La mission LISA

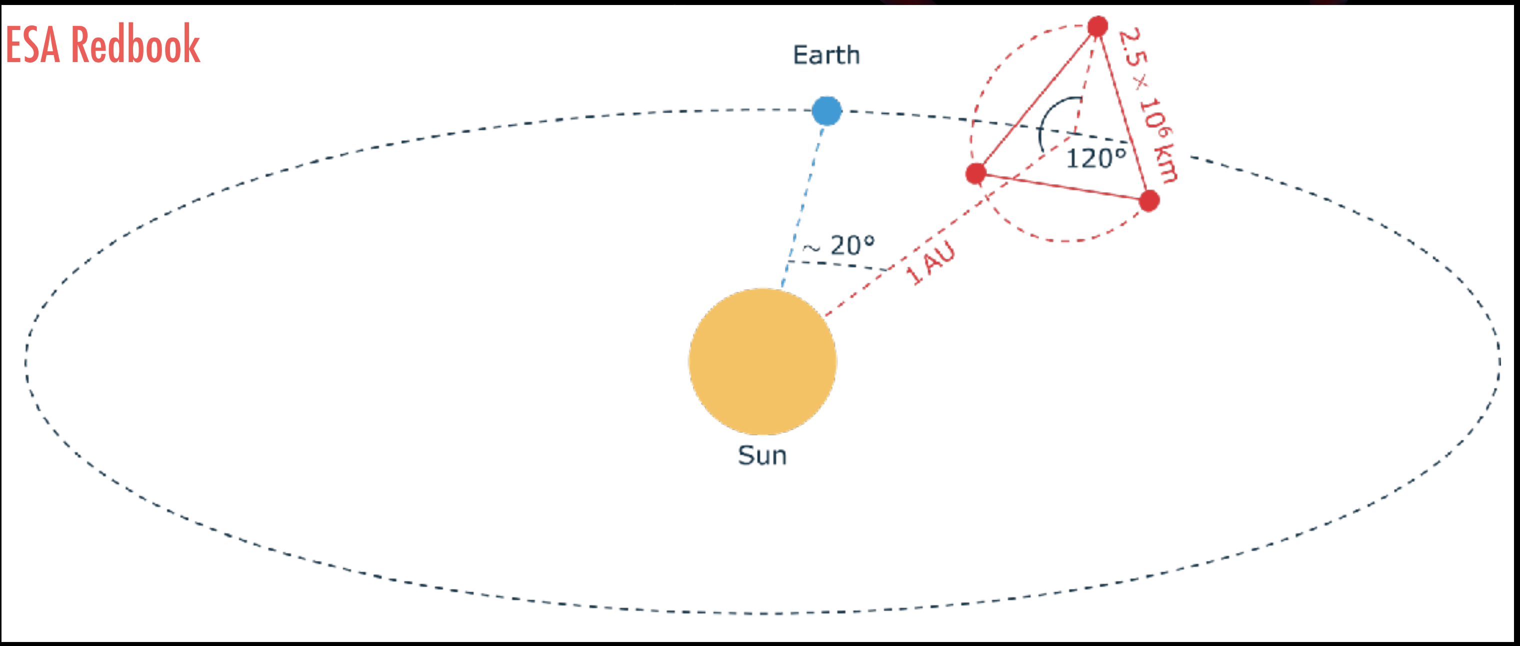
Antoine Petiteau (CEA/IRFU/DPhP & APC)

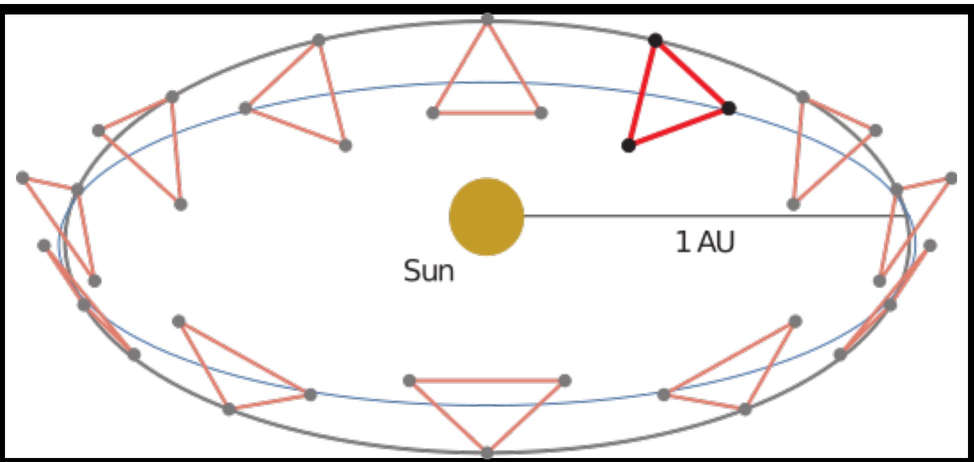
Journées PNHE

IAP - 6th September 2023

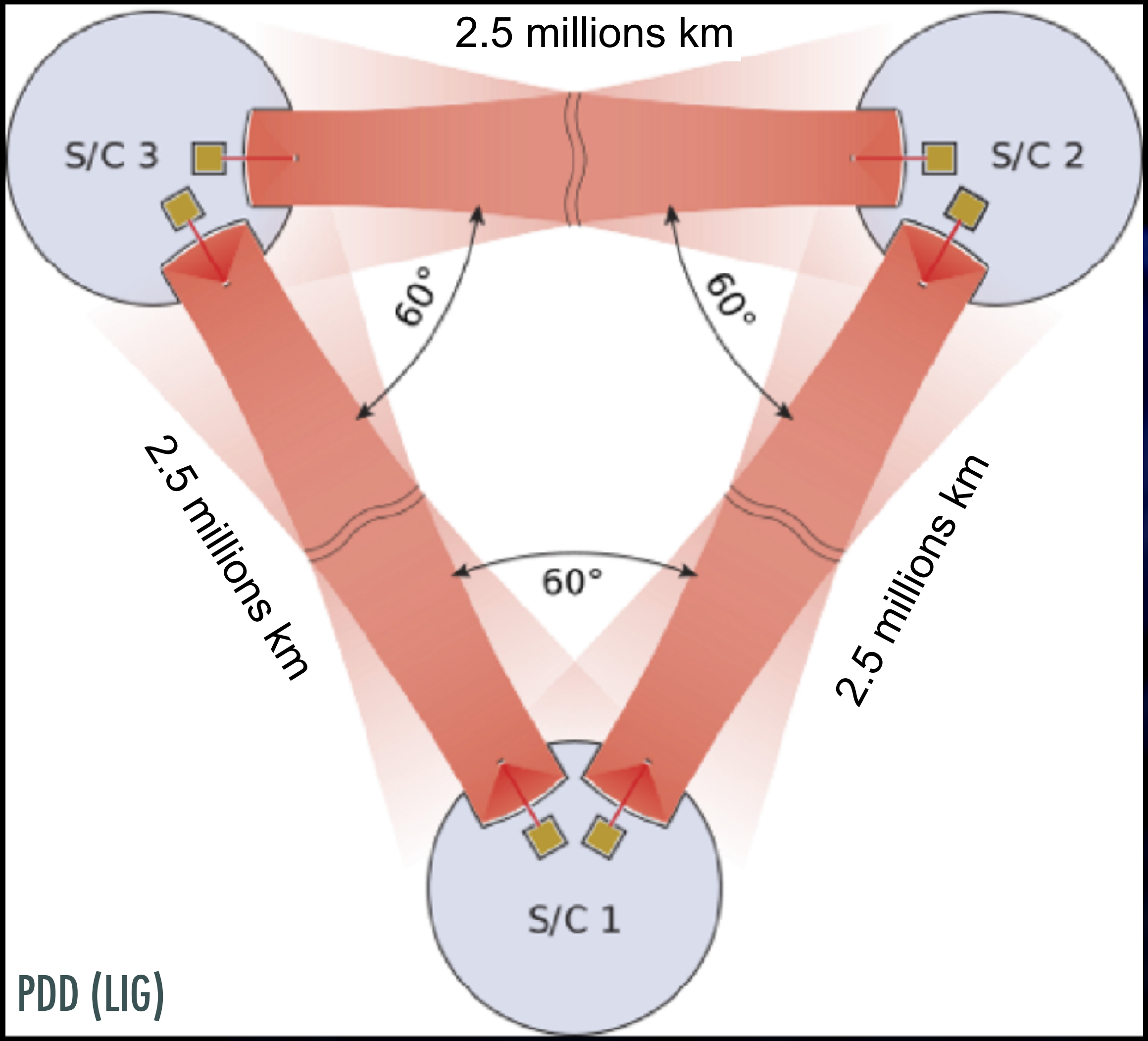
LISA mission

- 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

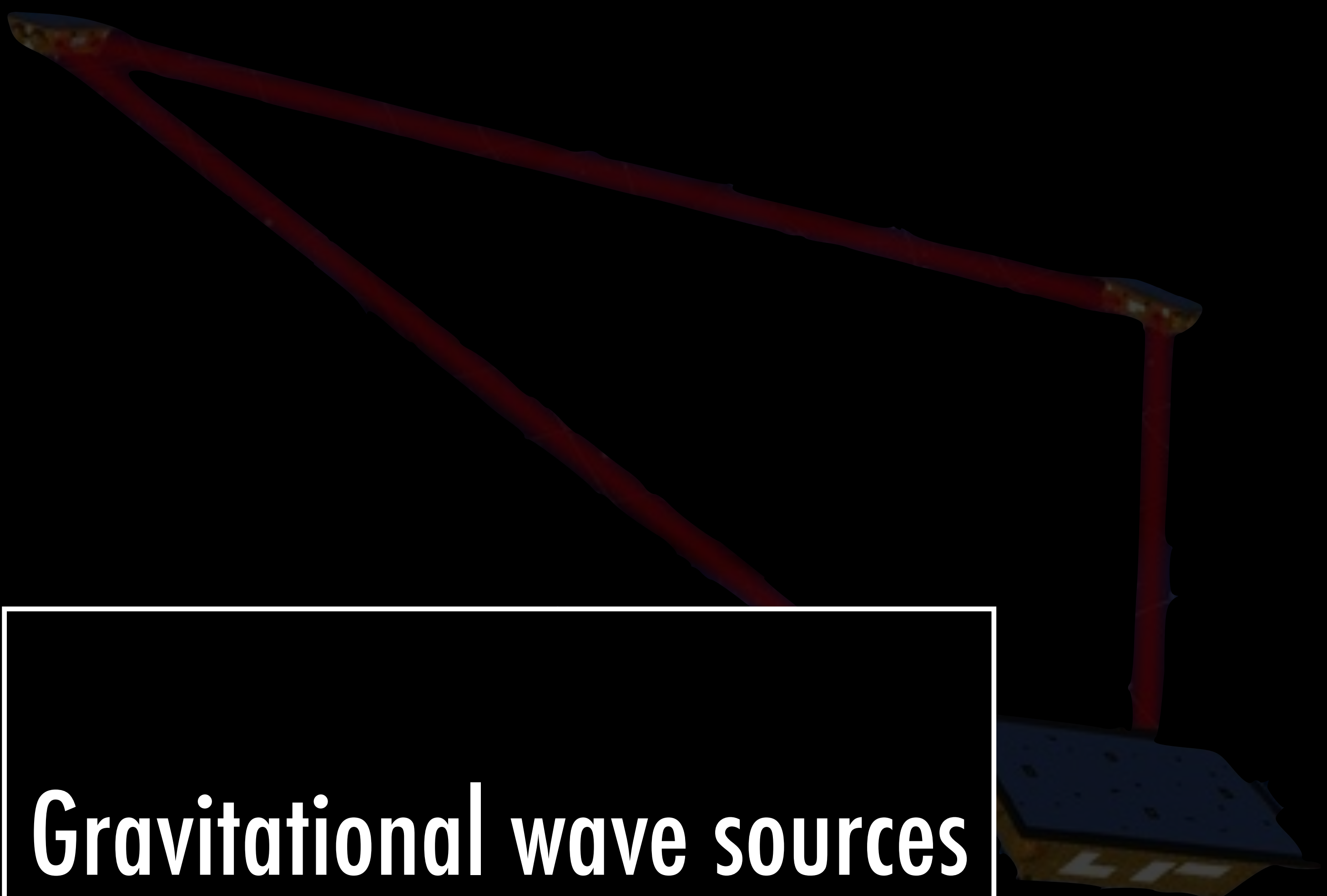




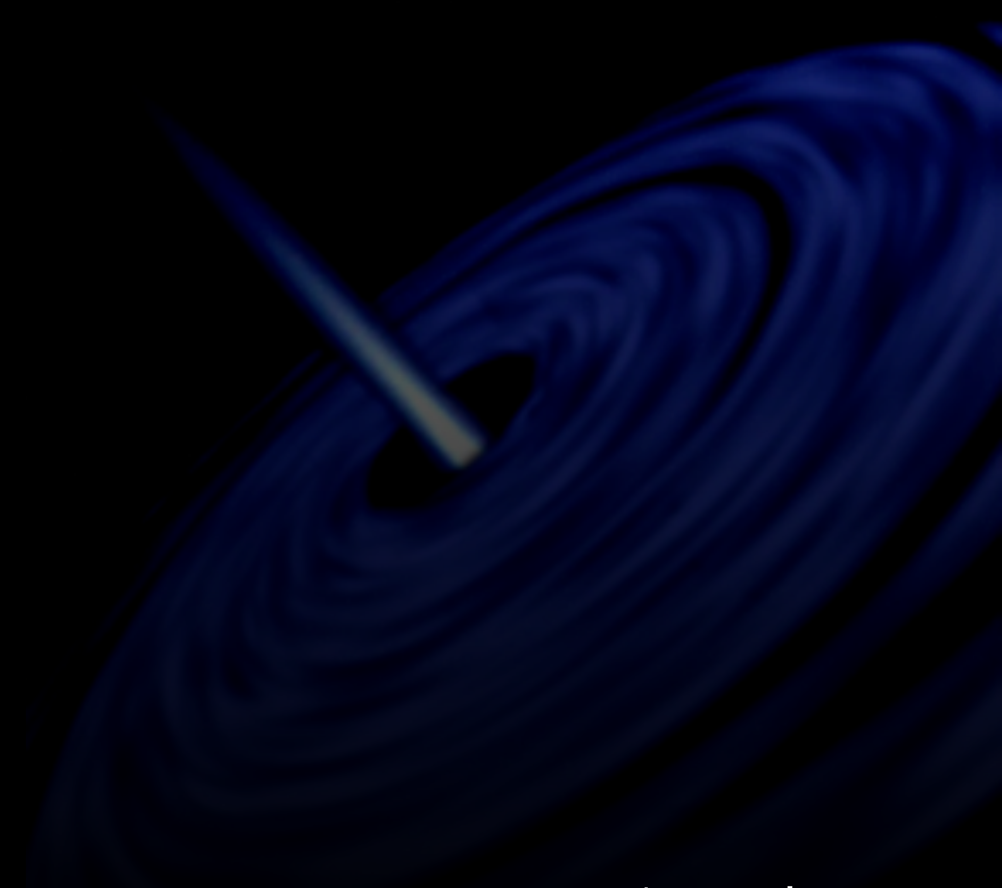
L3 proposal (LISA Consortium)



LISA data



Gravitational wave sources emitting between 0.02mHz and 1 Hz



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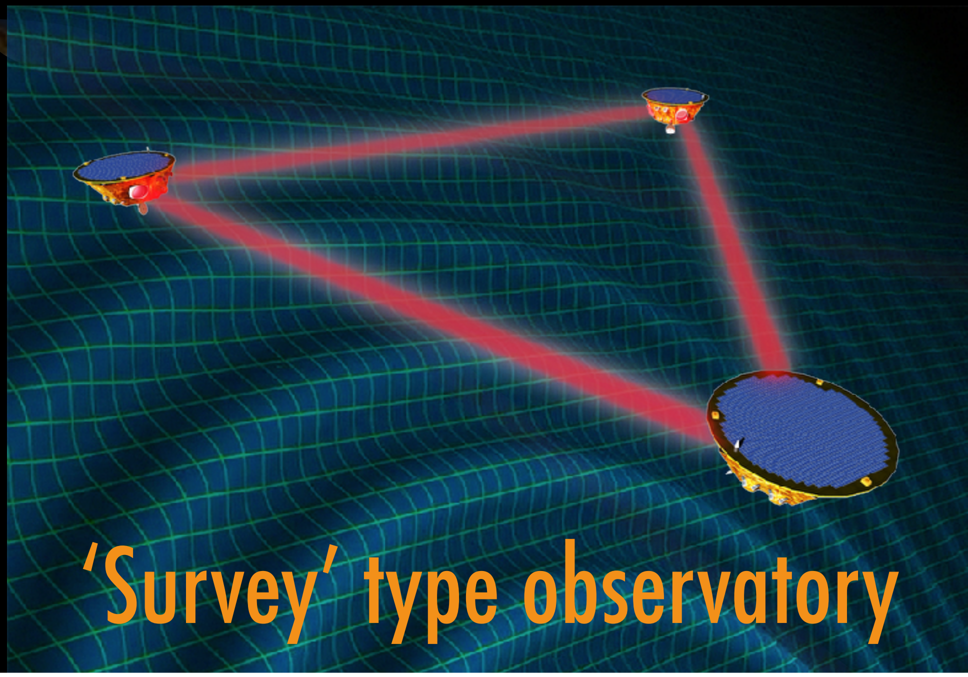

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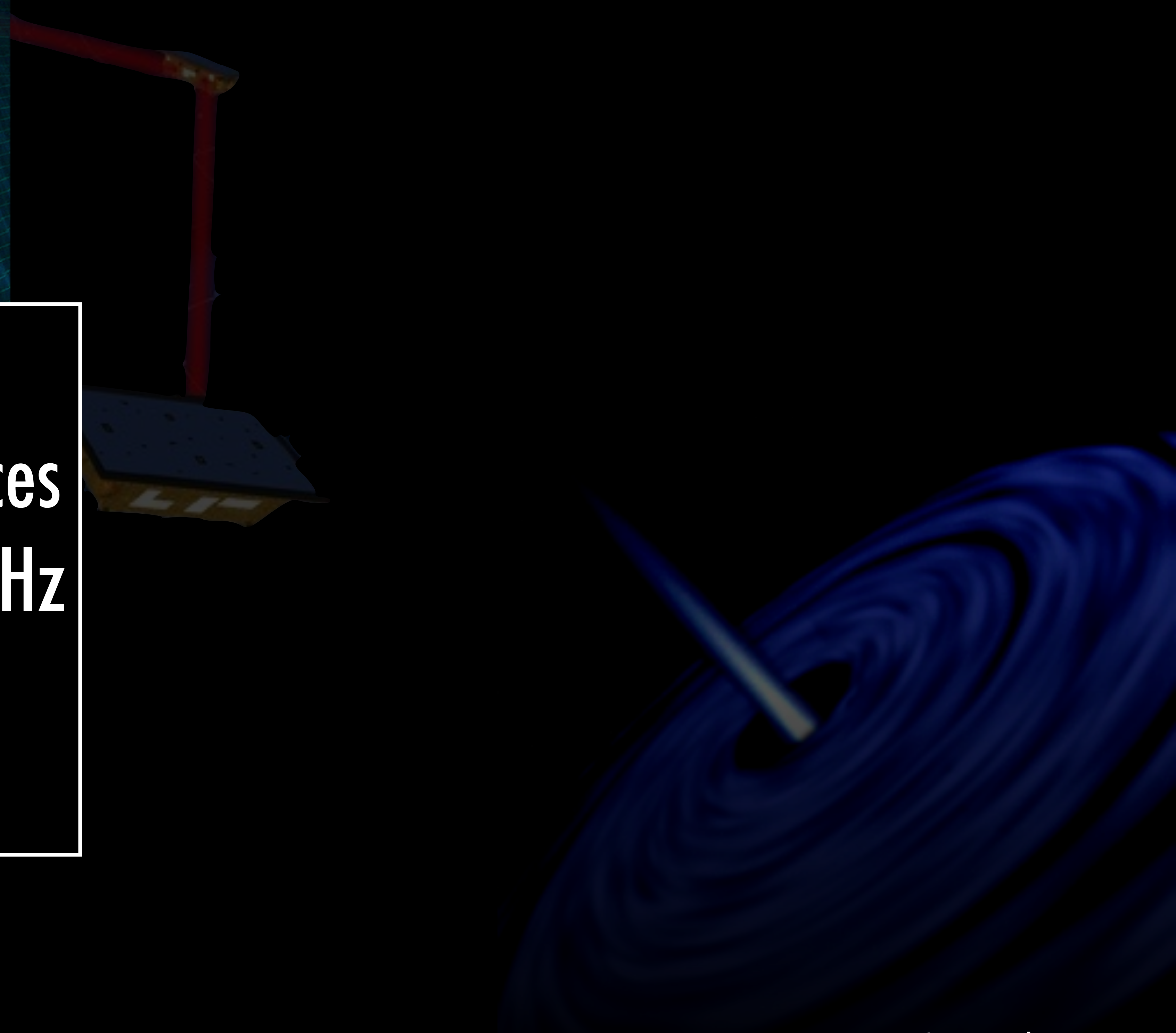

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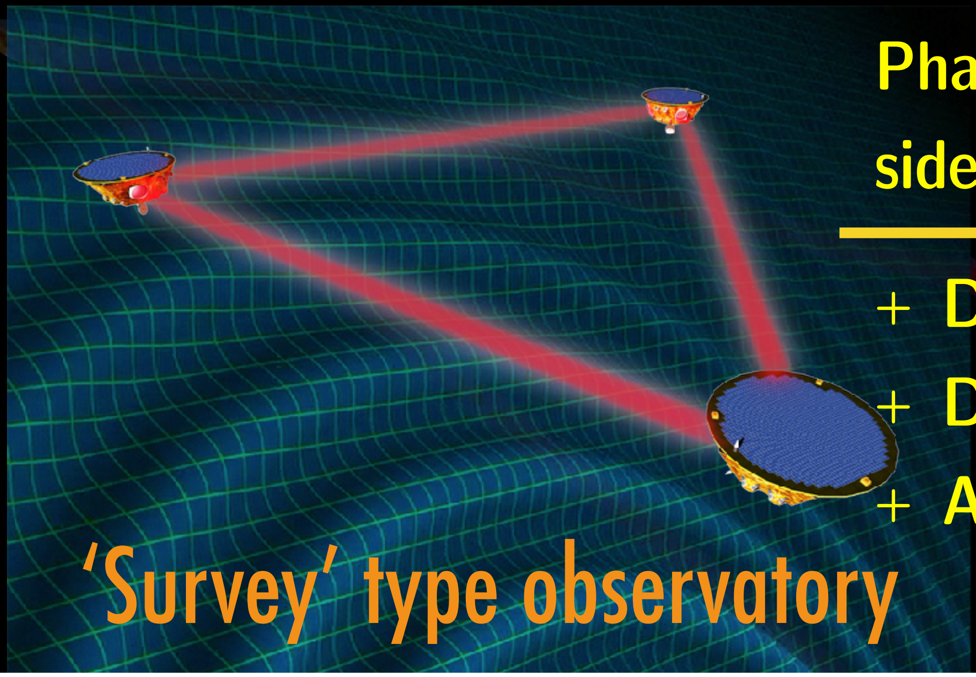

Phasemeters (carrier, sidebands, distance)

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

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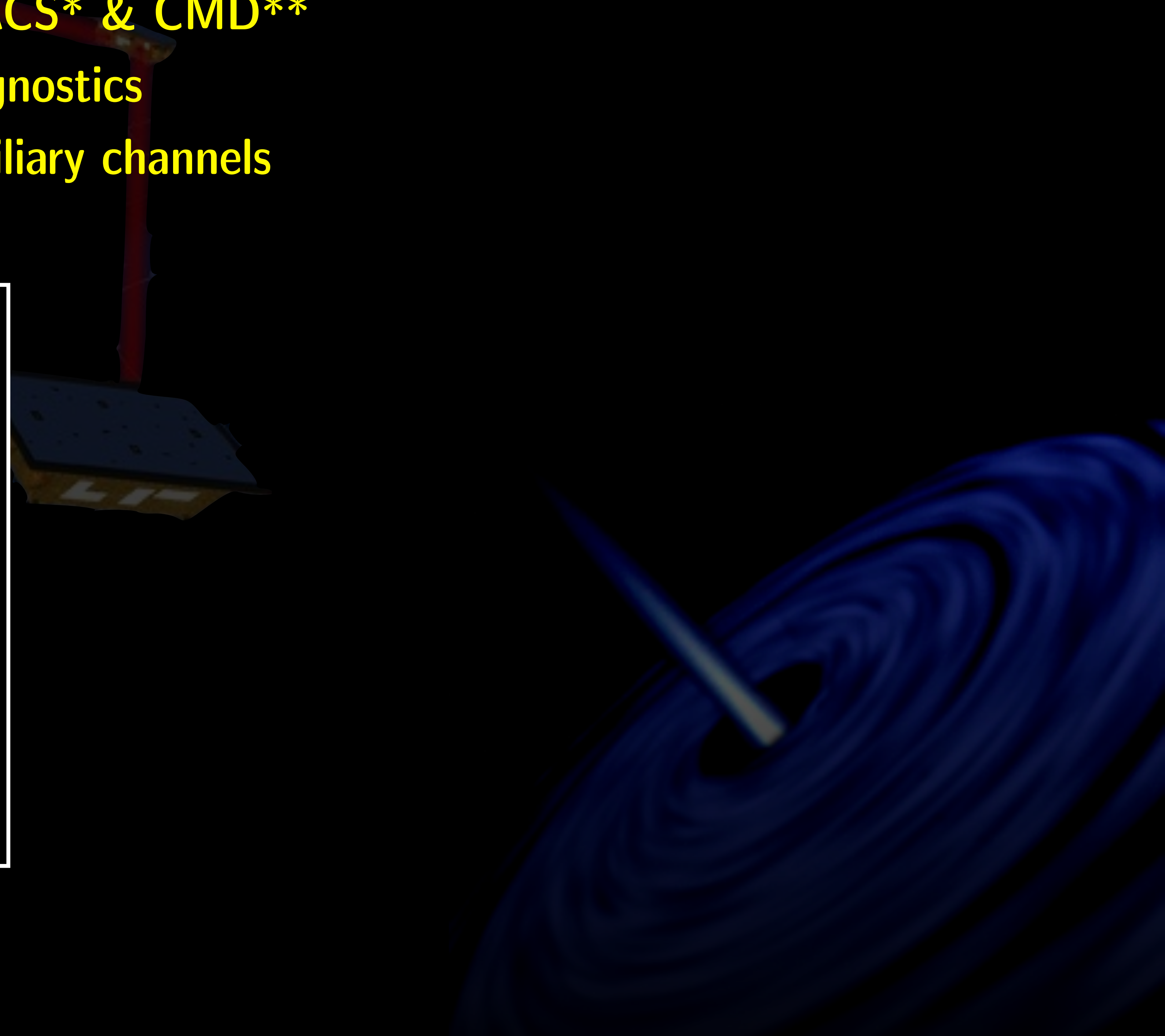
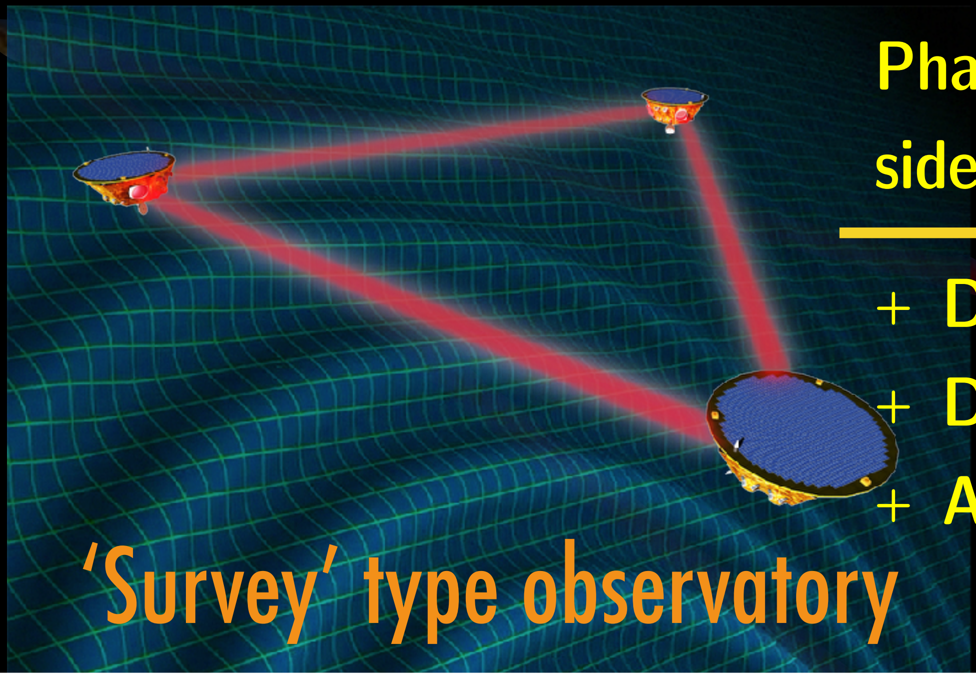


* Drag-Free Attitude Control System

** Charge Management Device

LISA data



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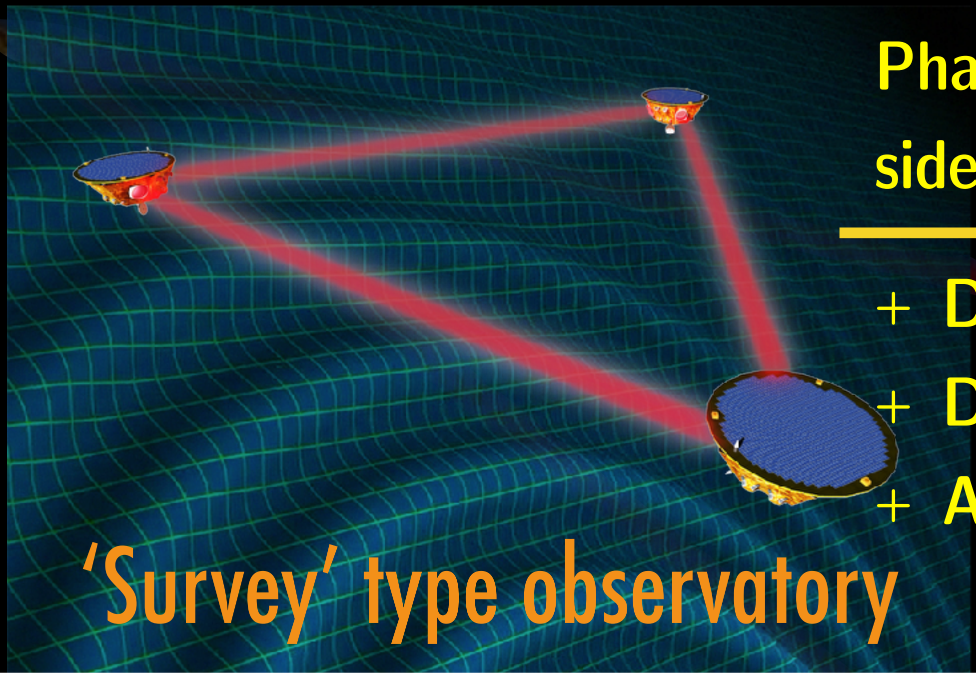

Phasemeters (carrier, sidebands, distance)

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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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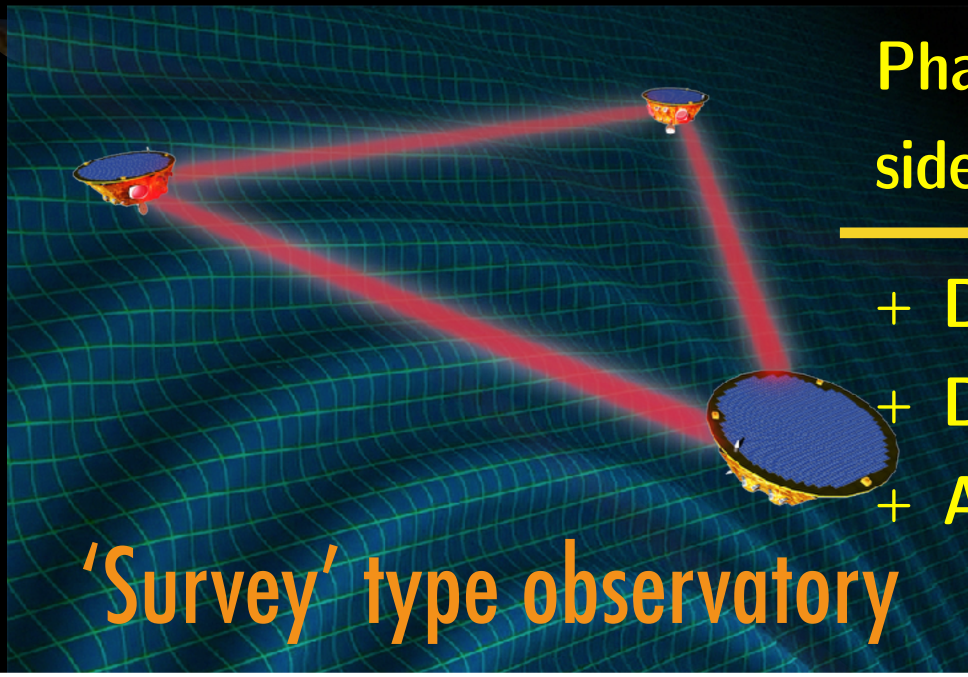

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'Survey' type observatory

Gravitational wave sources emitting between 0.02mHz and 1 Hz

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Data Analysis of GWs

Catalogs of GWs sources with their waveform

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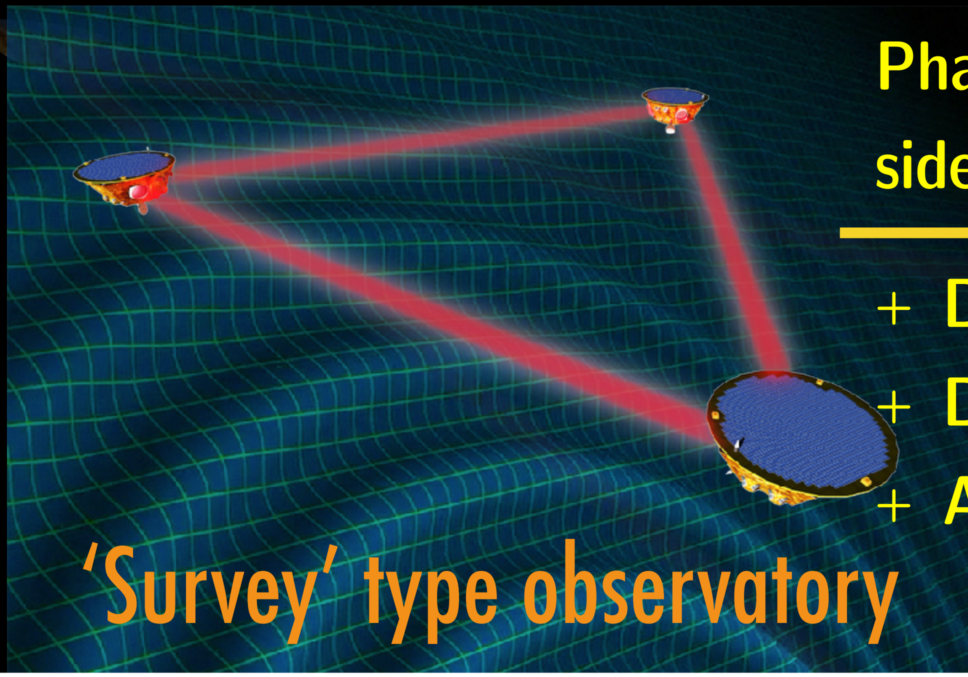

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L0

L0.5

Calibrations corrections
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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

Phasemeters (carrier, ...ds, distance)

...CS* & CMD**

+ Diagnostics

+ Auxiliary channels

'Survey' type observatory

Gravitational wave sources emitting between 0.02mHz ...

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"

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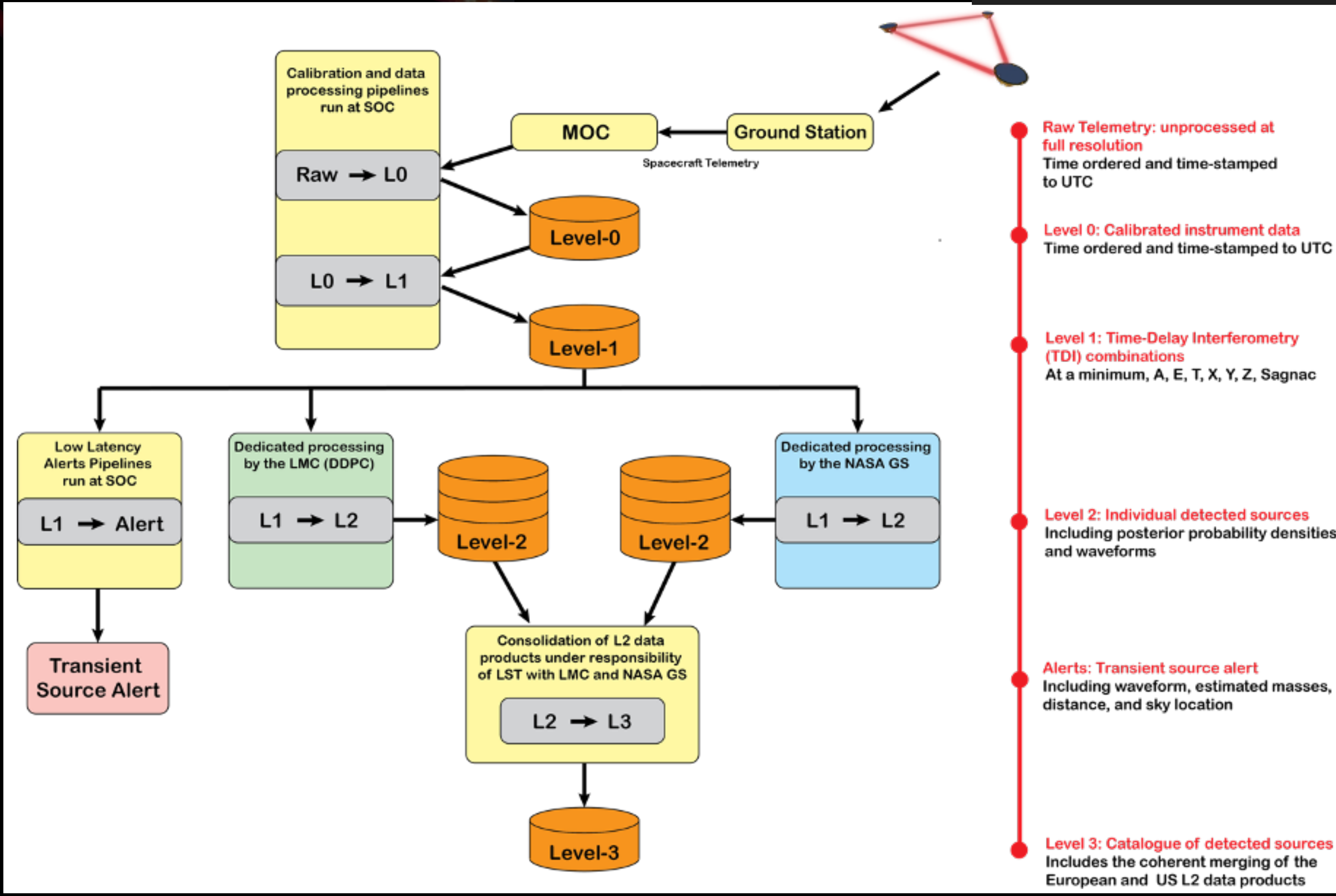
Ground Segment

- Organisation of the ground segment:

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



Ground Segment

- Organisation of the ground segment:

Development by DDPC and NSGS, execution by SOC

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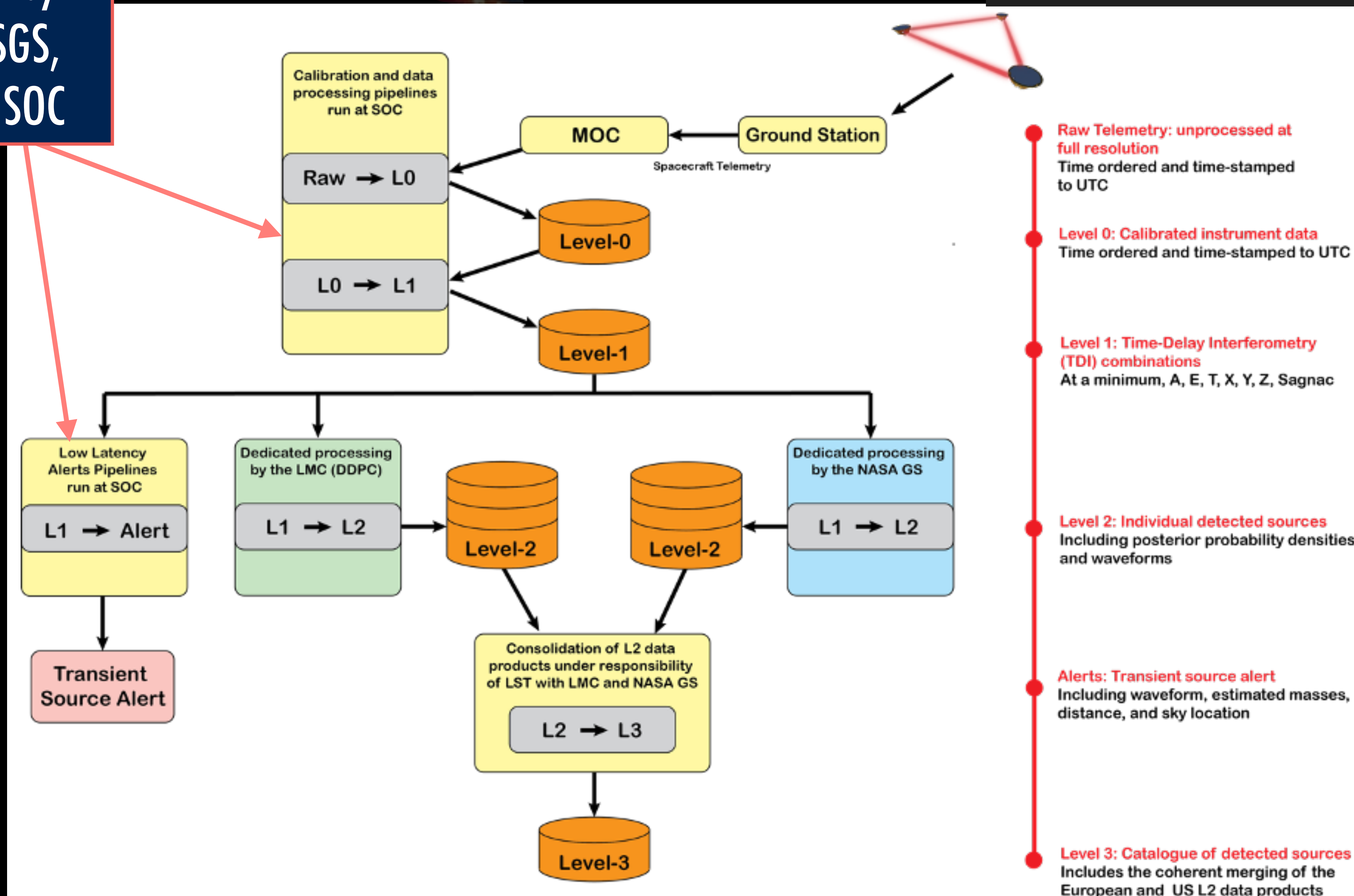

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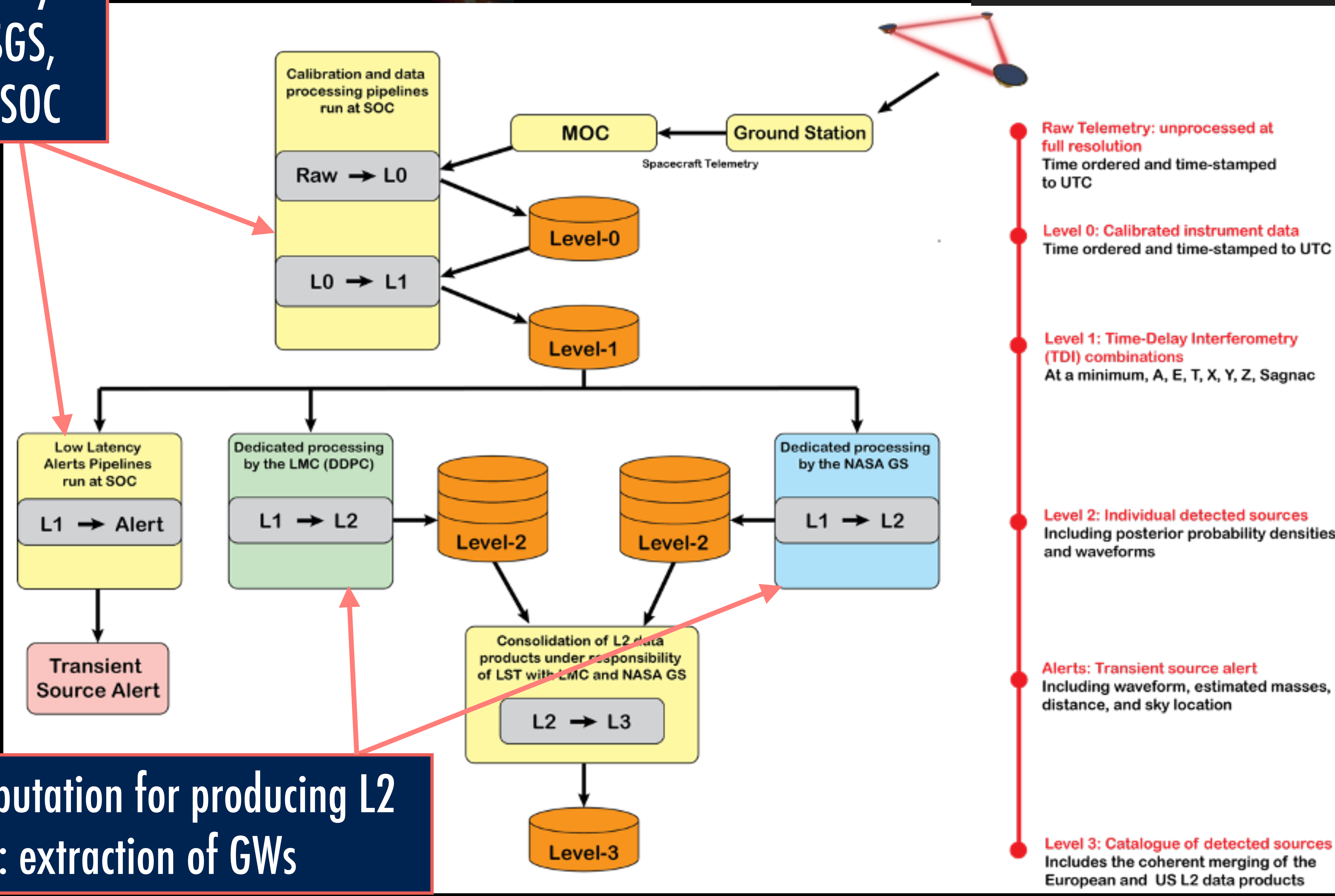
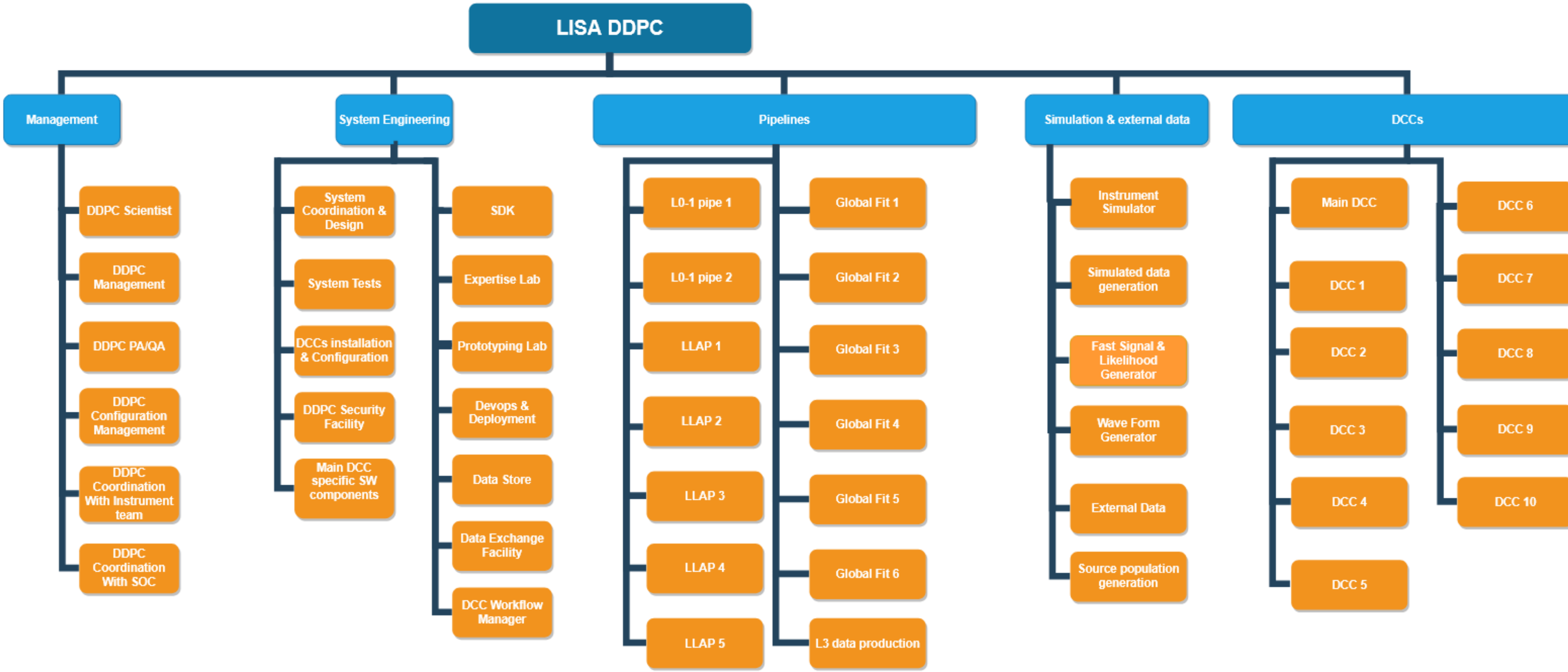


Large computation for producing L2 data: extraction of GWs

DDPC

- Responsibility of France
- Work Break Down structure



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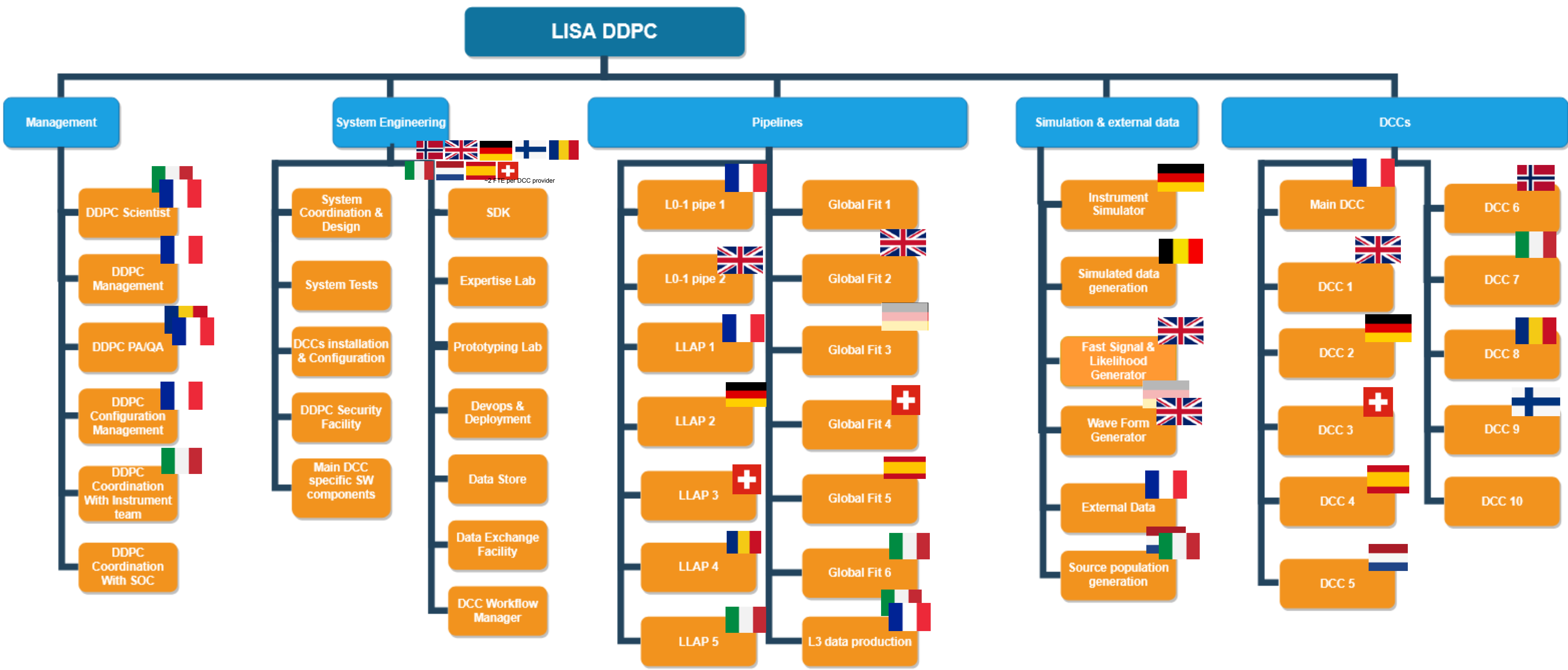

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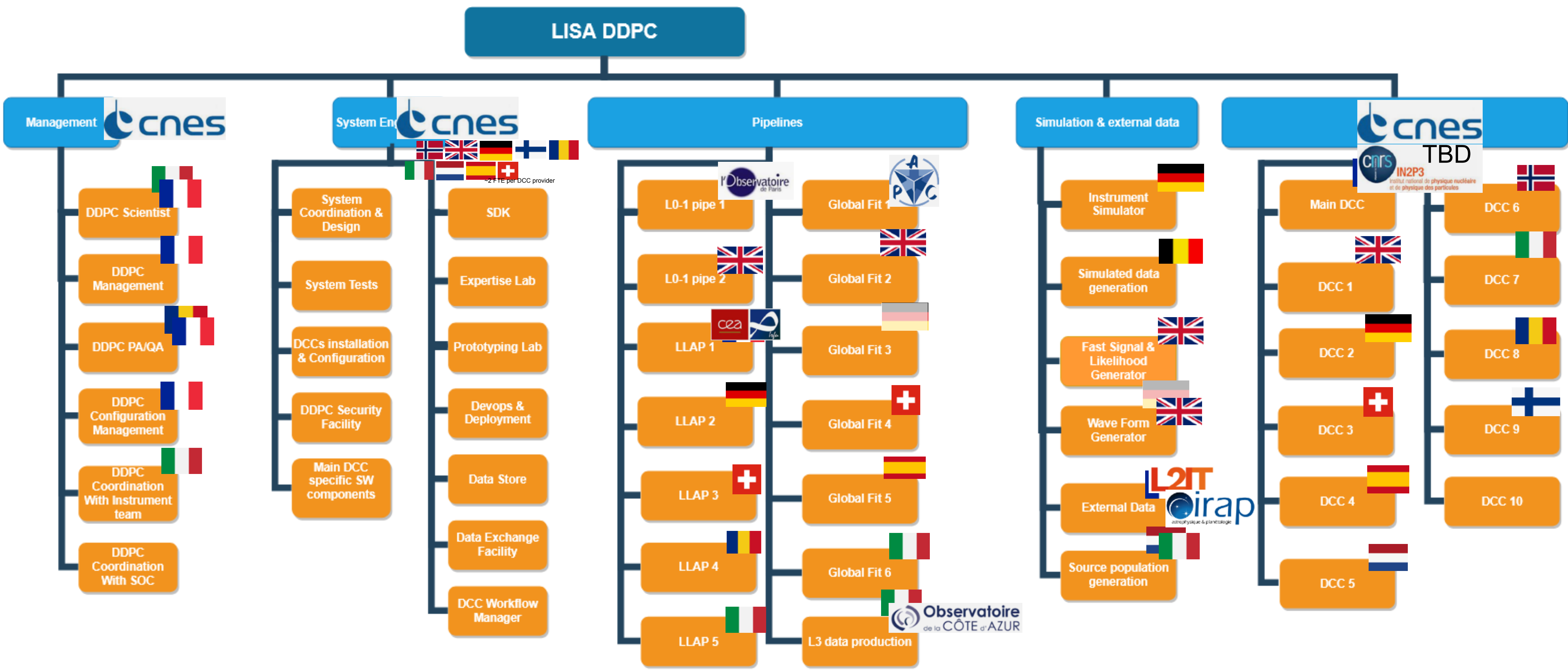
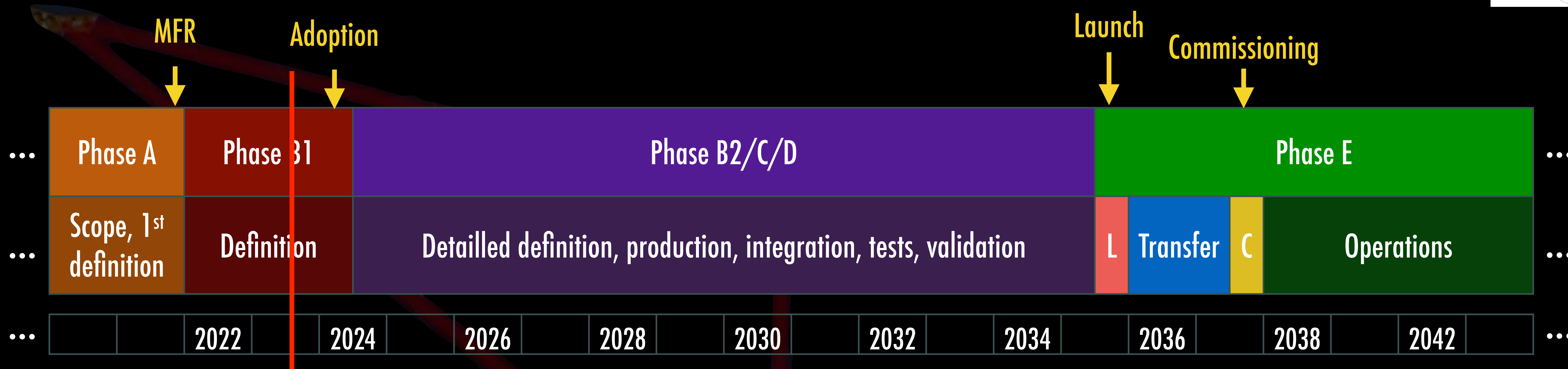


Timeline



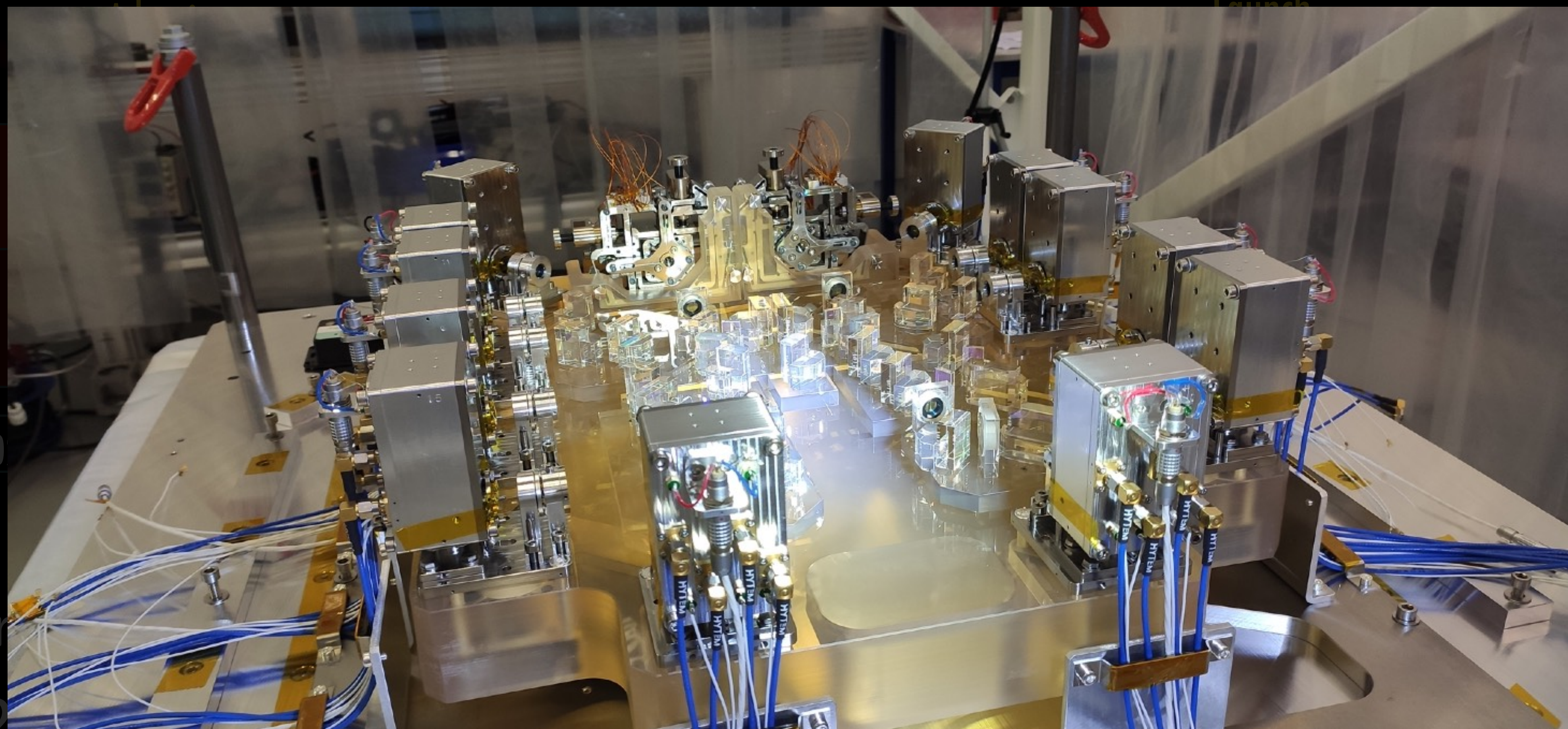
- 1993: first proposal ESA/NASA
- 20/06/2017: LISA mission approved by ESA Science Program Committee
- End 2021: success of the ESA Mission Formulation Review
- Now: accelerated phase B1 with ESA Adoption 25/01/2024
- Long building phase of multiple MOSAs: 6 flight models + test models
- Building of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

Timeline

MFR

Launch

Phase A		E	
Scope, 1st definition		Operations	
20		2042	



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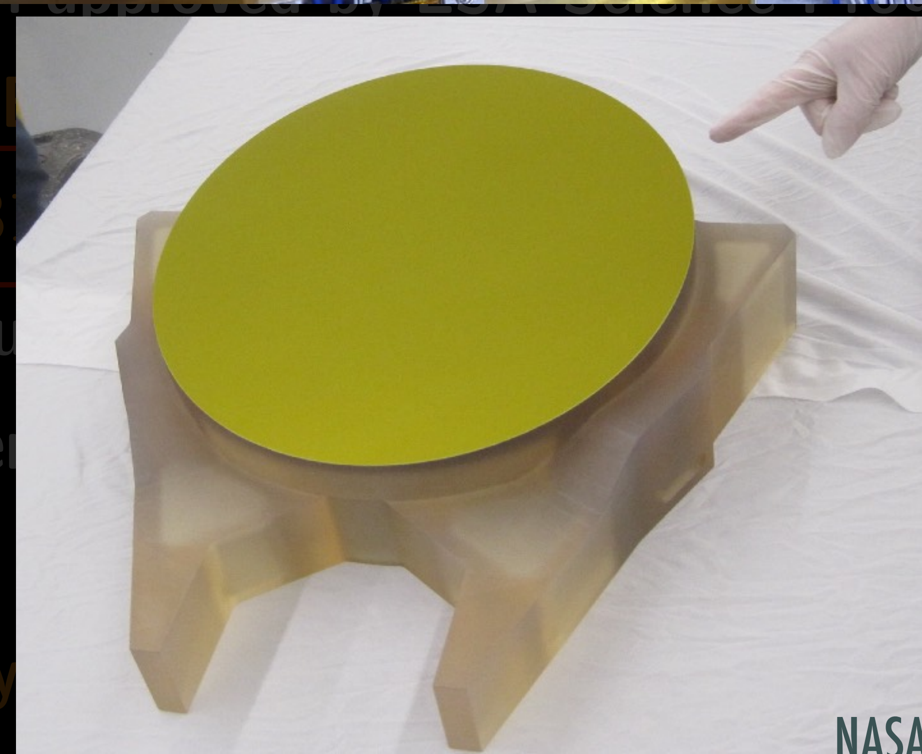
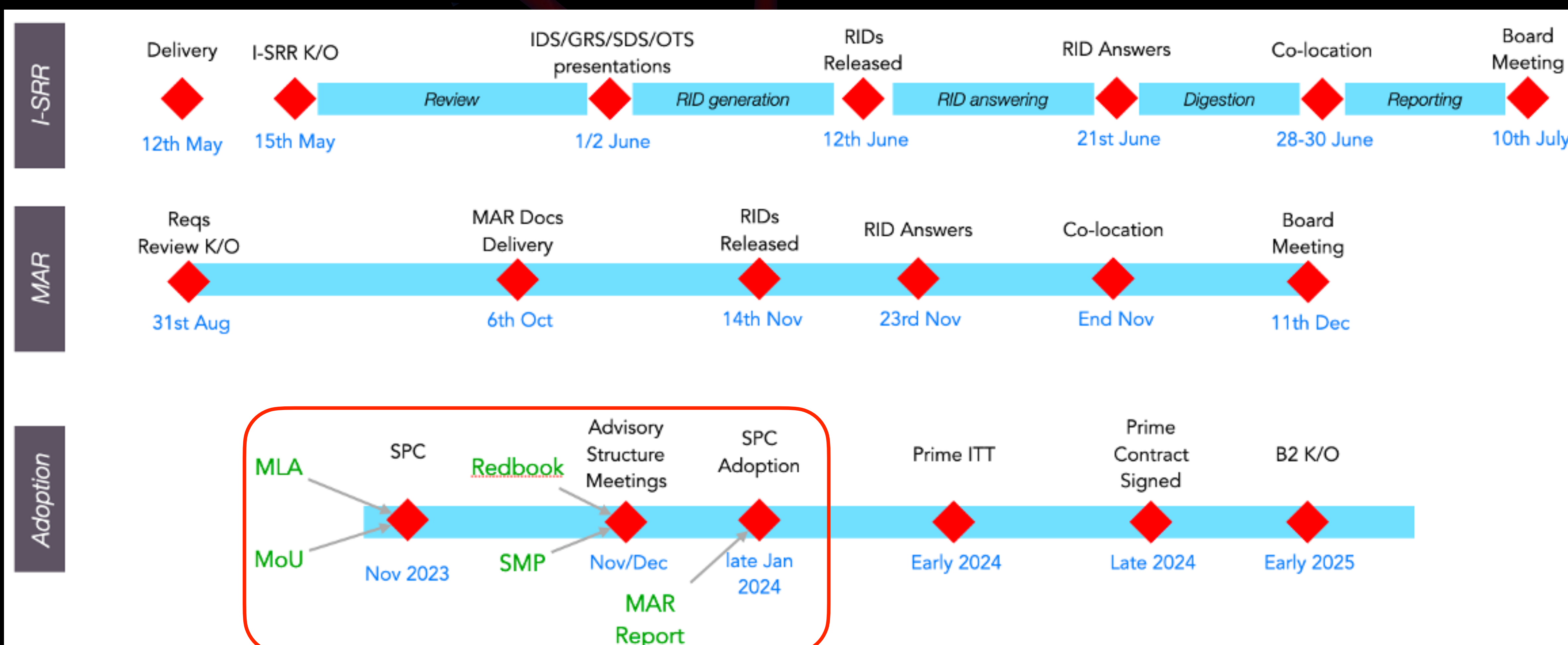
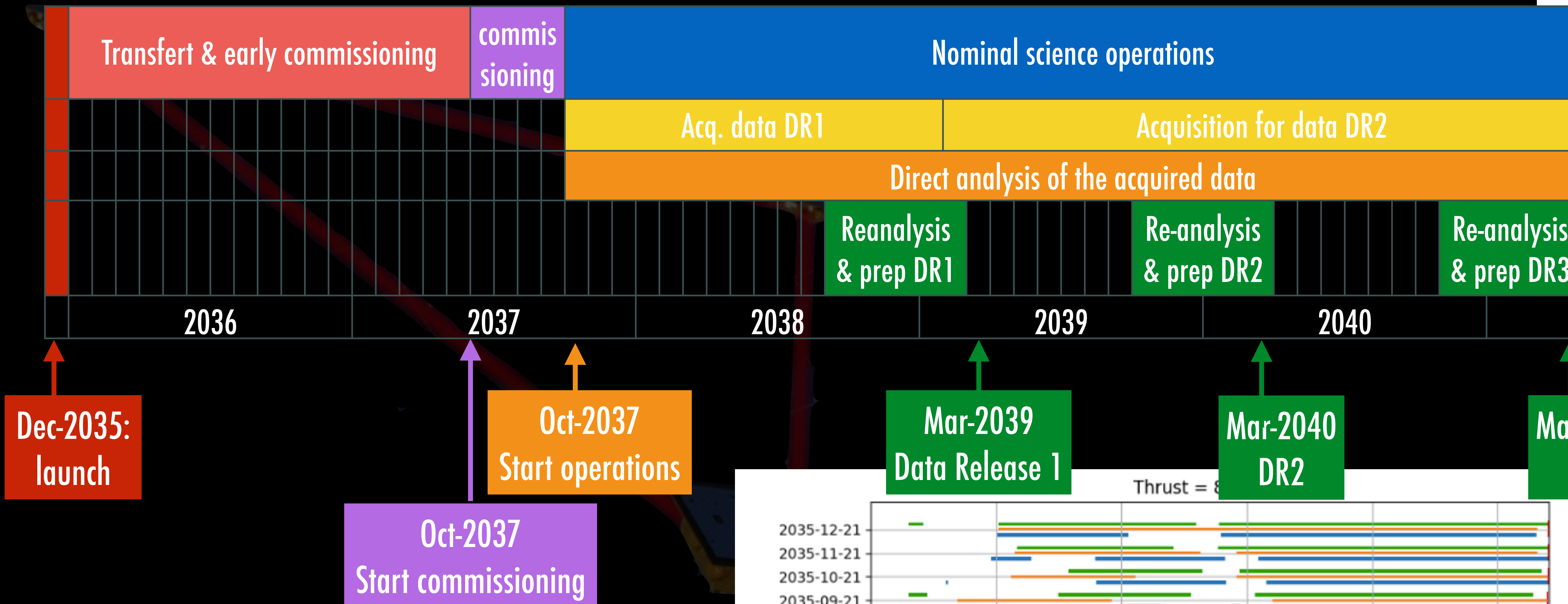


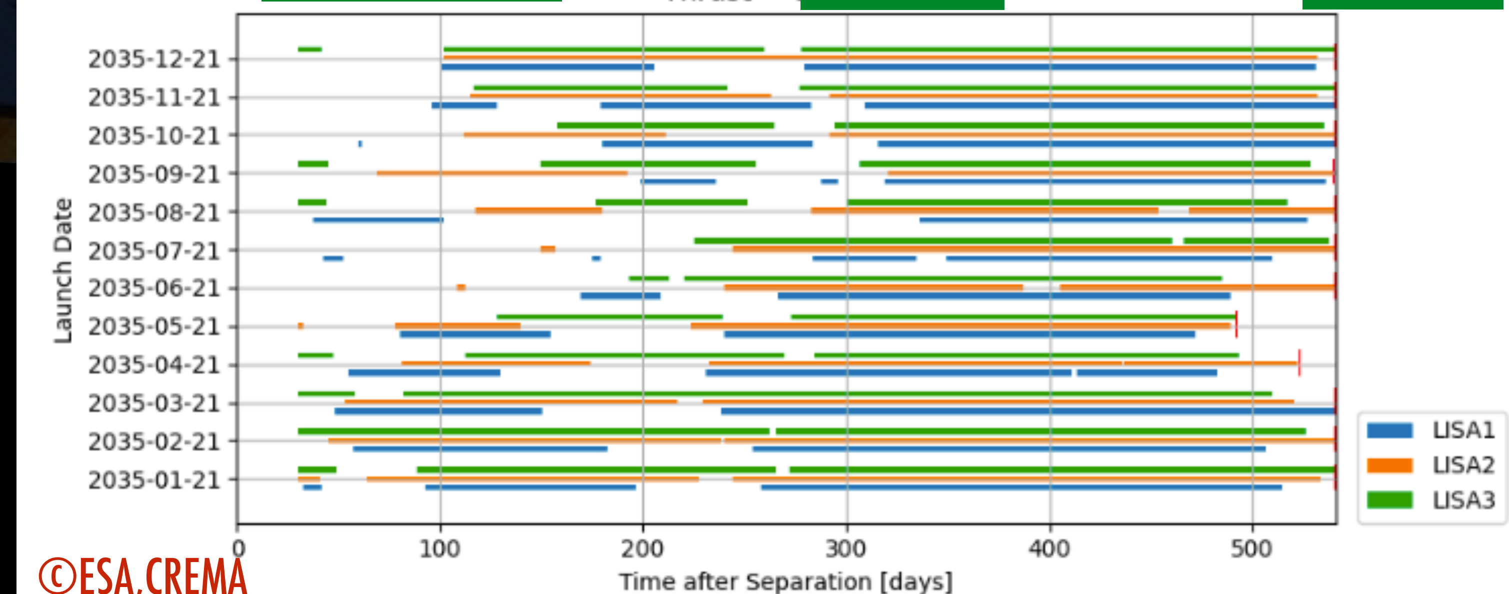
Timeline

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

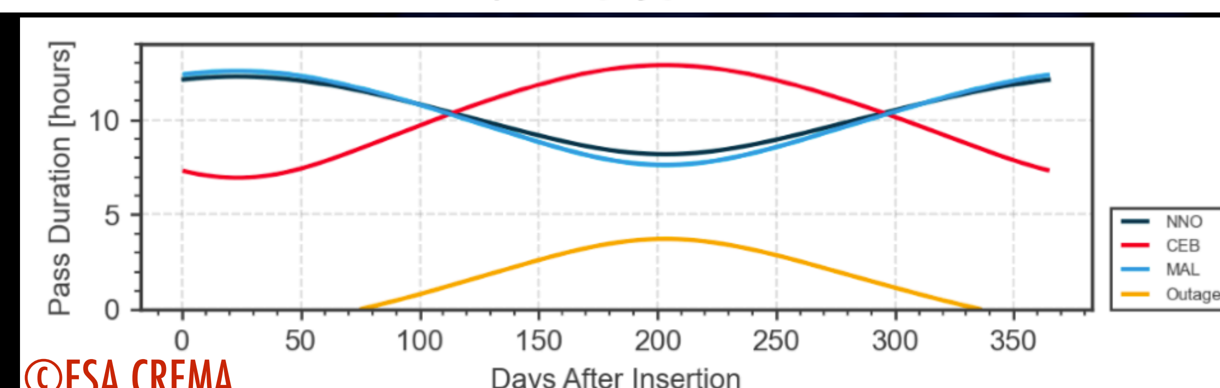


Example of Data Release Scenario





- 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

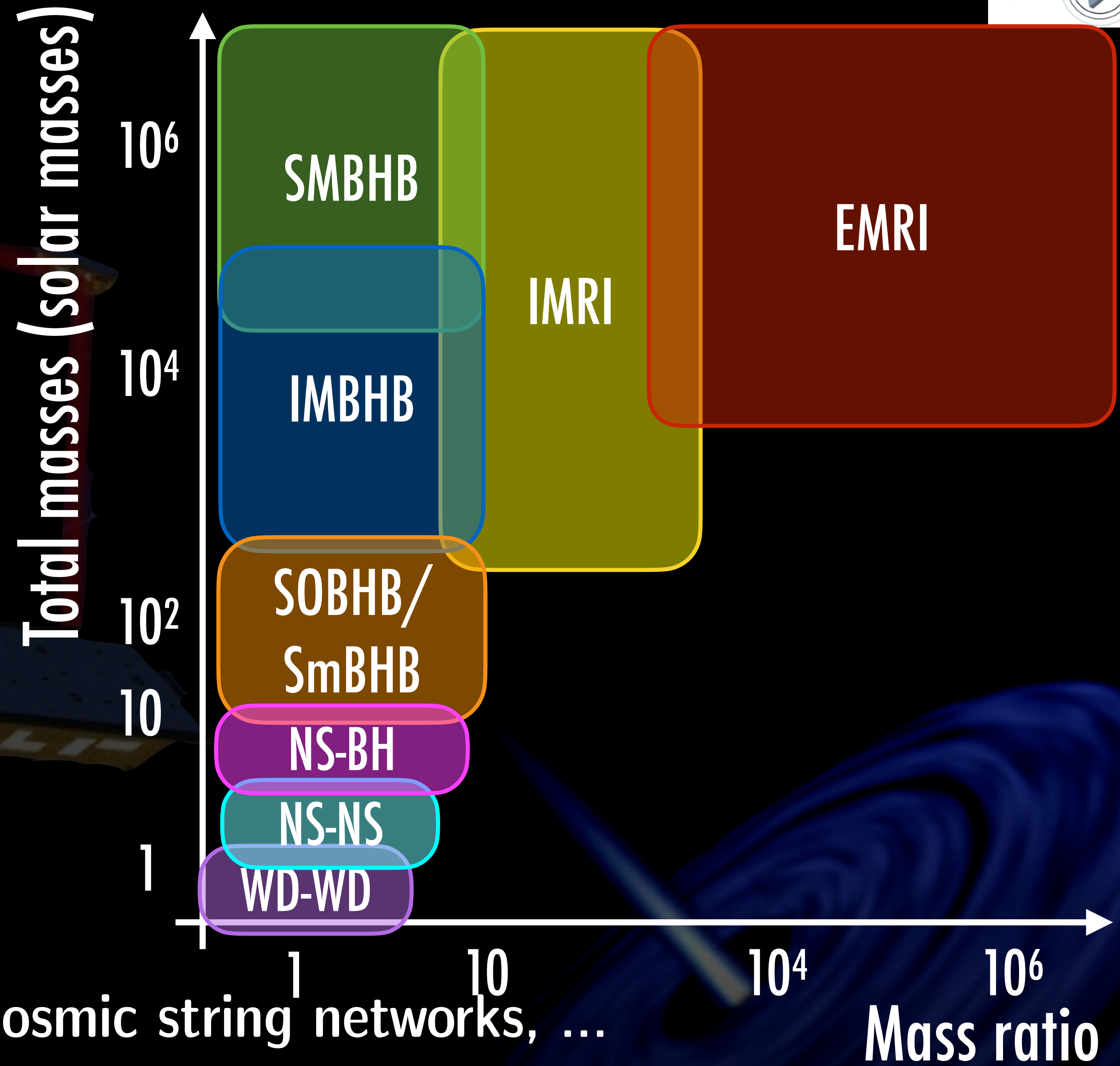


Mission configuration for adoption

Payload		
Lasers		2 per spacecraft • 2 W ouput power at end-of-life • wavelength 1064 nm • frequency stability (pre-stabilised) $300\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$
Optical Bench		2 per spacecraft • double-sided use• low thermal expansion (Zerodur)
Interferometry		heterodyne interferometry • $15\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ requirement • Inter-spacecraft ranging to ~1 m
Gravitational Reference System		$46\,\mathrm{mm} \times 46\,\mathrm{mm} \times 46\,\mathrm{mm}$ 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)

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?

Science Objectives

Defined in the Science Requirements Doc.:

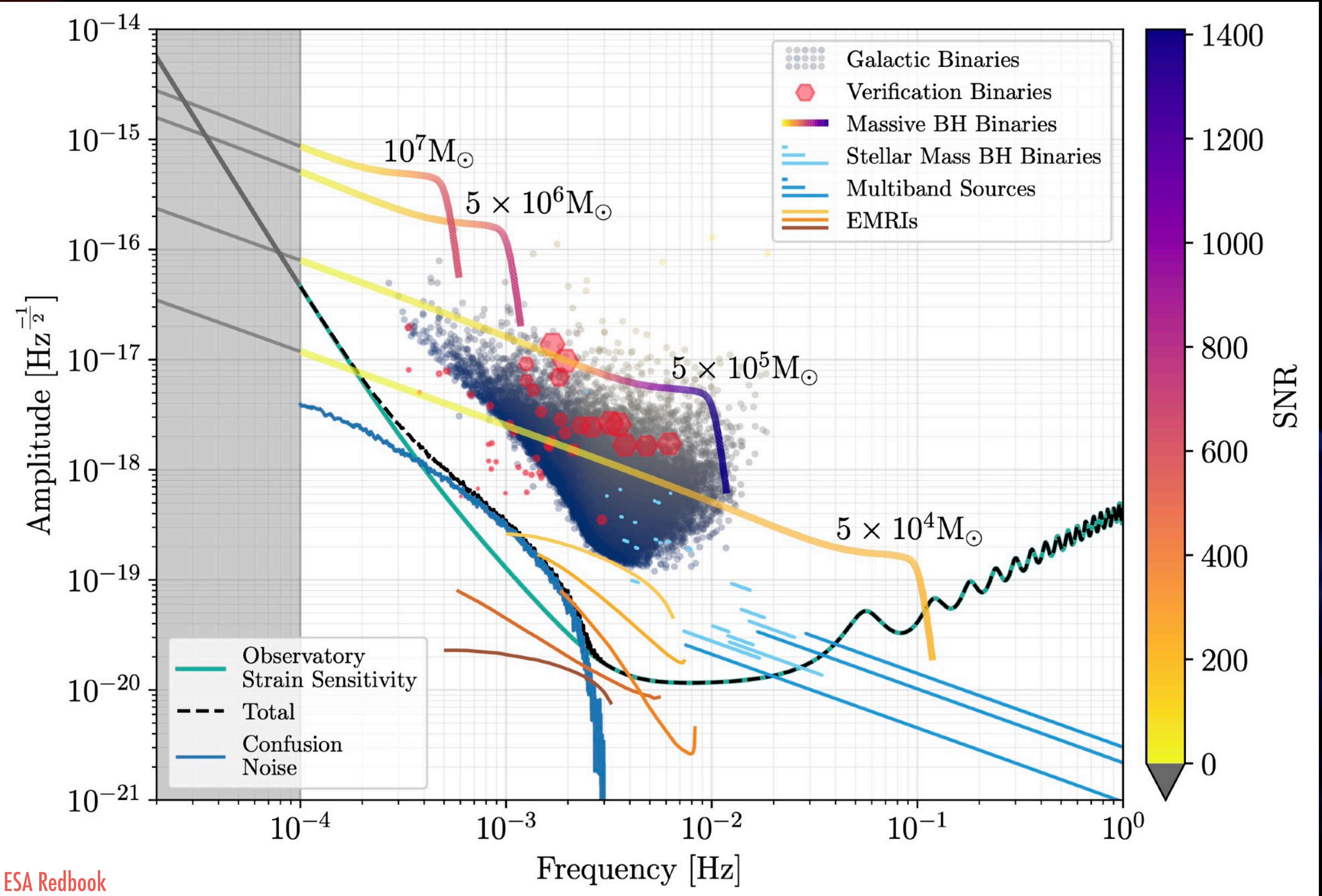
- SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages.
- SO3: Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs.
-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

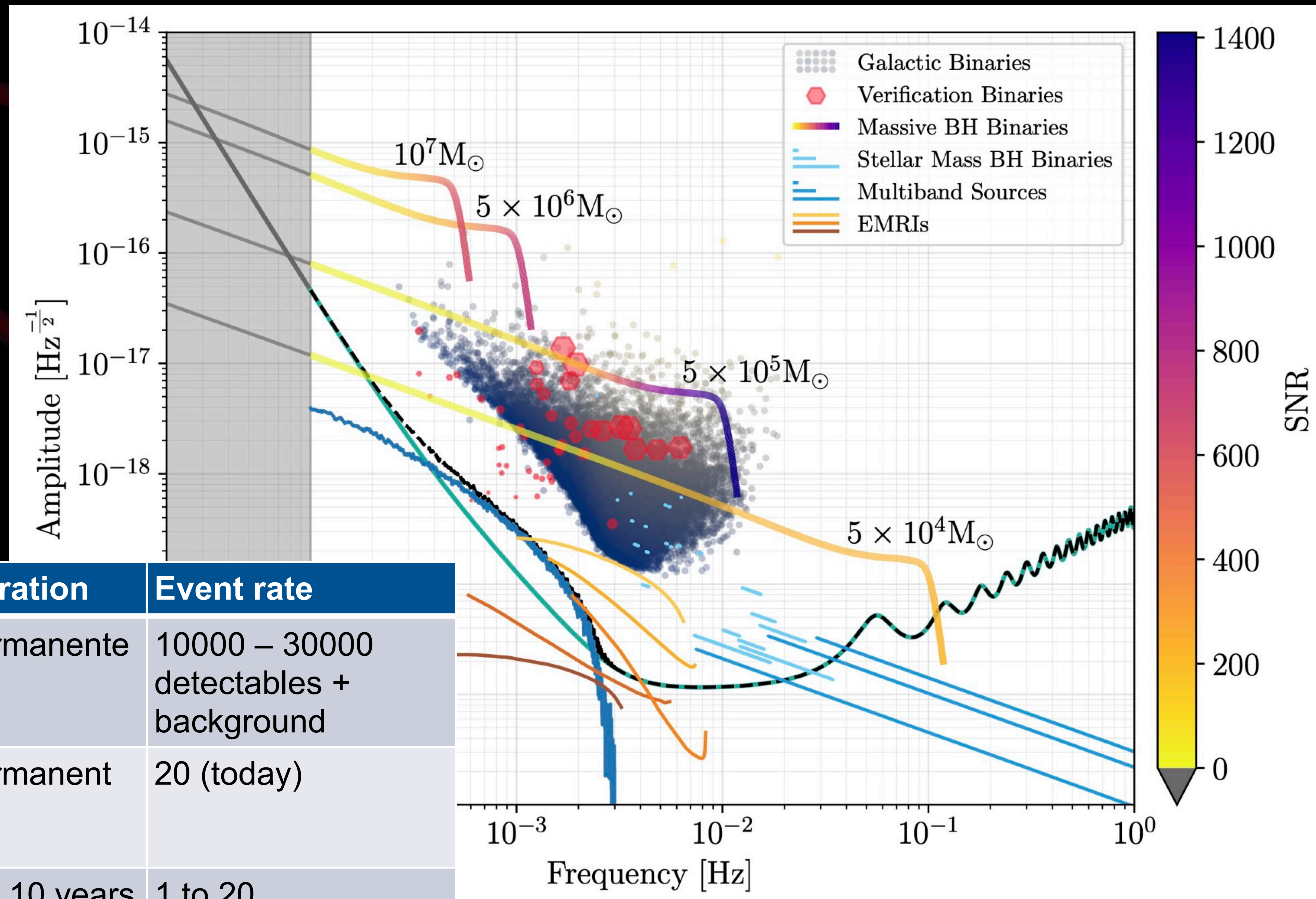
Cosmology

Binaries observed by LISA



ESA Redbook

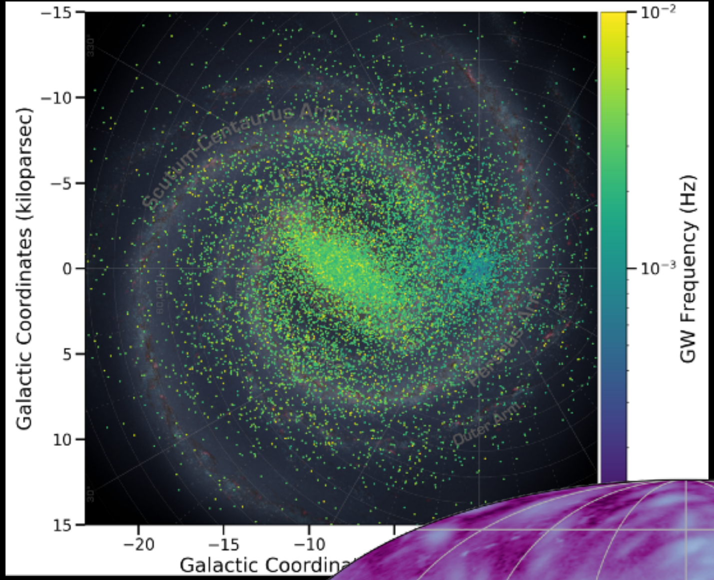
Binaries observed by LISA

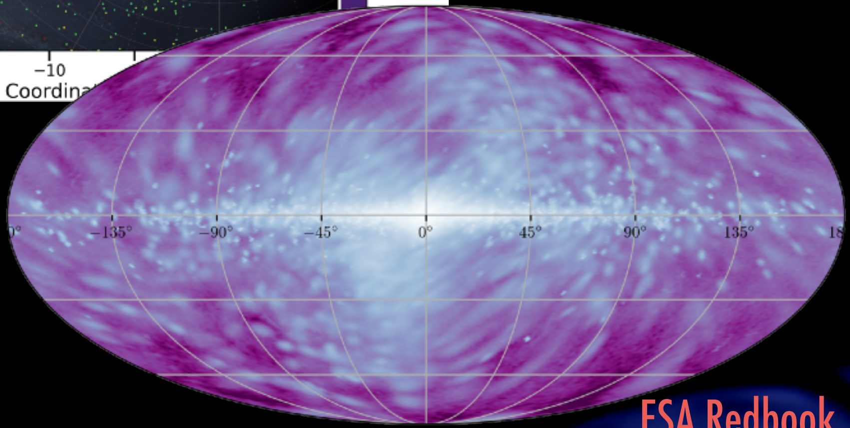


Sources	SNR	Duration	Event rate
Galactic binaries	10 – 500	permanentes	10000 – 30000 detectables + background
Verification binaries	7 - 100	permanent	20 (today)
Stellar mass black hole binaries	7 - 30	1 à 10 years	1 to 20
EMRIs	7 - 60	1 year	1 to 2000 / year
Massive Black Hole binaries	10 - 3000	Hours - months	10 to 1000 / year

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.
- Link to:
    - Multimessanger
    - Population modelling
    - SN1a





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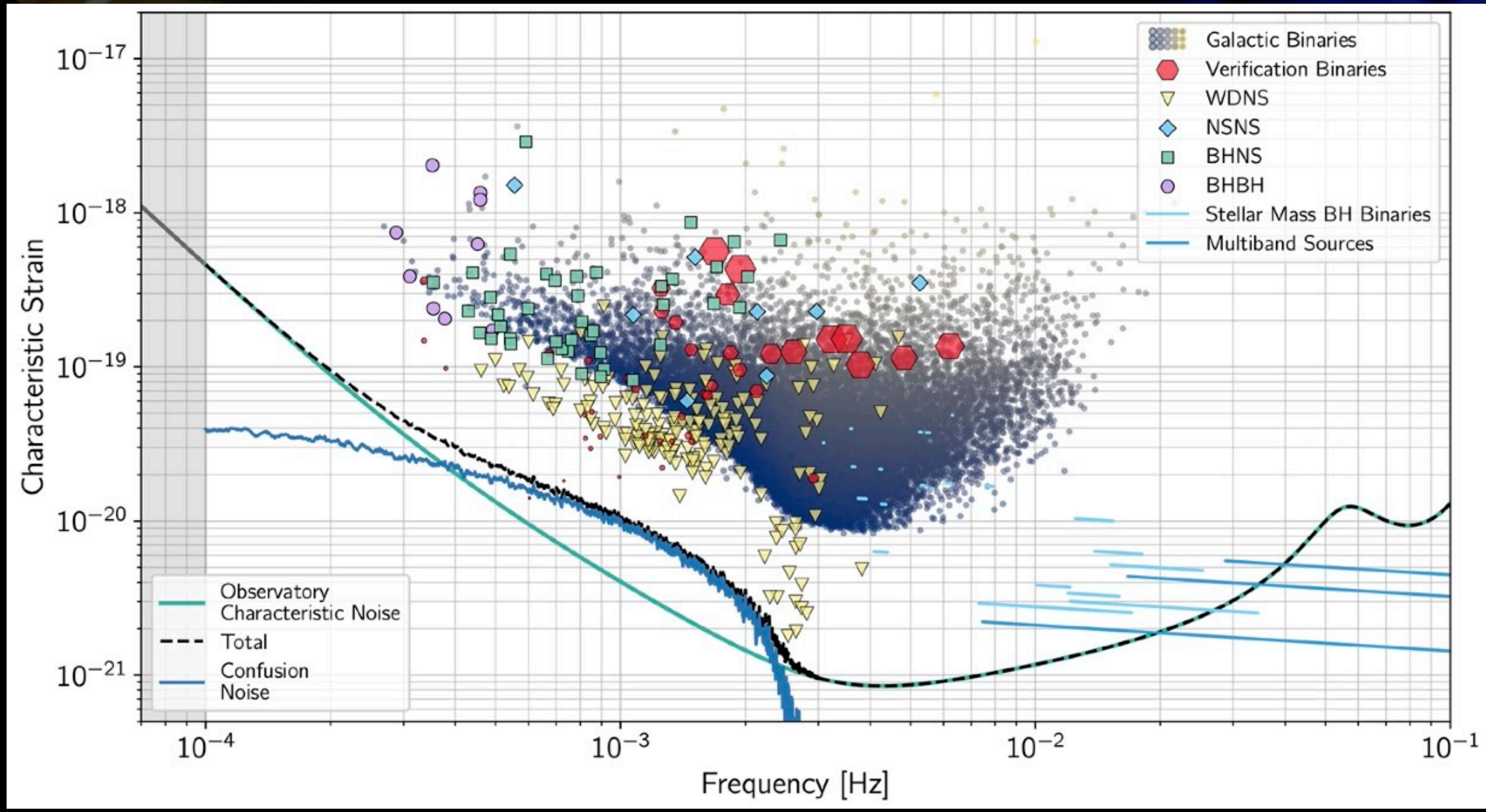
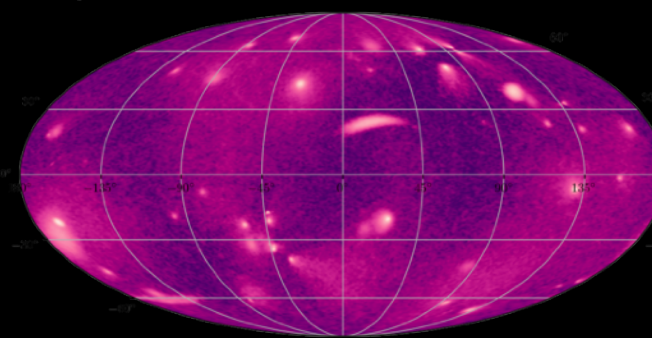
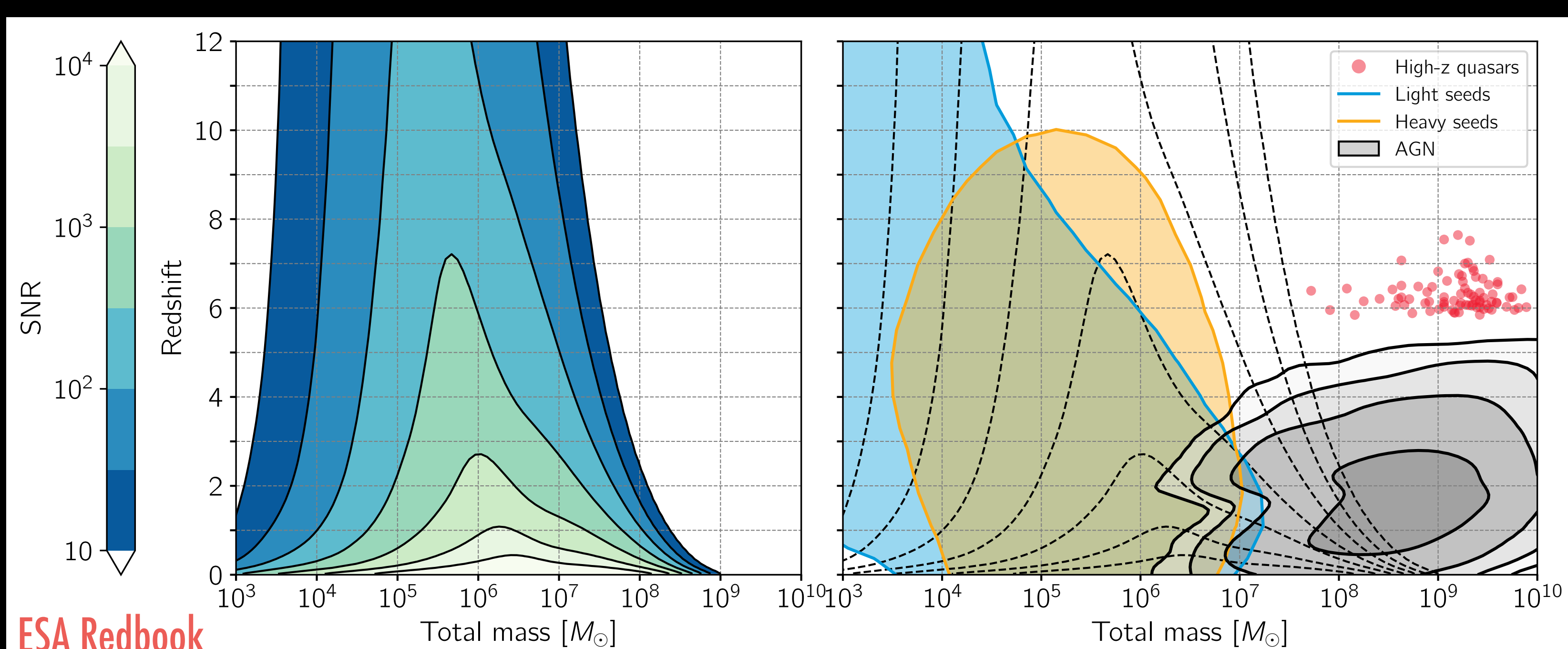


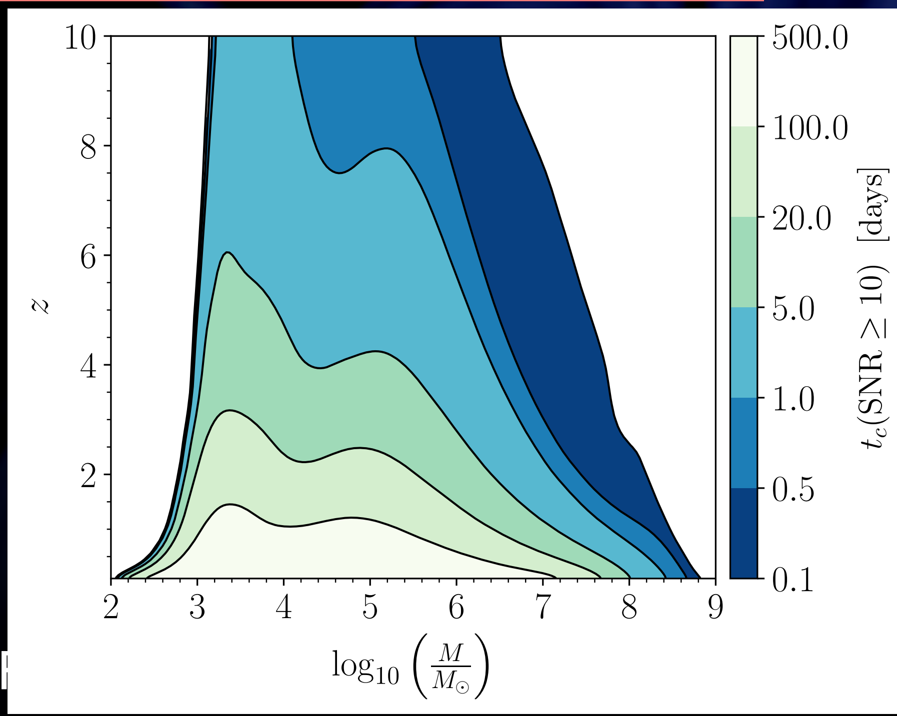
Science Objectives

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



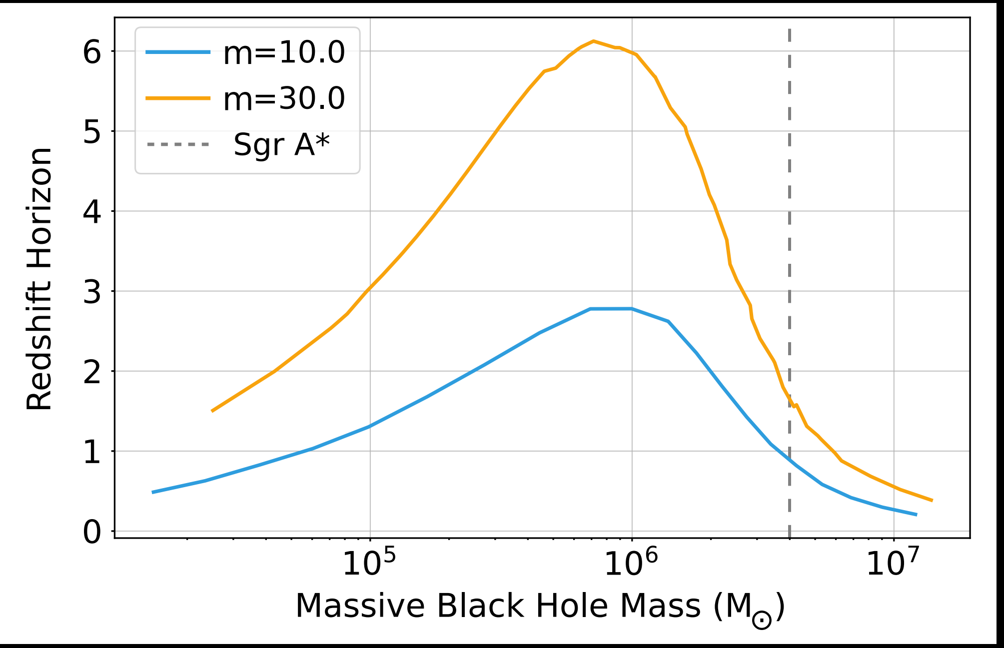
- Discover seed black holes at cosmic dawn;
- Study the growth mechanism and merger history of massive black holes from the epoch of the earliest quasars;
- Identify the electromagnetic counterparts of massive black hole binary coalescences.



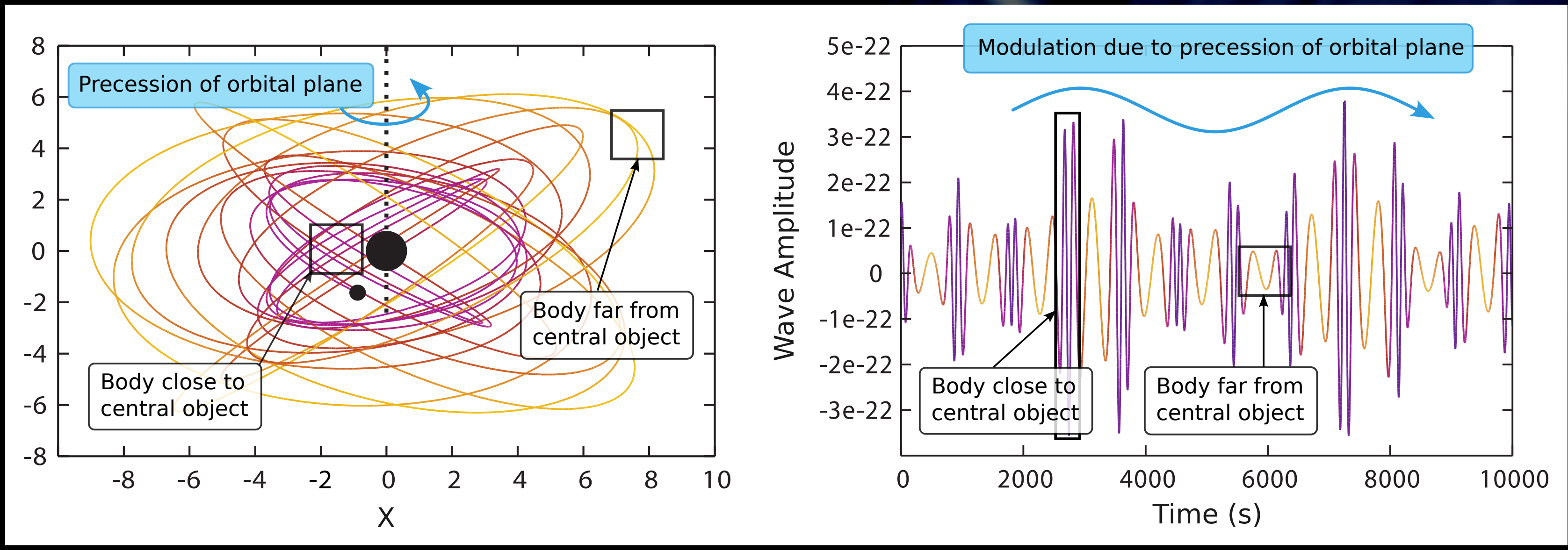


Science Objectives

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

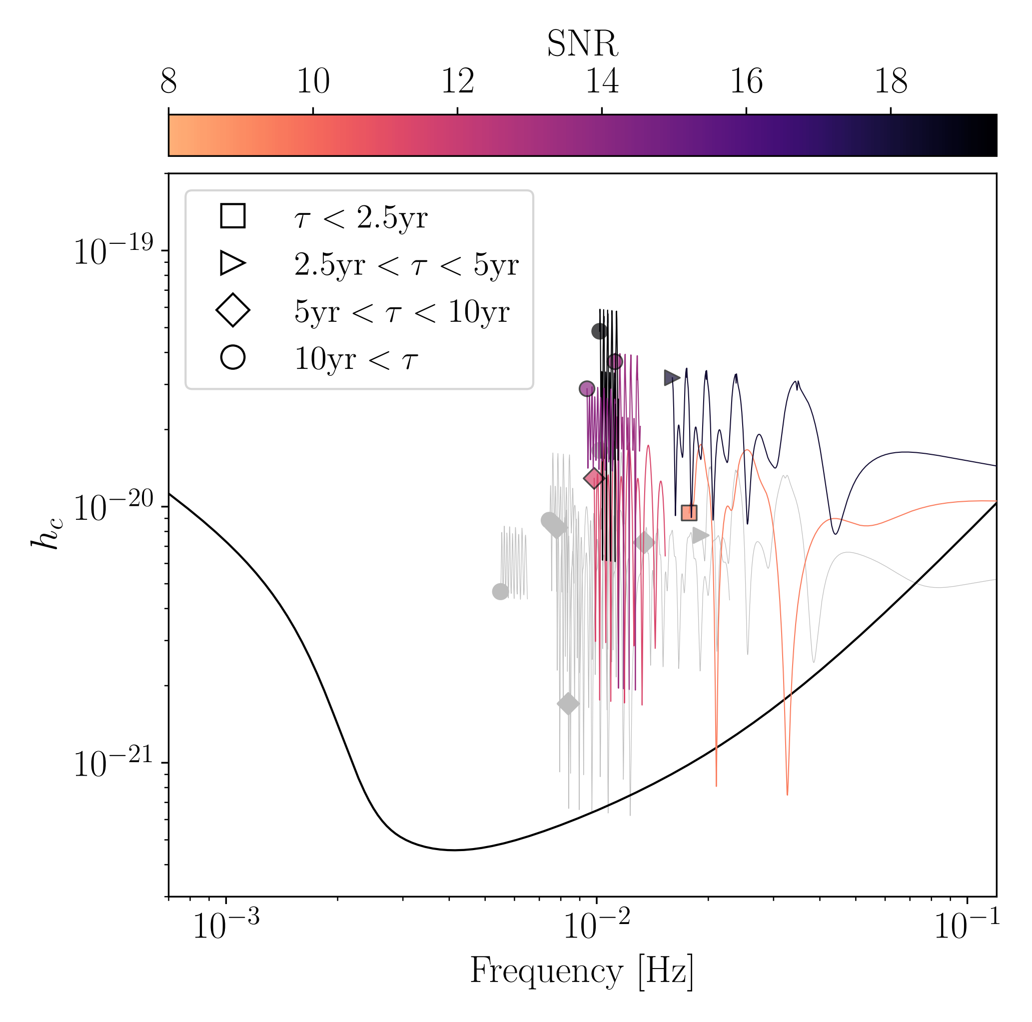


- Link to Tidal Disruption Event



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.



LISA / HE

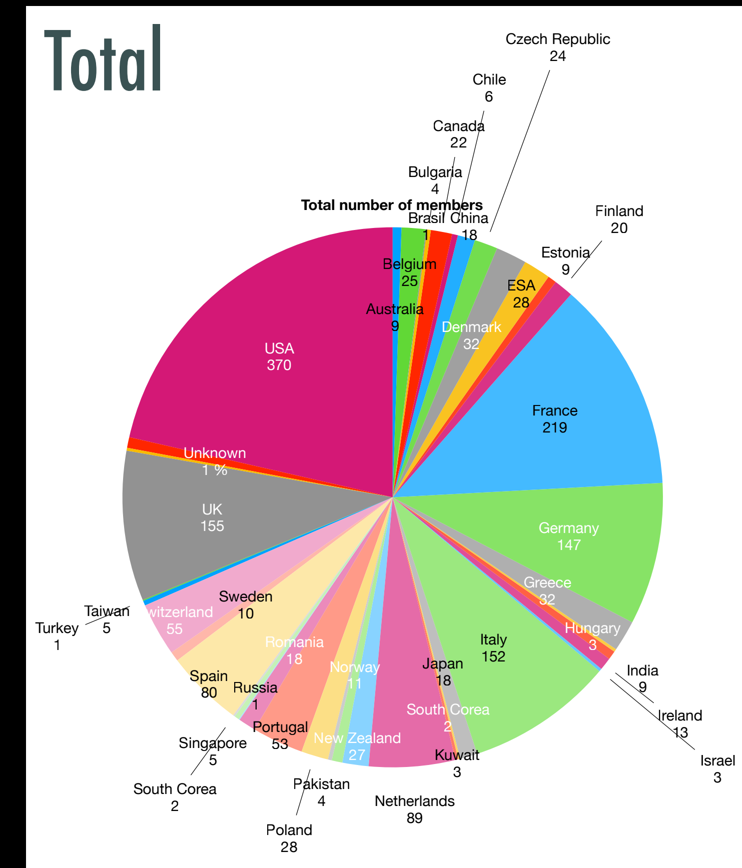
- **Multi-messenger**: observation of the same event (alerts, live update)
  - Interacting galactic binaries,
  - Massive BH Binaries,
  - EMRIs?
  - IMRIs?
  - Tidal Disruption Events?

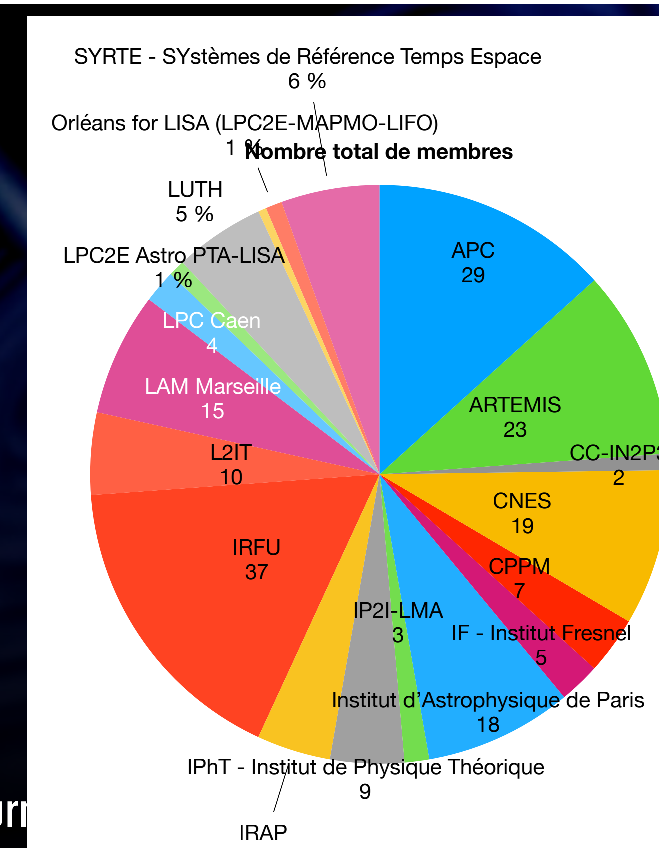
More in LISA astrophysics white paper: arXiv:2203.06016 / LRR, 26-1

- **Populations**:
  - Galactic sources (i.e. X-ray binaries, cataclismic variables, ...),
  - Massive BHs,
  - Other sources
- LISA and High Energy observatories observe same category of objects.

LISAFrance

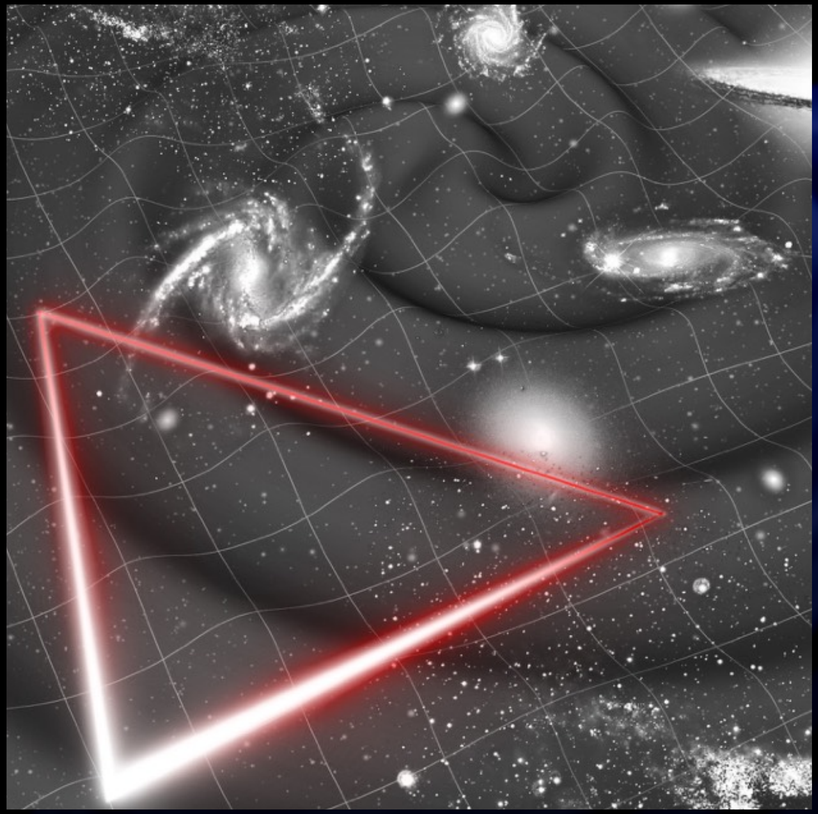
- **Responsibilities**:
  - DDPC
  - AIVT Inteferometric Detection System + Optical Test System
  - Performances management
- **LISAFrance** collaboration:
  - 219 members / 153 full members
  - 15 laboratories / 6 institutes
  - Telecon every 2 weeks / LISAFrance day every year (next: 20th Nov)
  - PIs: Antoine Petiteau & Astrid Lamberts
- **SNO LISA** accepted in 2023
- How to join:
  - Possible to join the current Consortium (just note the reorganisation in 1.5y)
  - In future:
    - French contribution: DDPC and/or instrument
    - ESA LISA Science Team, its working group and Science Topical Panel
    - Consortium



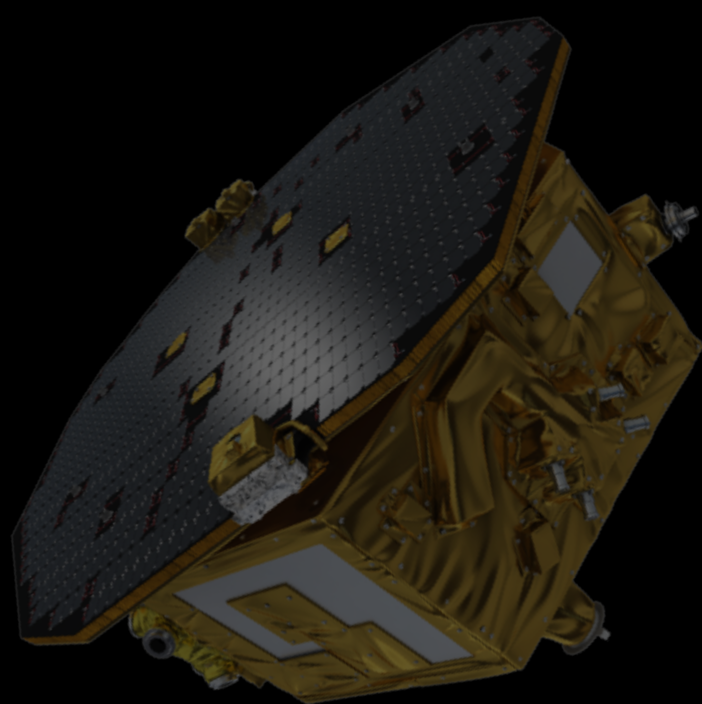


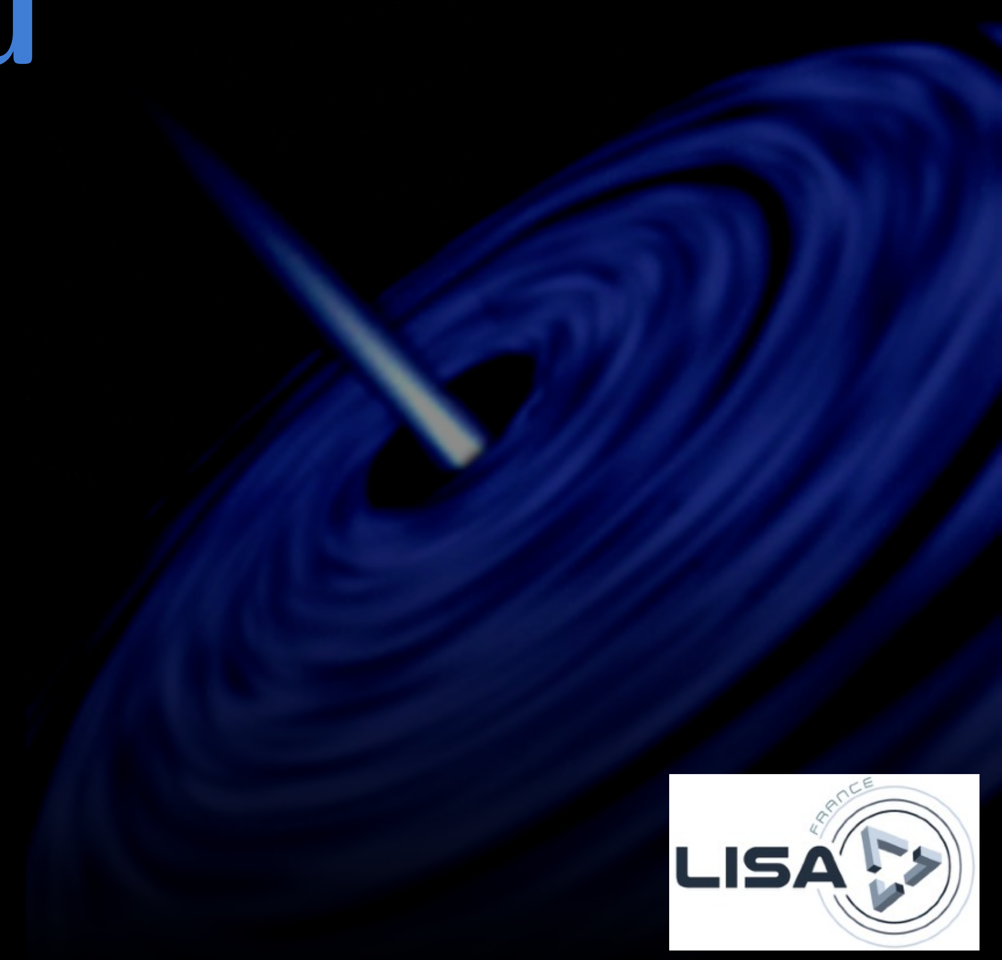
Conclusion

- LISA is a large space mission to observe Universe with gravitational wave;
- Planning: adoption in January 2024, launch 2035
- ESA led mission with contributions from NASA and member states in particular France : Distributed Data Processing Center, AIVT Interferometric Detection System, performances
- Huge science case with many links to High Energy astronomy:
  - Multi-messenger (Interacting galactic binaries, MBH Binaries, ...)
  - Populations (galactic sources, MBHs, ...)
- LISAFrance:
  - SNO LISA
  - Next "journée LISAFrance": 20th November 2023 at CNES



Thank you





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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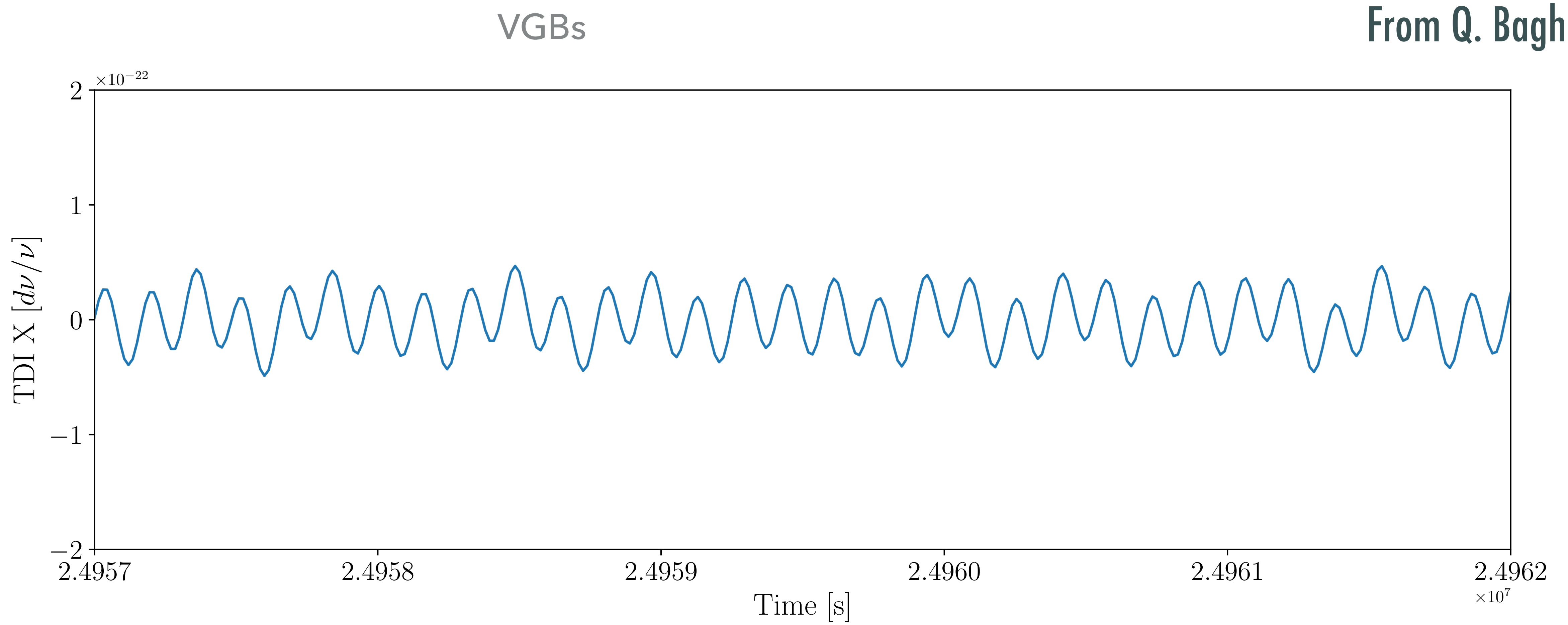
From Q. Baghi



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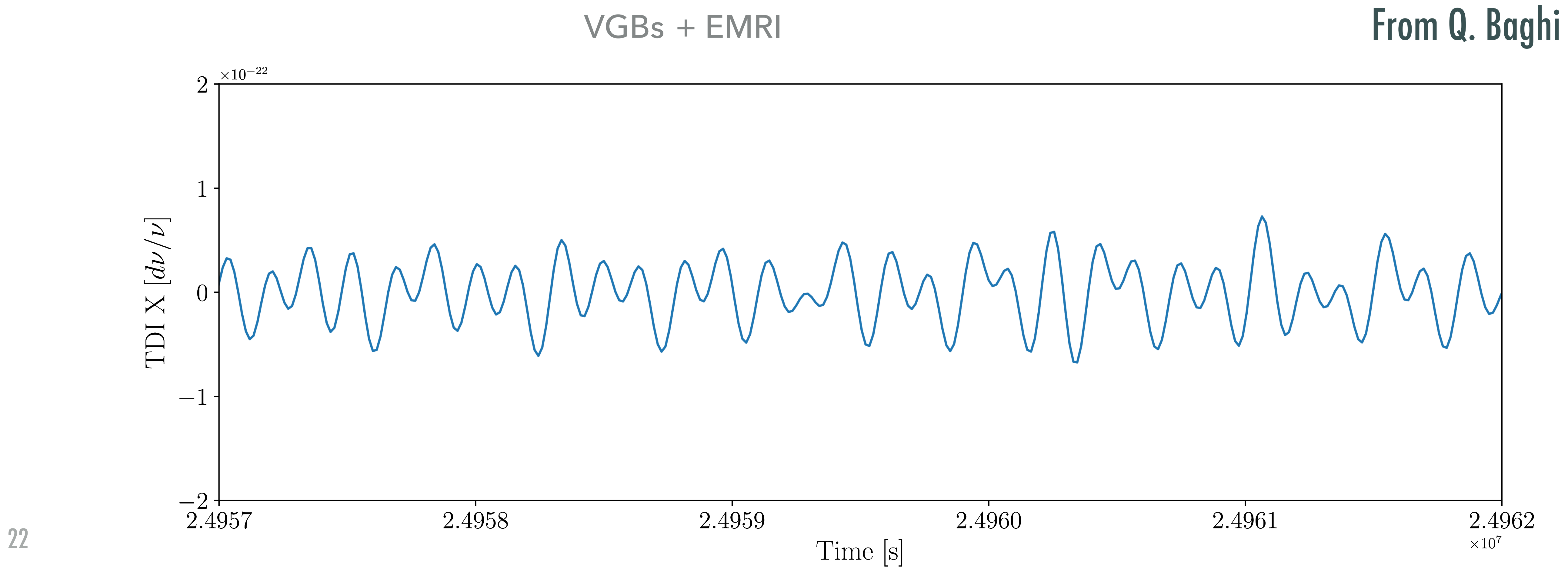

LISA data

- 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
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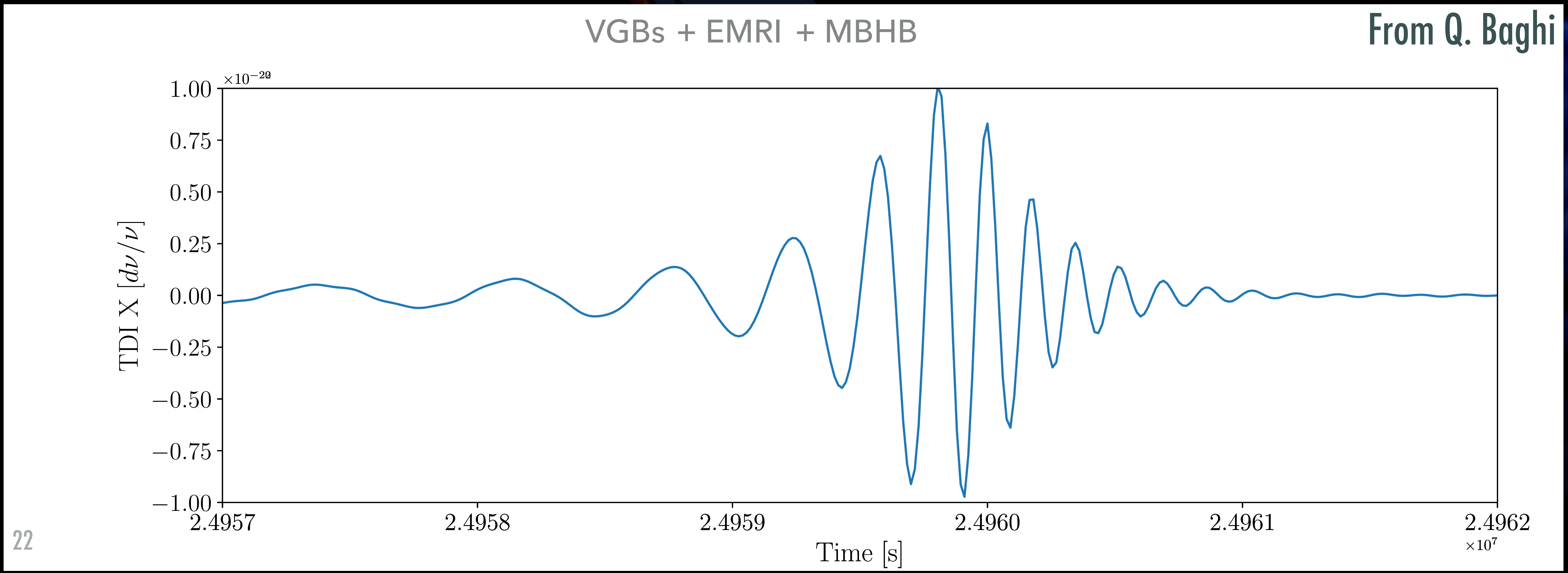

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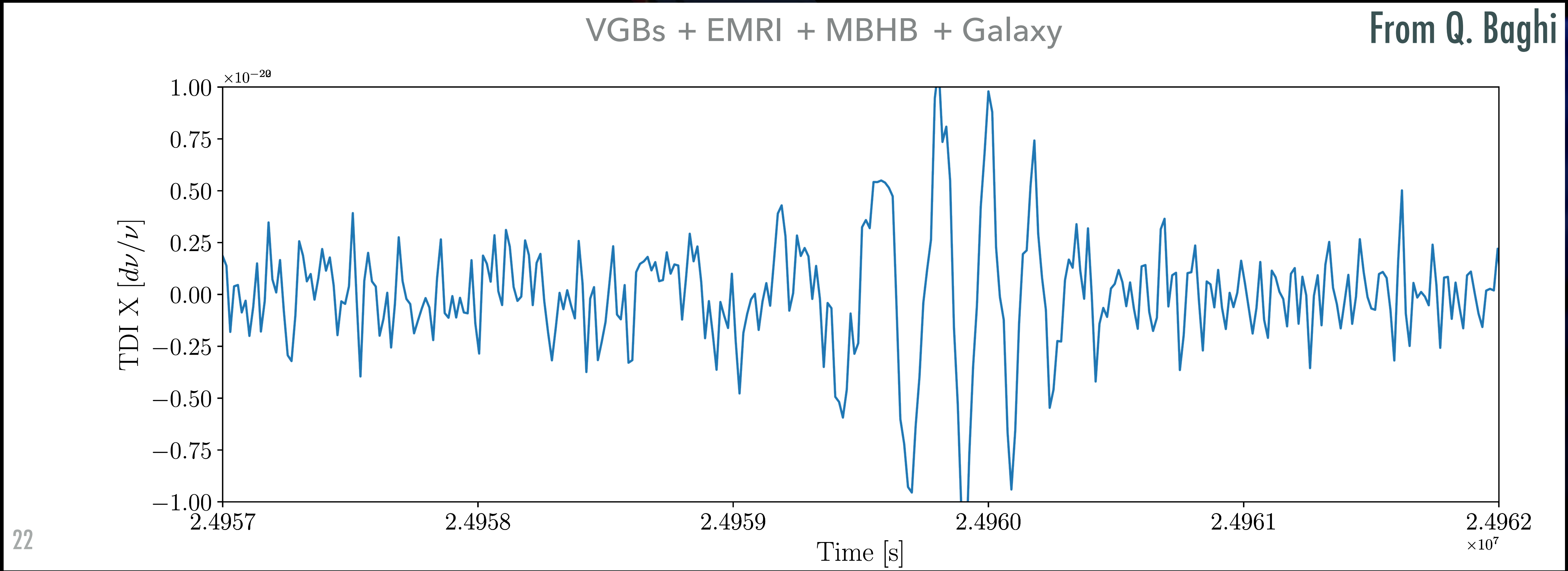

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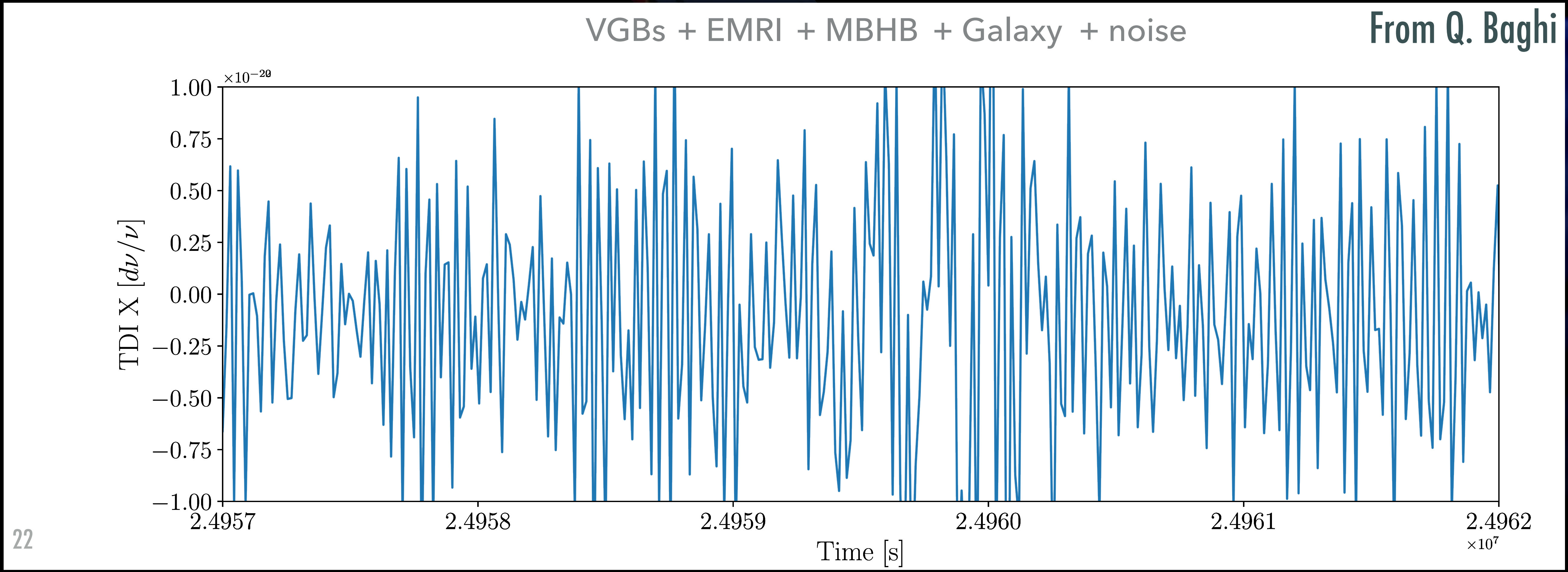

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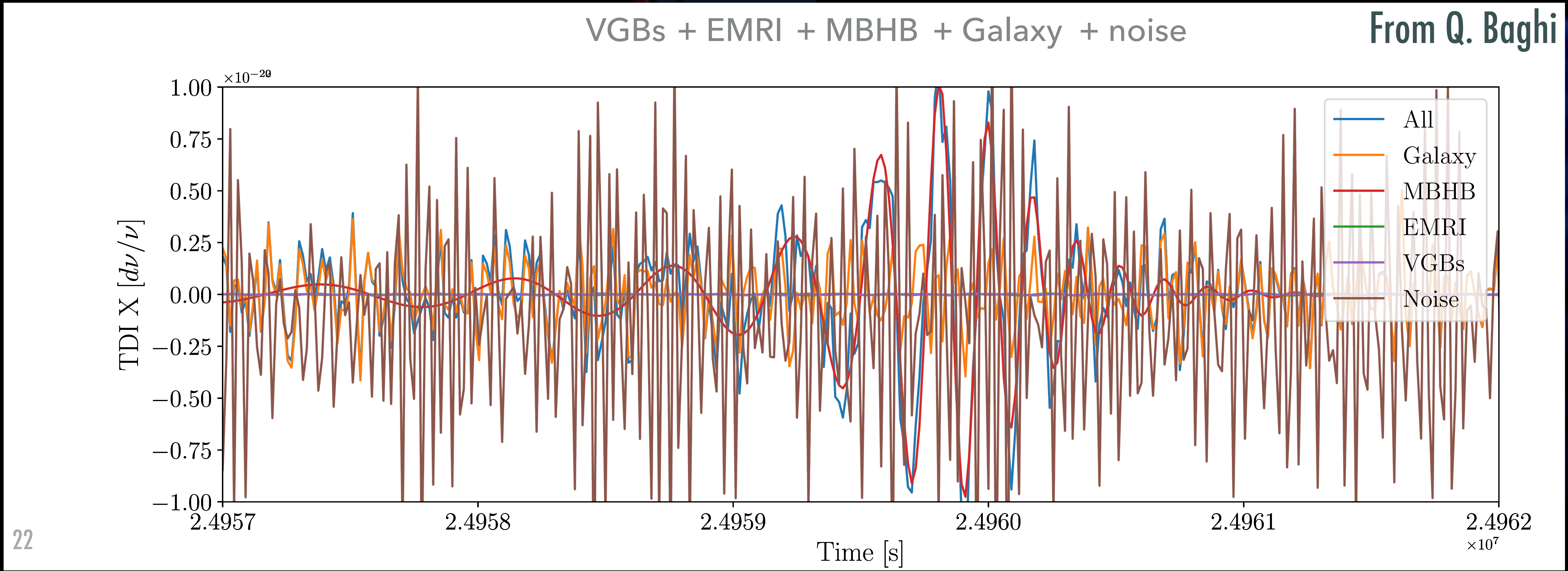

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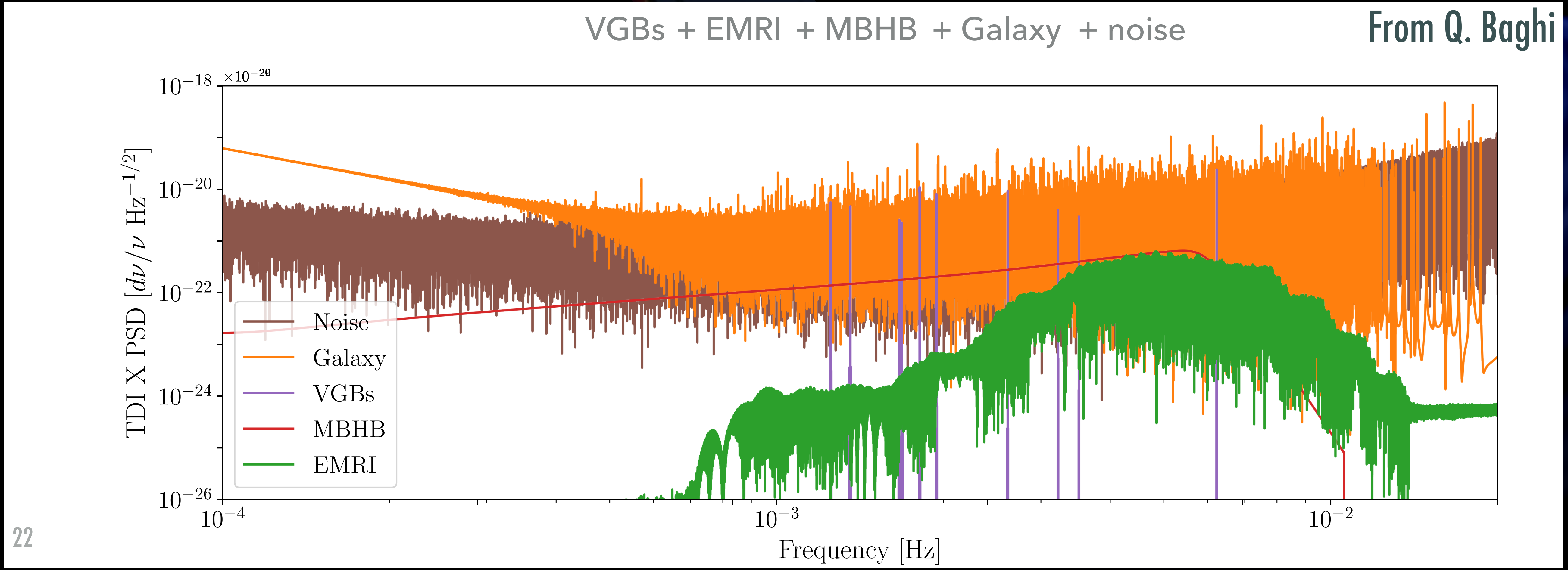
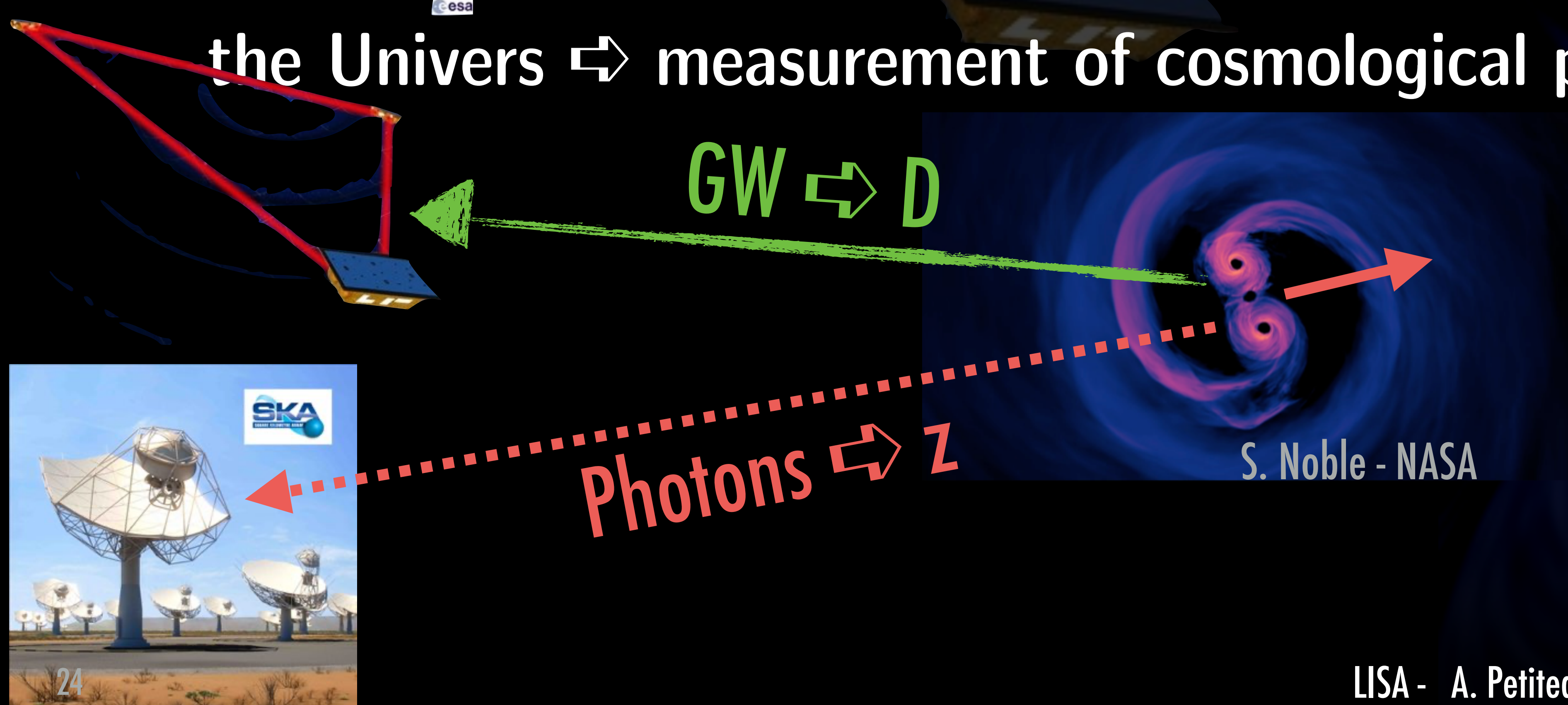


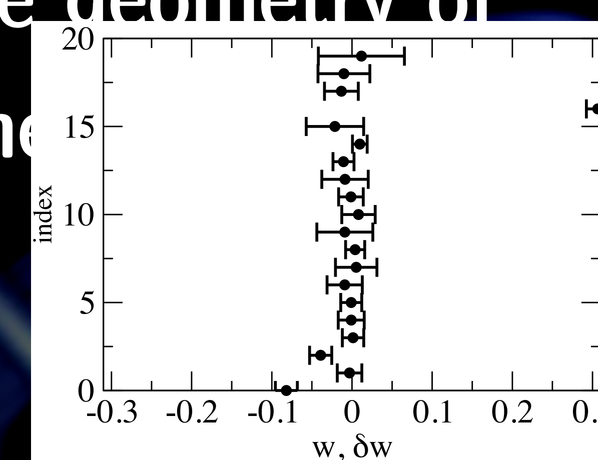
Science Objectives

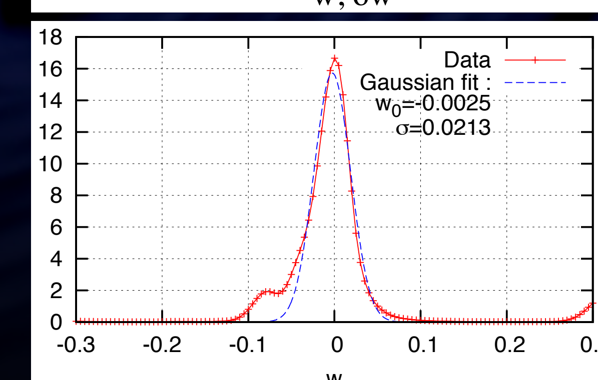
- SO5 : Explore the fundamental nature of gravity and black holes :
  - Use ringdown characteristics observed in MBHB coalescences to test whether the post-merger objects are the MBHs predicted by GR;
  - Use EMRIs to explore the multipolar structure of MBHs and search for the presence of new light fields;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

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 parame

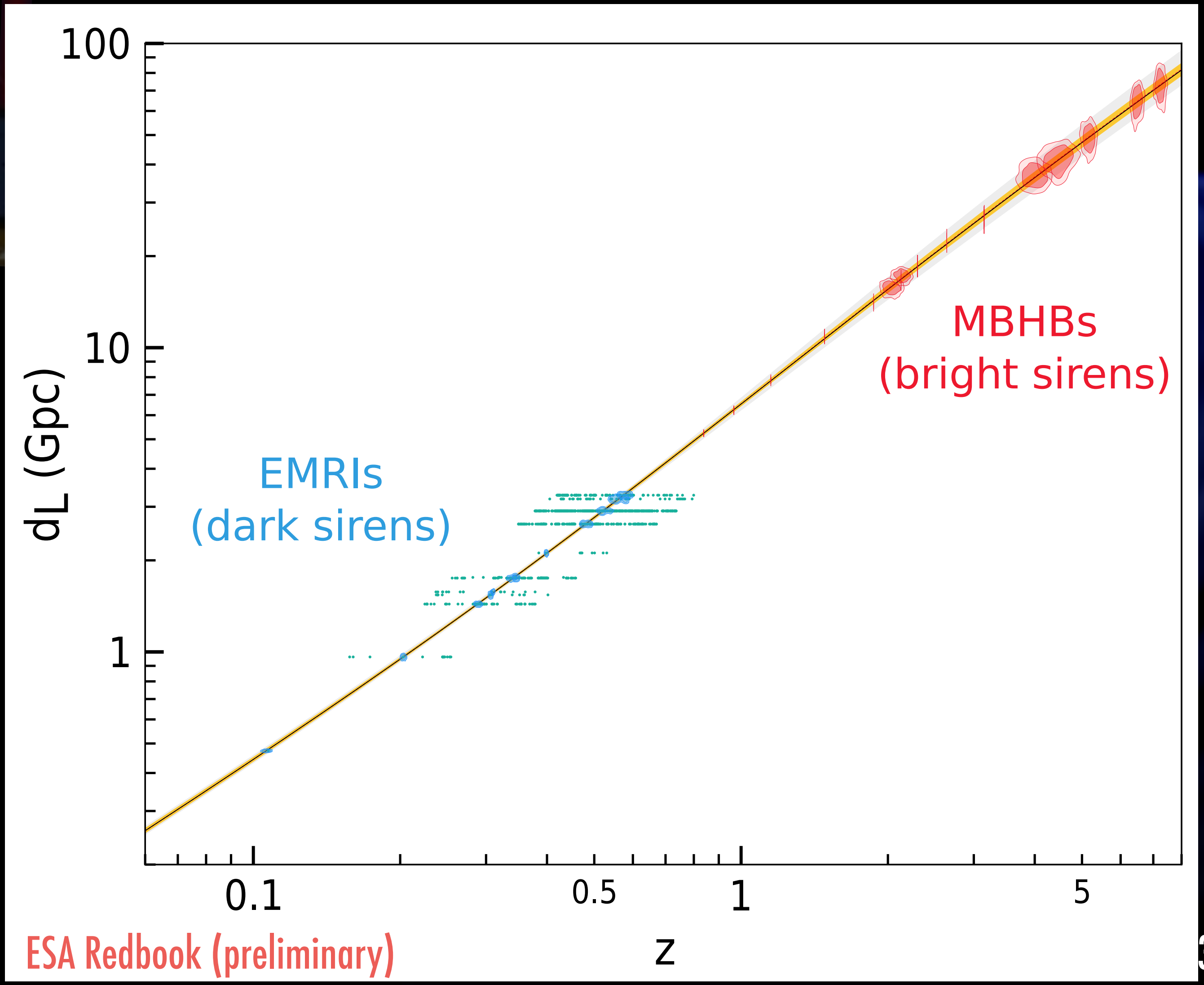






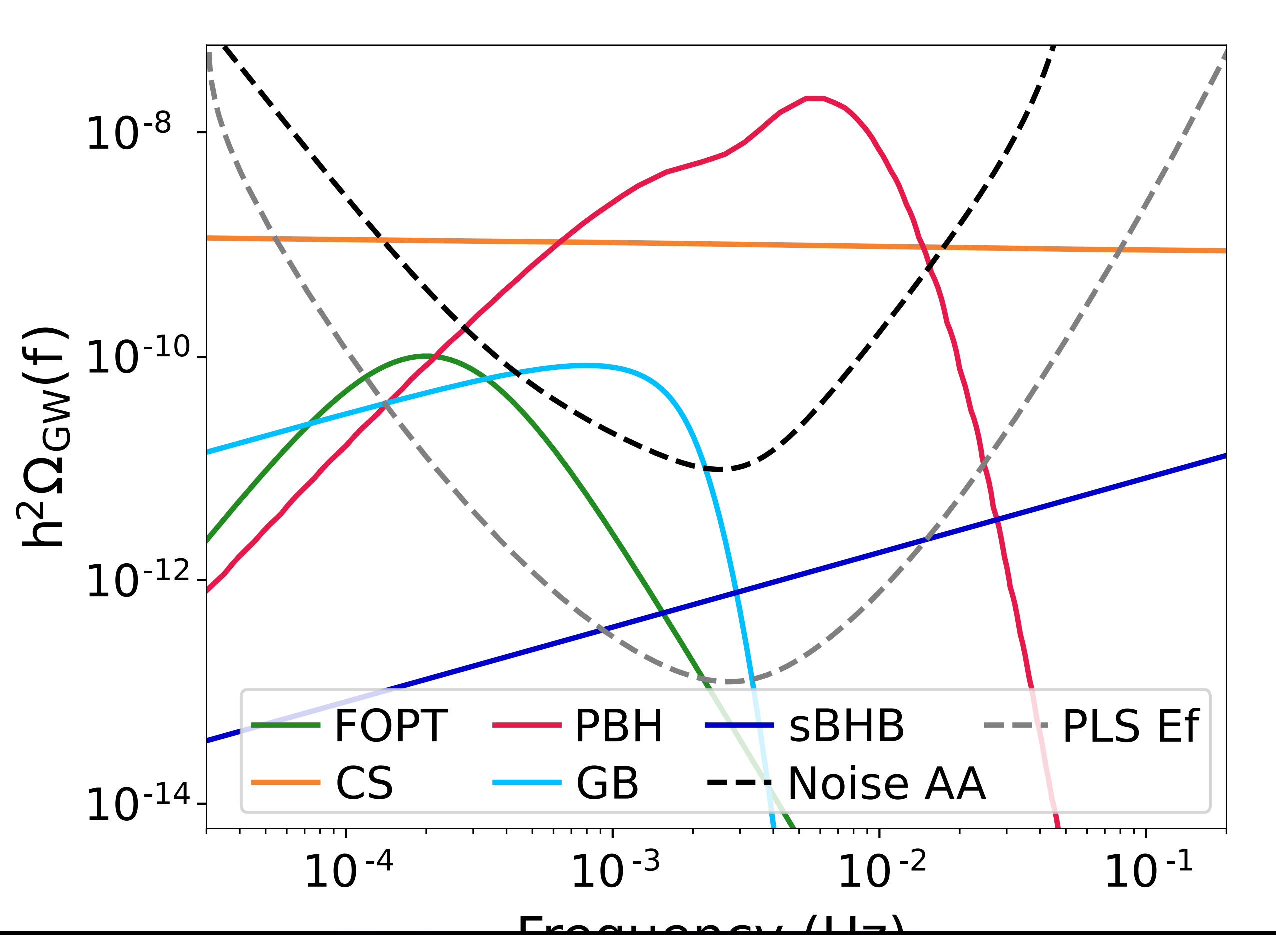
Science objectives

- 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

- **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.



Science Objectives

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