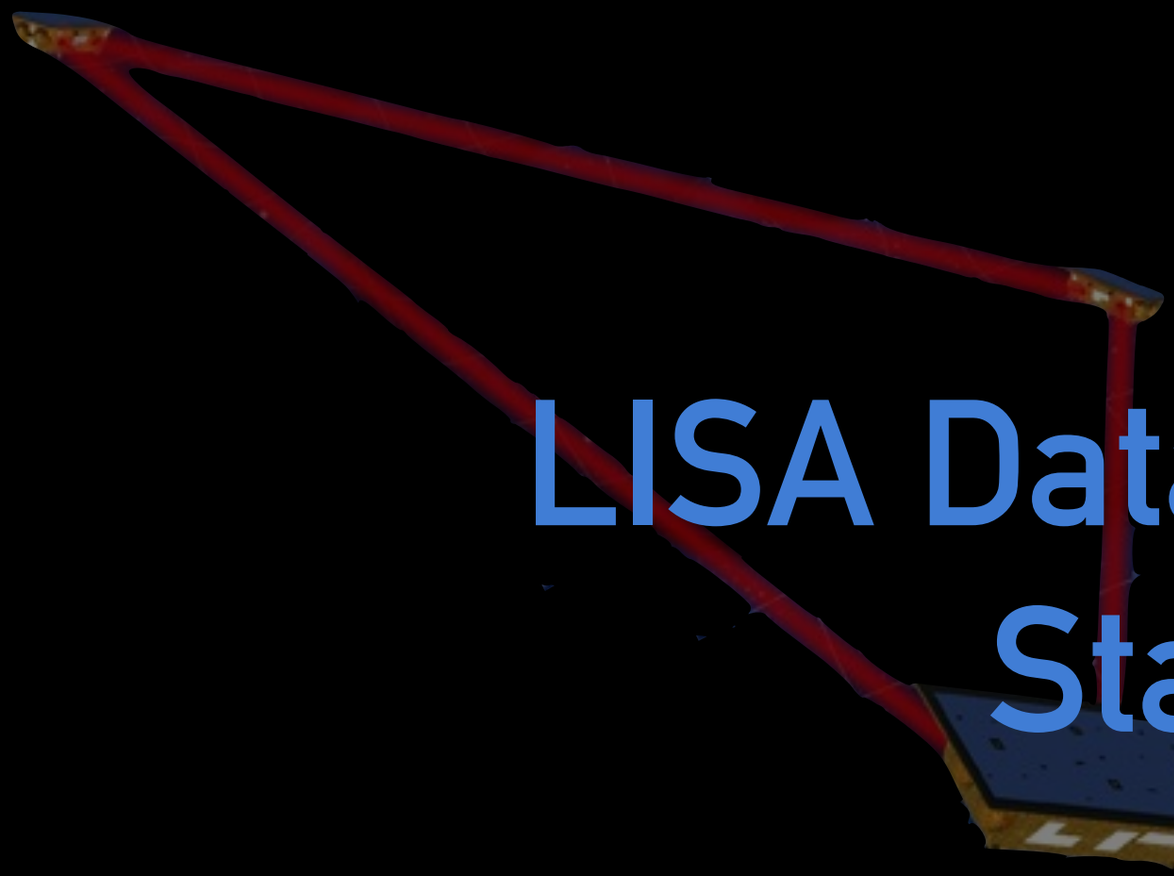


LISA Data Analysis Status

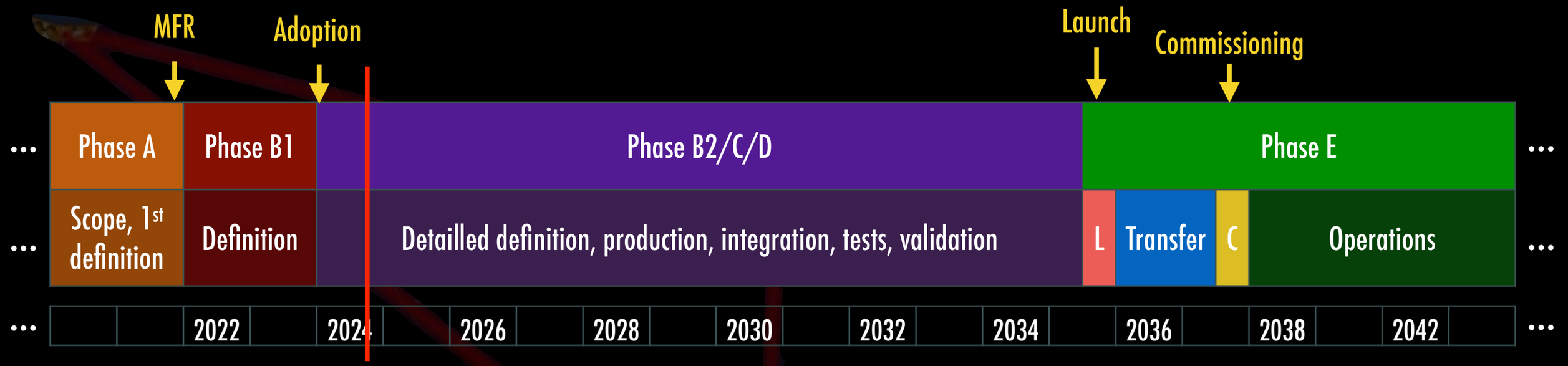
Antoine Petiteau (CEA/IRFU/DPhP)

For the LISA DDPC

Journée Analyse de données du GdR OG

Marseille - 16/10/2024

Timeline and status



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- (New) LISA Science Team in place
- Long building phase of DDPC + multiple MOSAs (6 flight models + test models) + spacecrafts
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- 1.5 years of transfer, 4.5 years nominal mission, 6.5 years extension

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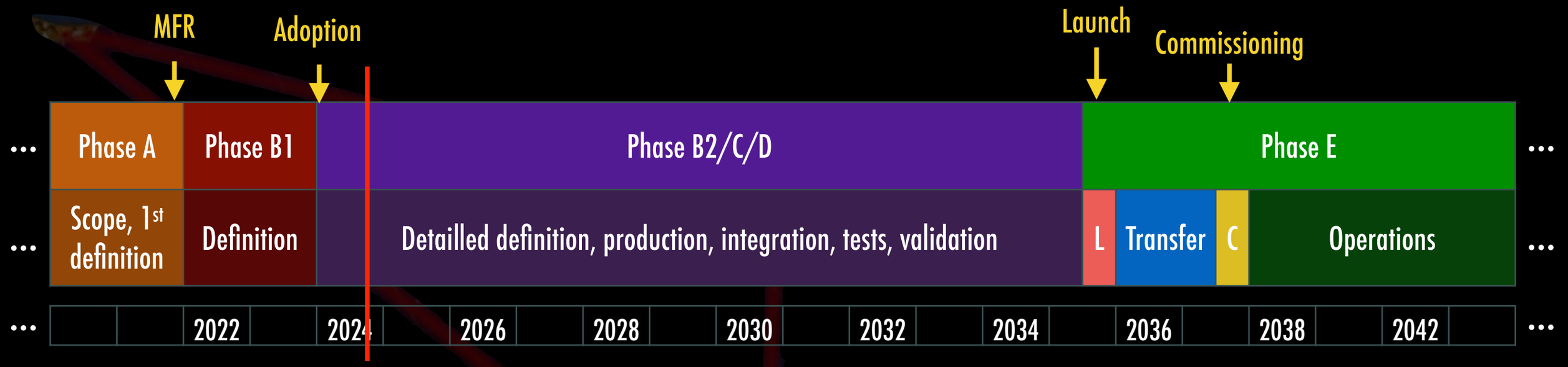

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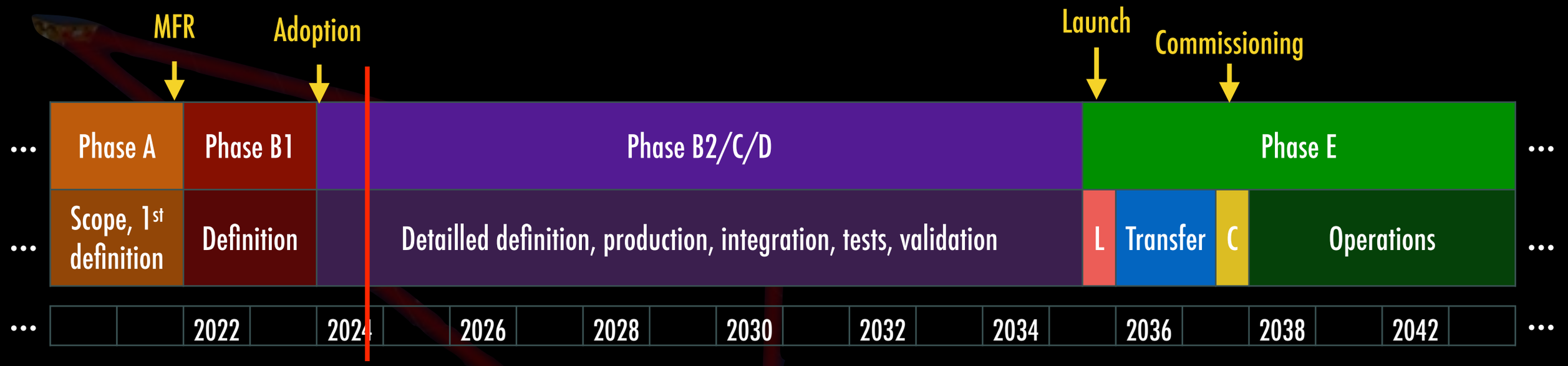

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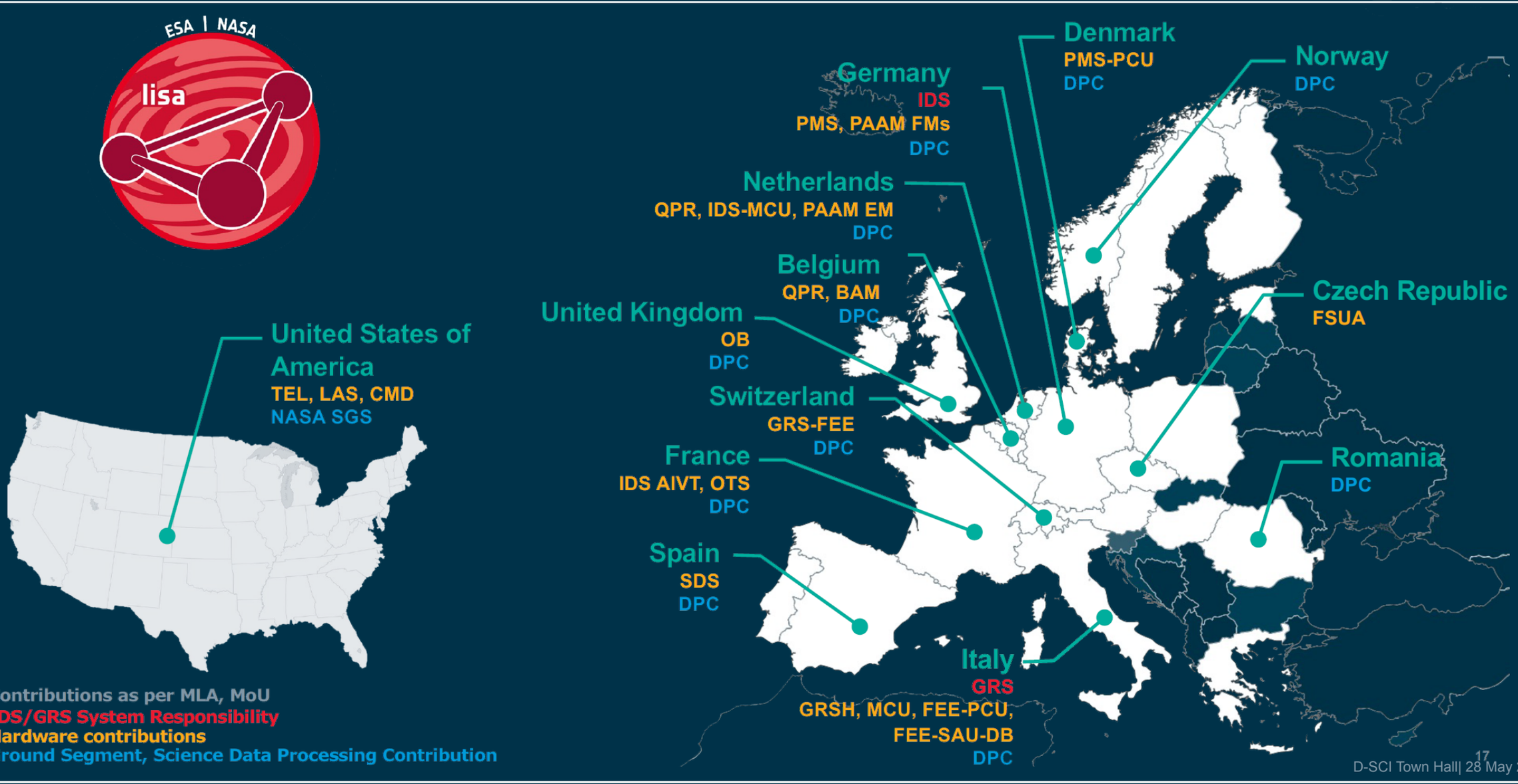
LISA collaboration

LISA CONSORTIUM

LISA - An international mission led by ESA

esa



Contributions as per MLA, MoU
IDS/GRS System Responsibility
Hardware contributions
Ground Segment, Science Data Processing Contribution

17
D-SCI Town Hall| 28 May 2024

→ THE EUROPEAN SPACE AGENCY

Science Objectives

- SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages.
- SO3: Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs.
- SO4: Understand the astrophysics of stellar origin black holes.
- SO5: Explore the fundamental nature of gravity and black holes.
- SO6: Probe the rate of expansion of the Universe.
- SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics.
- SO8: Search for GW bursts and unforeseen sources.

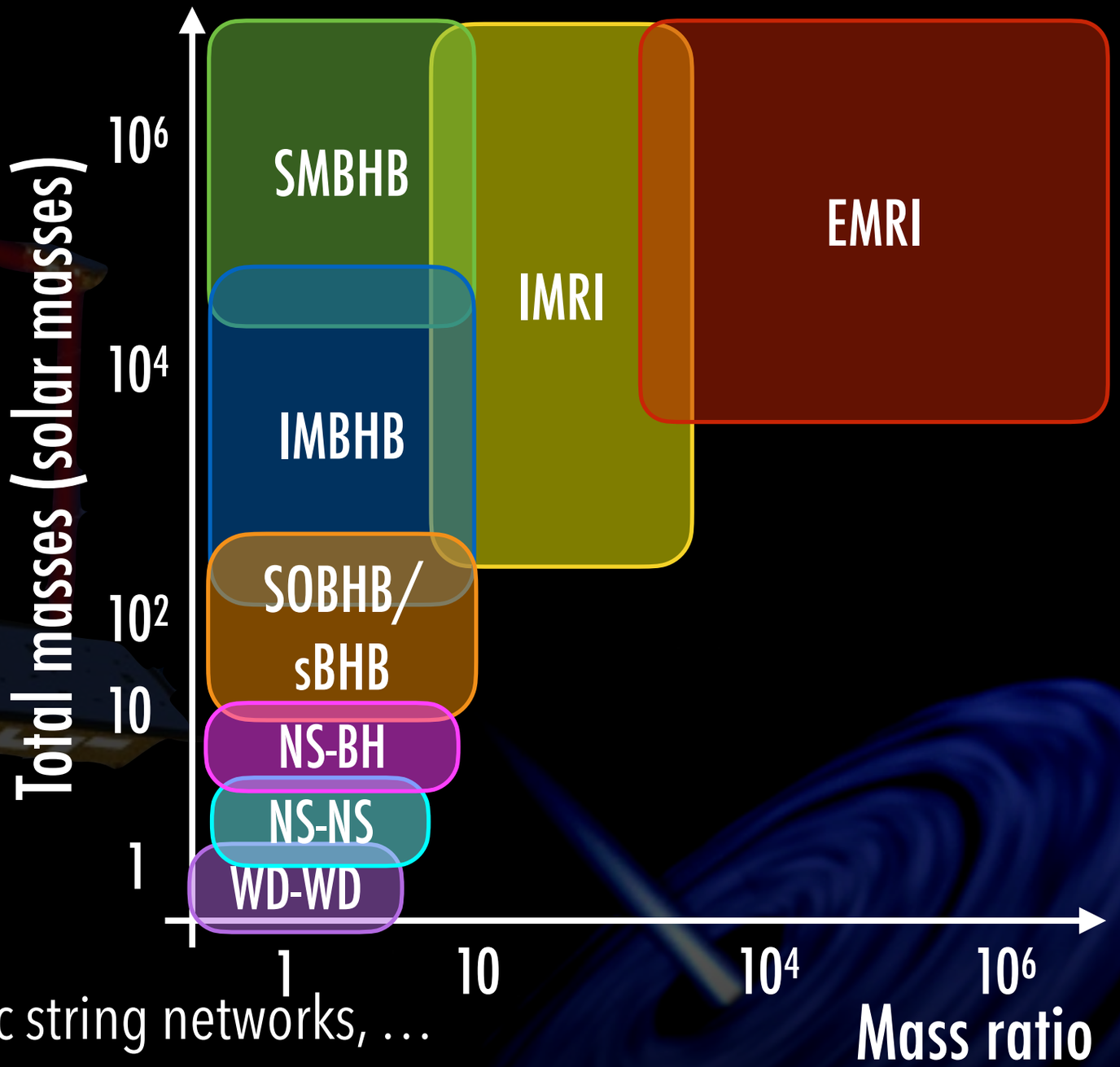
Astrophysics

Fundamental physics

Cosmology

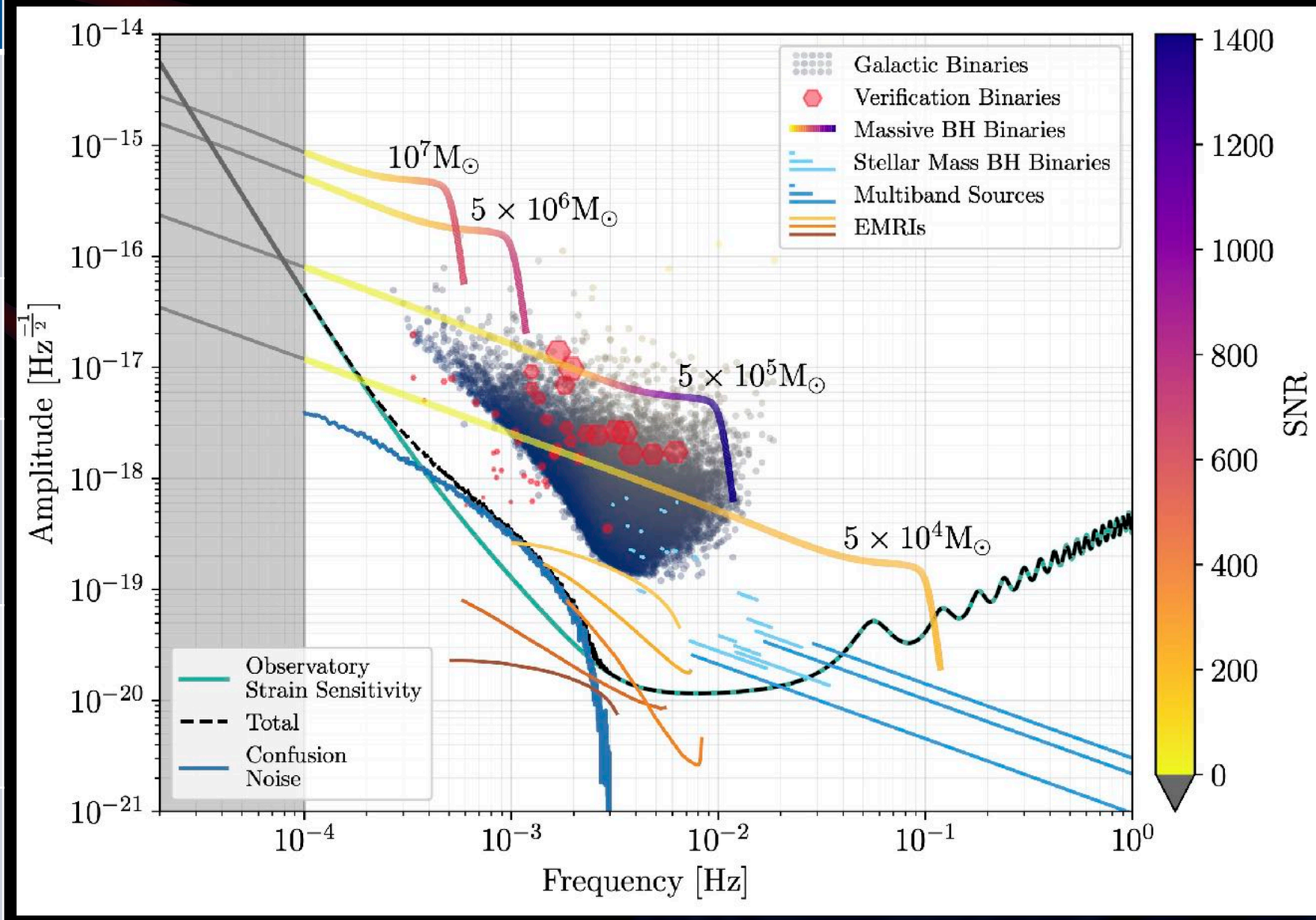
GW sources in the mHz band

- 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?



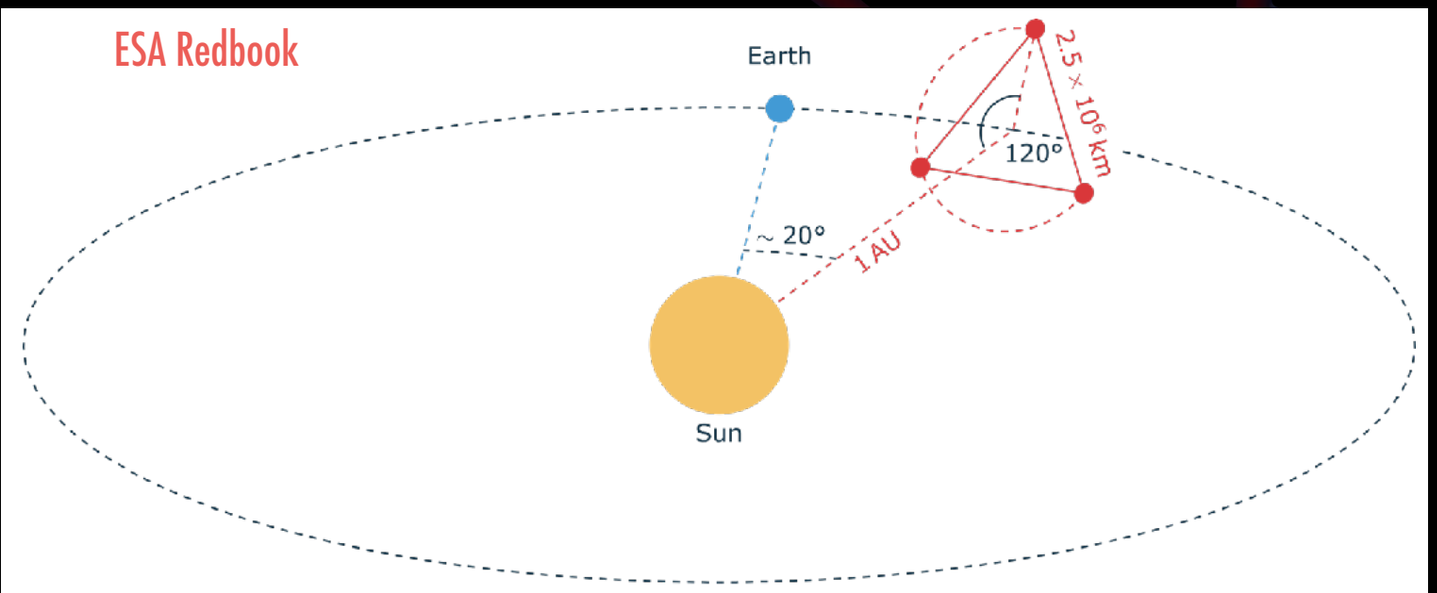
Binaries observed by LISA

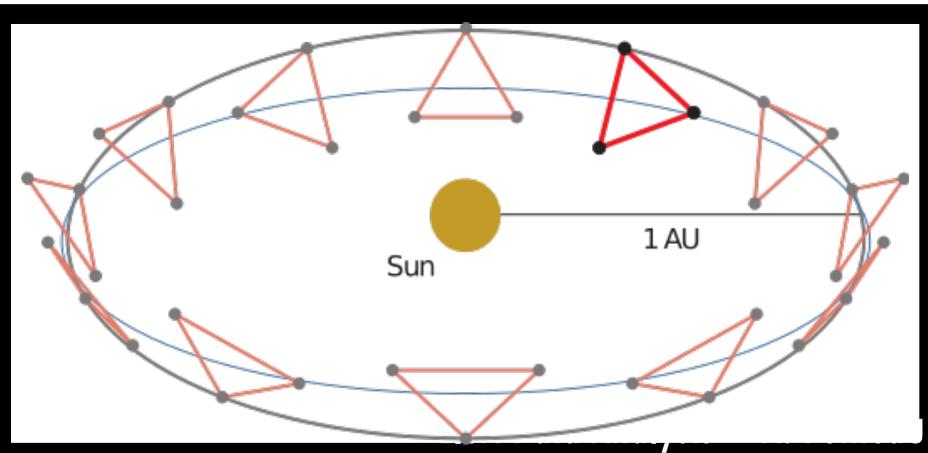
Sources	SNR	Duration	Event rate
Galactic binaries	10 – 500	permanent	10000 – 30000 detectables + background
Verification binaries	7 - 100	permanent	20 (today)
Stellar mass black hole binaries	7 - 30	1 à 10 years	1 to 20
Extreme Mass Ratio Inspirals	7 - 60	1 year	1 to 2000 / year
Massive Black Hole binaries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



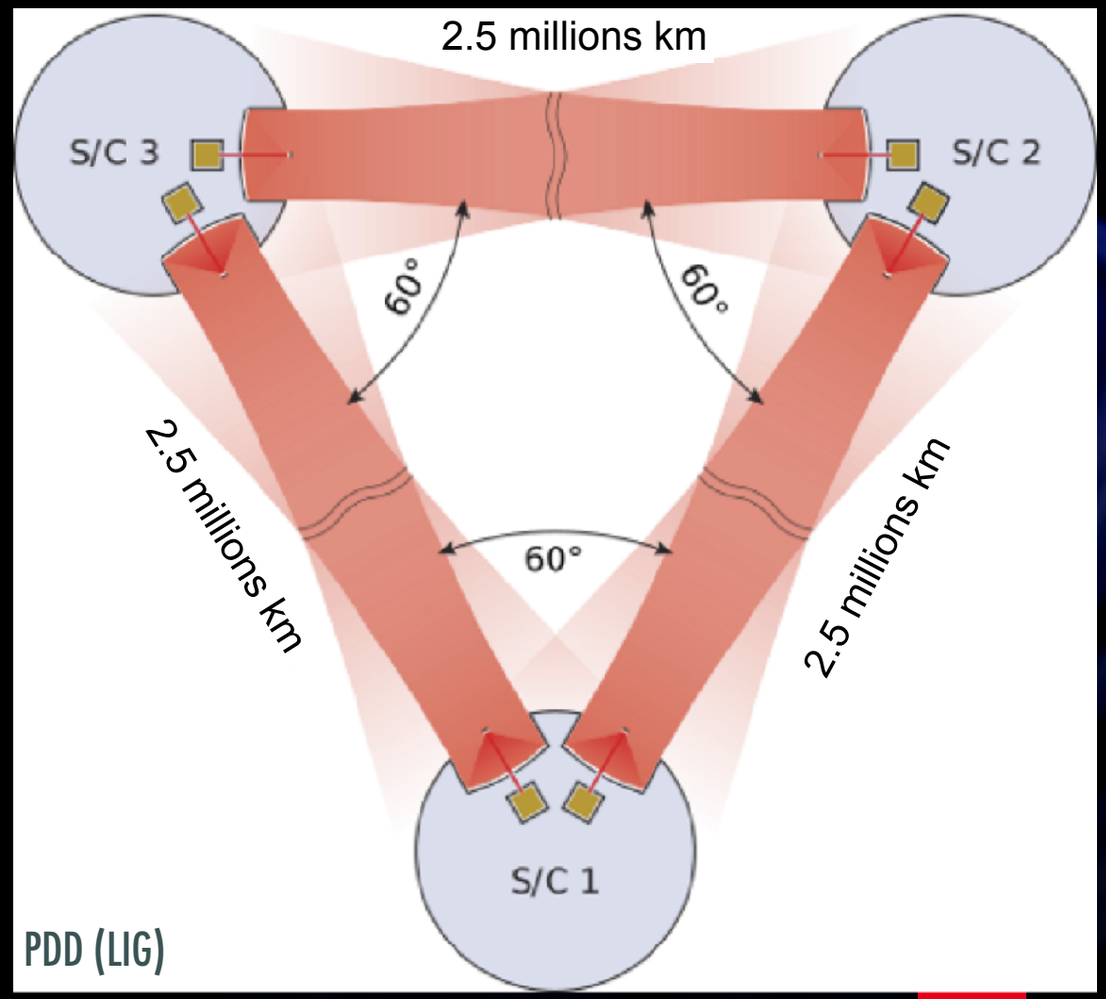
Mission design

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



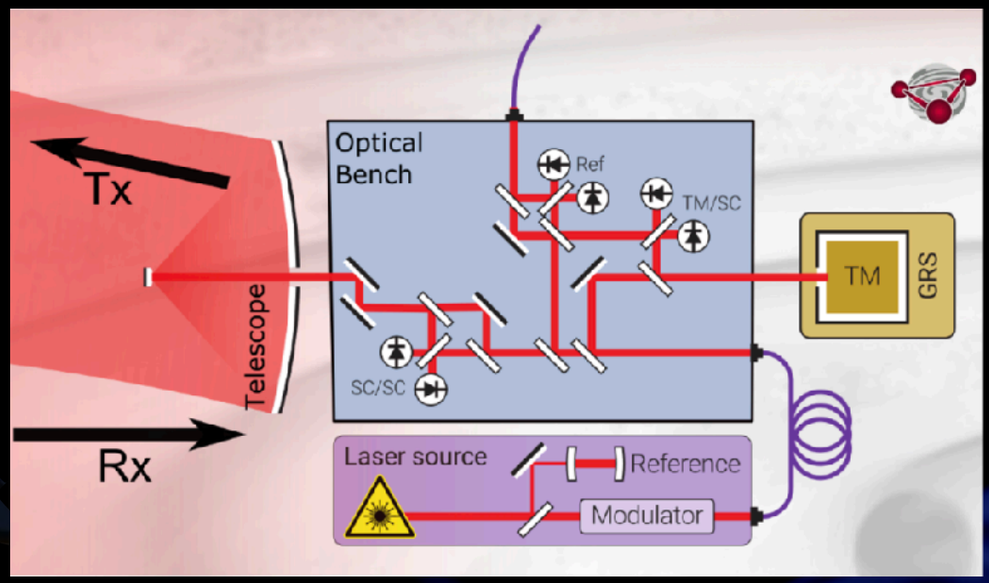


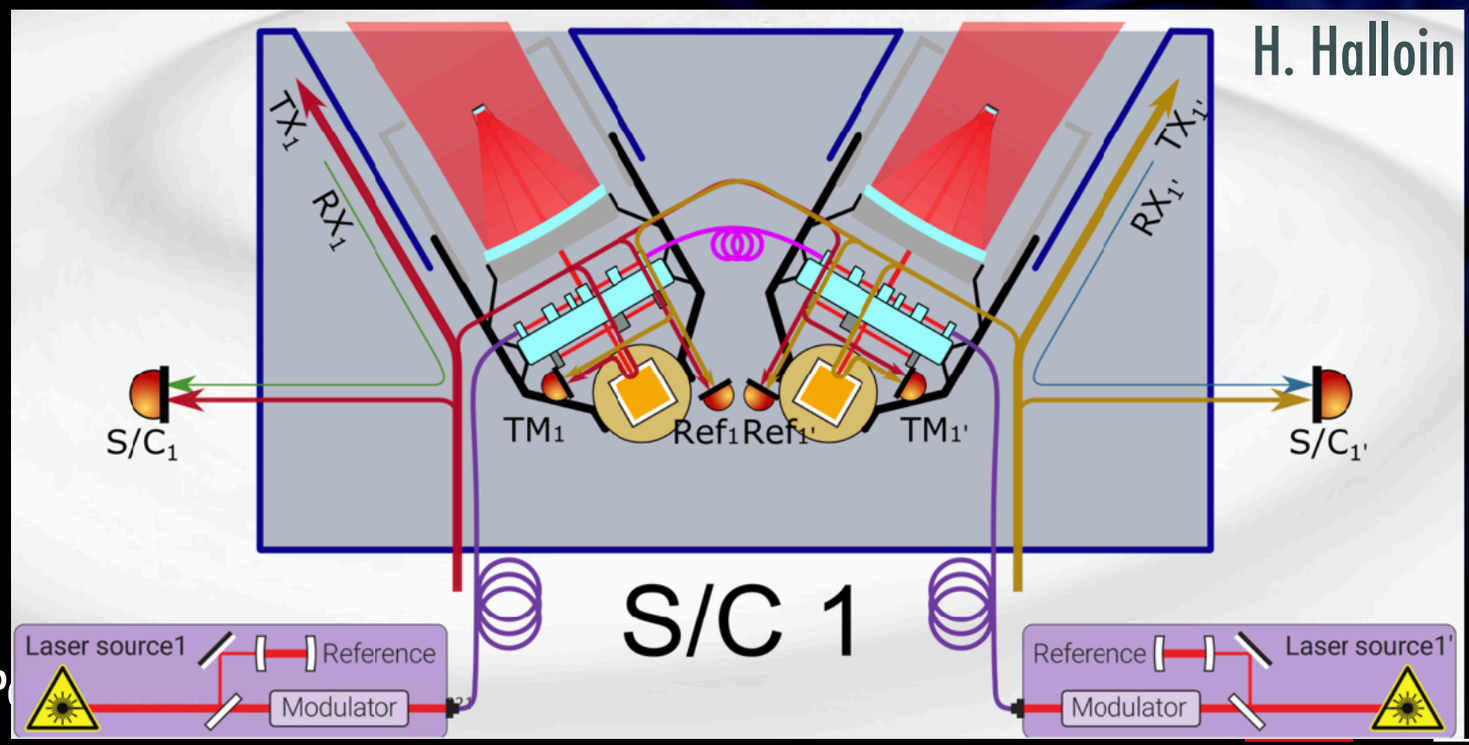
L3 proposal (LISA Consortium)



Interferometric measurements

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





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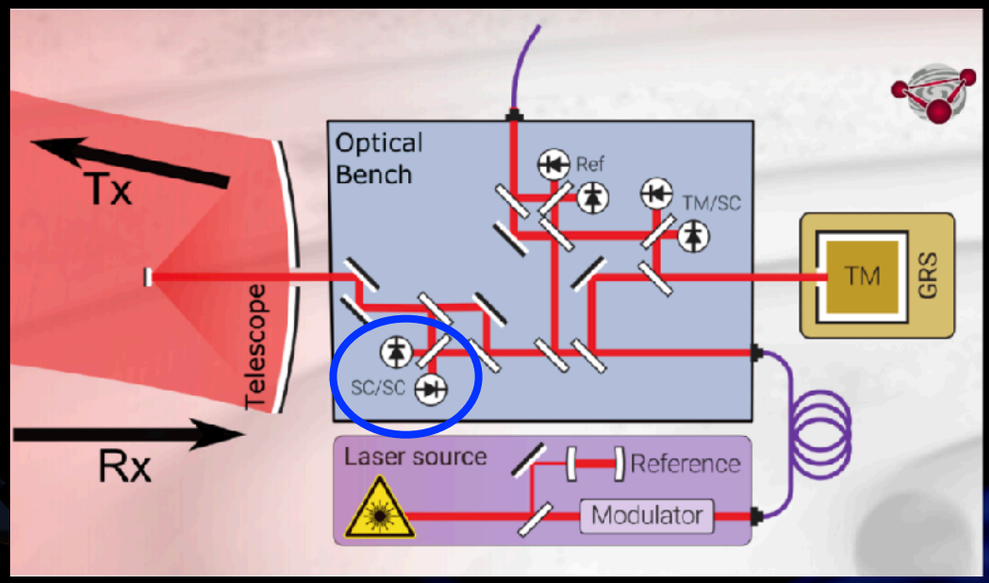

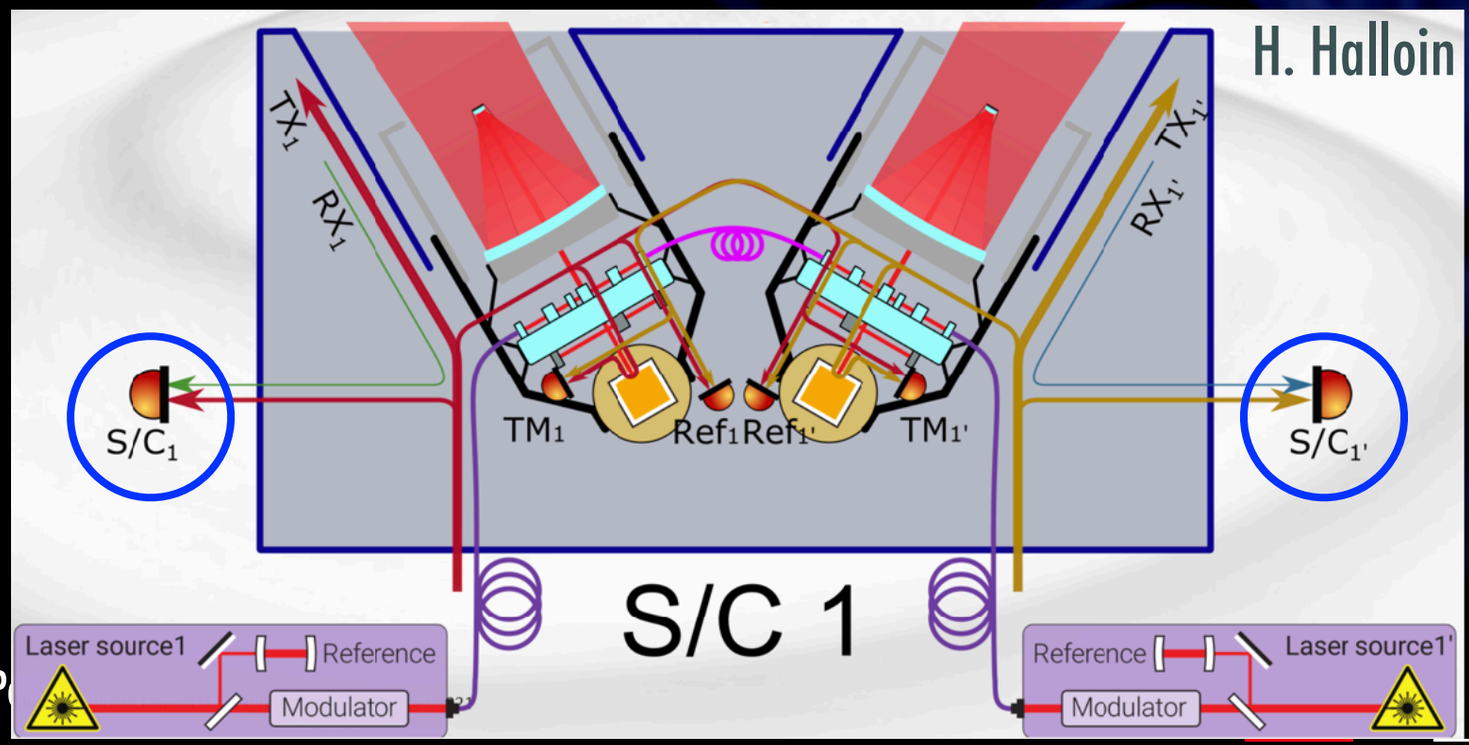

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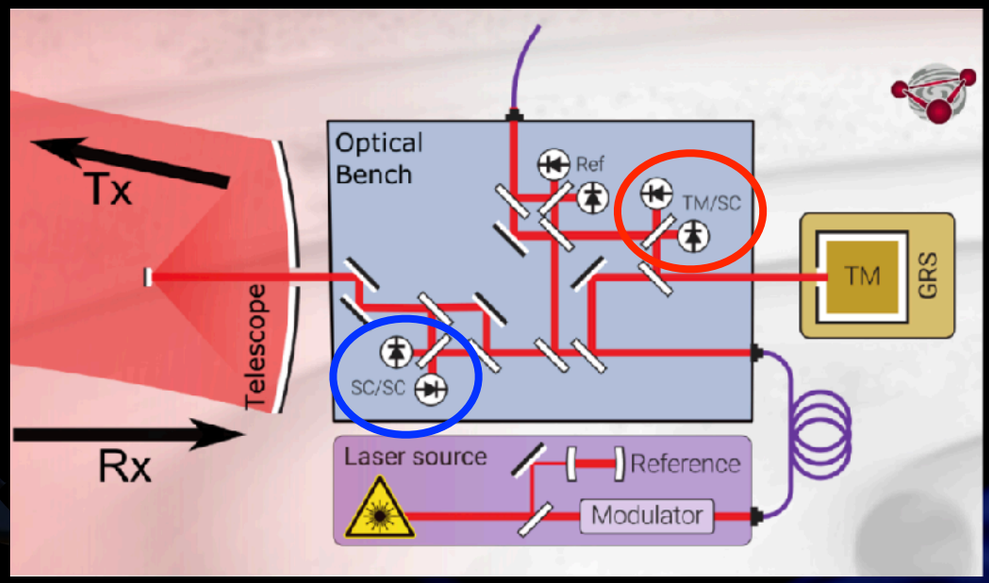

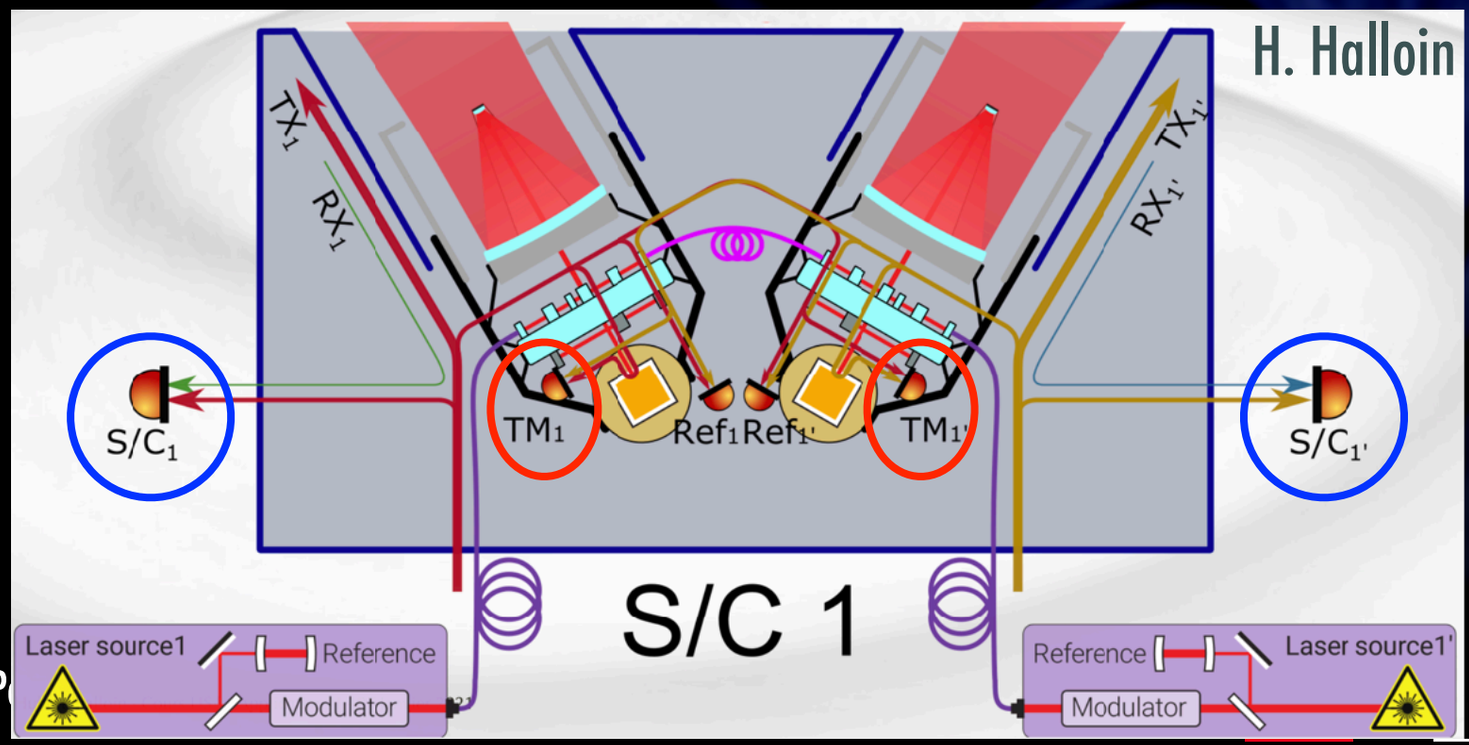

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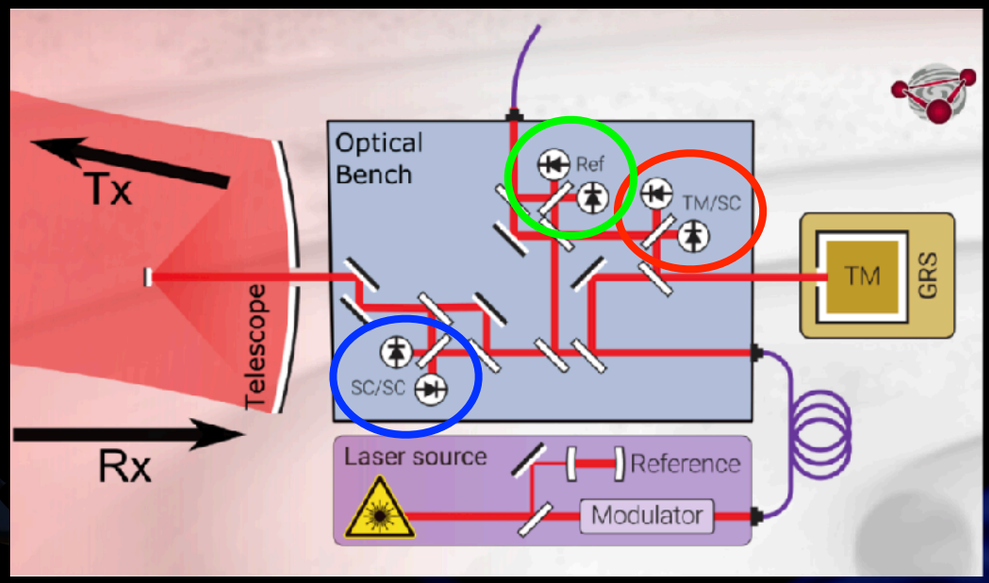
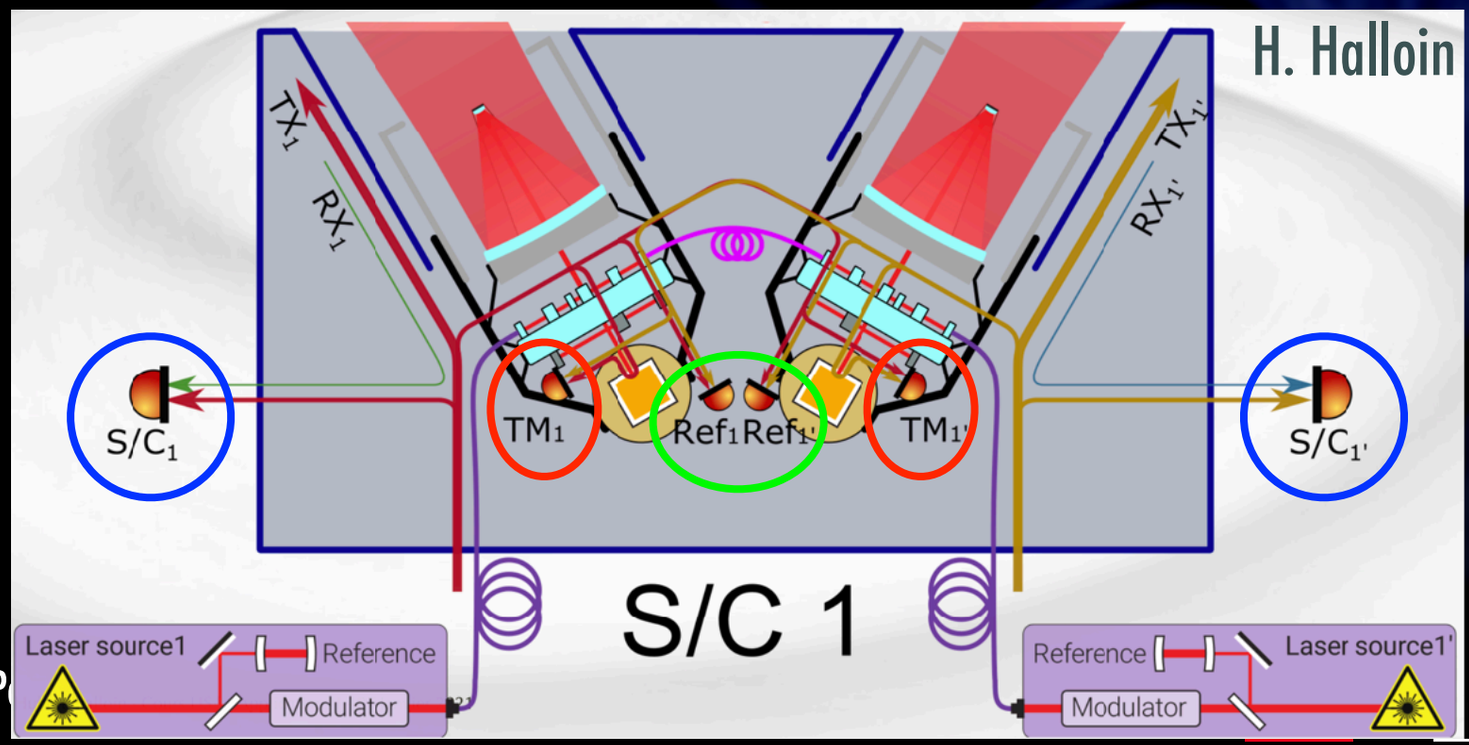
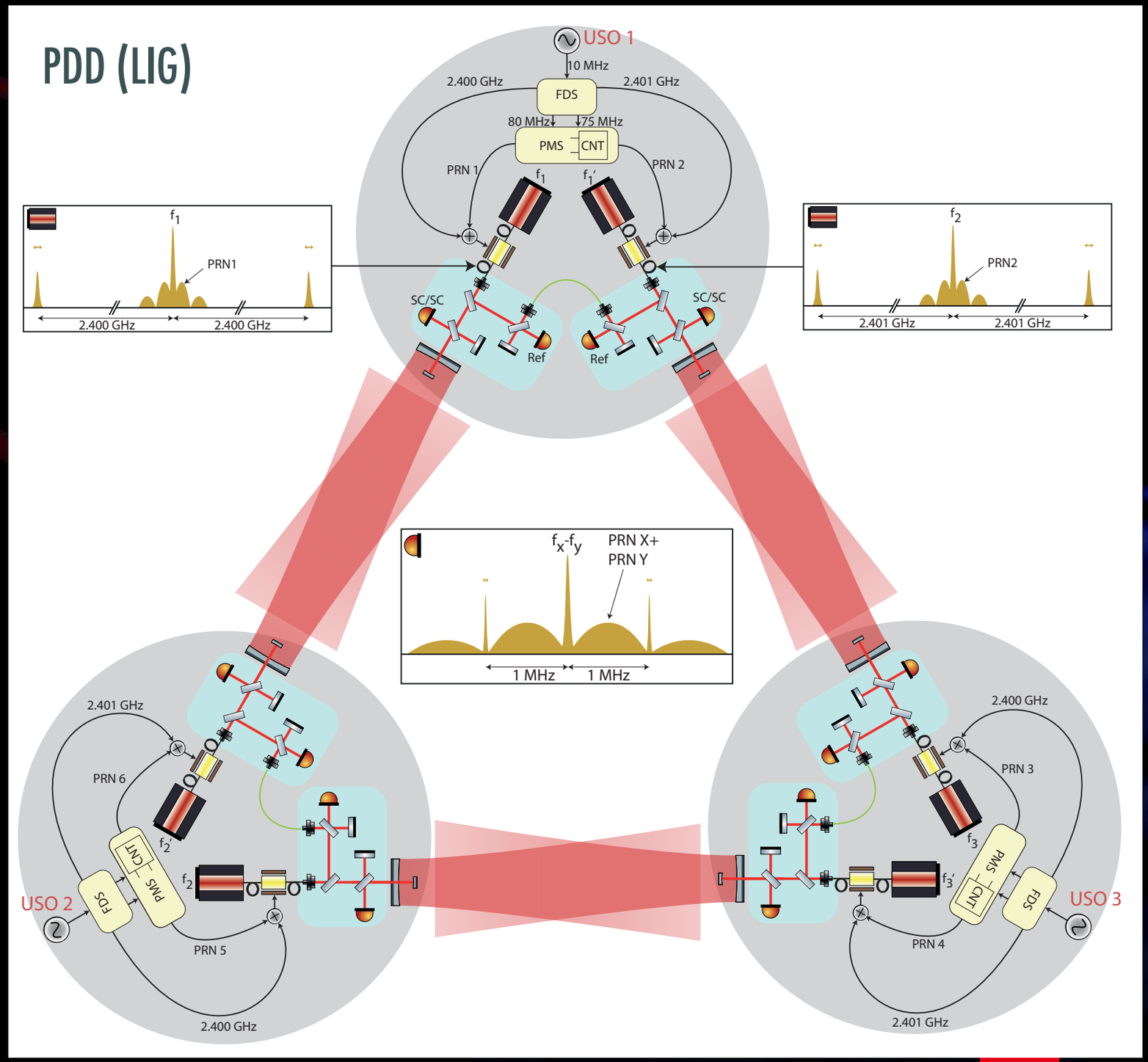




Interferometric measurements

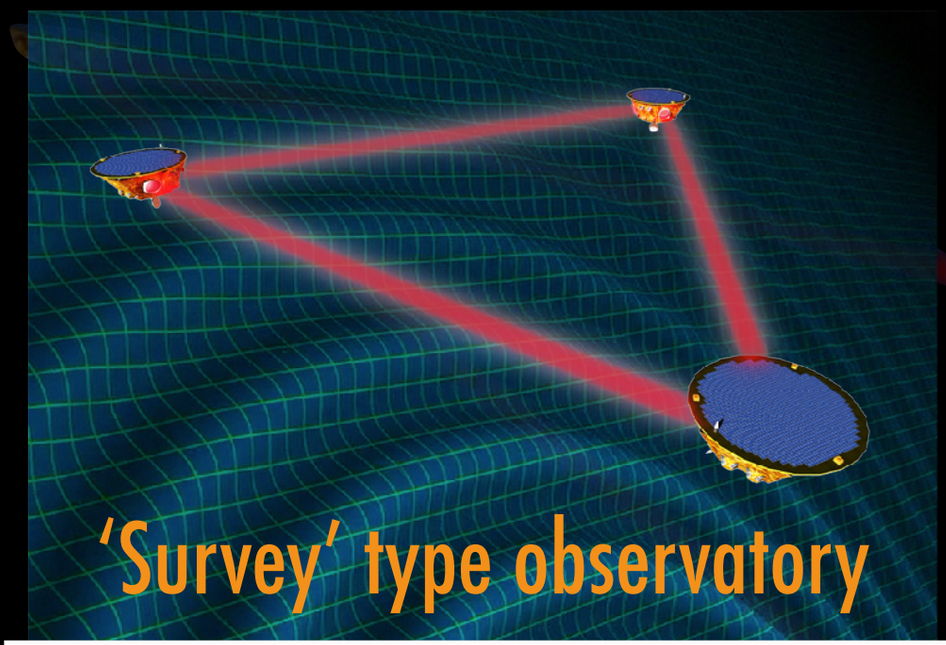
- Measurements via exchange of beams:
  - Heterodyne interferometry with carrier for inter-spacecraft measurement => GWs
  - Sideband for transferring amplified clock jitter => correction of additional clock jitter
  - Pseudo-Random Noise => ranging (measure arm length)
  - Laser locking



Data

Gravitational wave sources emitting between 0.02mHz and 1 Hz

Data



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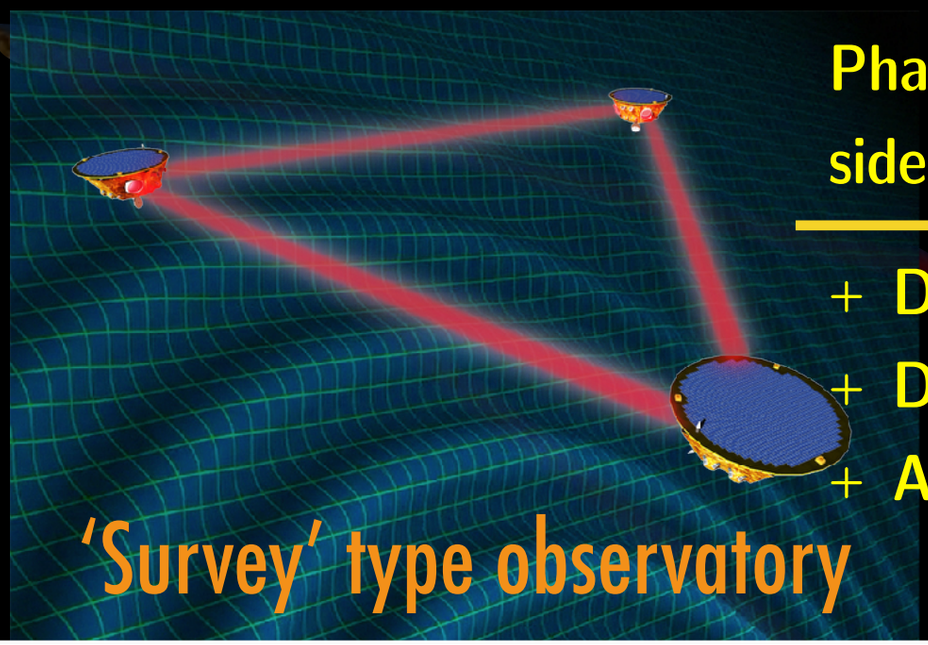


Phasemeters (carrier, sidebands, distance)

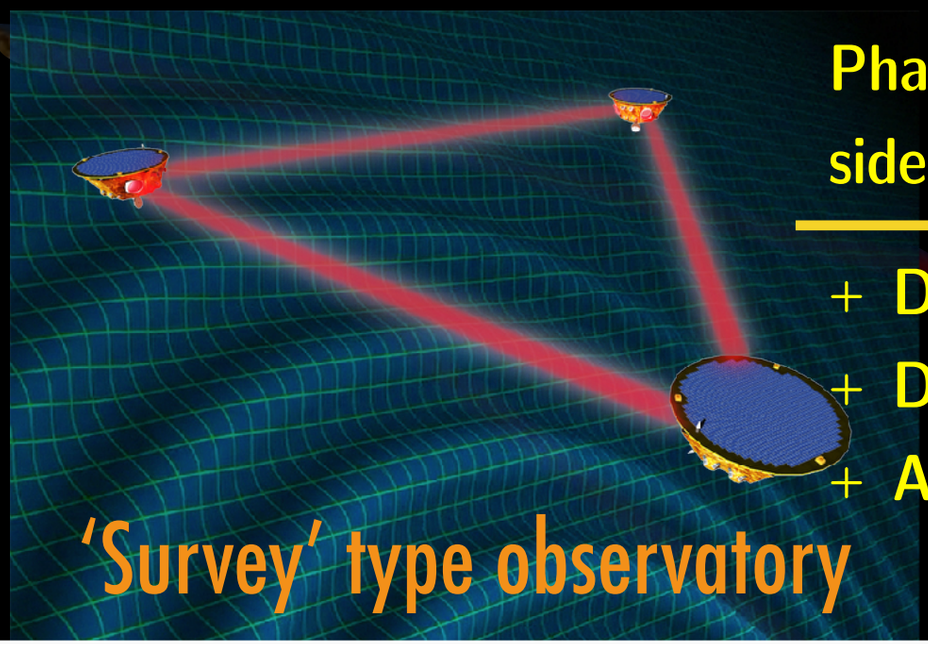
+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

Data



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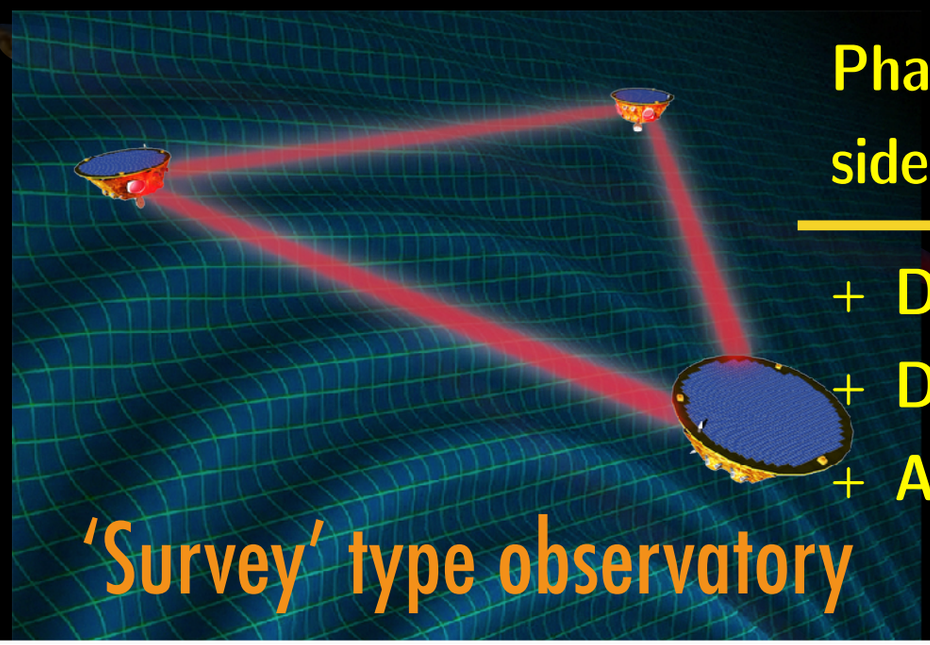

'Survey' type observatory

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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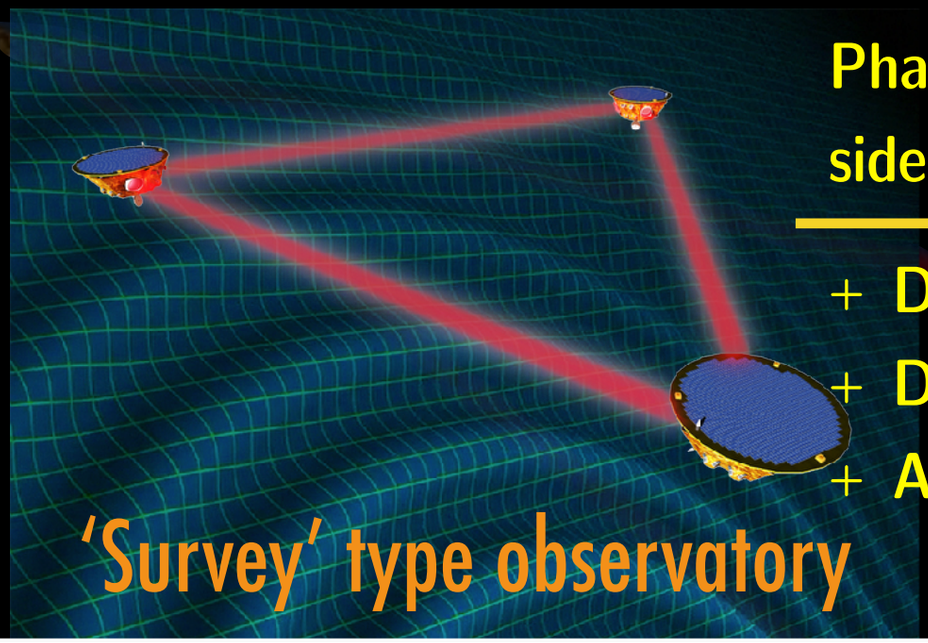

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Data Analysis of GWs

Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

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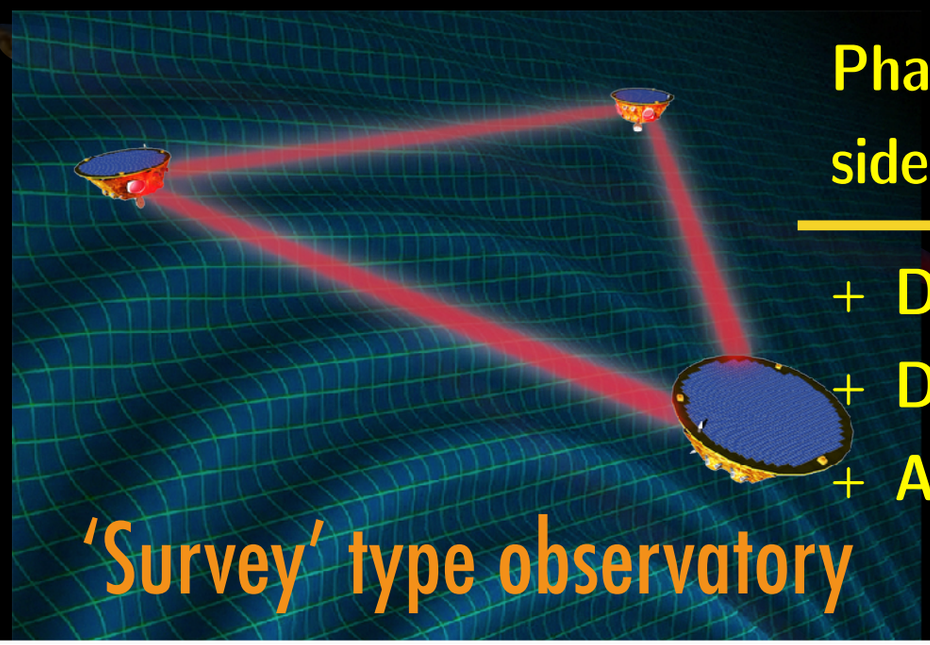


'Survey' type observatory

Gravitational wave sources emitting between 0.02mHz and 1 Hz

Phasemeters (carrier, sidebands, distance)

L0

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

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

* Drag-Free Attitude Control System

** Charge Management Device

Data

Phasemeters (carrier,
ds, distance)
CS* & CMD**
+ Diagnostics
+ Auxiliary channels

Mission Operation Center (ESA)

'Survey' type observatory

Science Operation Center (ESA)

Gravitational wave sources
emitting between 0.02mHz
z

DDPC: Distributed Data Processing Center (ESA Member States)

NASA Ground Segment

L0

L0.5

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

L1

3 TDI channels with 2 "~independents"

L2

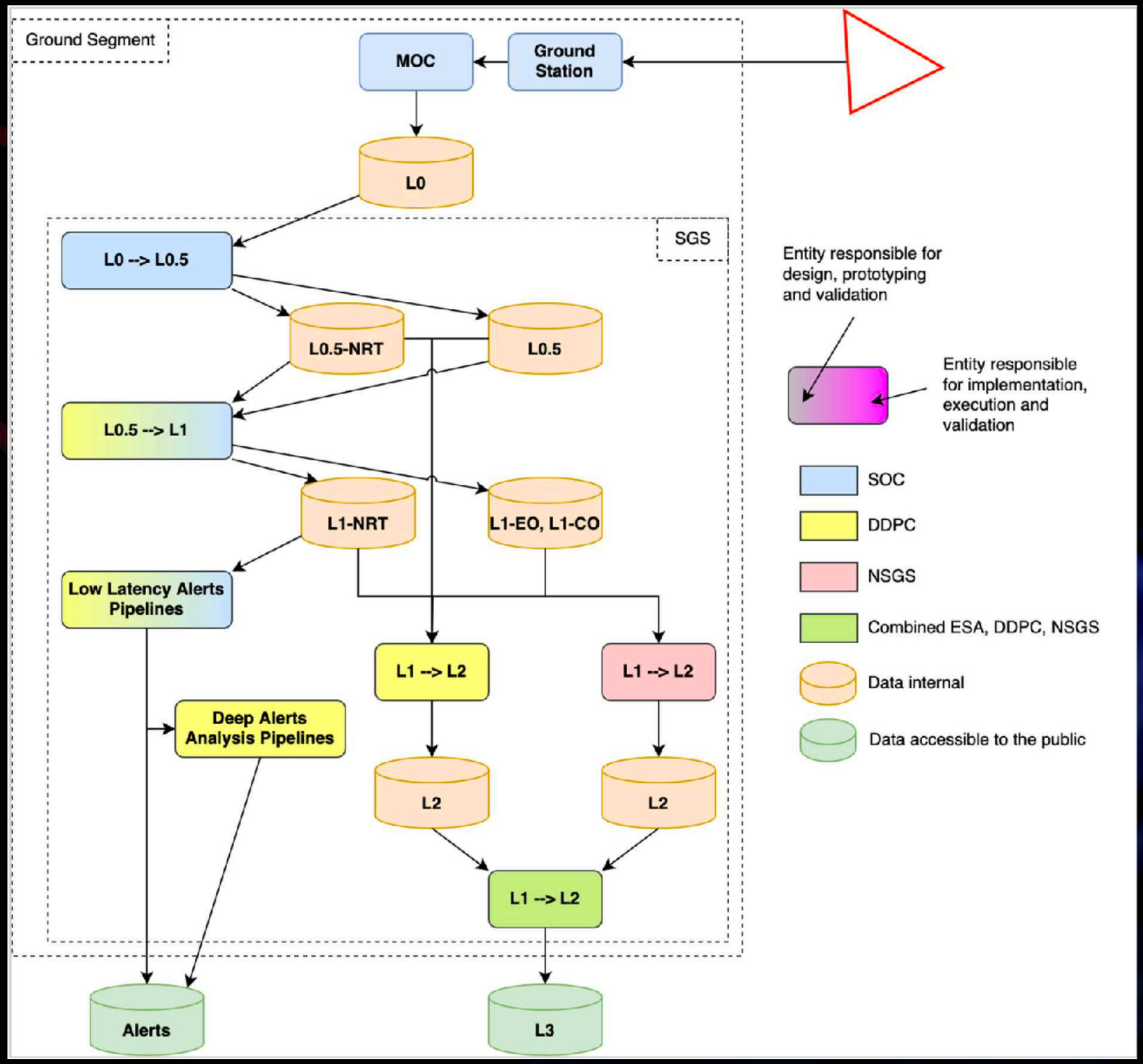
Data Analysis of GWs

L3

Catalogs of GWs sources with their waveform

Ground segment

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

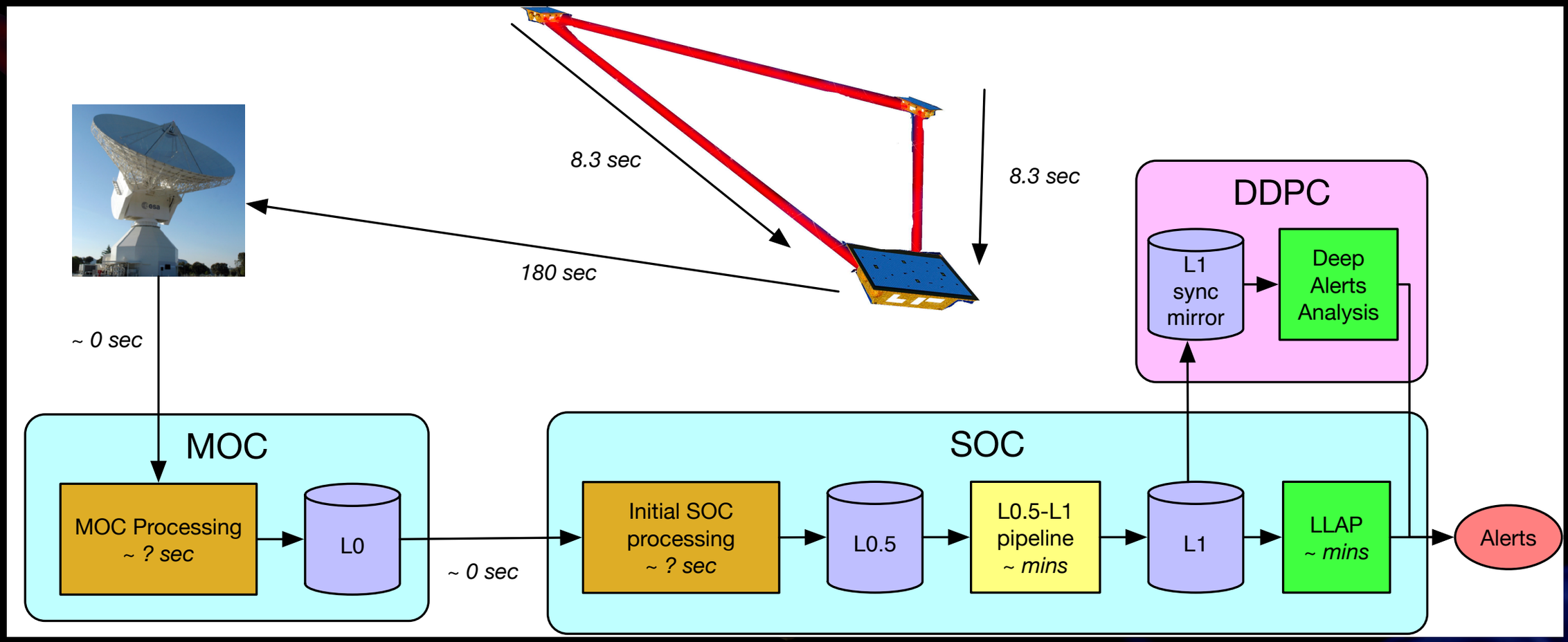


Data Analysis

- Analysis of all signals and noises together
  => global analysis
- Flexibility: first data of this kind
  challenge:
  - Multiple approaches, multiple pipelines
  - Quick development from prototyping to production
- General approach with with multiple iterative (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
- Distributed Data Computing Center (DDPC)


CC-IN2P3

L1 to L2: alerts

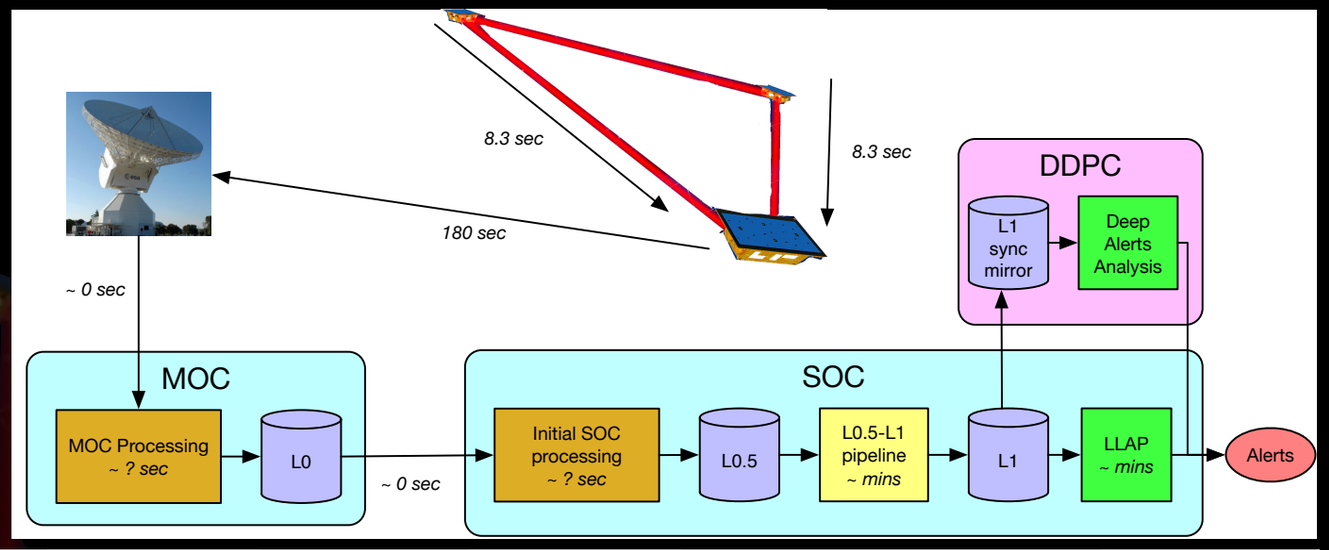


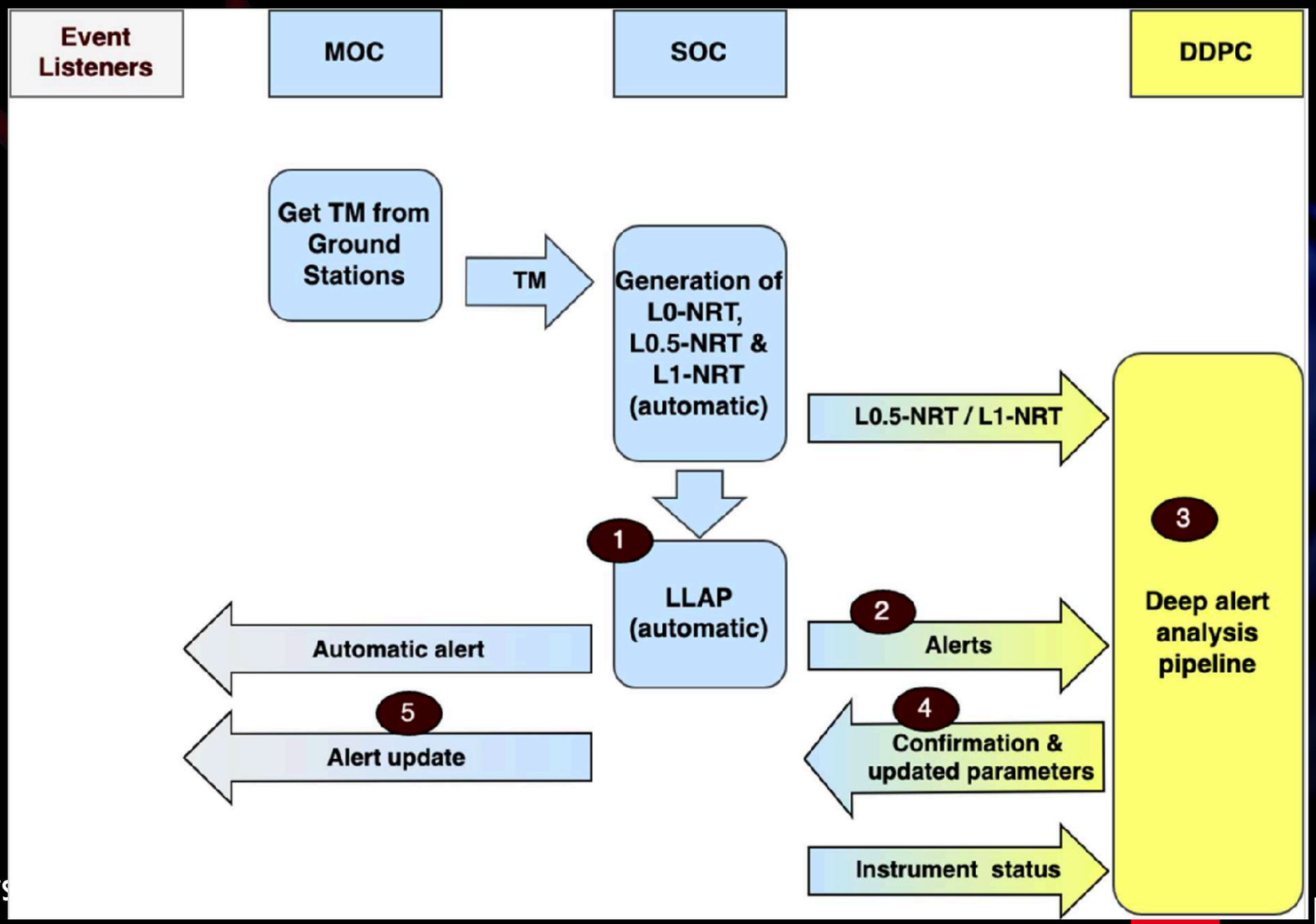
- Low Latency Alerts Pipeline: automatic near-real time analysis to release an alert as fast as possible
- Deep Analysis Alerts Pipeline: when an alert has been detected, analysis to:
  - Confirm the nature of the events
  - Refine the parameters

LLAP Operations

Generation of alerts

- 2 components:
  - "Near-real time" (< 1h) generated by SOC
  - "Offline" generated by the DDPC
- 2 main functions:
  - Detection of the new events
  - Update events to follow





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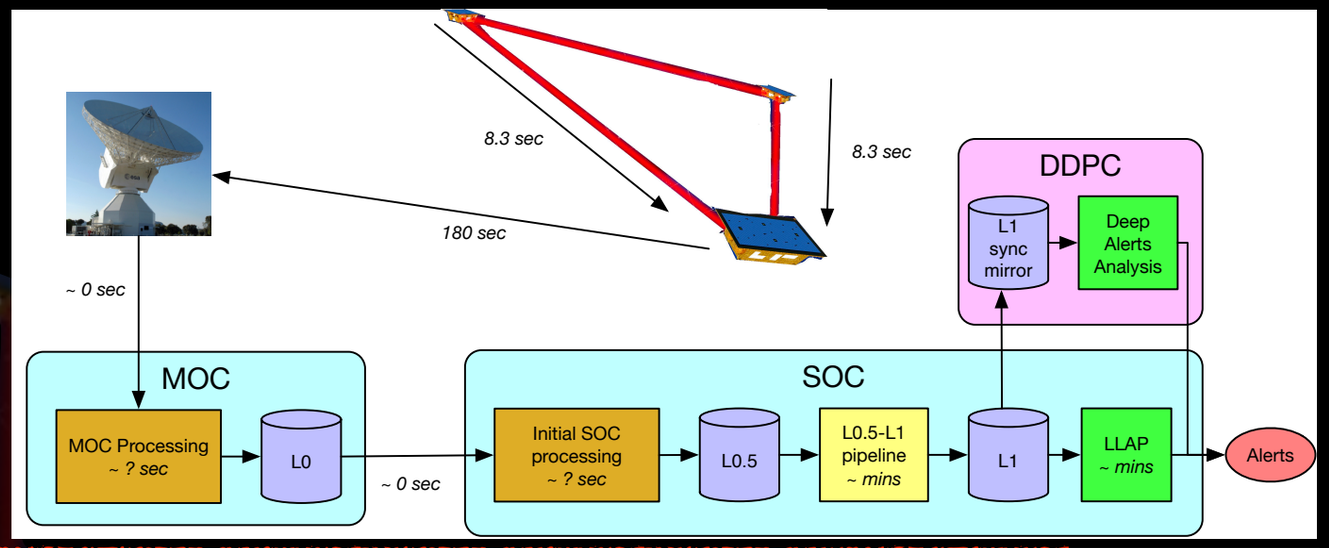

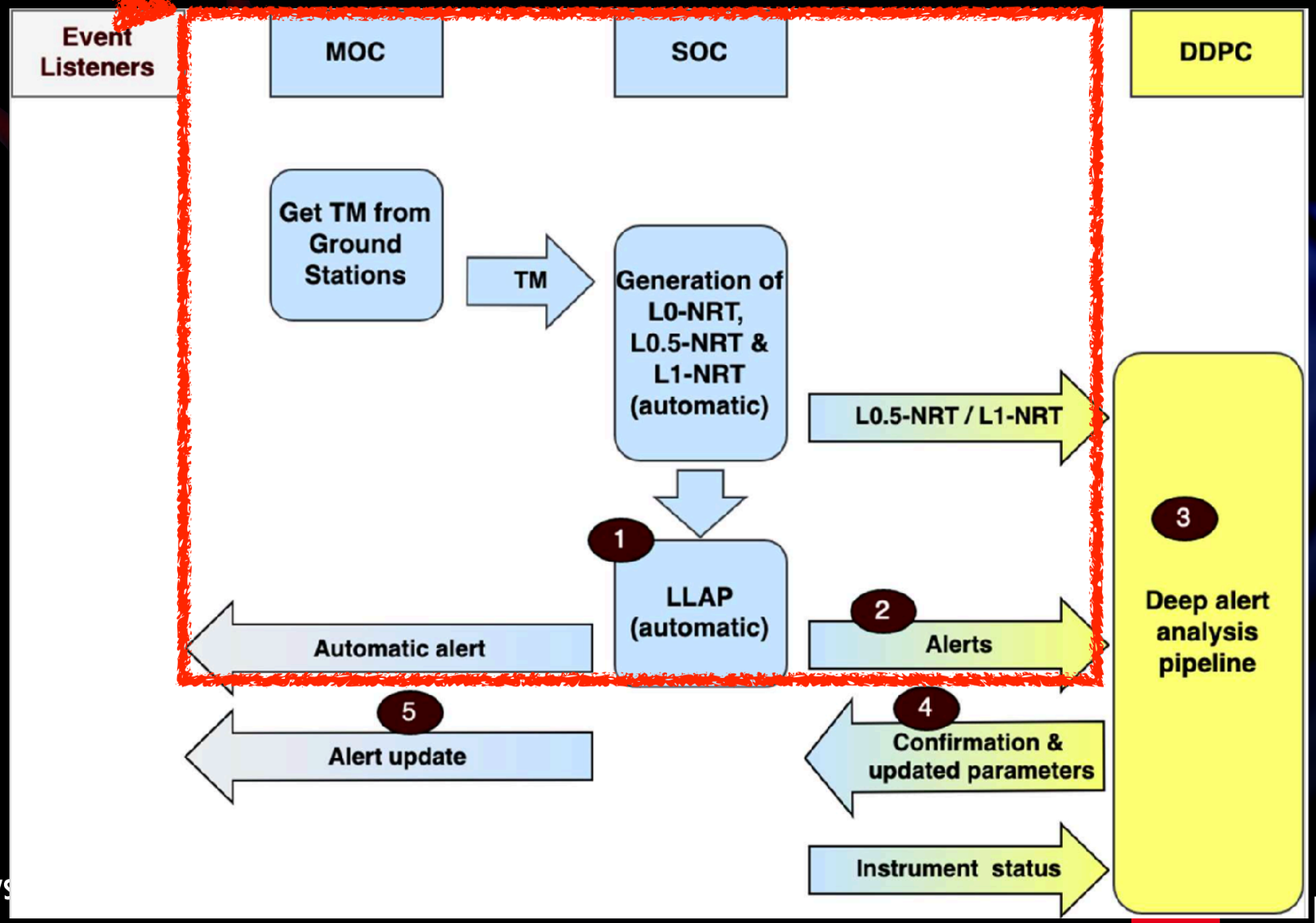

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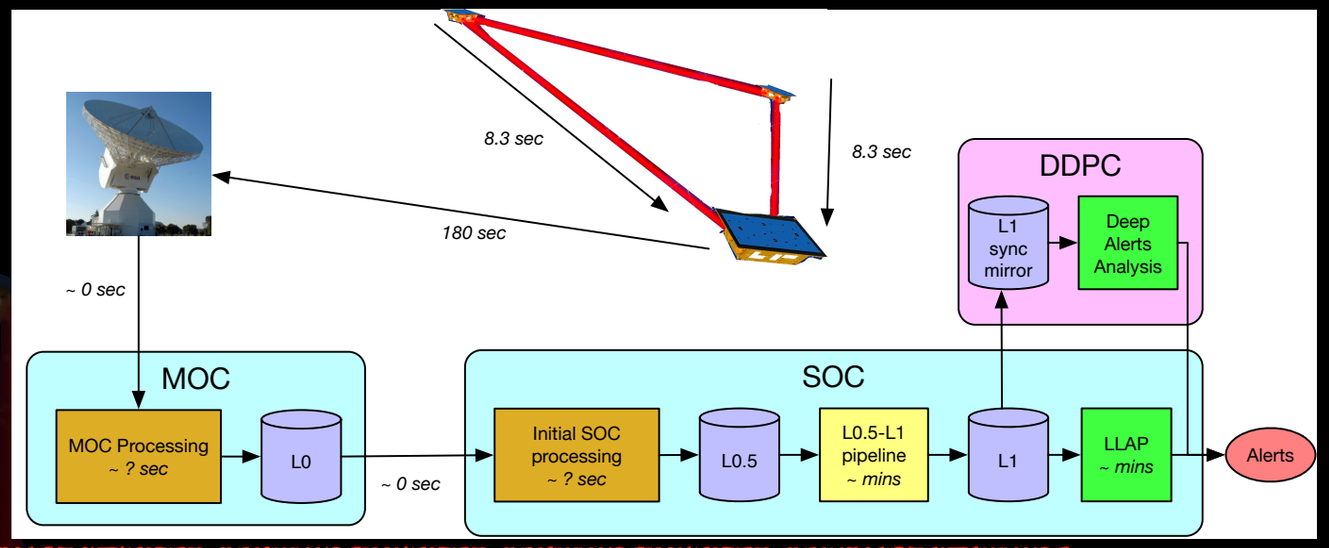
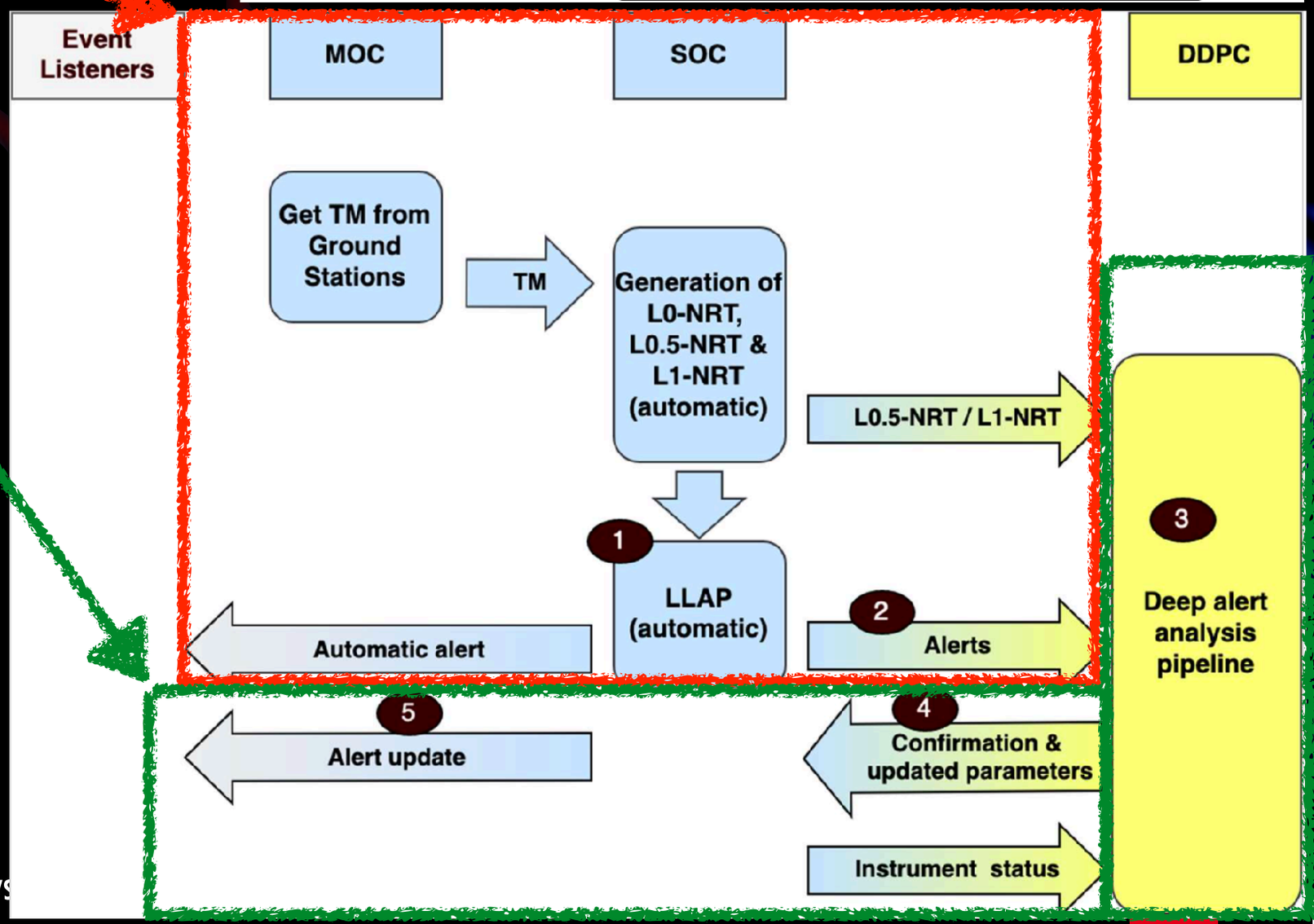


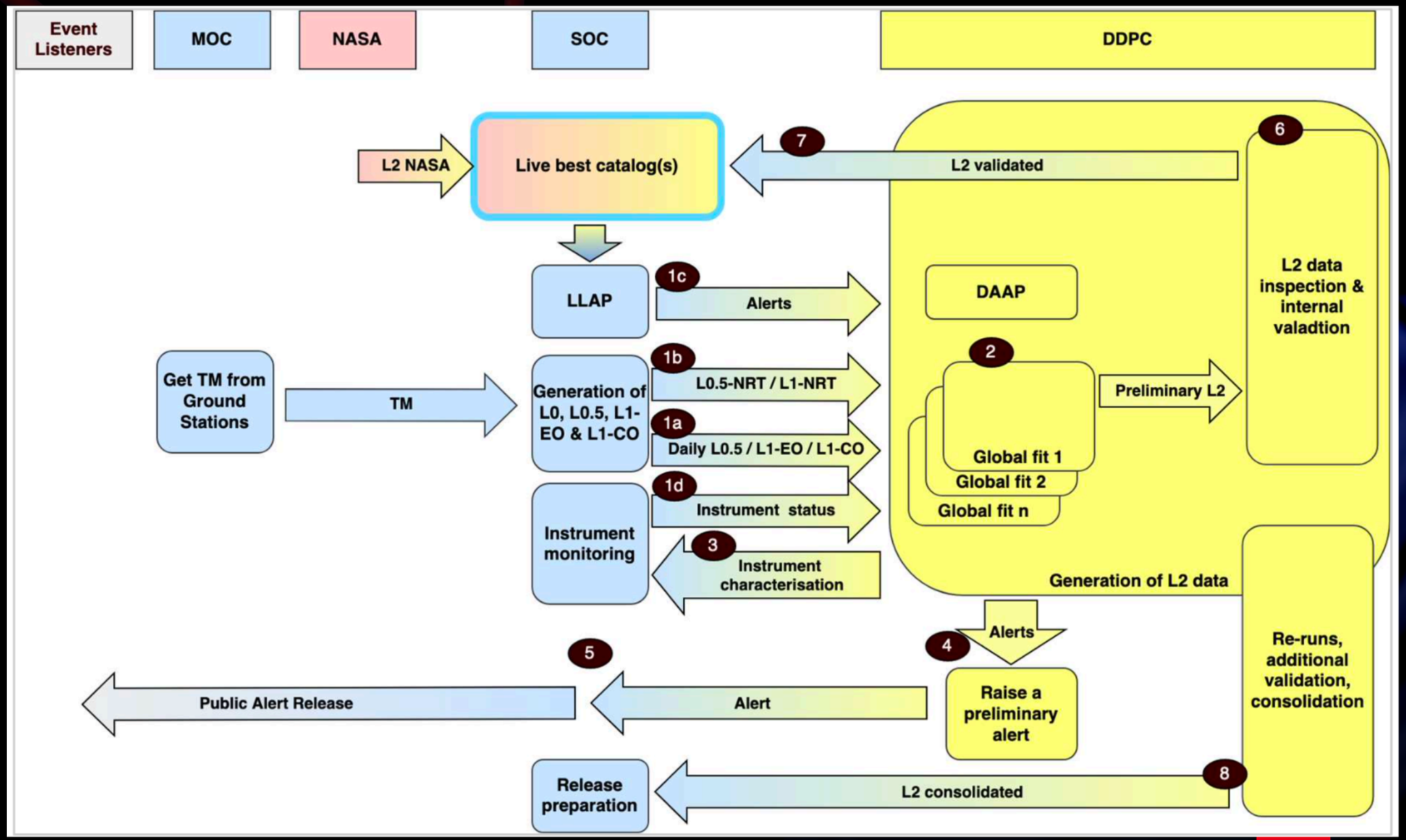


Data analysis in LLAP

- Goals:
  - Detect new events
  - Update parameters of a known events (in the list of event to follow)
- Strategy:
  - Fast and online
  - Multiple approaches/ pipelines in parallel
  - Analysis on accumulated data
- Operations:
  - 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) And update of parameters
    - Low latency analysis on the High Priority Data (from the 16h without communication)
      - 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

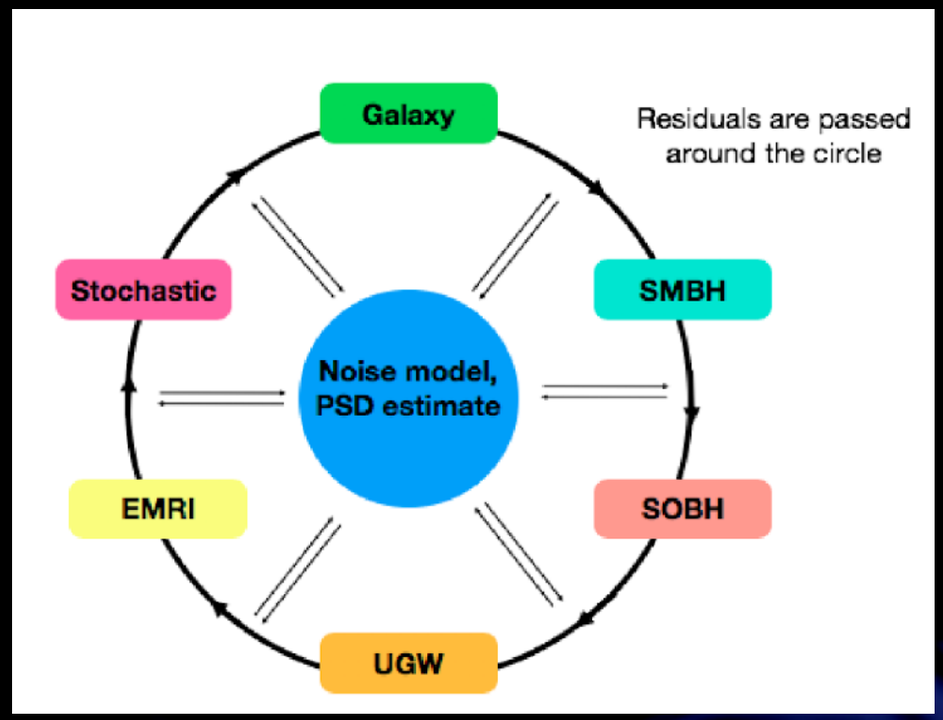
Operations

- Deep Analysis:
  - Several "global fits";
  - Daily update of a "Live best catalog(s)" (proto-L3, temporary catalogs).
- Preparation of a release:
  - Processing and re-processing for generating consolidated L3
  - Contribution to the generation of L3 data led by ESA



Global fit (deep analysis)

- Goals: GW sources extraction + better understanding of noises and instrument with multiple pipelines
- Challenge: large number of overlapping sources:
- Input data availability:
  - Every day, 24h of new L1 data available
  - + every X days a refined version of L1 data
- Strategy: multiple global fits:
  - Large number of parameters
  - Disentangle sources
  - Several timescale for the analysis depending on sources:
    - 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,
  - Current approaches in the prototypes:
    - Bayesian analysis, matched filtering;
    - Start to use some Artificial Intelligence;
    - Others approaches (sparsity, …)
- Cost for one global fit ~ 200 millions cpu.h per year



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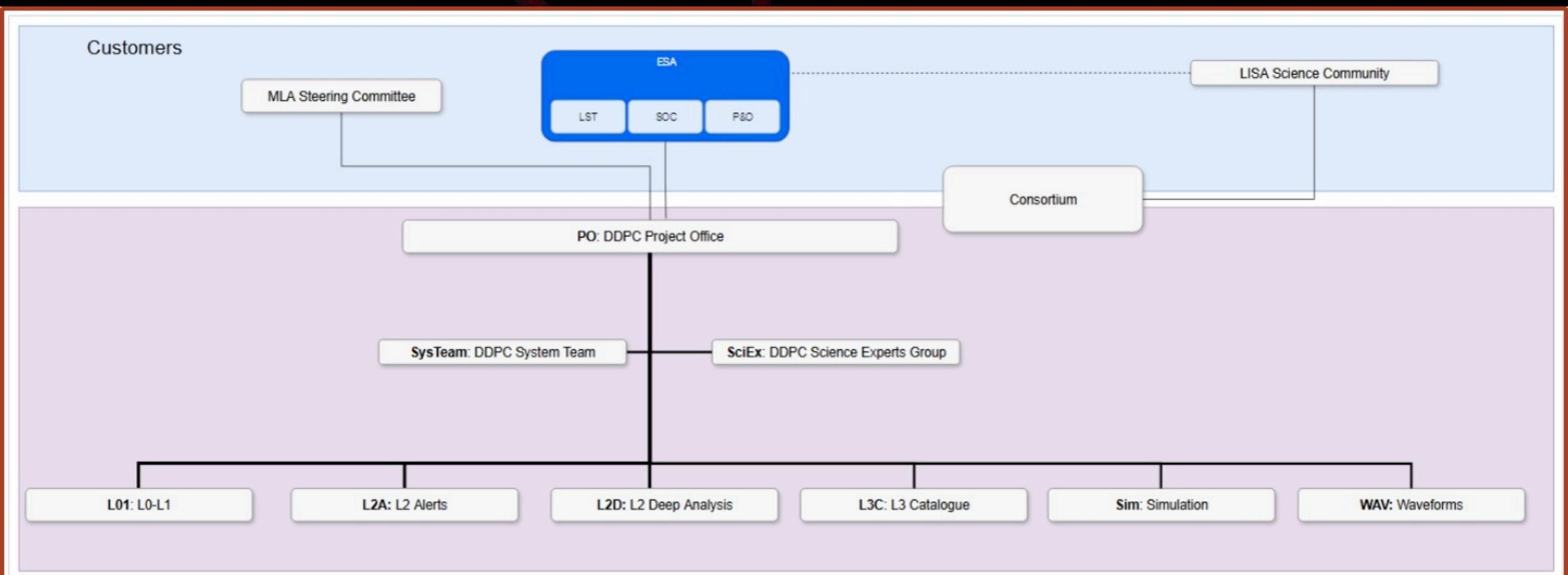
DDPC Role

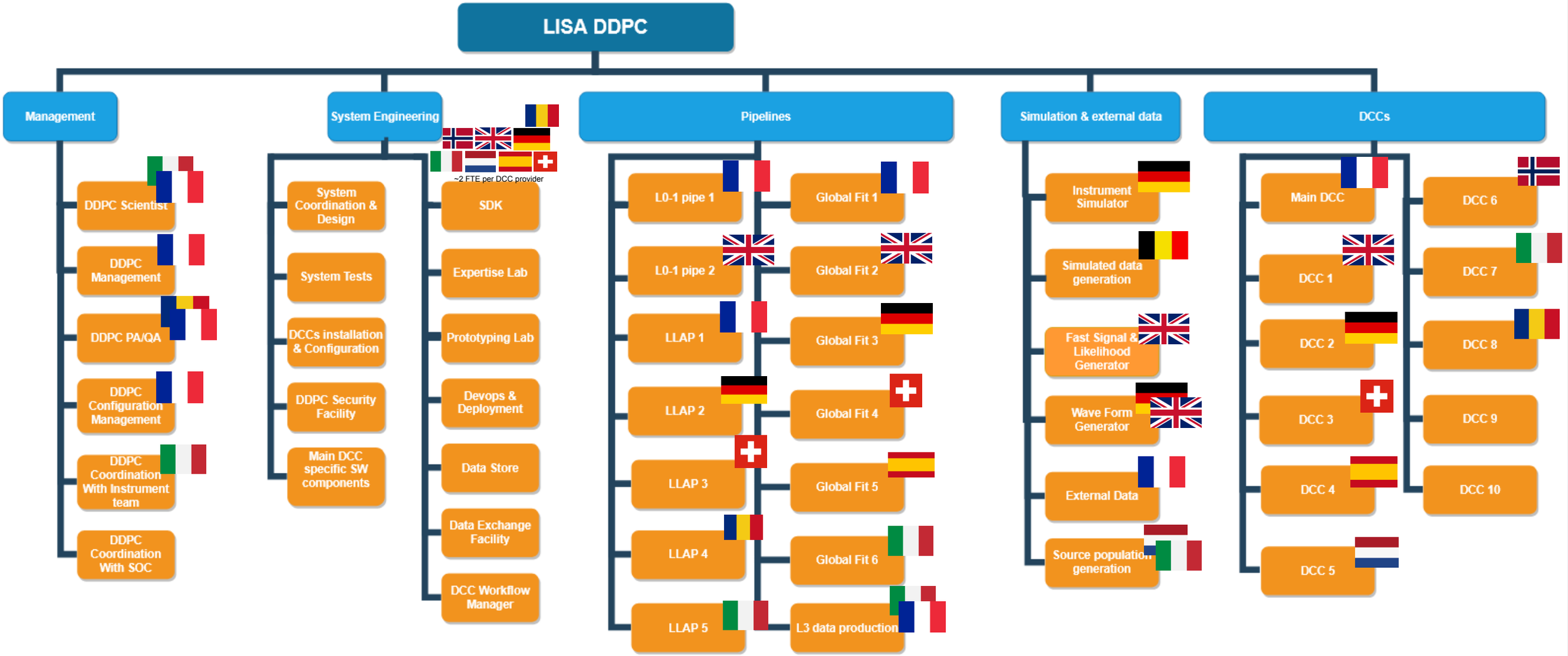
- Reception from the SOC:
  - Multiple data levels L0.5 and L1
  - L2 data from NSGS (NASA)
  - Alerts data
- Processing :
  - Generation of L2 data
  - Generation of event notices (alerts)
  - Deep analysis on event notices (alerts)
  - Re-processing for L2 and L3
  - Noise characterisation
- Provision of software (design and development) :
  - Provide to the SOC a prototype of the L0.5 to L1 pipeline
  - Provision of a Low Latency Alert Pipeline (LLAP) to the SOC
- Provision of products (operations) :
  - Release of L2 data products to the SOC
  - Provide to the SOC the list of sources to be monitored
- Contribute towards the generation of the L3 data (science products)
- Coordinate development and implementation of simulations
- "Services" :
  - Working storage of the internal data
  - Use a common framework
  - Support the assessment of the data quality
  - Data access and support for all DDPC contributors

DDPC

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



DDPC Work Breakdown Structure



- Commitment of 10 countries in the Multilateral Agreement signed at adoption
- Current discussions with Finland, Portugal, Ireland, Greece, Canada and New Zealand who want to join the DDPC.

DDPC timeline

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

DDPC timeline

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  - Populations

Source	Description of catalogue
Galactic Binaries	• Interacting binaries

Extra-galactic binaries (option?)	• *What is exactly ?*
	  ◦ *Satellites to the MW*
	  ◦ *"Extra-extra"*

MBHBs	• Mixture of models • Include few model outliers (ex: high mass ratio, ...) ; look at the distribution and see what to add
EMRIs	• Plan A: Model M1 from Babak+2017
	• *(option) Plan B (if we can): populate Milan model with EMRIs*
xEMRIs	No

sBHB	• O3/O4-based empirical population
	• Mixture of field and dynamic formed (eccentricity)
	• *(option) Full O4 if available*
	• *(option?) Background like GB ?*
	  ◦ *Ariana:*
	  ▪ *sBHB should come from LVK O4 population*
	  ▪ *Including eccentricity if possible*
	  ◦ *open item*

SGWB	• Mainly as a noise component • Plausible models • We will see based on the result of the Stochastic Challenge (LEGO type, ongoing effort) → educated guess • For the components, see the ongoing activity • *(option) Background of EMRIs*

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  - Populations
  - Waveforms

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

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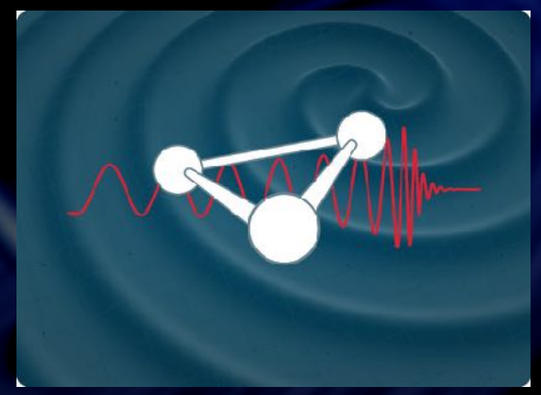
  - Waveforms
  - Instrument

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

Conclusion

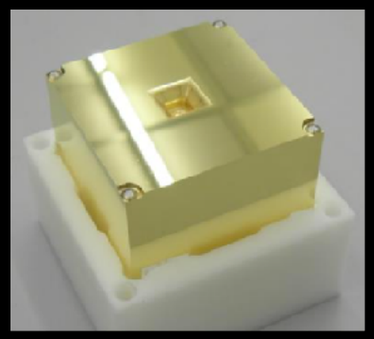
- LISA is a large mission led by ESA to explore the Universe with gravitational wave in the mHz band.
- It has been adopted in January and is now in its development and building phase for a launch in 2035 for 4.5 to 10 years of operations.
- LISA will cover a large range of domains and has a huge science case for astrophysics, cosmology and fundamental physics.
- Data analysis is challenging (large number of overlapping sources, new type of data)
- Two main pipelines:
  - Low Latency Alerts Pipeline
  - Deep analysis
- DDPC started:
  - Coordination Units active on all key domains: waveforms, simulation, L0-L1, alerts, global fits, catalogs
  - Prototyping until 2030

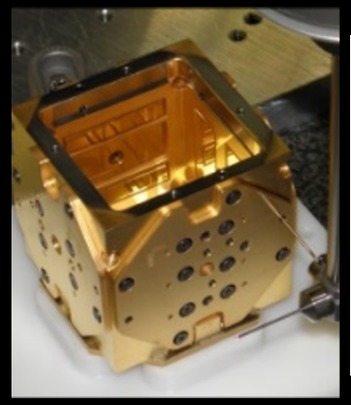


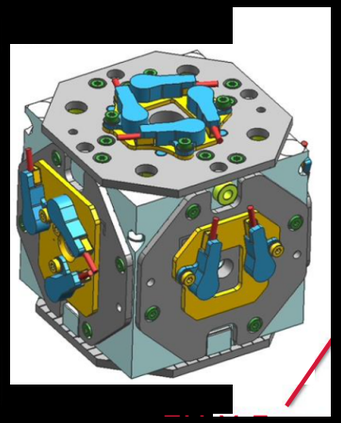
Merci !

Mission design

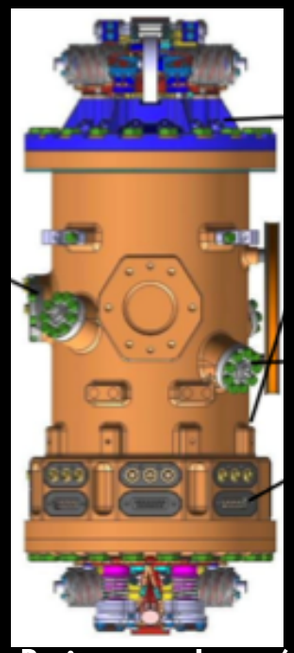
- Measurement points must be shielded from fluctuating non-gravitational influences:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing

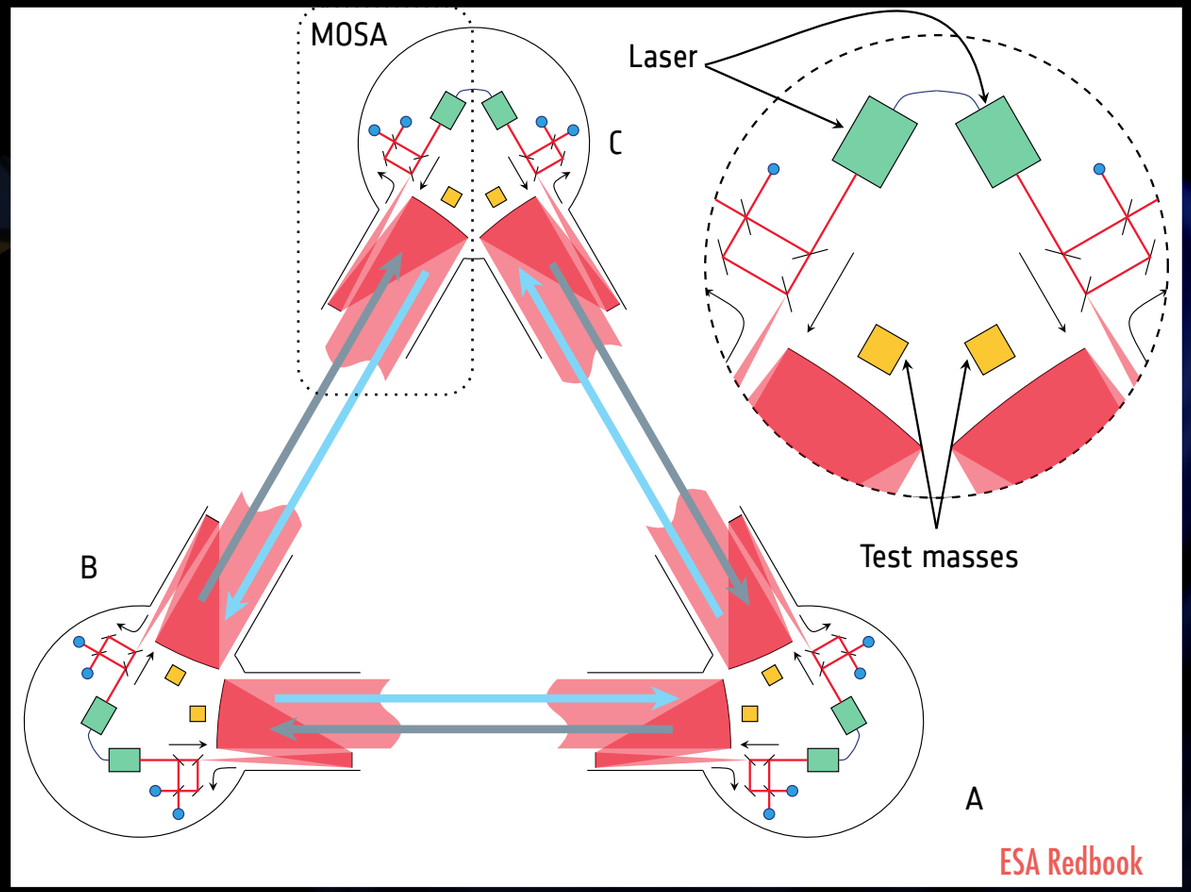






ESA Redbook - OHB Italia

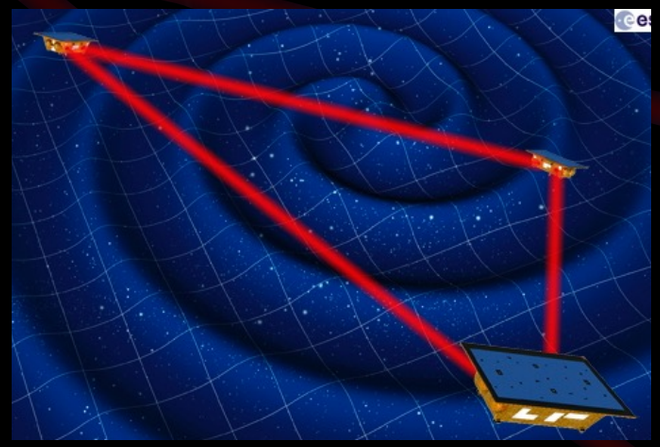




ESA Redbook

Mission design

- Several steps towards the required precision of measurement



Mission design

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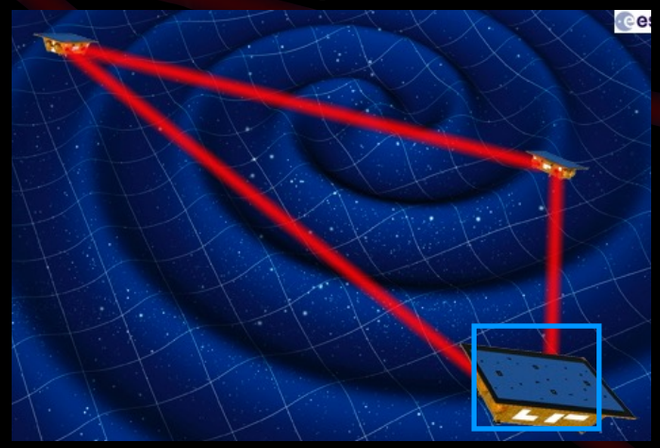

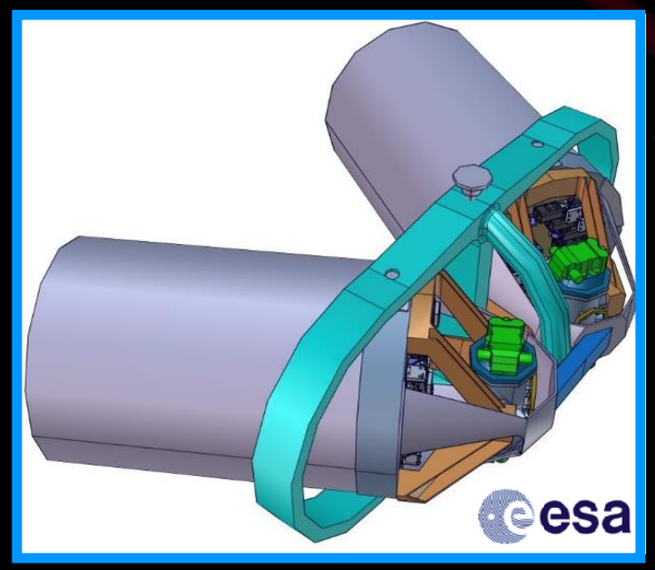

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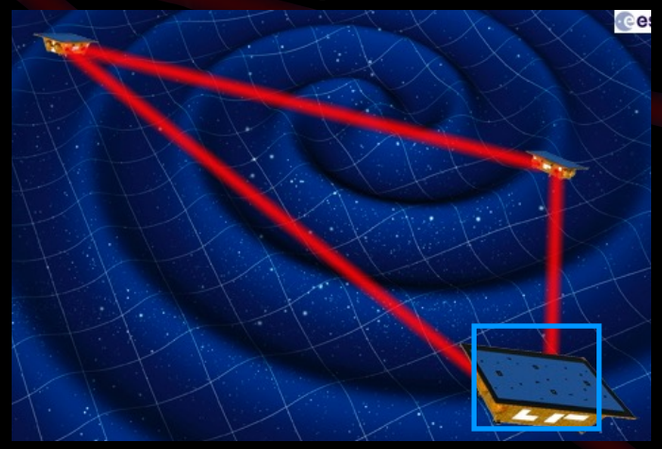

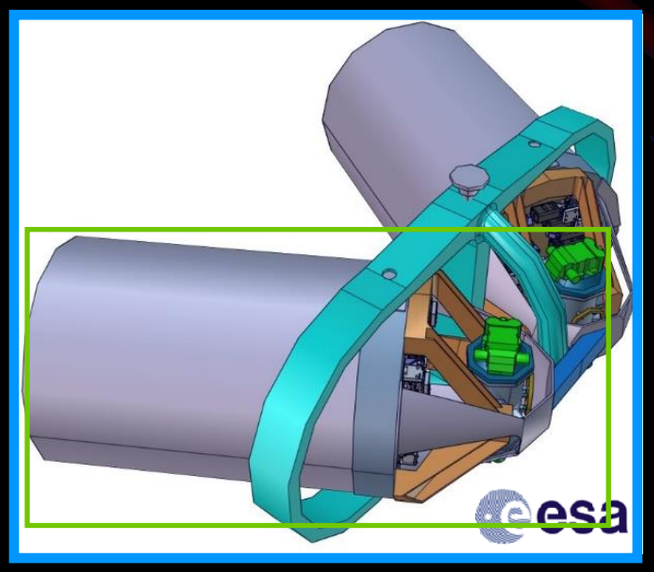

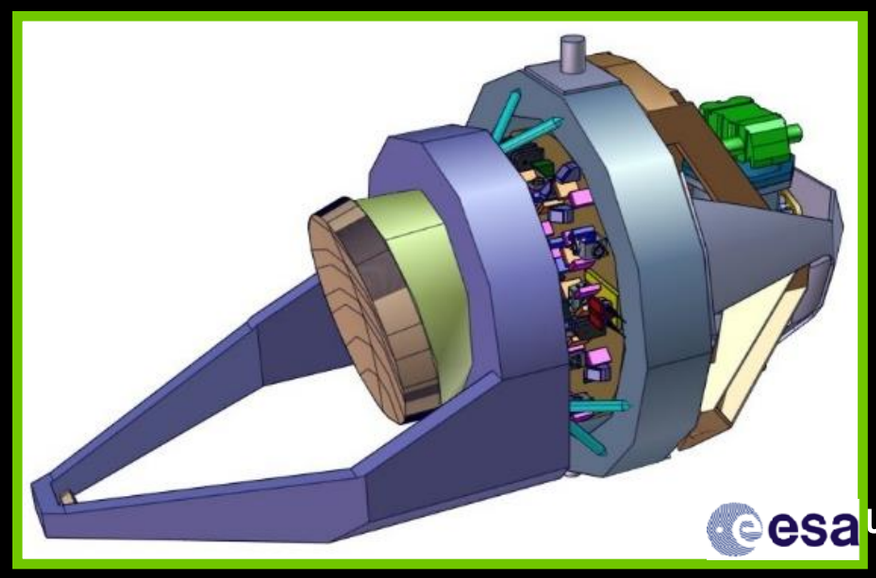

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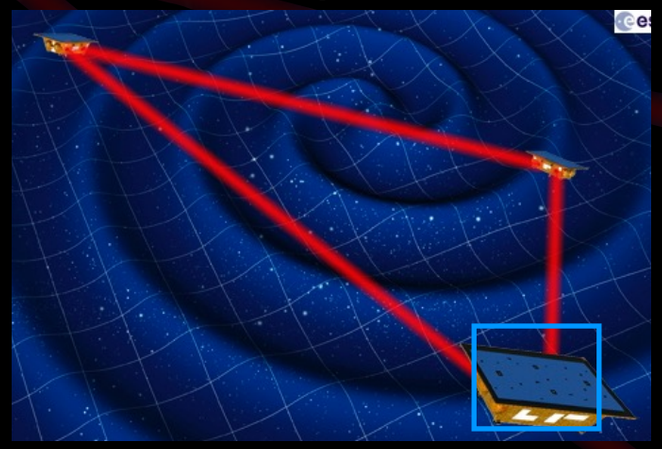

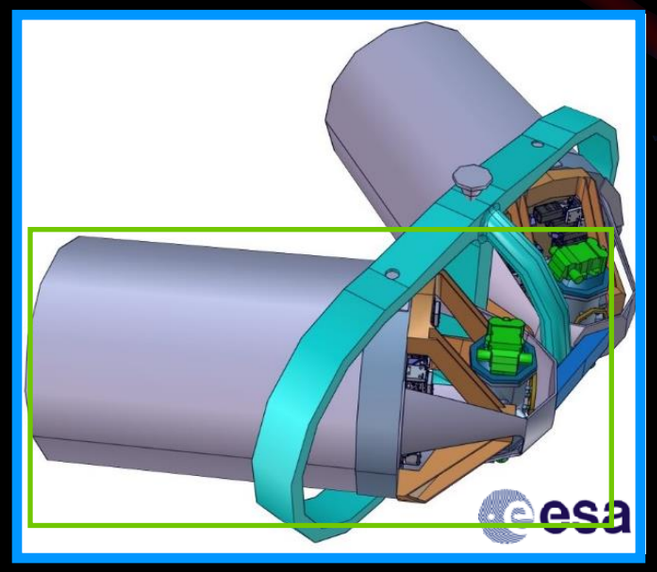

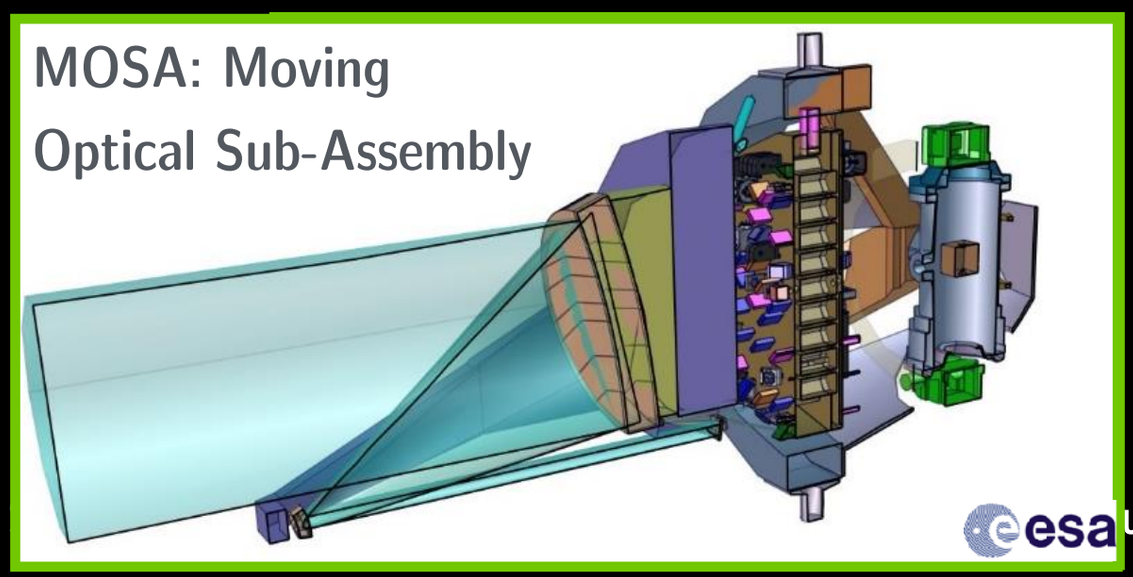

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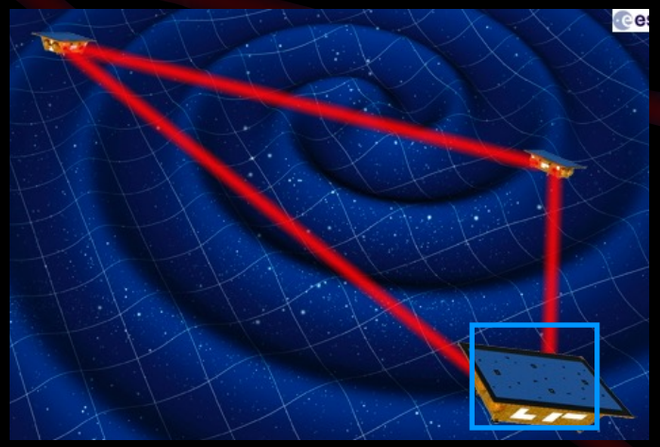

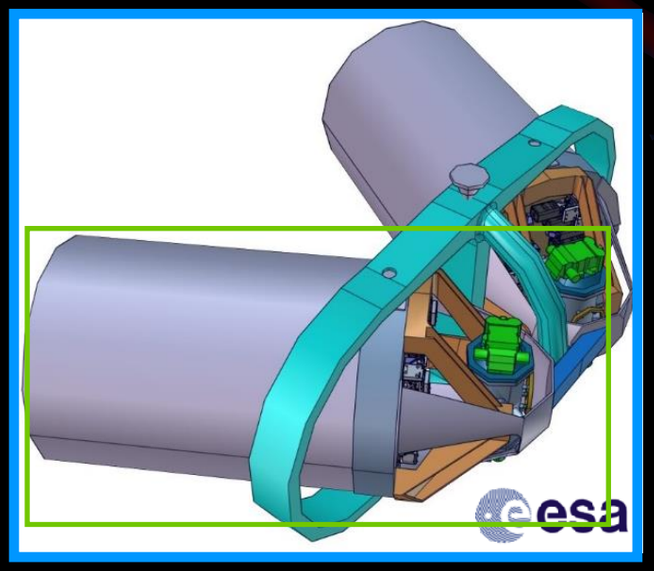

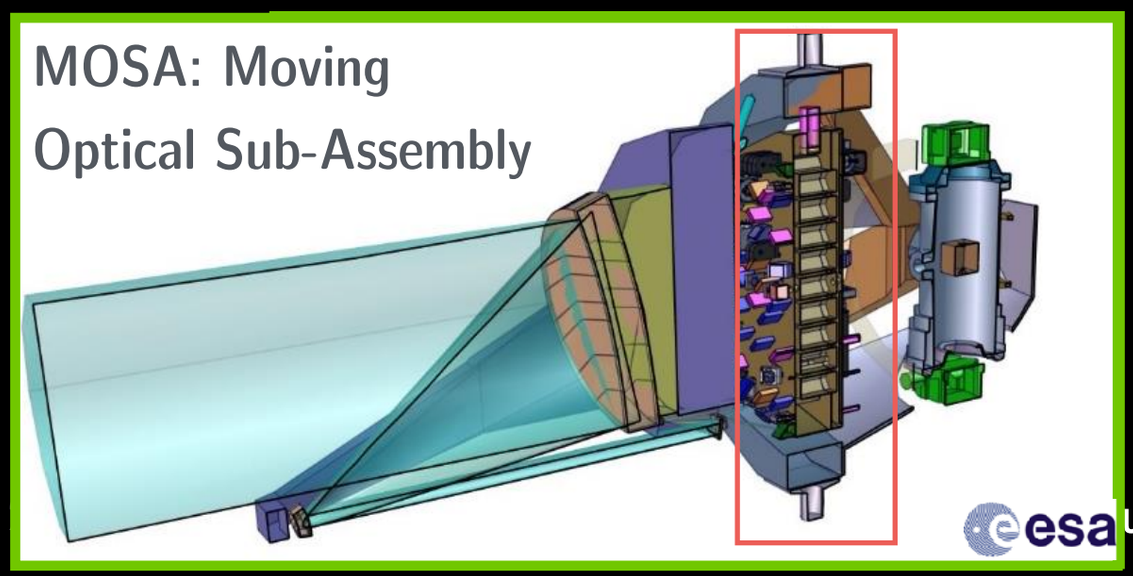

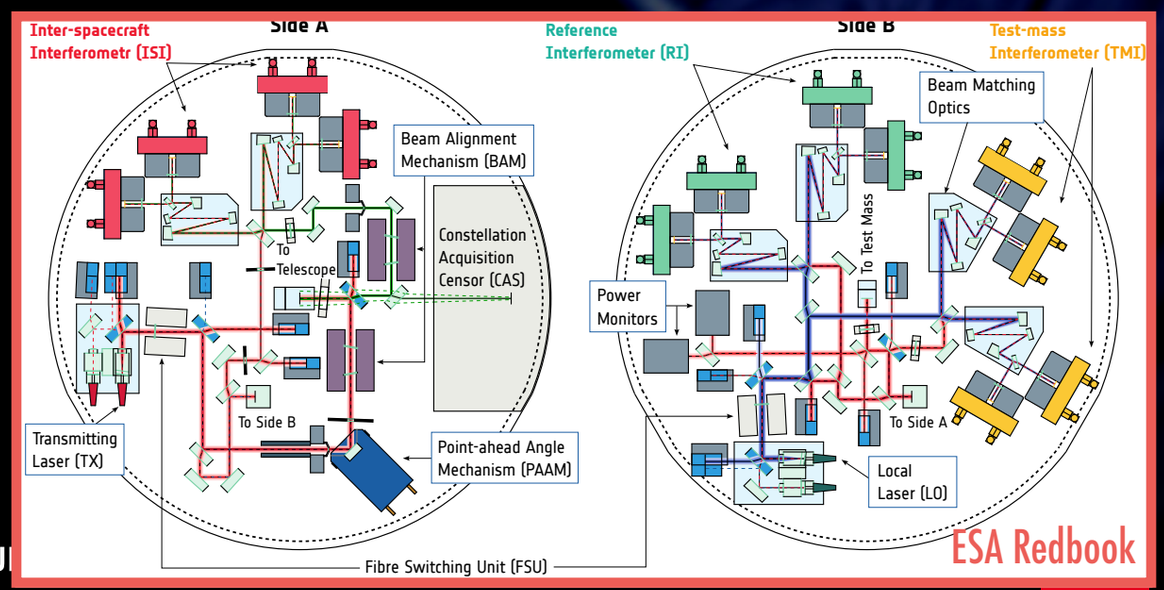

ESA Redbook

Mission design

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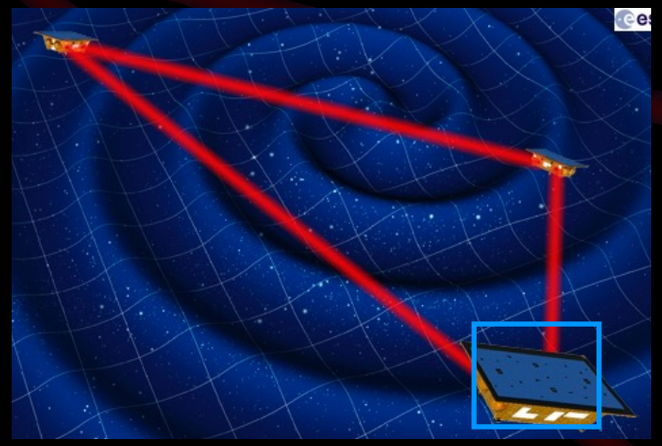
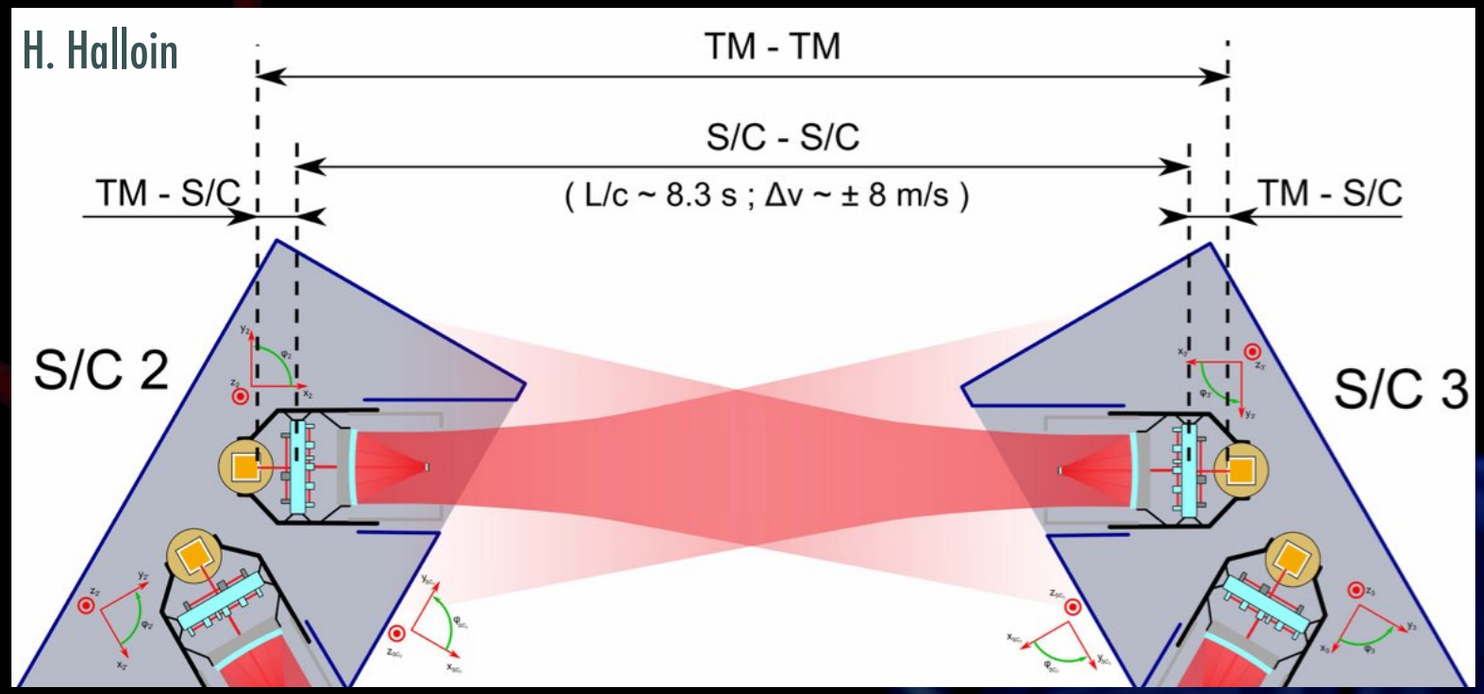
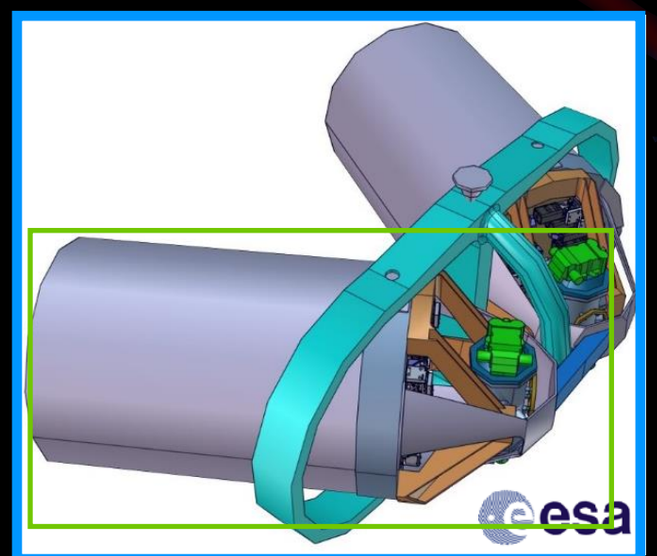
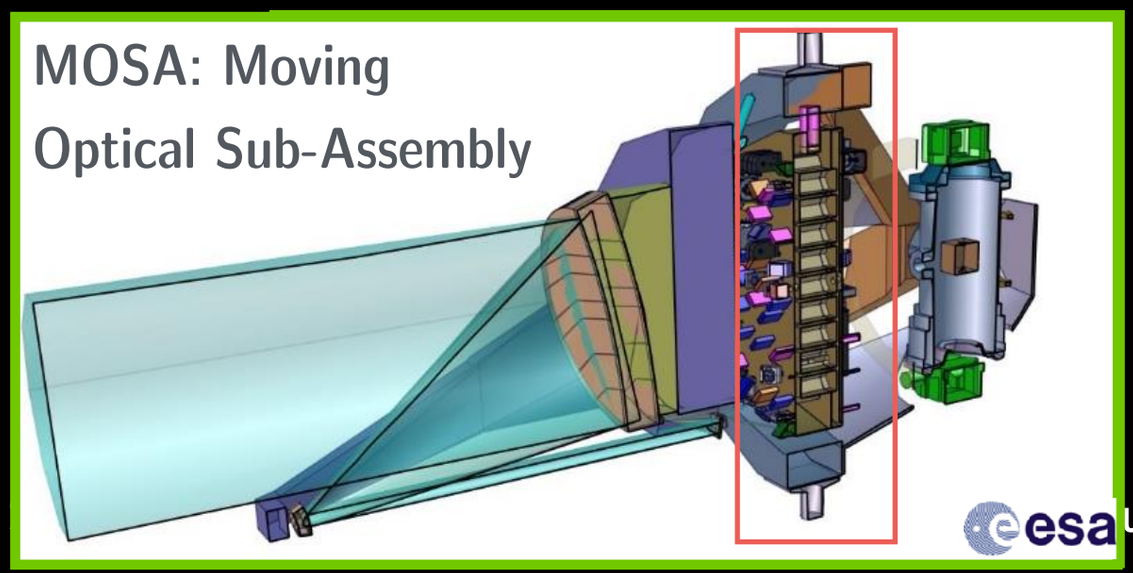
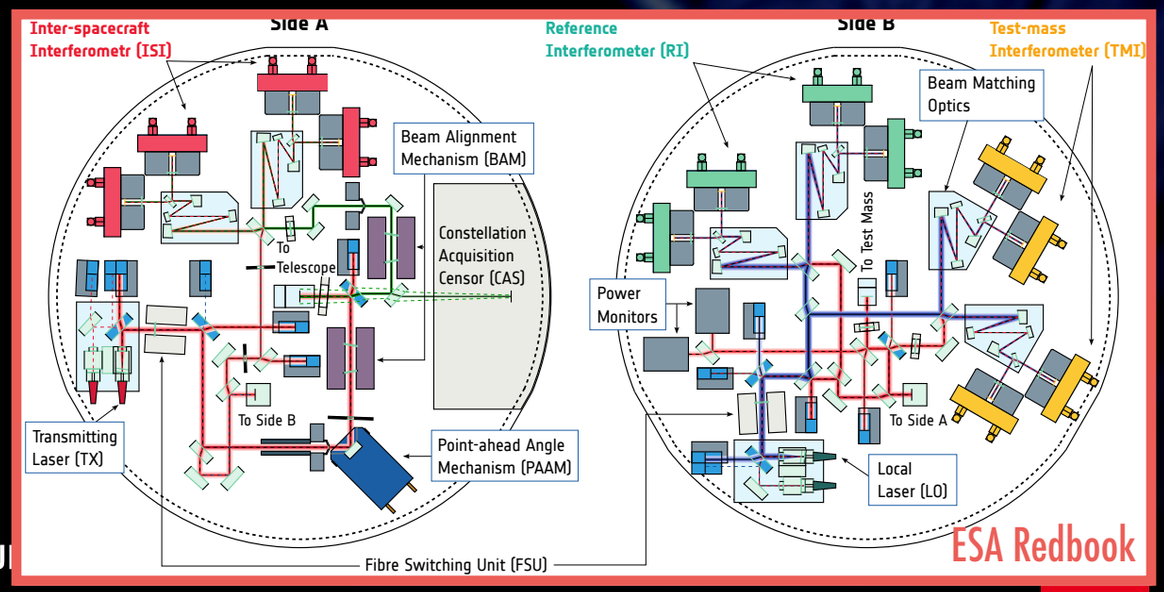


(TM2→SC2) + (SC2→SC3) + (SC3→TM3)









LISA Consortium

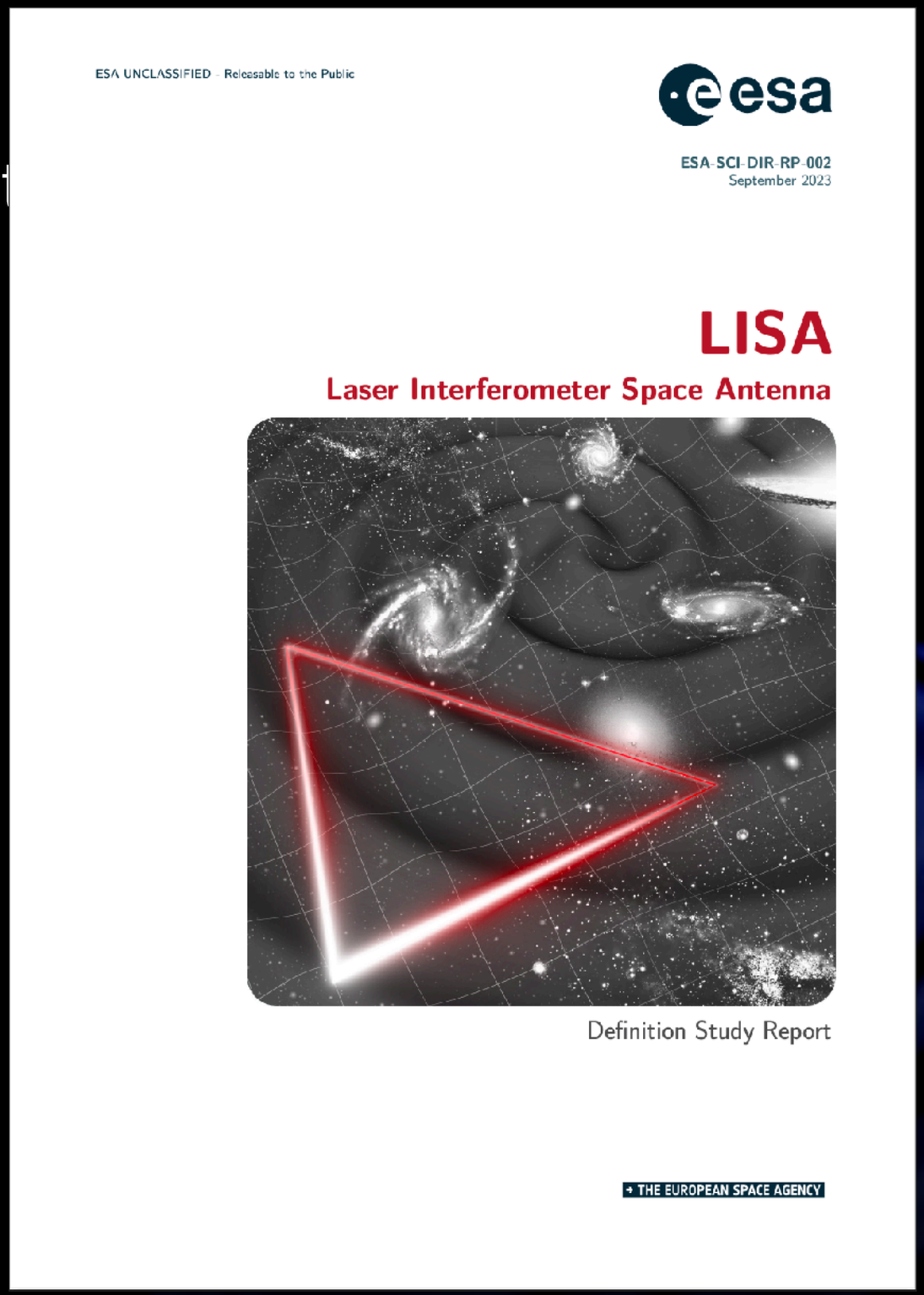
- LISA Consortium submitted the L3 LISA proposal to the ESA call in 2017
- It has many very active working groups
- It was organised for the formulation phases (0, A and B1)
- With the start of the development phase, a new organisation is necessary.

=> ongoing reorganisation:

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

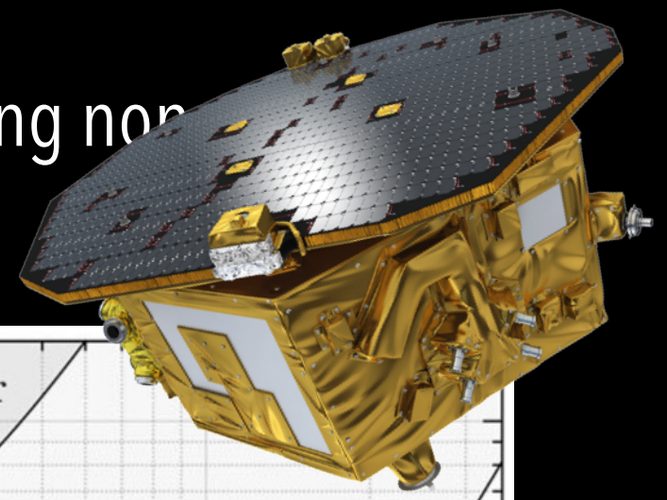
LISA RedBook

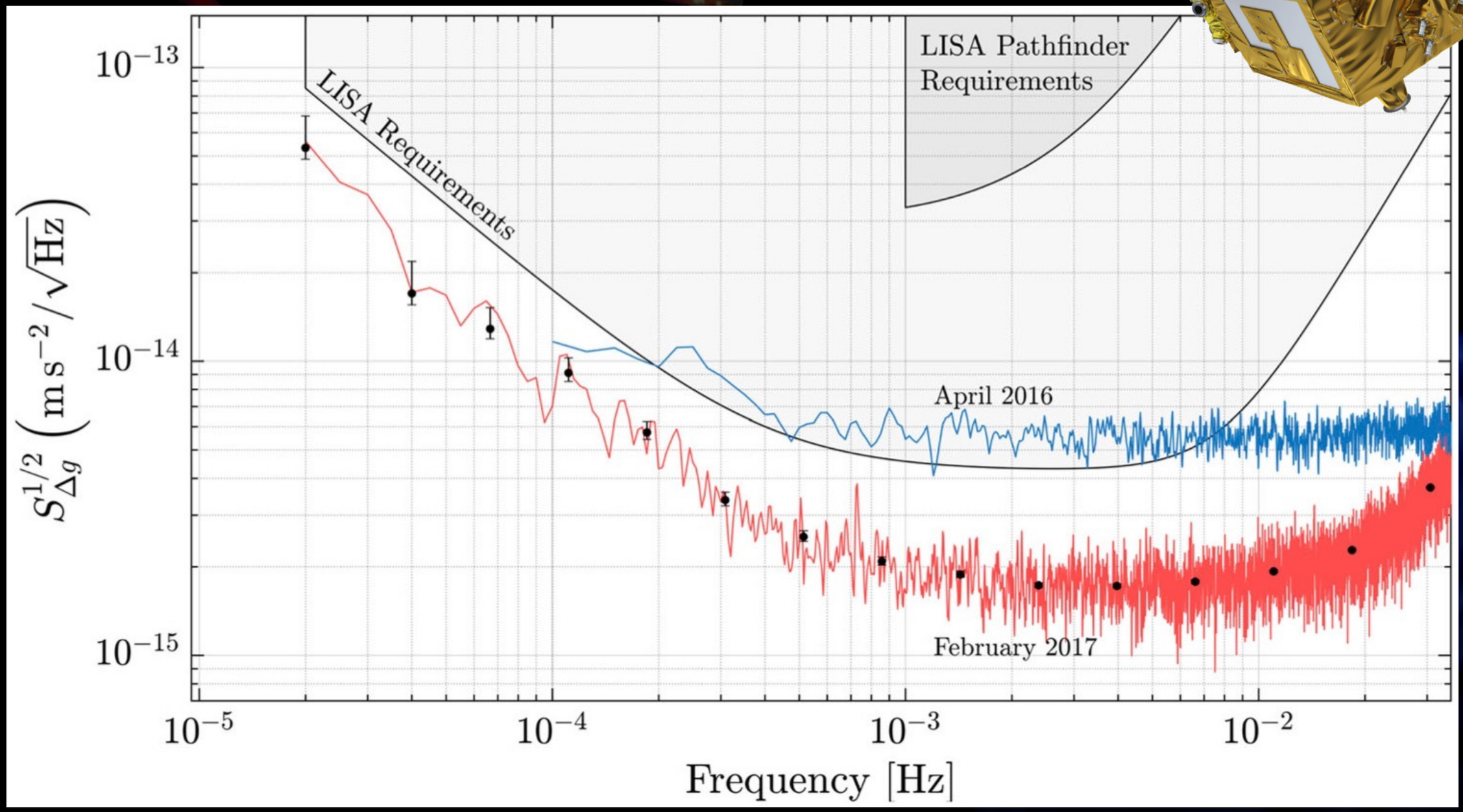
- LISA Definition Study Report (Redbook):
  - written by the LISA Science Study Team with t
  - submitted and validated at adoption
- Content:
  - Science of LISA
  - Instrument
  - Data processing
  - Organisation
- Available at :
  - arXiv:2402.07571
  - www.cosmos.esa.int/web/lisa/lisa-redbook



LISAPathfinder final main results

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





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