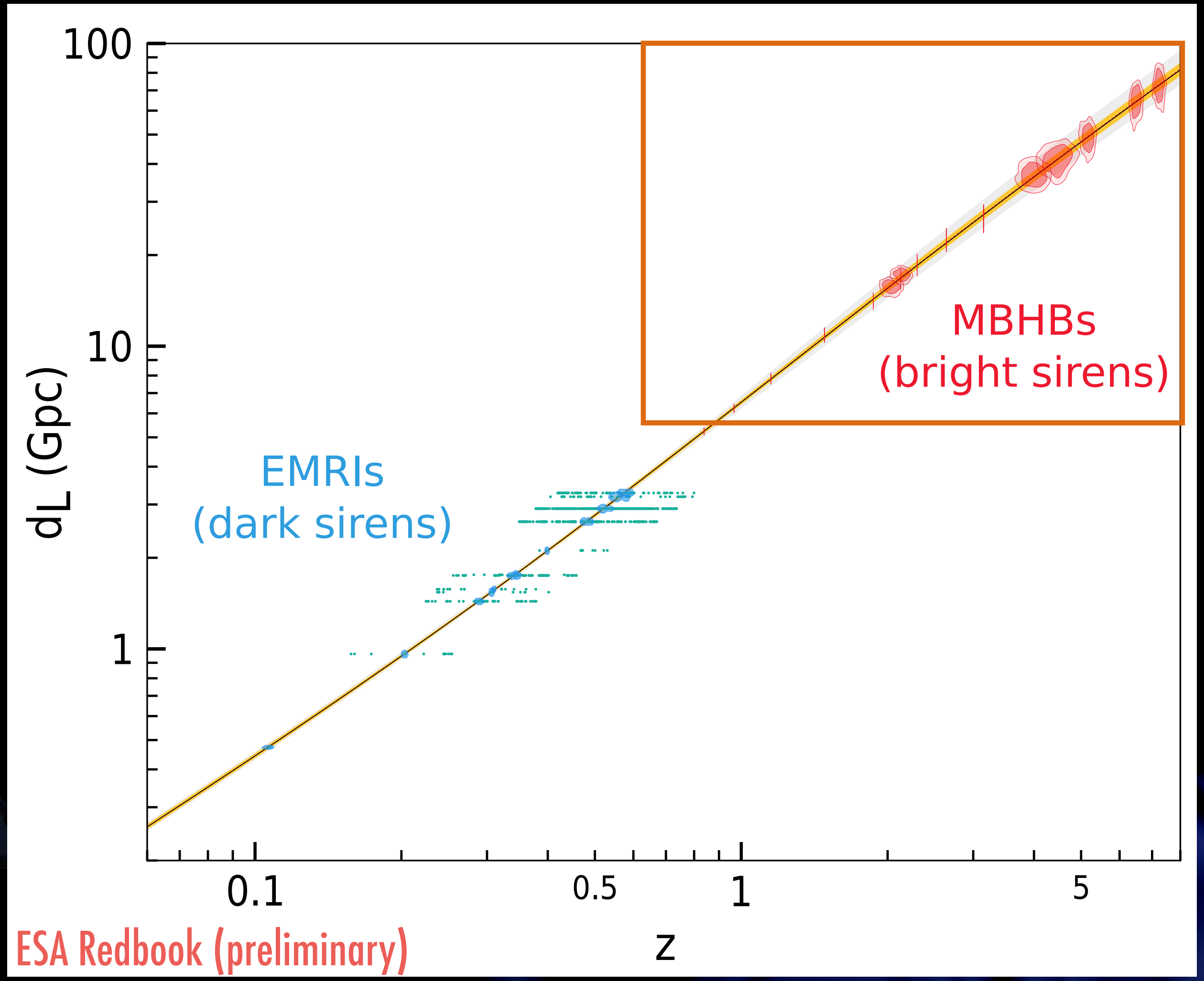
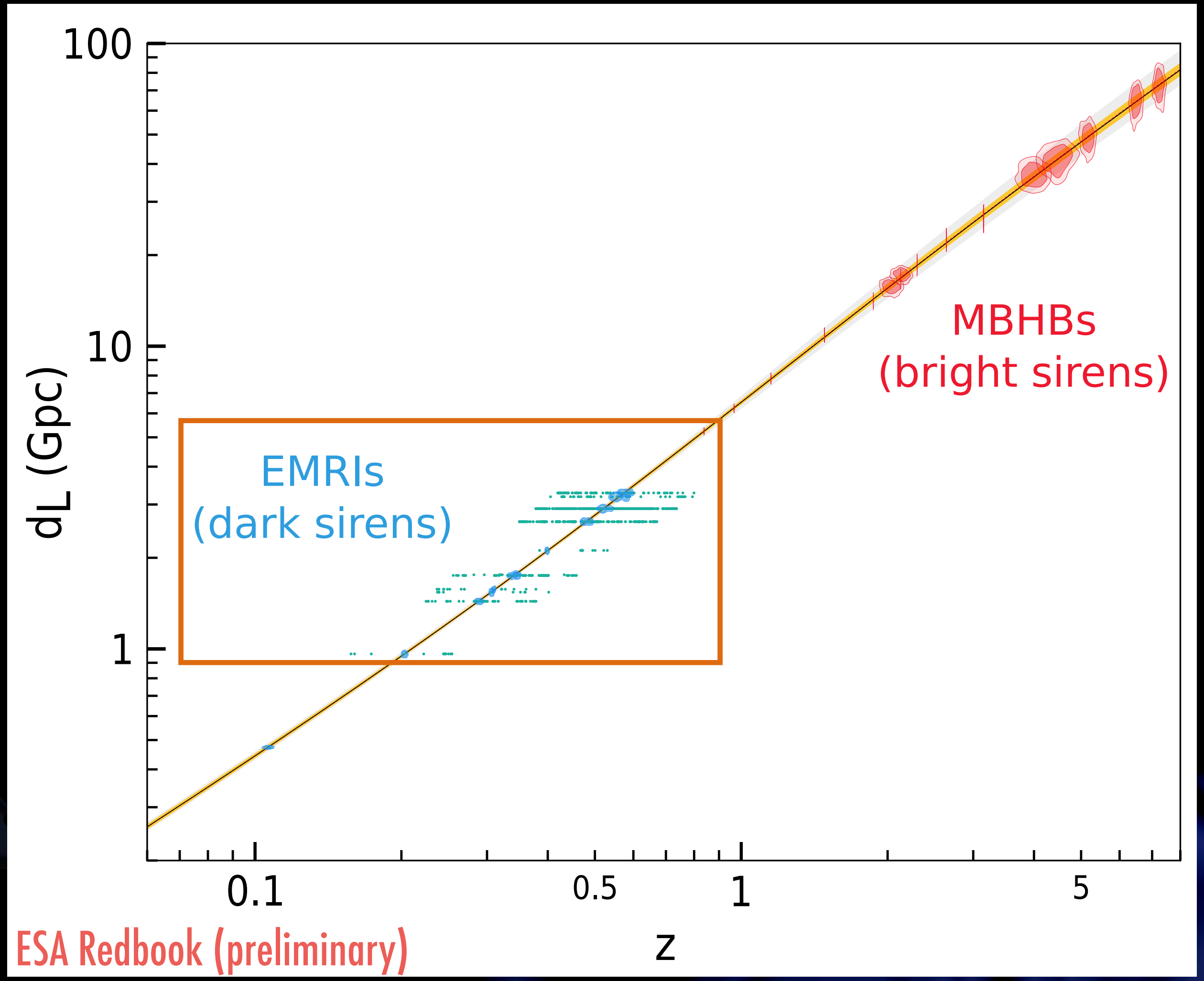


- **How fast did the Universe expand beyond $z \sim 2$?**
- **Is there any deviation from ΛCDM at high-redshift?**

SI 6.1 aims at constraining the expansion rate of the Universe by combining multimessenger GW and EM observations from MBHB mergers in the range of $10^5\,M_\odot$ to $10^6\,M_\odot$ range at $z \lesssim 6$.

Science objectives

- 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;



Science objectives

- SO6 : Probe the rate of expansion of the Universe :
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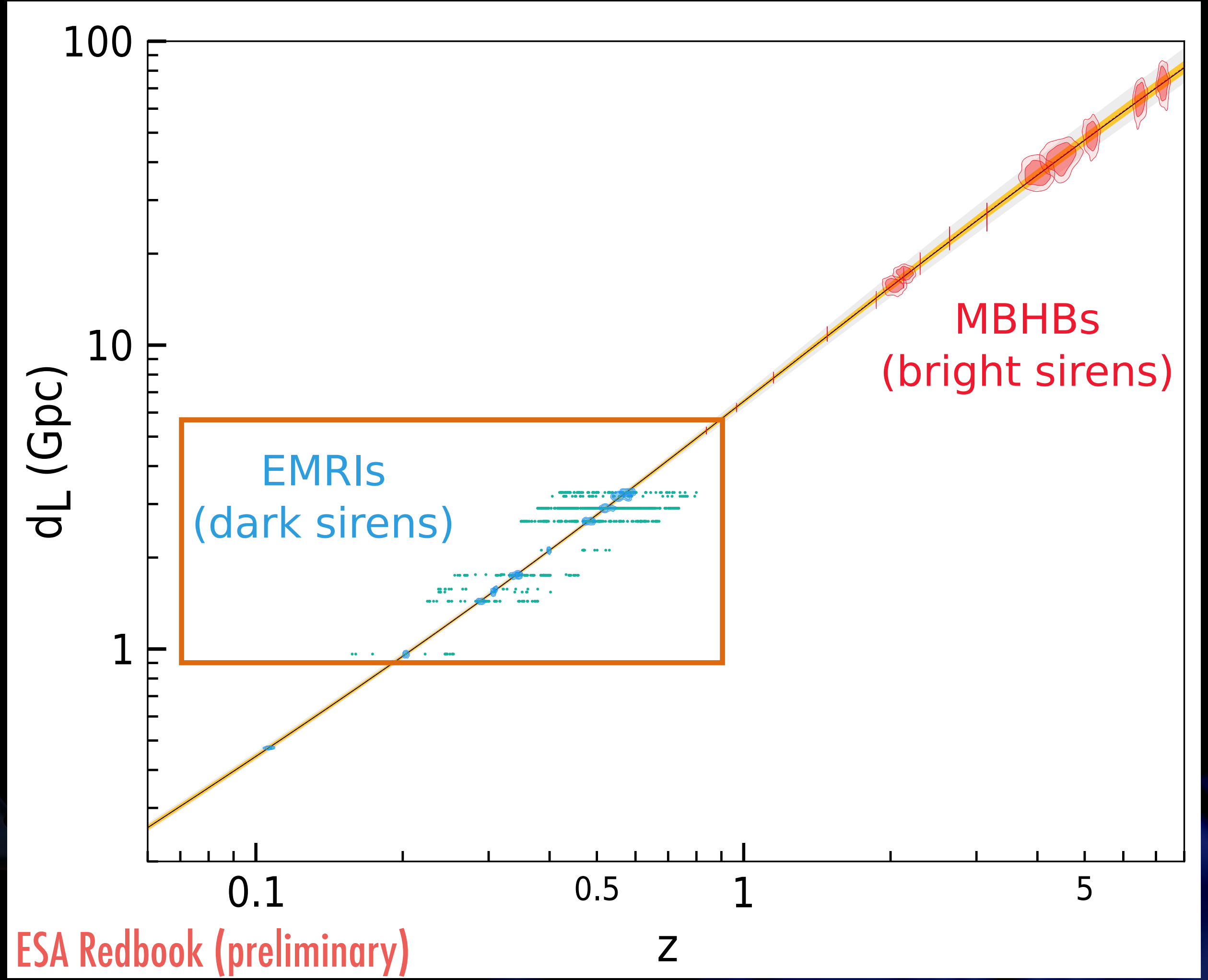
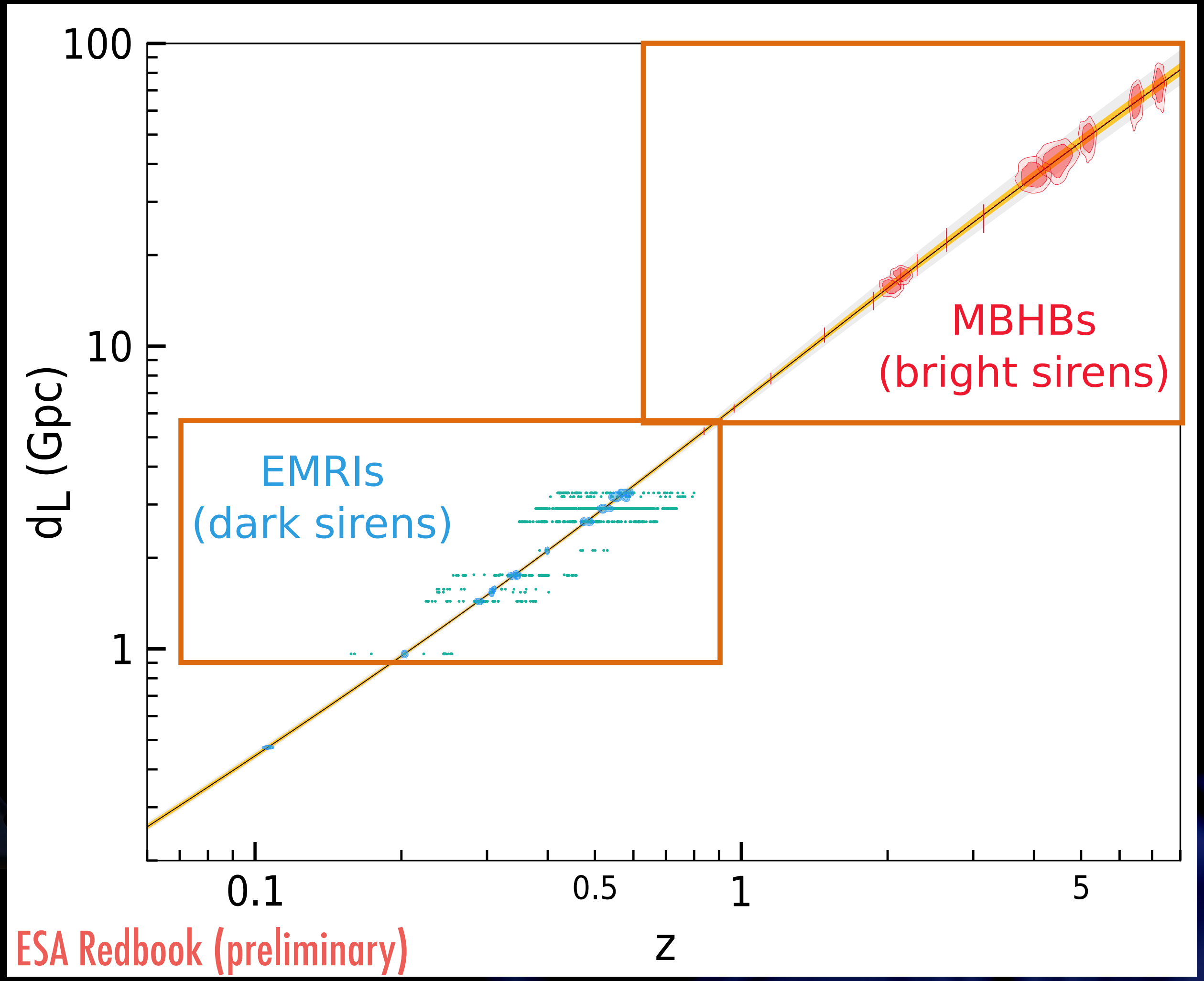


- What is value the Hubble constant H_0 as determined by GW?
- What is the equation of state of dark energy?
- How does the expansion of the Universe look like around the matter to dark energy transition ($z \sim 0.7$)?

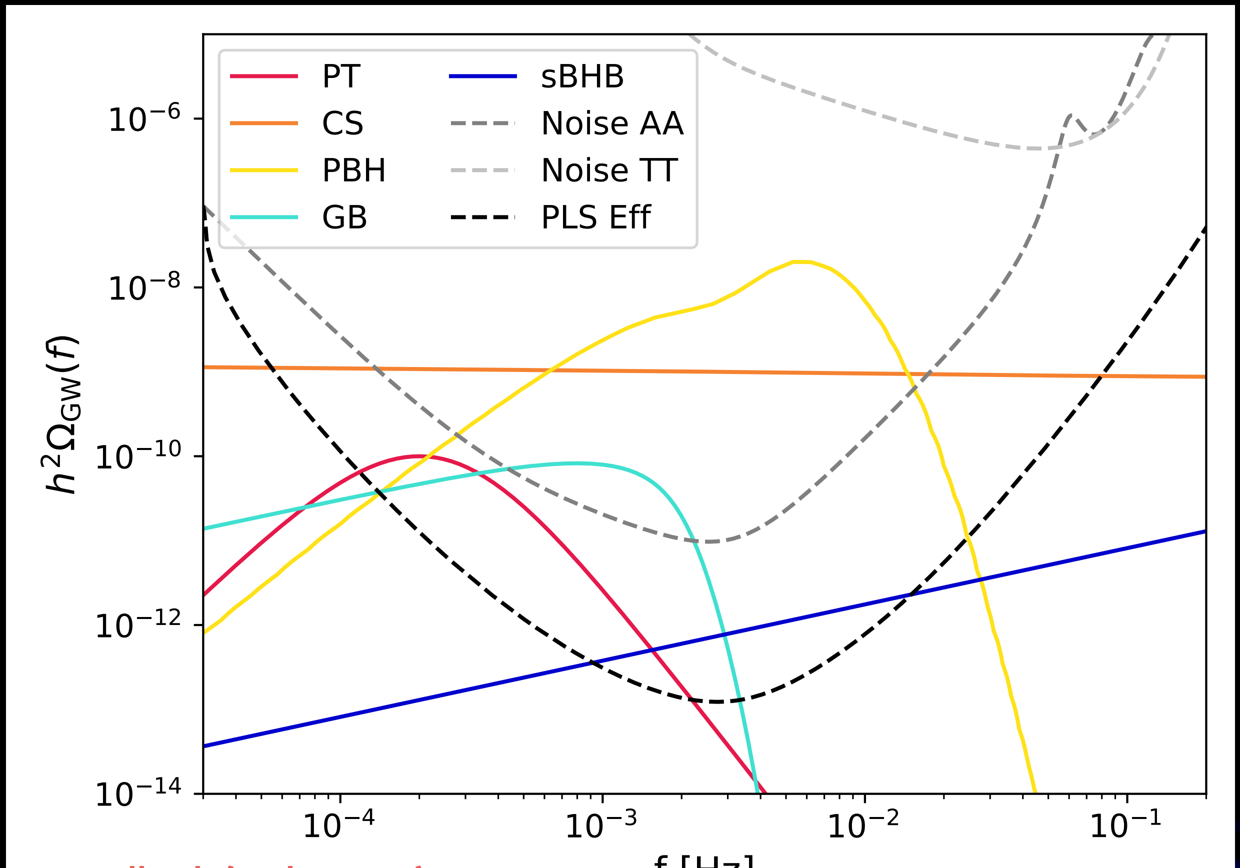
SI 6.2 aims to constrain the expansion rate of the Universe with EMRIs out to $z \lesssim 1$.

Science objectives

- 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.



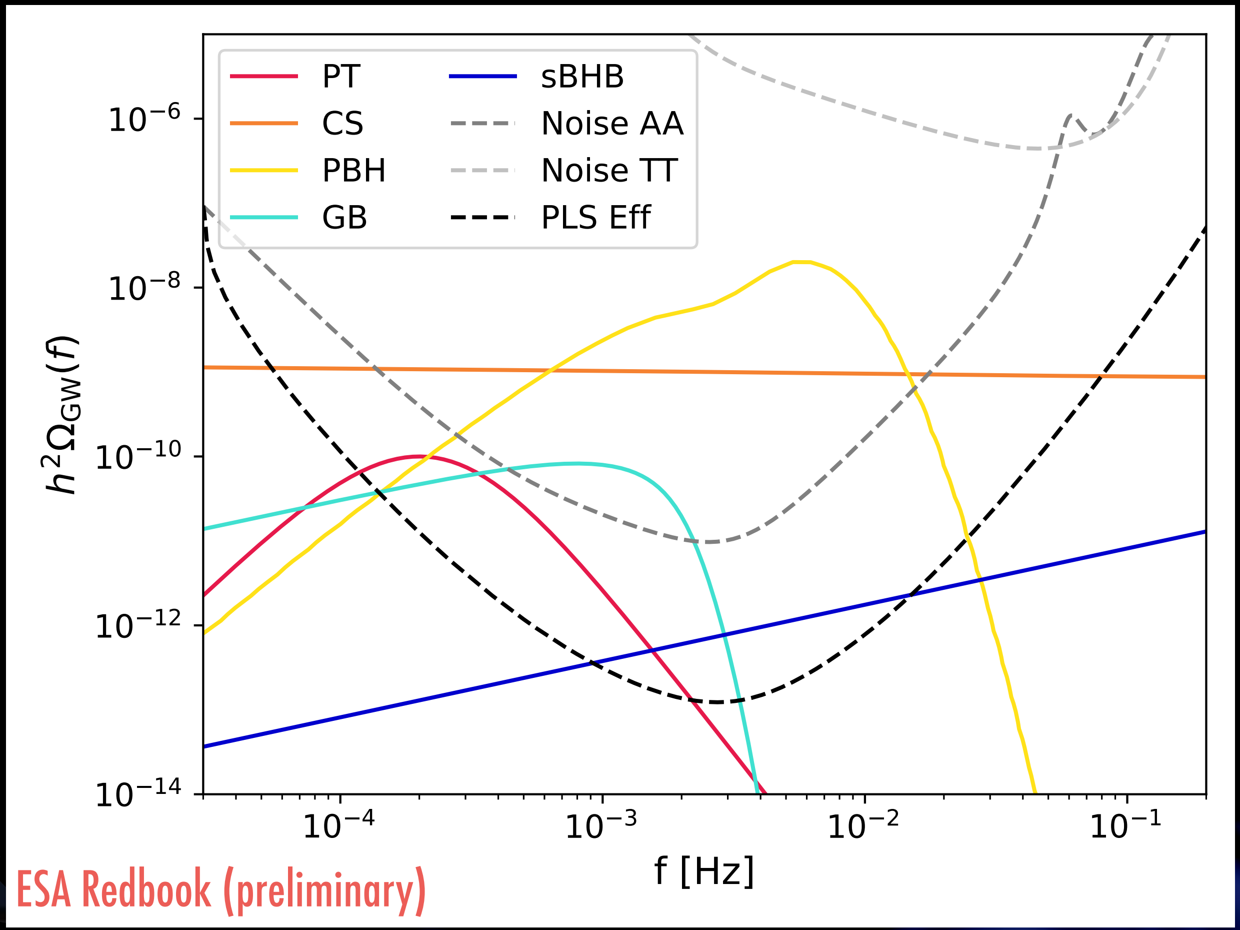
Science Objectives



ESA Redbook (preliminary)

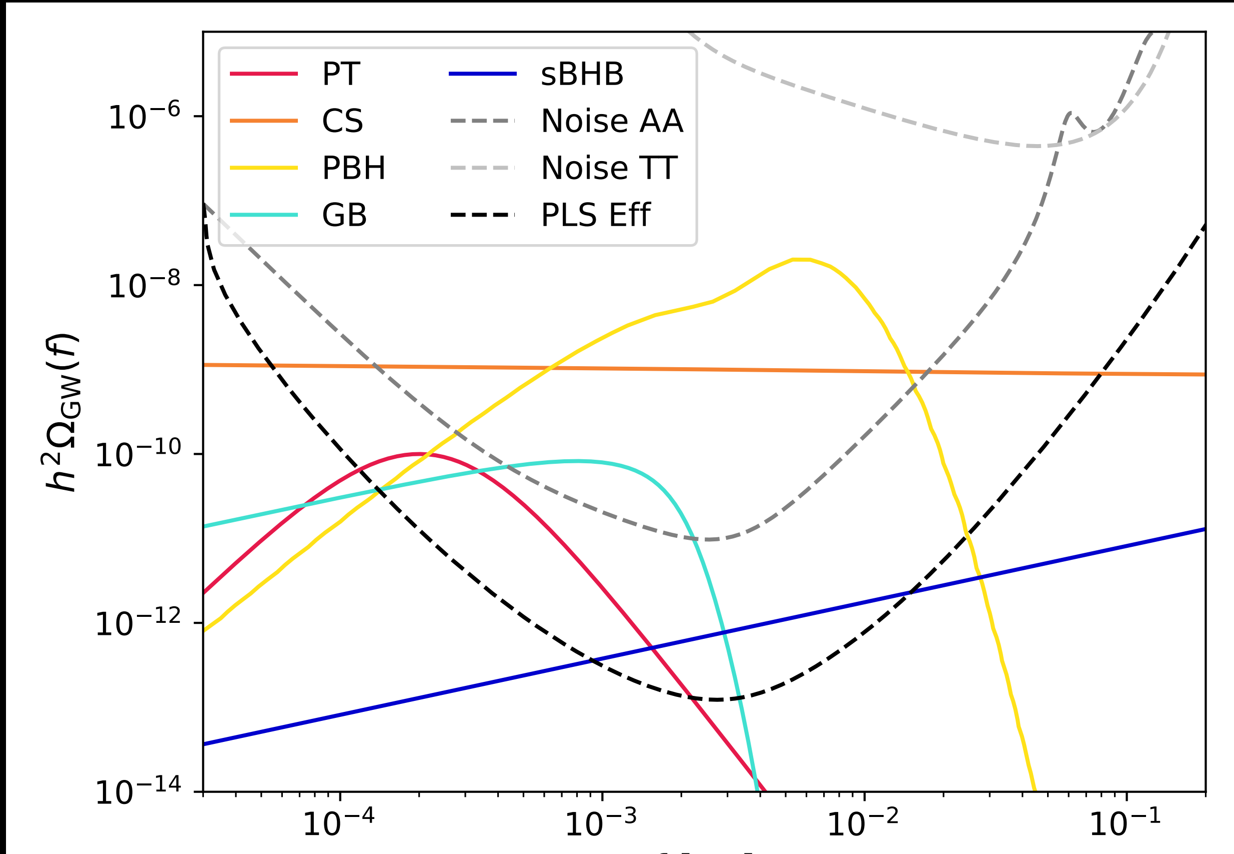
Science Objectives

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



Science Objectives

- SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics :
    - Characterise the astrophysical SGWB;



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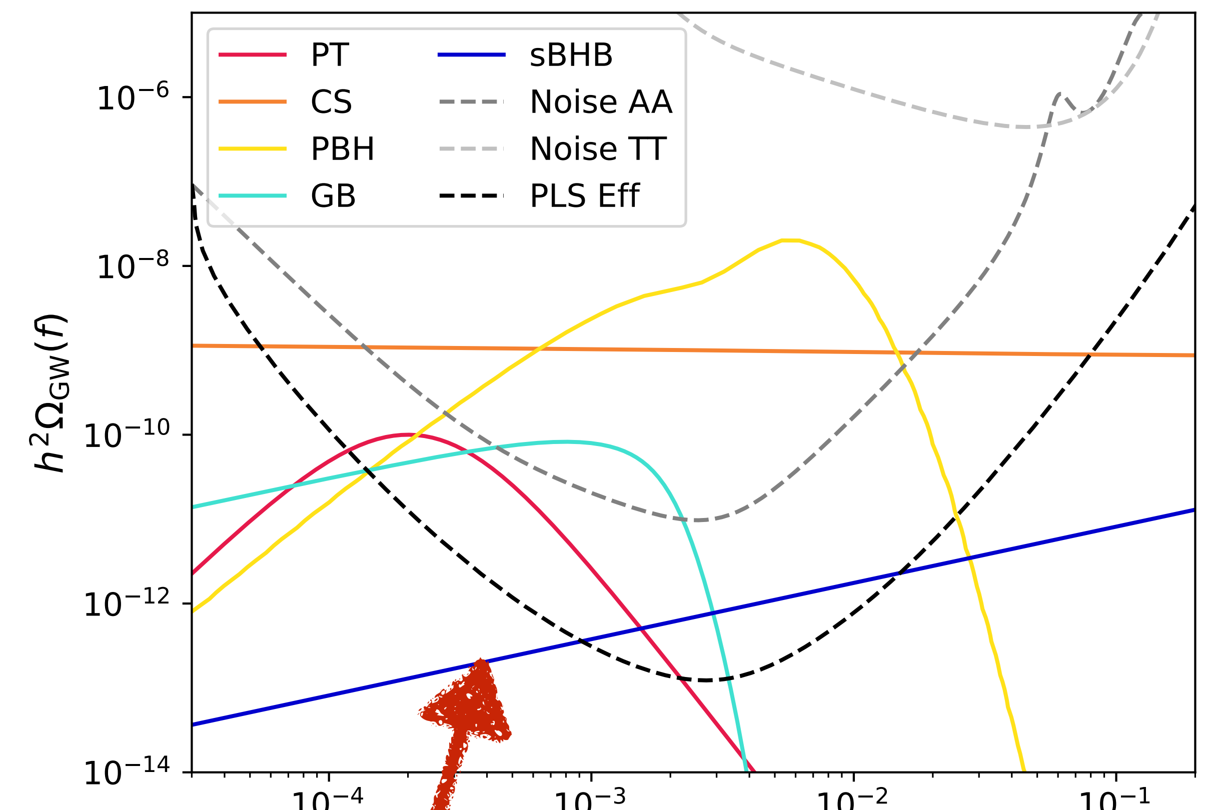


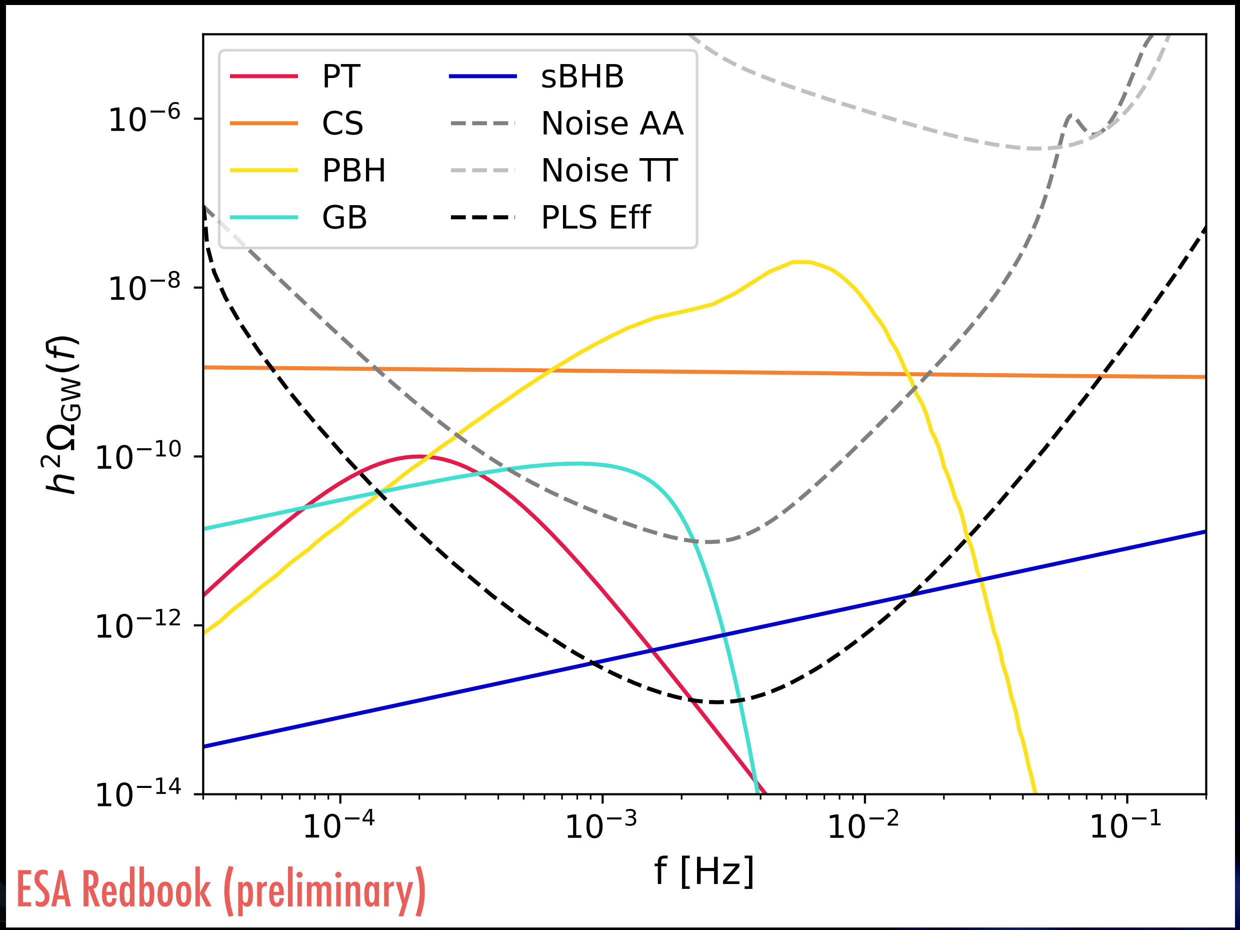
ESA Redbook (preliminary)

- **Can we identify the presence of a SGWB from sBHBs in LISA data?**
- **Can we measure the amplitude and spectral tilt of the sBHB background?**

SI 7.1 demonstrates that LISA can detect and characterise the SGWB from sBHBs, if their population obeys current LVK modelling, together with the GB SGWB and the instrument noise.

Science Objectives

- 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;



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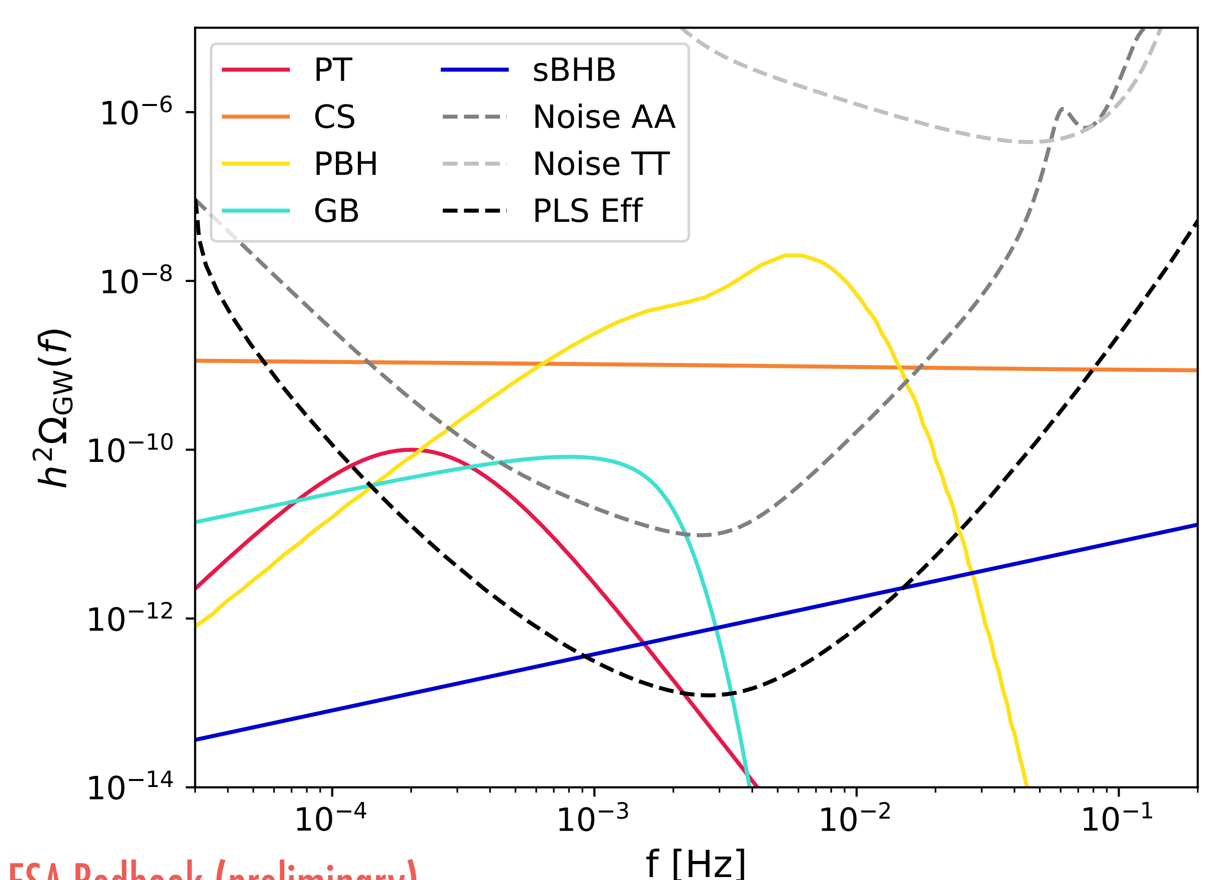

ESA Redbook (preliminary)

- **Can we identify the presence of a SGWB of cosmological origin in LISA data?**
- **Can we agnostically reconstruct the cosmological SGWB spectral shape, to gather information about the process generating it?**

SI 7.2 demonstrates that cosmological SGWBs can be identified in LISA data under minimal assumptions on the instrument noise, thereby allowing the application of agnostic searches aimed at reconstructing the signal spectral shape.

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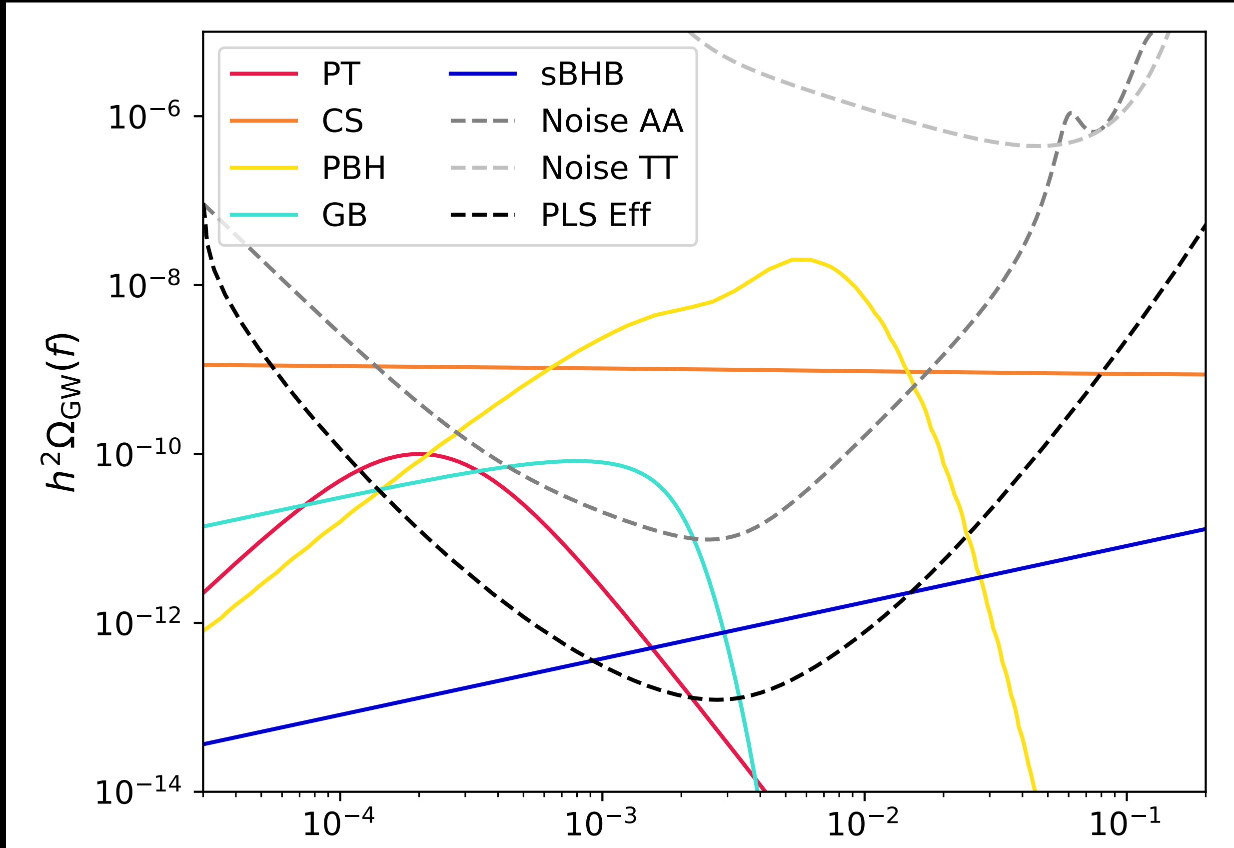
Science Objectives

- 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.



ESA Redbook (preliminary)

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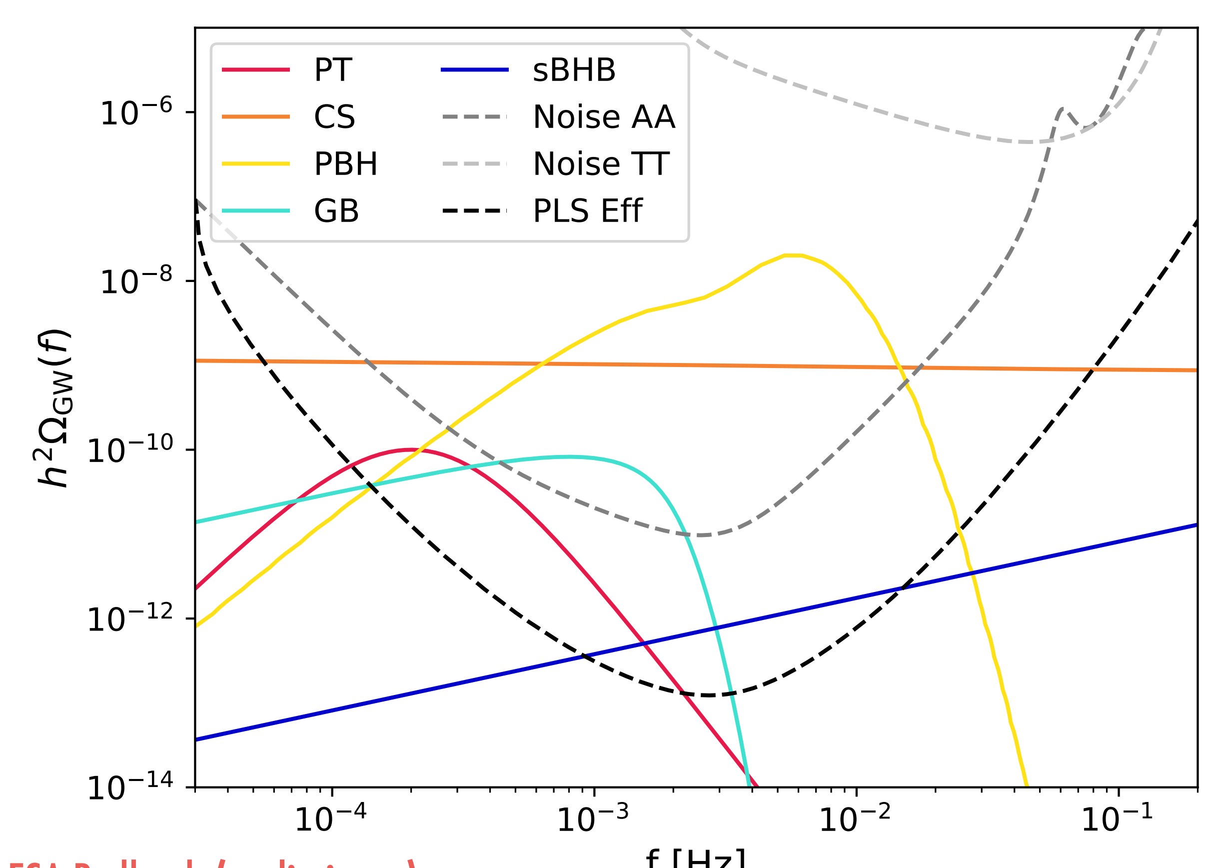
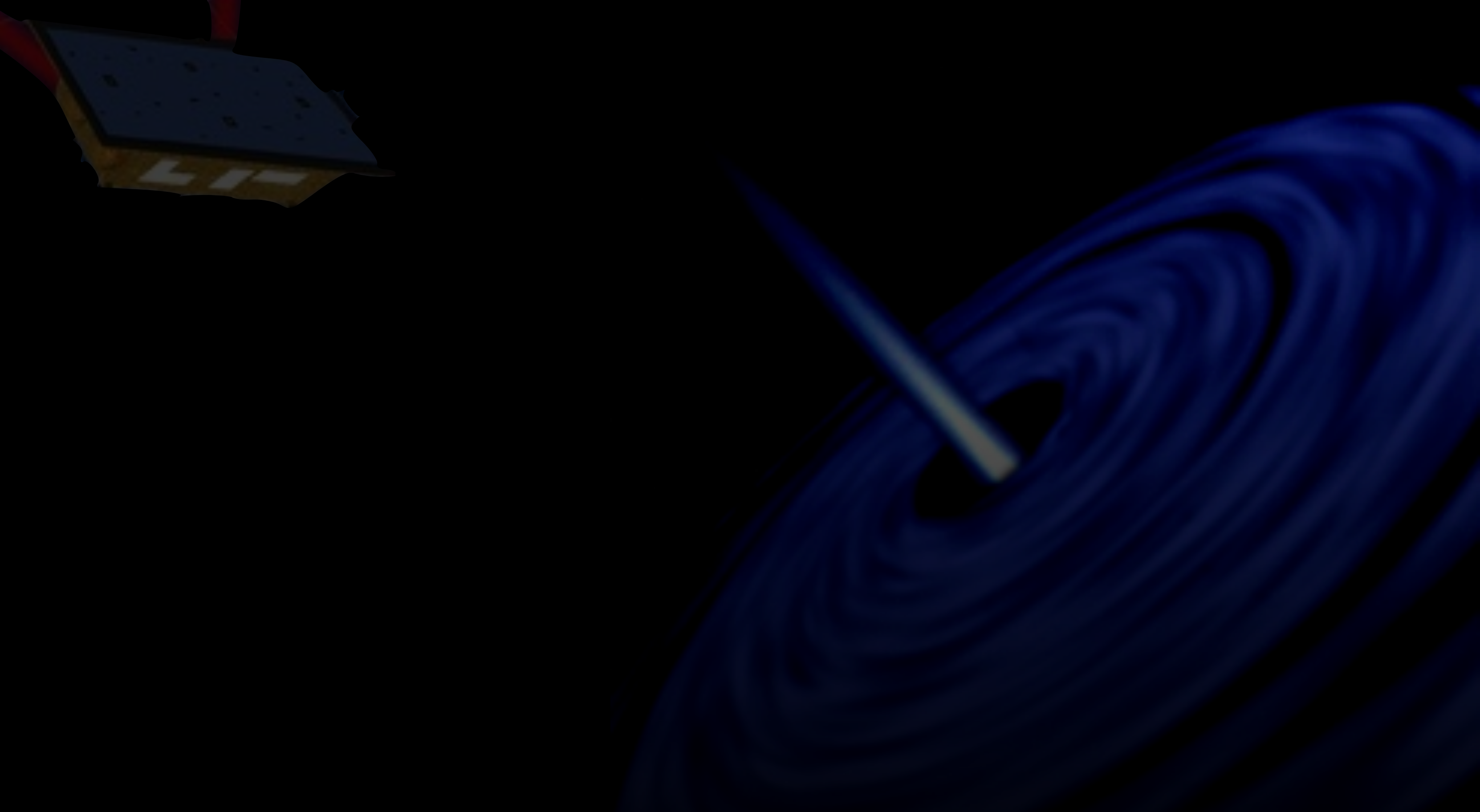


ESA Redbook (preliminary)

- **Is the SGWB frame the same as the Cosmic Microwave Background (CMB) one?**
- **What are the host galaxies of sBHBs ?**

Science Objectives

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



Science Objectives

Defined in the Science Requirements Doc.:

- 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 dynamics of dense nuclear clusters using EMRIs.
- 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.

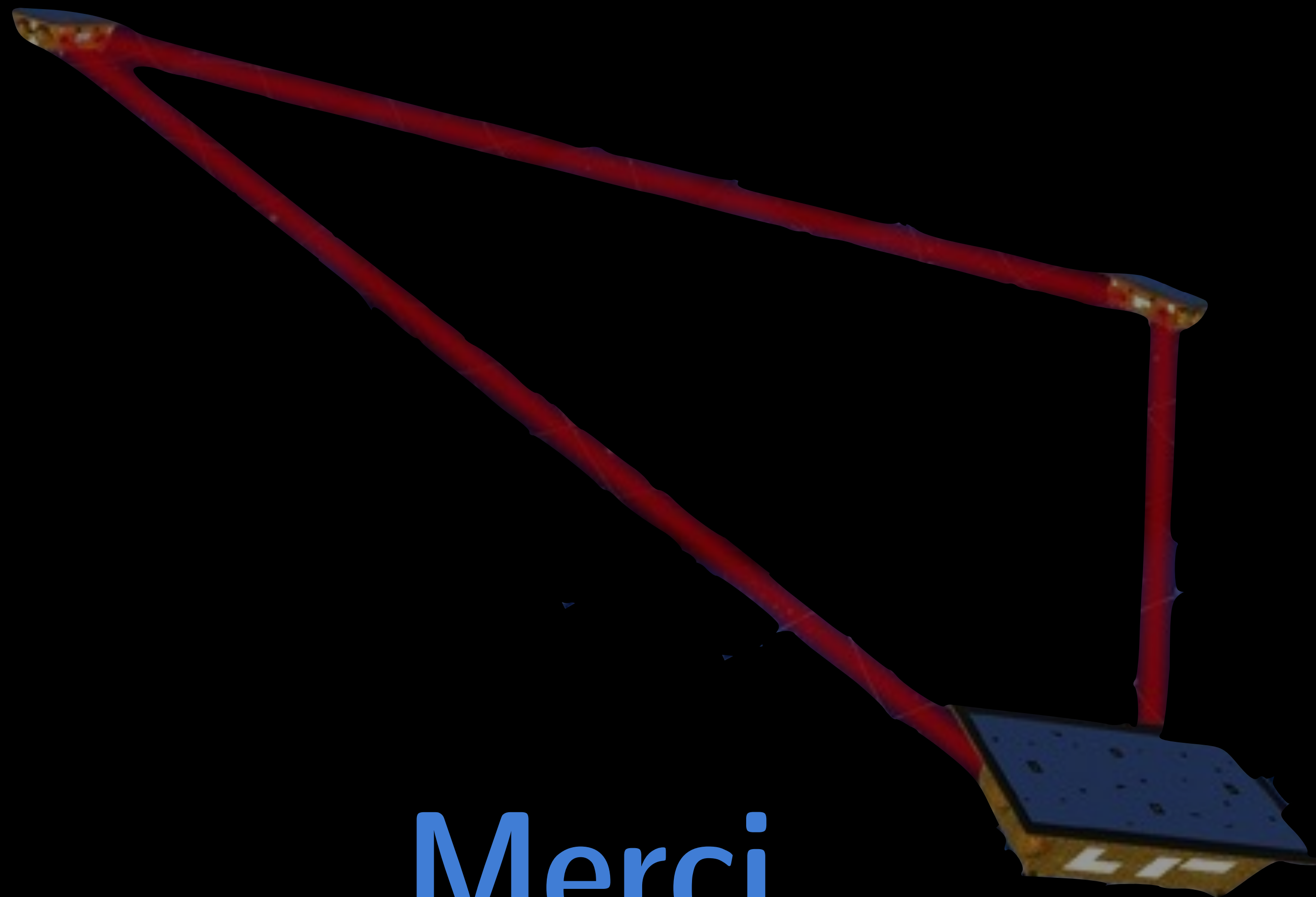
Astrophysics

Fundamental physics

Cosmology

Conclusion

- LISA is a space-based interferometer to observe the Universe with Gravitational Waves
- ESA large mission at ESA to be adopted in January 2024 and launch in 2035 for 4.5 to 10 years of operations
- Complex and very integrated mission but no technological showstopper.
- Challenges:
  - Data analysis with very large number of overlapping sources
  - High precision metrology in space
- Huge science case for astrophysics, cosmology and fundamental physics organised in 8 science objectives



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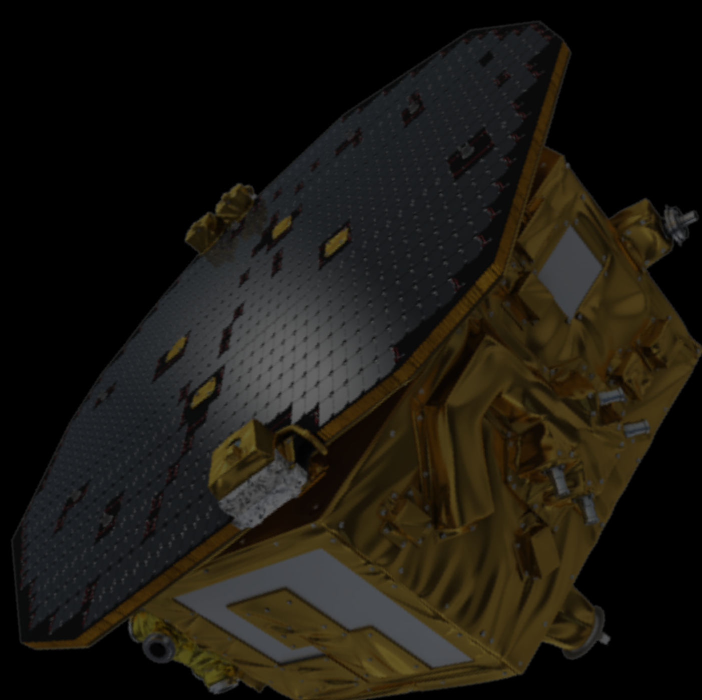
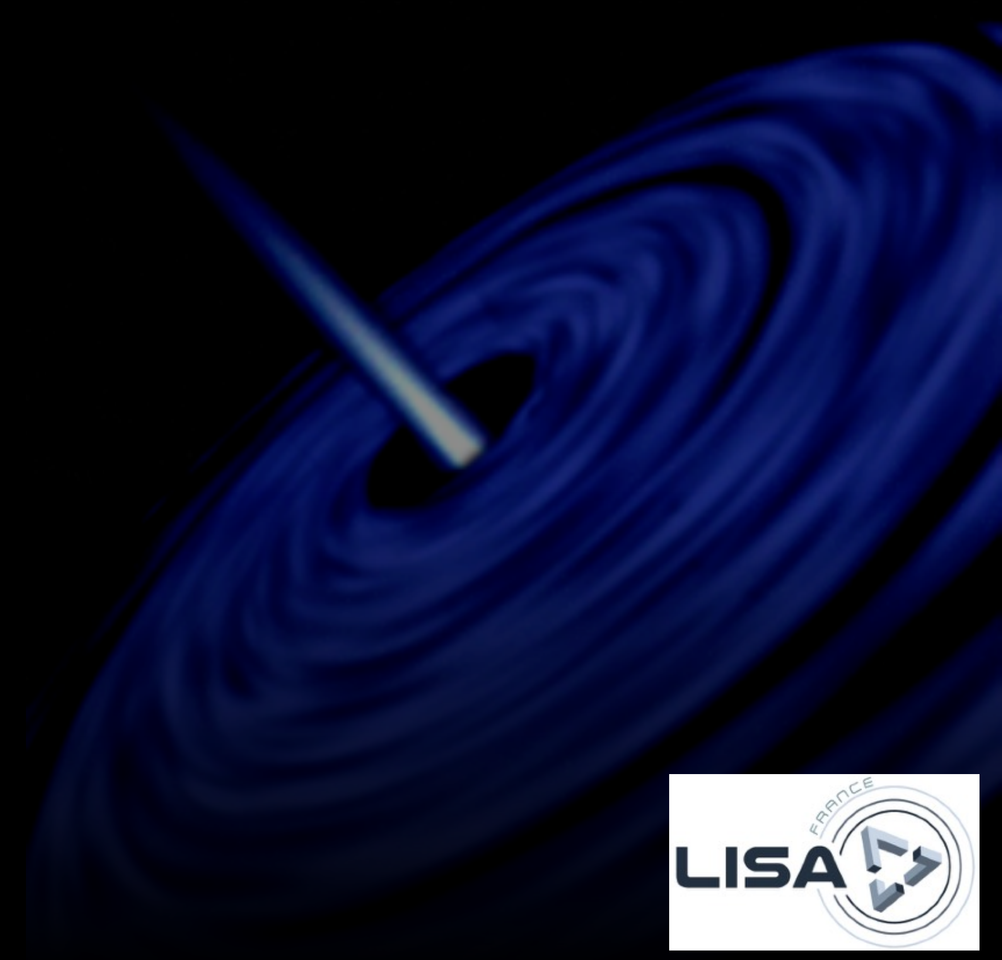




Data availability during operations

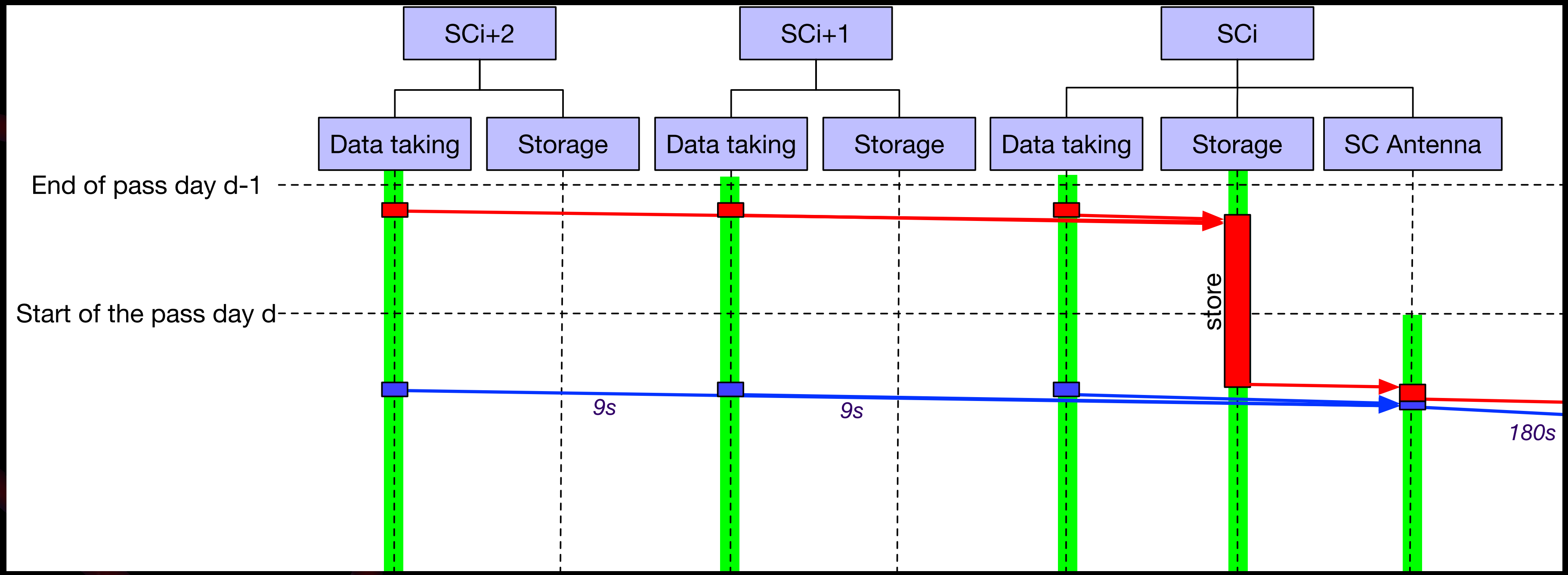
- Data available from MOC for SOC assuming 8h visibility per day every 24h:
  - During visibility phase 1 (0 to about 2h):
    - Stream of Near Real Time Data by chunk of 5mn (TBC) every 5mn (TBC).
    - Stream of High Priority Data by chunk of 2x5mn (TBC) every 5mn (TBC).
  - During visibility phase 2 (about 2h to end of visibility):
    - Stream of Near Real Time Data by chunk of 5mn (TBC) every 5mn (TBC).
  - End of visibility + 8h (TBD) for consolidation:
    - All data acquired from 16h before the start of visibility to end of visibility, 1 day of data consolidated.

Low latency

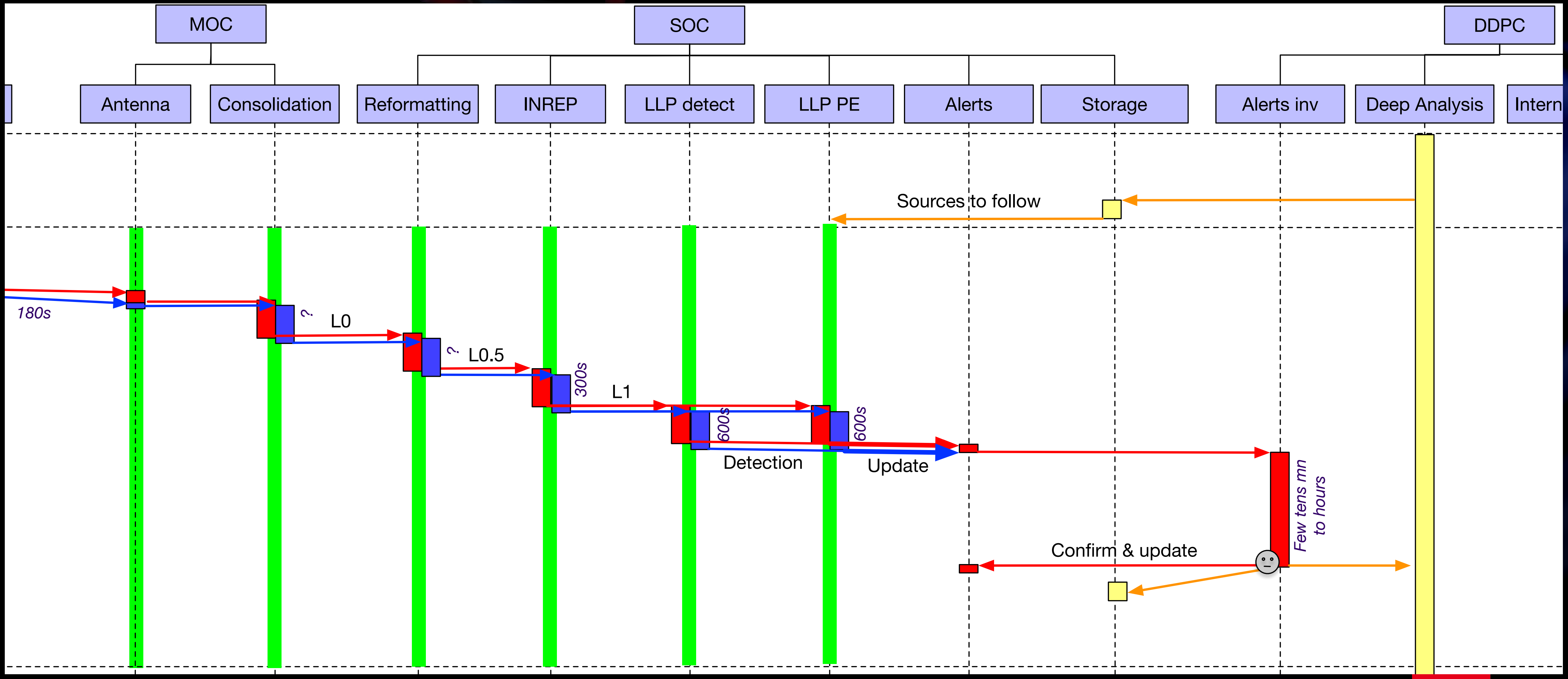
- For each candidate detection, dedicated pipelines are started in order to
  - confirm,
  - consolidate,
  - refine the alerts
- using
  - data used for the detection
  - + new Near Real Time Data

LISA DA in operations: alerts

- Sequence diagram Segment



Time



LISA DA in operations: deep analysis