



# LISA status and data processing organisation

**Antoine Petiteau (CEA / IRFU / DPhP & APC)**

Co-lead LISA Consortium, ESA Science Study Team, Formulation Management Team, Lead LISA Data Processing Group, co-PI France

LISA Data Analysis workshop

Toulouse - 23<sup>rd</sup> November 2022

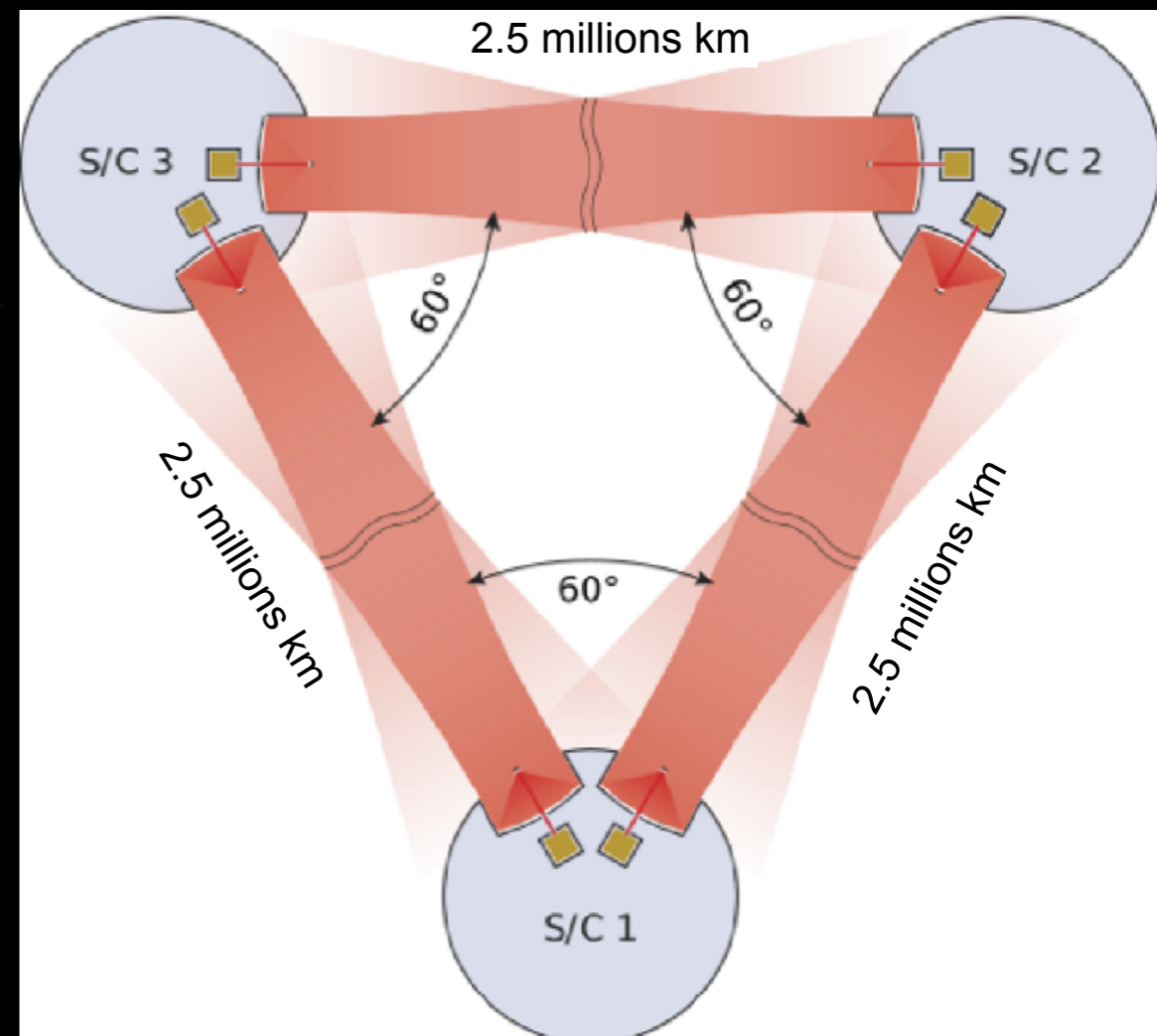
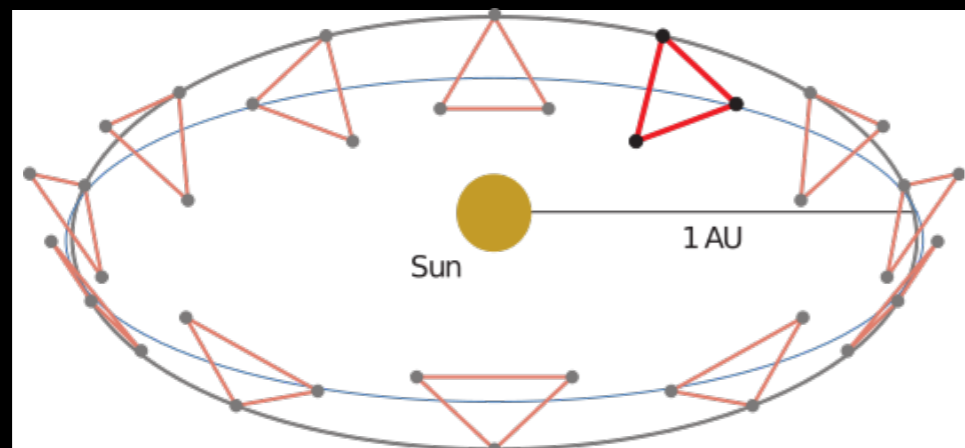
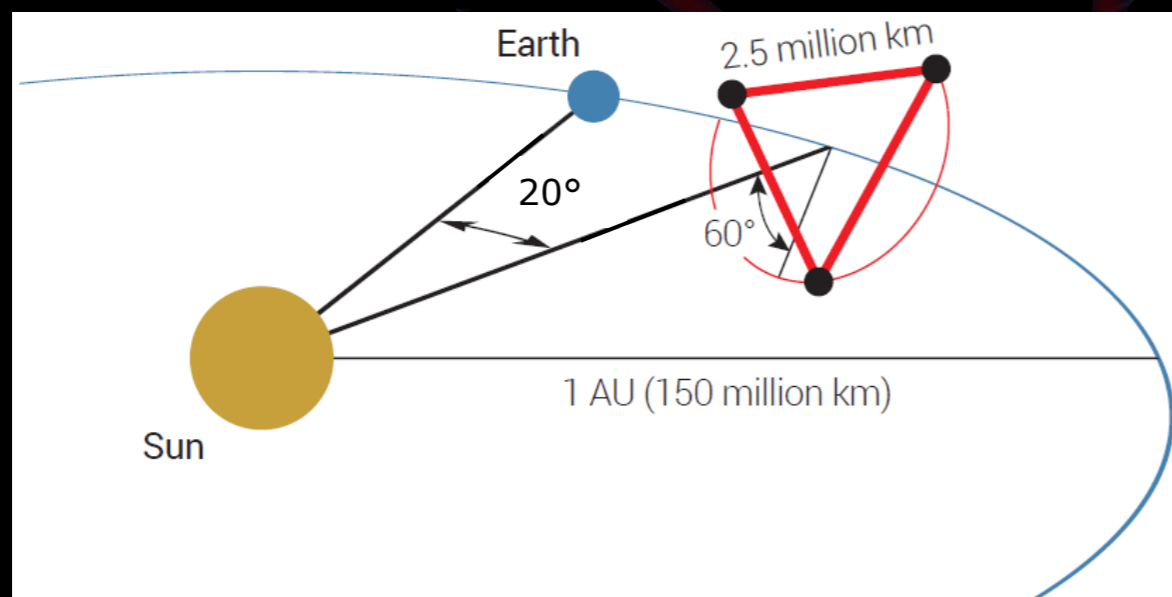


# Overview

- ▶ LISA mission
- ▶ Mission status and organisation
- ▶ Data Analysis Logic
- ▶ Data Analysis Organisation
- ▶ Ground Segment and DDPC

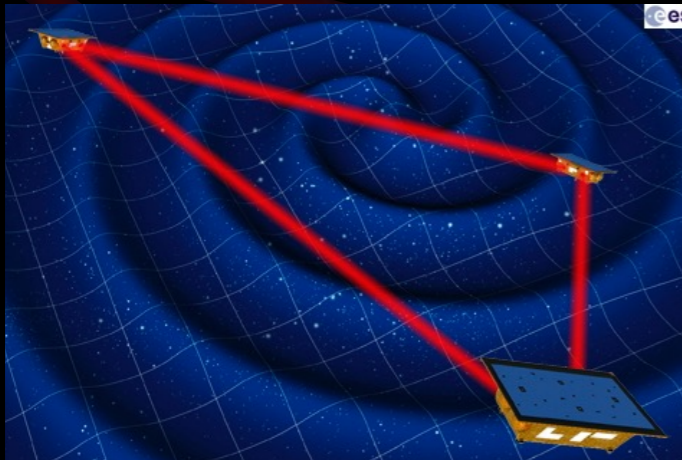
# LISA mission

- ▶ 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



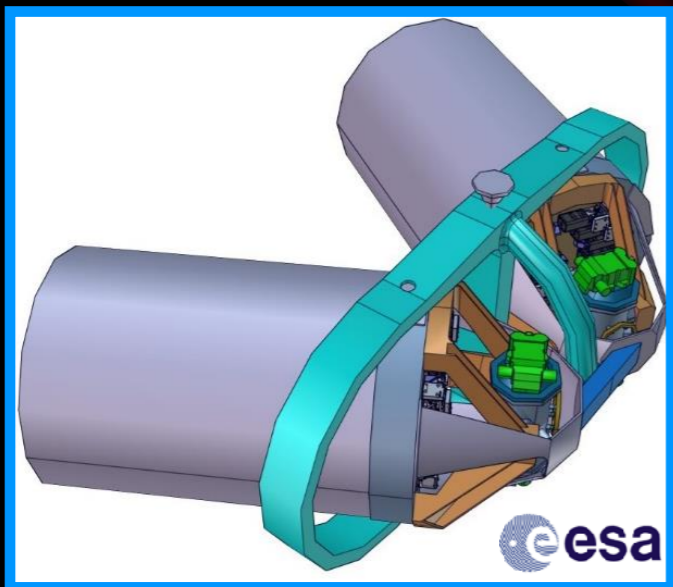
# LISA mission

- ▶ Several steps towards the required precision of measurement



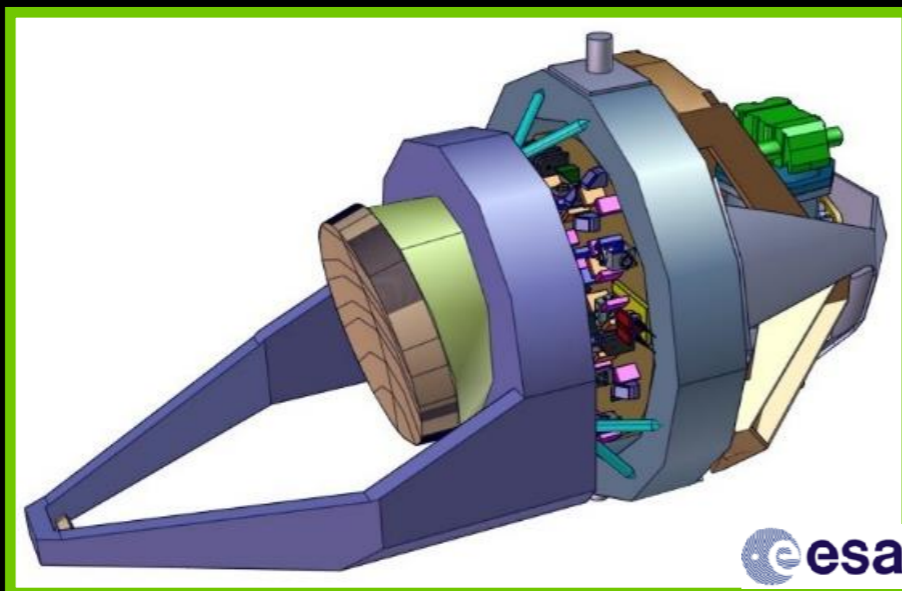
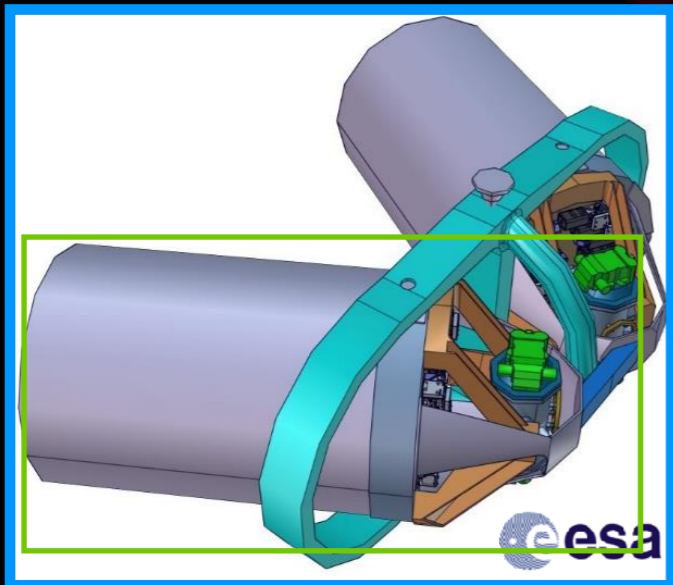
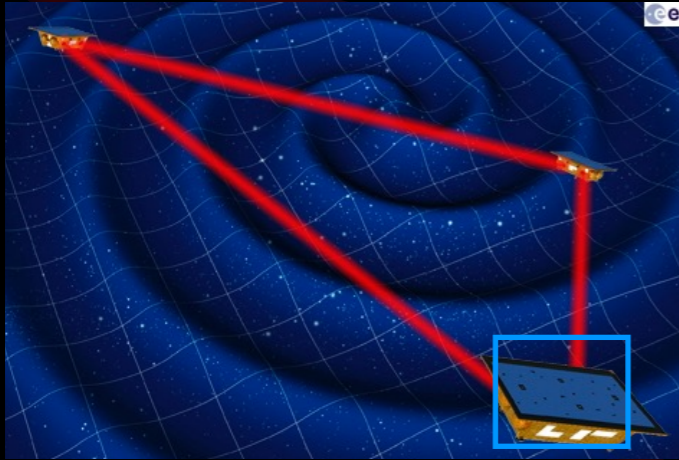
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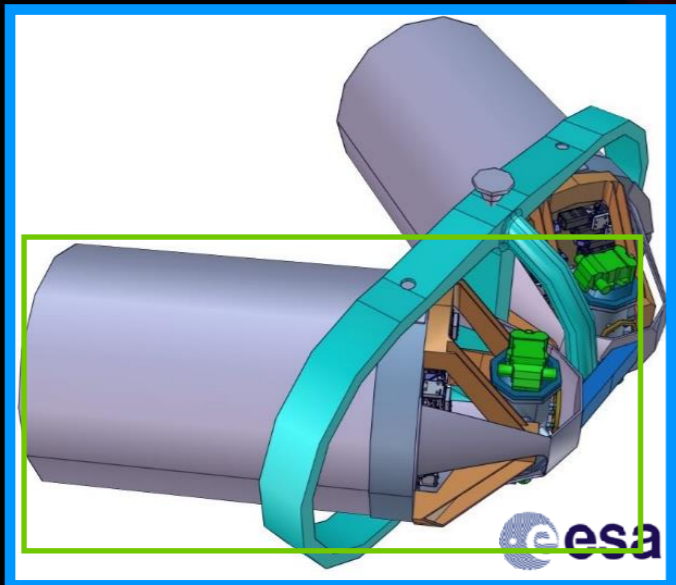
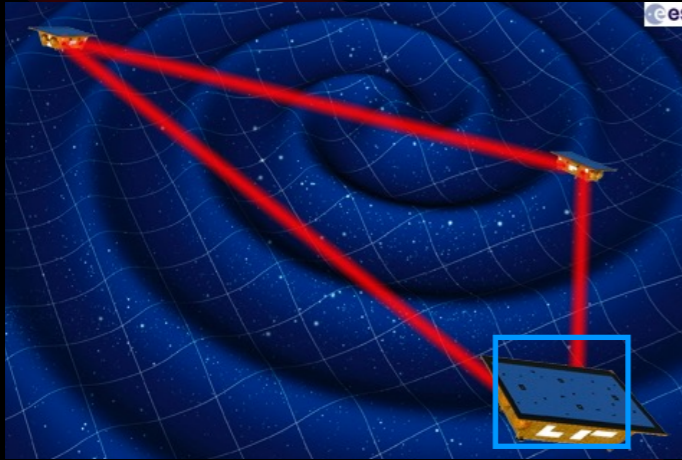
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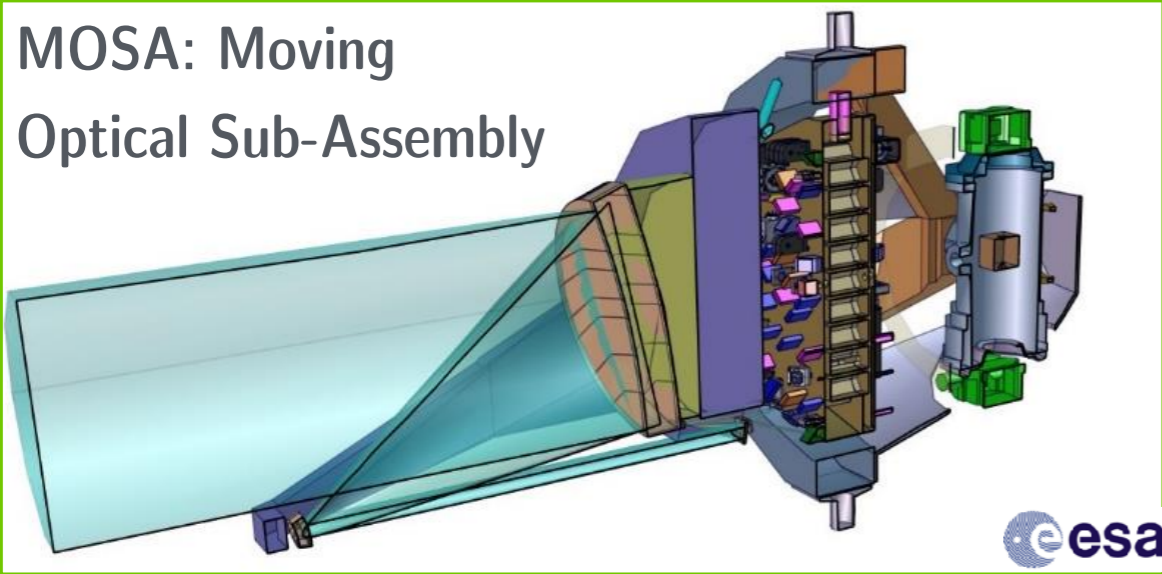


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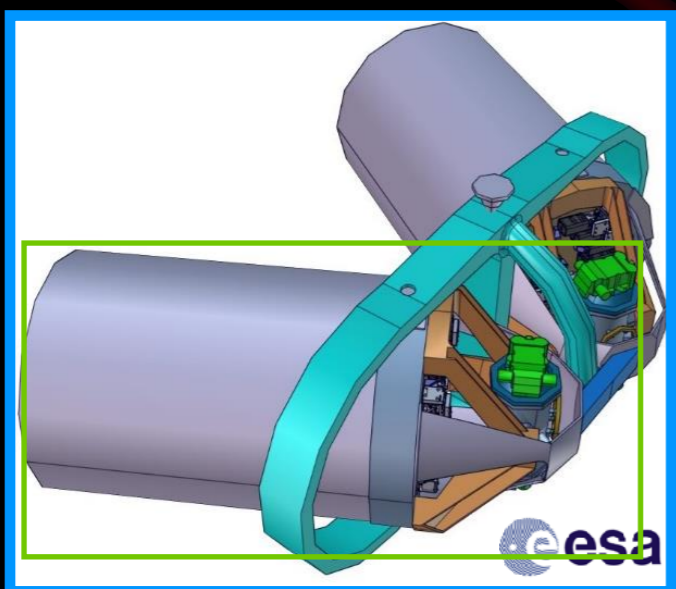


MOSA: Moving  
Optical Sub-Assembly

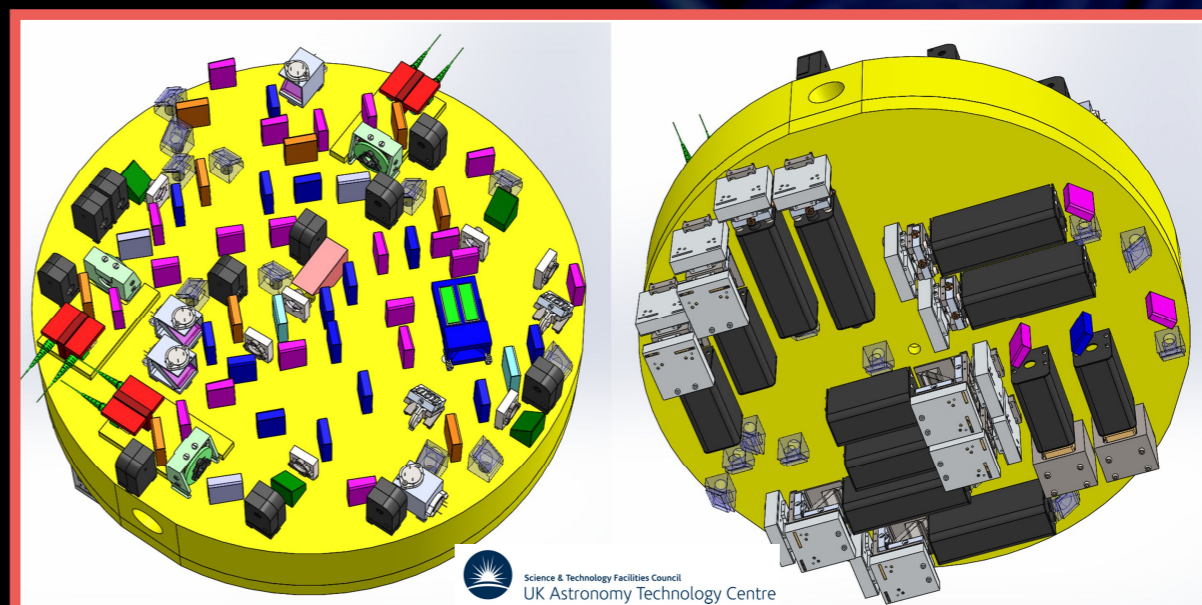
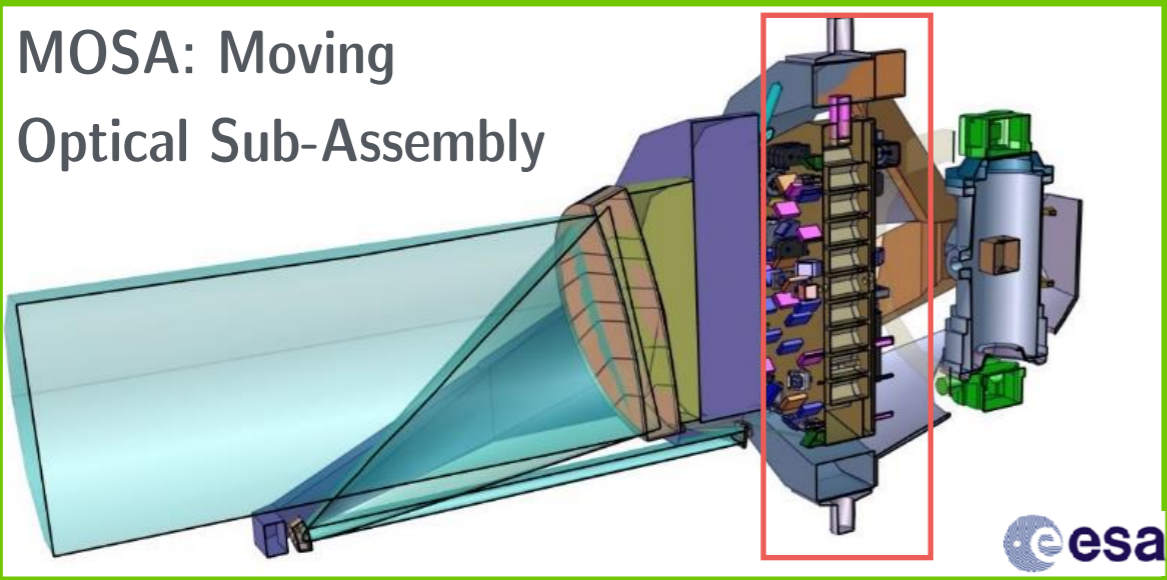


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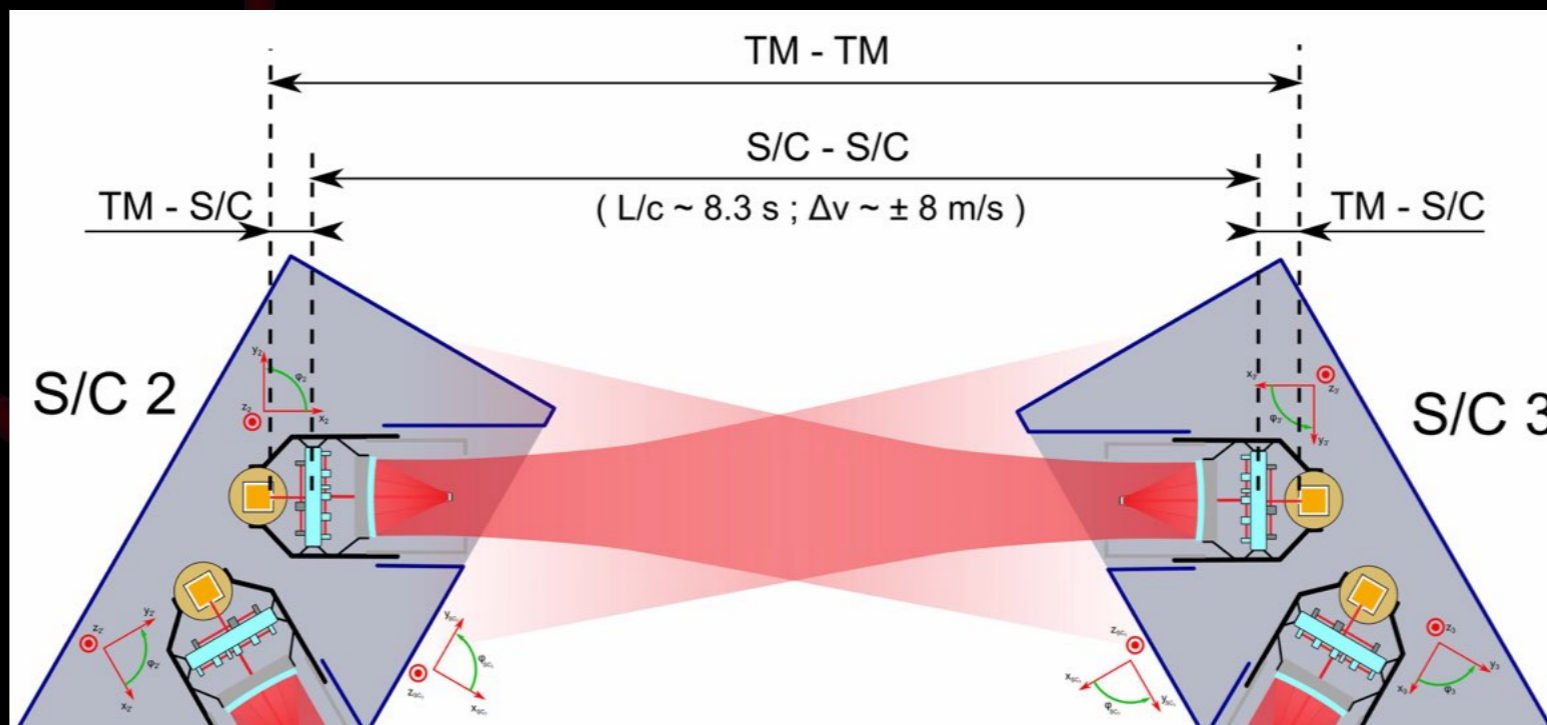
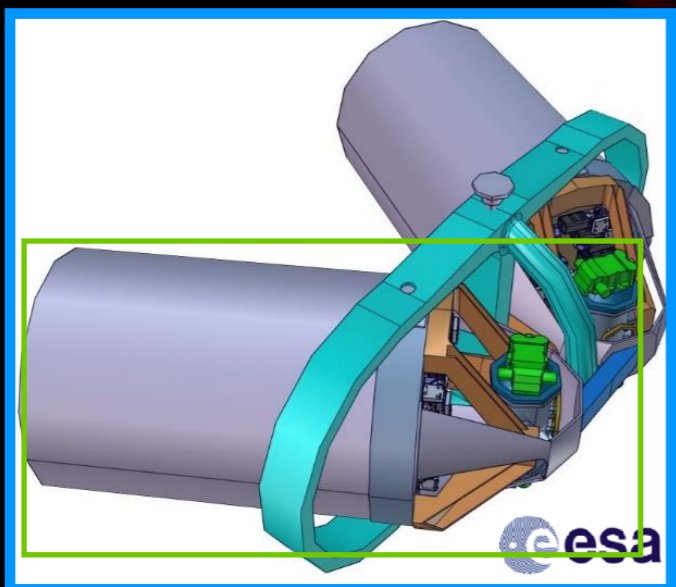




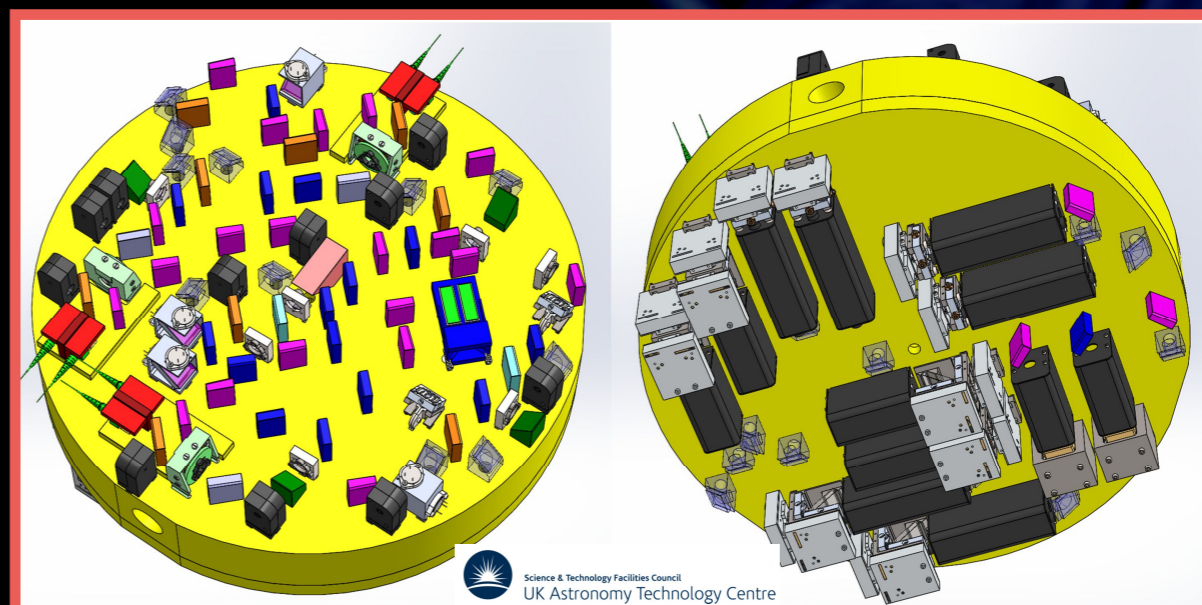
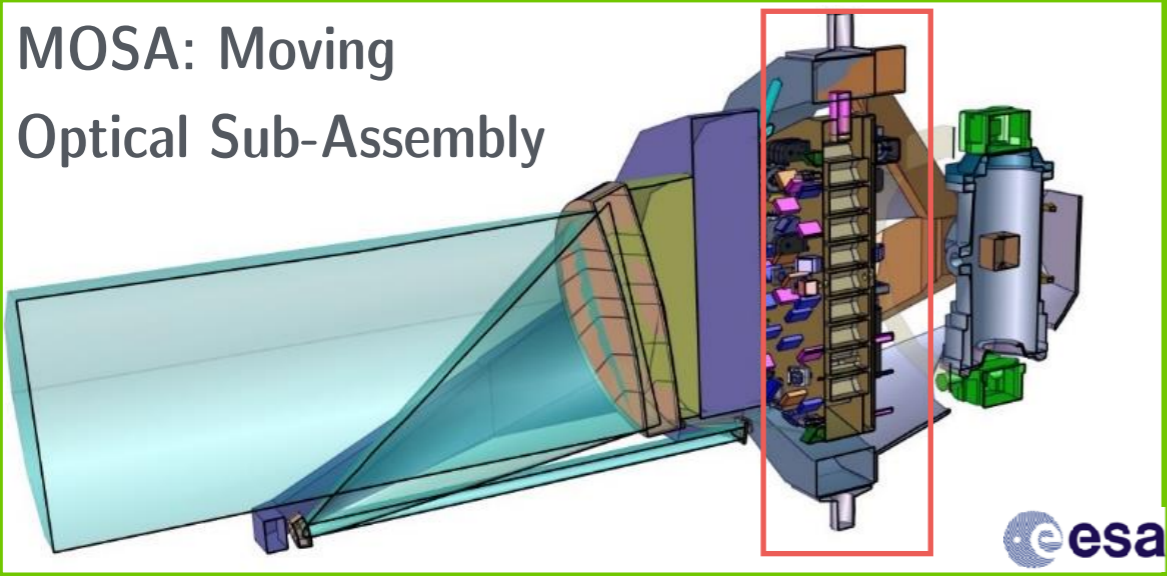
# LISA mission

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

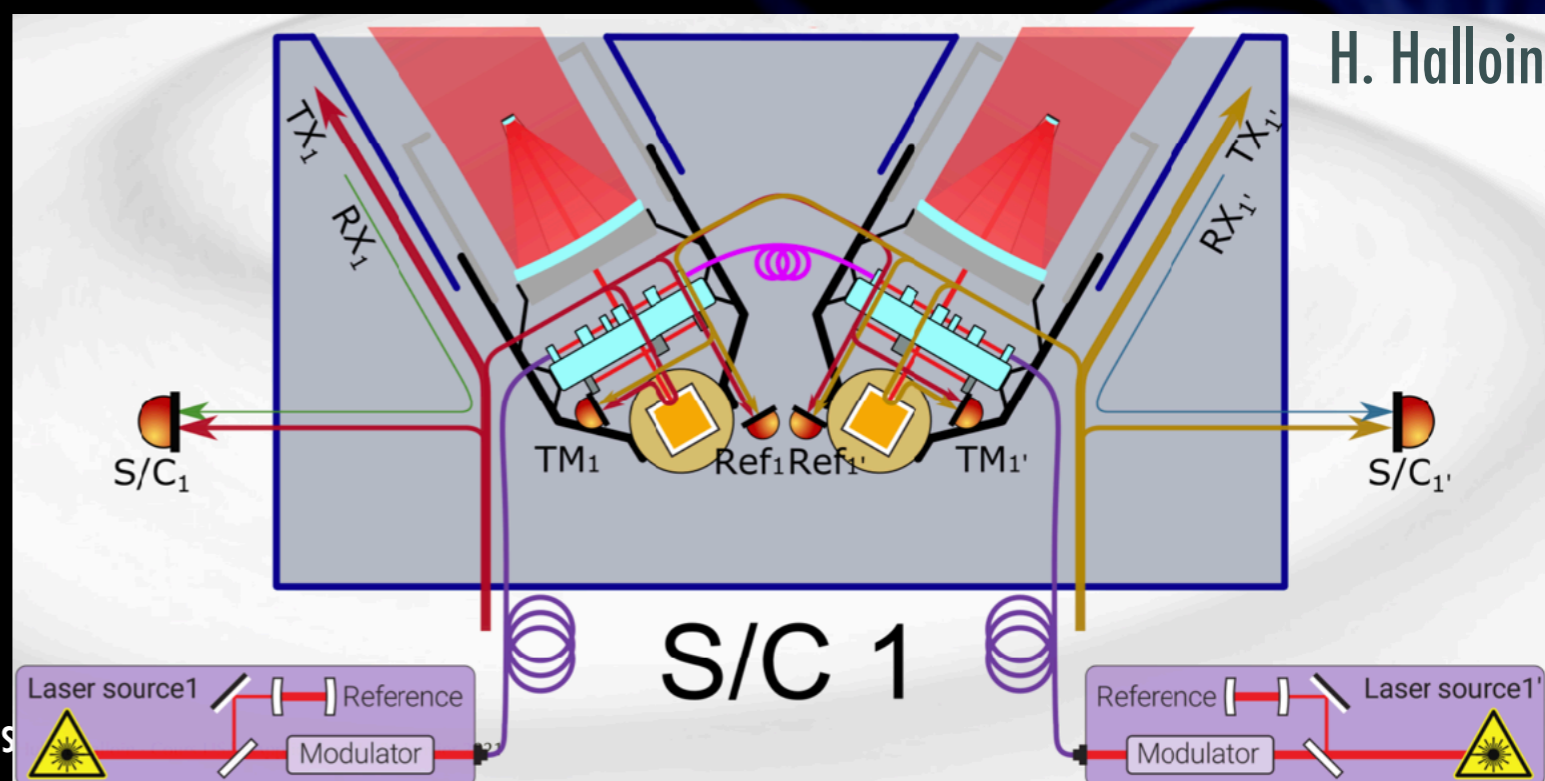
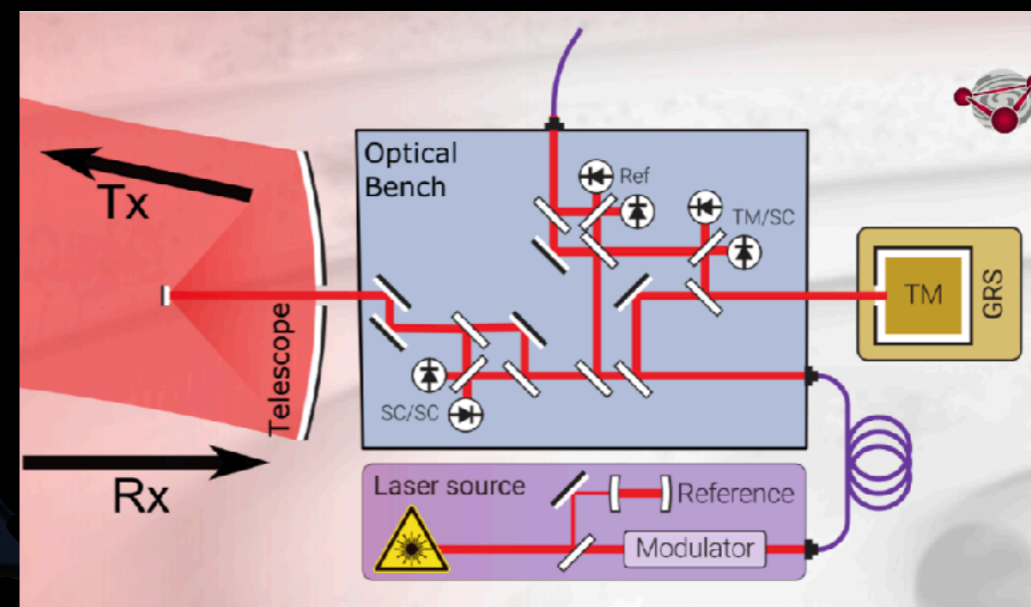


MOSA: Moving Optical Sub-Assembly



# Interferometric measurements

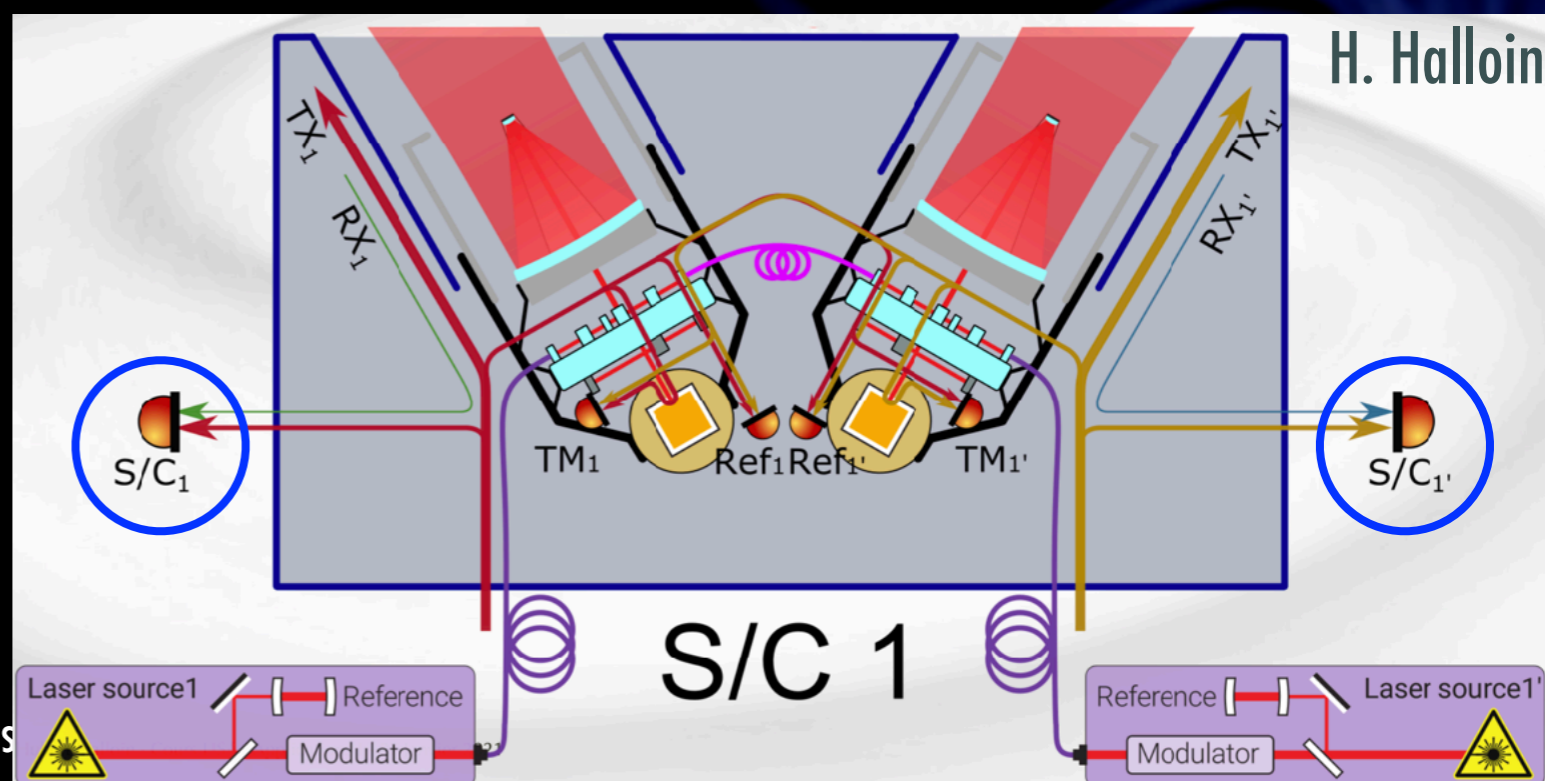
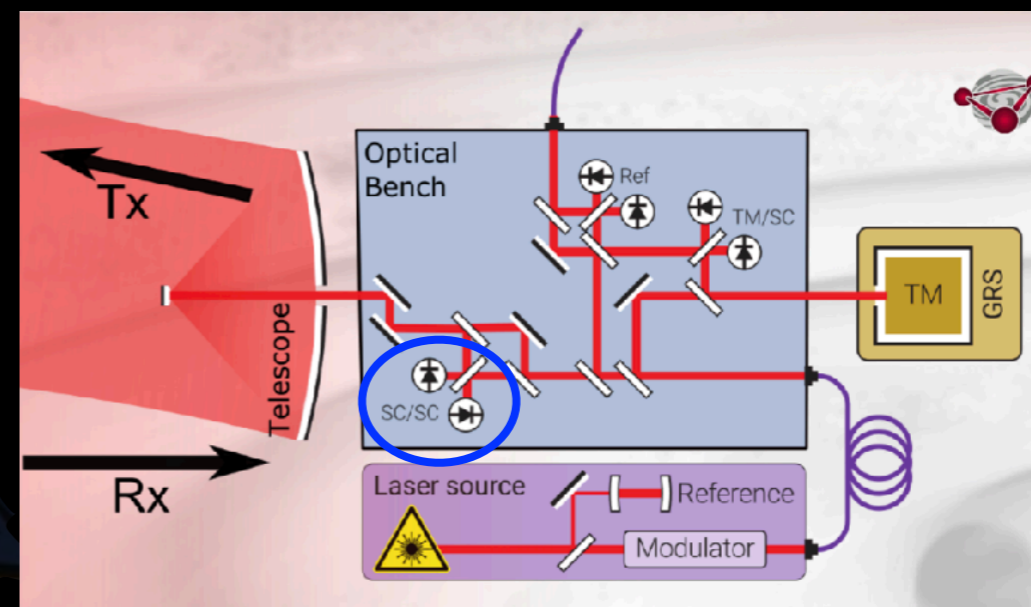
- ▶ Exchange of laser beams to form **several interferometers**
- ▶ **Phasemeter measurements** on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts



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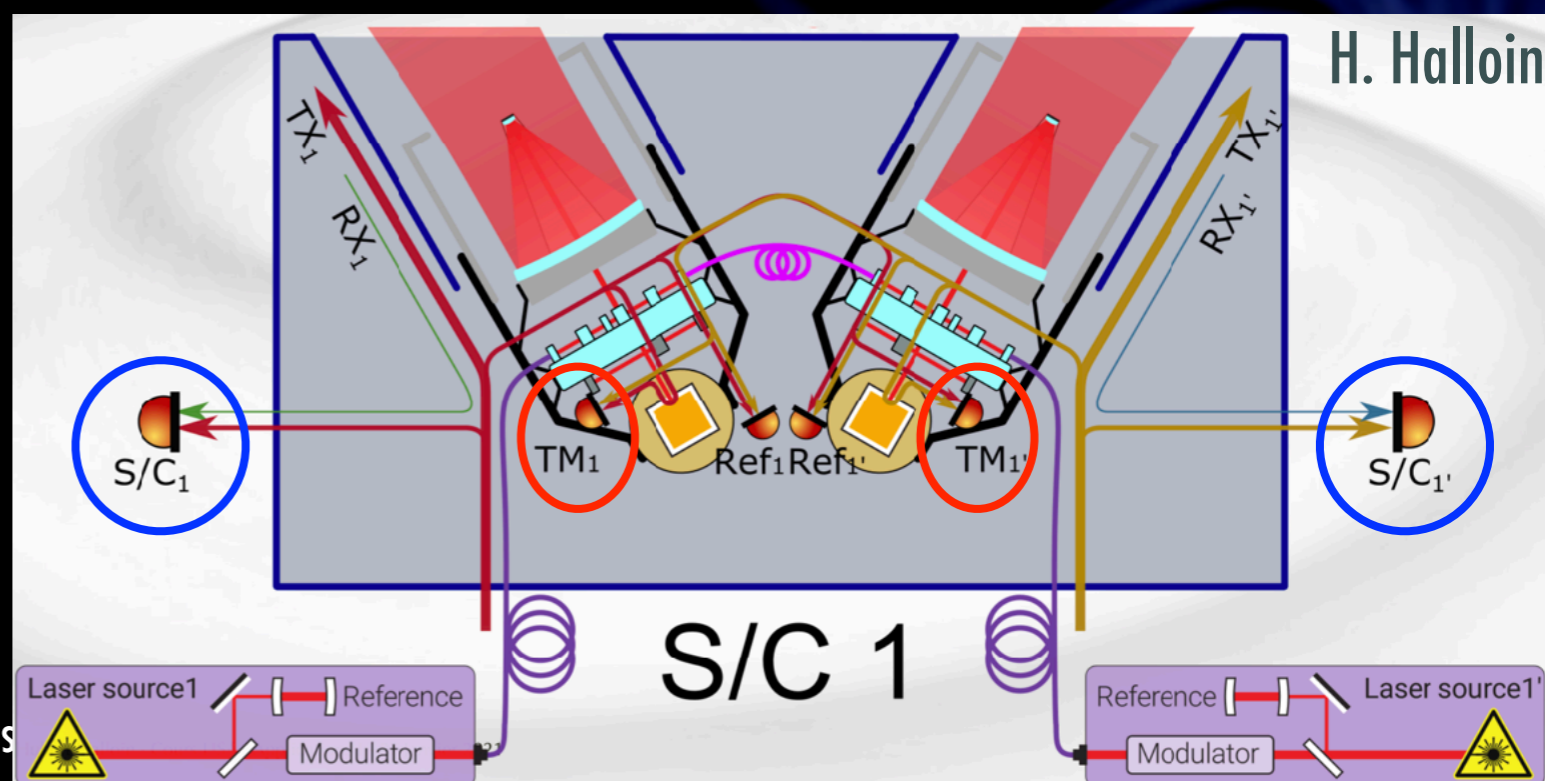
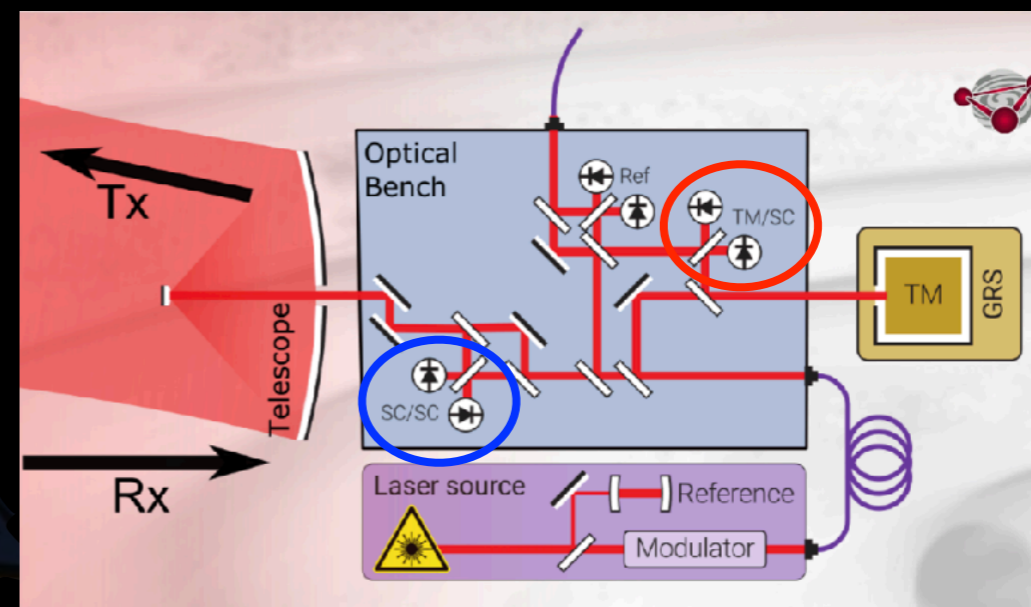
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# Interferometric measurements

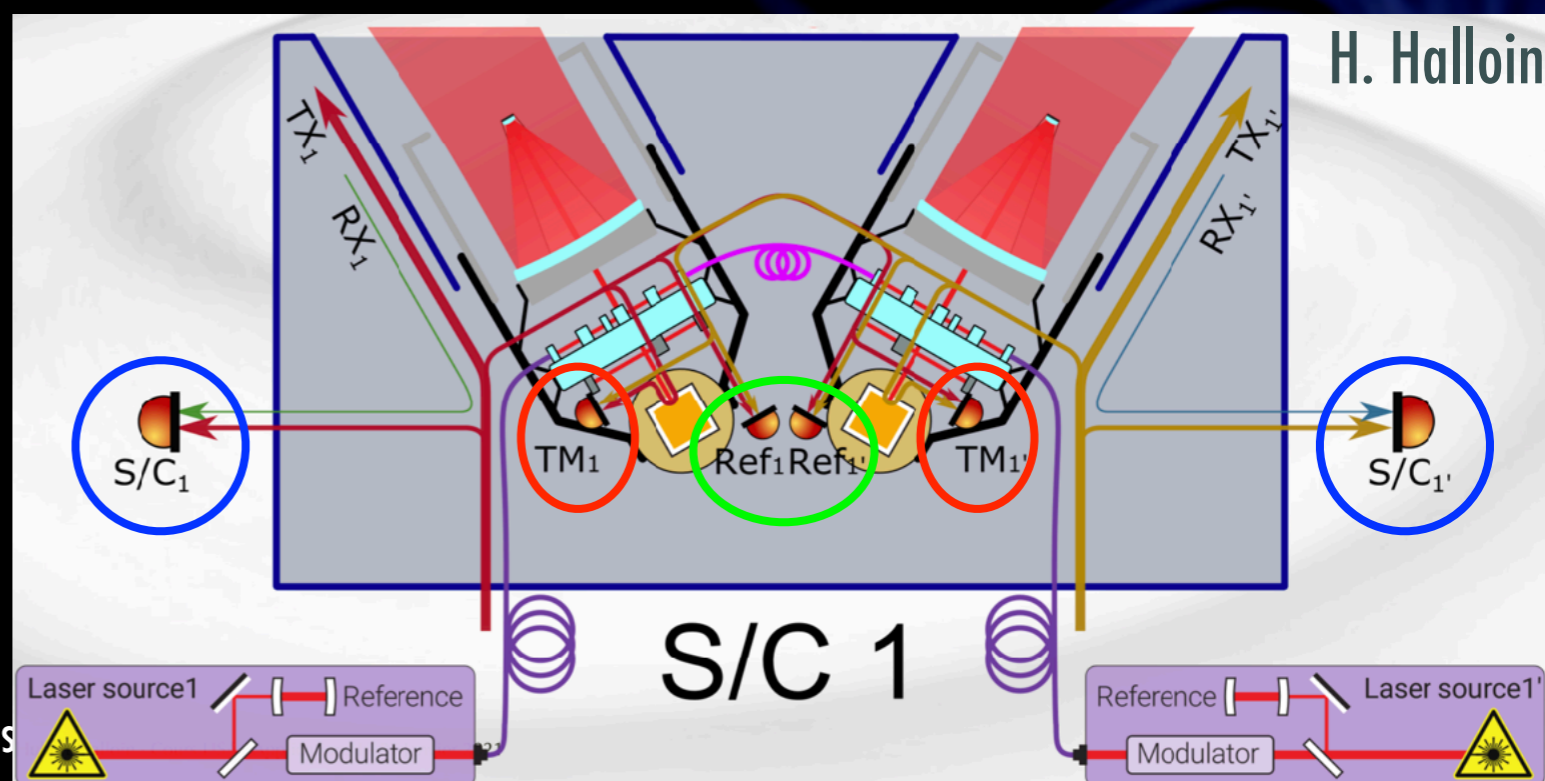
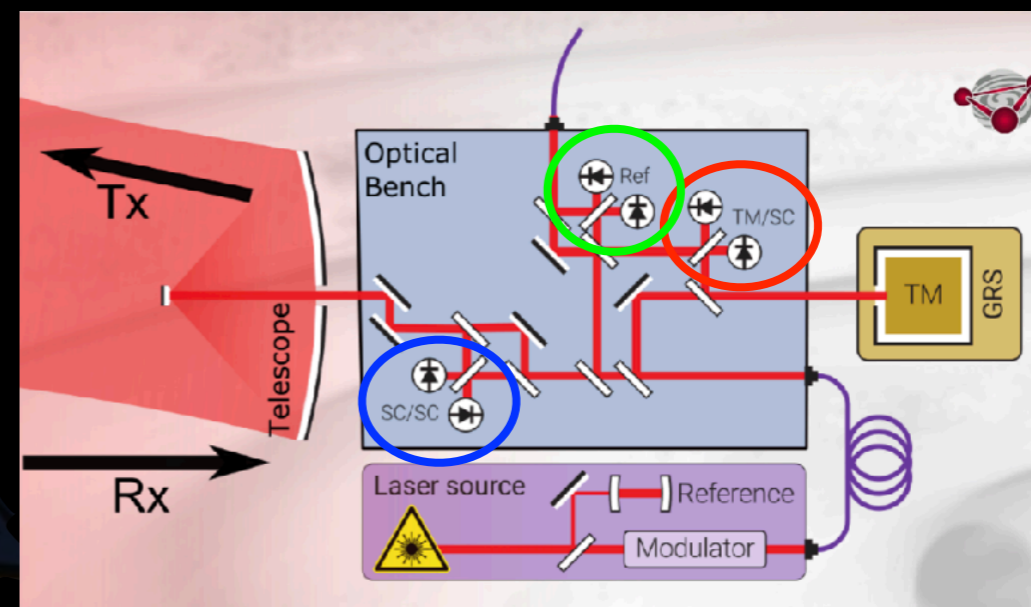
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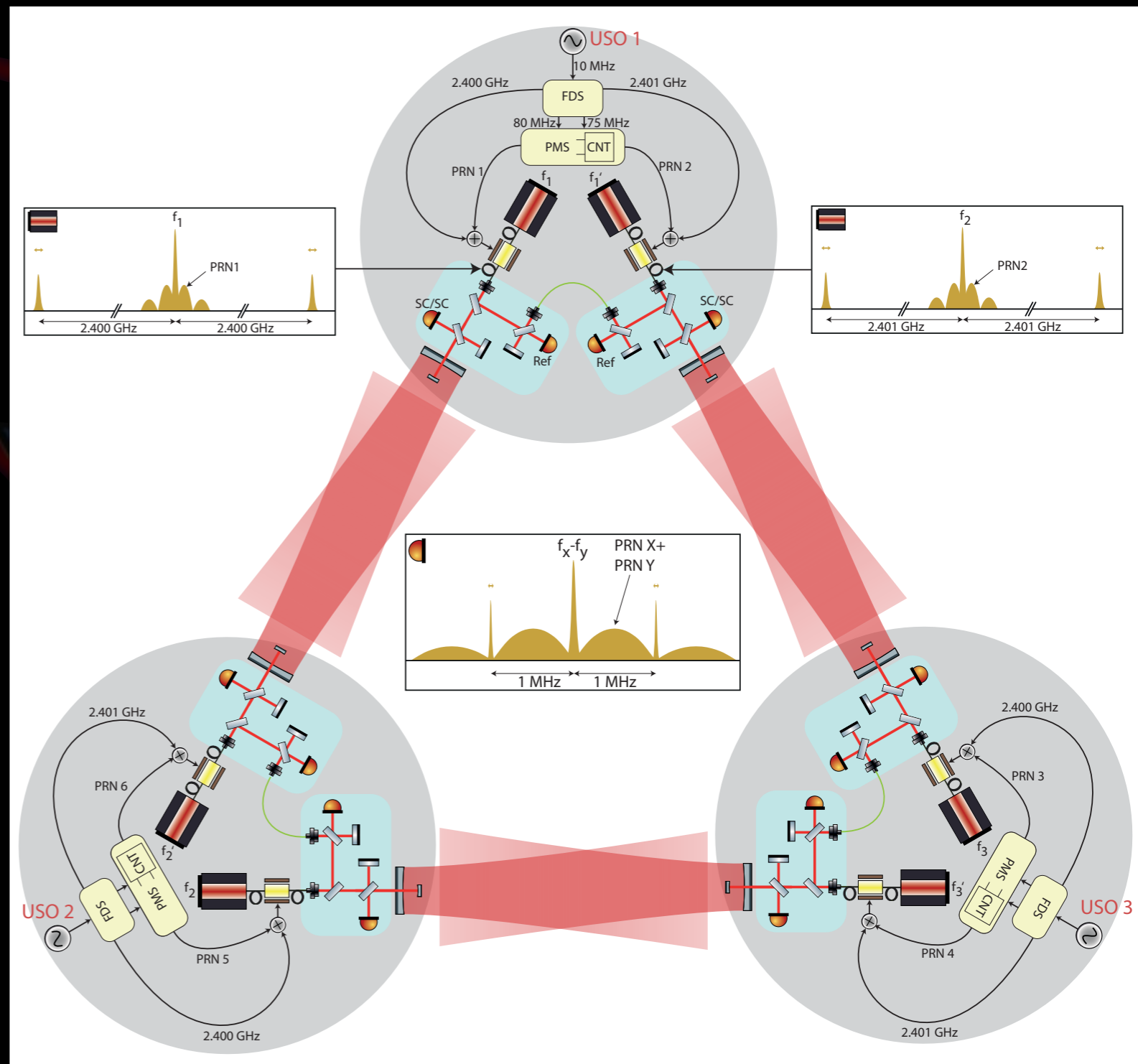
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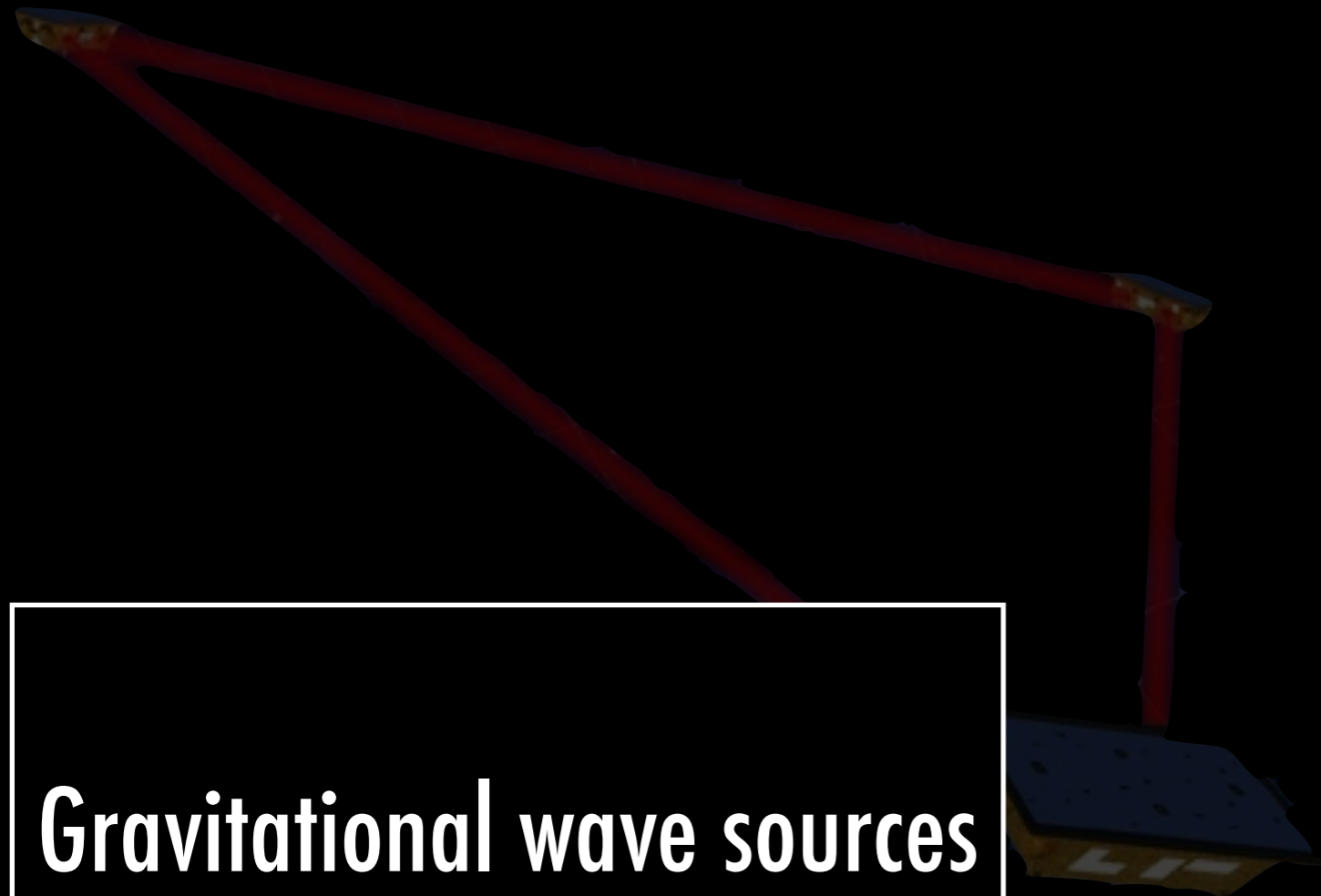
# Interferometric measurements

► Measurements via exchange of beams:

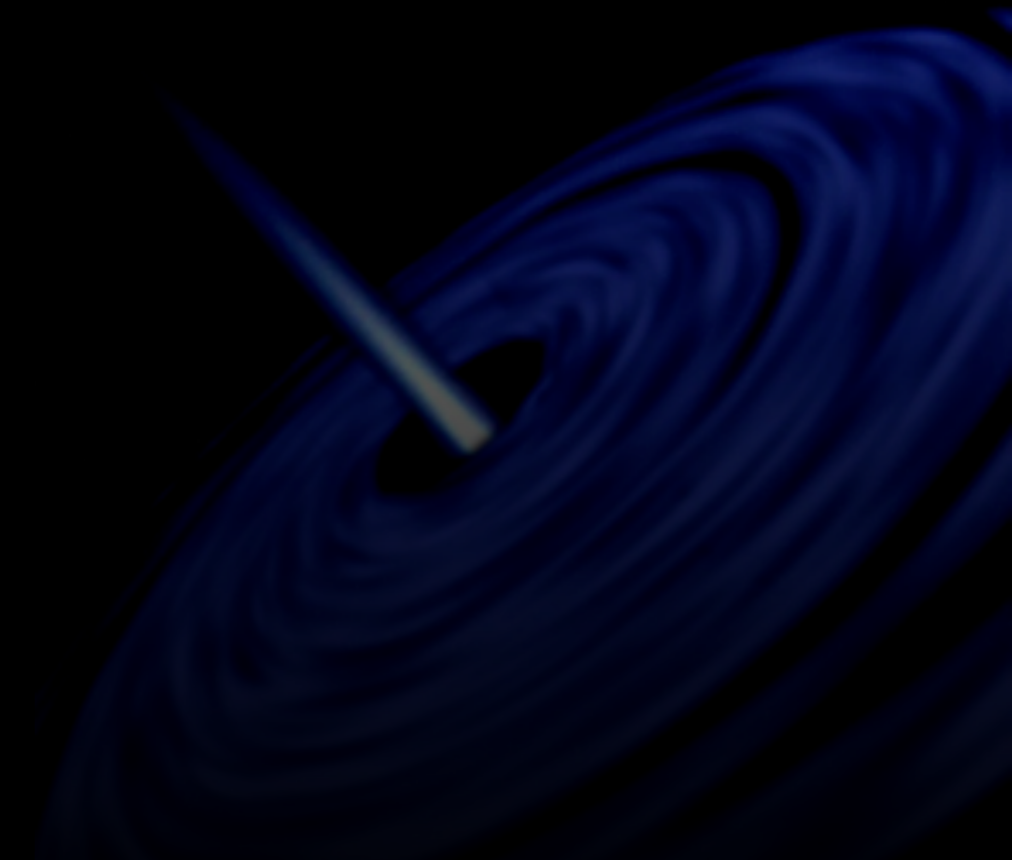
- **Heterodyne interferometry** with carrier for inter-spacecraft measurement  $\Rightarrow$  GWs
- **Sideband** for transferring amplified clock jitter  $\Rightarrow$  correction of additional clock jitter
- **Pseudo-Random Noise**  $\Rightarrow$  ranging (measure arm length)
- Laser locking



# LISA data

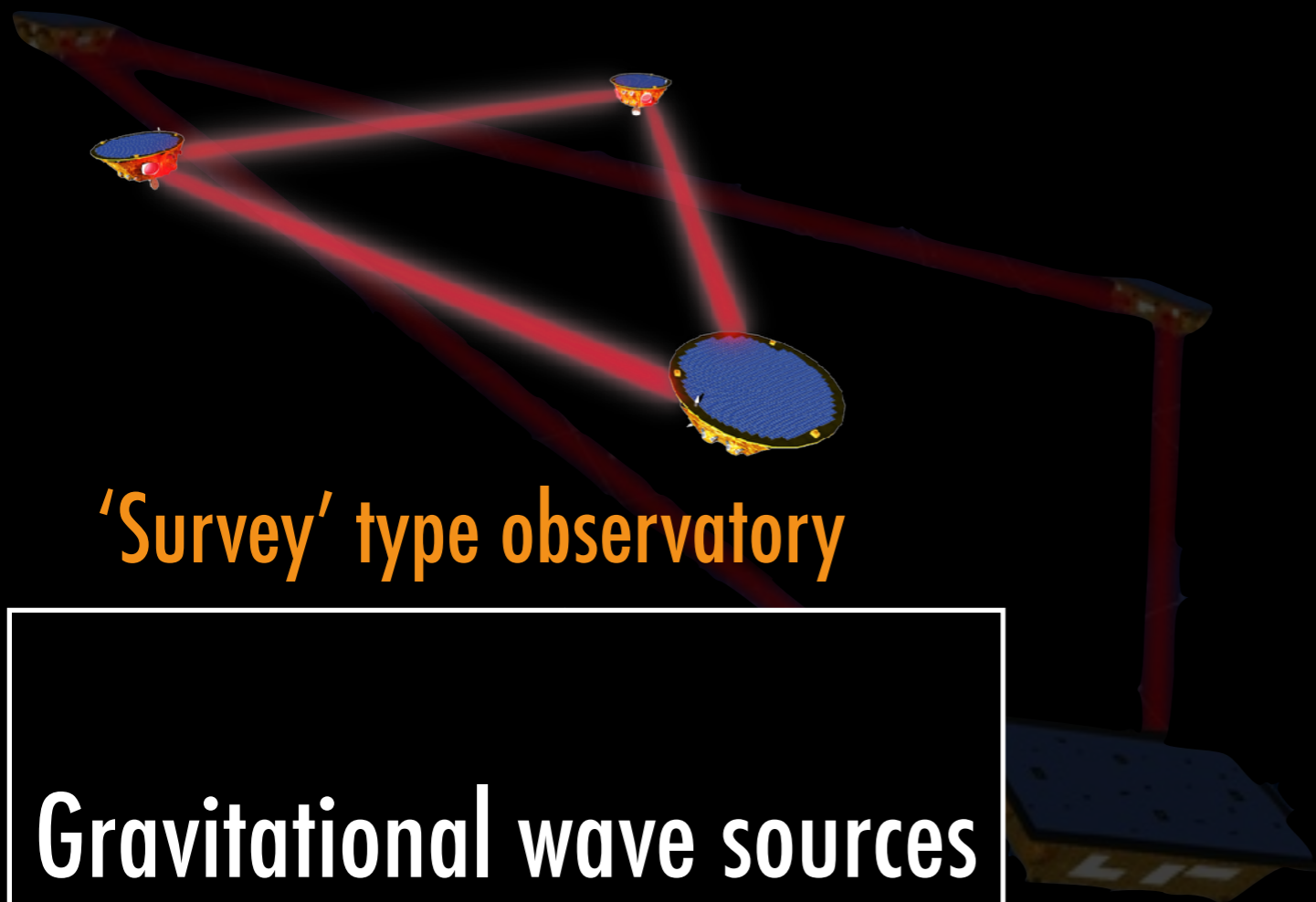


**Gravitational wave sources  
emitting between 0.02mHz  
and 1 Hz**



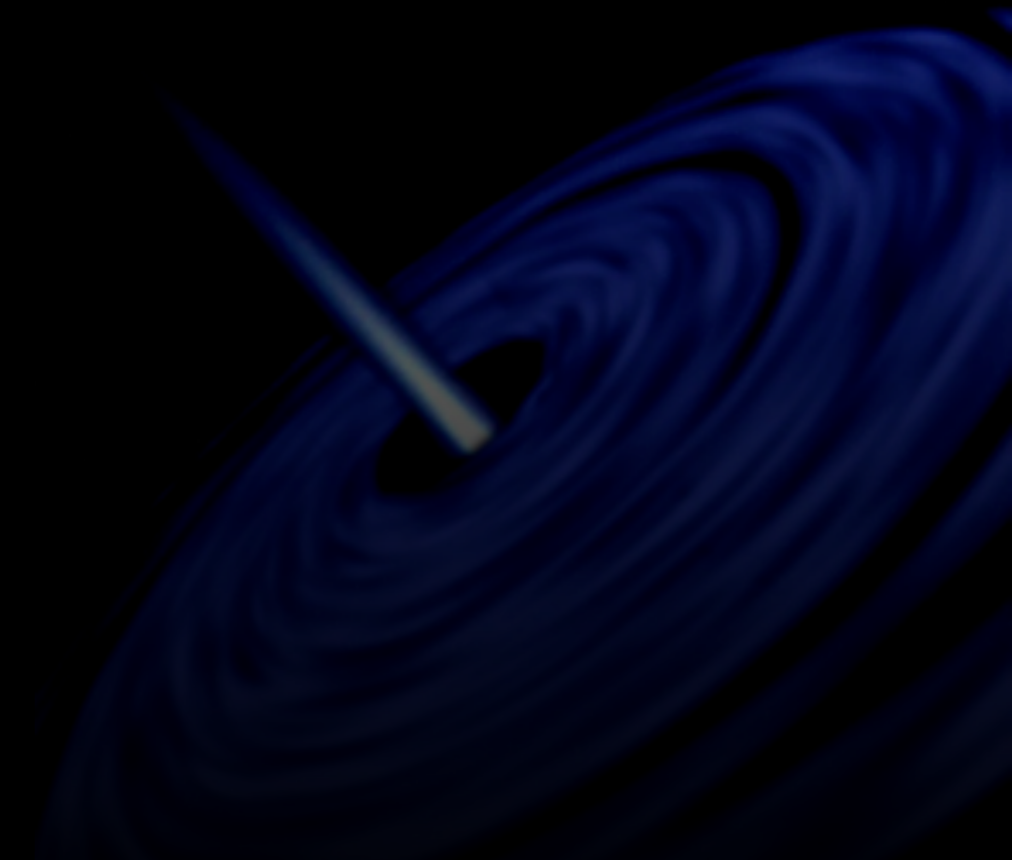


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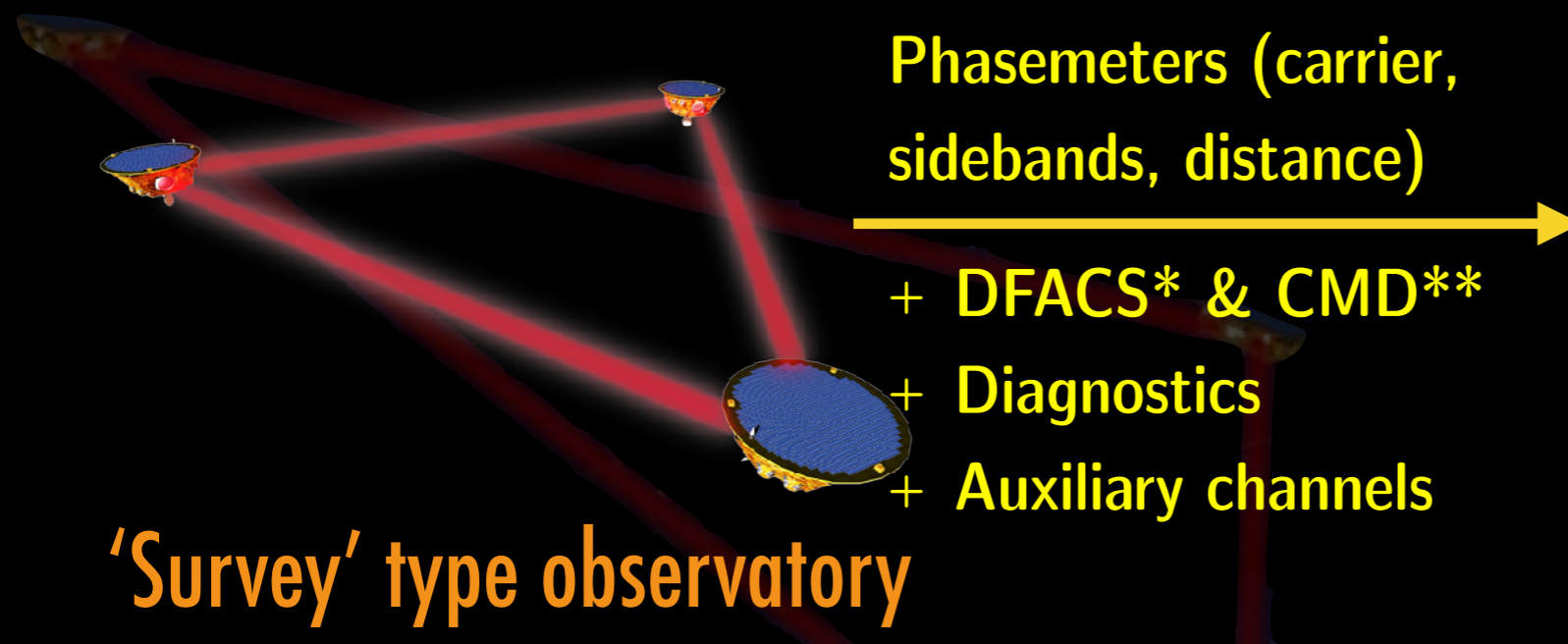
'Survey' type observatory

Gravitational wave sources  
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# LISA data

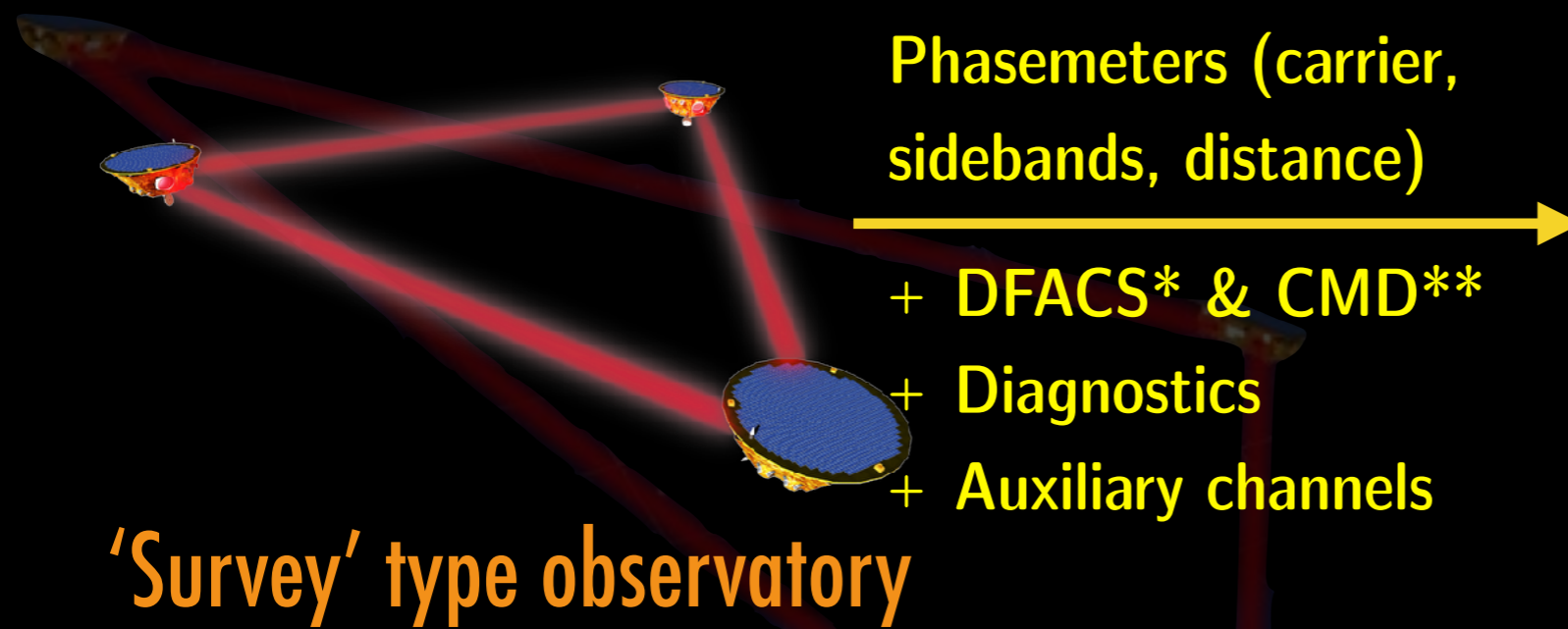


Gravitational wave sources emitting between 0.02mHz and 1 Hz

\* Drag-Free Attitude Control System

\*\* Charge Management Device

# LISA data



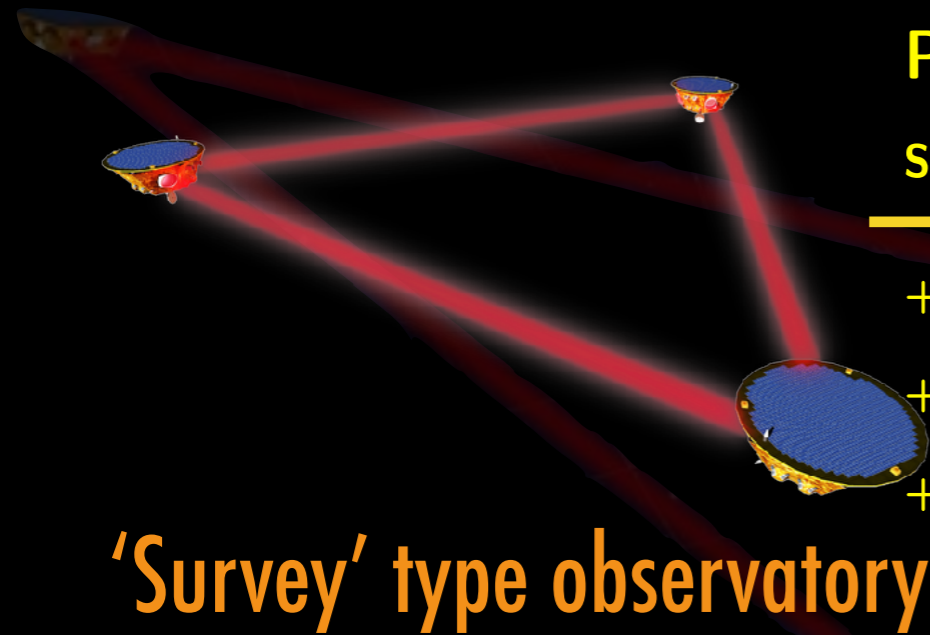
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# LISA data



Phasemeters (carrier, sidebands, distance)

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

'Survey' type observatory



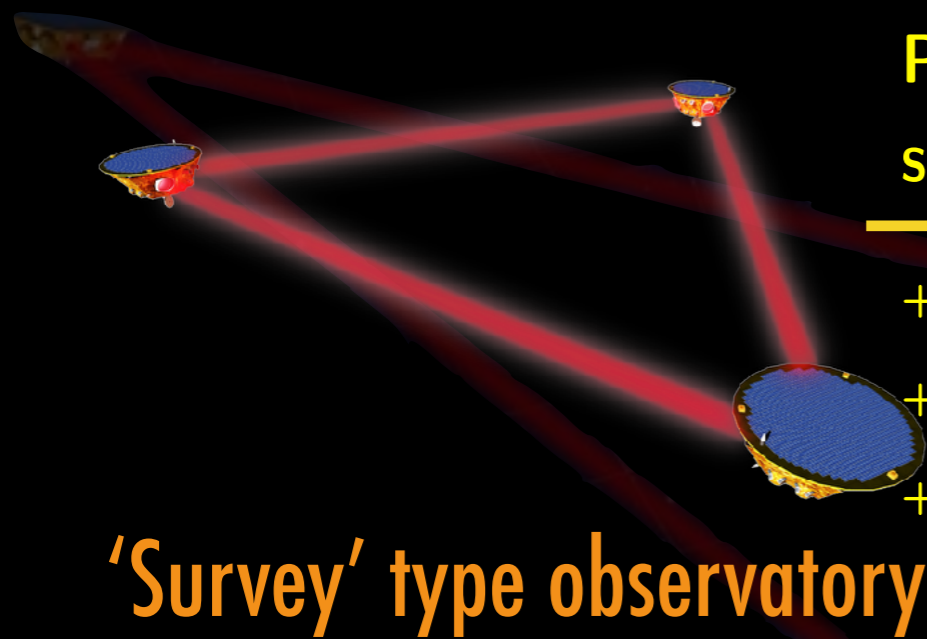
Calibrations corrections  
 + Resynchronisation (clock)  
 + Time-Delay Interferometry  
 reduction of laser noise

Gravitational wave sources  
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3 TDI channels with 2 " ~independents"

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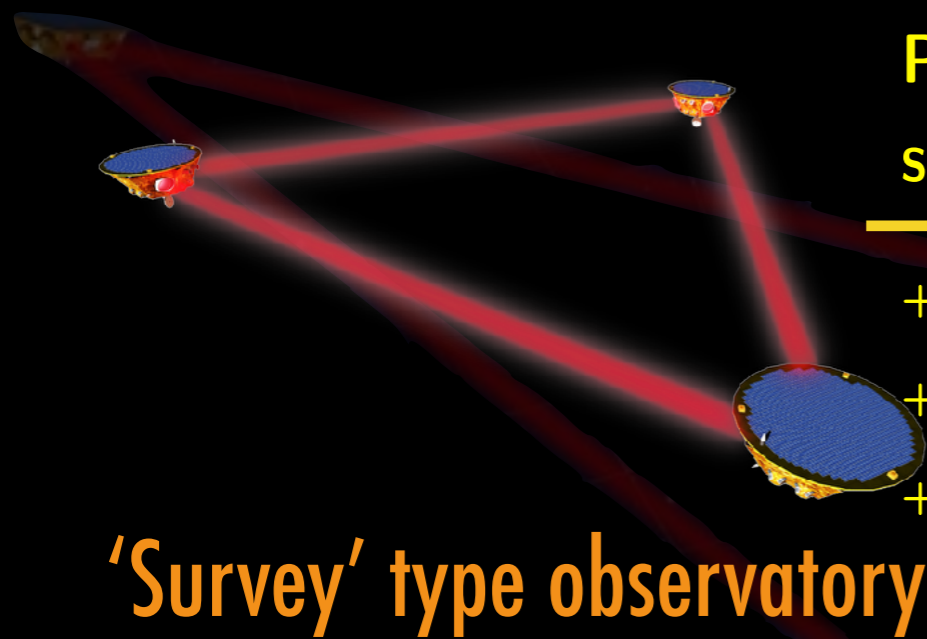
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Data Analysis of GWs

Catalogs of GWs sources with their waveform

\* Drag-Free Attitude Control System  
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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

# LISA data

Mission Operation Center  
(ESA)

Science Operation Center  
(ESA)

DDPC: Distributed Data  
Processing Center  
(Consortium)

Phasemeters (carrier, ds, distance)

CS\* & CMD\*\*

+ Diagnostics

+ Auxiliary channels

'Survey' type observatory

Gravitational wave sources  
emitting between 0.02mHz

L0

L0.5

L1

L2

L3



Calibrations corrections  
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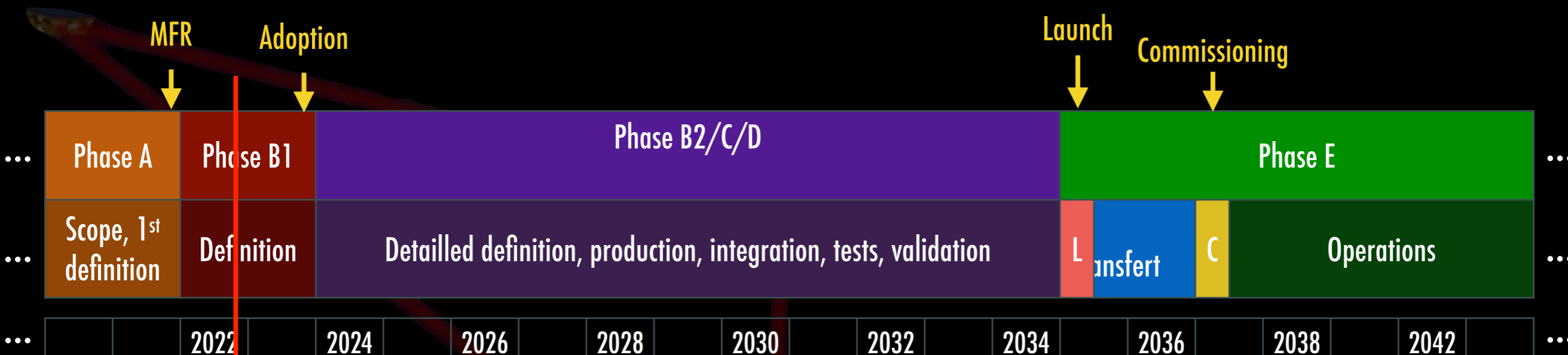
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# Planning & status

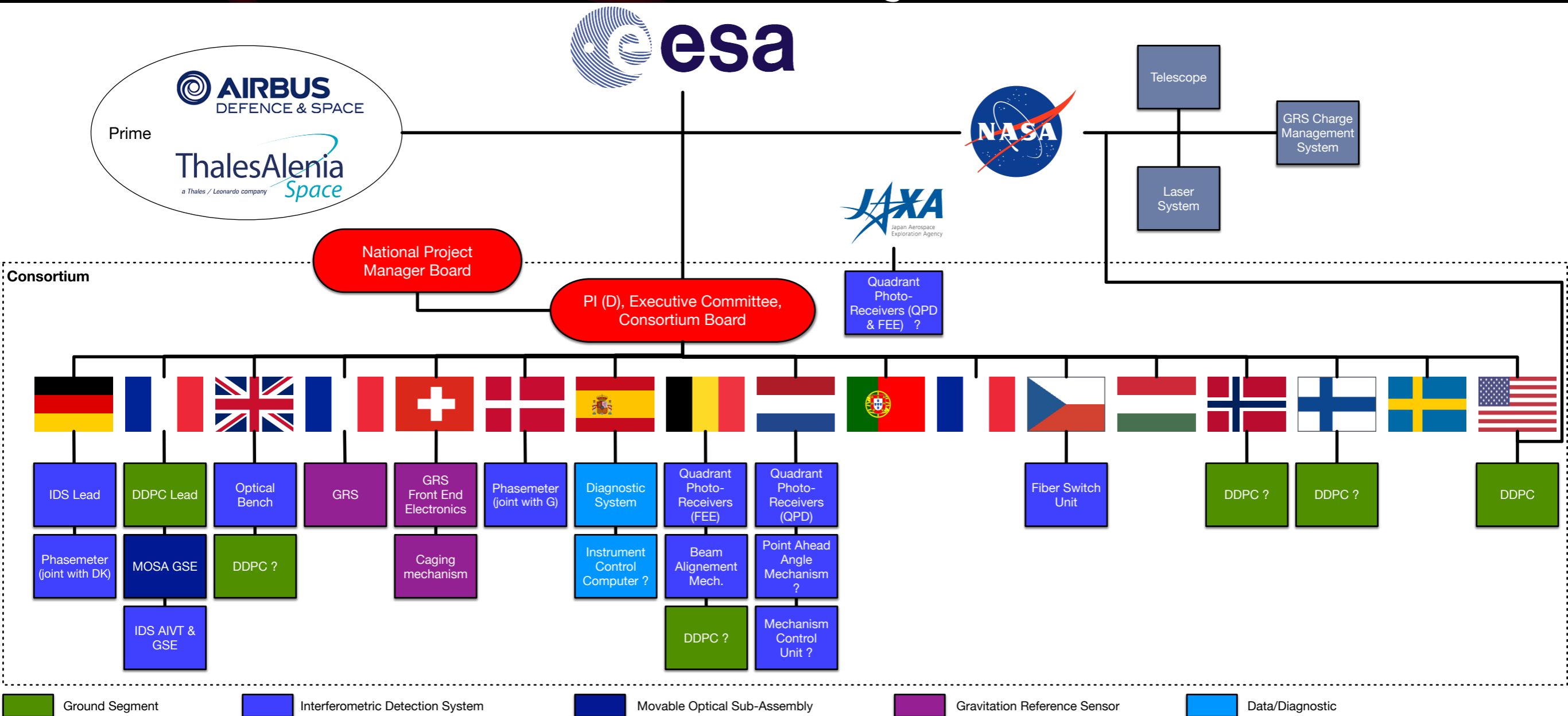


- ▶ 1993: first proposal ESA/NASA
- ▶ 20/06/2017: LISA mission approved by ESA Science Program Committee
- ▶ End 2021: success of the ESA Mission Formulation Review
- ▶ **Now: accelerated phase B1 with ESA Adoption nov 2023**
- ▶ Long building phase of multiple MOSAs: 6 flight models + test models
- ▶ Building of some subsystem models already started
- ▶ Launch 2035
- ▶ 1.5y of transfer, **4.5y nominal mission**, 6.5y extension



# LISA Organisation

- ▶ Lead: ESA
- ▶ Most of the ESA members are contributing

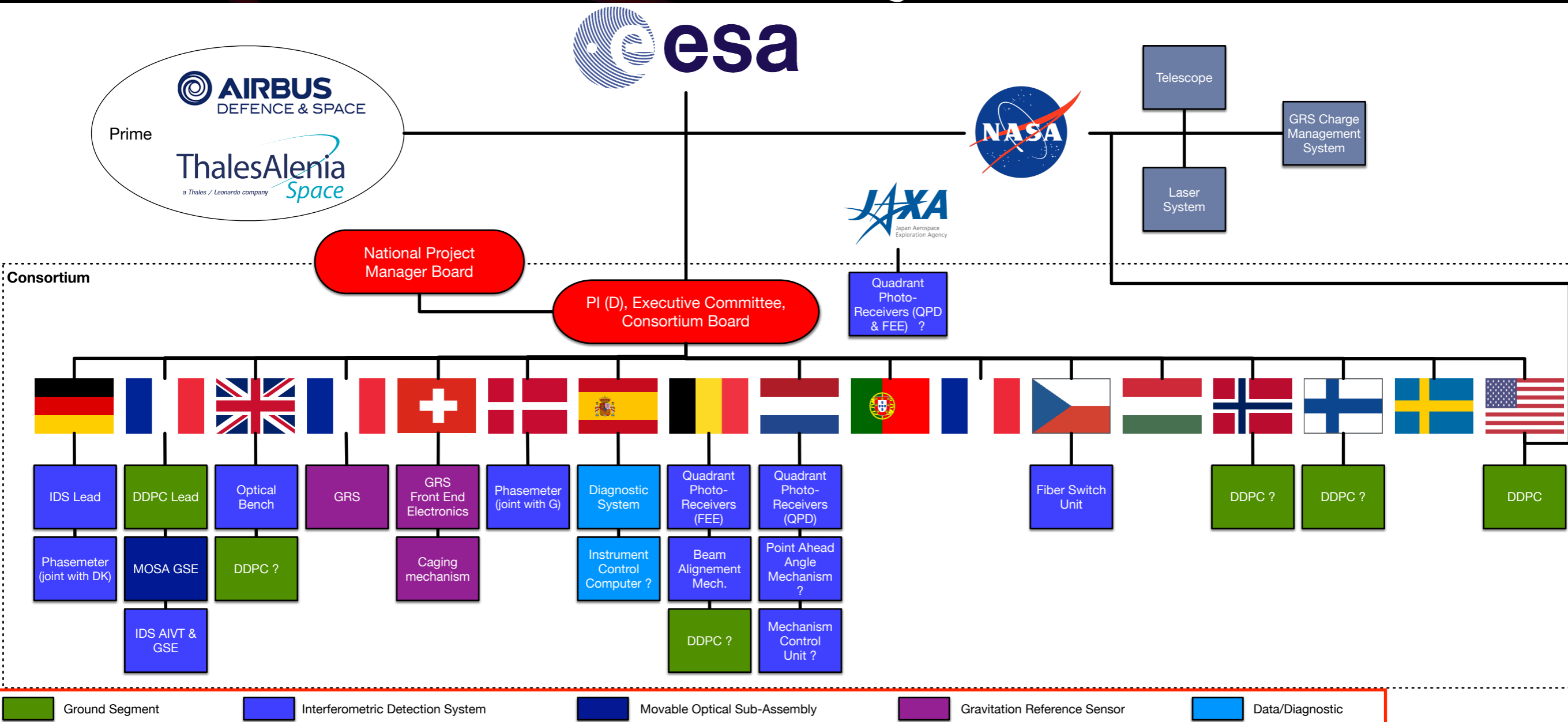






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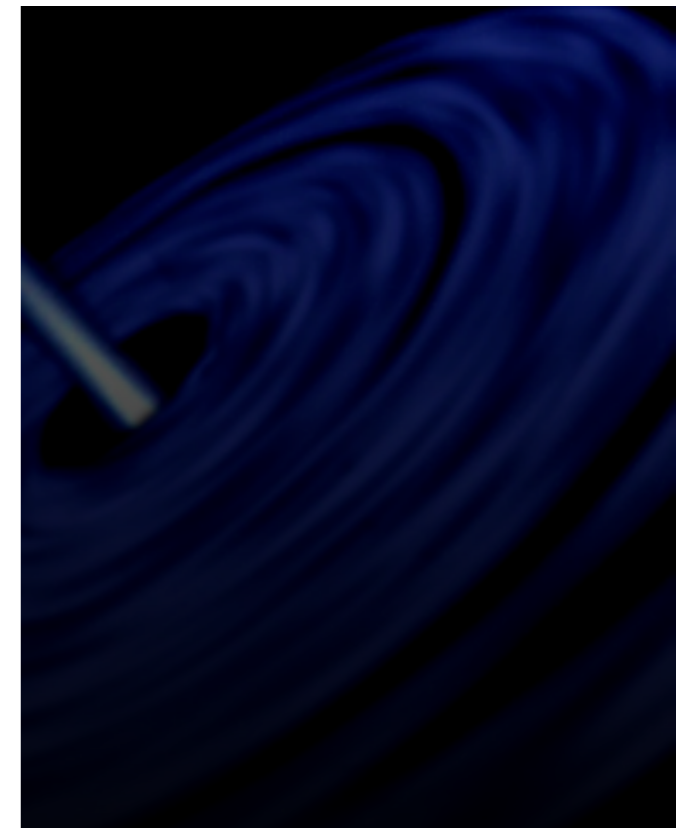
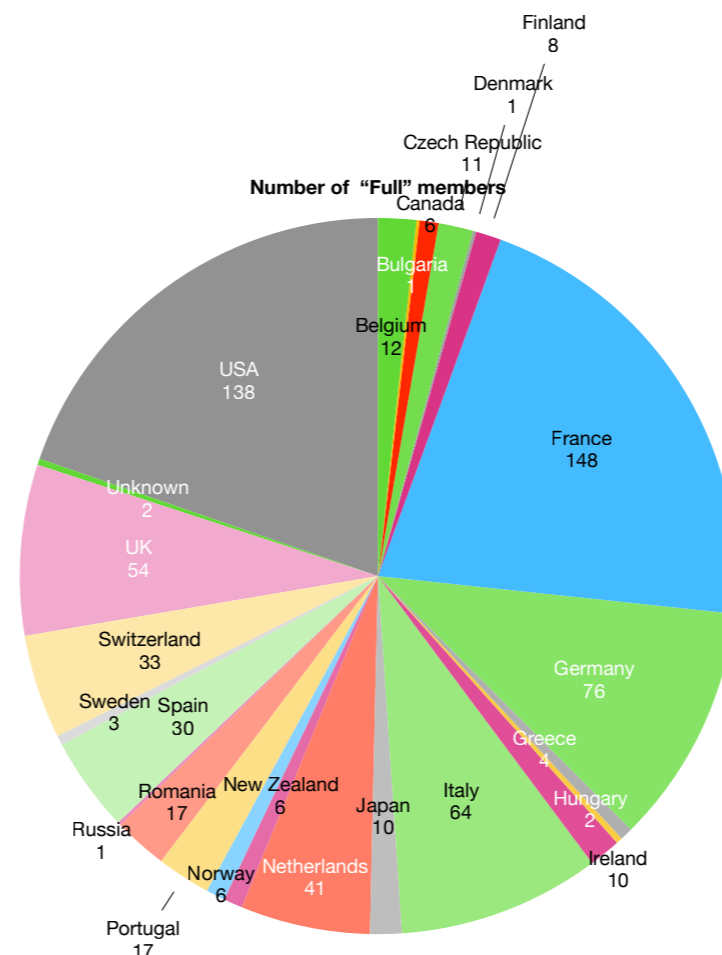
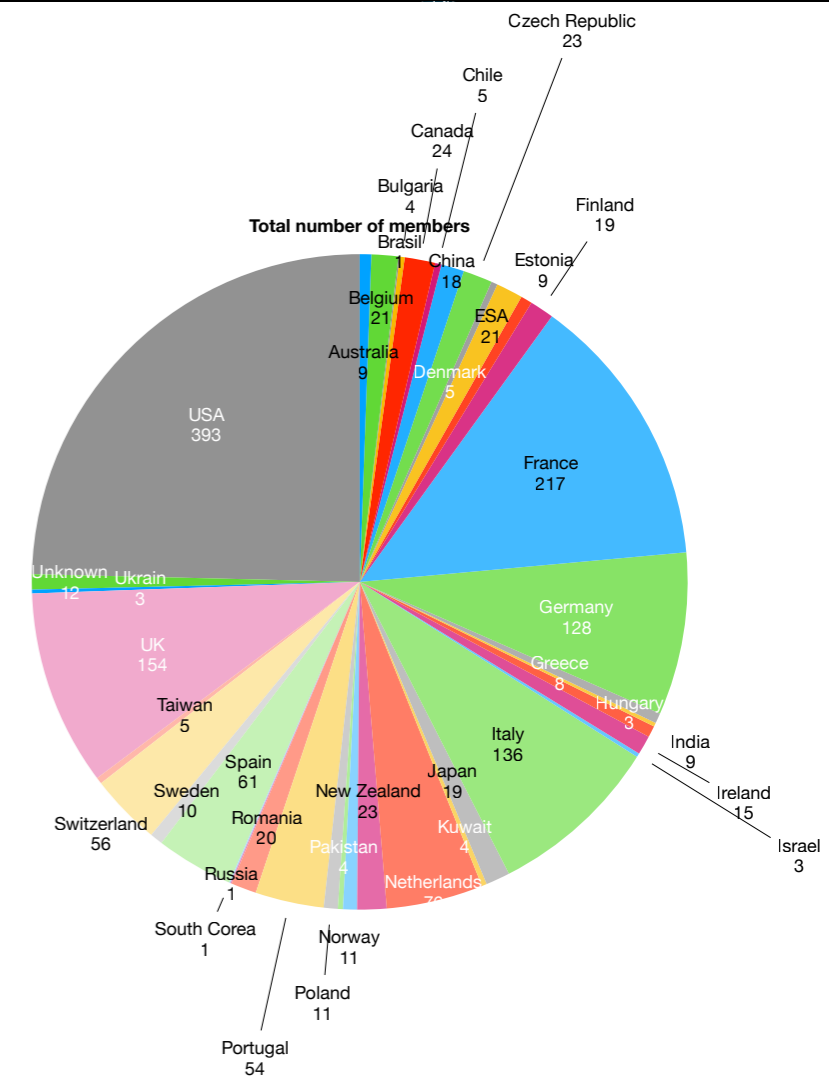


## 5 Consortium Furnished Items

# LISA Consortium

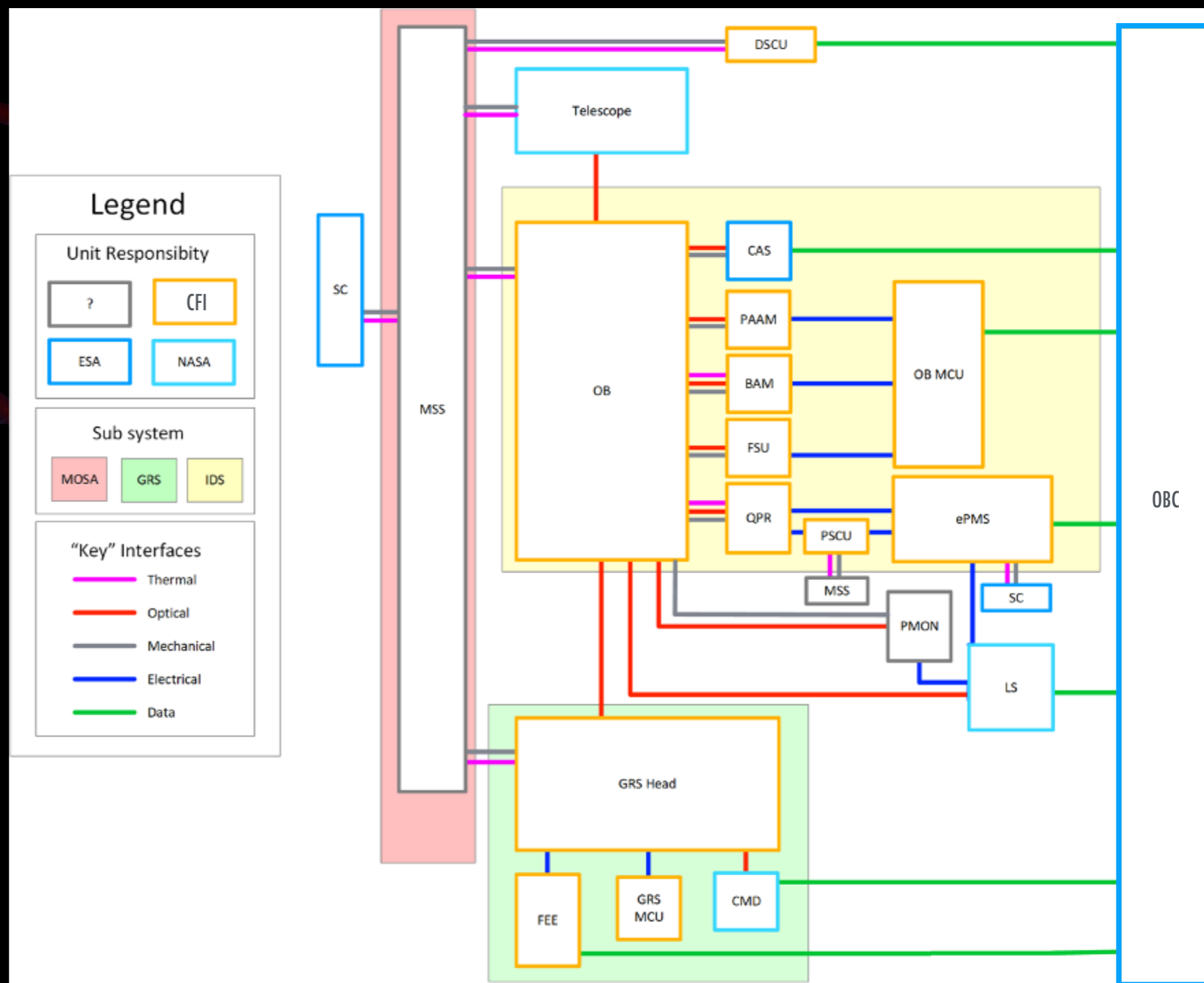
- ▶ 1596 members (July 2022):
  - 701 "full members" committing time
  - 895 associates participating to the 5 WGs:
    - Astrophysics,
    - Cosmology,
    - Fundamental Physics,
    - LISA Data Challenge,
    - Waveforms

▶ If you are interested: join at <https://signup.lisamission.org/>



# Consortium: Space Segment

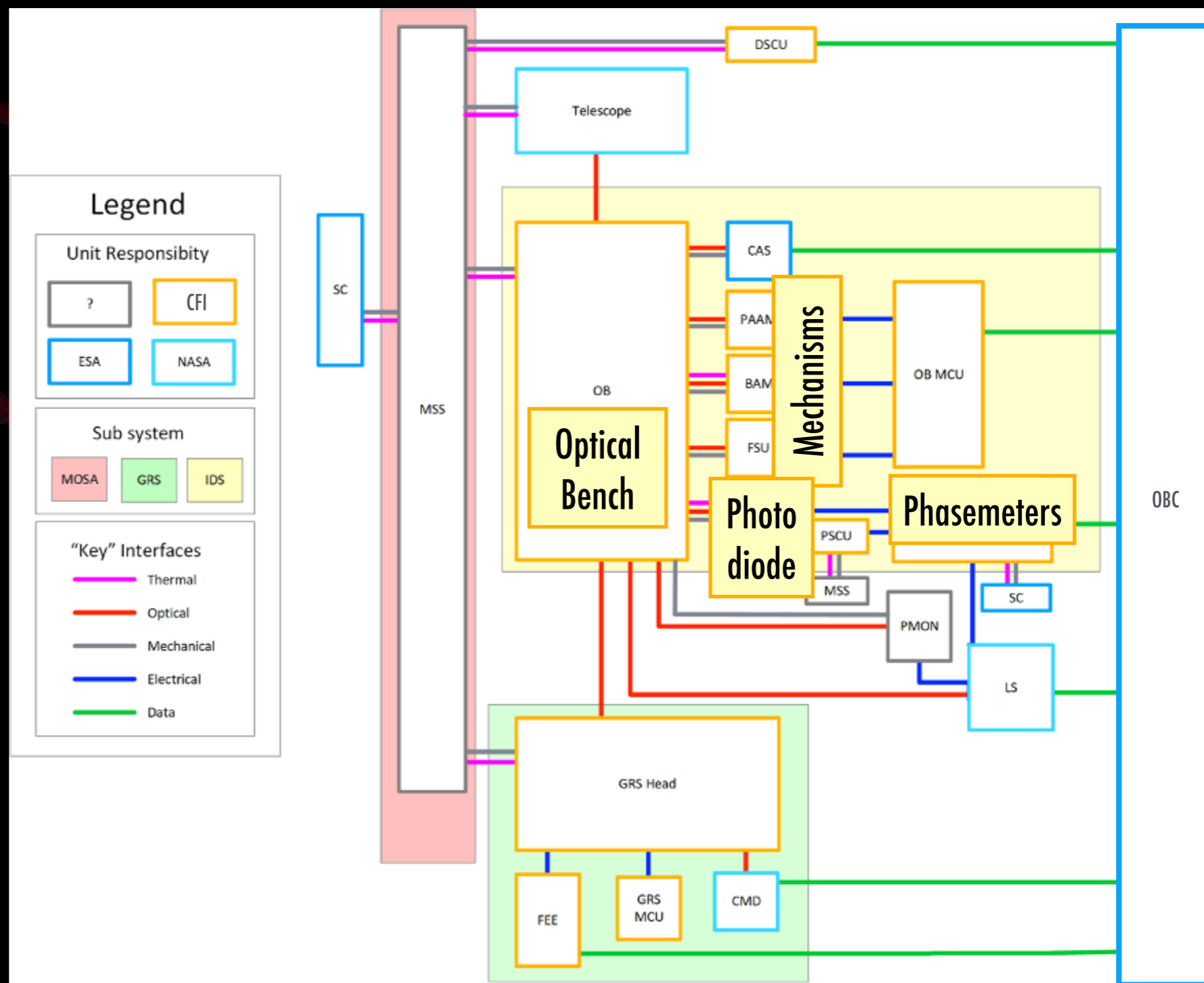
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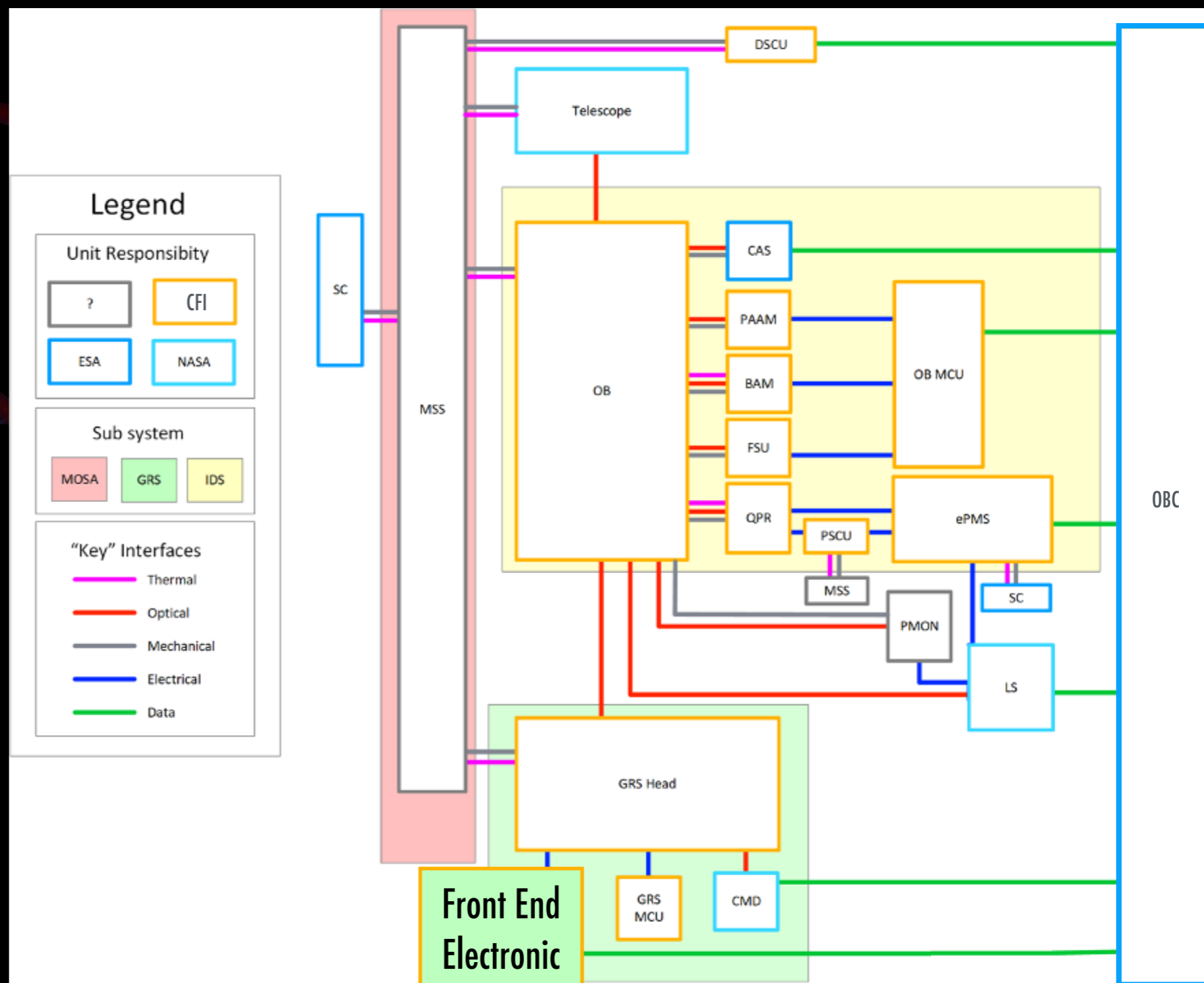
- **IDS** (Interferometric Detection Subsystem)



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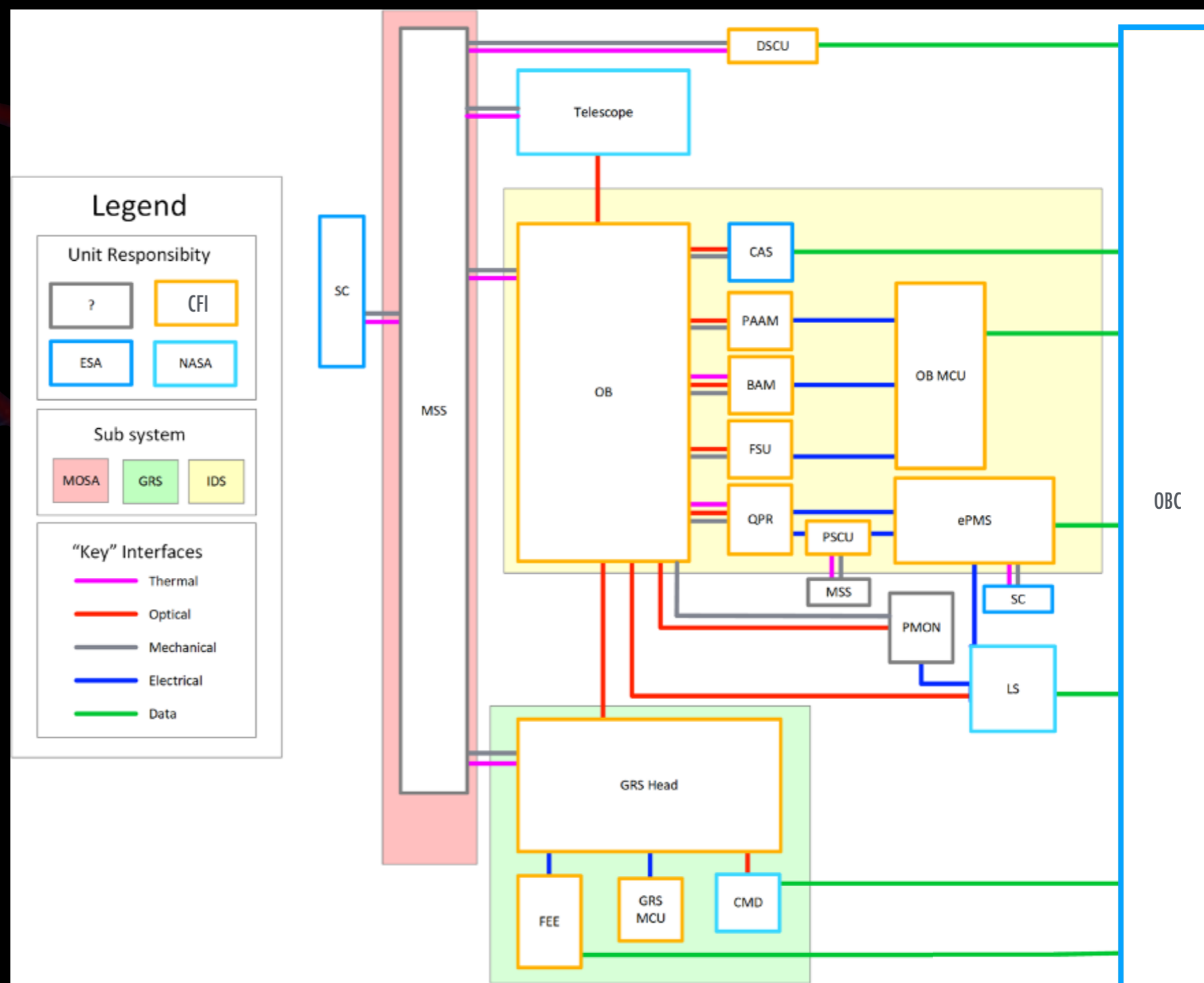
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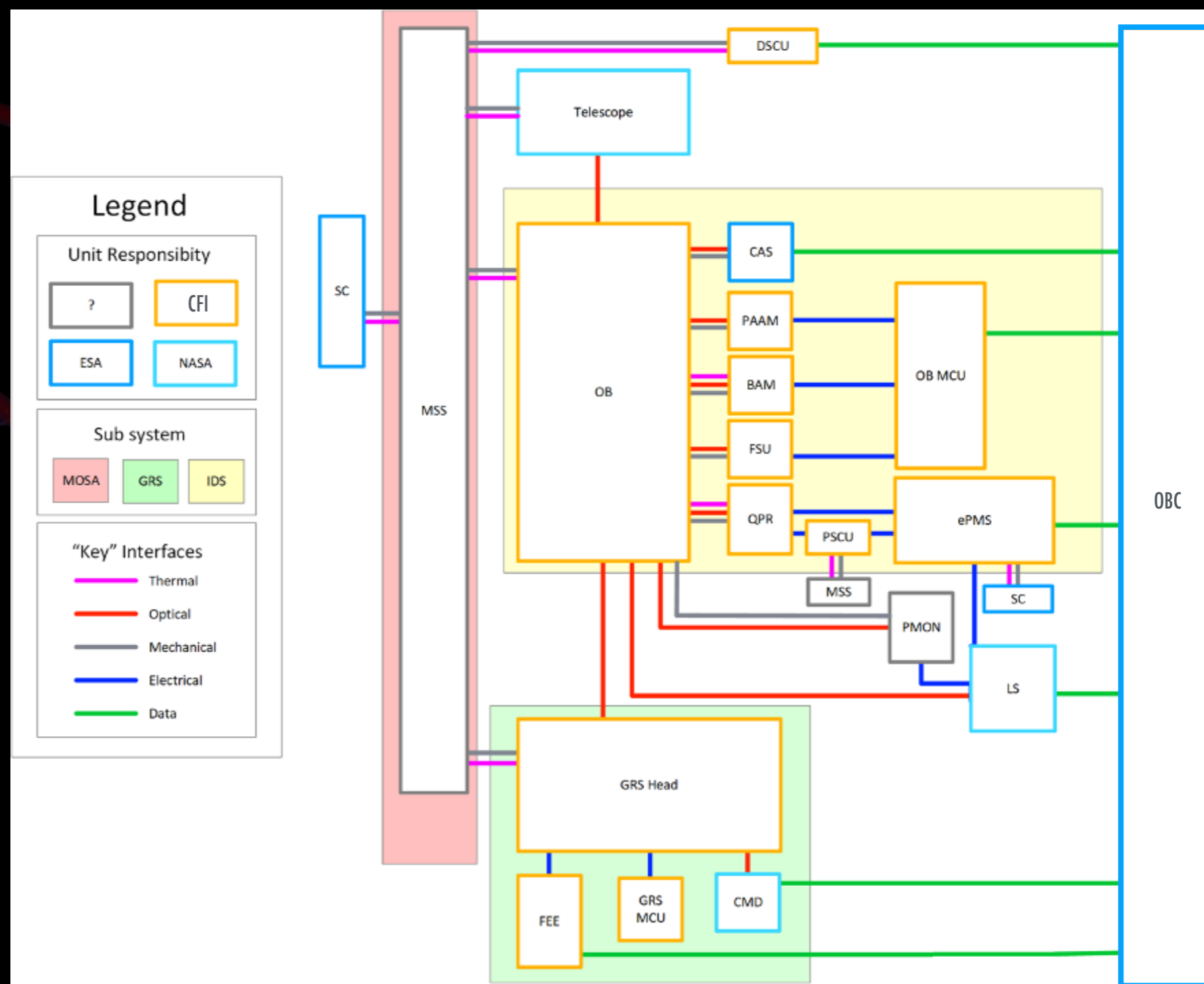
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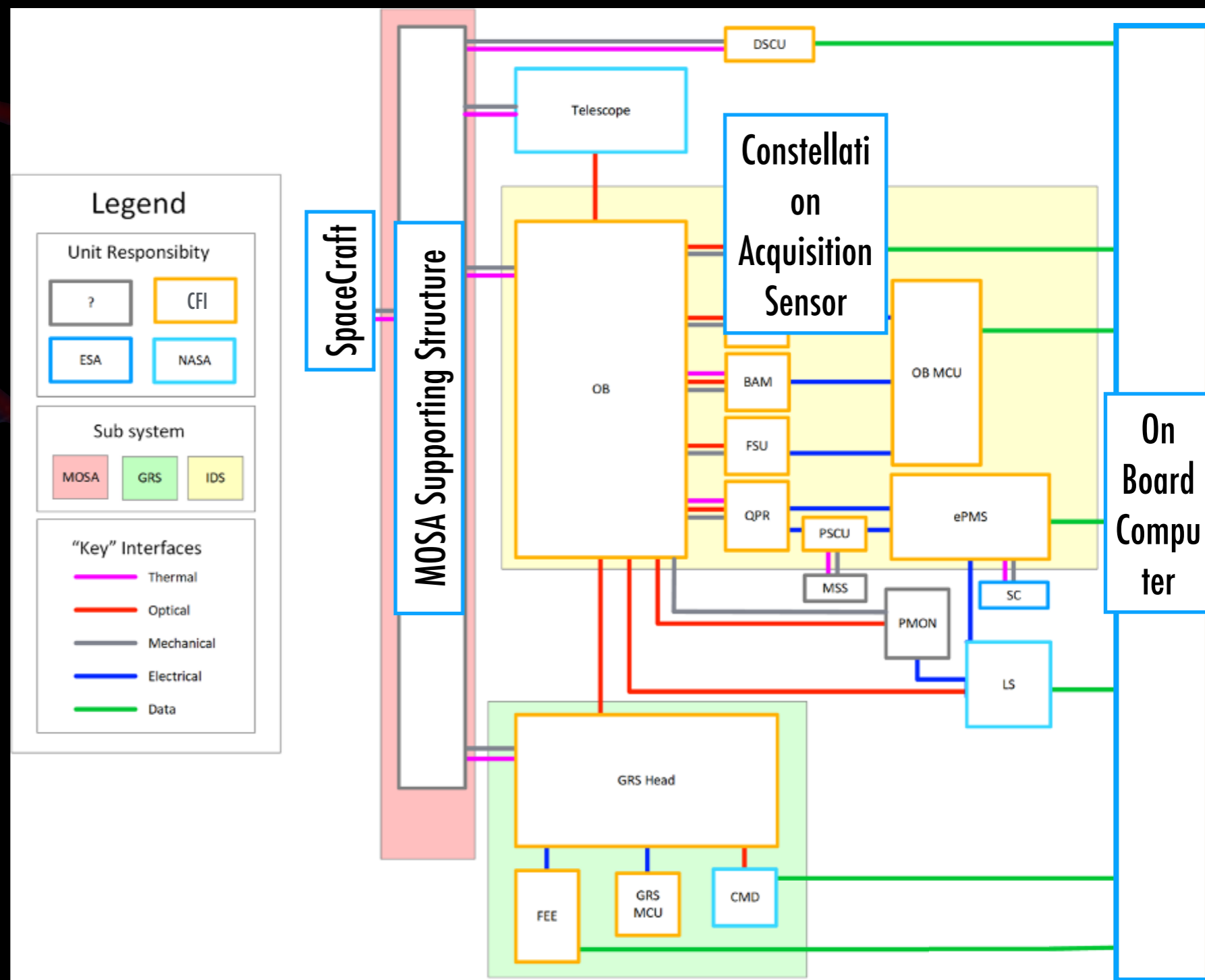
- ▶ Optical Metrology Qualification & Verification **Ground Support Equipment**
- ▶ Science **Diagnostics Subsystem**



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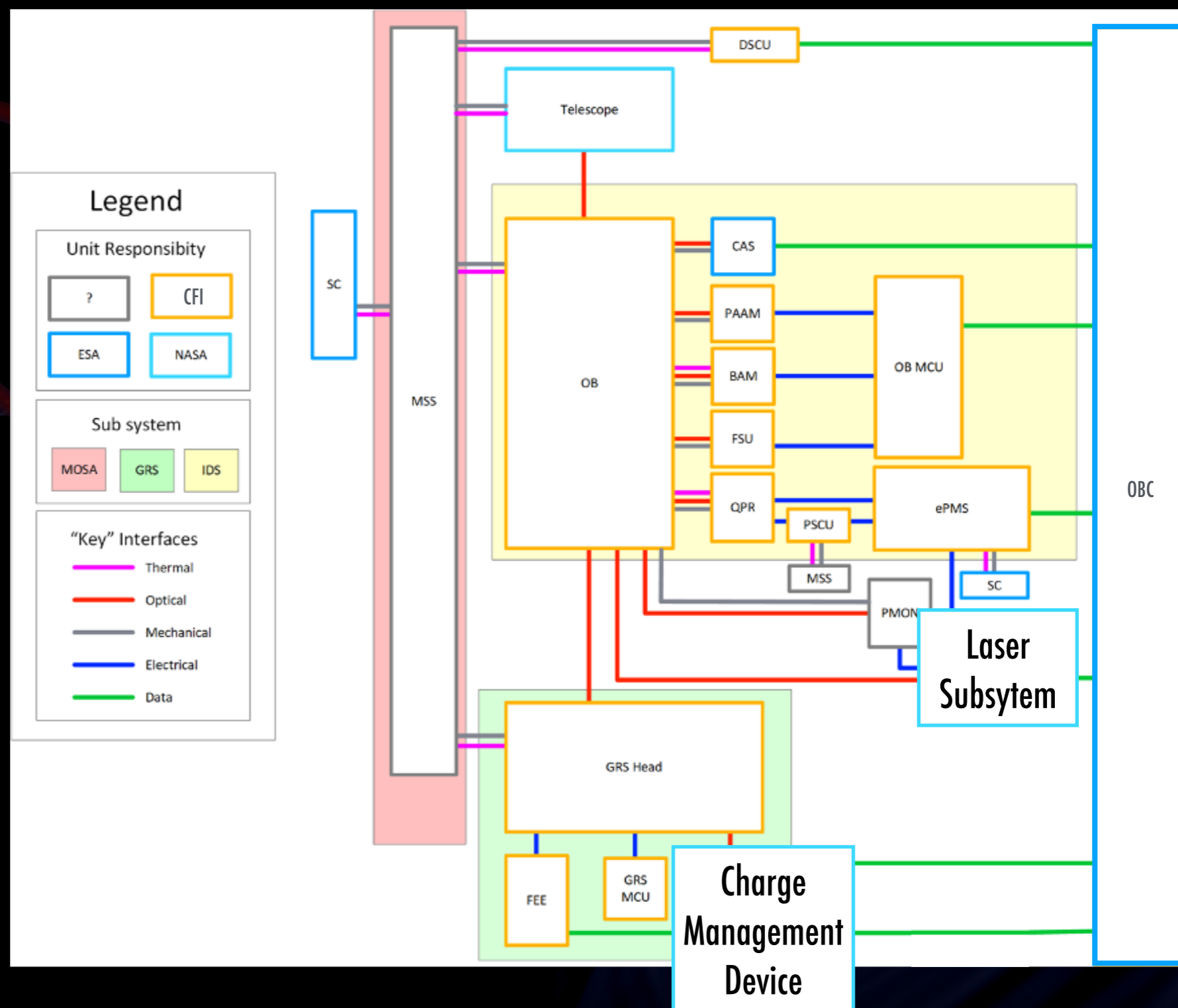
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# Consortium: Ground Segment



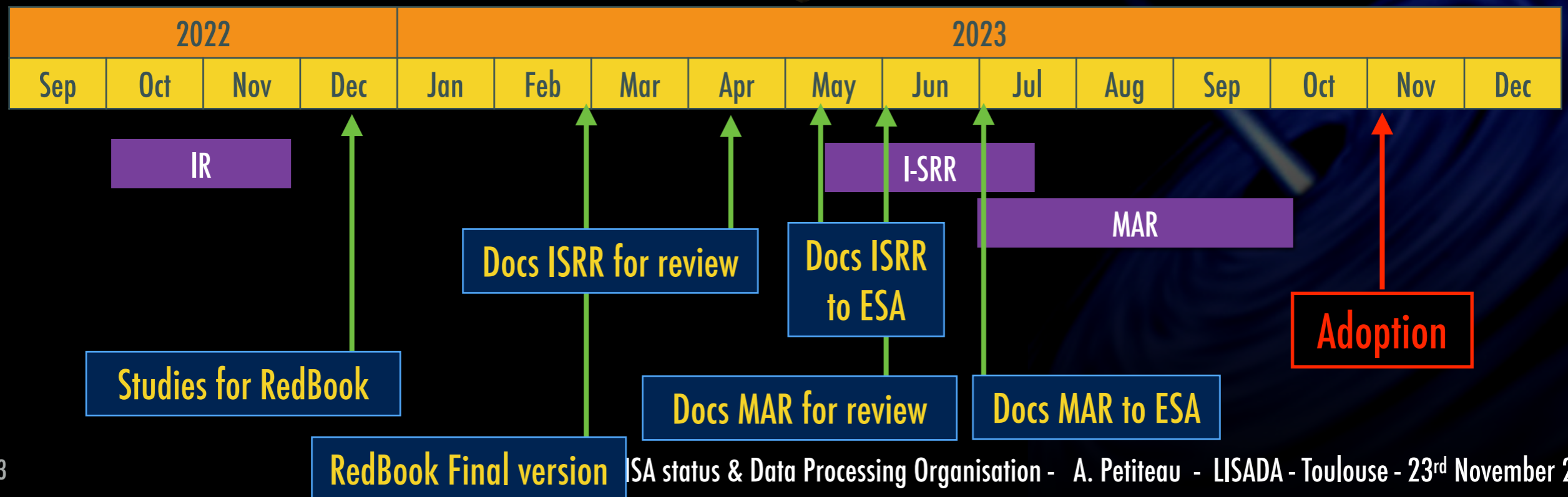
## ► Distributed Data Processing Center

- L1 - L2 - L3
- + strong contribution to L0.5 - L1



# Timeline for B1

Global planning						
Scope	Consortium activities	Group in charge	Documents	Review	Due date for internal review	Final due date
Space segment	<b>FMT tasks</b>	<b>FMT</b>	<b>Technical notes</b>	<b>I-SRR</b>	<b>12/04/2023</b>	<b>12/05/2023</b>
Ground Segment	DDPC Work Breakdown Structure	LDPG	MLA + doc	Negotiation ESA - partners	24/10/2022	04/11/2022
	<b>DDPC design, organisation, etc</b>	<b>LDPG</b>	<b>SIP, SIRD</b>	<b>MAR</b>	<b>01/06/2023</b>	<b>01/07/2023</b>
Science	<b>Contribution to the Redbook writing</b>	<b>LSG</b>	<b>RedBook</b>	<b>Scientific review</b>	<b>27/01/2023</b>	<b>28/02/2023</b>
	<b>Studies for the Red book</b>	<b>LSG</b>	<b>RedBook</b>	<b>Scientific review</b>	<b>05/12/2022</b>	<b>28/02/2023</b>
Management	Data Policy	Data Policy board WG, EC	SMP	Negotiation ESA - partners	05/09/2022	12/09/2022
	Management of the Consortium for next phases	EC	MP	MAR	28/02/2023	01/07/2023



# Science for phase B1

- ▶ **Redbook**: science objectives + from data to science
  - **"Figure of merits"**: figures and key numbers characterising the science performances
  - Show that we know how to analyse the data:
    - **Partial demonstration**: not full demonstration but key elements => LDC
    - **Plan** of development and organisation (DDPC)
- ▶ **"Project"**: **detailed design**:
  - L0.5 data, detailed processing for the noise cleaning, "end-to-end" simulation + data analysis
  - Robustness to **realistic data**: gaps, glitches, non-stationarities, limited knowledge of the noise
  - Design of the ground segment: DDPC

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See talks from Stas B.,  
Kirsten L., Sylvain M.,  
Elie L., ...

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See talk from Martina M.

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See talk from Olaf H. & Jean-Baptiste B.



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**See talk from Olie B.**

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  - L0.5 data, detailed processing for the noise cleaning, "end-to-end" simulation + data analysis
  - Robustness to **realistic data**: gaps, glitches, non-stationarities, limited knowledge of the noise
  - Design of the ground segment: DDPC

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- ▶ **Redbook**: science objectives + from data to science
  - **"Figure of merits"**: figures and key numbers characterising the science performances
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Defined in the Science Requirements Doc.:

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- ▶ 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
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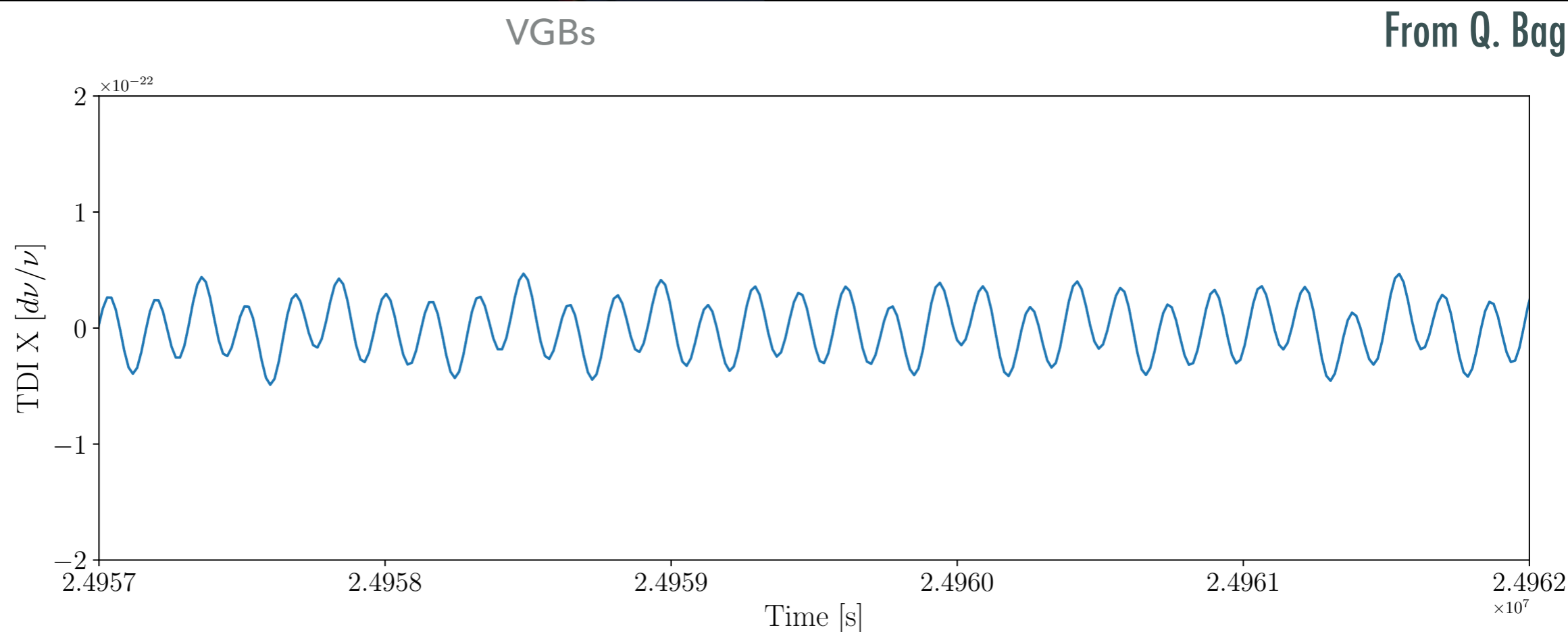
# LISA data

- ▶ What kind of data will we measure?
  - Fractional frequency deviations (relative doppler shifts) from 27 interferometers
  - Times series sampled at 4 Hz, observed over 4+ years with 89% duty cycle
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  - After pre-processing, obtain 3 time-delay interferometry (TDI) data streams (X, Y, Z)



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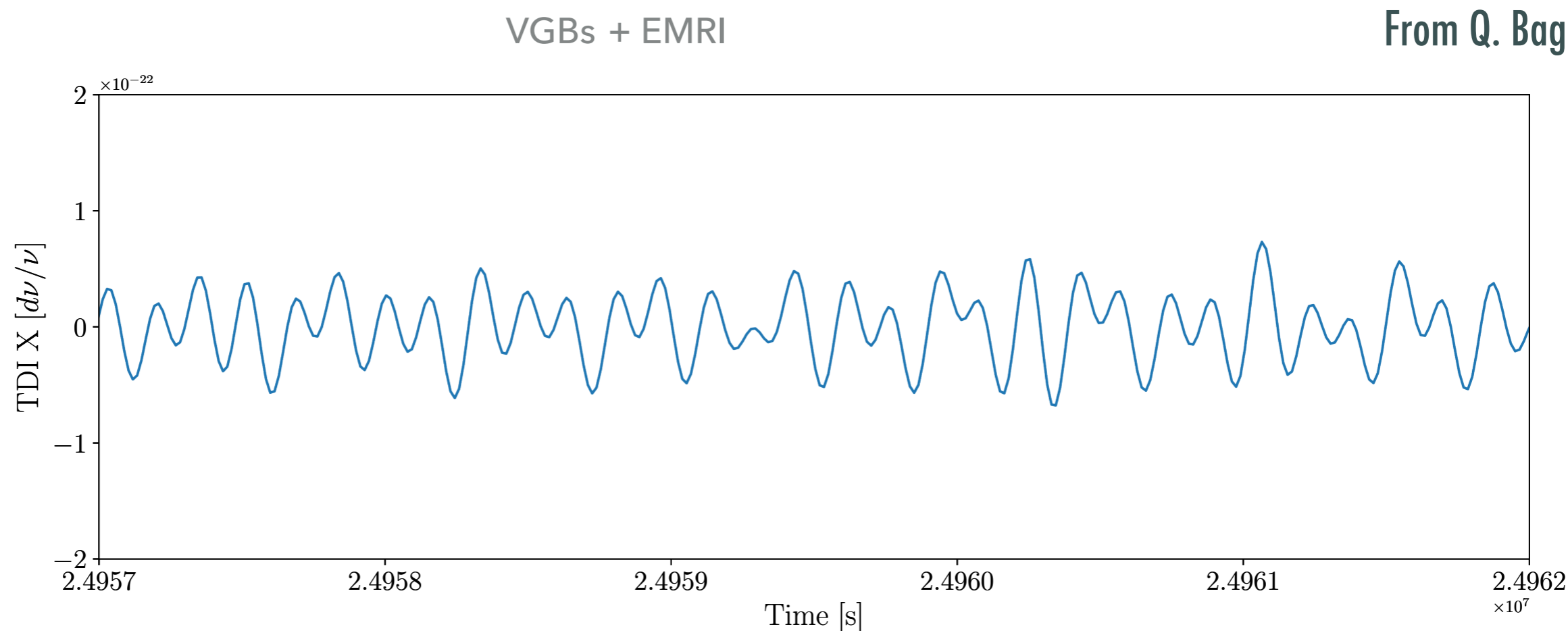






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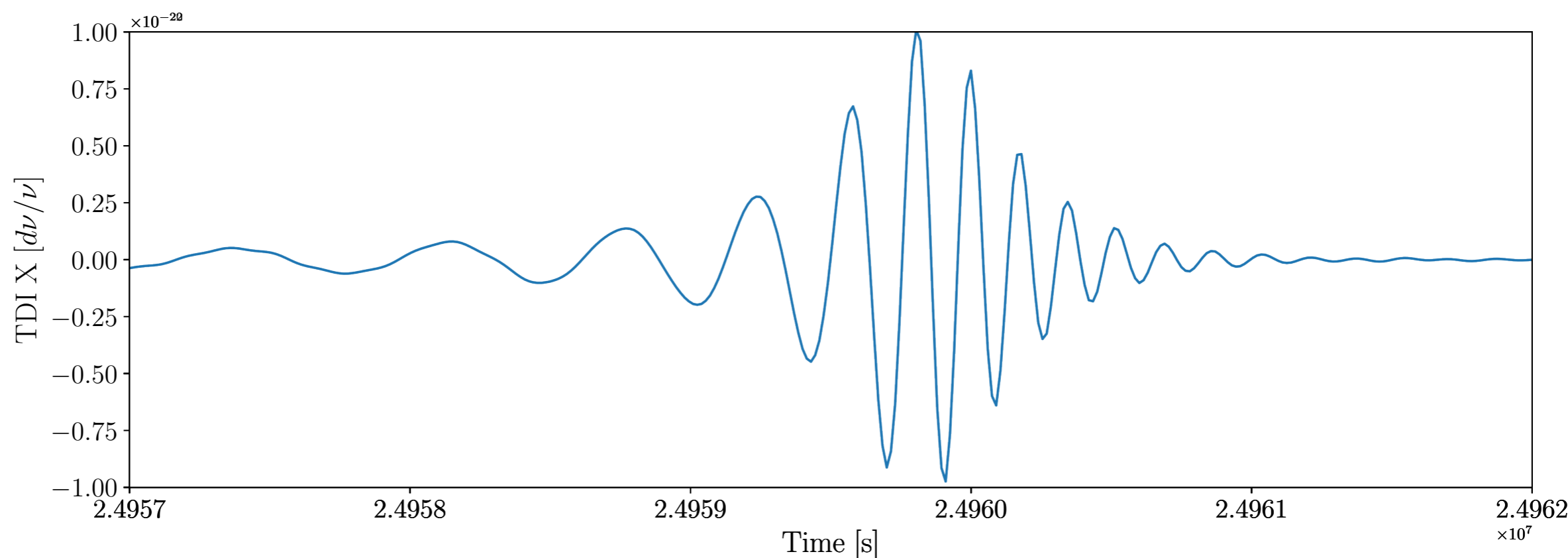


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VGBs + EMRI + MBHB

From Q. Baghi

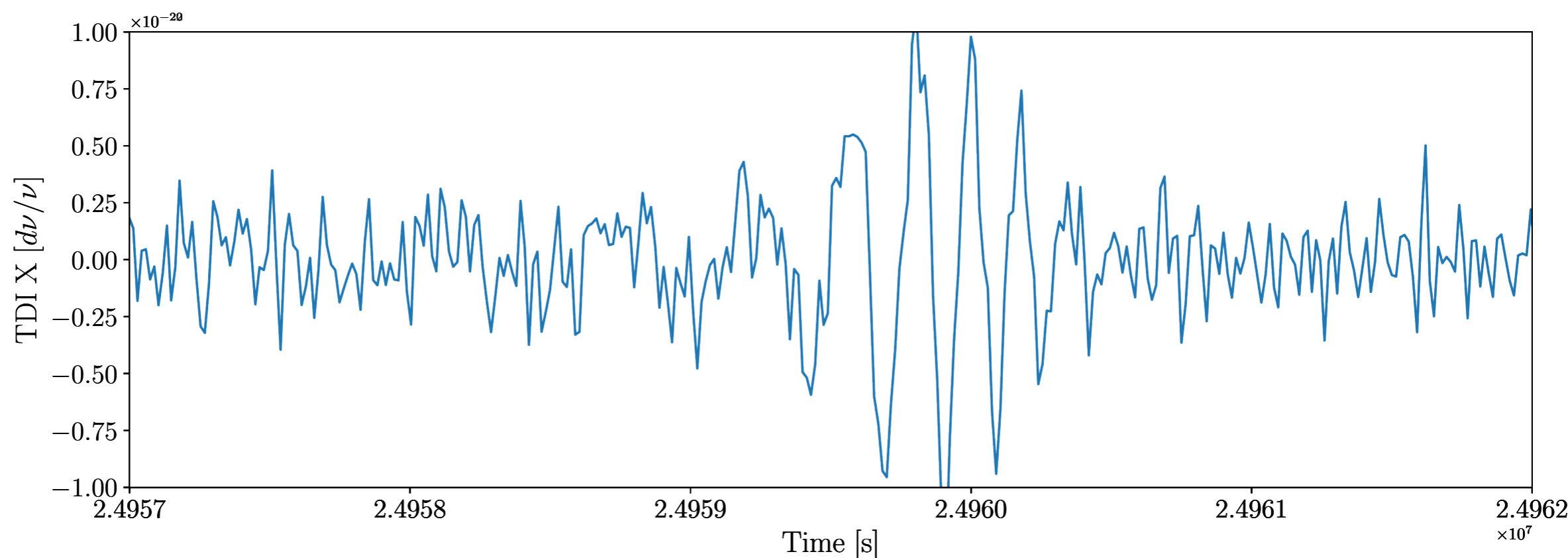


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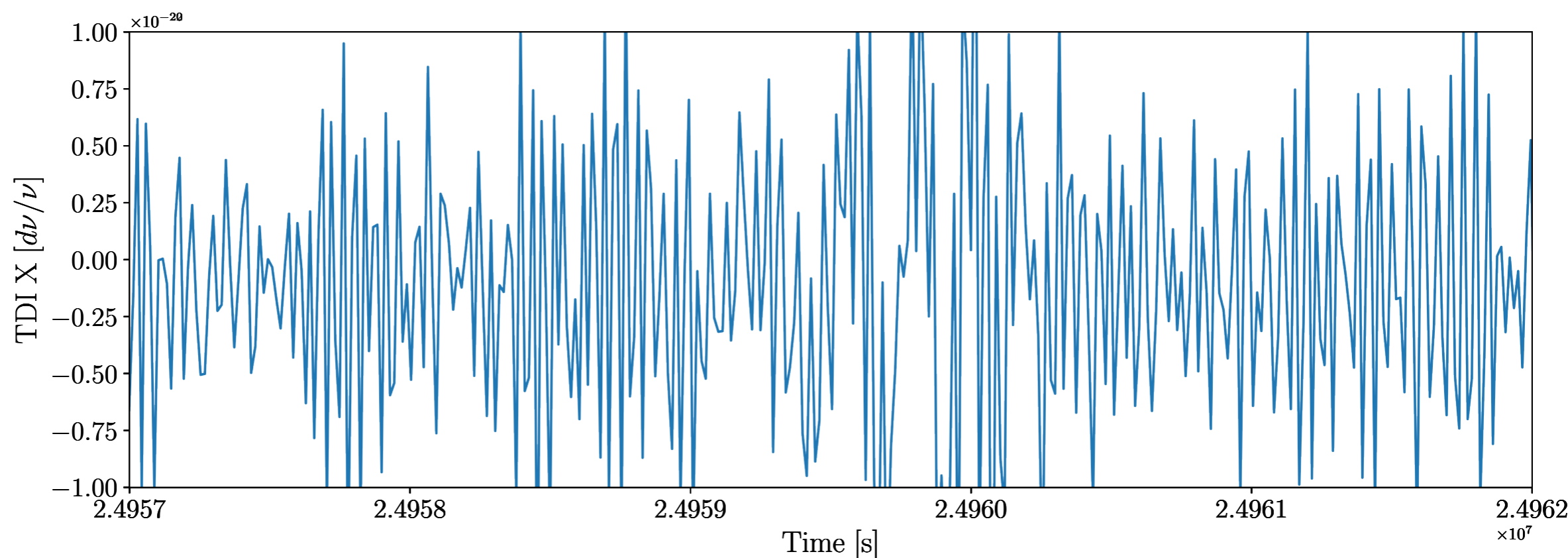


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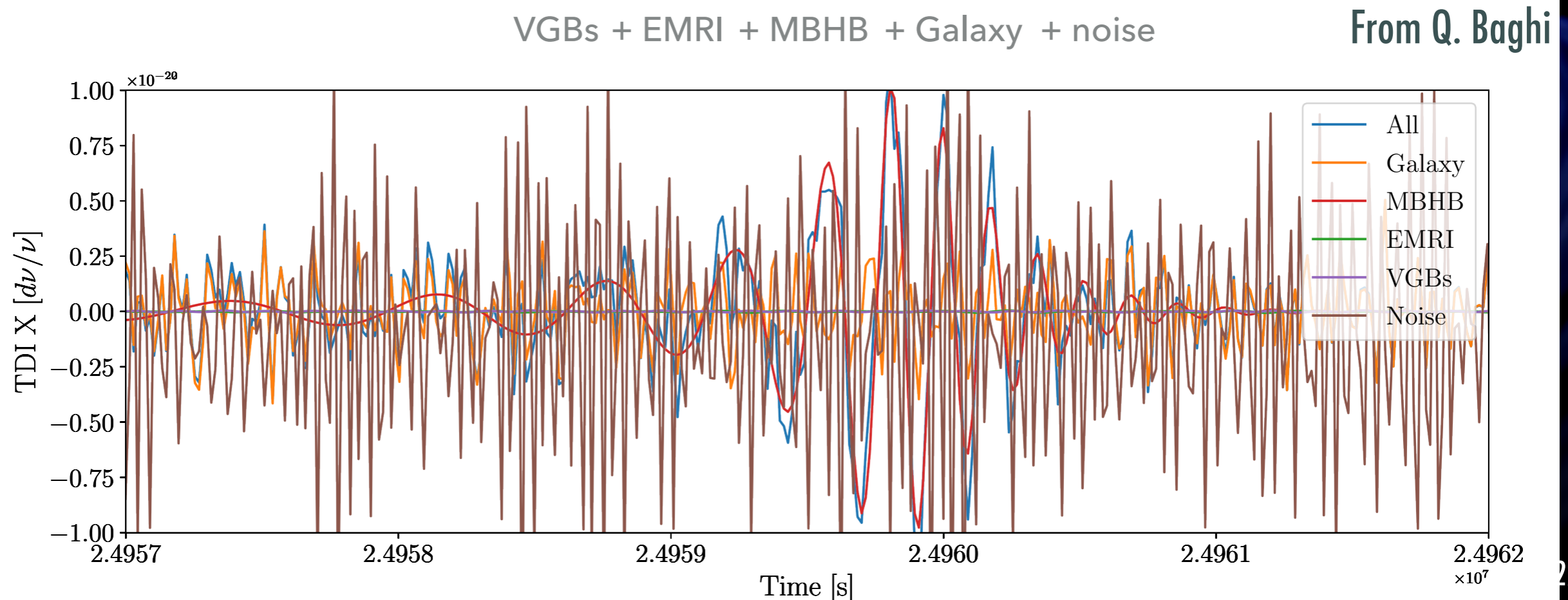
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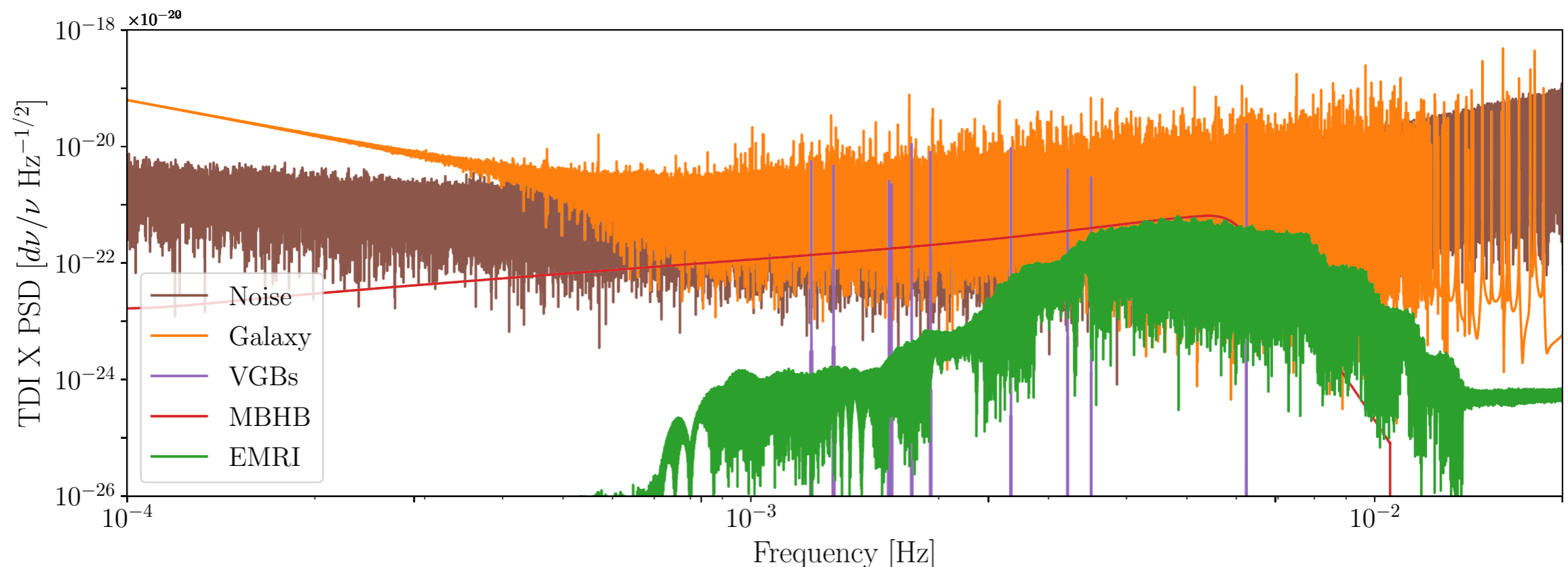


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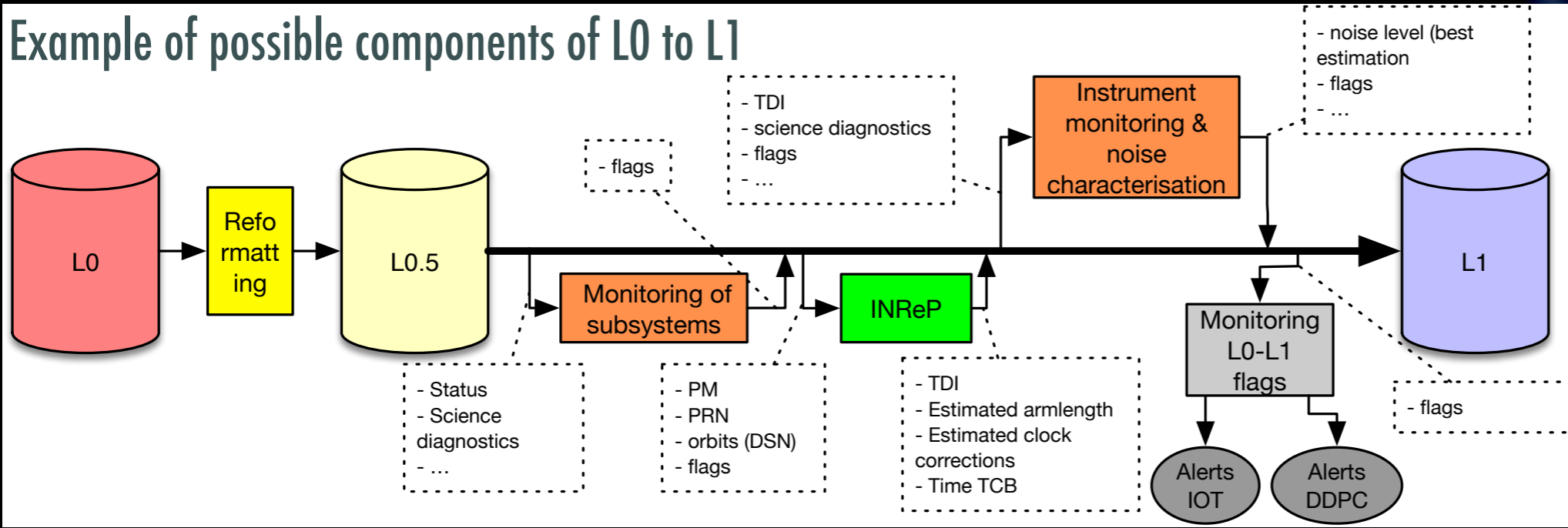
From Q. Baghi



# LISA data analysis logic

- ▶ 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 (devOps)
- ▶ **Multiple steps approach** with iterations between steps because data products are very interconnected:
  1. Reduce dominant noises (Time Delay Interferometry) and partial correction on instrument artefacts => L1 data (TDI data)
  2. 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
- ▶ **Science exploitation**, mainly on L3 data: Consortium is expecting to do science as well as the world wide community.

# L0 to L1

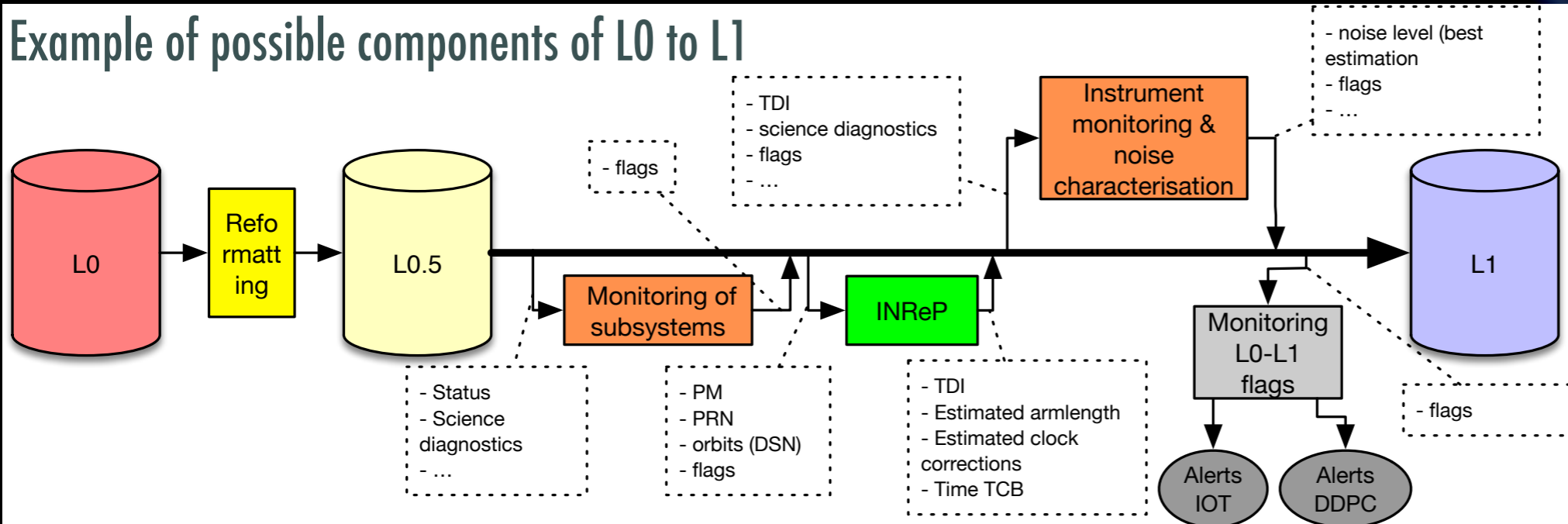




# L0 to L1

## ► Data levels:

- L0.5: L0 reformatted: engineering/physical values
- L1: All requested data for GW extraction



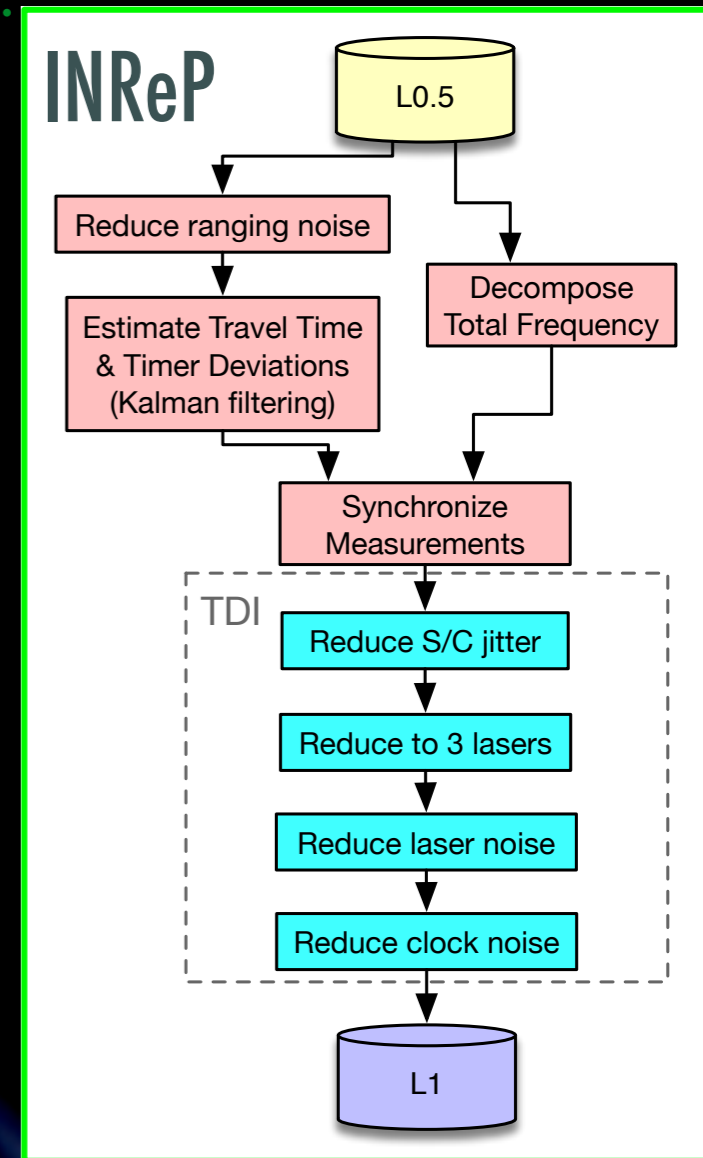
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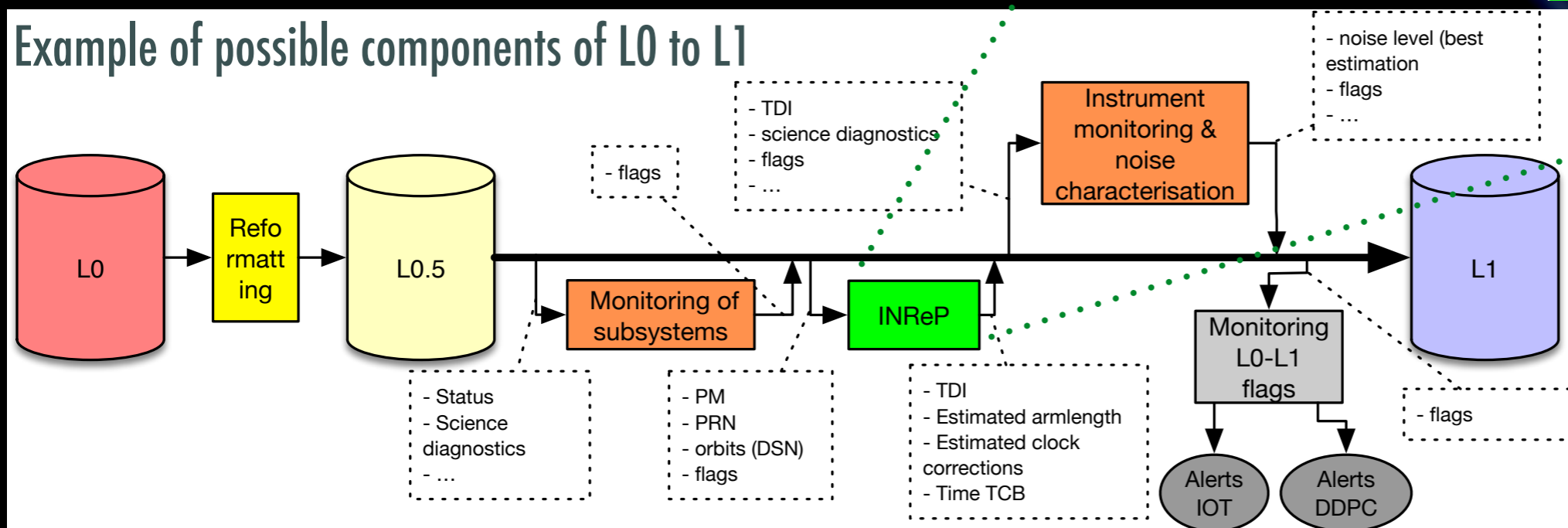
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## ► L0 to L1 processing: **INReP (Initial Noise Reduction Pipeline)**

- **TDI+**: Suppress laser noise, clock noises, spacecraft jitter noise
- Data synchronisation
- Reduce Tilt-To-Length noise



## Example of possible components of L0 to L1



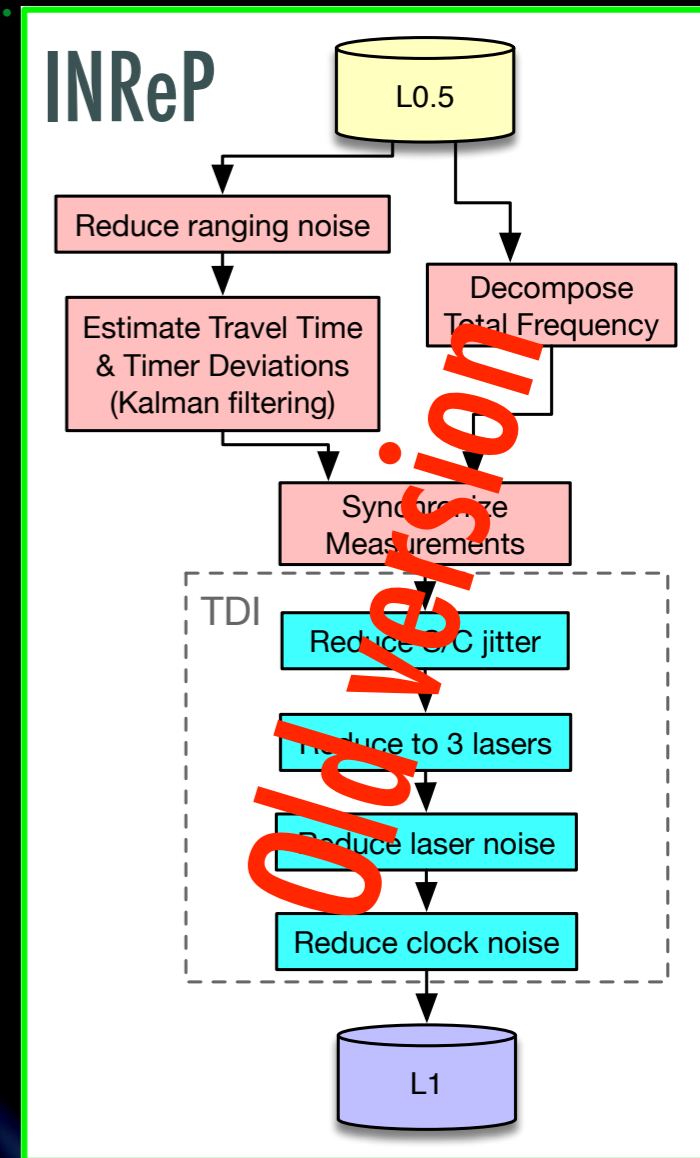
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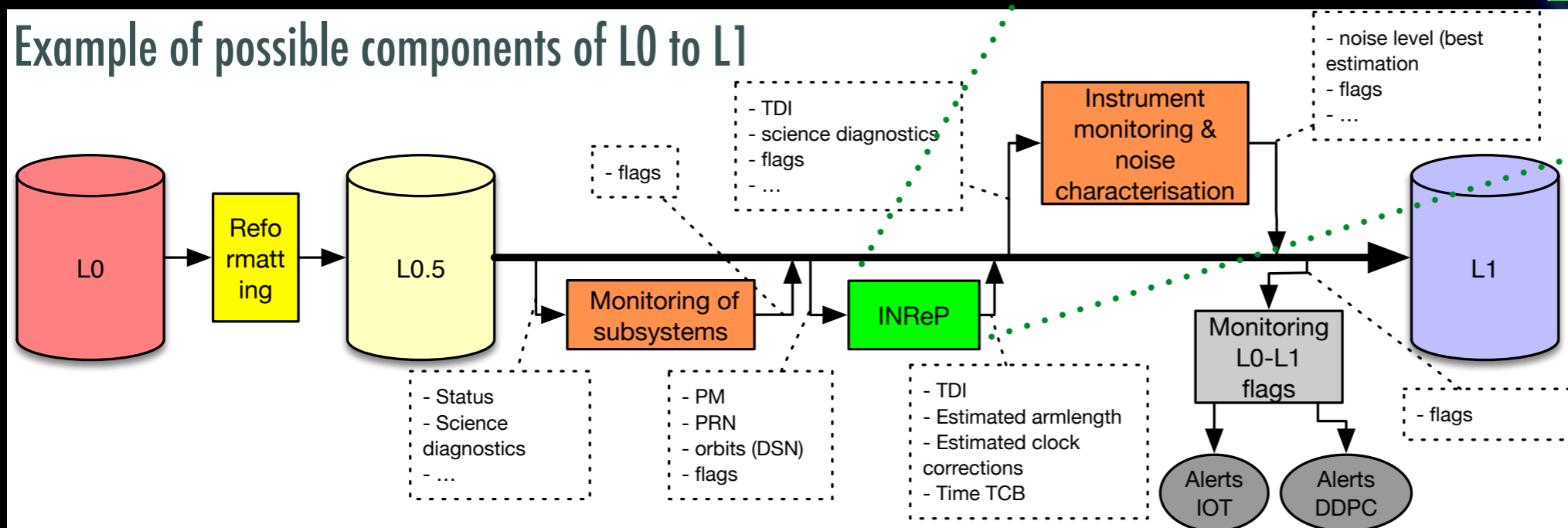
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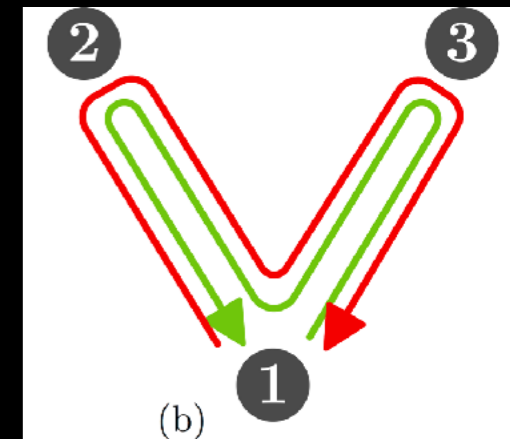
## Example of possible components of L0 to L1



# TDI for reducing laser noise

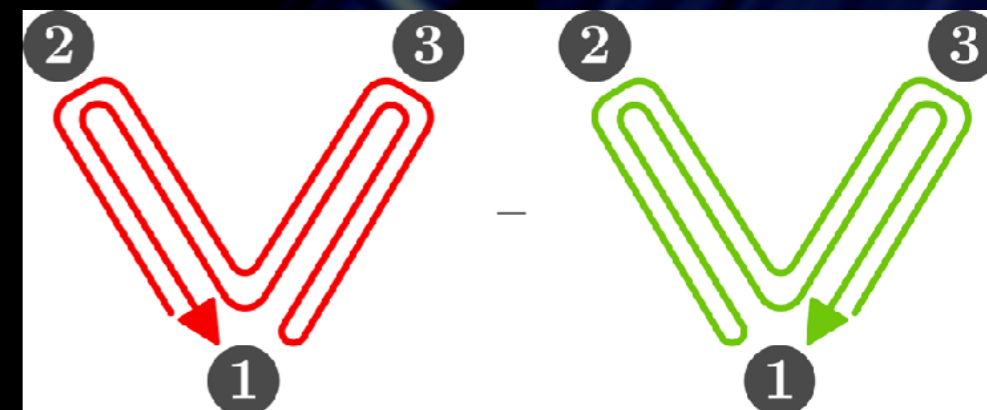
- ▶ Combine measurements to reduce laser noise by 8 order of magnitude
- ▶ Several complex combinations
- ▶ Can be seen as virtual interferometer
- ▶ TDI generation 1.5 takes into account the unequal arms

$$X_1 = \eta_{1'} + \mathcal{D}_{2'}\eta_3 + \mathcal{D}_{2'2}\eta_1 + \mathcal{D}_{2'23}\eta_{2'} - \eta_1 - \mathcal{D}_3\eta_{2'} - \mathcal{D}_{33'}\eta_{1'} - \mathcal{D}_{33'2'}\eta_3$$



- ▶ TDI generation 2 takes into account first order time evolution of arm length

$$\begin{aligned} X_2 = & \eta_{1'} + \mathcal{D}_{2'}\eta_3 + \mathcal{D}_{2'2}\eta_1 - \mathcal{D}_{2'23}\eta_{2'} + \mathcal{D}_{2'233'}\eta_1 \\ & + \mathcal{D}_{2'233'3}\eta_{2'} + \mathcal{D}_{2'233'33'}\eta_{1'} + \mathcal{D}_{2'233'33'2'}\eta_3 \\ & - \eta_1 - \mathcal{D}_3\eta_{2'} - \mathcal{D}_{33'}\eta_{1'} - \mathcal{D}_{33'2'}\eta_3 - \mathcal{D}_{33'2'2}\eta_{1'} \\ & - \mathcal{D}_{33'2'22'}\eta_3 - \mathcal{D}_{33'2'22'2}\eta_1 - \mathcal{D}_{33'2'22'23}\eta_{2'} . \end{aligned}$$



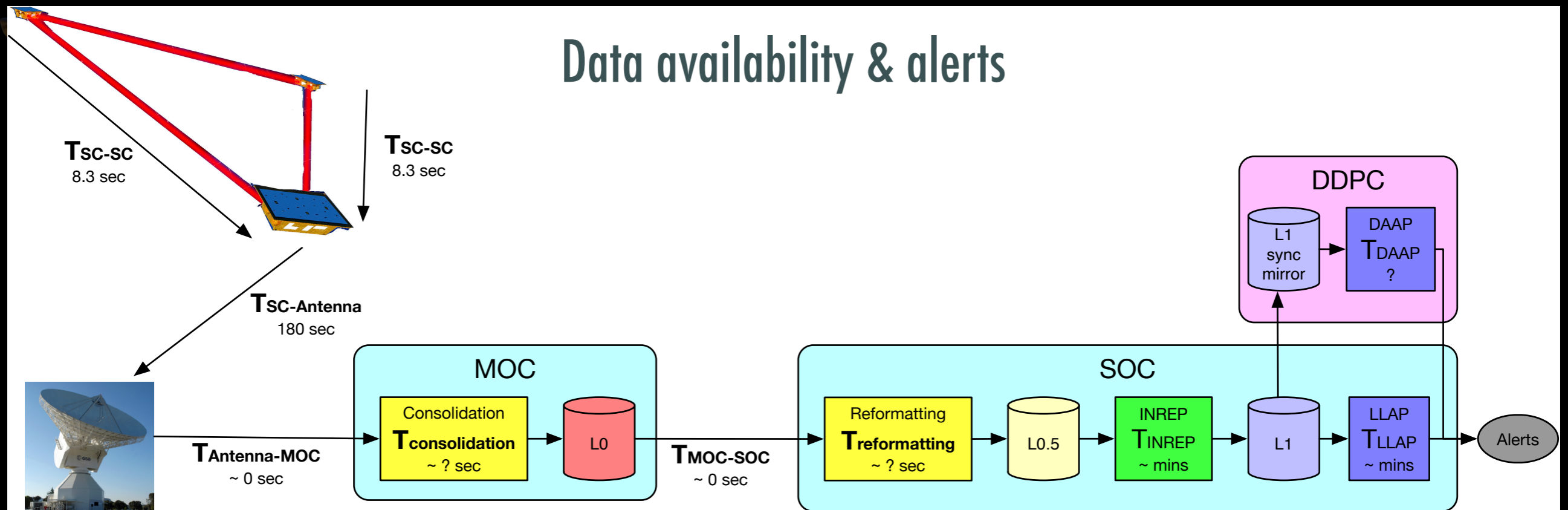
# L1 to L2

- ▶ « Global fits »
- ▶ **Multiple pipelines** with multiple approaches
- ▶ Different steps in each pipeline
- ▶ **Flexibility**
- ▶ Two main aspects
  - **Alerts** (as quick as possible  $\Rightarrow$  less than 1 hour):
    - Low Latency Alerts
    - Deep Alert Analysis
  - **Full analysis** (long term) for extracting the best knowledge of observed GW sources + the best understanding of instrument

# L1 to L2: alerts

- ▶ Two types of near-real time analysis for alerts:
  - **Detect** new events
  - **Improve** of **parameters estimation** for already detected events (ex: sky)
- ▶ Near-real time when communication ground-spacecraft: current plan 8h/24h
- ▶ Two steps:
  - 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

# L1 to L2: alerts

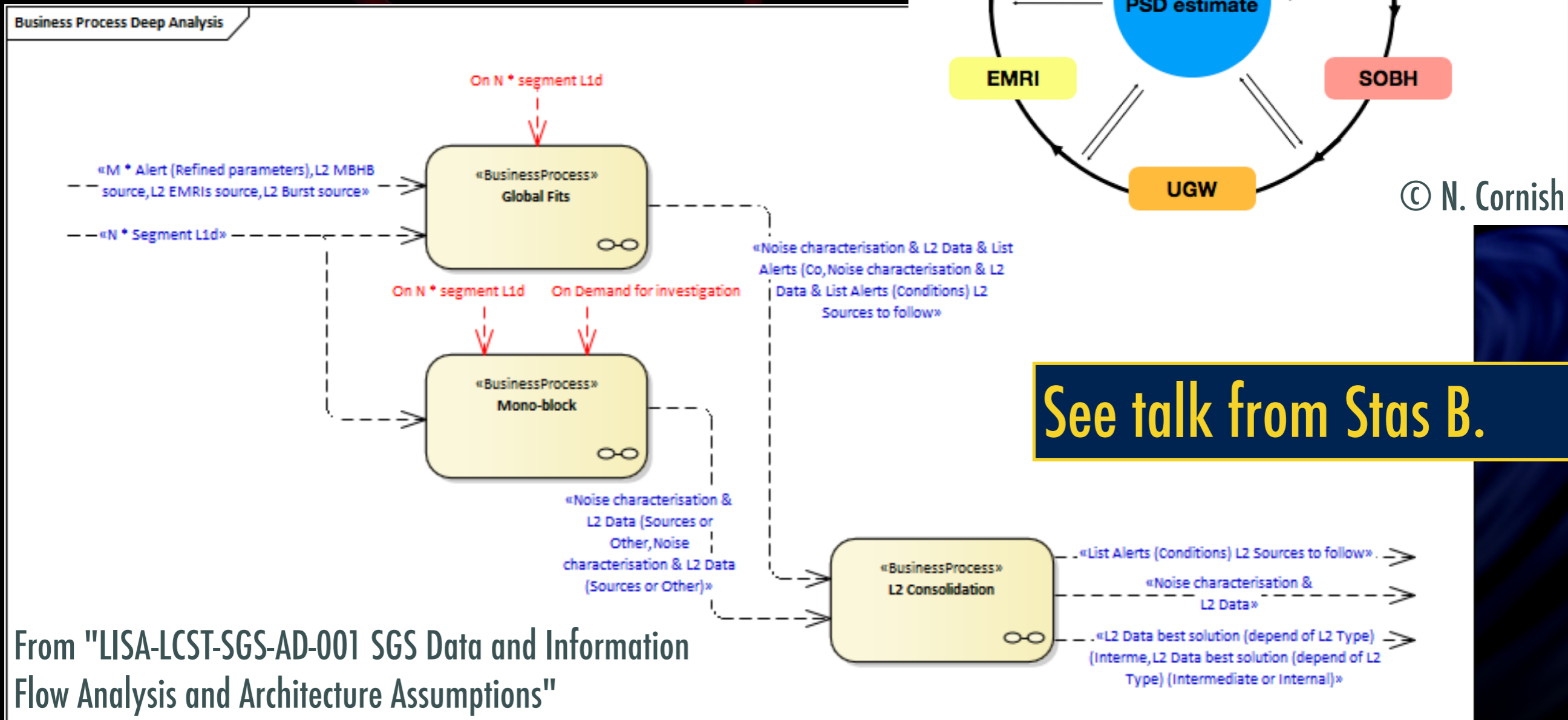
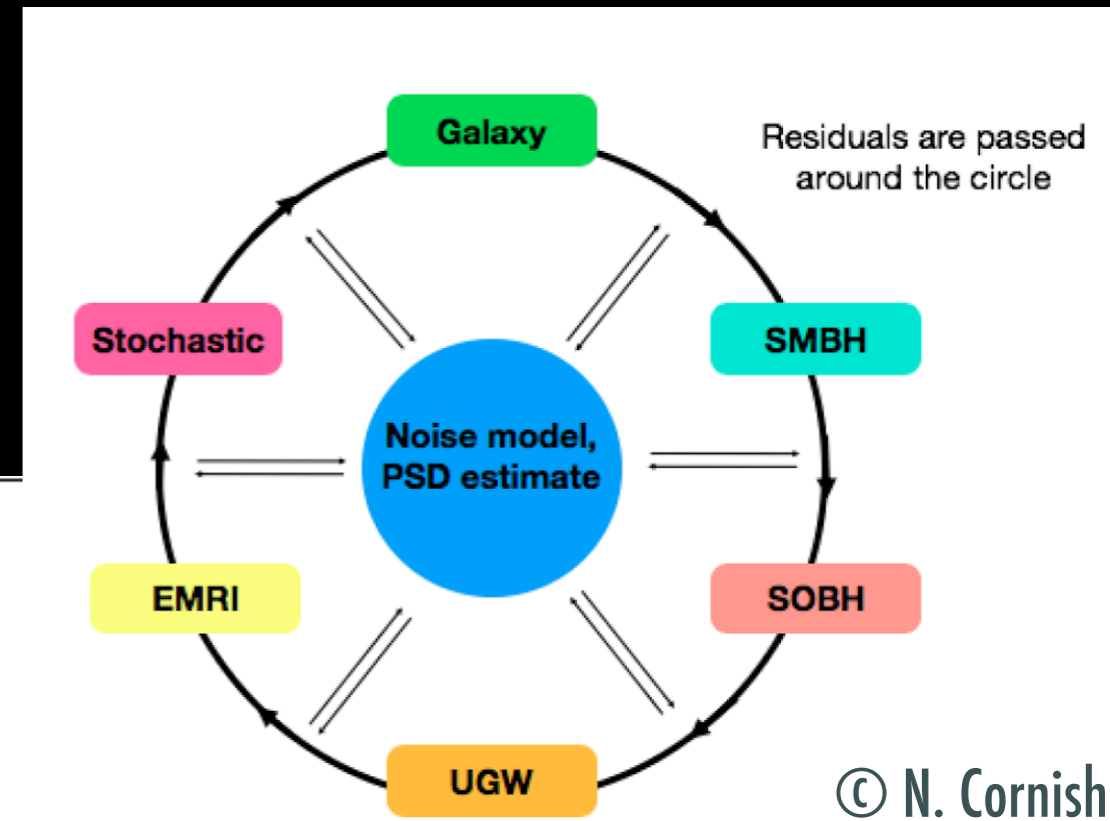


## ► Two steps:

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# L1 to L2: Deep Analysis

- ▶ Extract GW sources
- ▶ Global fits
- ▶ Sources investigations, ...



From "LISA-LCST-SGS-AD-001 SGS Data and Information Flow Analysis and Architecture Assumptions"



# L1 to L2: Deep Analysis

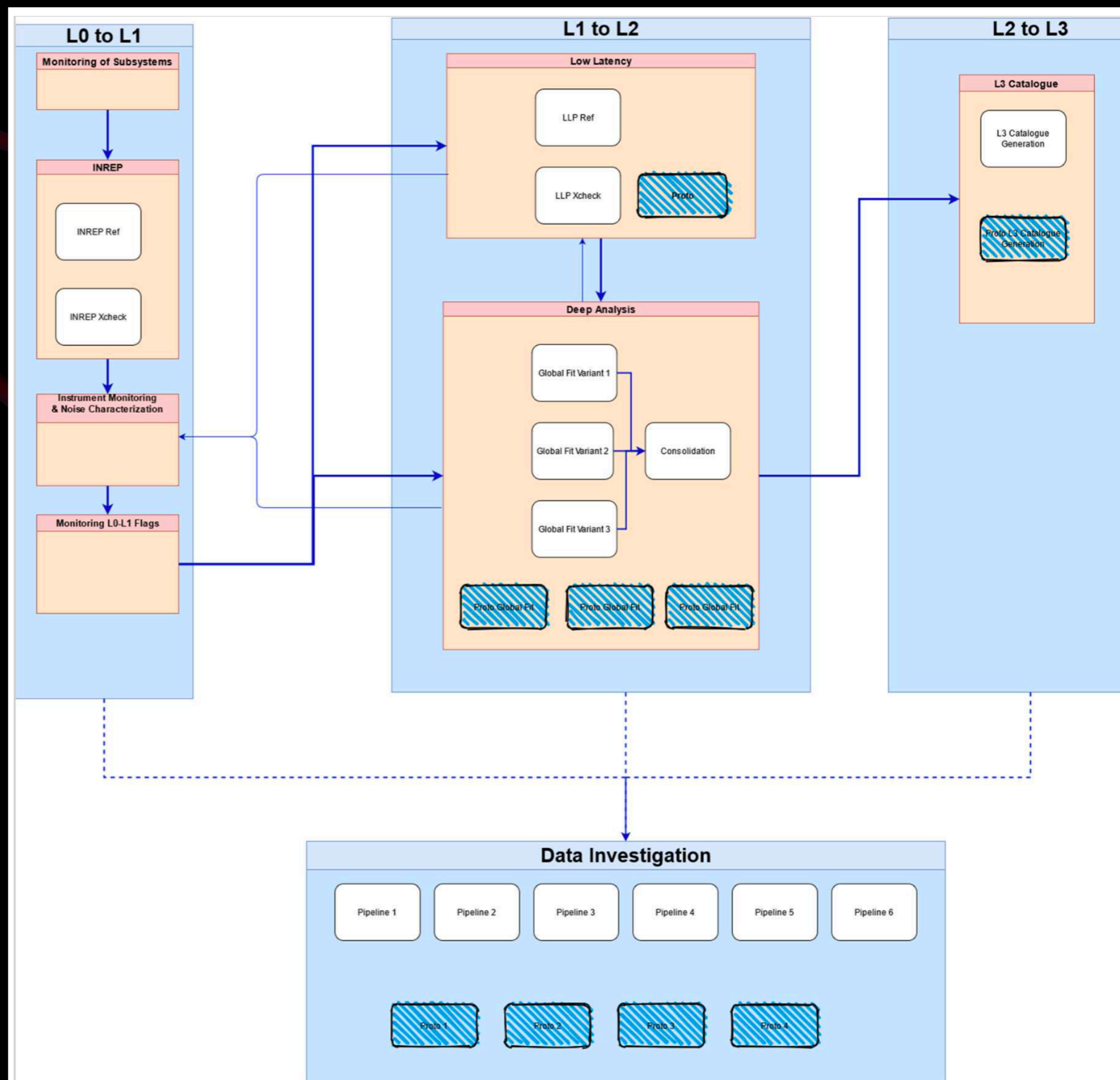
- ▶ Complex problem: Multiple approaches and Flexibility
- ▶ Large computing resources required:
  - Estimation per year extrapolated from the first LISA Data Challenge (2021 CPU -hours) BUT possible factor 10 to 100:

Per year of data	CPU-hours	Scratch volume	Informative volume
#1 With SBBH	30M	500TB	160GB
#1 without SBBH	17M	225TB	160GB
#2 with SBBH	(14.5-52.5)M	500TB	160GB
#2 without	(7.5-15)M	225TB	160GB
Low-latency	550K	52TB	6GB

- Considering multiple runs + multiple global fit => cpu costs estimated at 600 to 1000 millions cpu.h per year  
=> **Distributed Data Processing Center** sharing computation load (production and development) on multiple computing centres in Europe and USA.

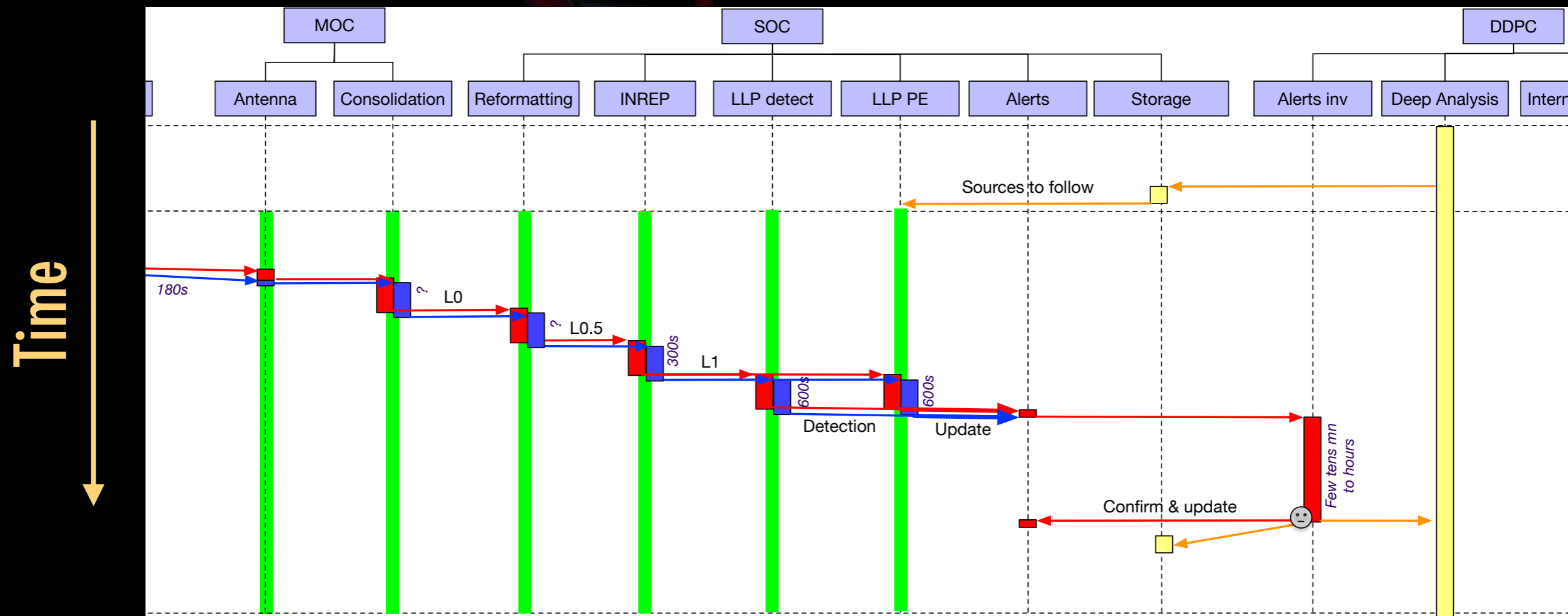
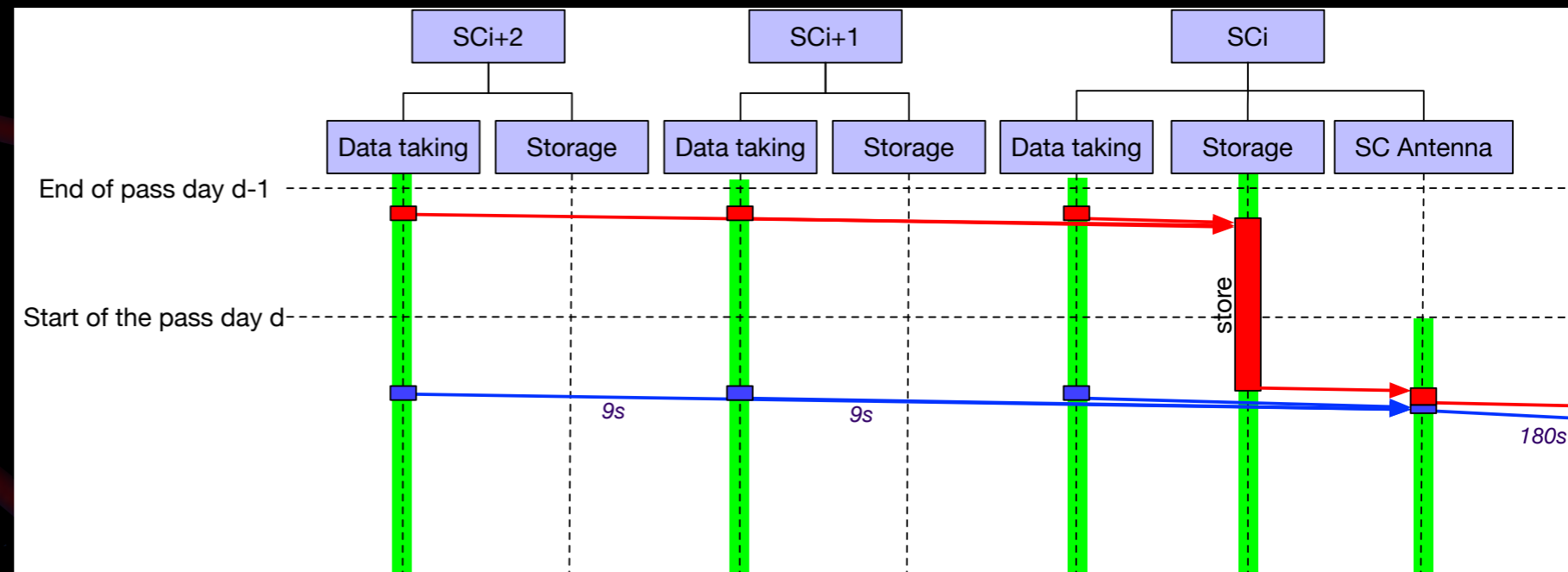
# Multiple analysis

- ▶ Multiple independent analysis/pipelines is already part of the SGS plan:
  - Mechanism of multiple analysis part of the construction of the SGS organisation
  - We will probably start with many global fits in the prototyping phase and reduced (combining & selecting) to 2-4 for the operations



# LISA DA in operations: alerts

- ▶ Sequence diagram for alerts: Space Segment + Ground Segment

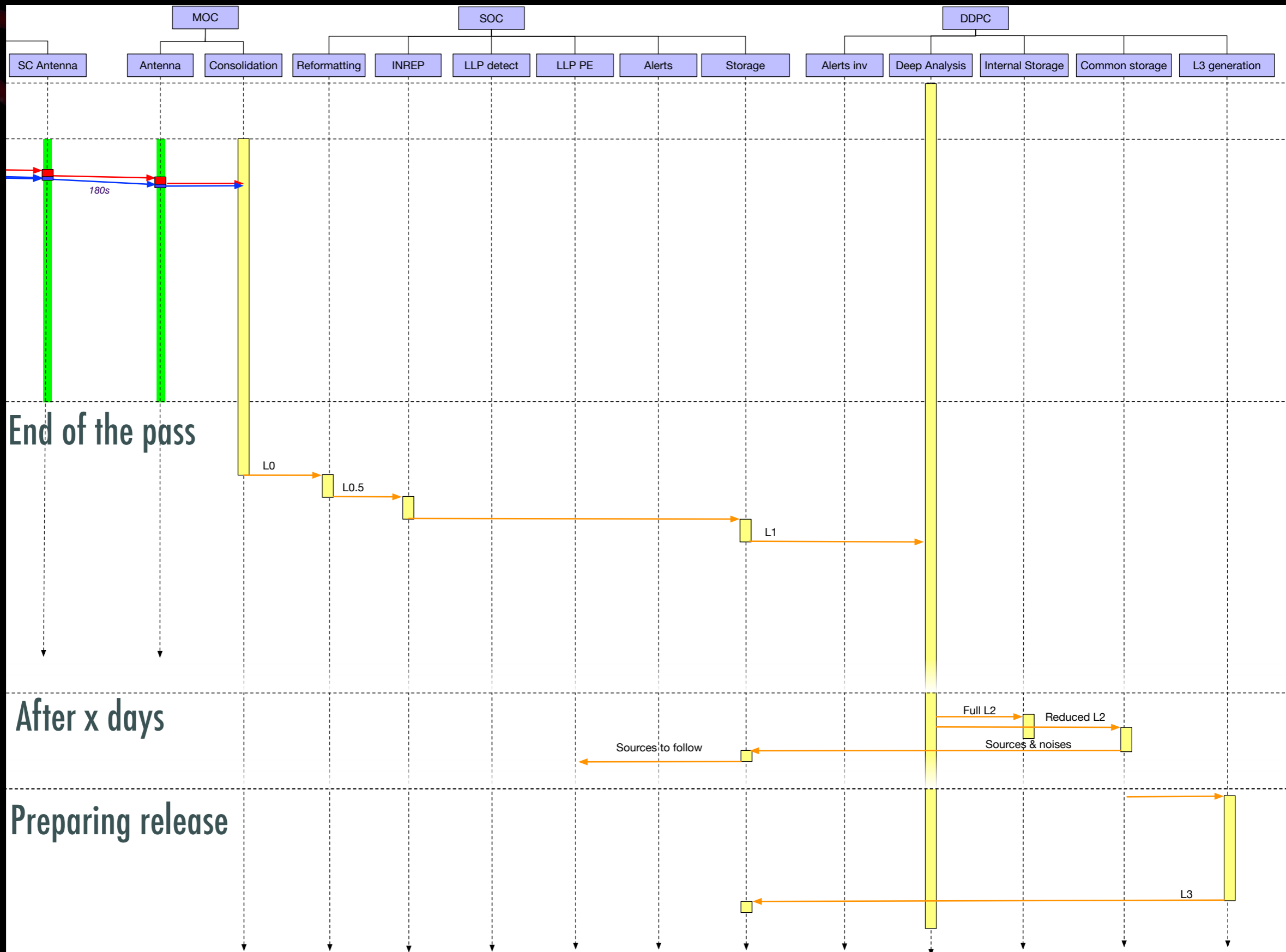


# LISA DA in operations: deep analysis



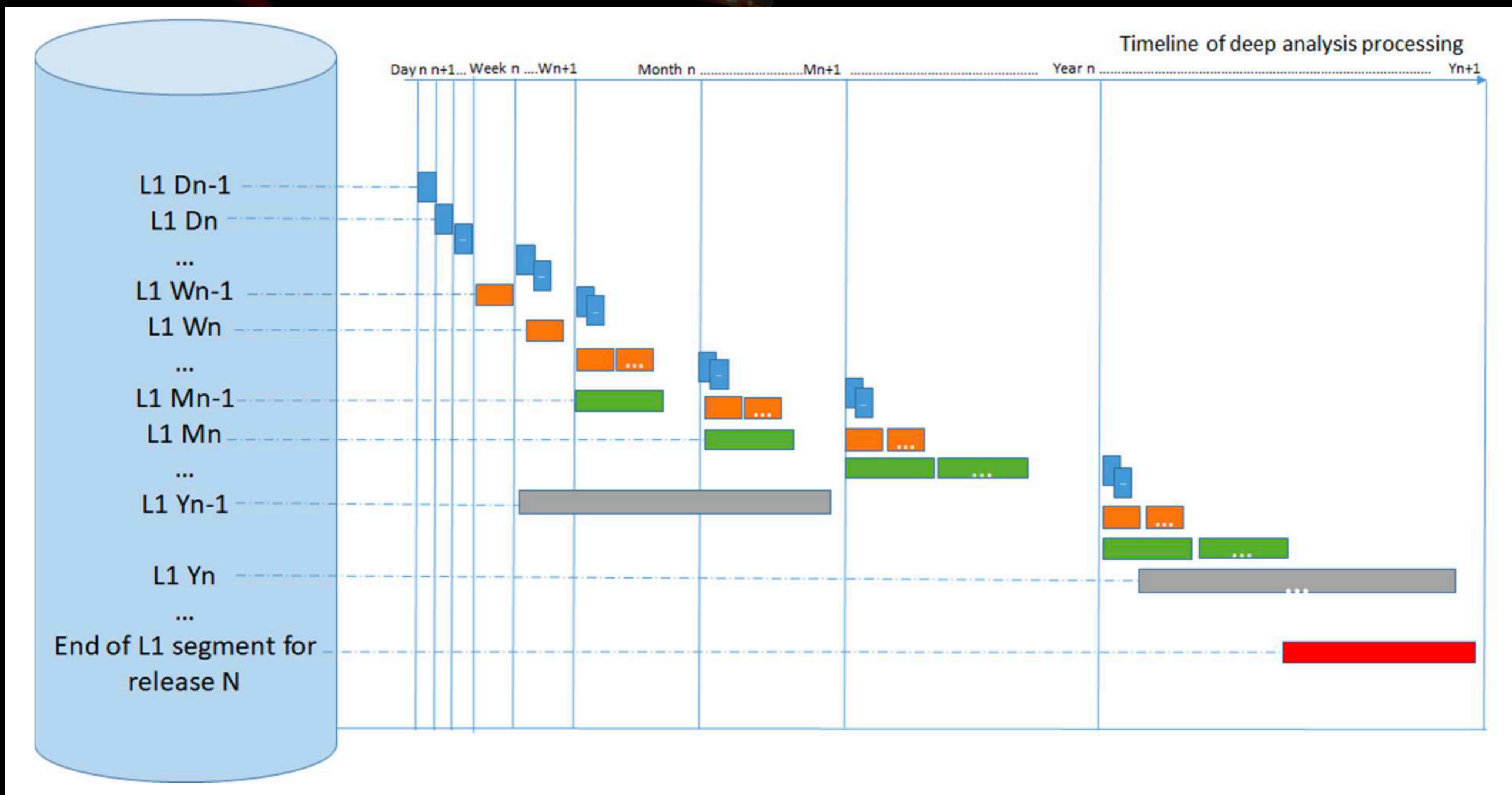
Time

Pass: SC → ground



# LISA DA in operations: deep analysis

- ▶ Global fits: multiple runs on multiple timescale with ingestion of data segment of different length



# Simulation

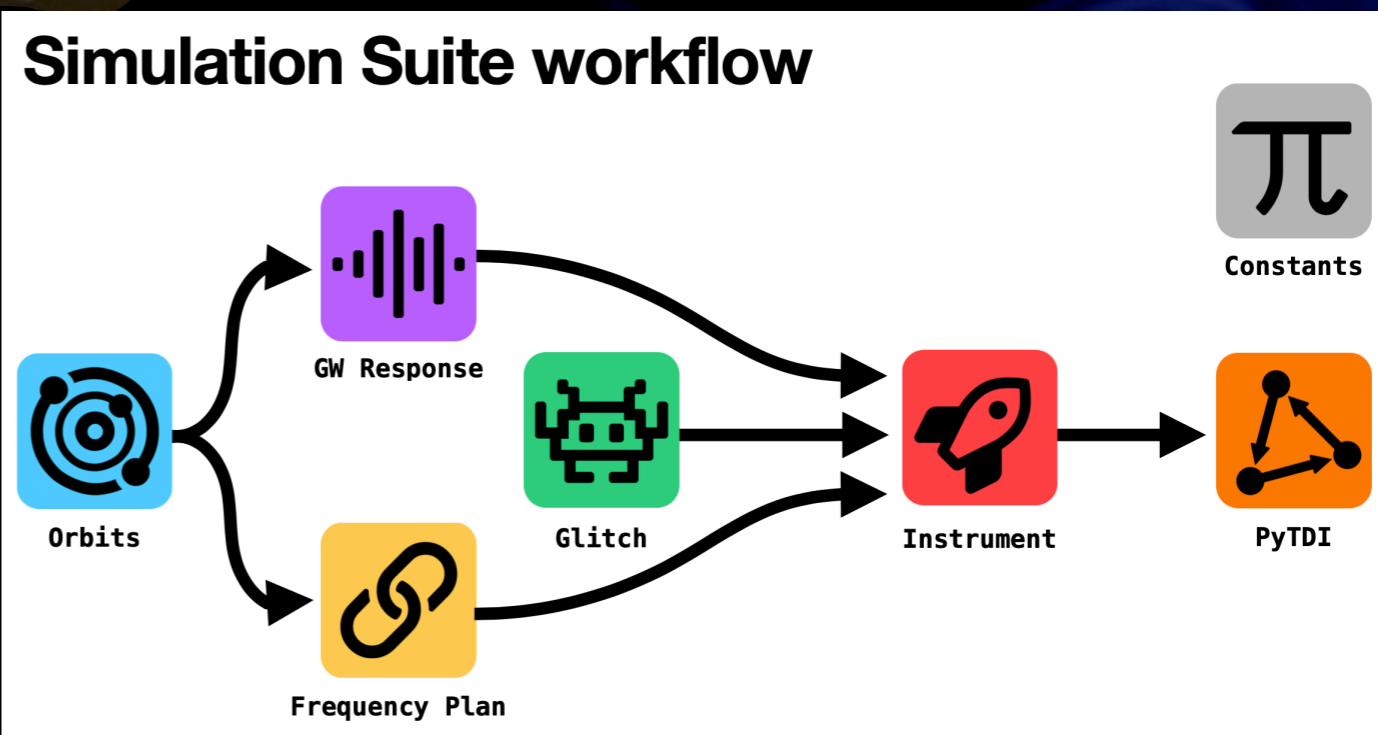
► Given the **complexity of the data** and the sensitivity of LISA to any perturbations, **simulations** are at the core of the development for **data analysis** and **instrument**:

- Validation performance model and instrument design
- Generation of realistic data
- Validation of pipelines

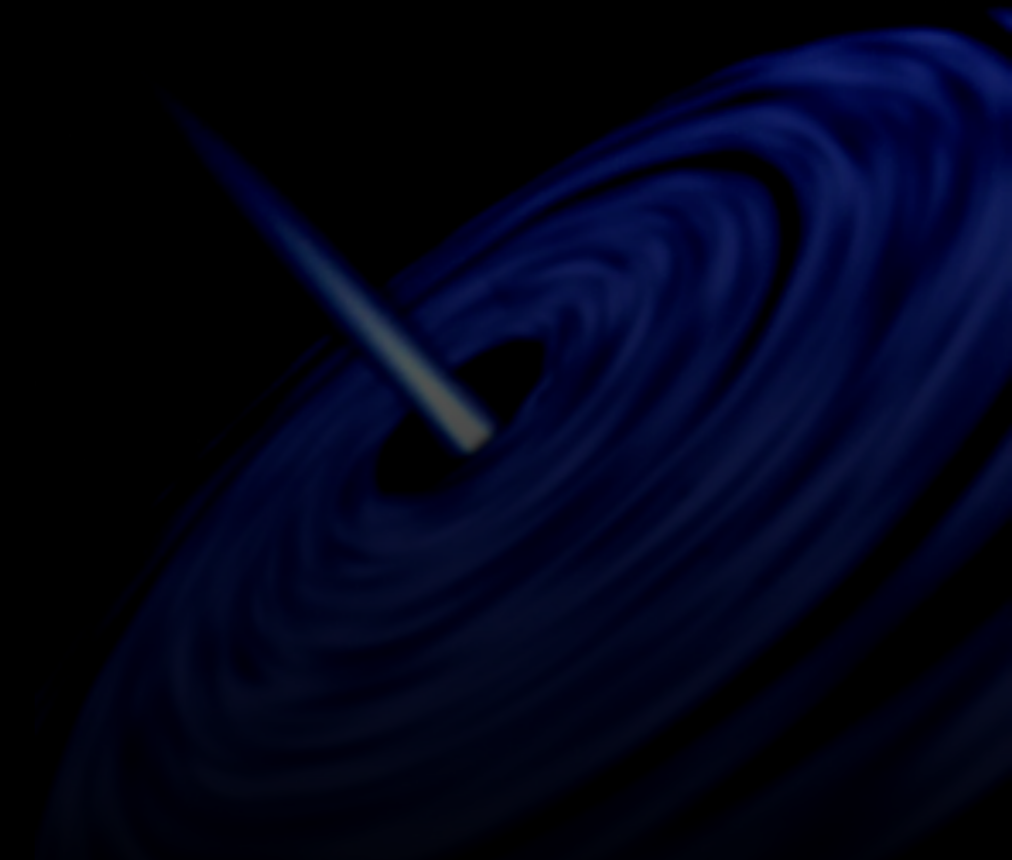
► Global simulation (GW+instrument): LISA Data Challenge infrastructure (**Maude L. et al.**)

► Simulation of the instrument:

- LISANode (official)
- LISA SimScape
- LISASim



# LISA Data Challenge





# LISA Data Challenge

- ▶ Two big purposes:
  - Provide a productive playground for research
  - Validate the LISA science ground segment
- ▶ LISA Data Challenge process:
- ▶ On going challenges:



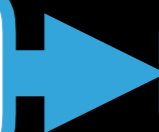
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Design specific challenges



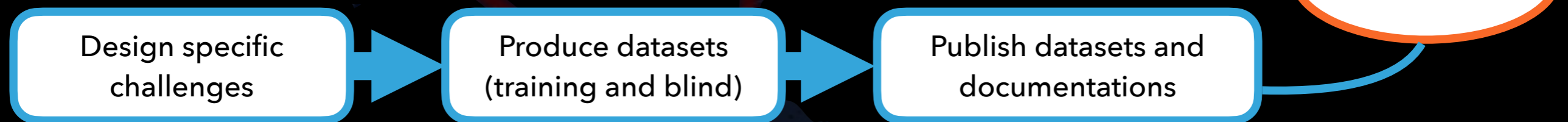
Produce datasets  
(training and blind)

- ▶ On going challenges:

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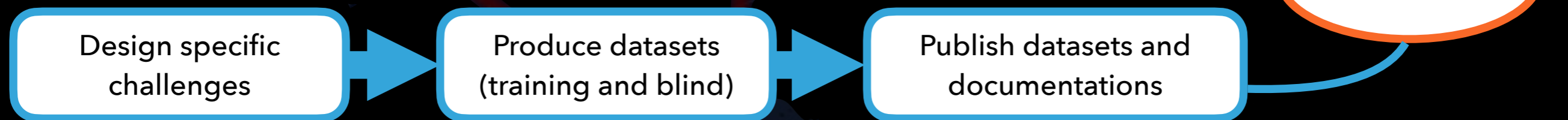


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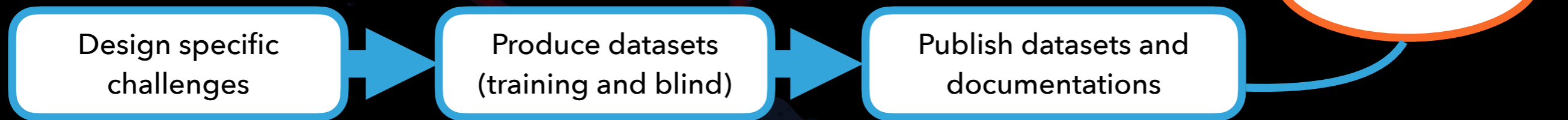
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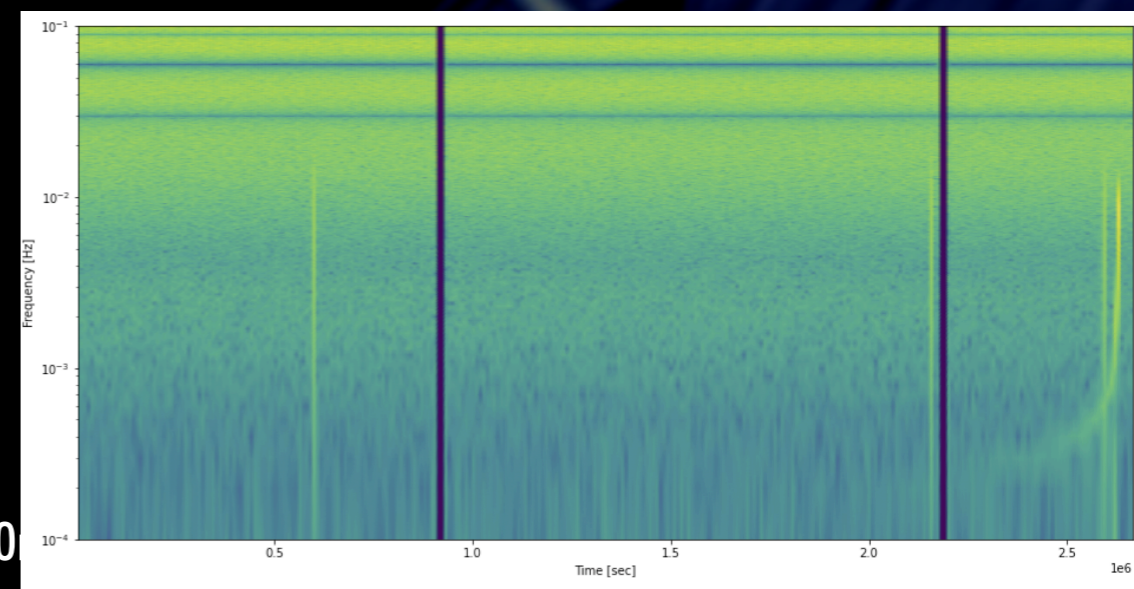
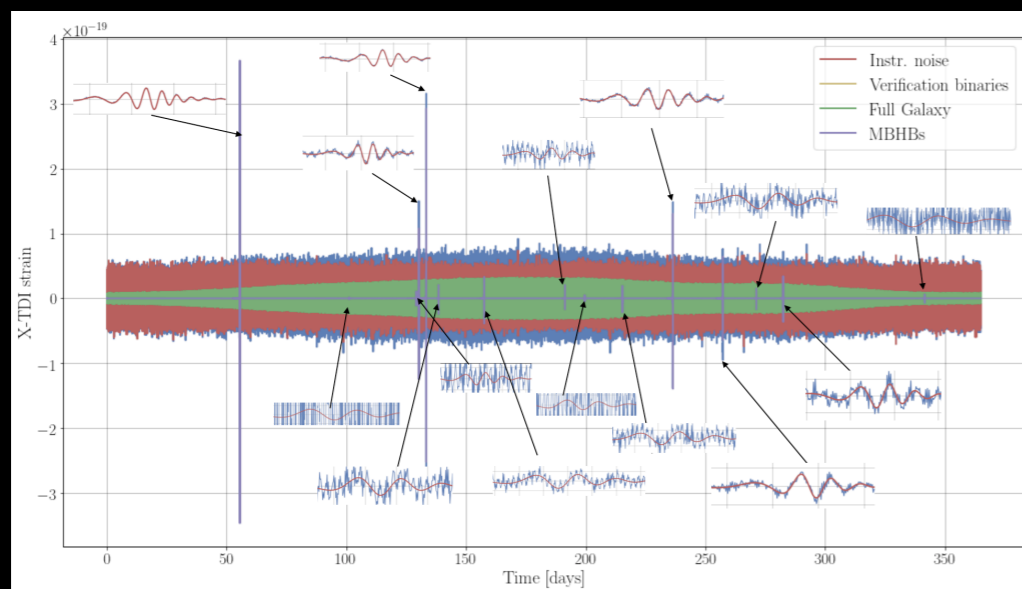
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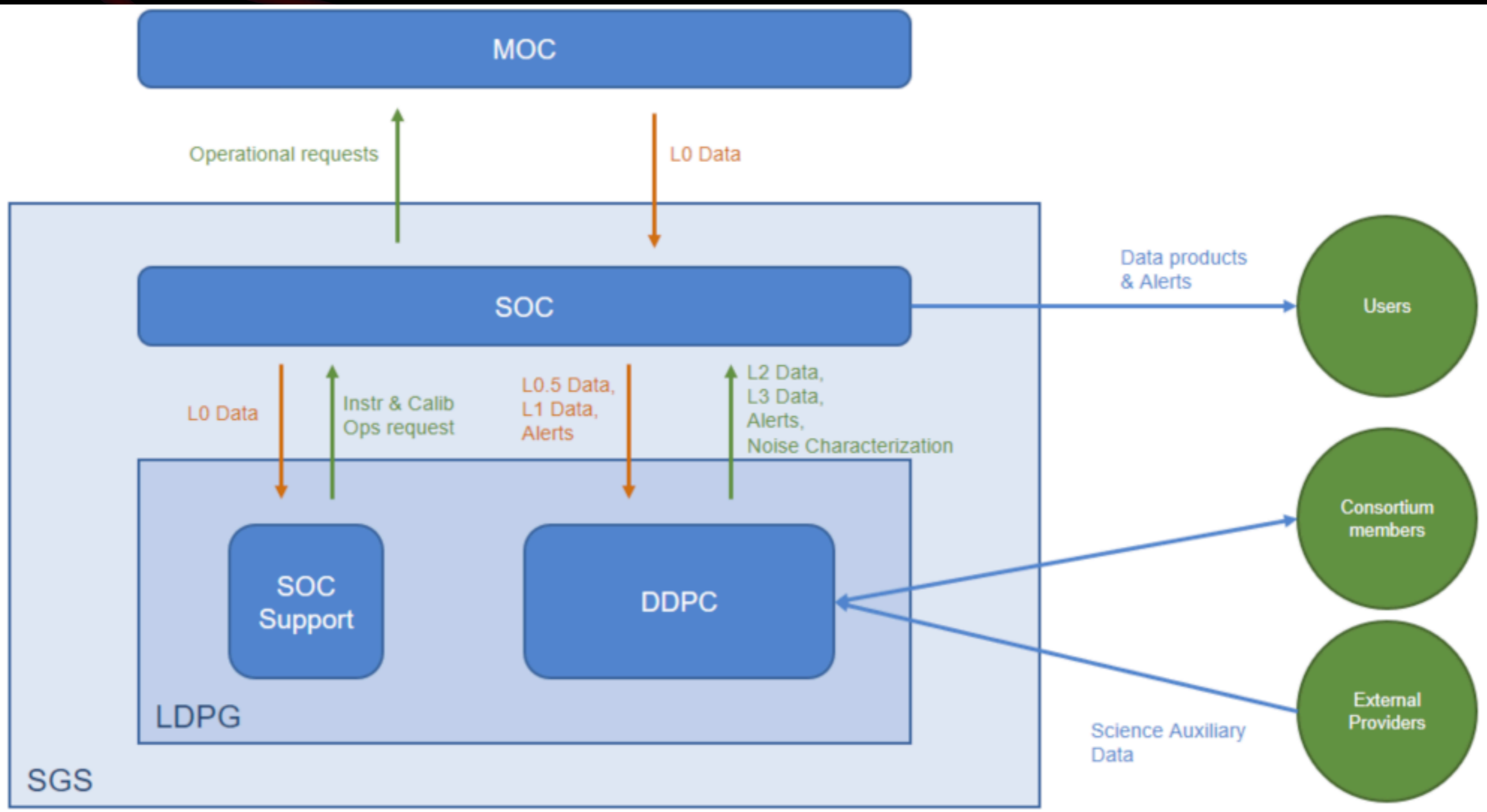
► On going challenges:

SMBHBs + Galactic binaries

One SMBHB + gaps + glitches



# Organisation of the SGS



# Consortium: Ground Segment

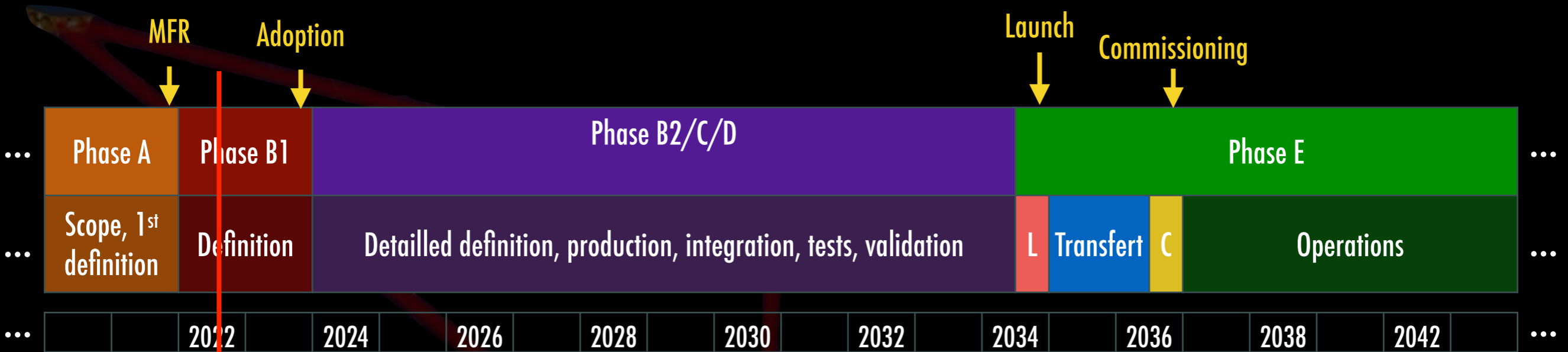
- ▶ Support ESA with the **development of the mission ground segment**, specifically:
  - by providing a **Distributed Data Processing Centre (DDPC)**
  - by providing a data processing software including **INReP routines**
  - by supporting the design of **science operations**
- ▶ **DDPC: Work Breakdown Structure:**
  - Science softwares:
    - L0 -> L1: INReP
    - L1 -> L2 Alerts (Low latency + Deep Alerts Analysis)
    - L1 -> L2 Deep Analysis + Mono-blocks
    - L2 -> L3
    - Simulation
    - Common software & Tools
  - System softwares
  - Infrastructure

# Global overview





# LISA SGS dev. & op.



- ▶ Prototyping, development and implementation will continue all over the operations but the load may be reduced after few years (?) in operations.

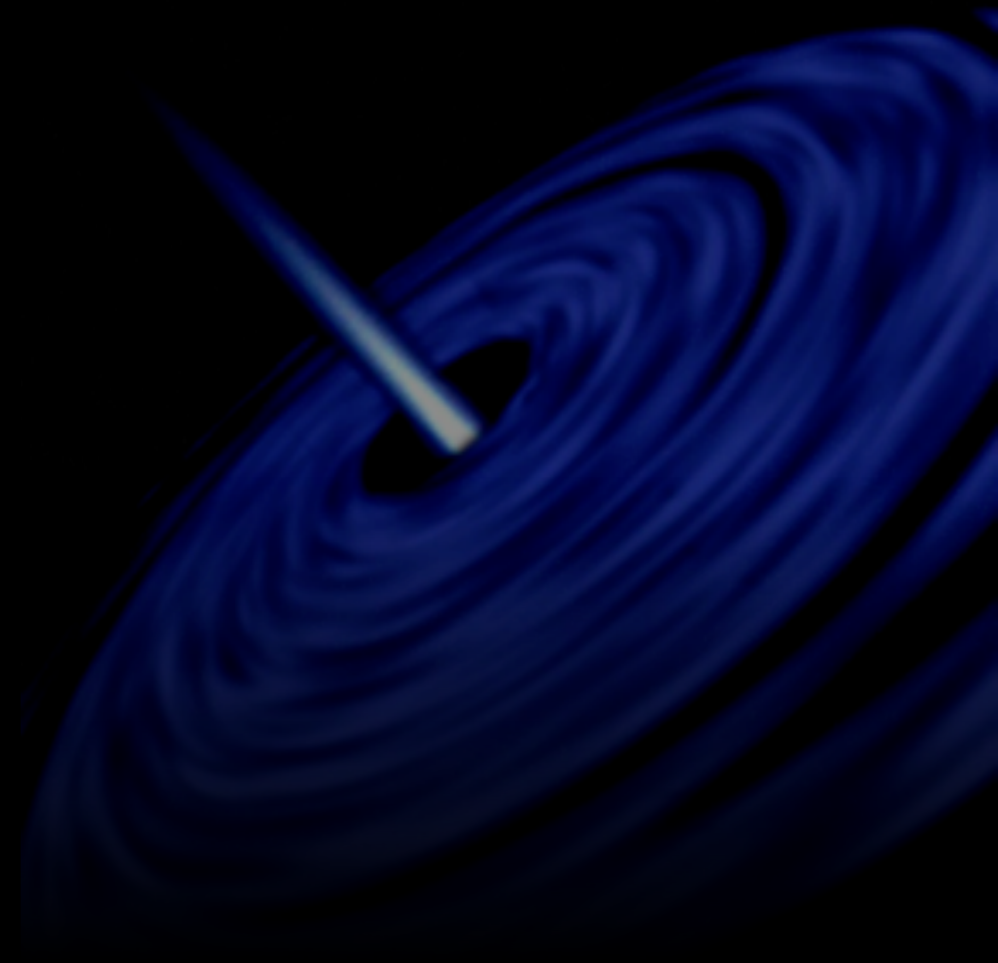
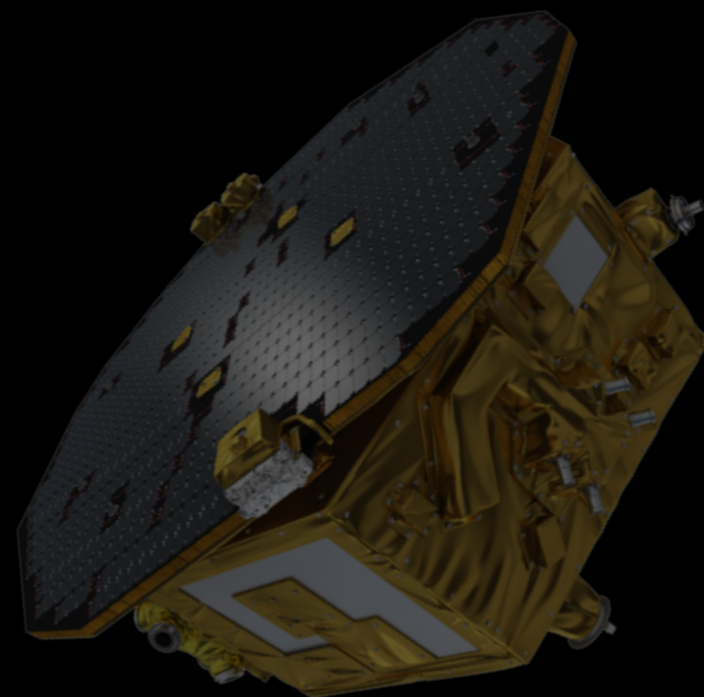


# Conclusion

- ▶ LISA is the next large science mission at ESA:
  - In **phase B1**: preparation for review and **adoption in Nov. 2023**
  - Launch in **2035**
  - 1.5 years of transfer, **4.5y on nominal science** operations, extension 10y
- ▶ **LISA Data Analysis**: challenge which requires some flexibility:
  - Multiple pipelines: cross-check and validation
  - Official data releases for the mission (L0/L1/L2/L3) from a coherent combination of all global fit results
  - **Alerts and Global fits**
  - Collaborative development and operations (LDC, etc)
  - Large computing resources needed: **Distributed Data Processing (DDPC)**
  - We are in the **prototyping phase**: exploration of all data analysis ideas and **options**



Thank you



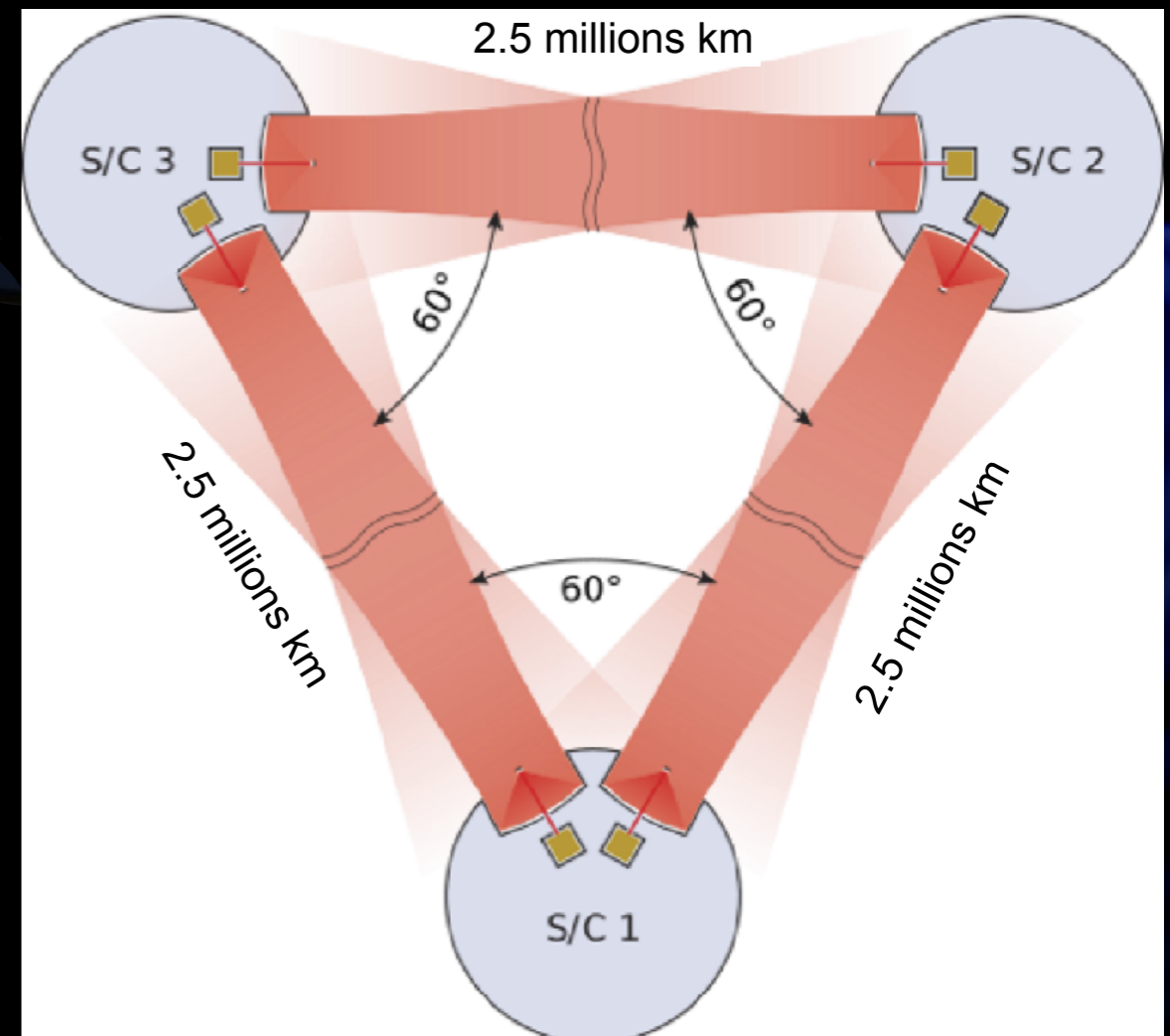
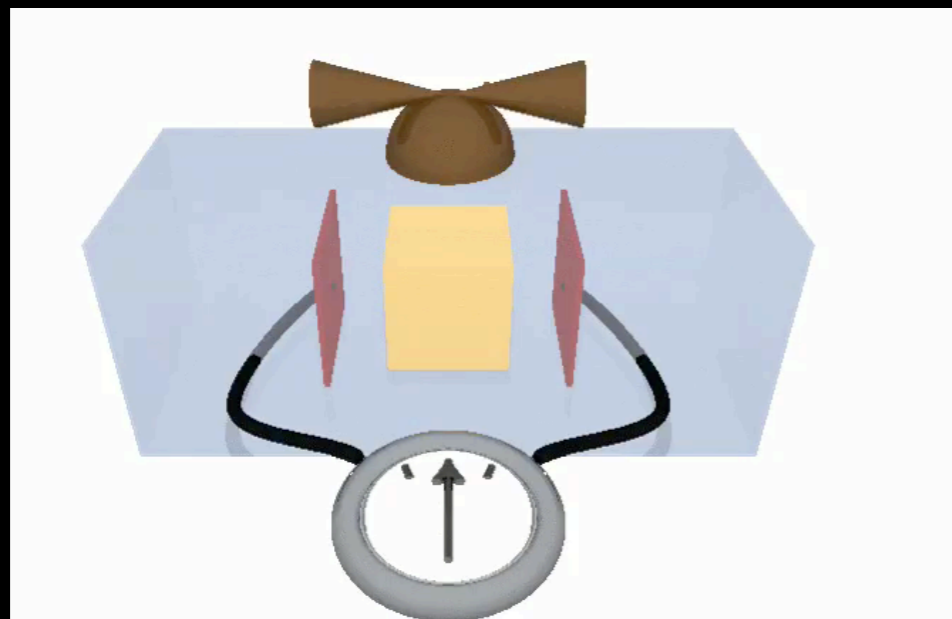
# LISA mission

► 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



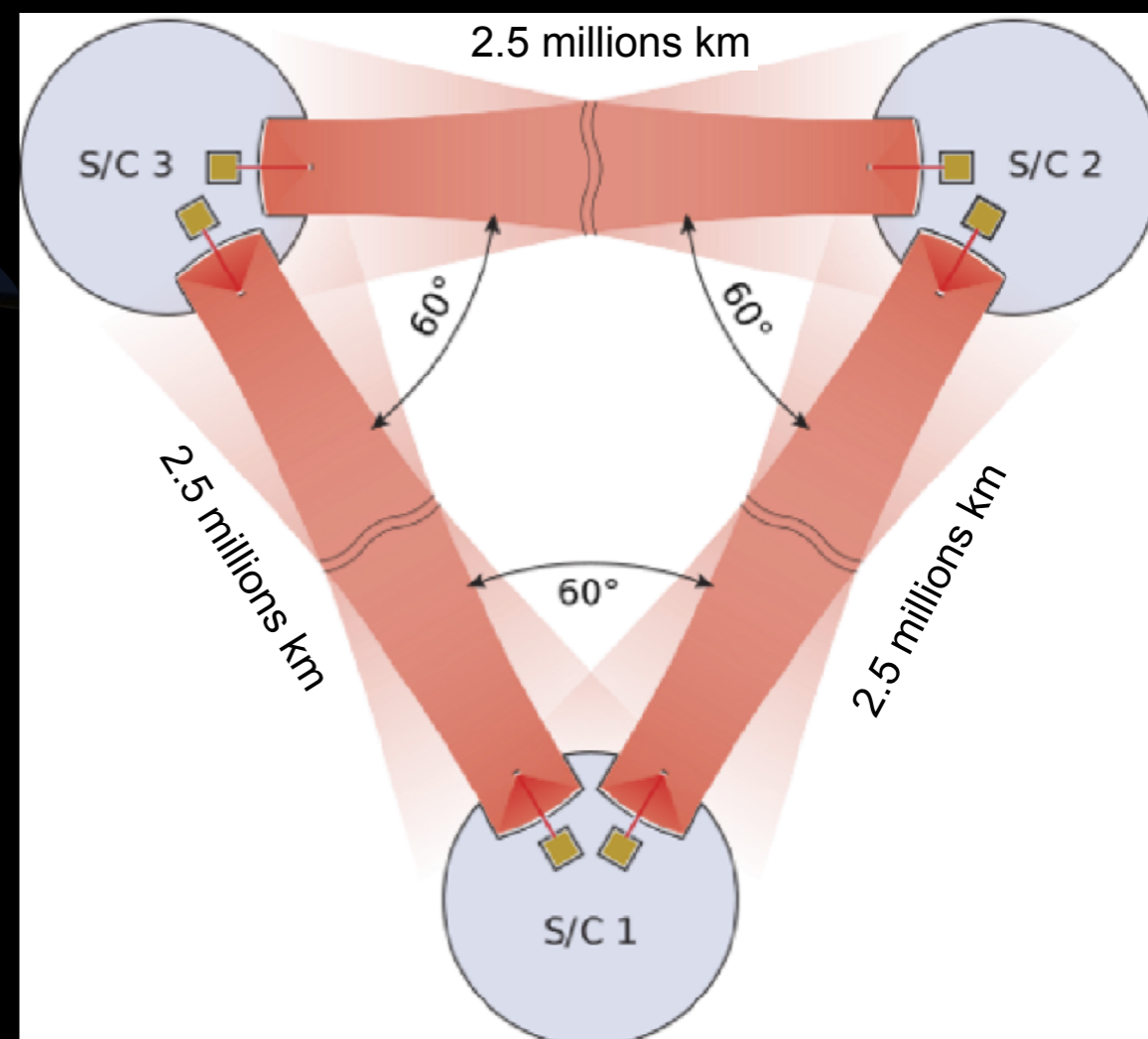
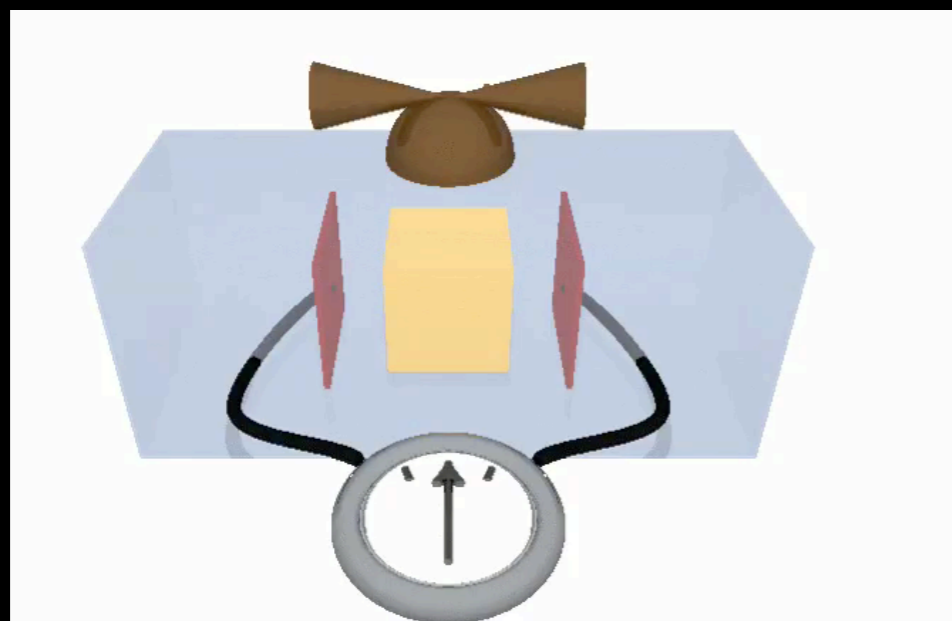
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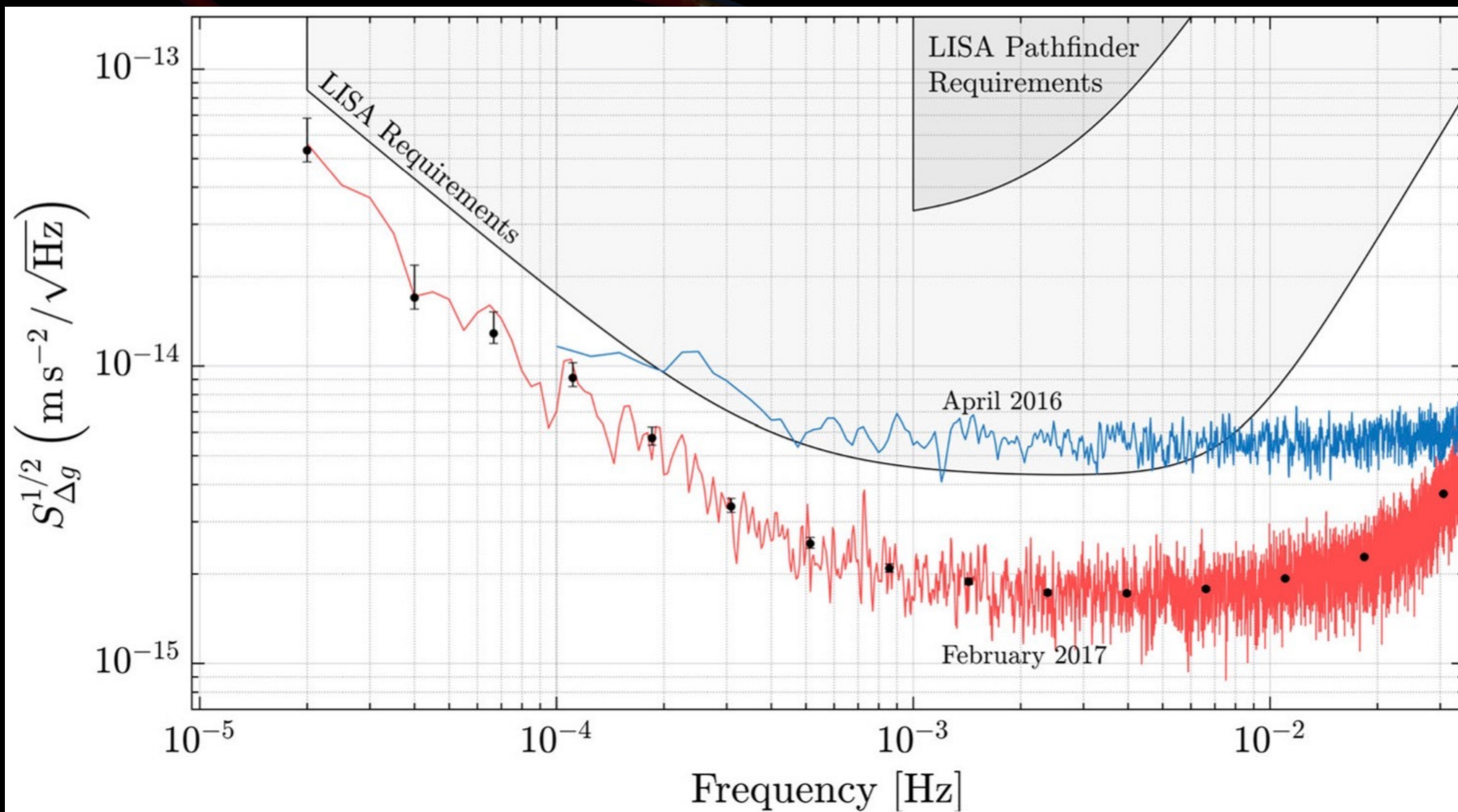
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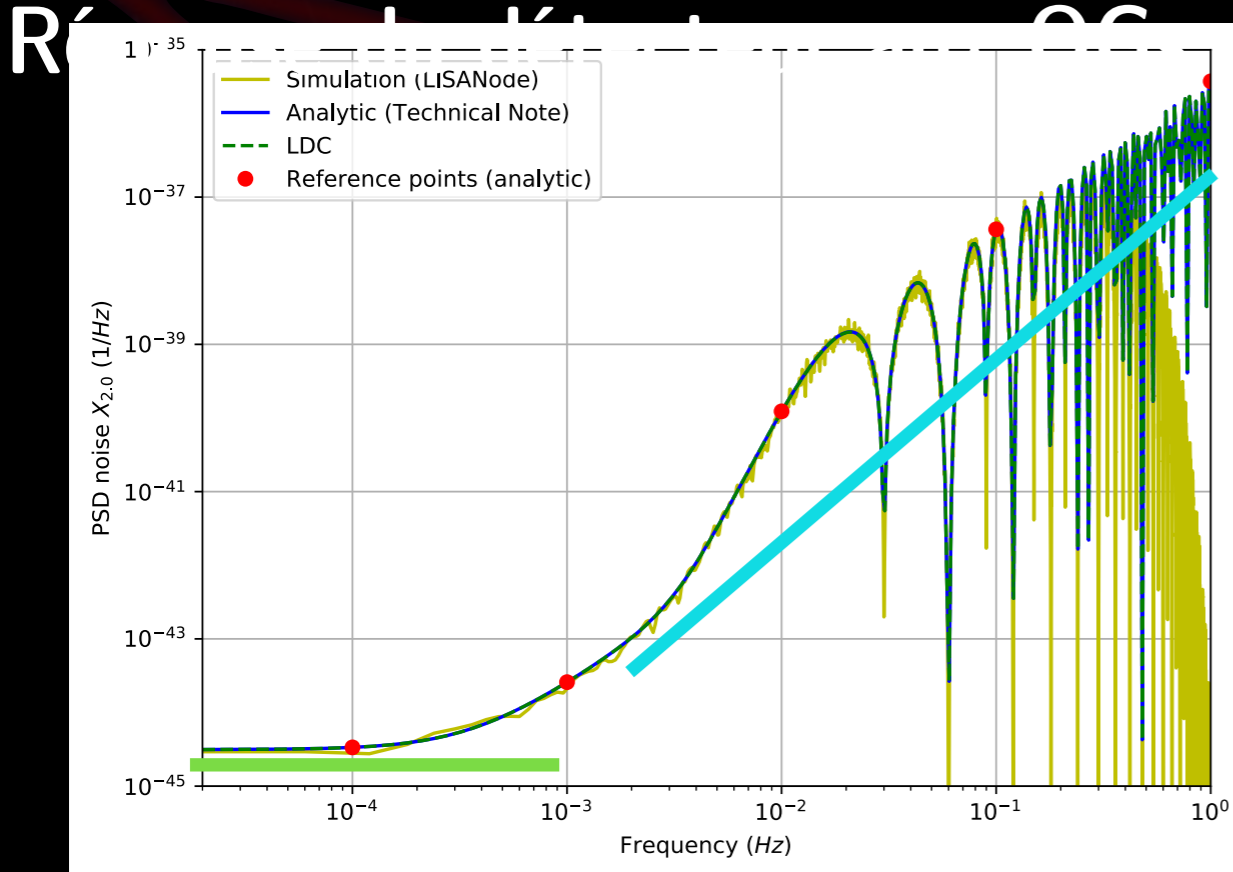
# LISAPathfinder final main results

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

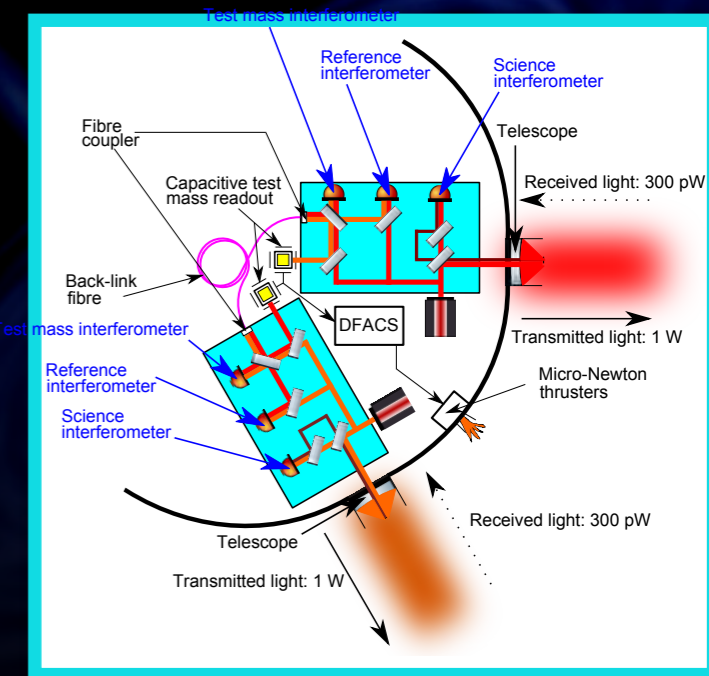
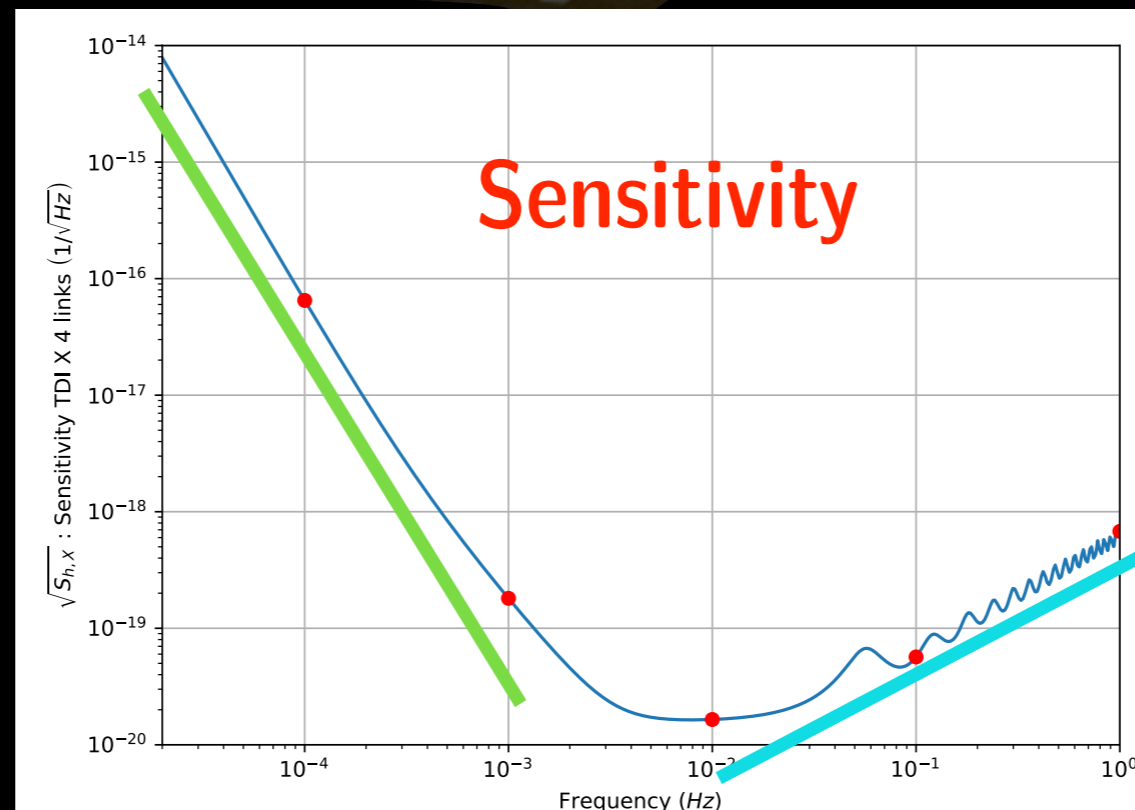
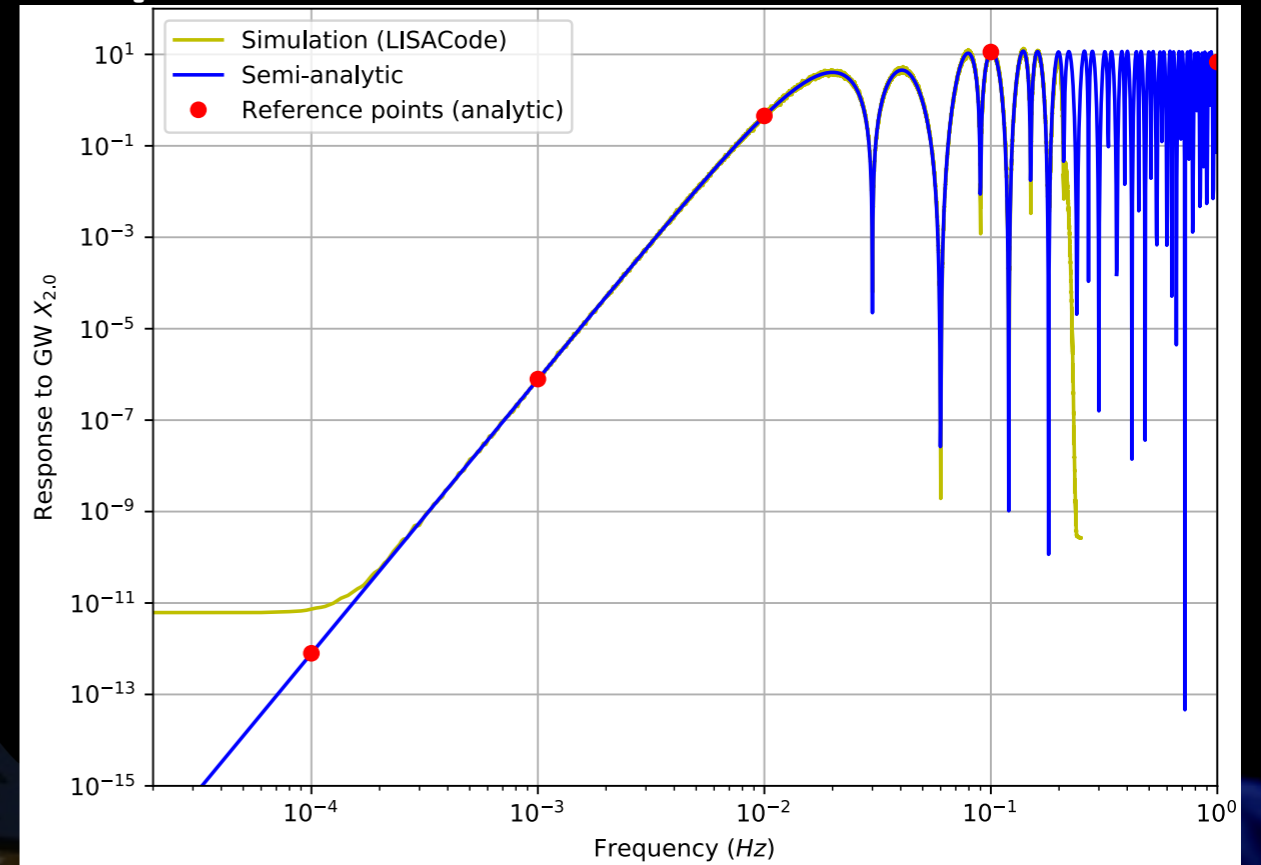


# Sensitivity

## Noises

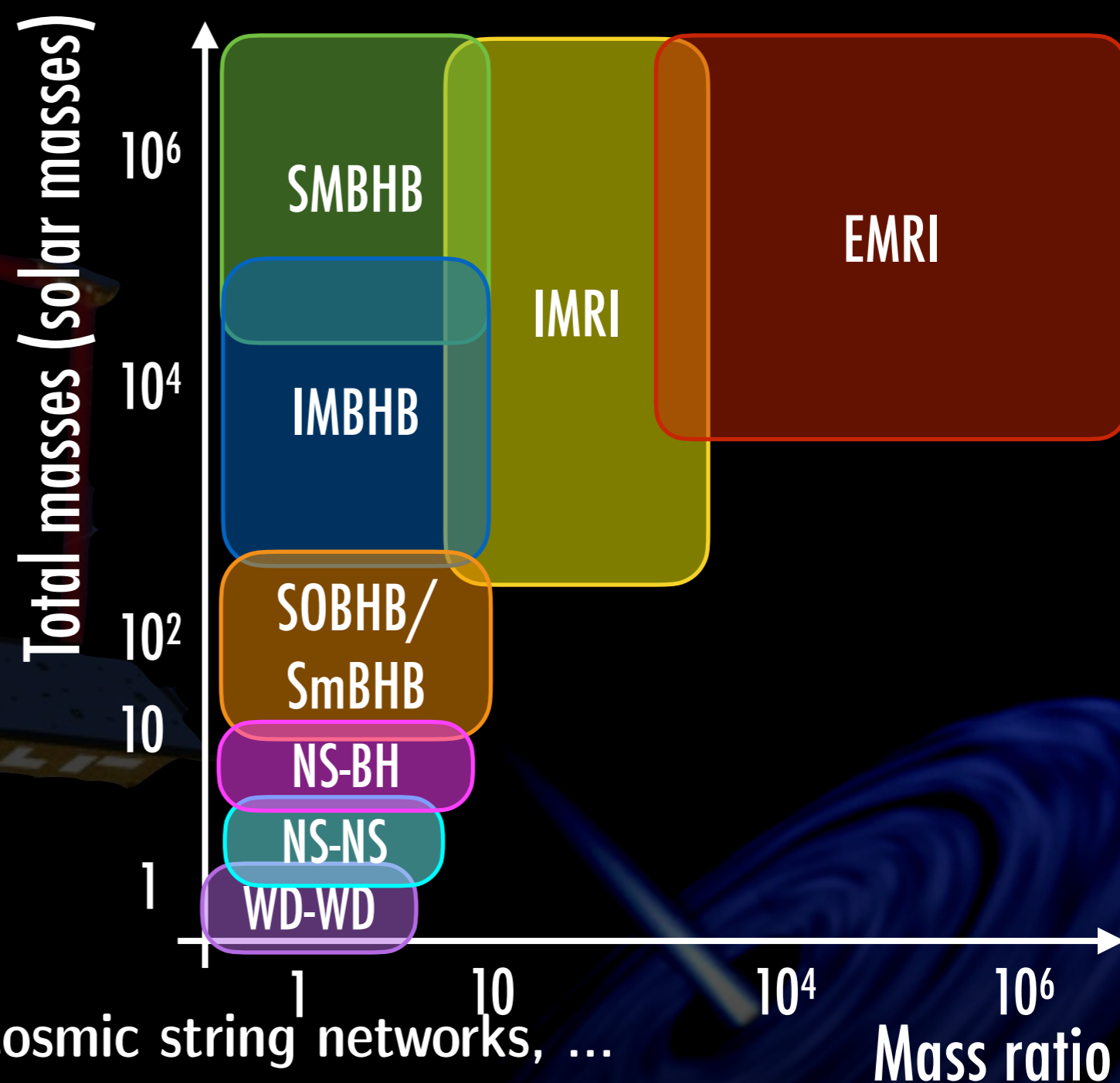


## Response of the detector to GWs



# GW sources in the mHz band

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



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