LISA: mission, objectives, status and Paris Observatory

Antoine Petiteau (DPhP/IRFU/CEA)

co-PI France, Consortium Board, ESA LISA Science Study Team,
lead LISA Data Processing Group

Journée LISA Observatoire de Paris

10th Dec 2021 - IAP

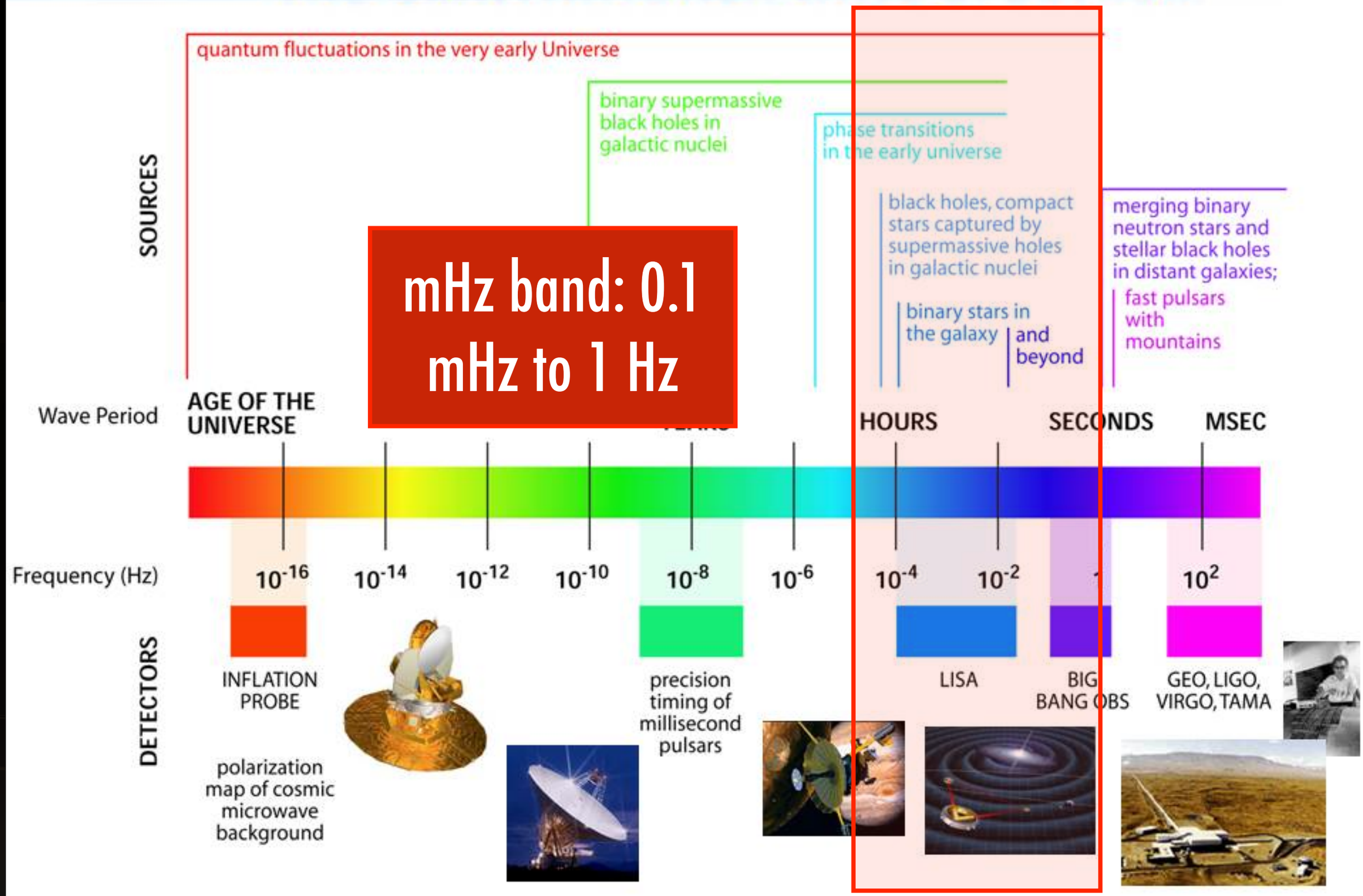
Overview

- Gravitational wave sources in the mHz band and LISA science objectives
- The mission
  - Space segment (hardware)
  - Ground segment (data analysis & science exploitation)
- Science performances
- Status: end of phase A (MFR) and Phase B1
- Organisations: Consortium & LISA France
- LISA at Paris Observatory

Overview

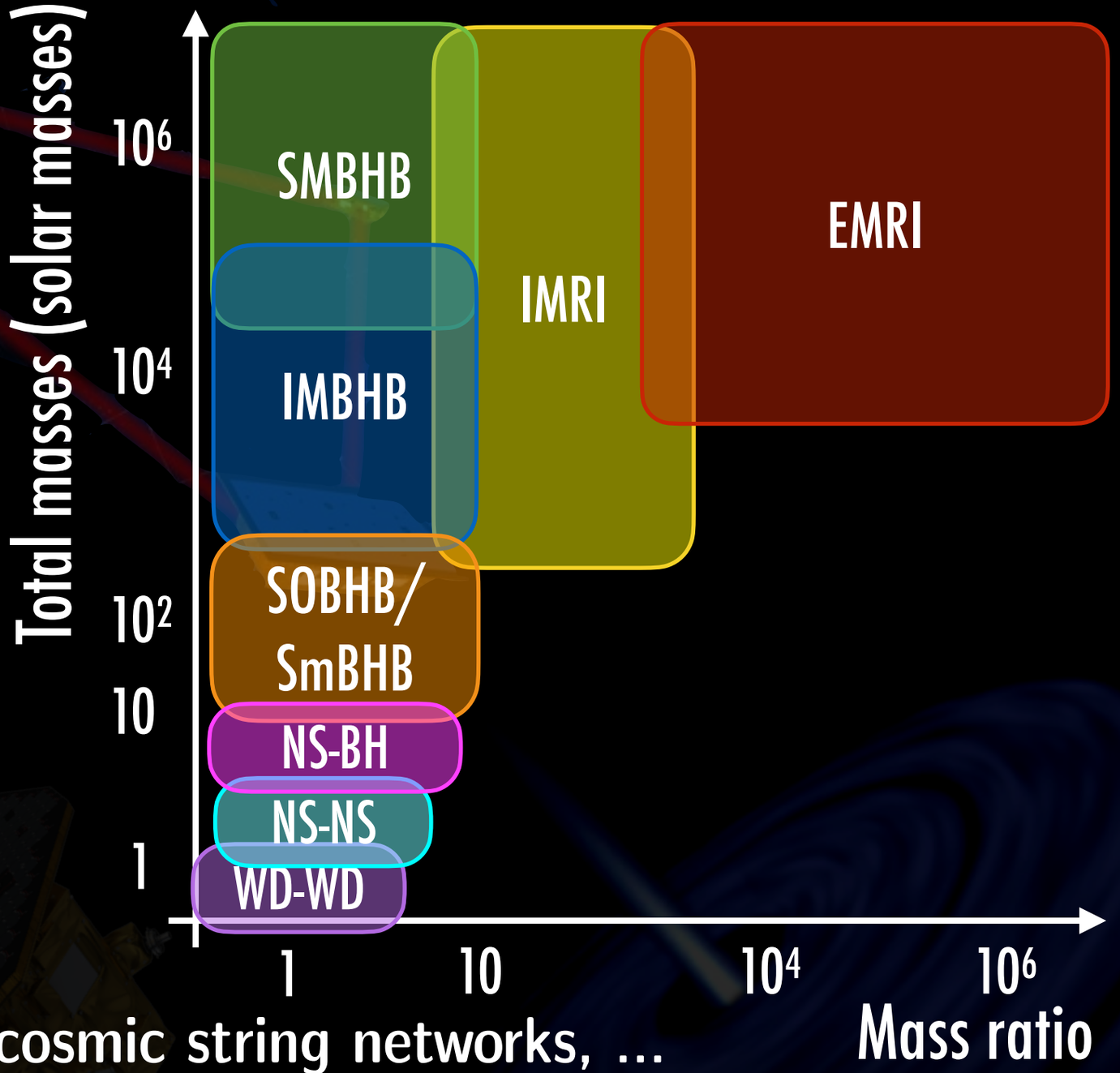
- Gravitational wave sources in the mHz band and LISA science objectives
- The mission
  - Space segment (hardware)
  - Ground segment (data analysis & science exploitation)
- Science performances
- Status: end of phase A (MFR) and Phase B1
- Organisations: Consortium & LISA France
- LISA at Paris Observatory

THE GRAVITATIONAL WAVE SPECTRUM



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 ?

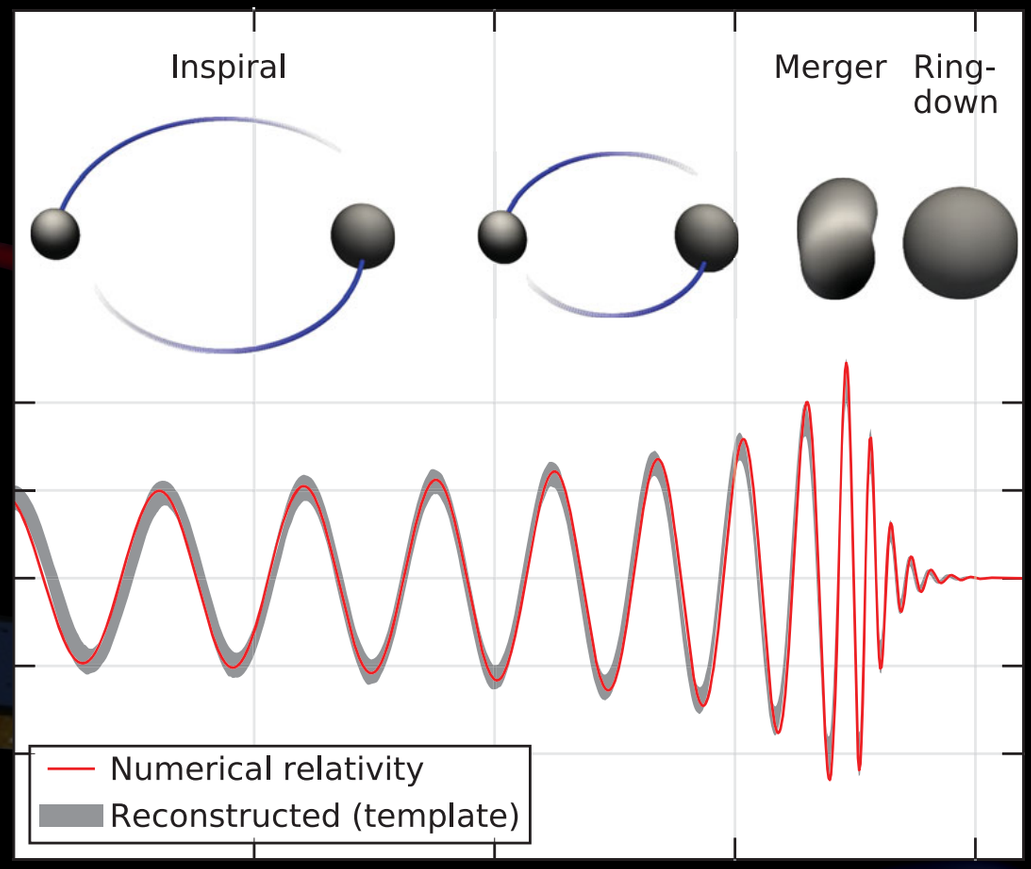


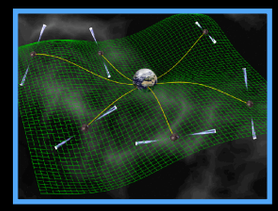
Stellar mass Black Hole Binaries

- Binaries with 2 black holes of masses between few M_{Sun} and 100 M_{Sun} , so called “Stellar mass BH Binaries”
- Inspiral: emission in the mHz band
- Merger: powerful emission around few tens Hz
  => many sources already observed
- Fast evolution: few years
  from tens mHz to tens Hz
  => multi-observatories
  observations

Super Massive Black Hole Binaries

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

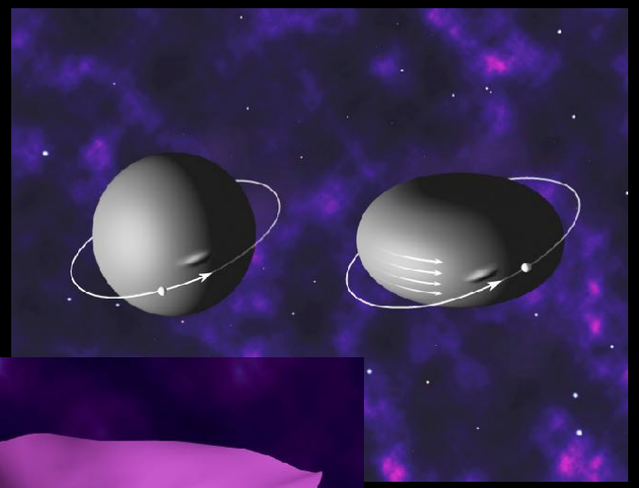


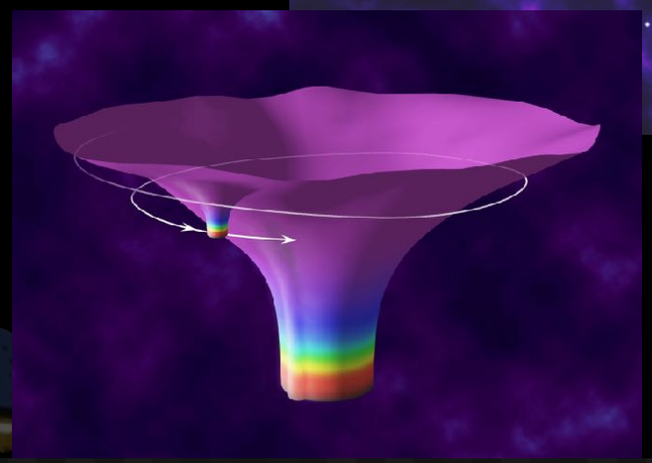


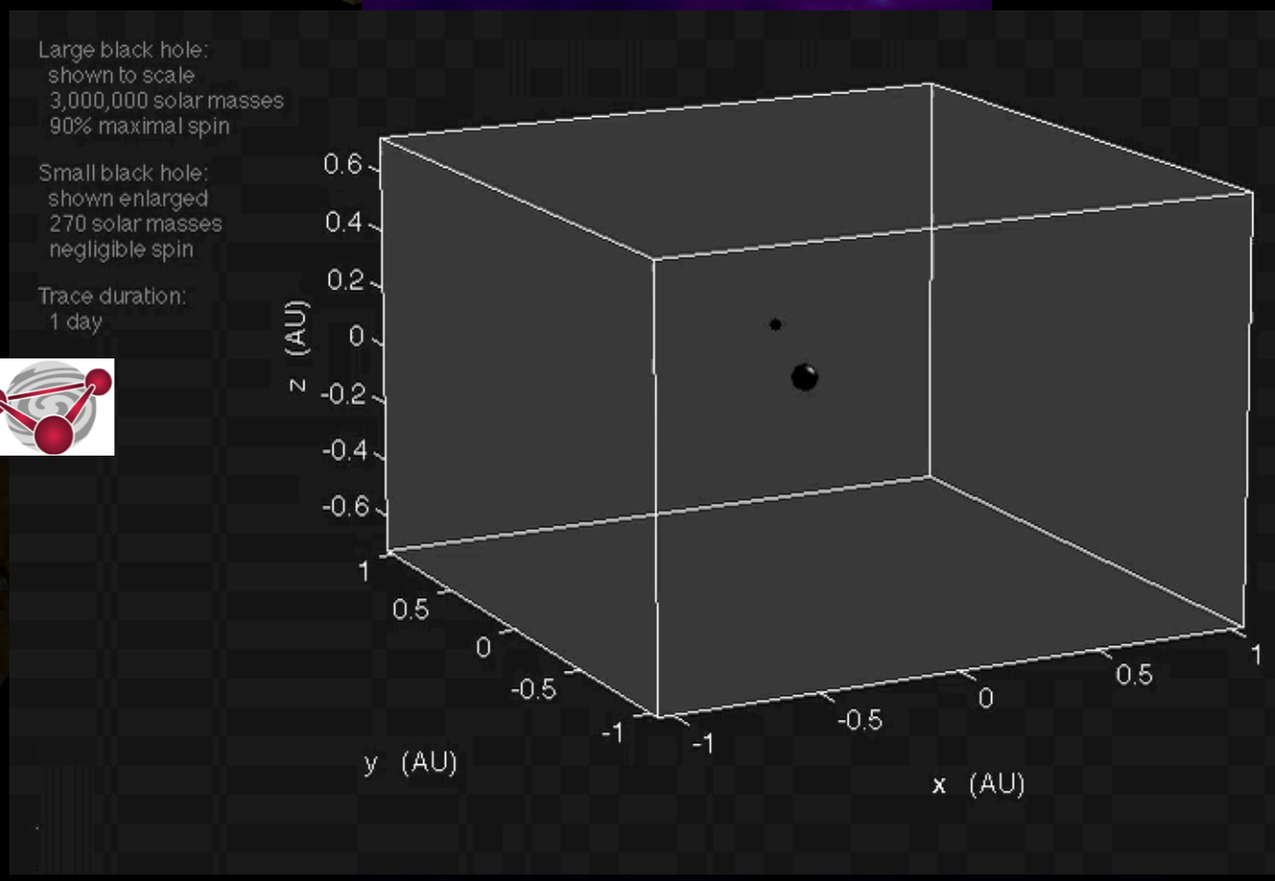
© EHT (2019)

EMRIs

- Capture of a “small” object by massive black hole (10 – 10^6 M_{Sun}): Extreme Mass Ratio Inspiral
  - Mass ratio $>$ 200
  - GW gives information on the geometry around the black hole.
  - Test General Relativity in strong field
  - Frequency : 0.1 mHz to 0.1 Hz
  - Large number of source could be observed by LISA

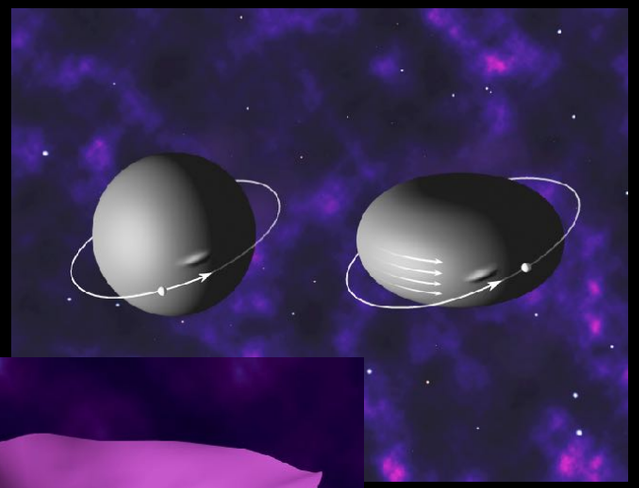


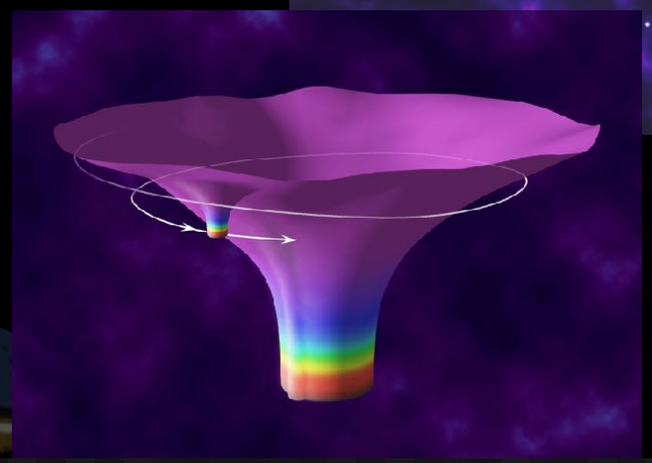


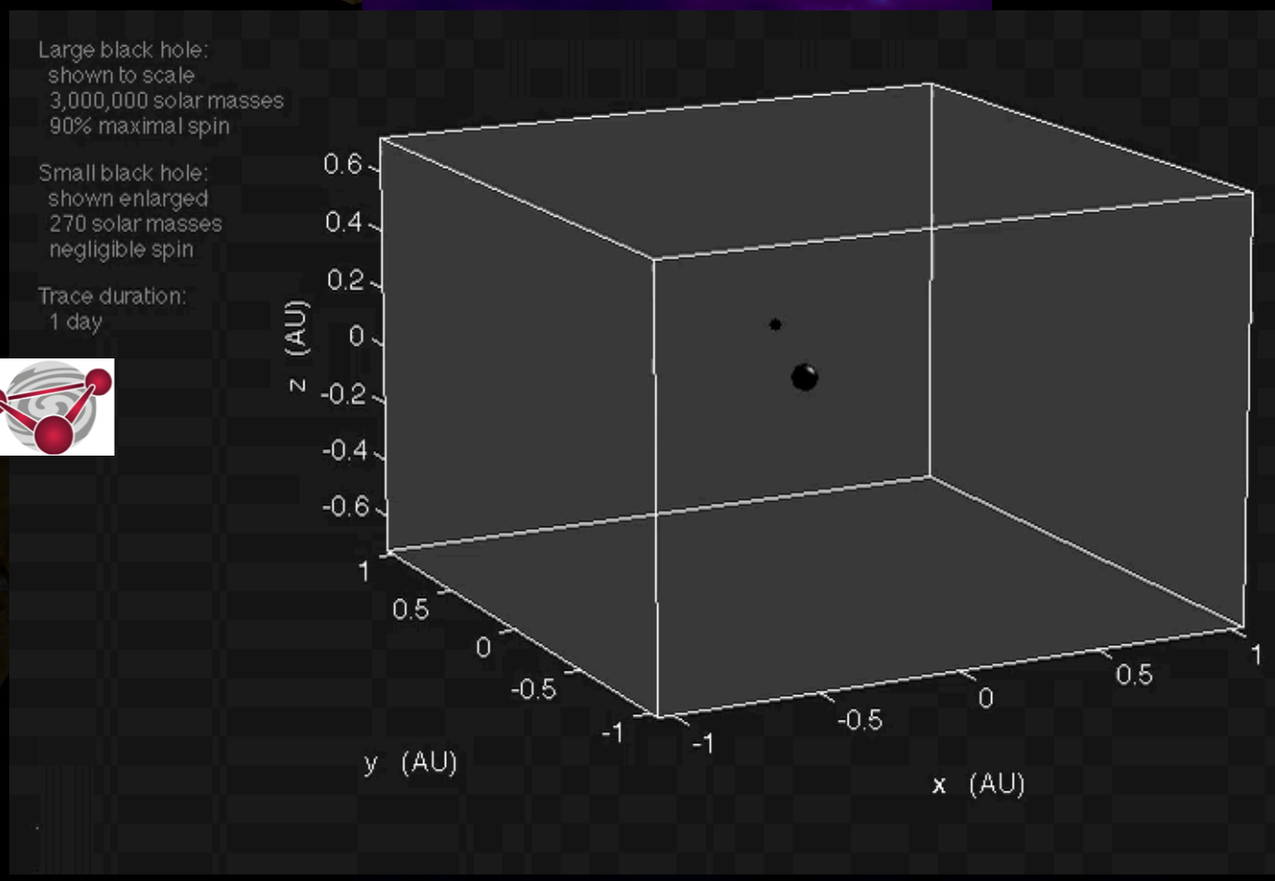


EMRIs

- Capture of a “small” object by massive black hole (10 – 10^6 M_{Sun}): Extreme Mass Ratio Inspiral
  - Mass ratio $>$ 200
  - GW gives information on the geometry around the black hole.
  - Test General Relativity in strong field
  - Frequency : 0.1 mHz to 0.1 Hz
  - Large number of source could be observed by LISA







Science Objectives

Define in the Science Requirements Doc.:

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

Science Objectives

Define in the Science Requirements Doc.:

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

Astrophysics

Funcdamental physics

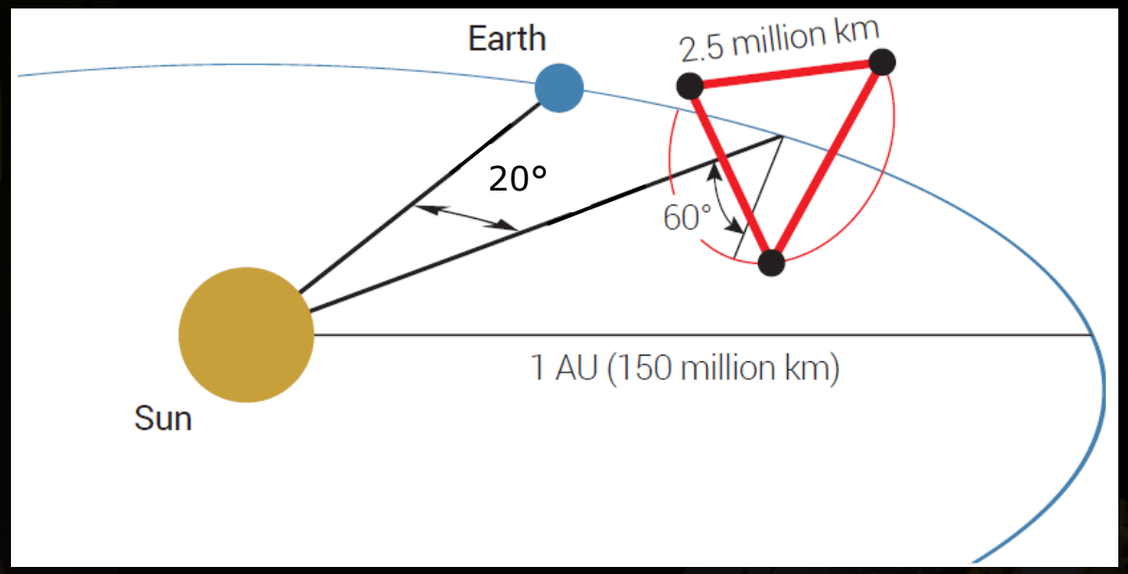
Cosmology

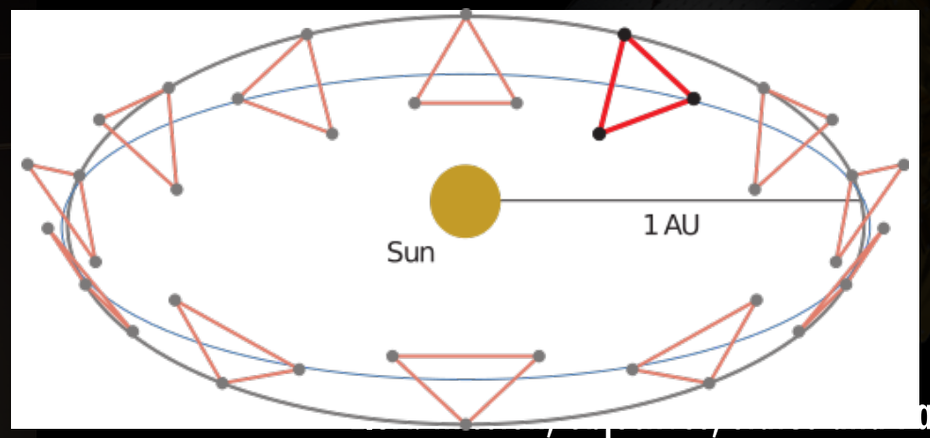
Overview

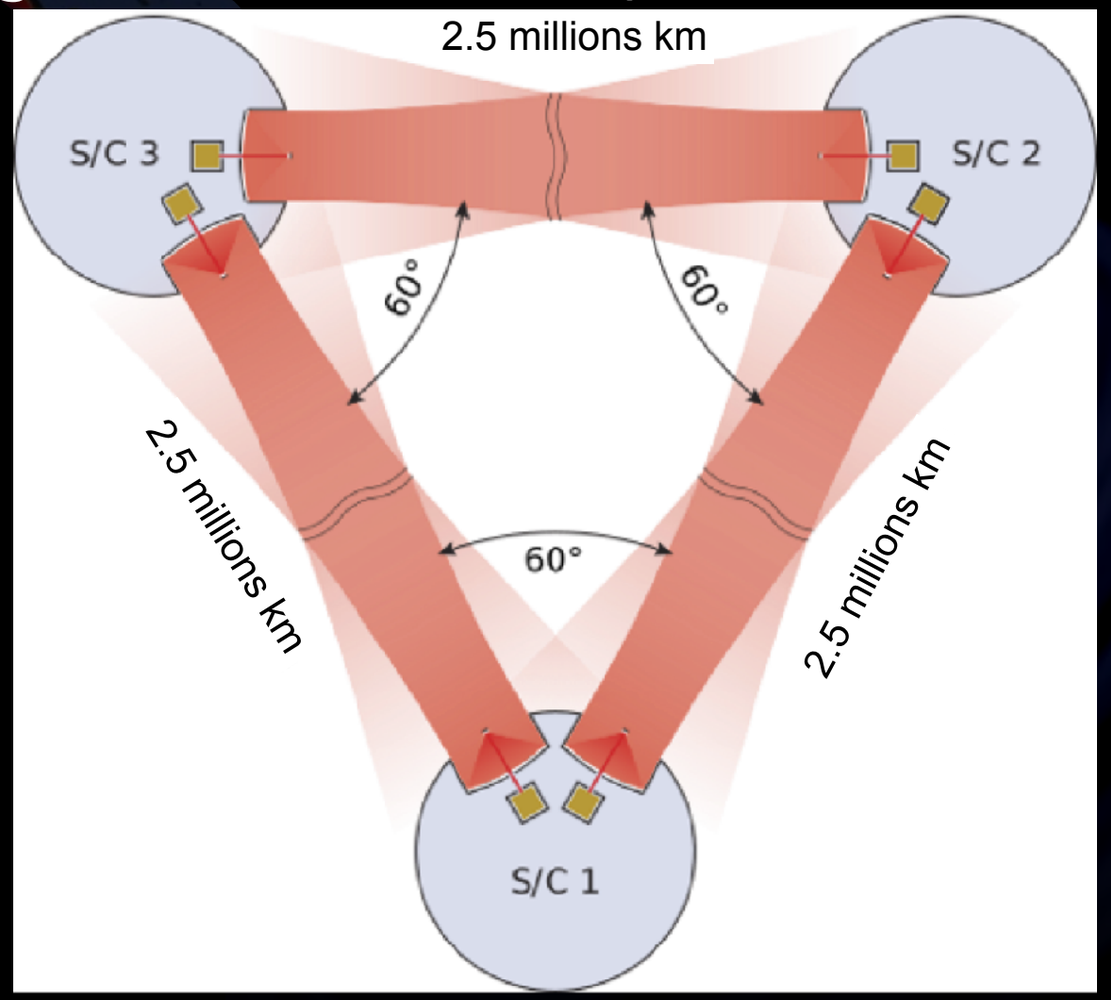
- Gravitational wave sources in the mHz band and LISA science objectives
- The mission
  - Space segment (hardware)
  - Ground segment (data analysis & science exploitation)
- Science performances
- Status: end of phase A (MFR) and Phase B1
- Organisations: Consortium & LISA France
- LISA at Paris Observatory

LISA mission

- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of 10^{-21}: few picometers

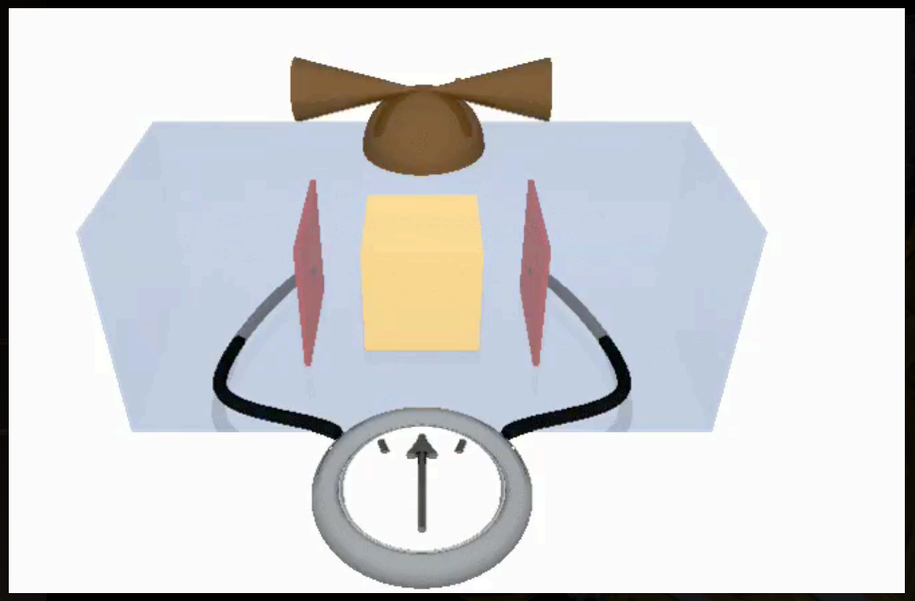


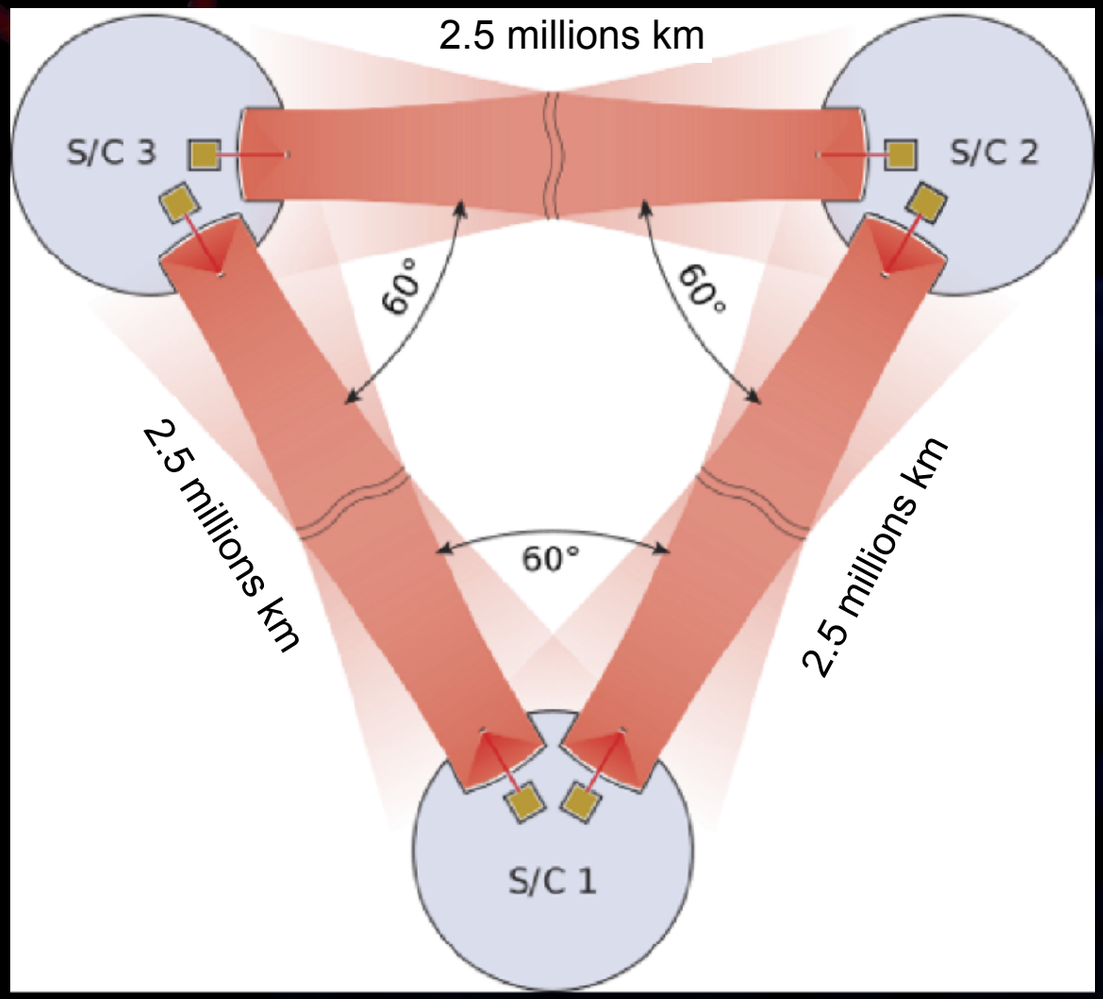




LISA mission

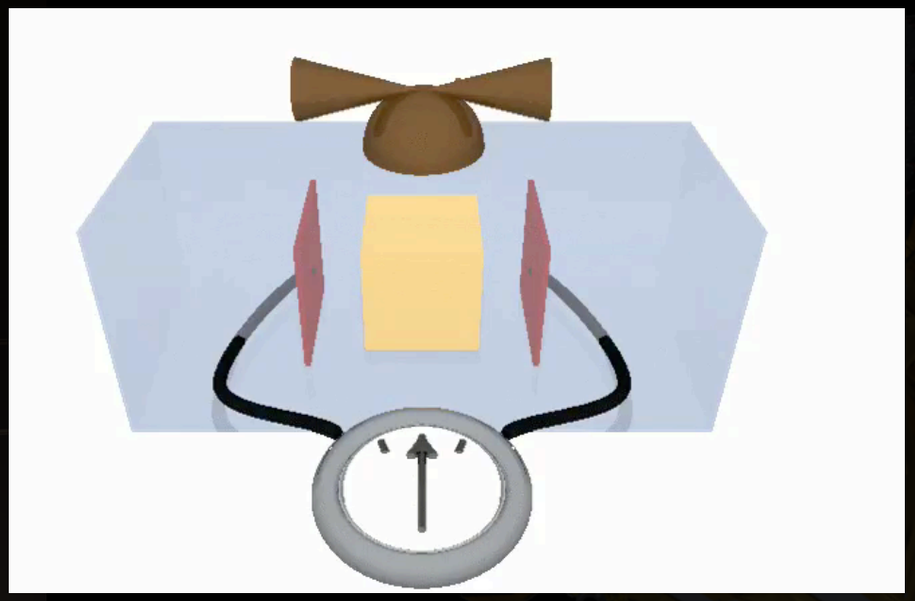
- Spacecraft (SC) should only be sensible to gravity:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing

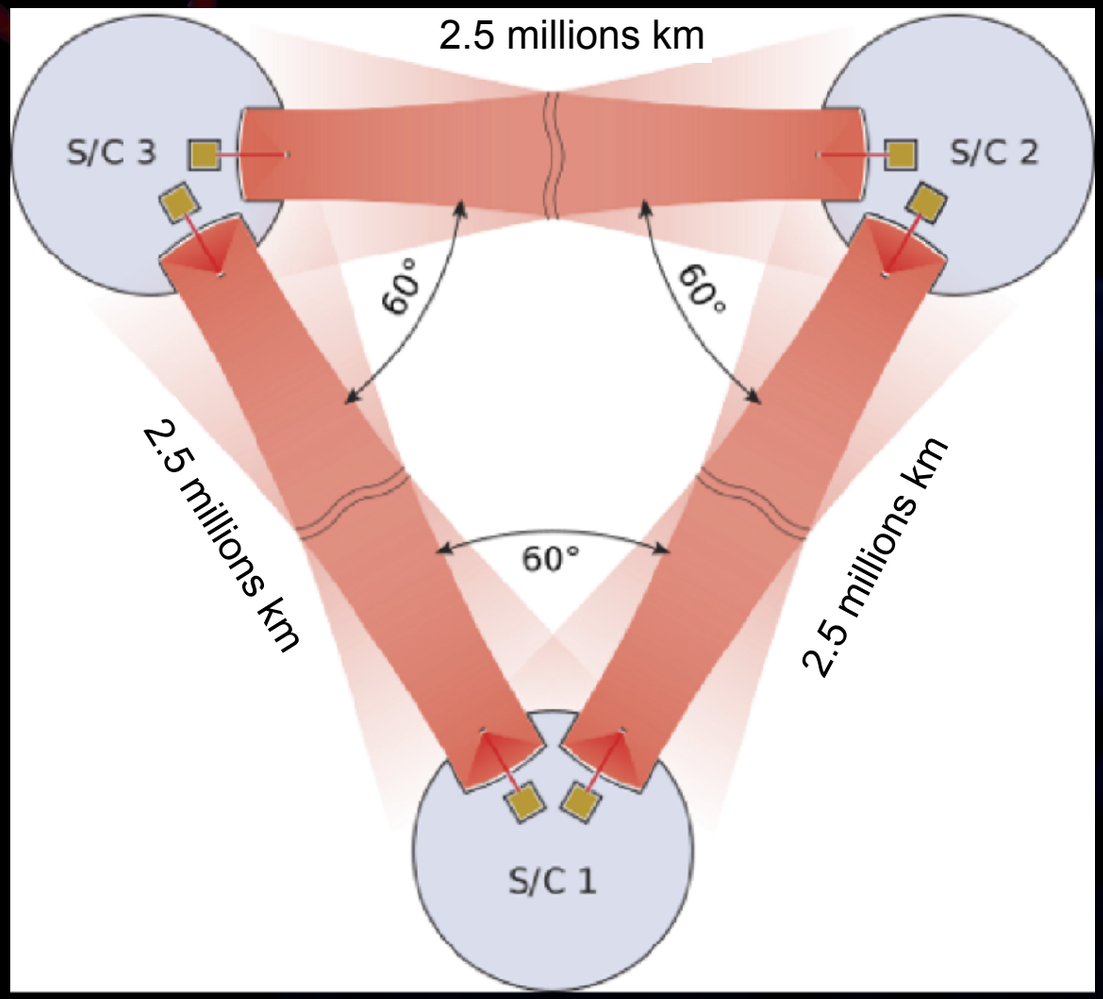




LISA mission

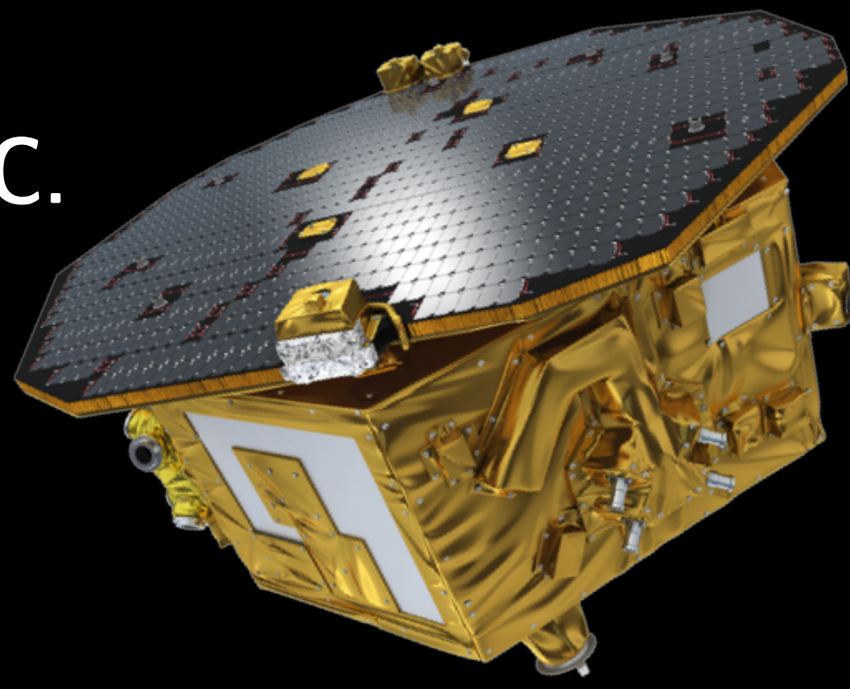
- Spacecraft (SC) should only be sensible to gravity:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing

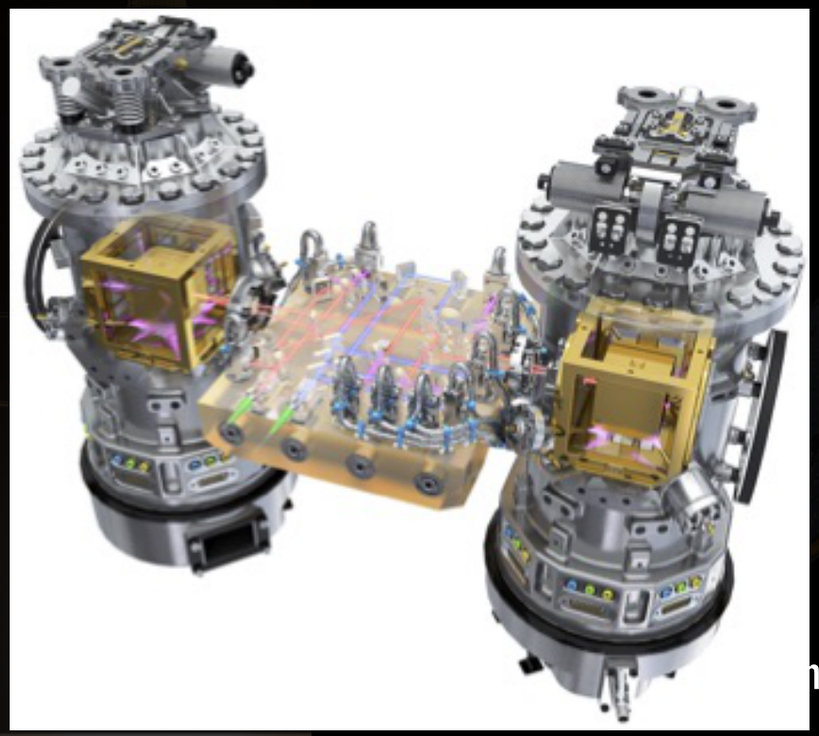


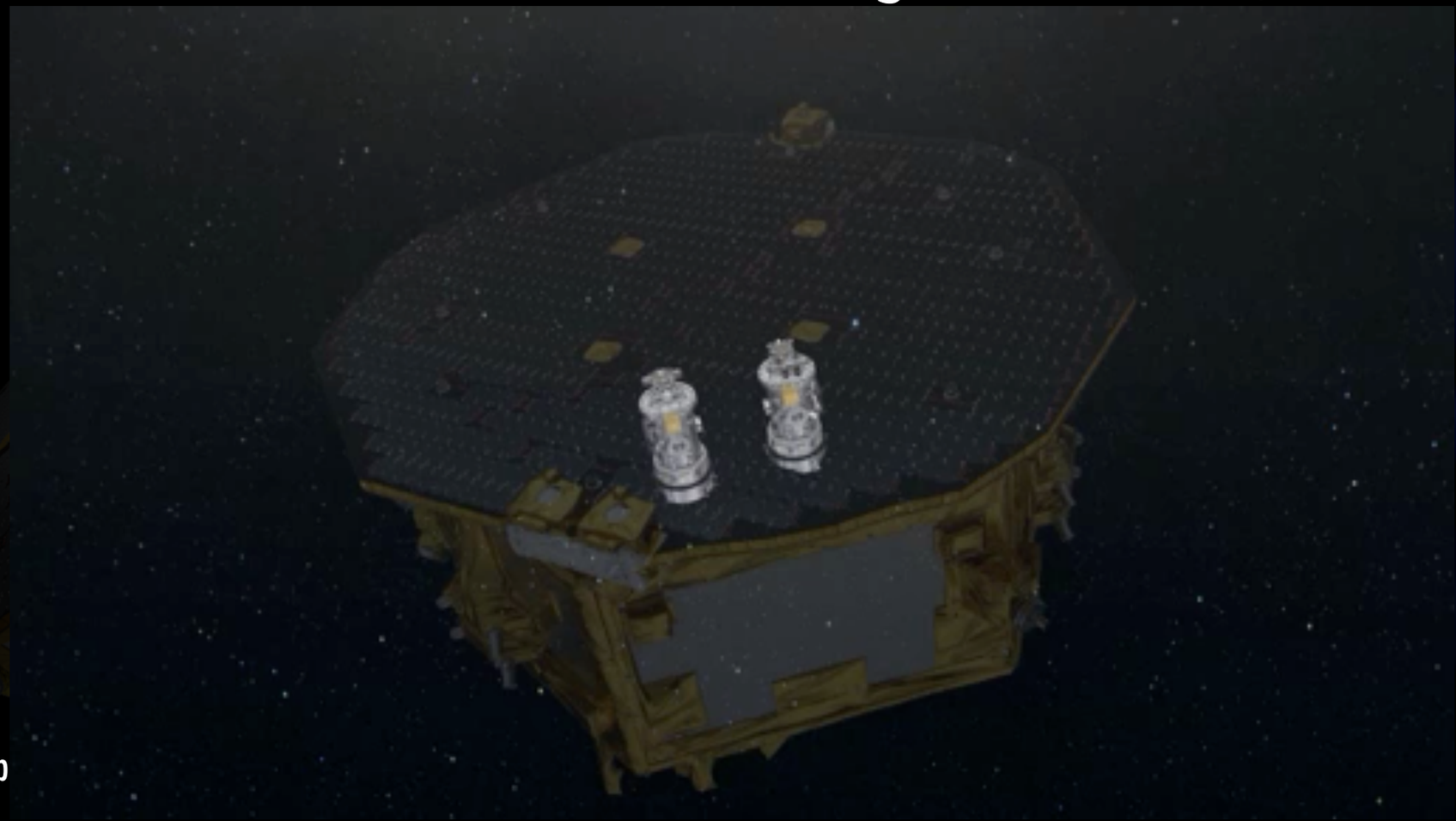


LISAPathfinder

- Basic idea: Reduce one LISA arm in one SC.
- LISAPathfinder is testing:
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
  - Micro-thrusters

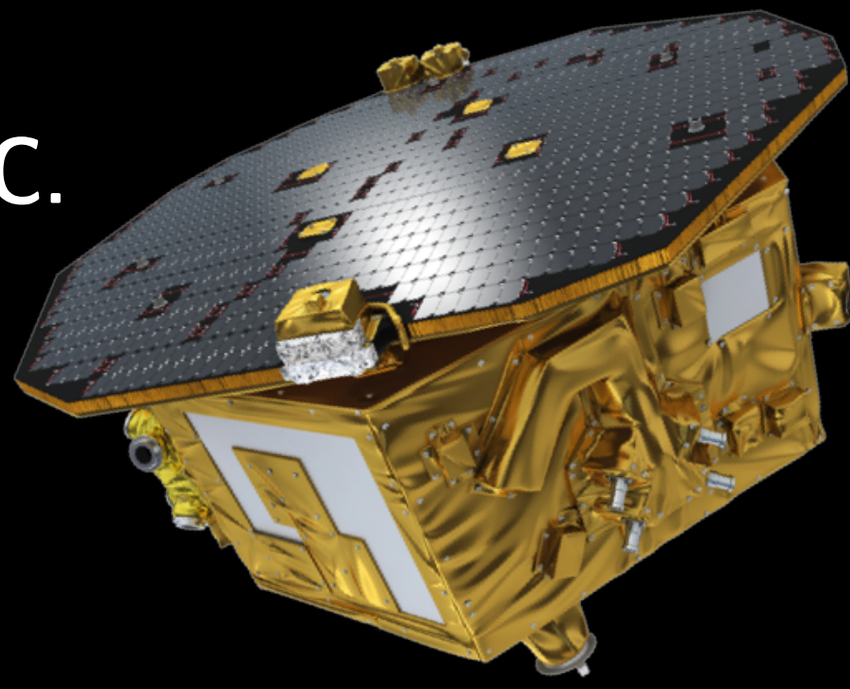


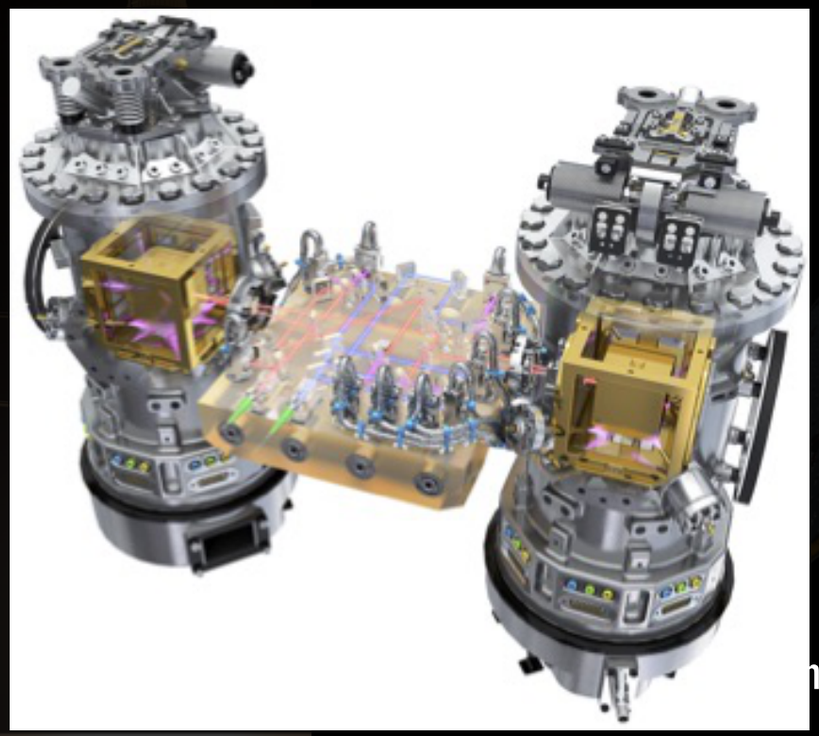


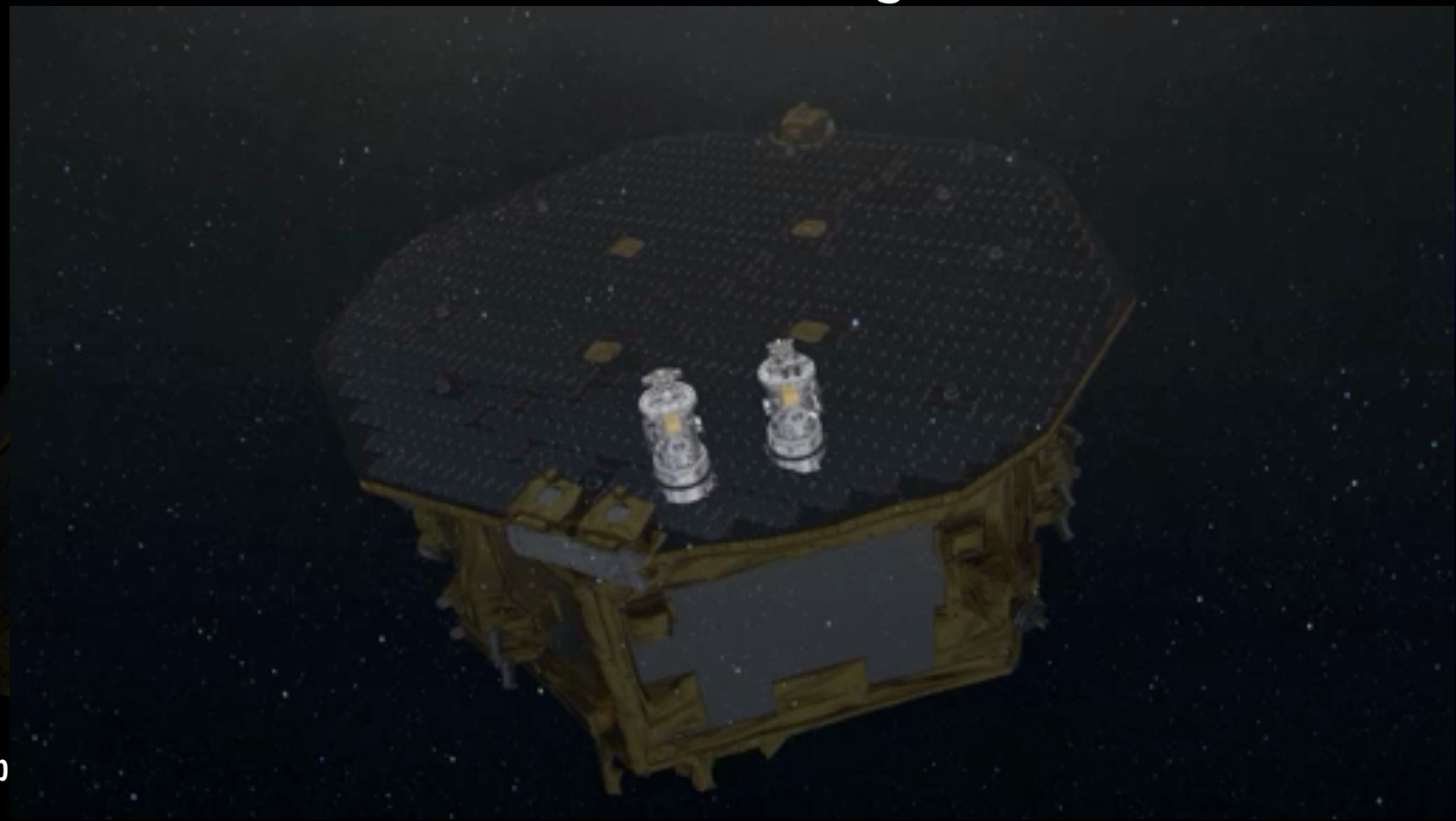


LISAPathfinder

- Basic idea: Reduce one LISA arm in one SC.
- LISAPathfinder is testing:
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
  - Micro-thrusters

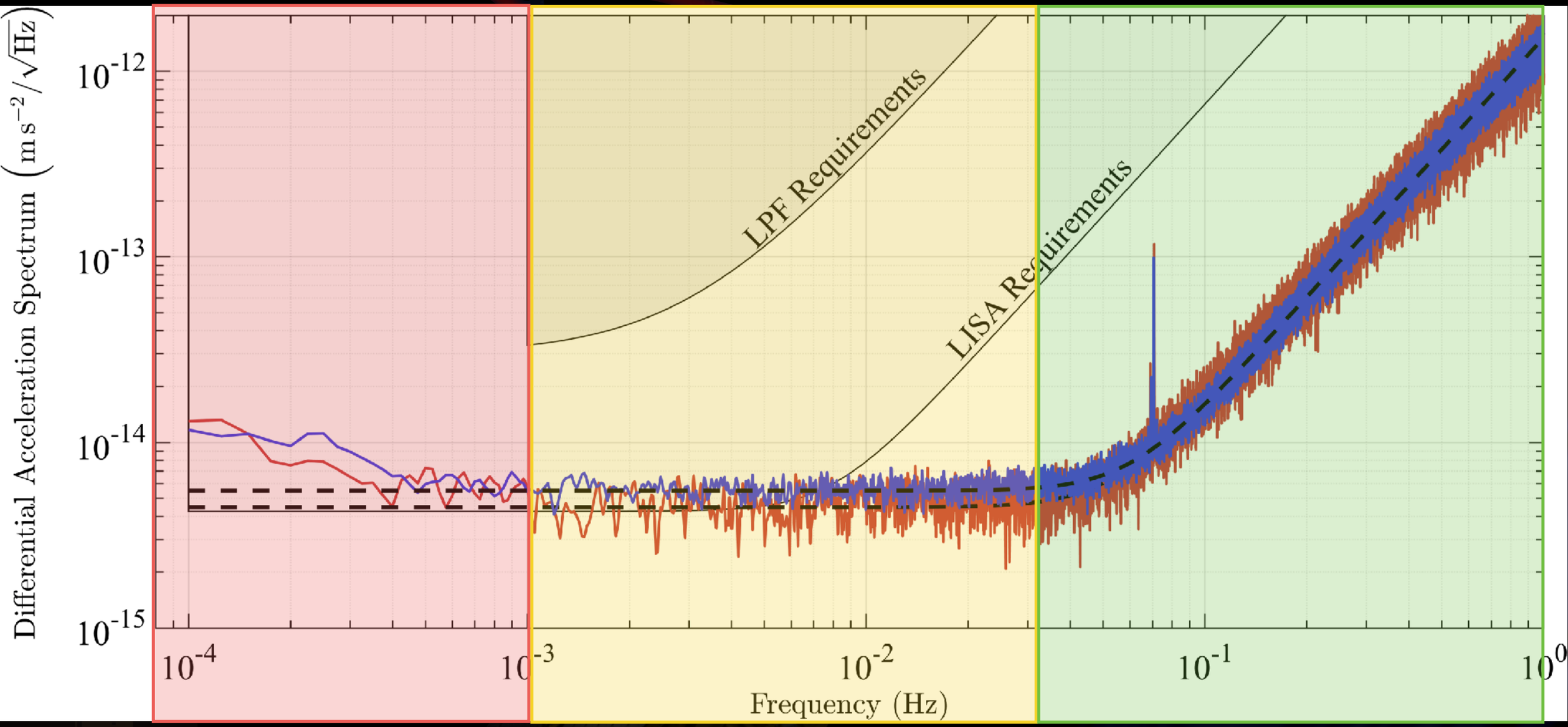






First results

M. Armano et al. PRL 116, 231101 (2016)



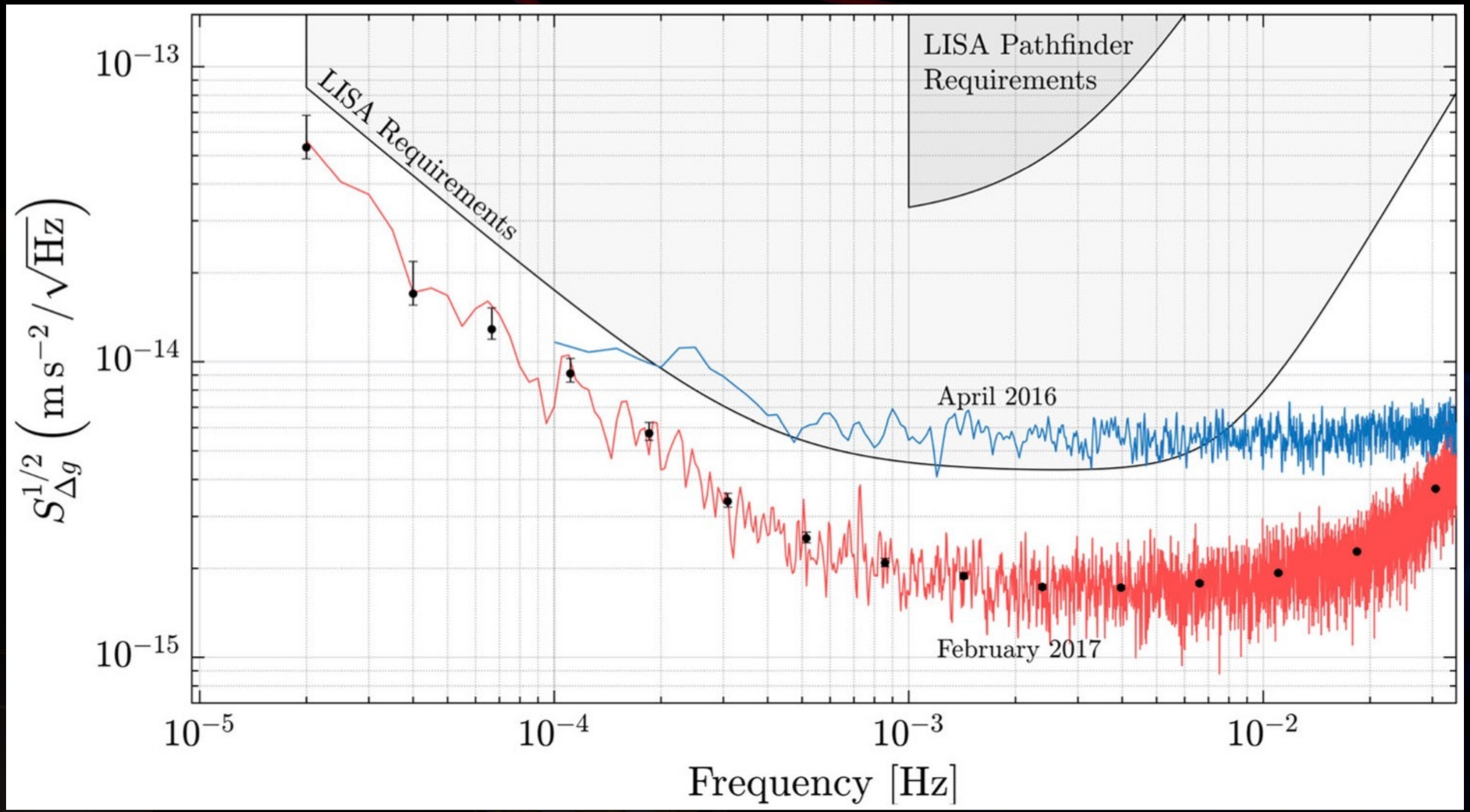
Low frequency noise
Investigation still in progress ...

Brownian noise
Molecules within the noise hit test-masses

Interferometric noise
Not real test-mass motion

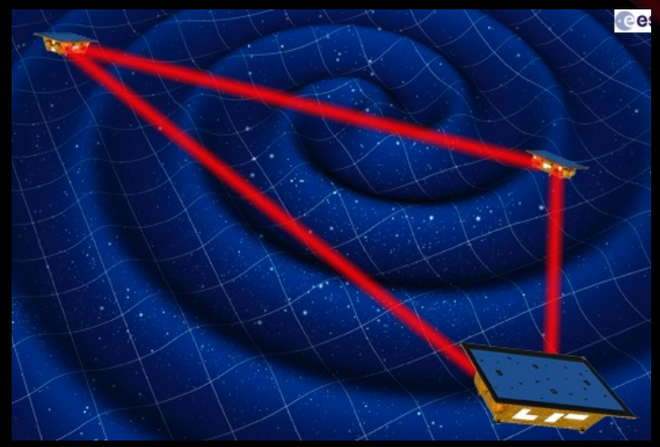
LISAPathfinder final main results

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



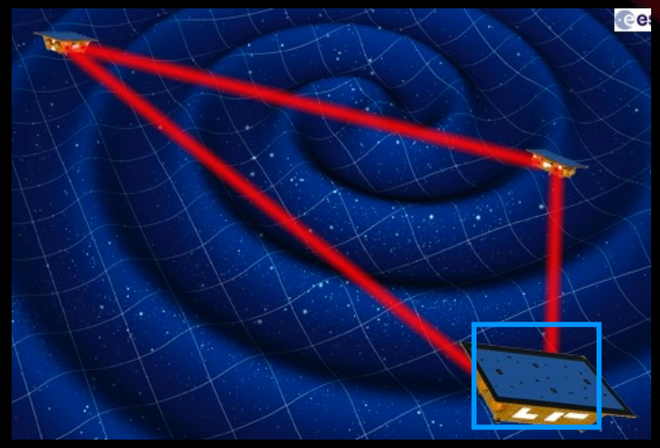
LISA mission

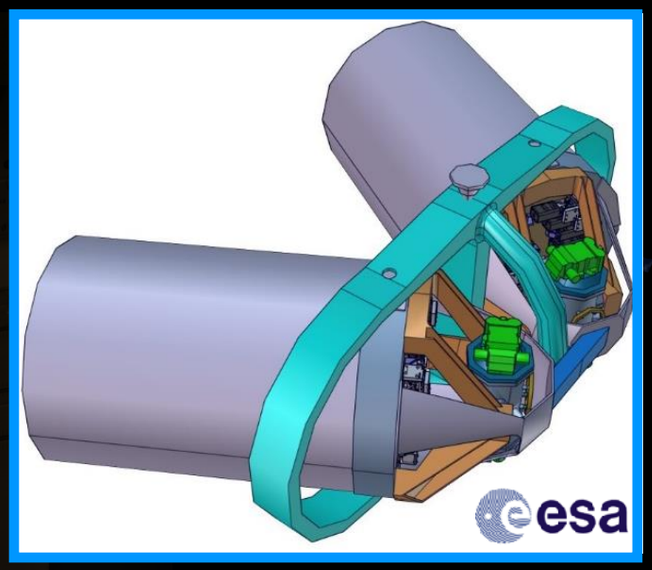
- Several steps for an extremely precise measurements



LISA mission

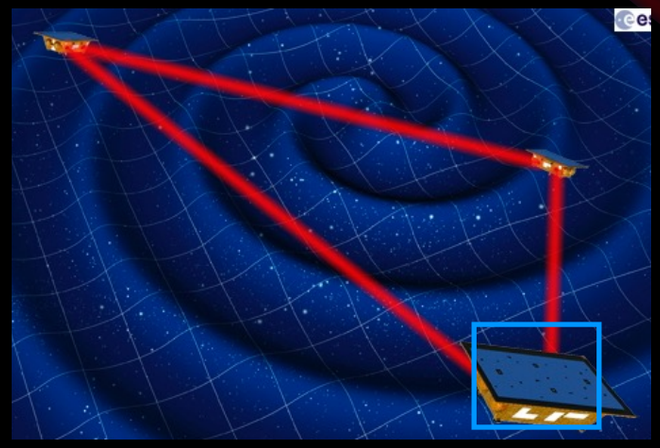
- Several steps for an extremely precise measurements

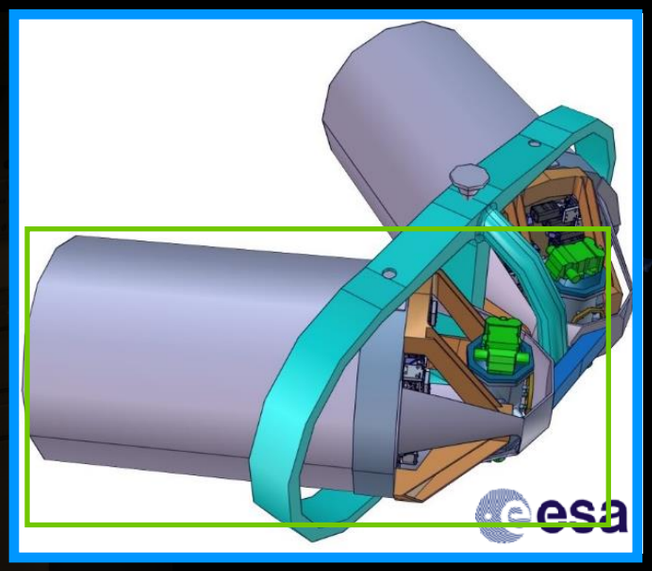


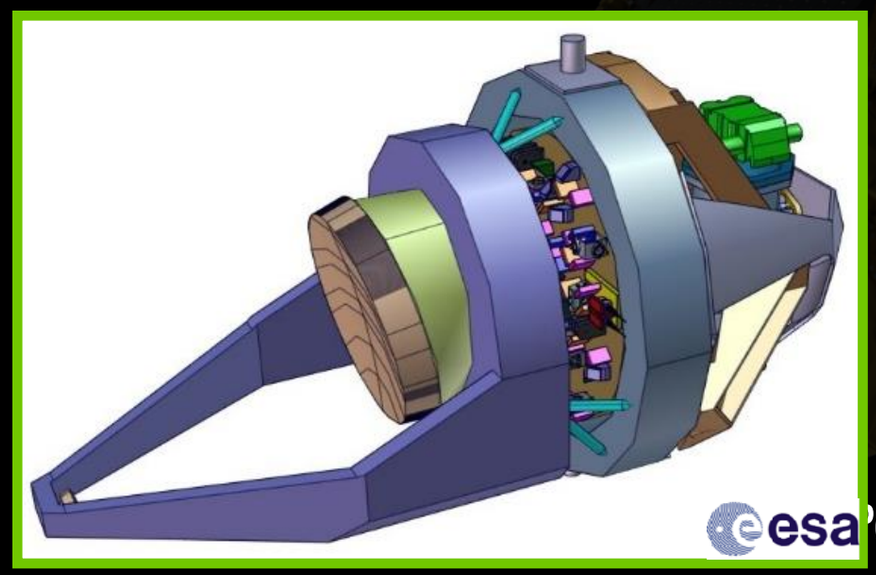


LISA mission

- Several steps for an extremely precise measurements

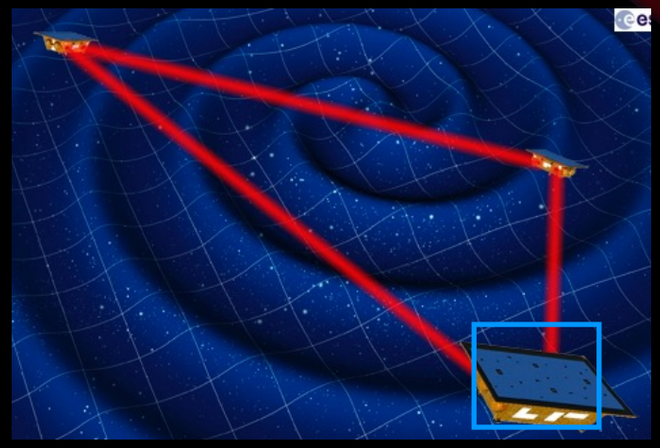


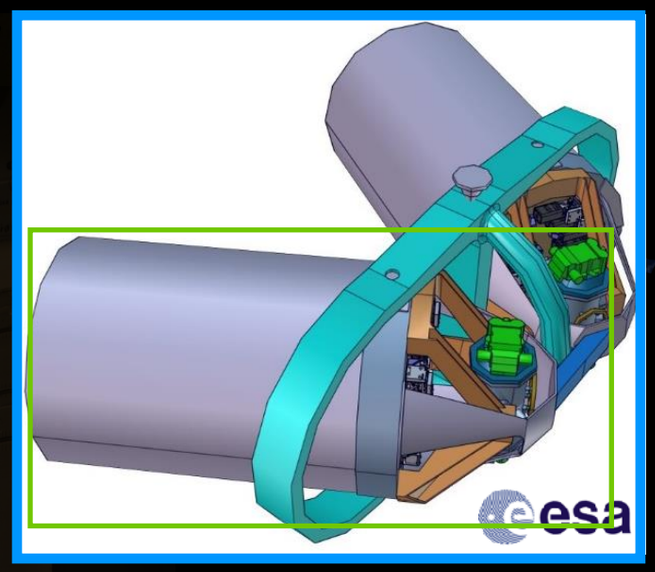


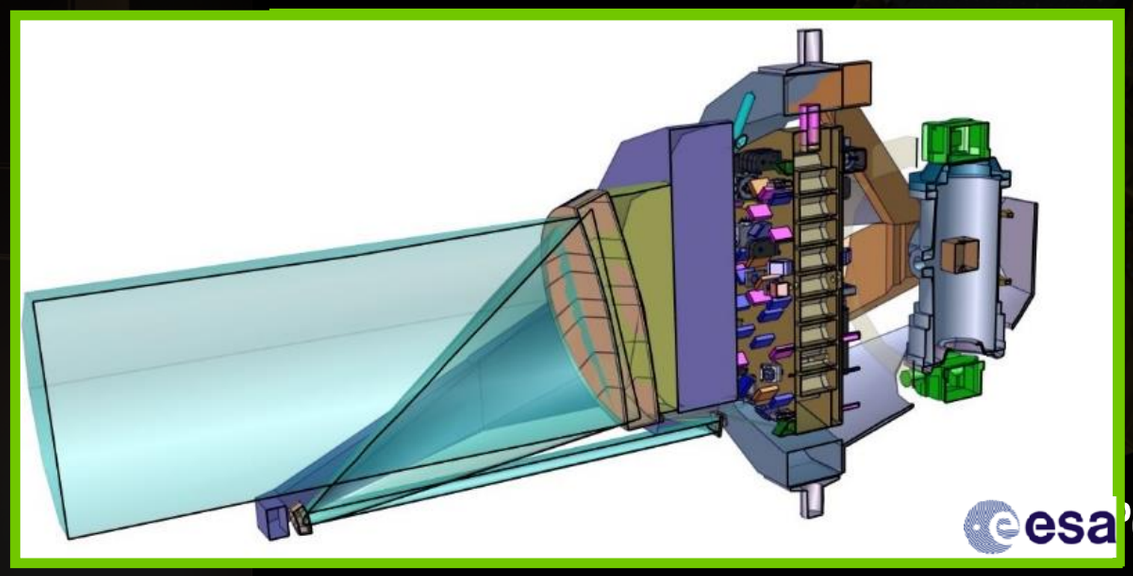


LISA mission

- Several steps for an extremely precise measurements

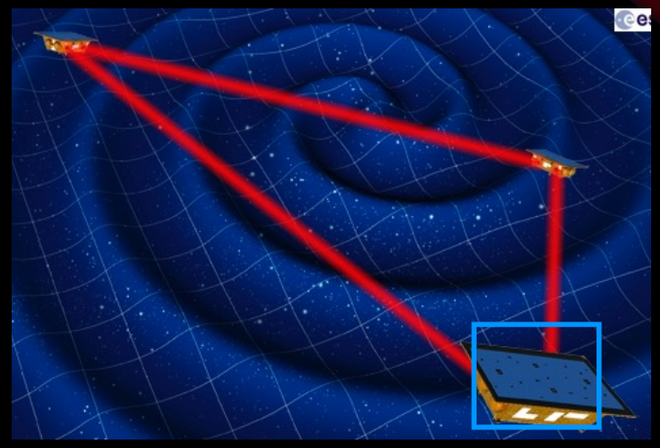


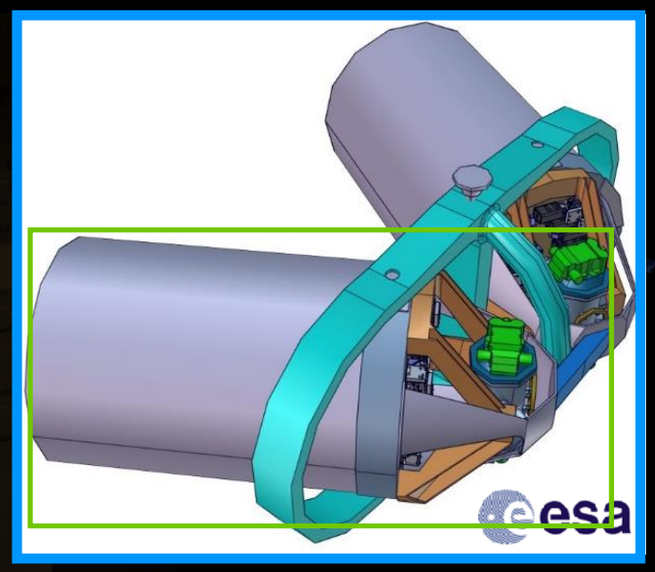


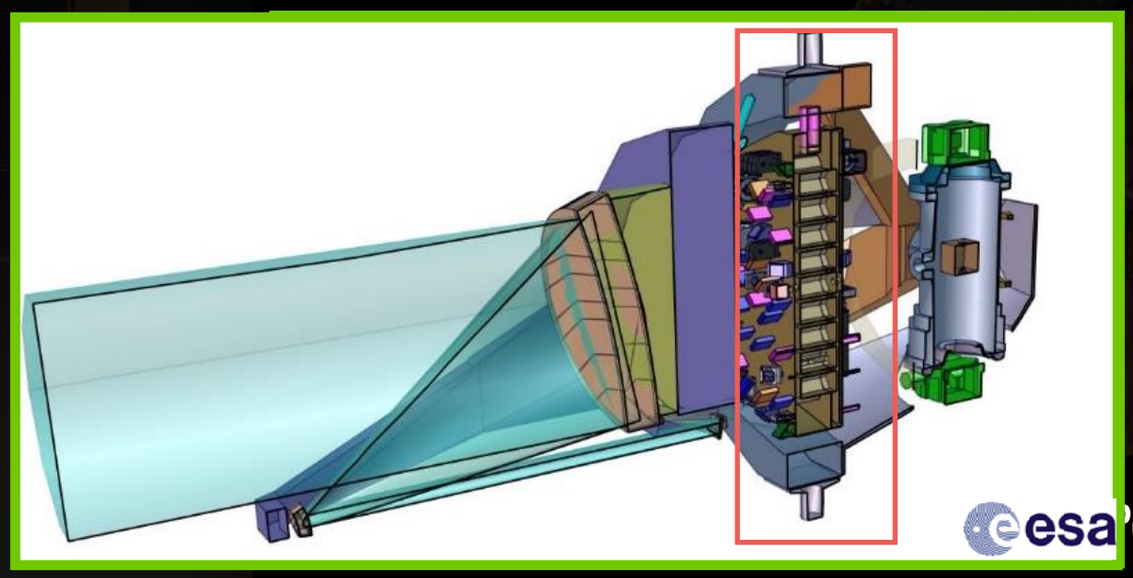


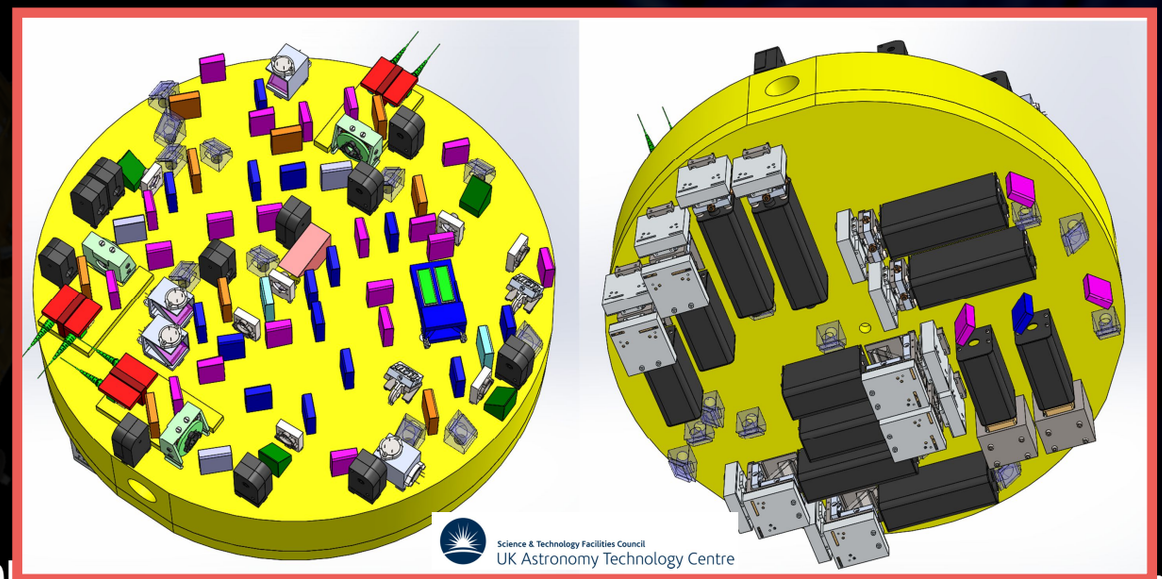
LISA mission

- Several steps for an extremely precise measurements



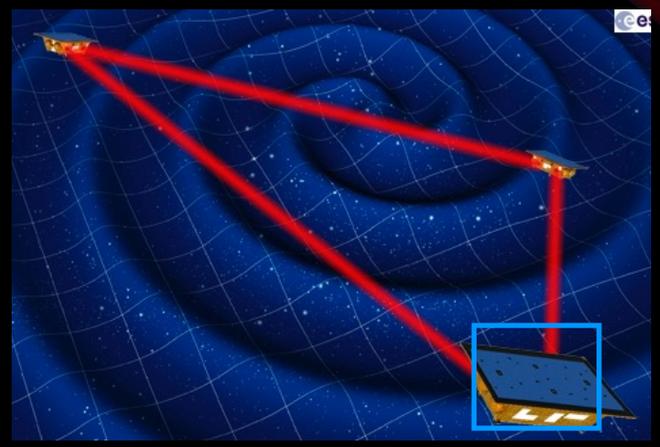




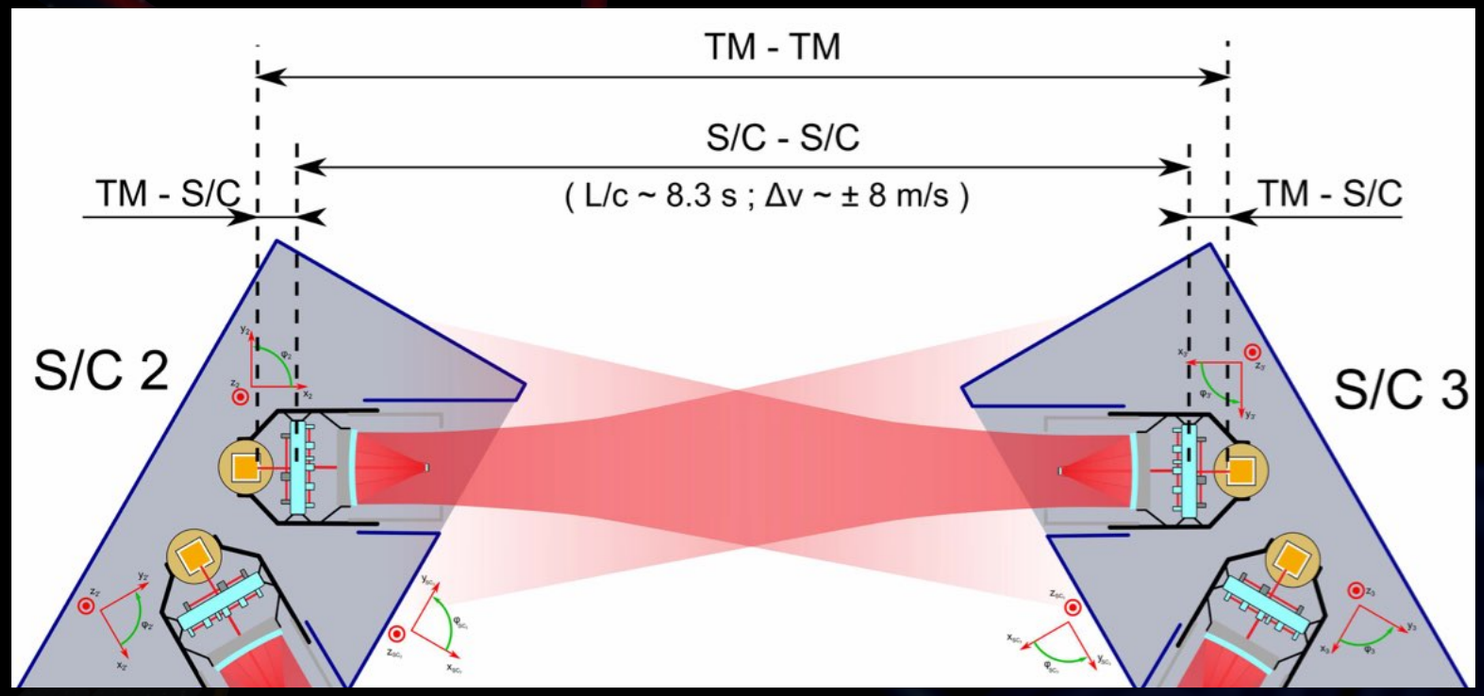


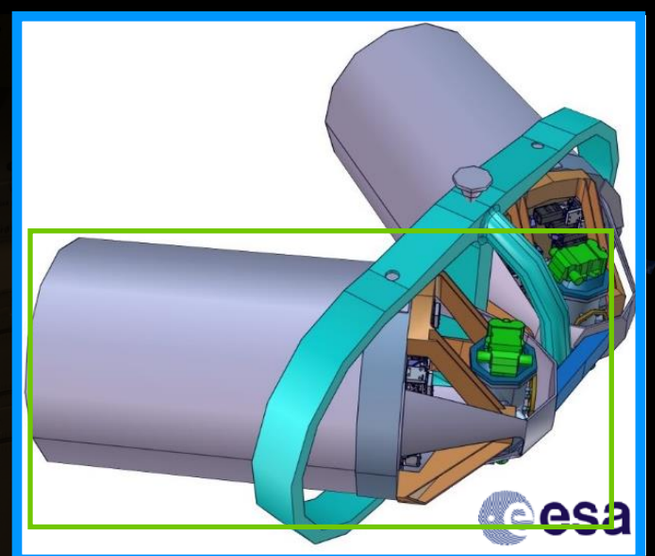
LISA mission

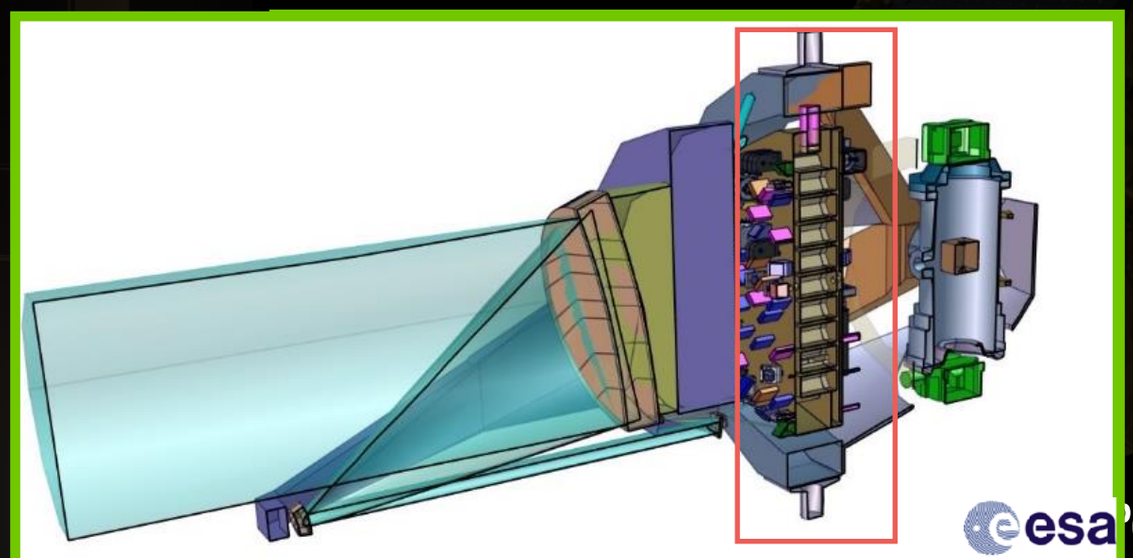
- Several steps for an extremely precise measurements

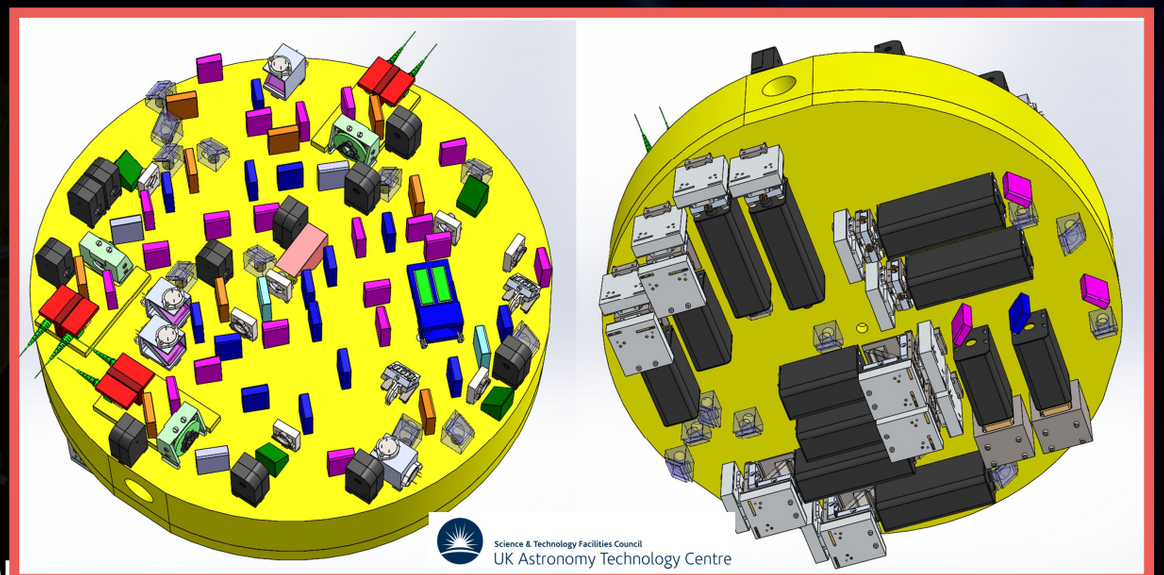


(TM2→SC2) + (SC2→SC3) + (SC3→TM3)



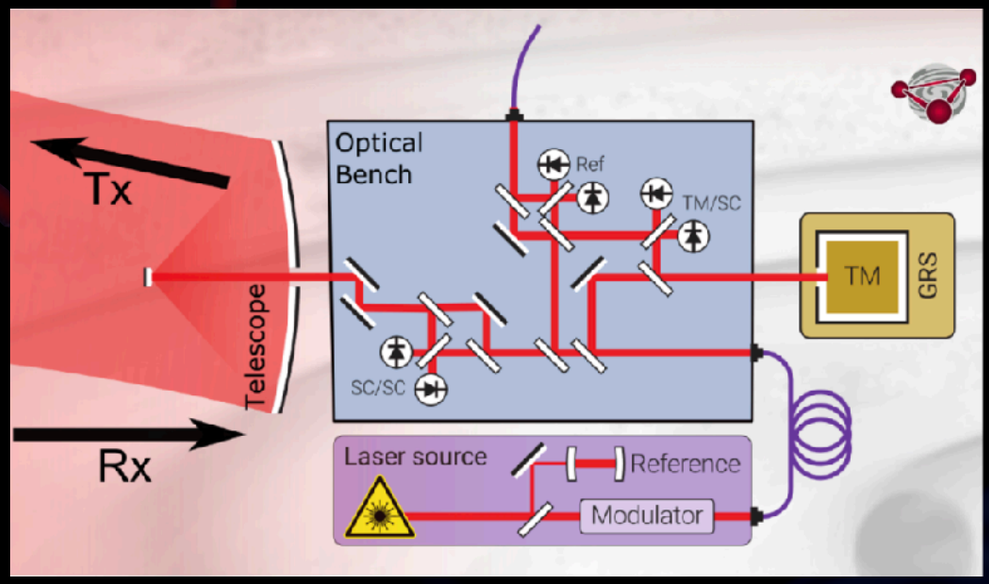


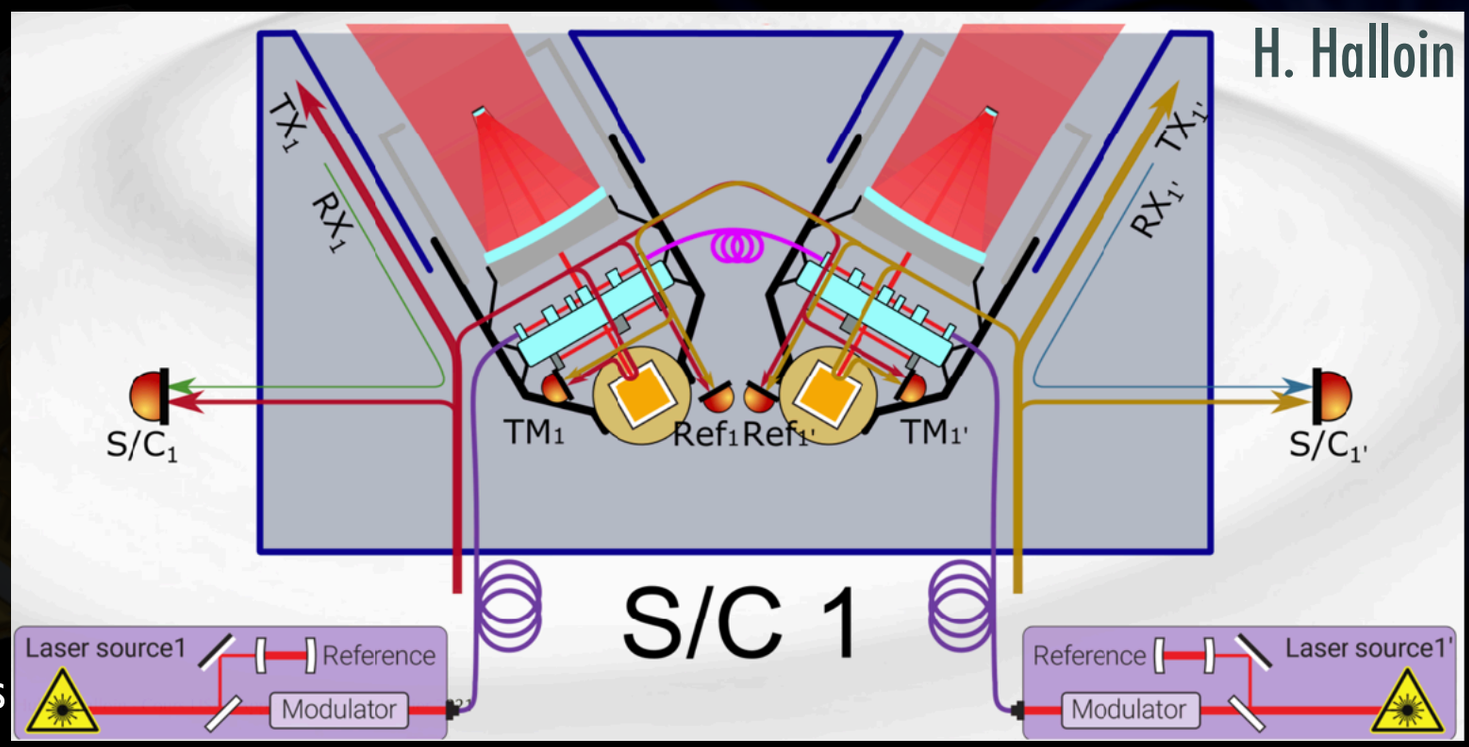




Interferometric measurements

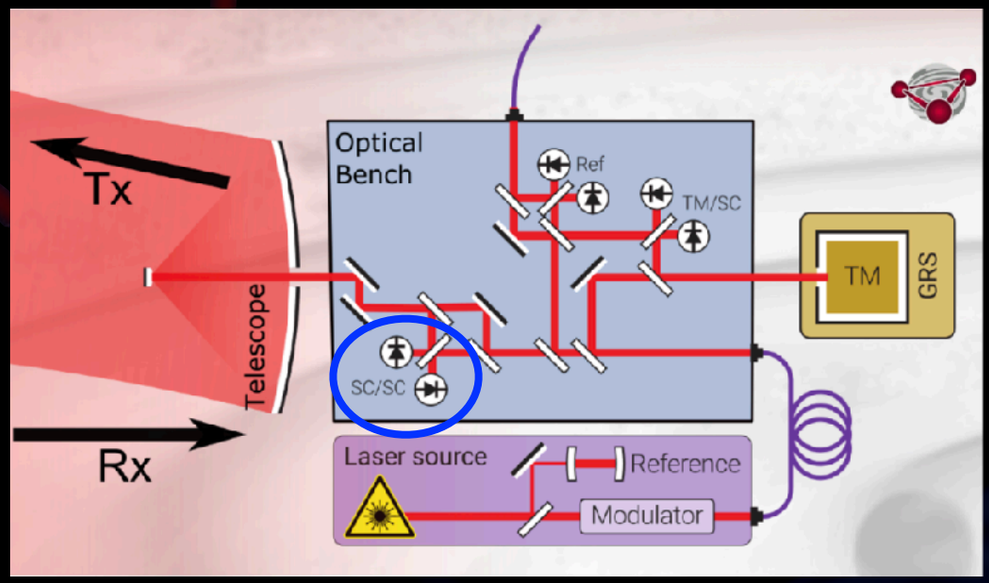
- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts

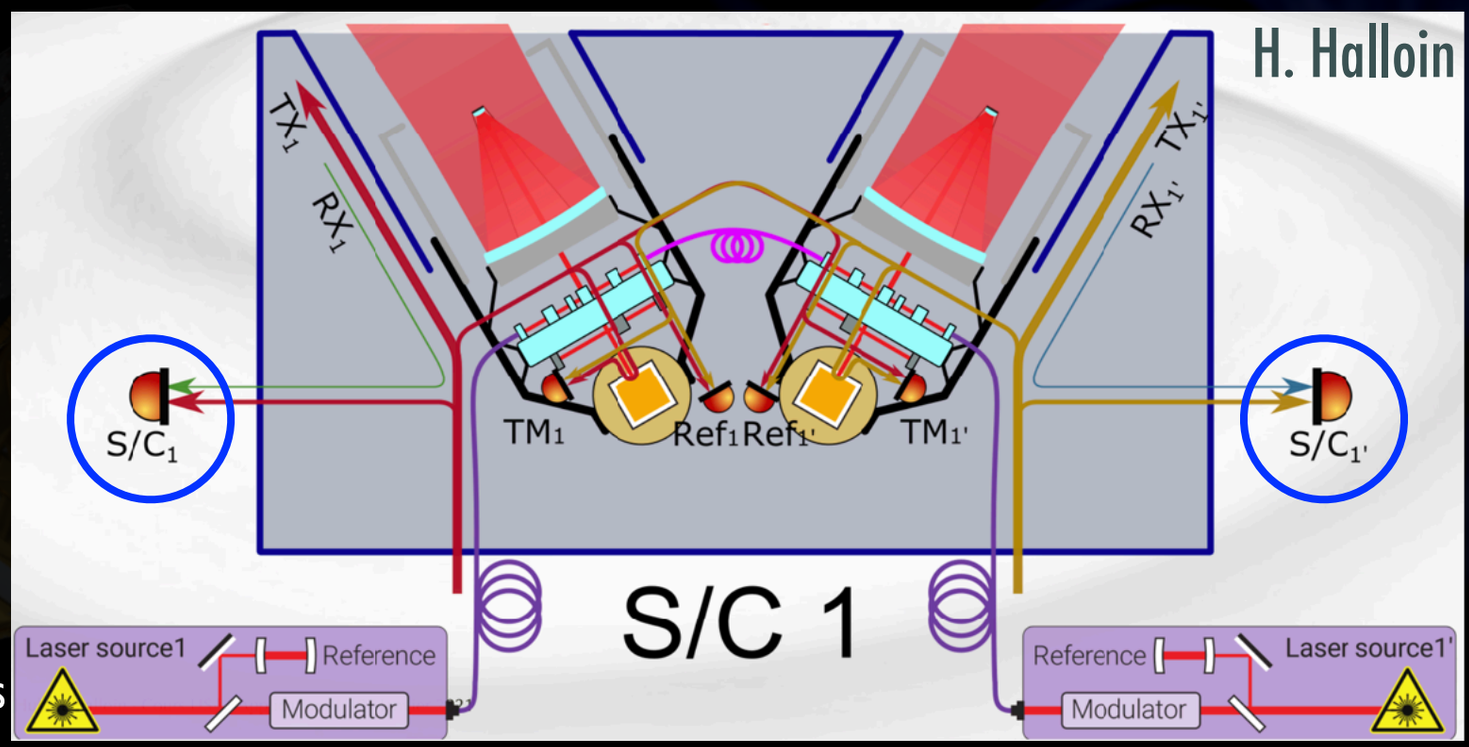




Interferometric measurements

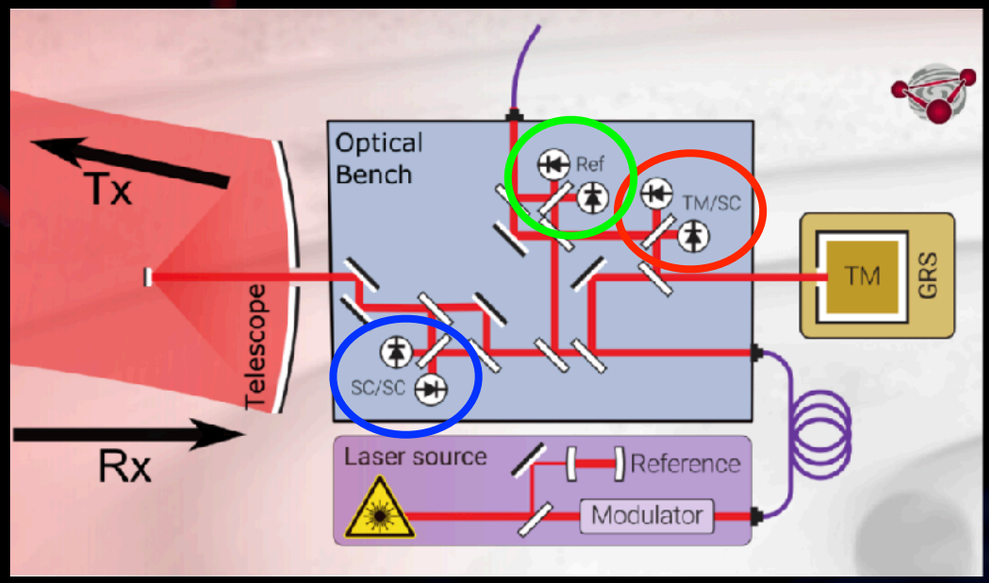
- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts

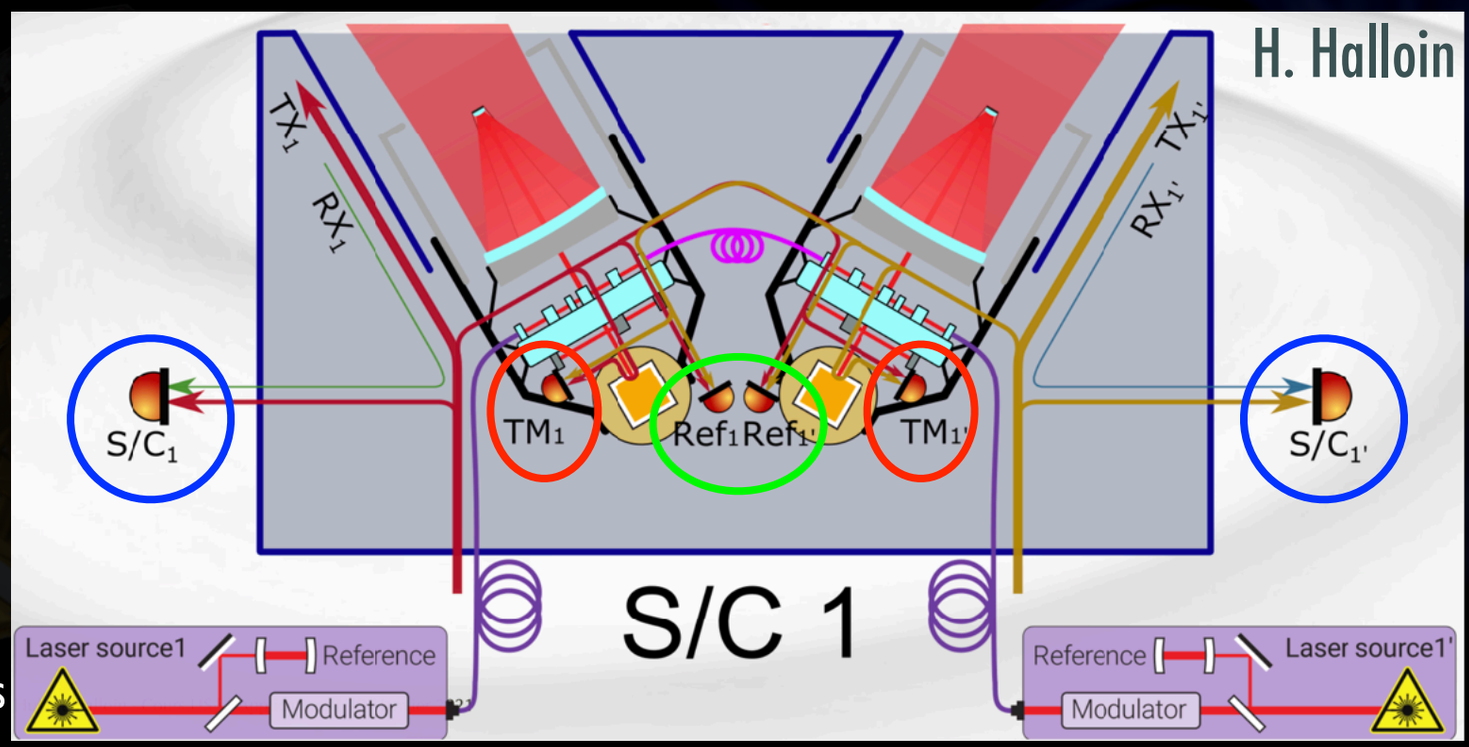




Interferometric measurements

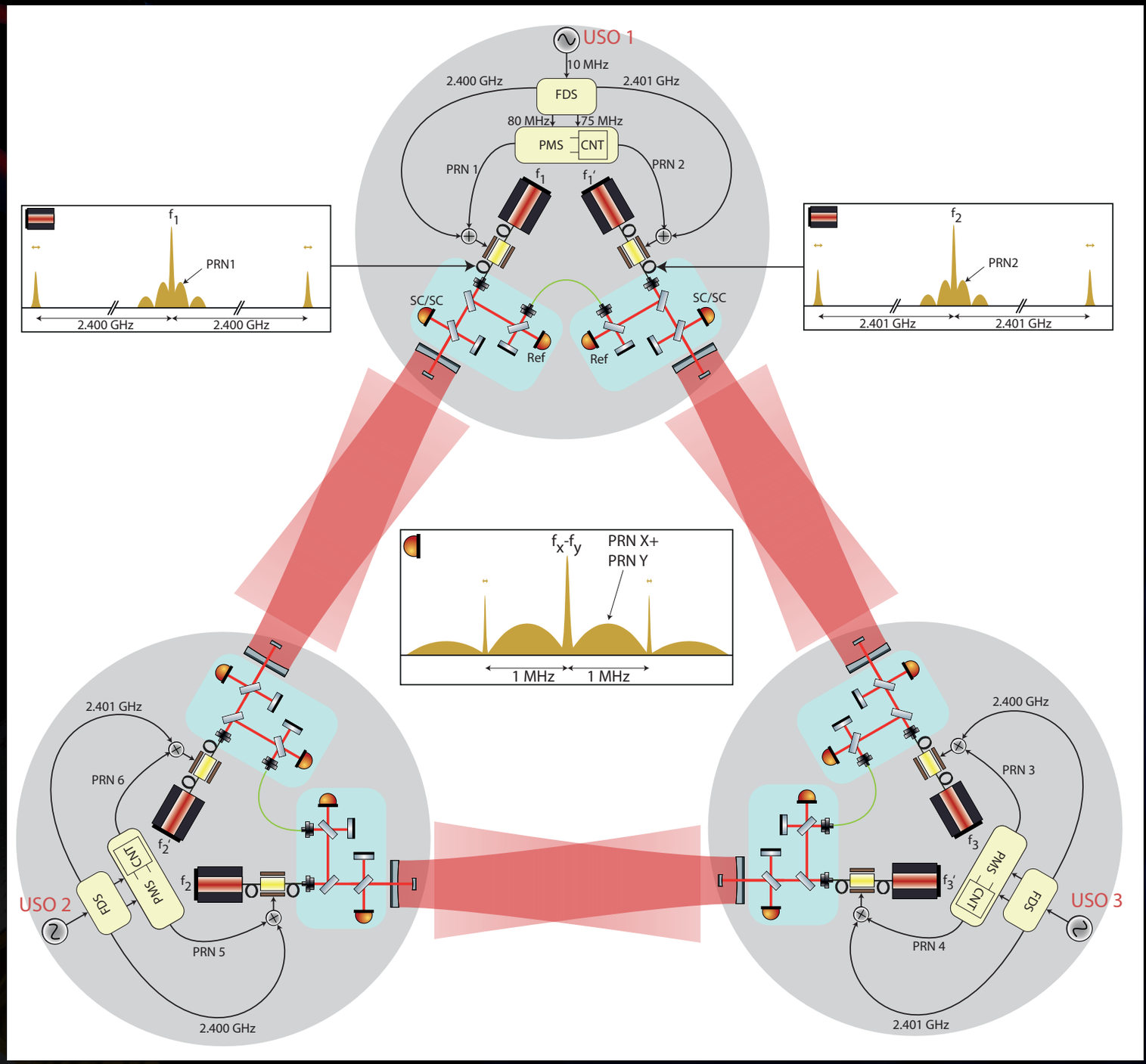
- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts





Interferometric measurements

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



LISA technology requirements

- Free flying test mass subject to very low parasitic forces:
  - Drag free control of spacecraft (non-contacting) with low noise microthruster
  - Large gaps, heavy masses with caging mechanism
  - High stability electrical actuation on cross degrees of freedom
  - Non contacting discharging of test-masses
  - High thermo-mechanical stability of spacecraft
  - Gravitational field cancellation
- Precision interferometric, local ranging of test-mass and spacecraft:
  - pm resolution ranging, sub-mrad alignments
  - High stability monolithic optical assemblies
- Precision million km spacecraft to spacecraft precision ranging:
  - High accuracy laser frequency stabilization + noise suppression with TDI
  - “Tilt to length” coupling (control of alignement + ground correction)
  - Low level of stray-light
  - High stability telescopes
  - High accuracy phase-meter and frequency distribution
  - Constellation acquisition
  - Precision attitude control of spacecraft

LISA technology requirements

- Free flying test mass subject to very low parasitic forces:
  - ✓ Drag free control of spacecraft (non-contacting) with low noise microthruster
  - ✓ Large gaps, heavy masses with caging mechanism
  - ✓ High stability electrical actuation on cross degrees of freedom
  - ✓ Non contacting discharging of test-masses
  - ✓ High thermo-mechanical stability of spacecraft
  - ✓ Gravitational field cancellation

Validated with LISAPathfinder

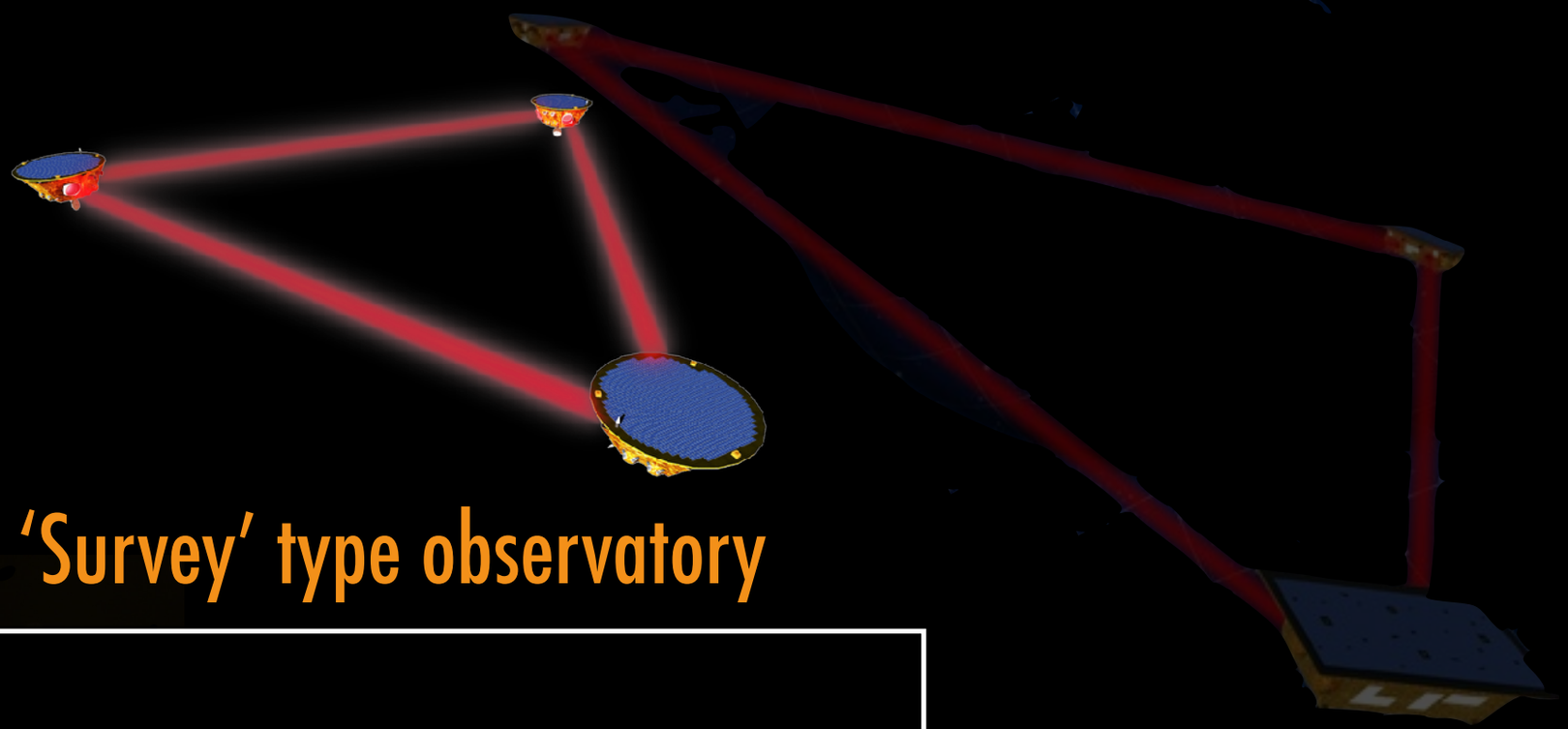
- Precision interferometric, local ranging of test-mass and spacecraft:
  - ✓ pm resolution ranging, sub-mrad alignments
  - ✓ High stability monolithic optical assemblies
- Precision million km spacecraft to spacecraft precision ranging:
  - ➡ High accuracy laser frequency stabilisation + noise suppression with TDI
  - ➡ "Tilt to length" coupling (control of alignement + ground correction)
  - ➡ Low level of stray-light
  - ➡ High stability telescopes
  - ➡ High accuracy phase-meter and frequency distribution
  - ➡ Constellation acquisition
  - ✓ Precision attitude control of spacecraft

On-ground demo. + simulation + GRACE-FO

LISA data

Gravitational wave sources emitting between 0.02mHz and 1 Hz

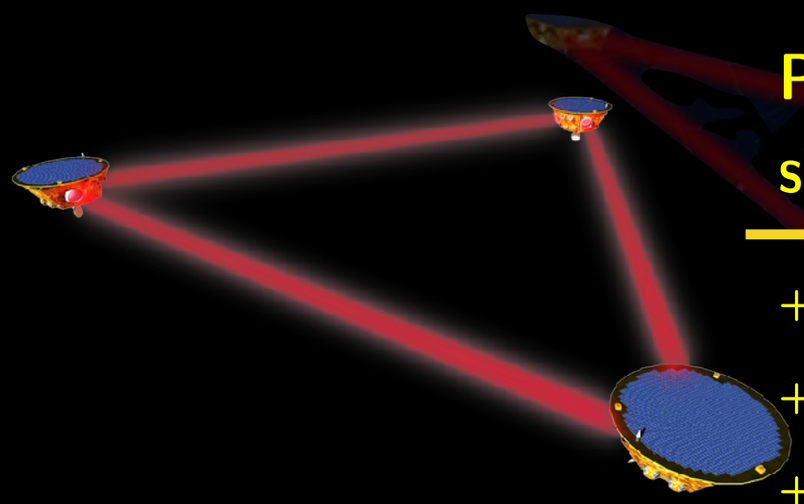
LISA data



‘Survey’ type observatory

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



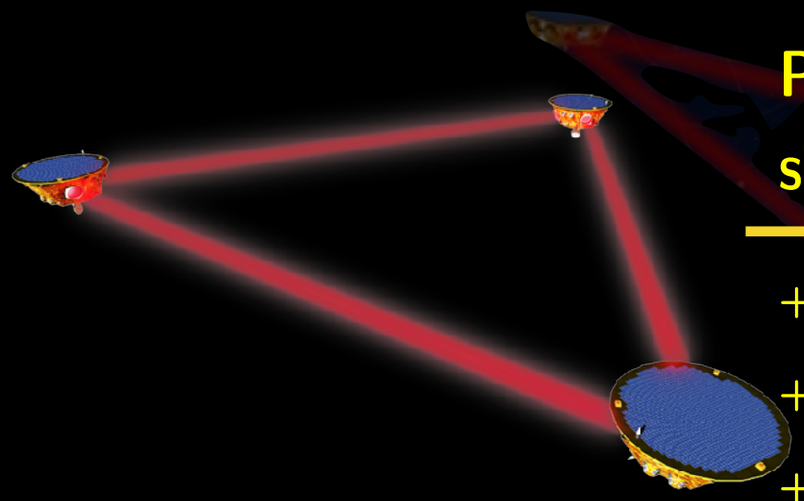
Phasemeters (carrier, sidebands, distance)

+ DFACS & CMD
+ Diagnostics
+ Auxiliary channels

‘Survey’ type observatory

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



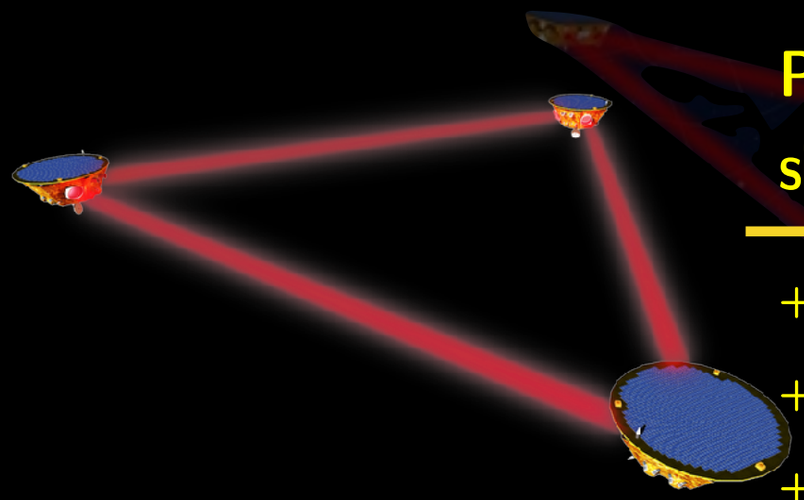
Phasemeters (carrier, sidebands, distance)

+ DFACS & CMD
+ Diagnostics
+ Auxiliary channels

‘Survey’ type observatory

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



Phasemeters (carrier, sidebands, distance)

+ DFACS & CMD
+ Diagnostics
+ Auxiliary channels

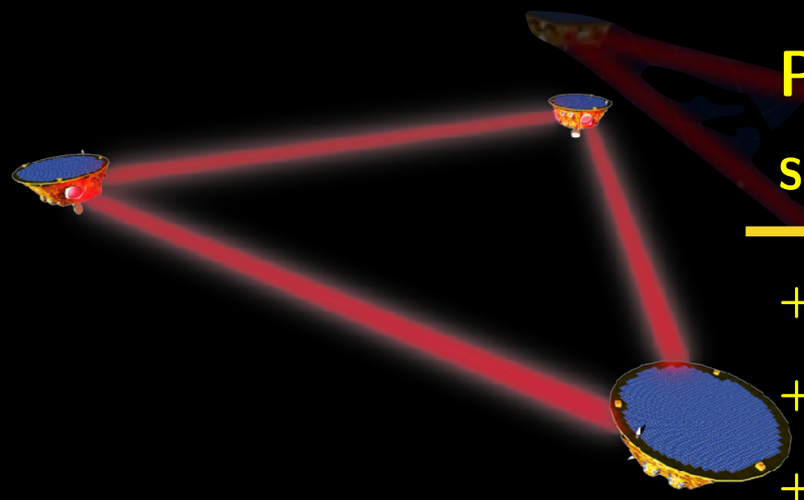
Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry
reduction of laser noise

3 TDI channels with 2 "~independents"

'Survey' type observatory

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



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"

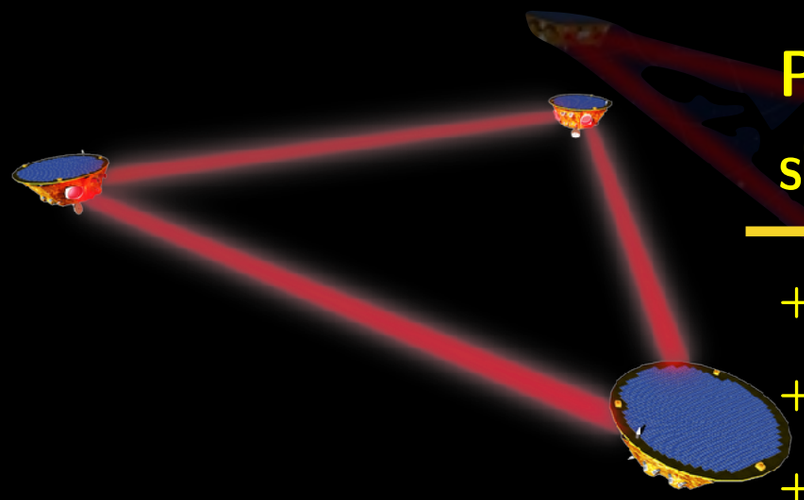
Data Analysis of GWs

Catalogs of GWs sources with their waveform

'Survey' type observatory

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



Phasemeters (carrier, sidebands, distance)

L0

\+ DFACS & CMD

\+ Diagnostics

\+ Auxiliary channels

L0.5

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

‘Survey’ type observatory

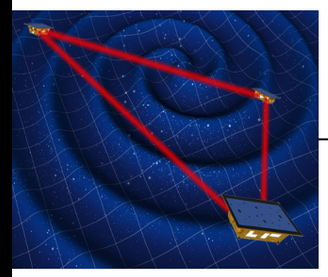
Gravitational wave sources emitting between 0.02mHz and 1 Hz

L1 3 TDI channels with 2 “~independents”

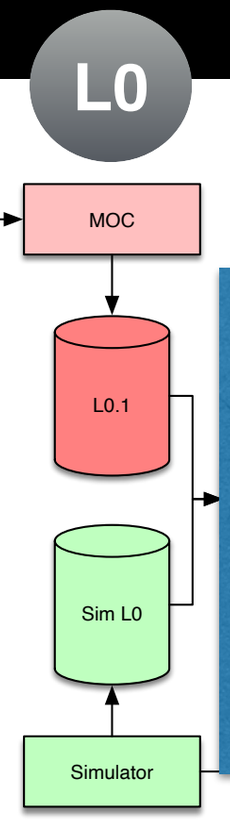
L2 Data Analysis of GWs

L3 Catalogs of GWs sources with their waveform

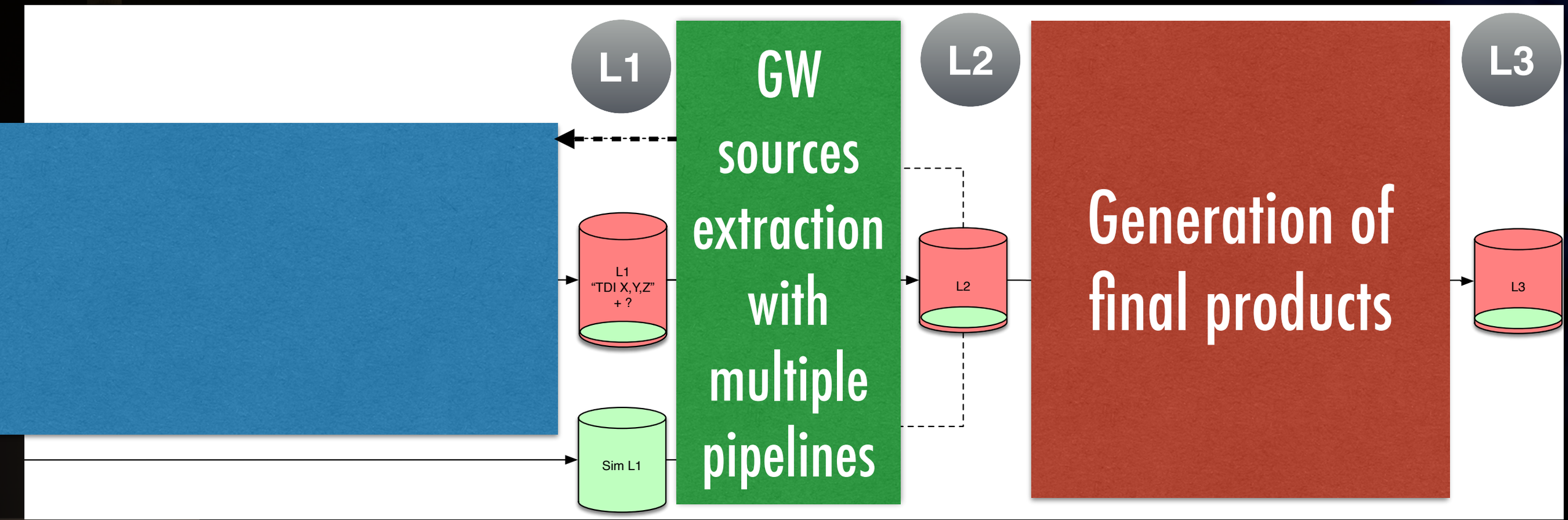
Ground Segment LISA



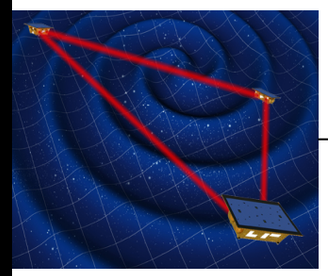
Telemetry:
+ Phasemeter
+ DFACS
+ GRS FEE
+ CGT
+ CMS
+ SciDiag
+ Housekeeping



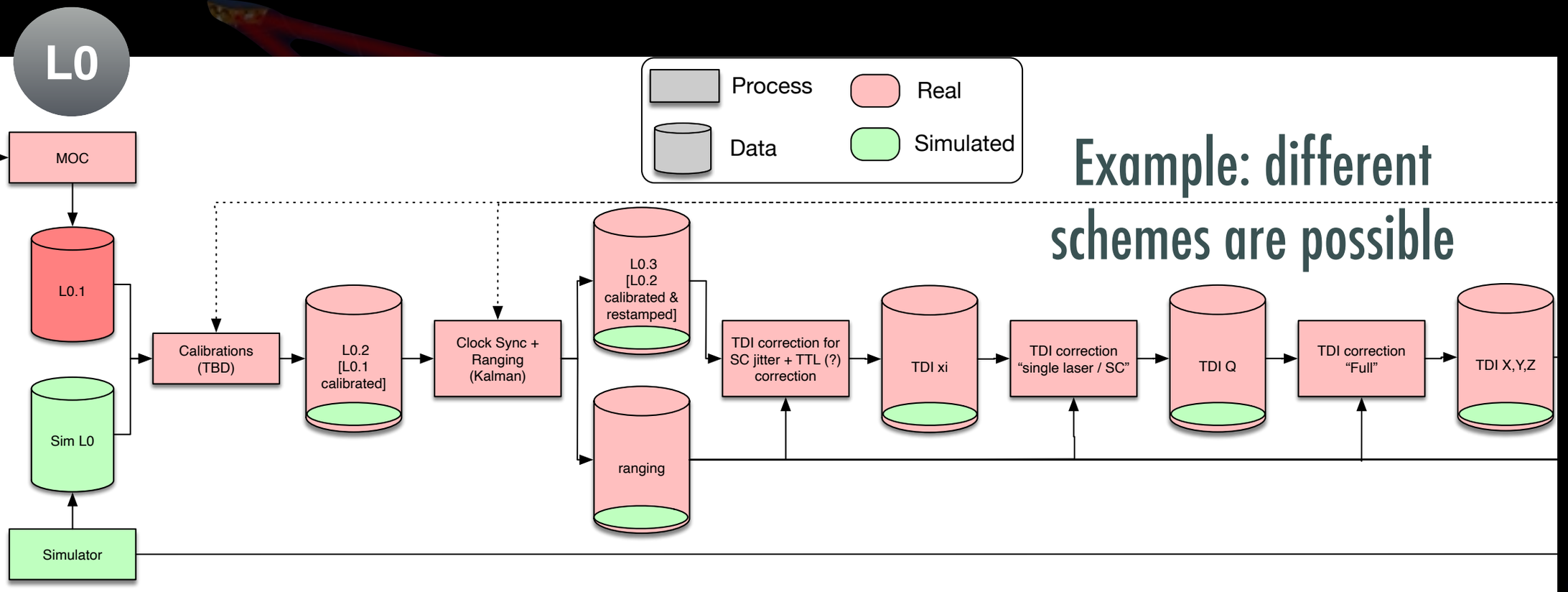
Initial Noise Reduction pipeline (TDI, etc)

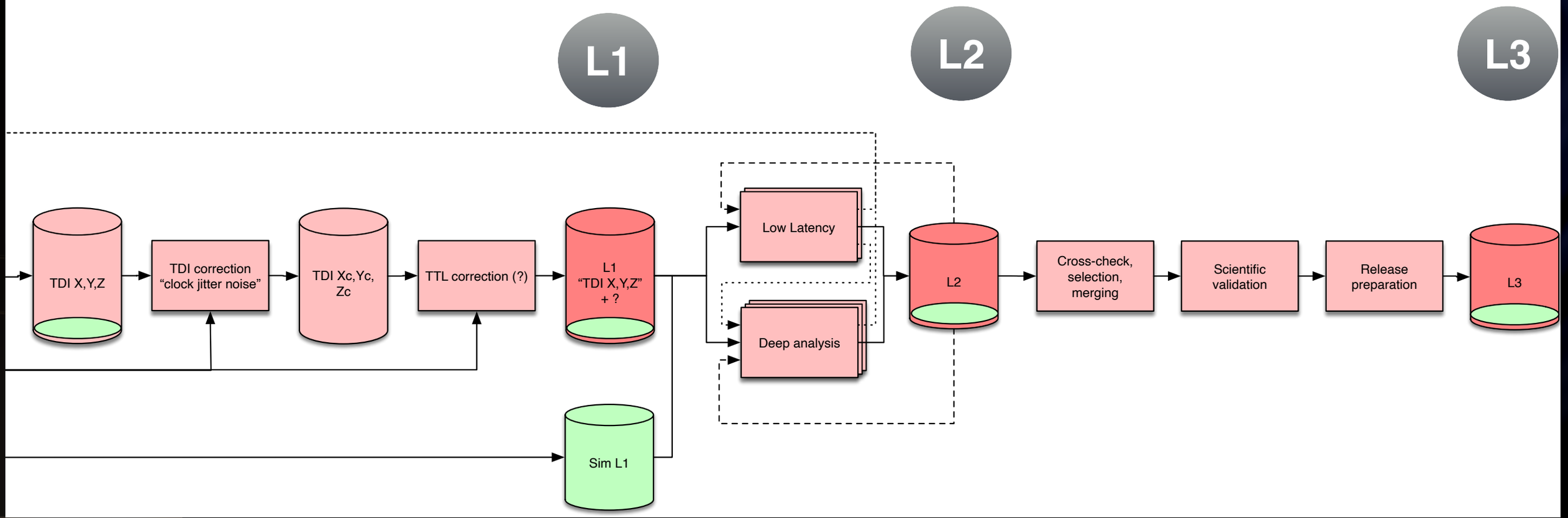


Ground Segment LISA



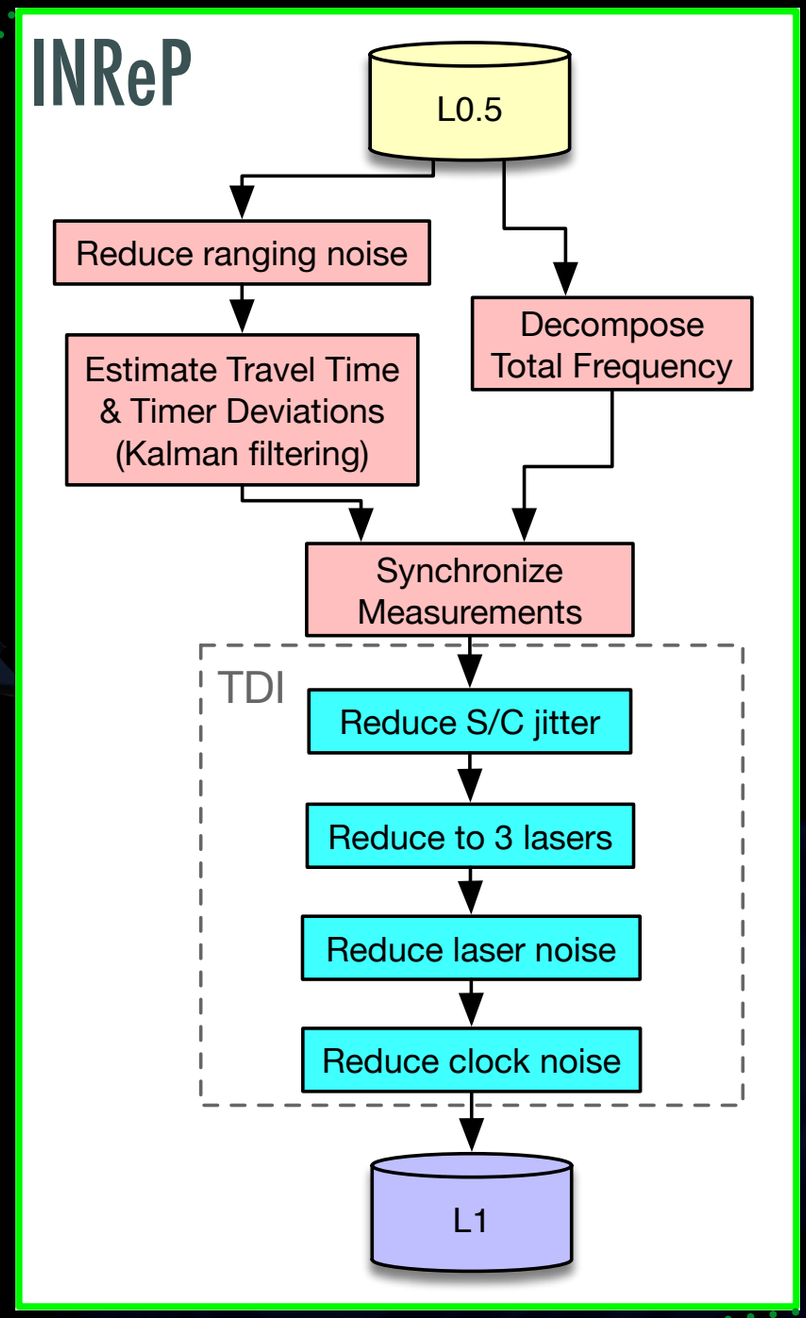
Telemetry:
+ Phasemeter
+ DFACS
+ GRS FEE
+ CGT
+ CMS
+ SciDiag
+ Housekeeping

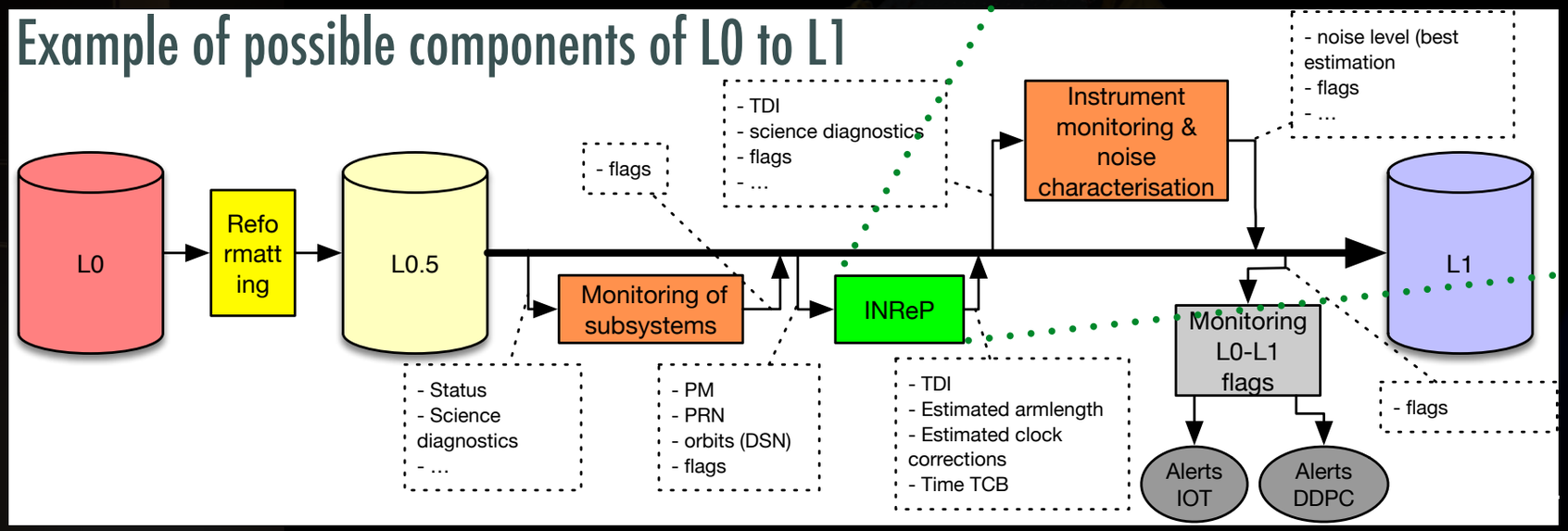




L0 to L1

- Data levels:
  - L0.5: L0 reformatted: engineering/physical values
  - L1: All requested data for GW extraction
- Core part of L0 to L1: Initial Noise Reduction Pipeline (INReP):
  - TDI+: Suppress laser noise, clock noises, spacecraft jitter noise
  - Data synchronisation
  - Reduce Tilt-To-Length noise



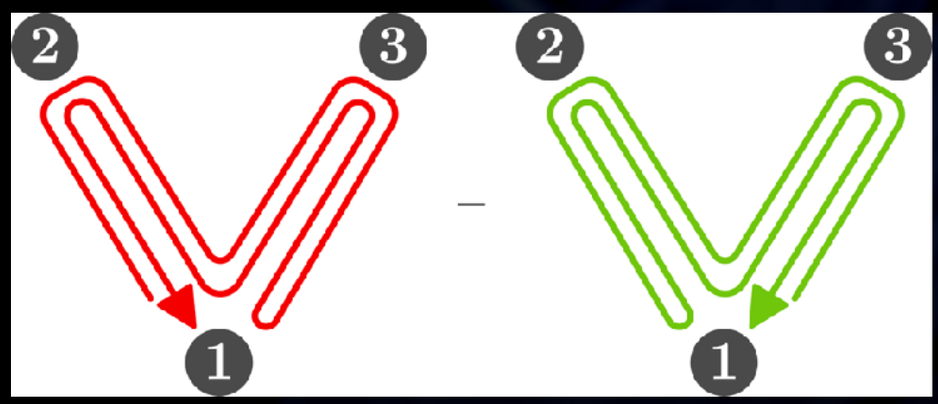


Initial Noise Reduction

- Reducing dominating noises for producing data in which GW sources can be extracted
- Laser frequency noise reduced by 8 orders of magnitude with Time Delay Interferometry:
  - Combination of delayed measurements reconstructing virtually several interferometers

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

$$D_i x(t) = x\left(t - \frac{L}{c}\right)$$



L1 -> L2 -> L3

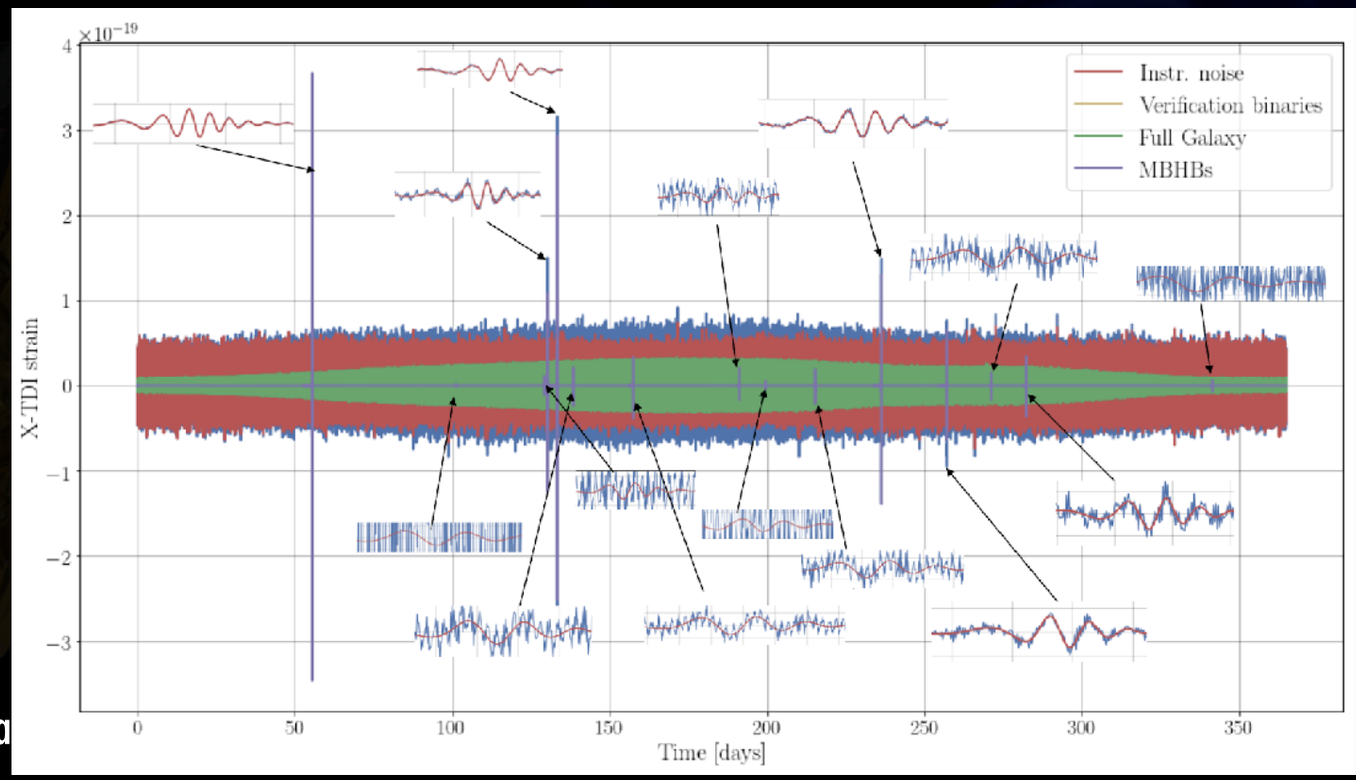
- Data levels:
  - L1: All requested data for GW extraction
  - L2: All outputs of multiple pipelines extracting sources
  - L3: Catalogs and other scientific products
- Extract GW sources:
  - detection & parameters estimations
  - Complexity: long term sources + short term sources (with alerts) all together
- Research and developments in the Consortium in the LISA Data Challenge (LDC) Working Group and the LISA Data Processing Group

GW data analysis

- Data levels:
  - L1: All requested data for GW extraction
  - L2: All outputs of multiple pipelines extracting sources
  - L3: Catalogs and other scientific products
- Large number of overlapping sources => challenges for data analysis
- First data of this kind + fluctuations of computational charge (fluctuations of event rates, new calibrations, ...)

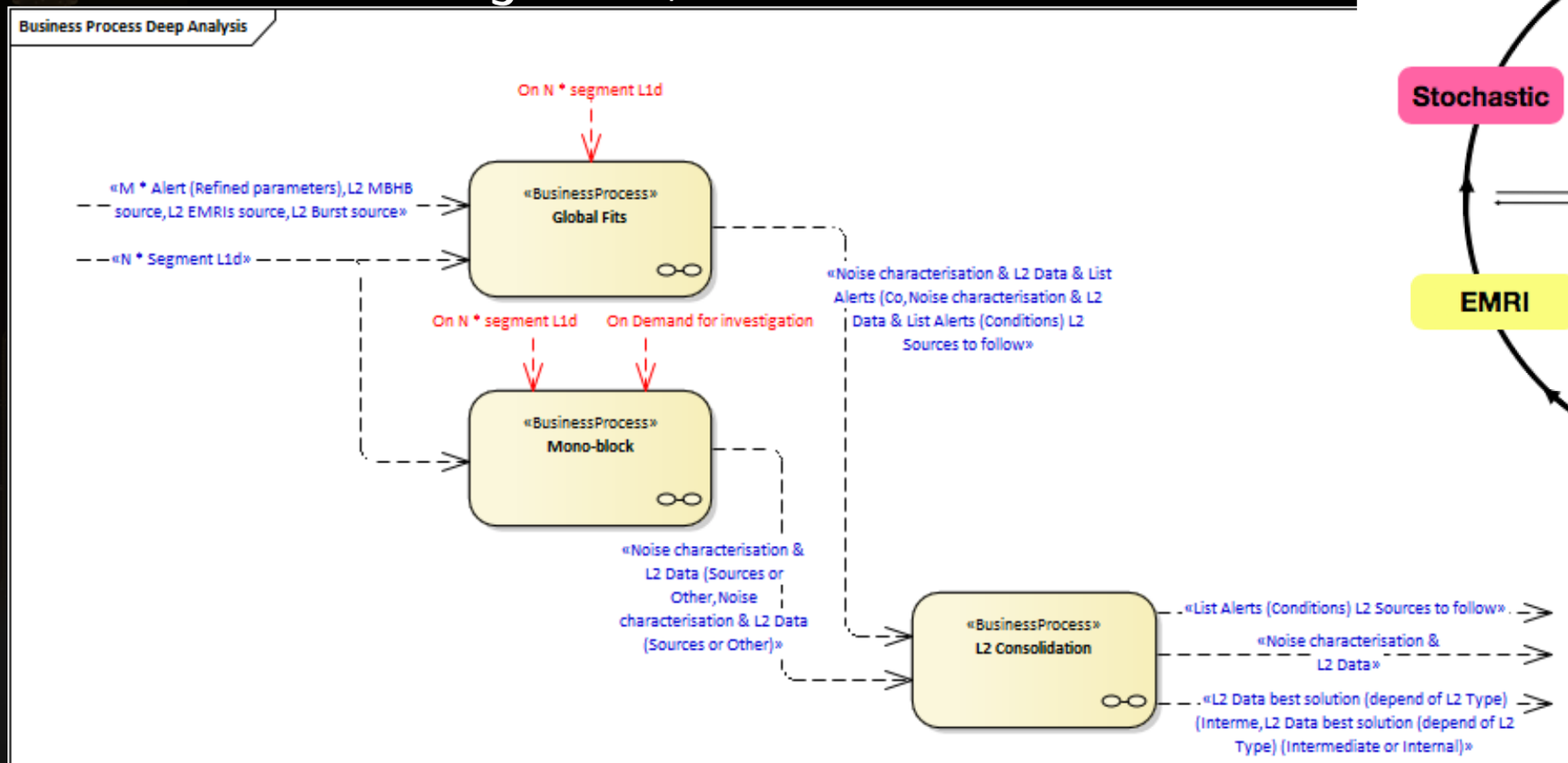
=> flexible Distributed Data Processing Center

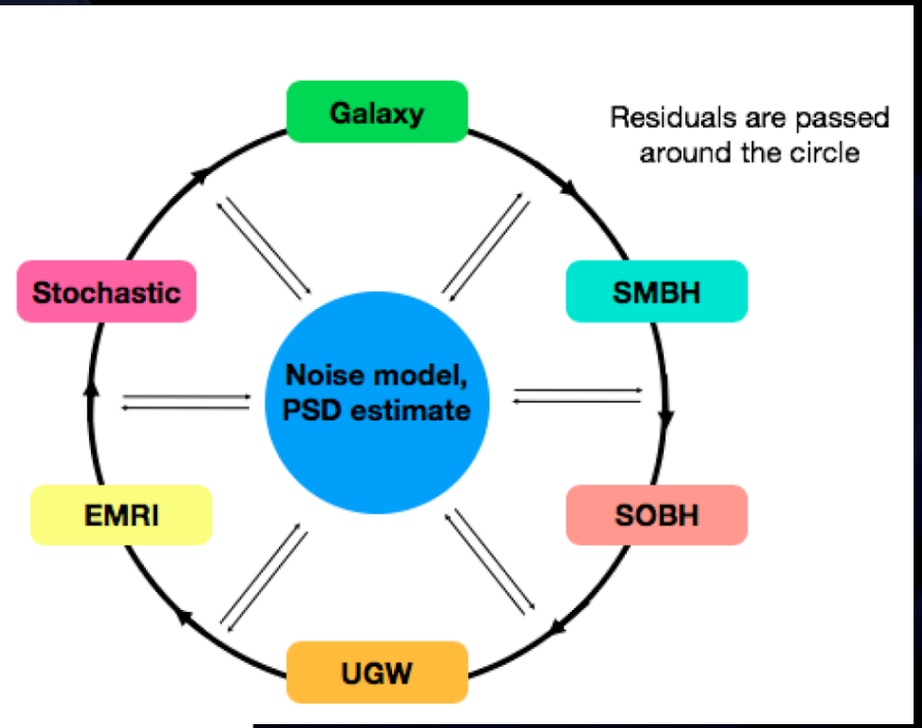
- Exploration of multiple technics
- Prototyping already started: LISA Data Challenge, detailed simulations (instrument & GW sources)



Data Analysis Logic

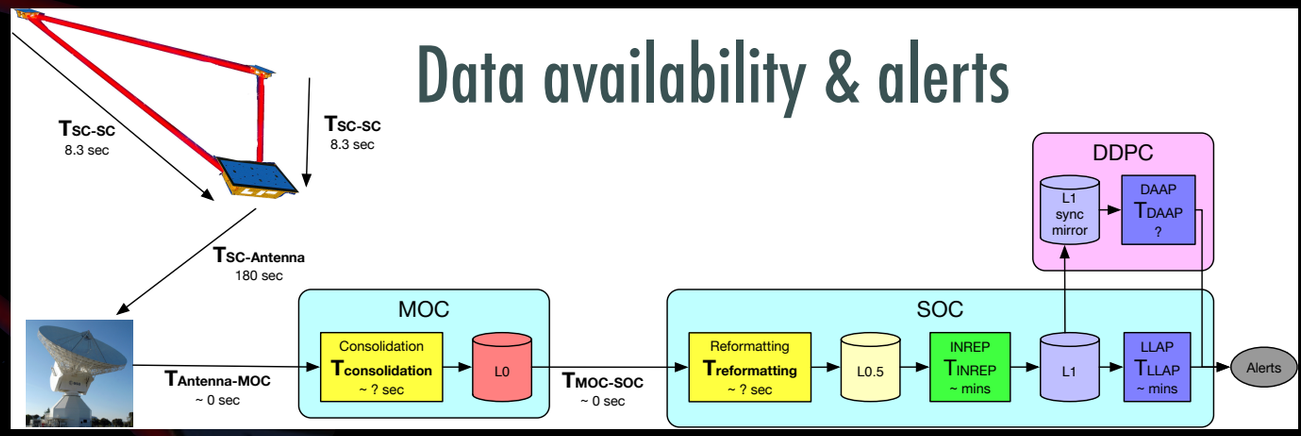
- Alerts and deep analysis
  with data provided daily and near real-time (during communication periods)
- Main processing and sources extraction from deep analysis:
  - Multiples methods running in parallel (complementarity & cross-validation)
  - Global fits
  - Sources investigations, ...

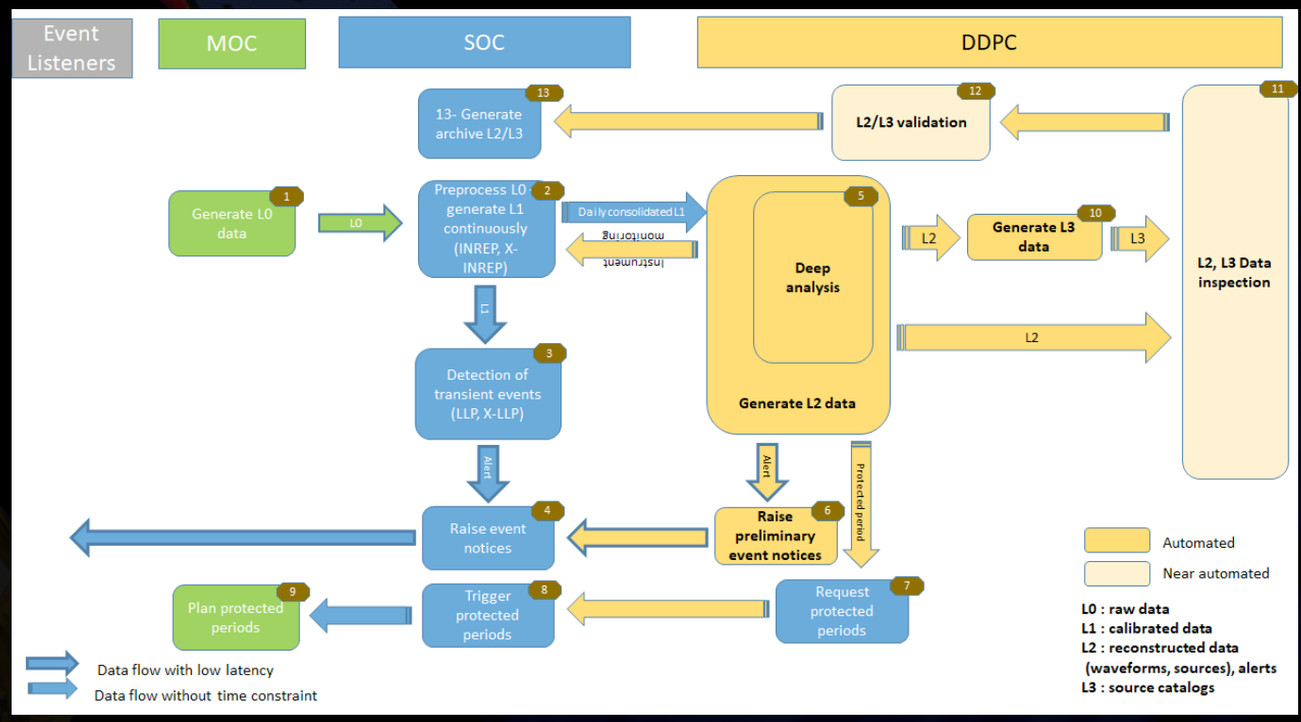




Distributed Data Processing Center

- **Operations** for the SGS
  - Definition of the global scenario
  - Data availability and time sequence with **near-real time analysis** for alerts
- Interfaces
  - Data levels: definition and content
- **Processing concepts:** global picture
  - Deep analysis
  - Alerts
  - Several methods for each processing steps (first data of this kind)
- Architecture assumptions
  - General principle & main use cases



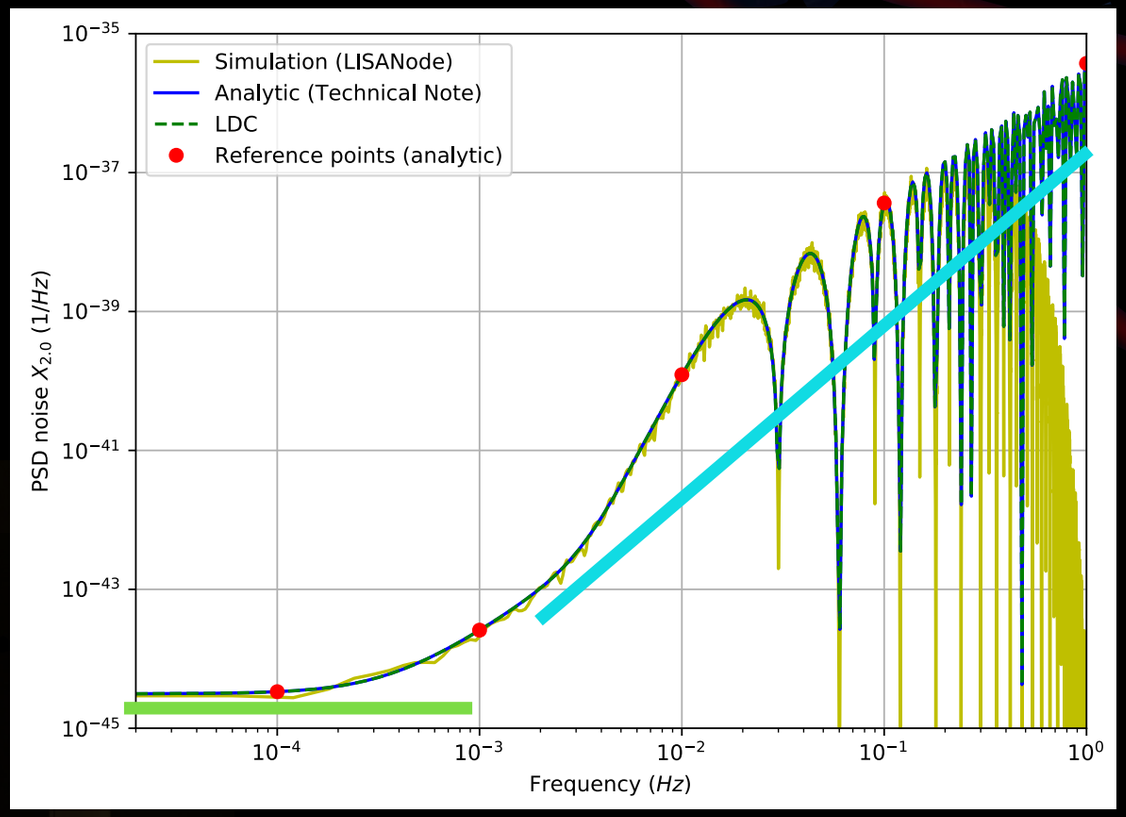


Overview

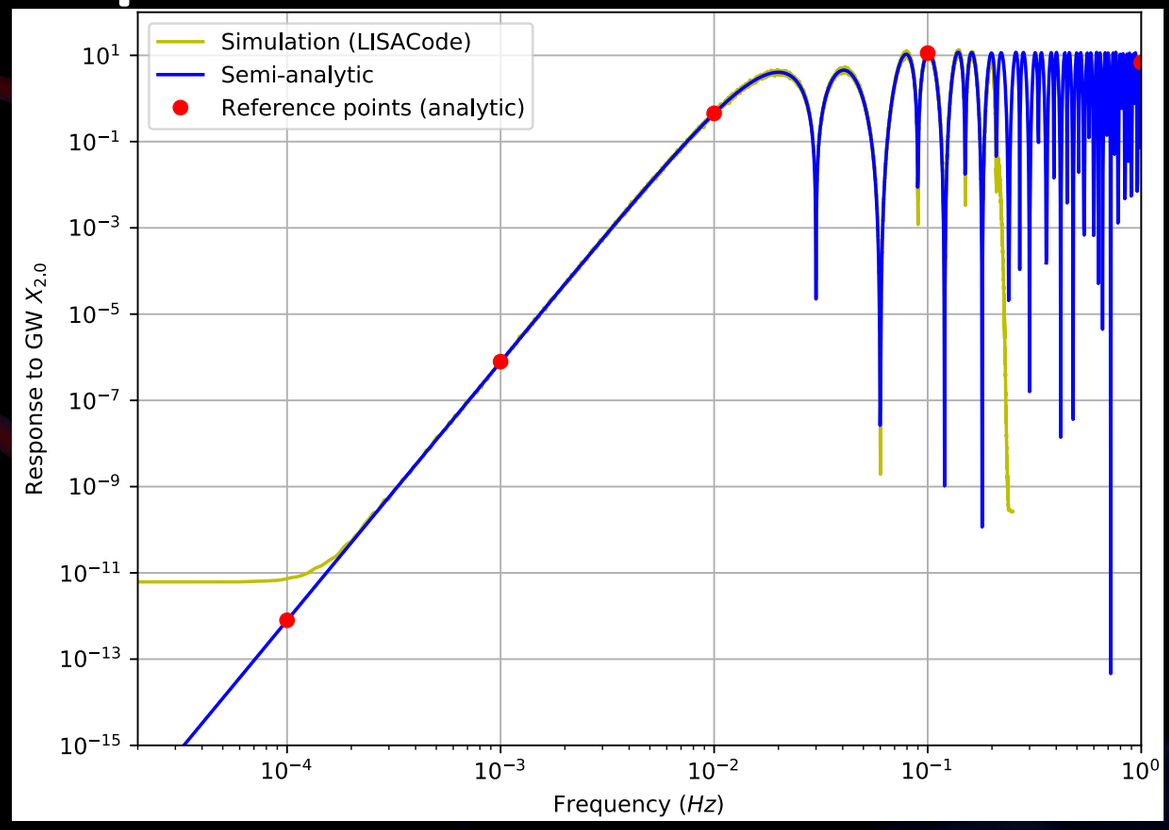
- Gravitational wave sources in the mHz band and LISA science objectives
- The mission
  - Space segment (hardware)
  - Ground segment (data analysis & science exploitation)
- Science performances
- Status: end of phase A (MFR) and Phase B1
- Organisations: Consortium & LISA France
- LISA at Paris Observatory

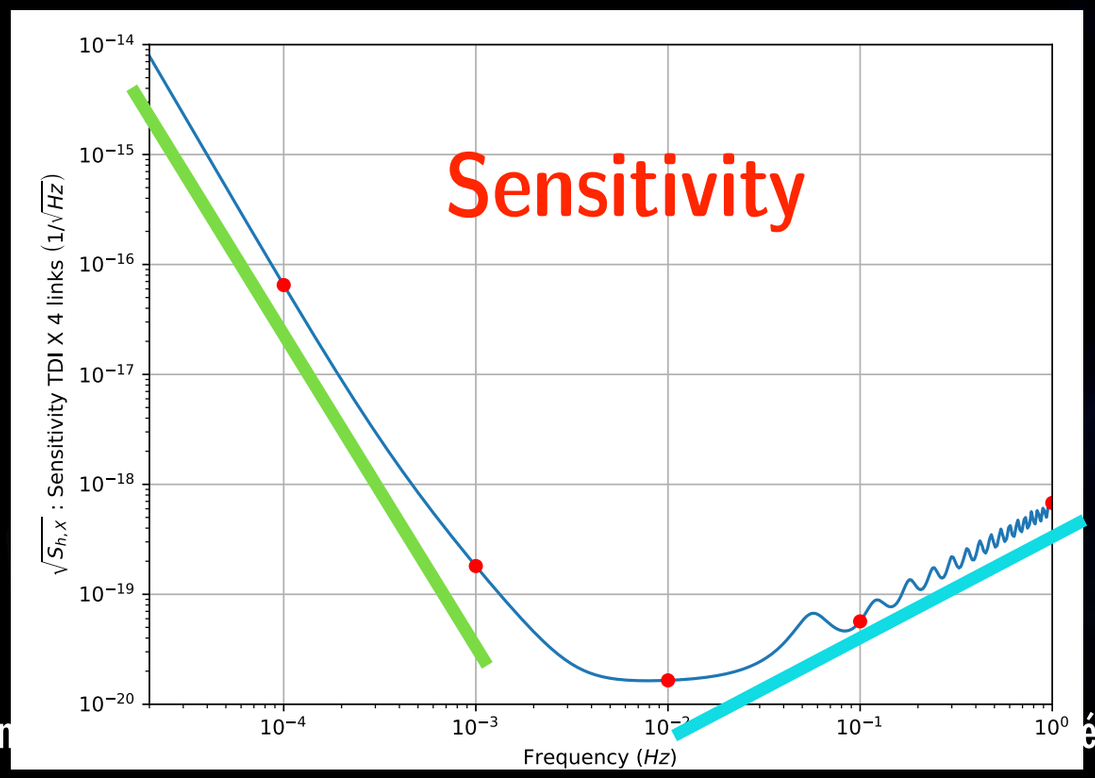
Sensitivity

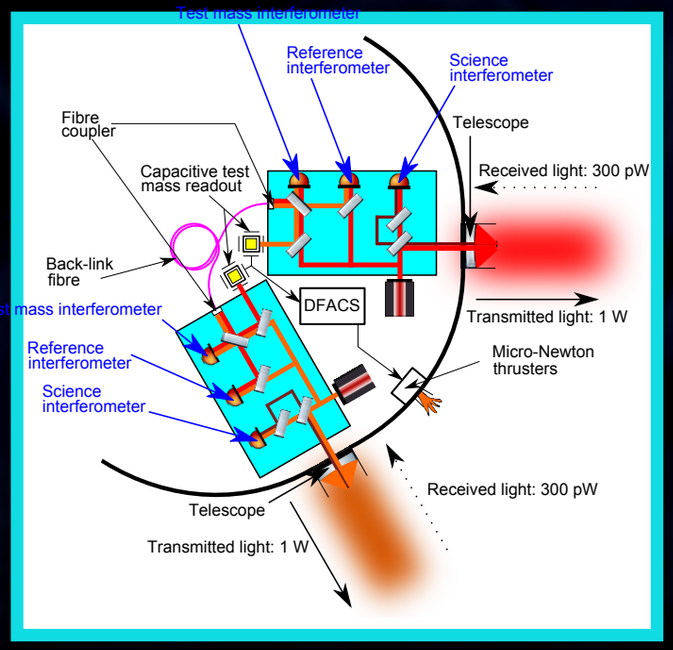
Noises



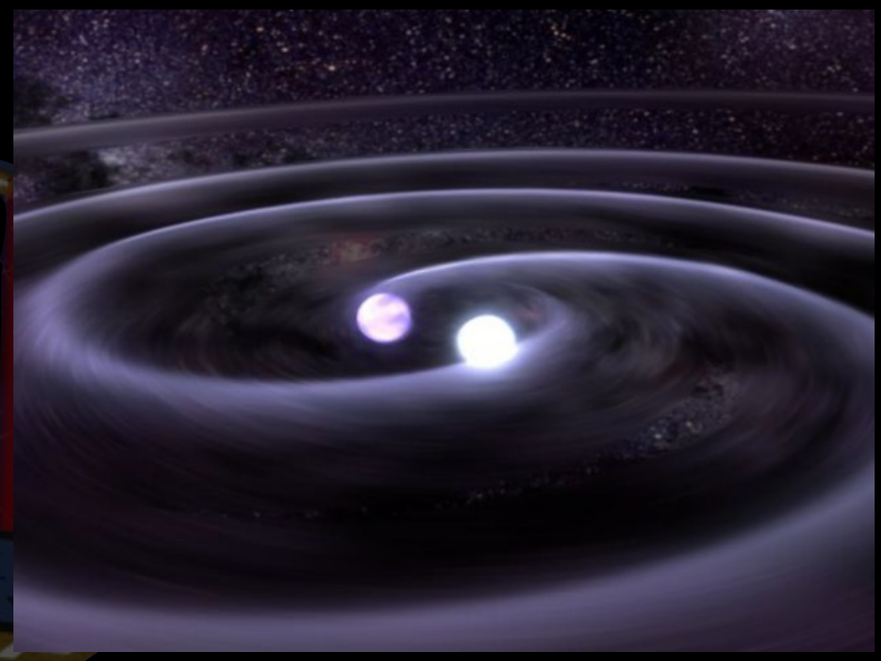
Response of the detector to GWs





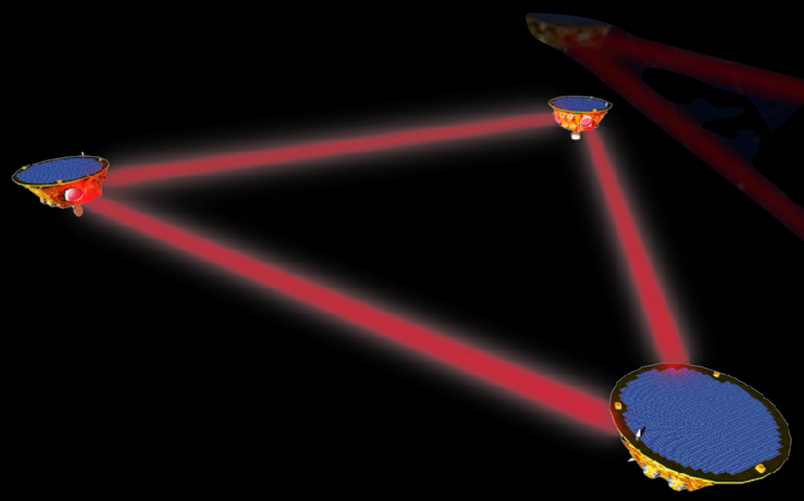


Galactic binaries



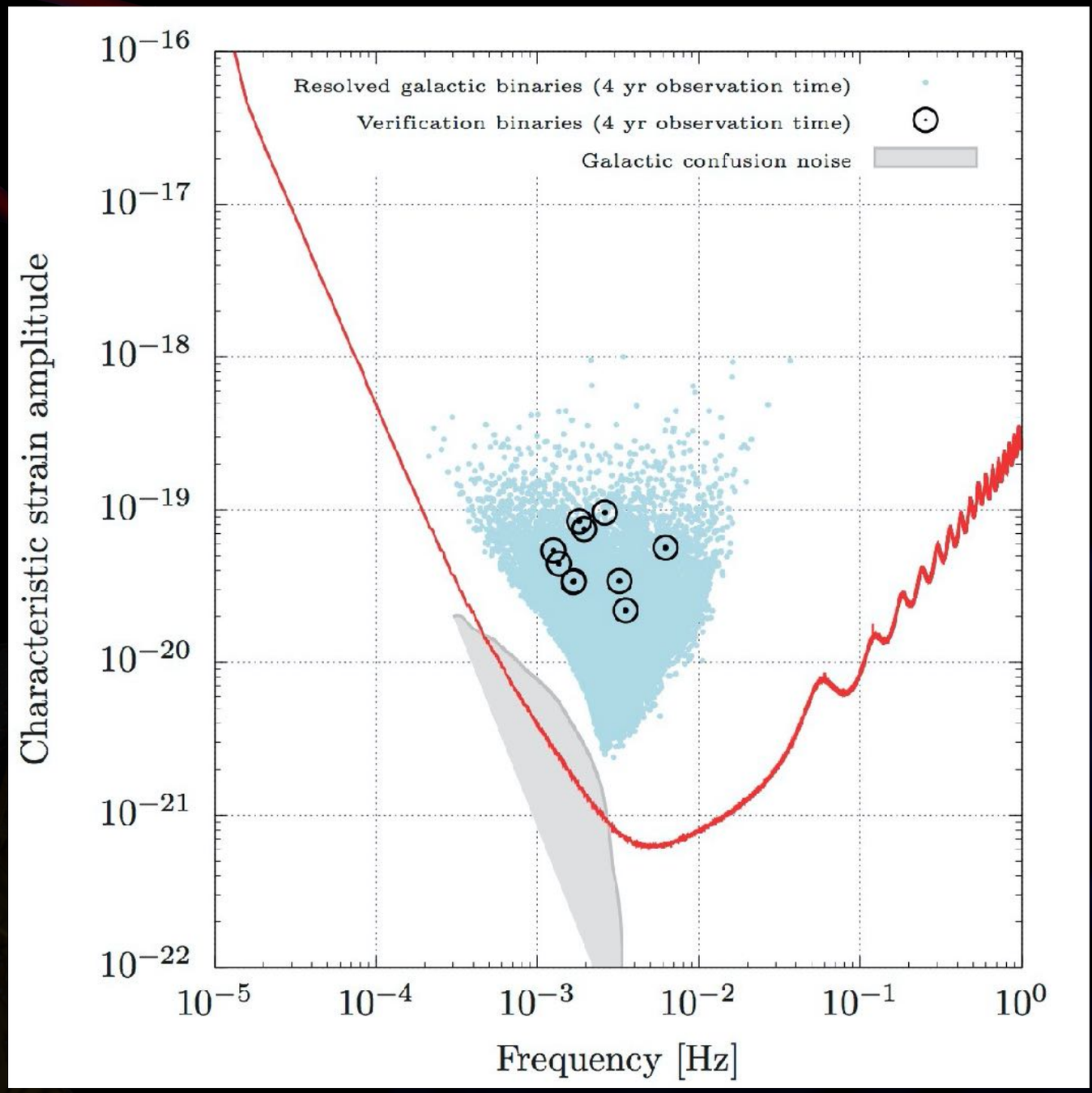
- Gravitational wave:
  - quasi monochromatic
- Duration: permanent
- Signal to noise ratio:
  - detected sources: 7 - 1000
  - confusion noise from non-detected sources
- Event rate:
  - 25 000 detected sources (over 60 millions sources)
  - more than 10 guarantied sources (verification binaries)

Galactic binaries



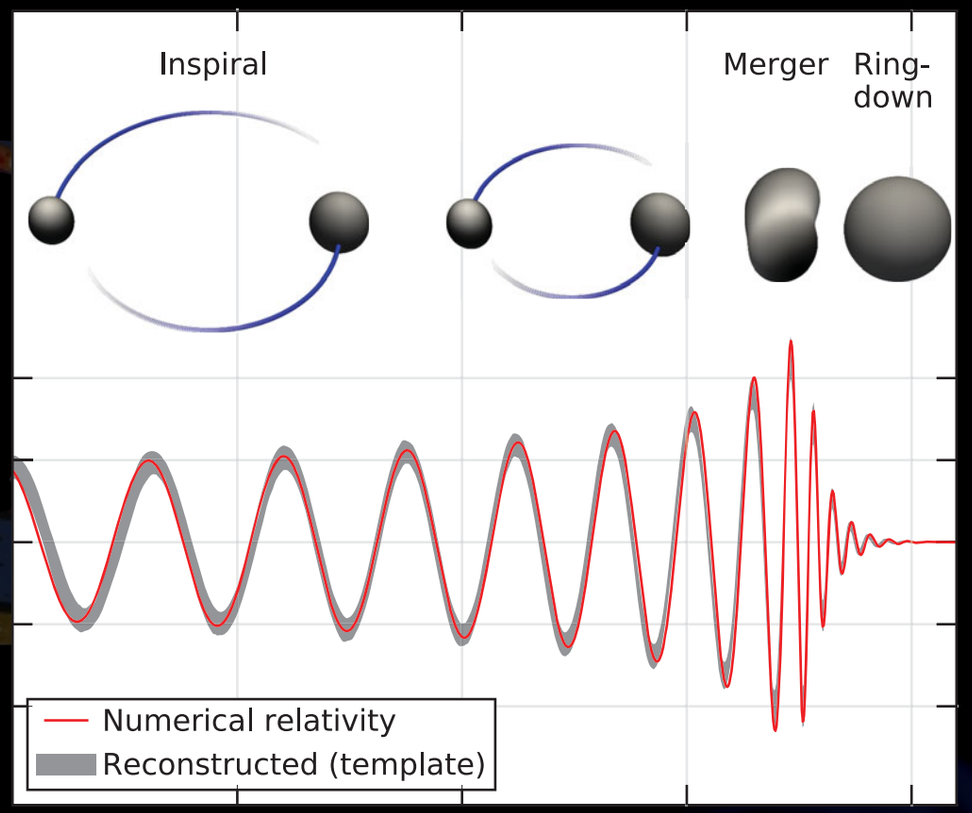
GW sources

- 3 x10^7 galactic binaries



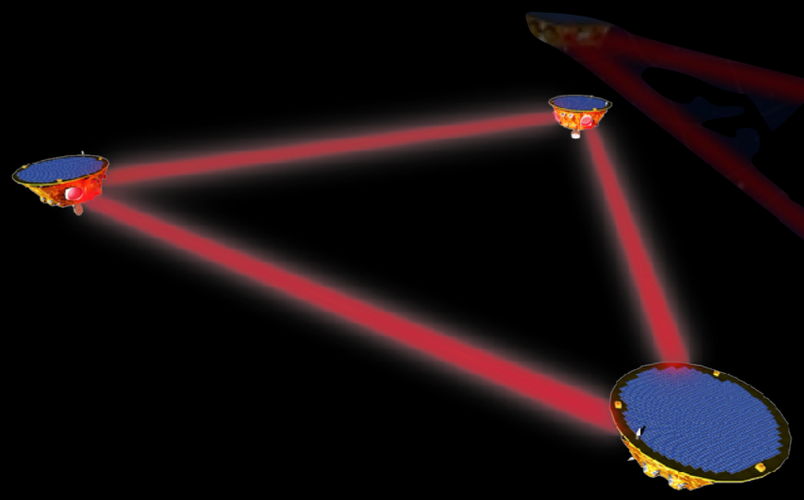
Super Massive Black Hole Binaries

- Gravitational wave:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.



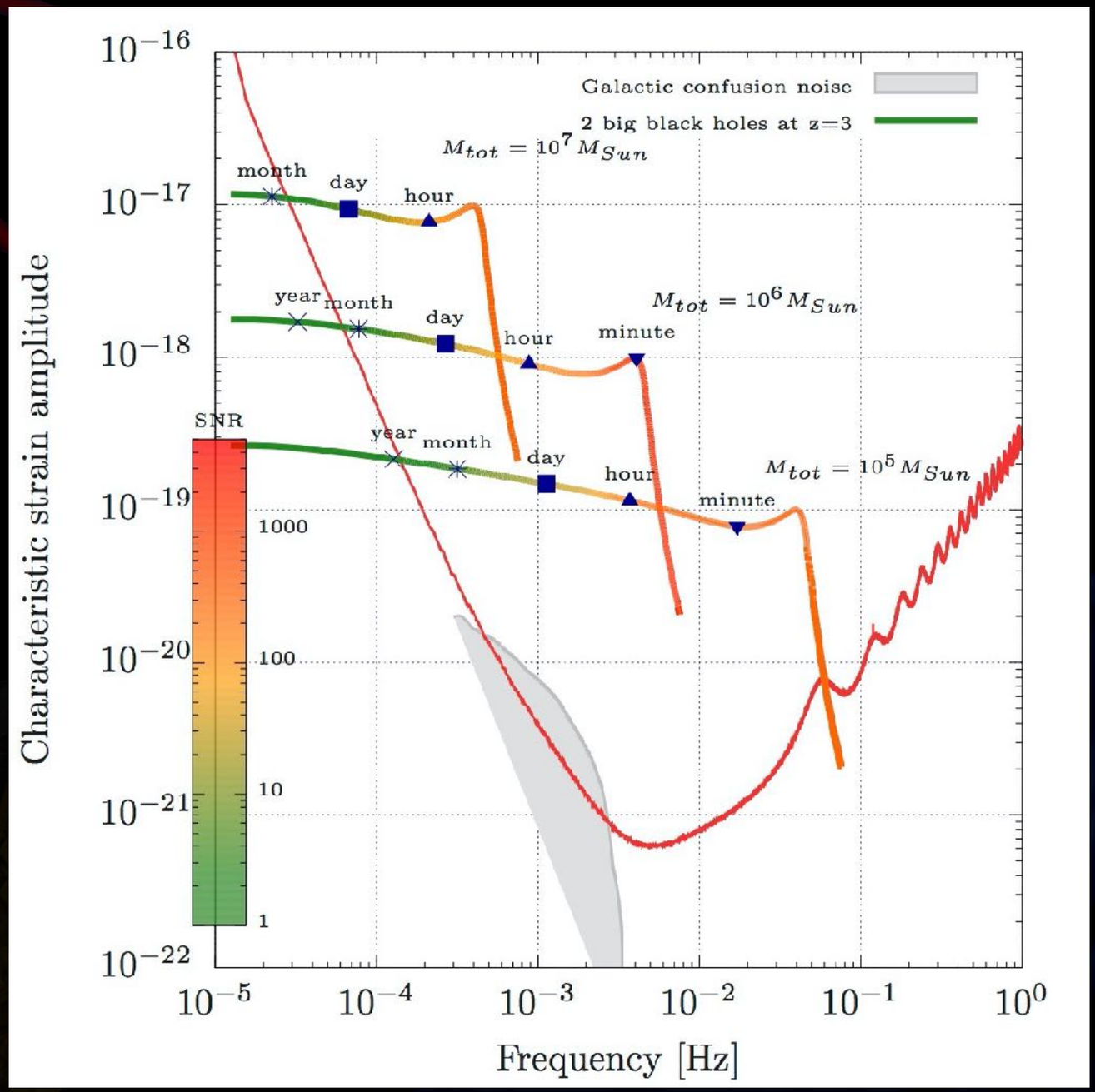
- Duration: between few hours and several months
- Signal to noise ratio: until few thousands
- Event rate: 10-100/year

Super Massive Black Hole Binaries



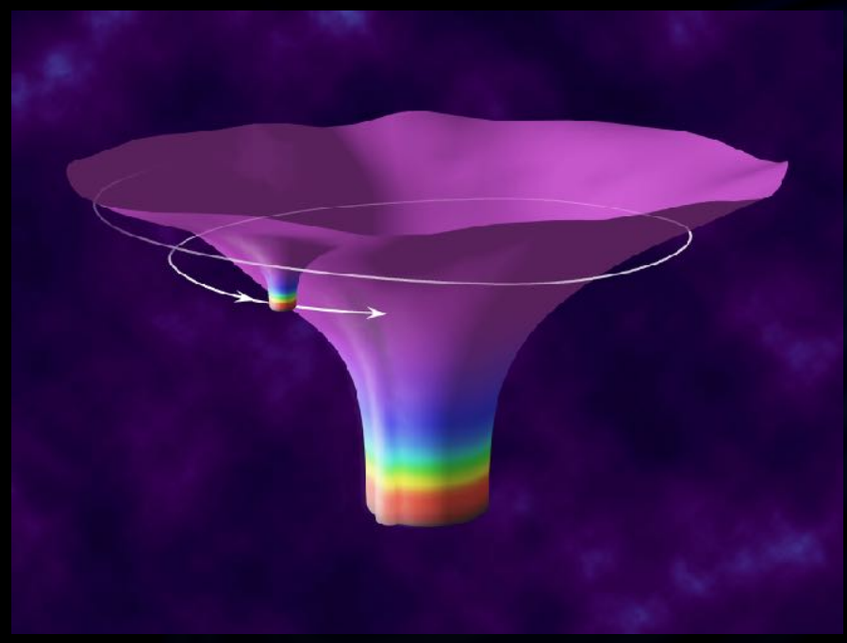
GW sources

- ✳ 3 x10^7 galactic binaries
- ✳ 10 - 100 / year SMBHBs

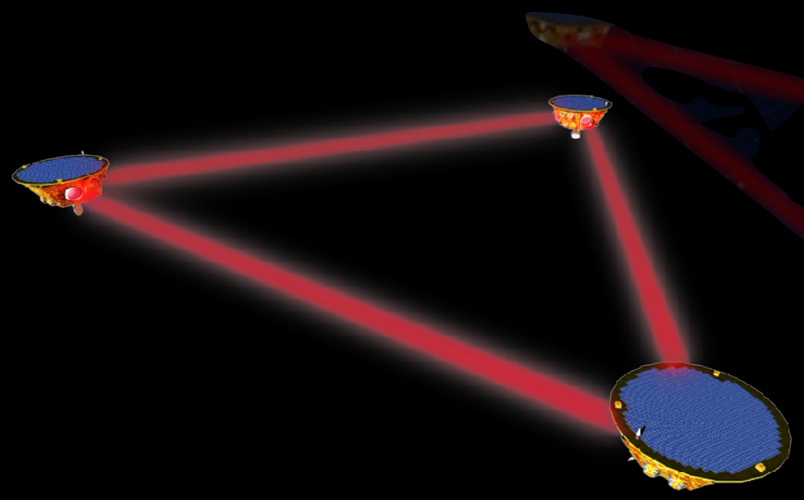


EMRIs

- Gravitational wave:
  - very complex waveform
  - No precise simulation at the moment
- Duration: about 1 year
- Signal to Noise Ratio: from tens to few hundreds
- Event rate:
  from few events per year to few hundreds

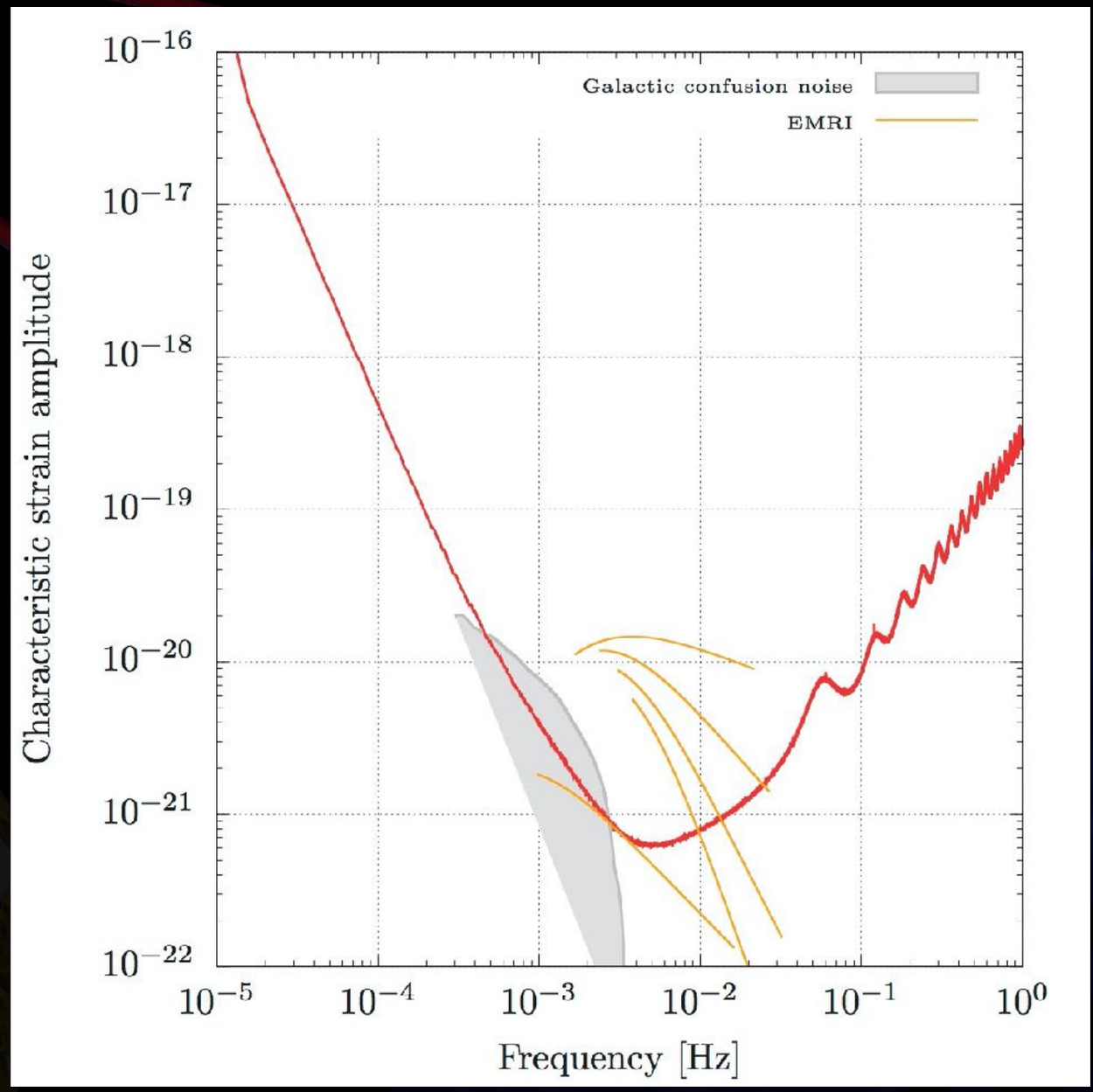


EMRIs



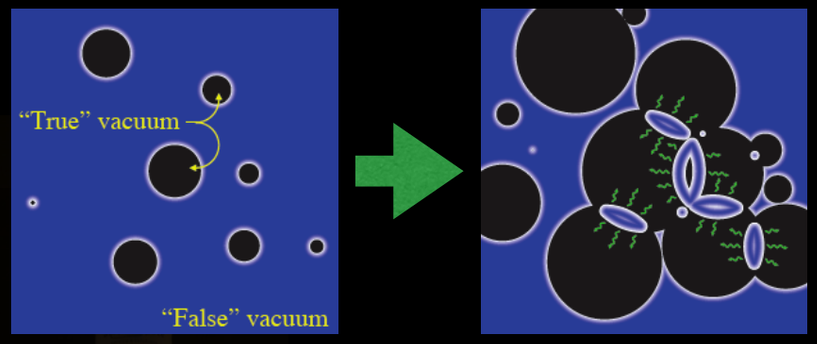
GW sources

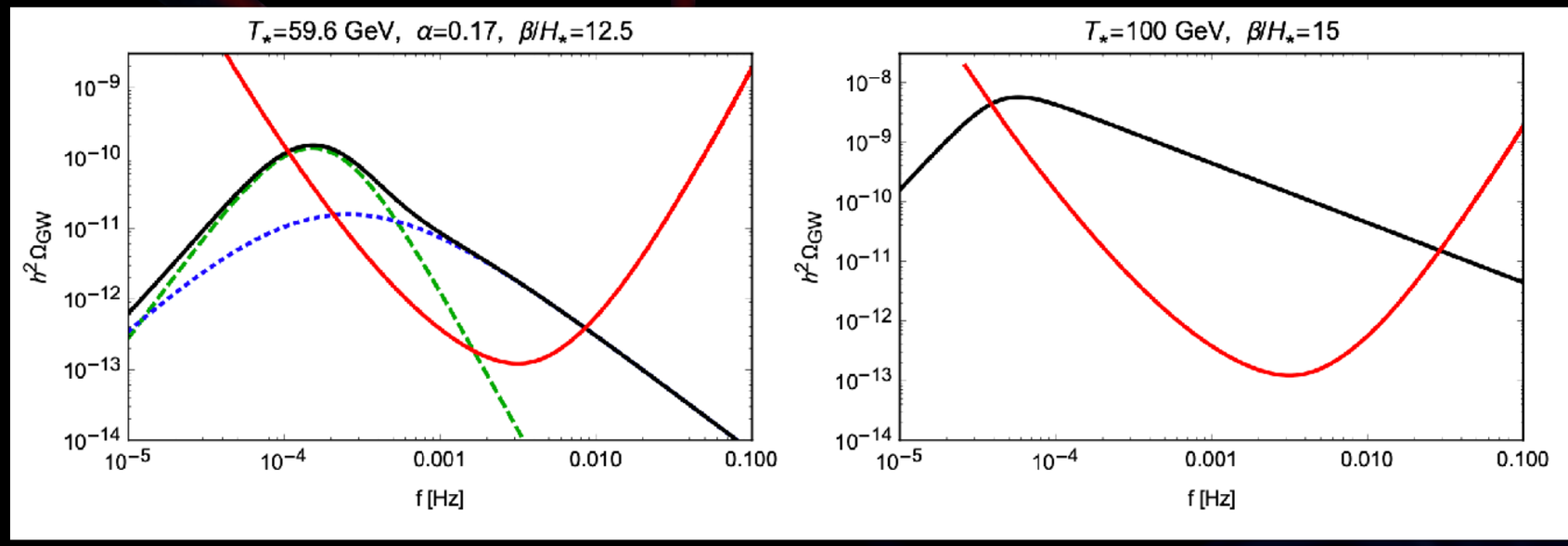
- 3 x10^7 galactic binaries
- 10 - 100 / year SMBHBs
- 1 - 1000 / year EMRIs



Cosmological backgrounds

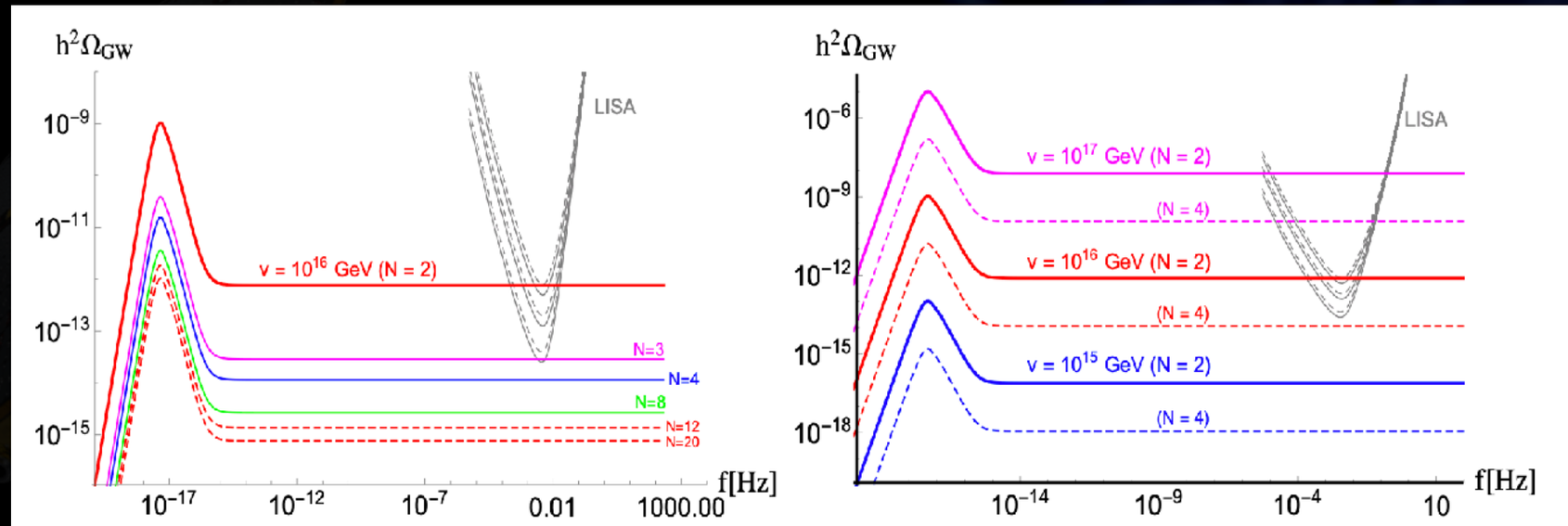
- Potential detection of cosmological background from:
  - First order phase transition in the very earlyUniverse



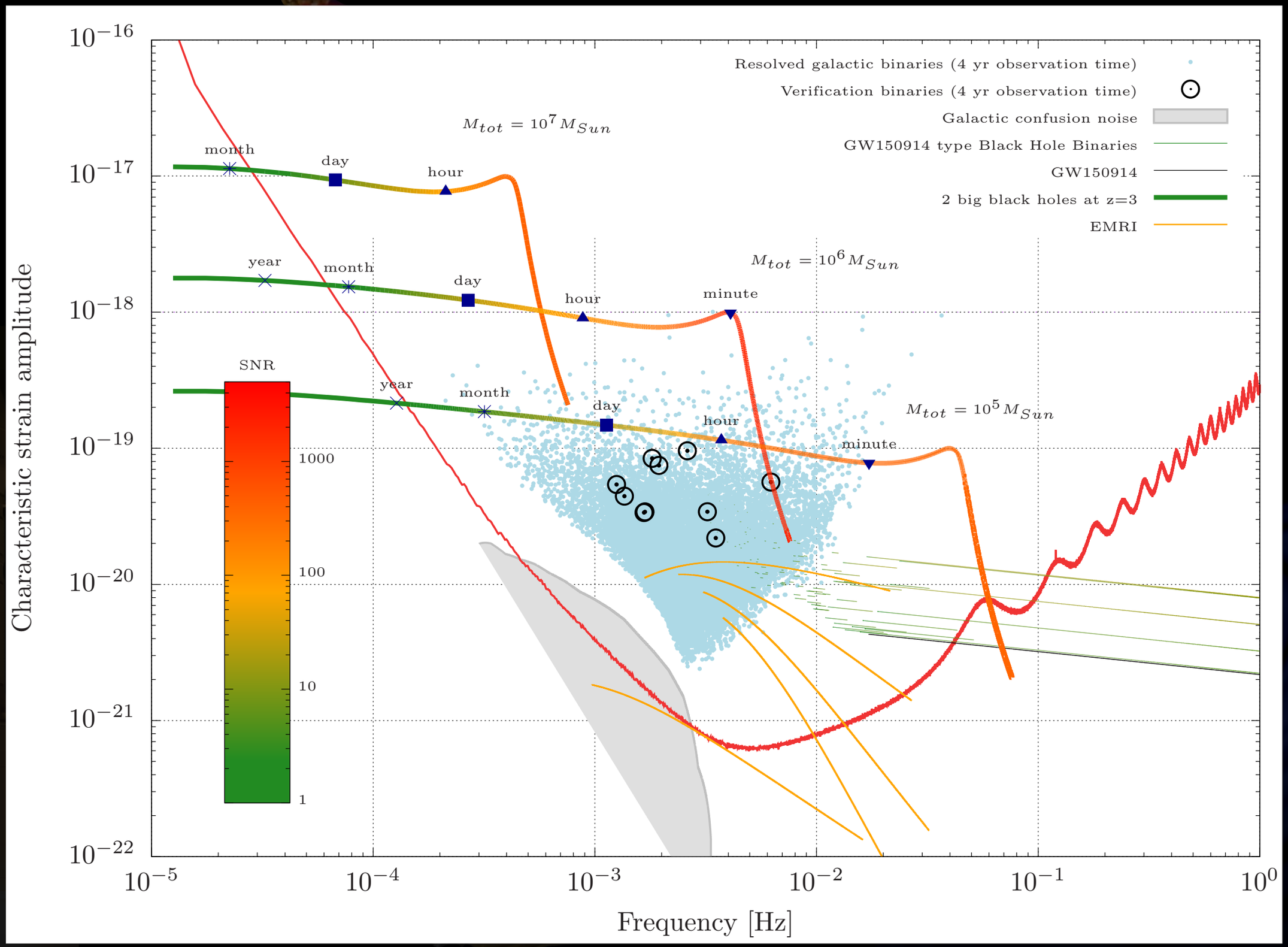


Caprini & Figueroa 2018, CQG 35,163001

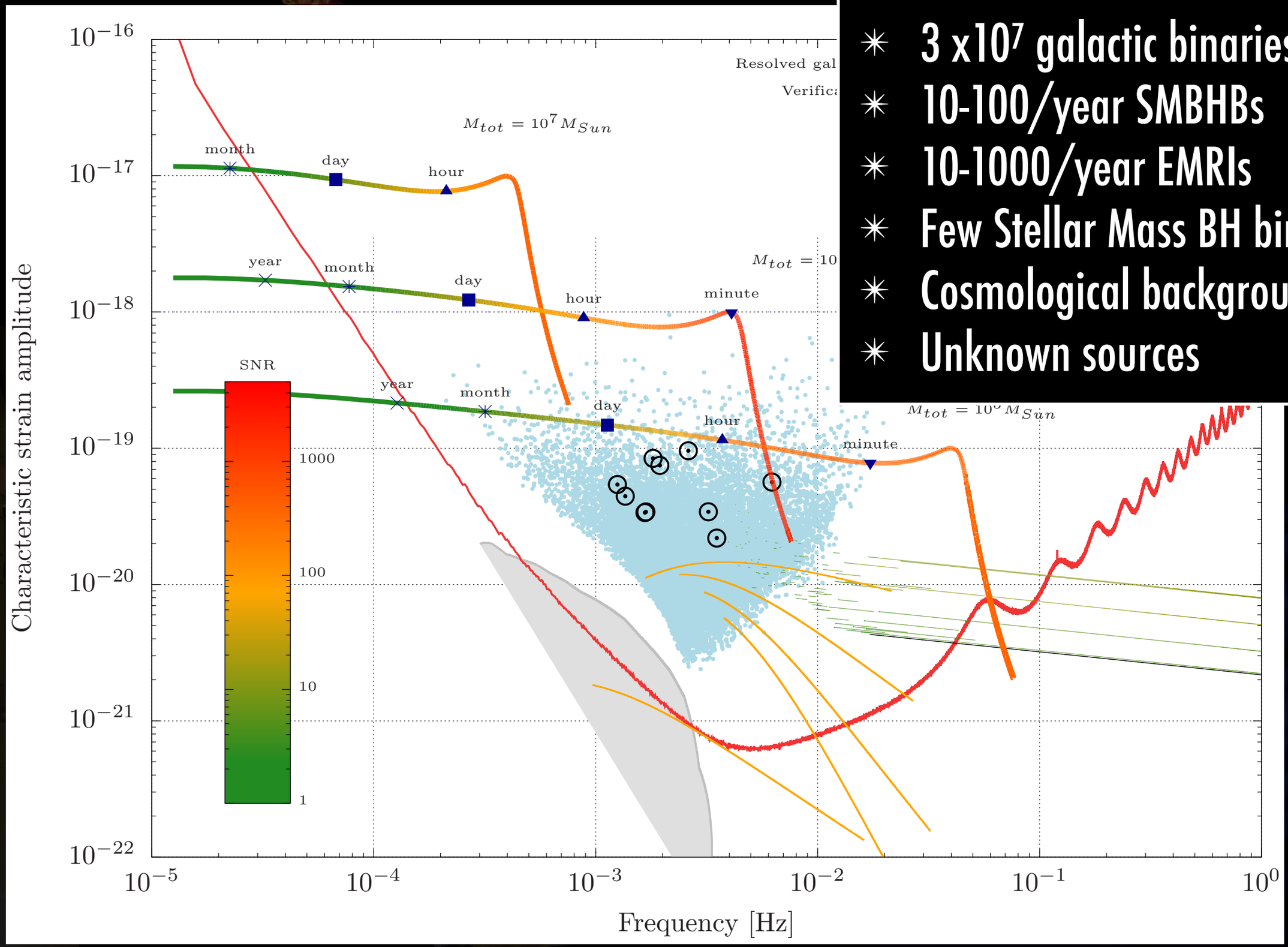
  - Cosmic strings network
  - …



GW sources


Resolved galactic binaries (4 yr observation time)
Verification binaries (4 yr observation time)
Galactic confusion noise
GW150914 type Black Hole Binaries
GW150914
2 big black holes at z=3
EMRI
$M_{tot} = 10^7 M_{Sun}$
$M_{tot} = 10^6 M_{Sun}$
$M_{tot} = 10^5 M_{Sun}$
month
day
hour
year
month
day
hour
minute
year
month
day
hour
minute
SNR
1000
100
10
1
Characteristic strain amplitude
Frequency [Hz]
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

GW sources

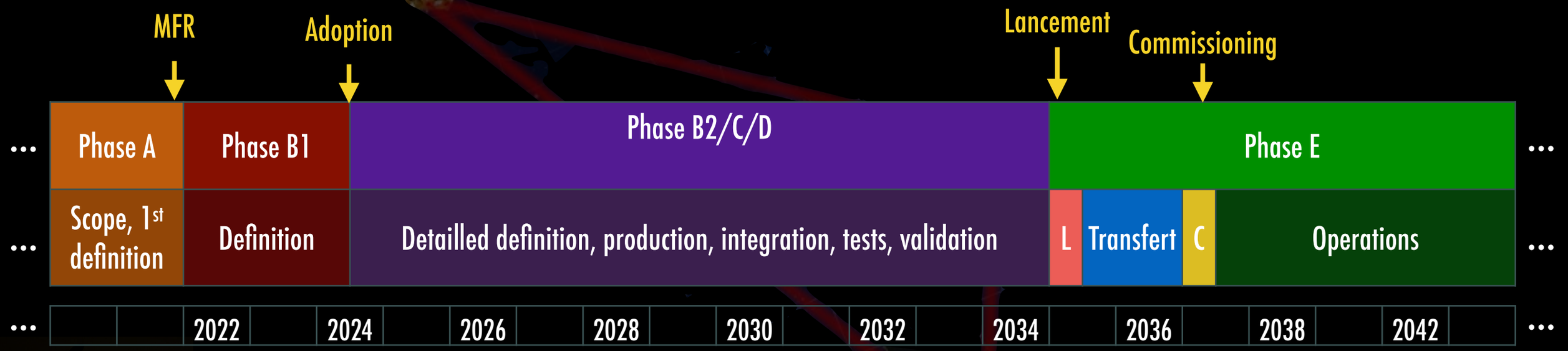


- 3 x10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Few Stellar Mass BH binaries
- Cosmological backgrounds
- Unknown sources

Overview

- Gravitational wave sources in the mHz band and LISA science objectives
- The mission
  - Space segment (hardware)
  - Ground segment (data analysis & science exploitation)
- Science performances
- Status: end of phase A (MFR) and Phase B1
- Organisations: Consortium & LISA France
- LISA at Paris Observatory

Planning & status



- 1993: first proposal ESA/NASA: 4 spacecrafts
- 20/06/2017: LISA mission approved by SPC
- Now: end of phase A with ESA Mission Formulation Review (October to December 2021)
- ESA Adoption end 2023
- Long building phase of multiple MOSAs: 6 flight models + test models
- Building of some model for subsystem already started
- Launch mid-2030s

MFR

- For FMT: 16 review docs + 34 reference docs:
  - Mission: Management plan of the Consortium
  - System Engineering Support
  - Calibrations and Operations
  - Performances:
  - Performances Model
    - Performance Model Validation
    - Figures of Merits
    - LISA Data Analysis Robustness Verification Plan
    - Implication of TDI Processing on Data Rates
  - SGS Data and Information Flow Analysis and Architecture Assumptions
  - TN L2/L3 Data Processing Simulations Result
  - TN SGS Technical Budget Estimation

MFR

- For FMT: 16 review docs
  + 34 reference docs
- More from Subsystems

Review Documents

LISA–LCST–MIS–PL–001	LISA Consortium Management Plan
LISA-LCST-INST-DD-002	Interferometric Detection System Description Document
LISA-LCST-INST-LI-001	Consortium Risk Register
LISA-LCST-INST-PL-003	Consortium Risk Management Plan
LISA-LCST-INST-PL-002	Technology Development Plan
LISA-LCST-INST-TN-003	Performance Model justifications
LISA-LCST-INST-ML-001	Performance Model
LISA-LCST-INST-RP-003	Performance Model CBE's and Allocations
LISA-AEI-INST-SP-001	Operations Assumptions Document
LISA-LCST-INST-TN-016	A Plan for LISA Calibration Studies
LISA-LCST-SGS-DD-002	INREP Description of the implementation and function
LISA-LCST-SGS-FI-001	INReP Software Reference Pipeline
LISA-LCST-SGS-MAN-001	INREP Software User Manual
LISA-LCST-SGS-RS-004	INREP Requirements Specifications
LISA-LCST-SGS-RP-001	INREP Study Case Results
LISA-LFRA-INST-RP-001	DEVELOPMENT APPROACH, MODEL PHILOSOPHY AND HIGH LEVEL SCHEDULE

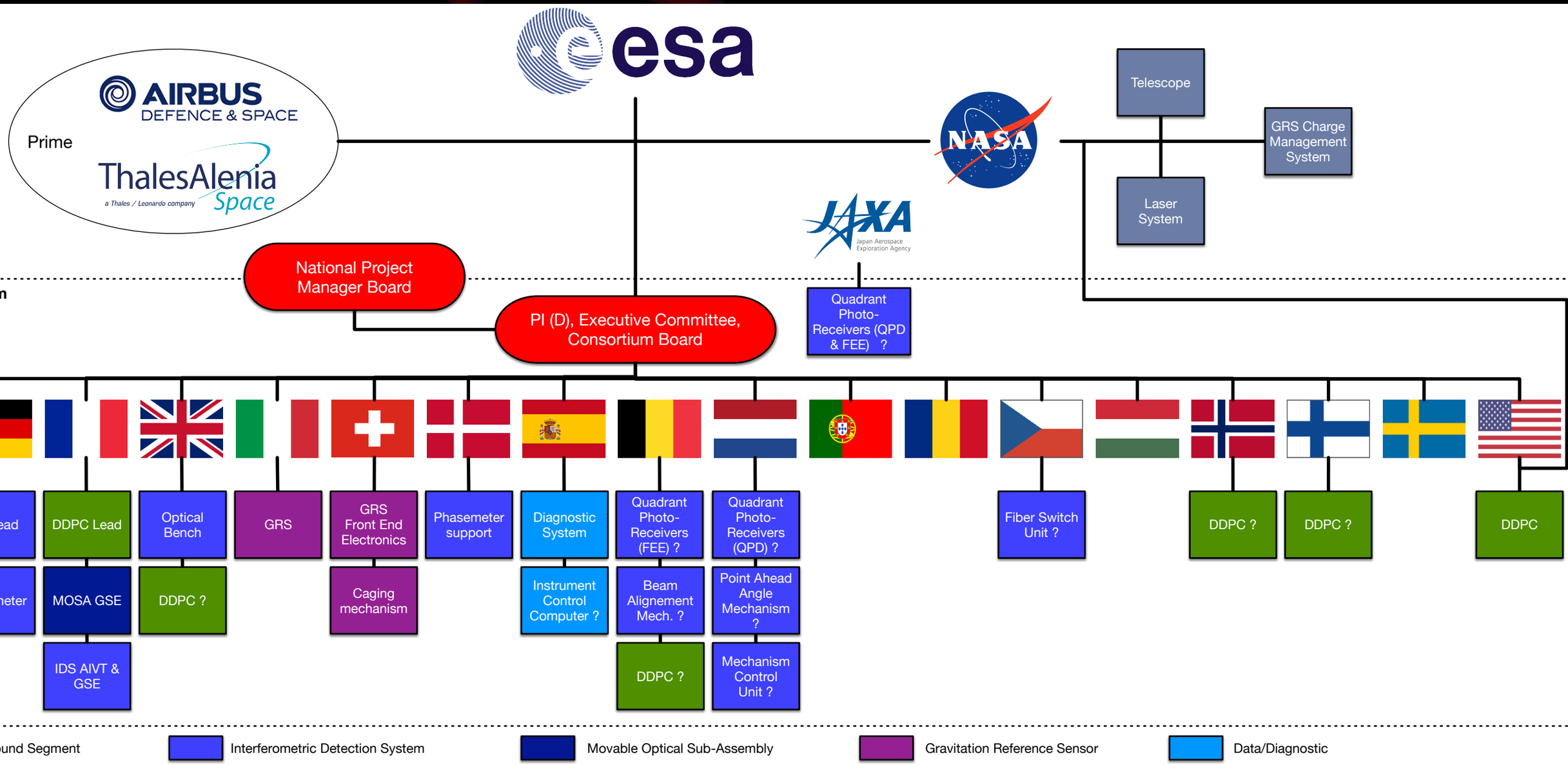
Reference Documents

LISA-LCST-SGS-AD-001	Science Ground Segment Data and Information Flow Analysis and
LISA-LCST-SGS-TN-002	TN L2/L3 Data Processing Simulations Result
LISA-LCST-SGS-RP-002	TN SGS Technical Budget Estimation
LISA-LCST-SGS-RS-005	Simulation Requirements & Planning
LISA-LCST-INST-DD-004	LISA Simulation in Simscape
LISA-LCST-INST-TN-012	Analytical TTL models for LISA
LISA-LCST-INST-DD-003	LISASim: An open-loop LISA simulator in MATLAB
LISA-LCST-INST-RP-004	LISA Simscape Performance Verification
LISA-LCST-INST-RP-002	Post-processing subtraction of Tilt-To-Length noise in LISA
LISA-LCST-INST-TN-013	Performance Model Risk Analysis
LISA-LCST-SGS-TN-003	FoM Justification document (LSG)
LISA-LCST-SGS-TN-004	FoM report comparing CBE and SciRD
LISA-LCST-SGS-RP-003	TDI transfer functions validation
LISA-LCST-INST-TP-001	Performance Model validation plan
LISA-LCST-INST-RP-005	Concept for balanced detection in LISA
LISA-LCST-SGS-TN-005	Implication of TDI Processing on Data Rates
LISA-LCST-SGS-PL-002	LISA Data Analysis Robustness Verification Plan
LISA-LCST-MIS-ST-001	Conventions and Nomenclature
LISA-LCST-INST-RP-001	TTL Mitigation Concept
LISA-LCST-INST-TN-014	Identified top-level failure modes
LISA-AEI-INST-RP-001	LISA Instrument Telemetry Budget
LISA-AEI-INST-DD-001	MOSA Design Definition File
LISA-AEI-INST-TN-004	Gravitational balance analysis
LISA-AEI-INST-TN-005	Thermal analysis
LISA-AEI-INST-TN-006	Deformation analysis
LISA-AEI-INST-TN-007	Static and dynamic stress analysis
LISA-AEI-INST-TN-008	Performance analysis report
LISA-AEI-INST-ML-001	CAD model
LISA-AEI-INST-ML-002	Thermal model
LISA-AEI-INST-ML-003	Structural model
LISA-LFRA-INST-TN-001	IDS PRELIMINARY TEST LIST
LISA-FZU-FSU-PL-001	LISA FSU MECHANISM ENGINEERING PLAN
LISA-LCST-INST-IF-001	QPR Interface Description Document
LISA-LCST-INST-ML-002	LISANode Simulation Model

MFR

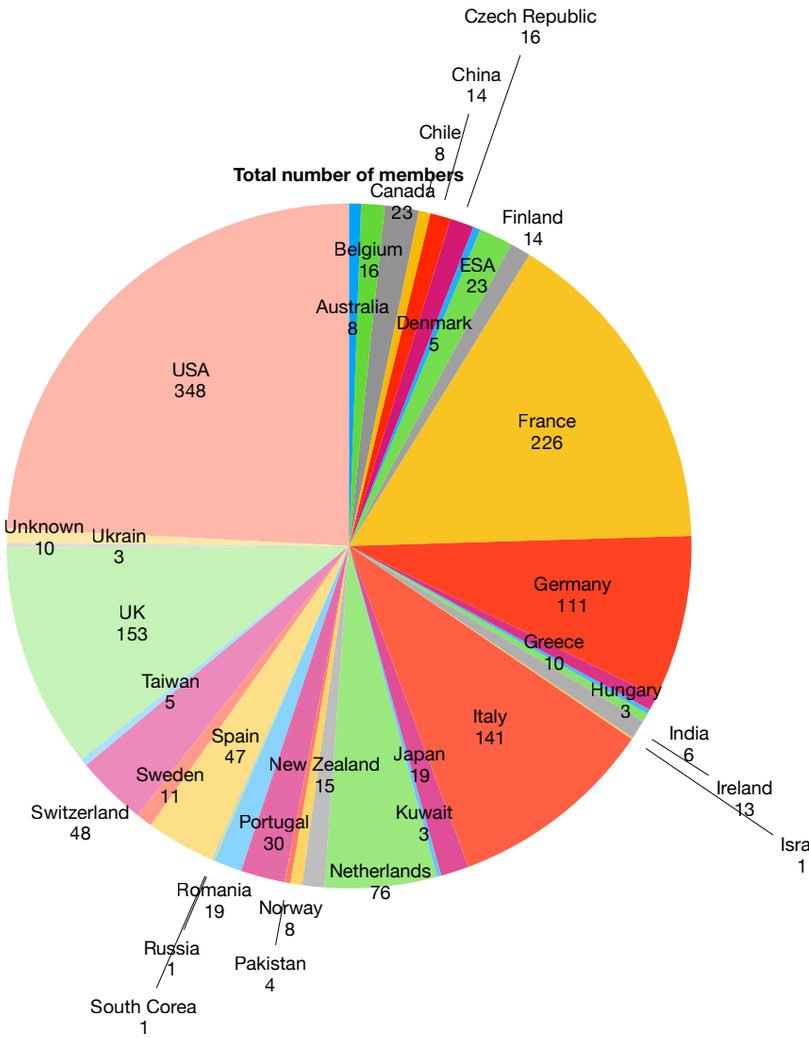
- 45 questions (RIDS) from ESA review panel:
  - 5 major
  - 20 on FMT
  - 7 on GRS
  - 5 on ePMS
  - 11 on OB
  - 2 on Diag & Control
  - All RIDs “closed”, some with actions
- Unofficial outcome: we passed phase A (TBC by the official report) but we have few items to consolidate and clarify!

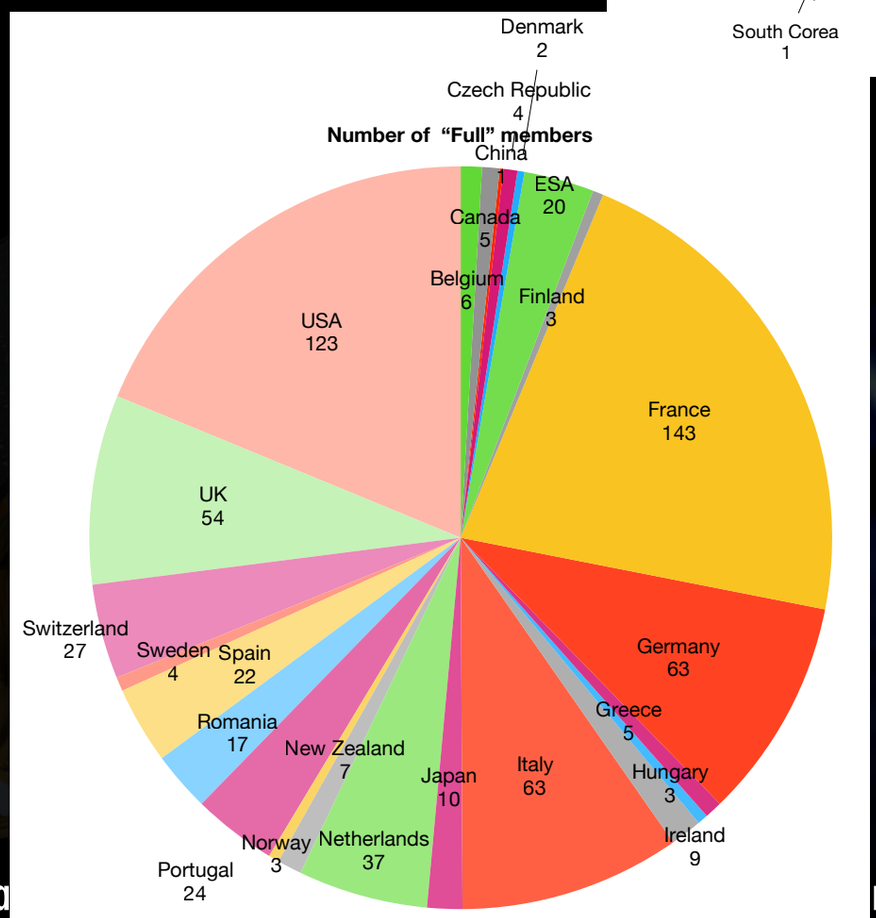
LISA organisation



LISA Consortium

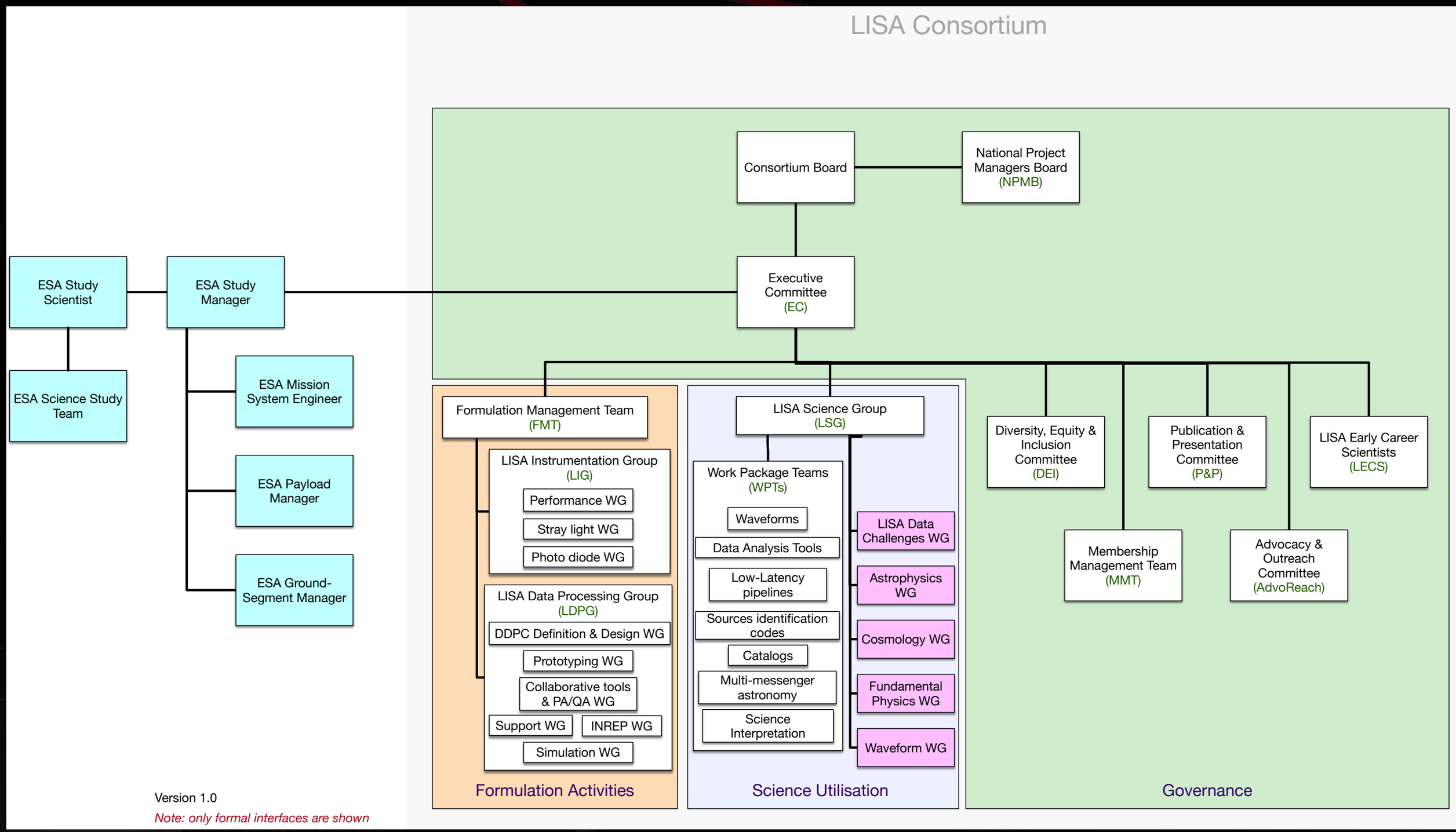
- 1527 members:
  - 730 "full members" committing time
  - 797 associates participating to the 5 WGs:
    - Astrophysics,
    - Cosmology,
    - Fundamental Physics,
    - LISA Data Challenge,
    - Waveforms





LISA Consortium

▸ Organisation



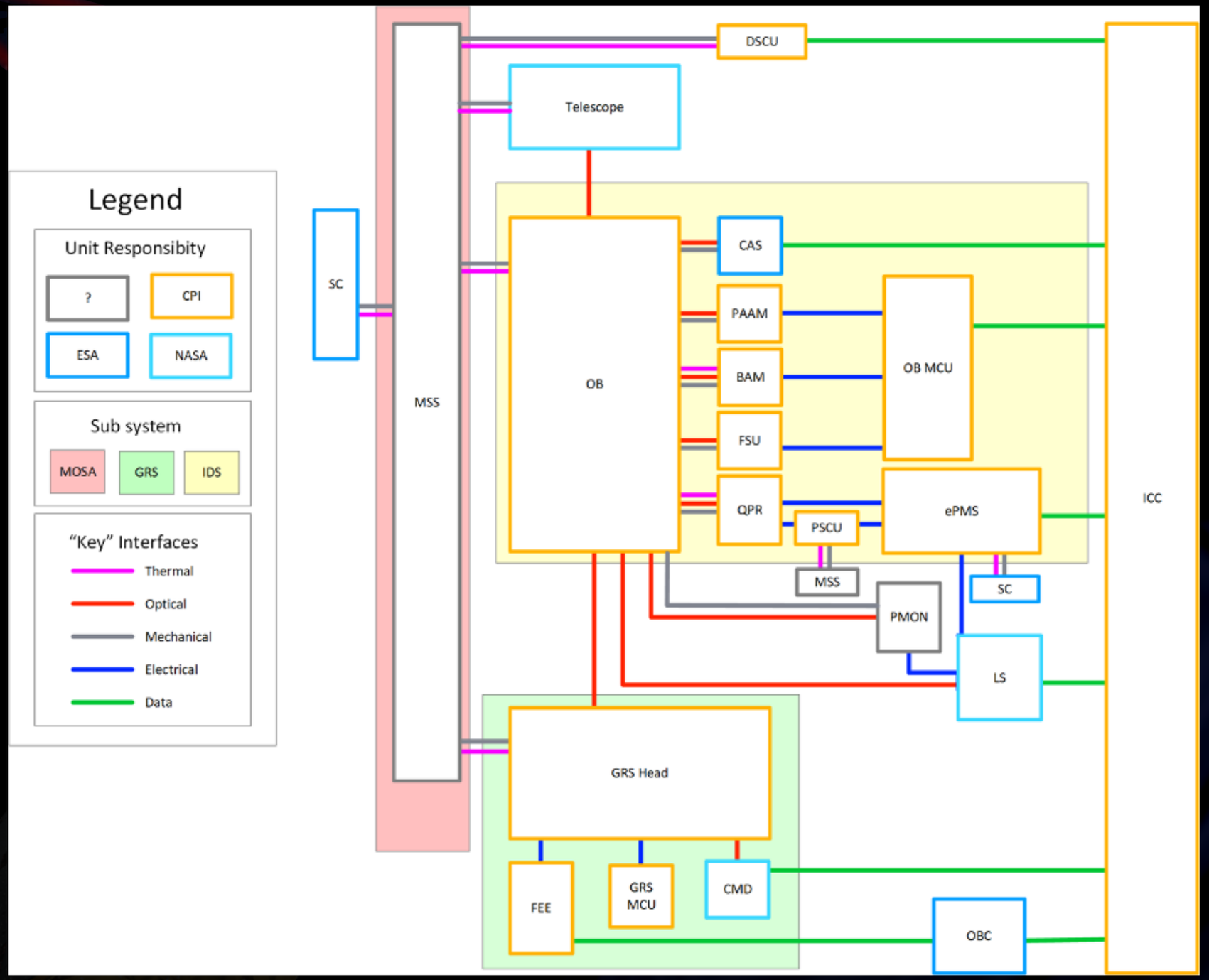
LISA Consortium

- LISA Consortium commits to:
  - support ESA with key personnel, providing expert knowledge on the critical aspects of the observatory;
  - deliver to ESA several key parts at the heart of the payload:
    - Interferometric Detection Subsystem,
    - Gravitational Reference Sensor Subsystem,
    - Optical Metrology Equipment for the ground qualification and verification,
    - and the Science Diagnostics
  - support ESA with the development of the mission ground segment, specifically:
    - by providing a Distributed Data Processing Centre
    - by providing a data processing software including TDI routines
    - by supporting the design of science operations
  - support to calibration and operations

Consortium: Space Segment

4 main CPI Consortium Provided Items:

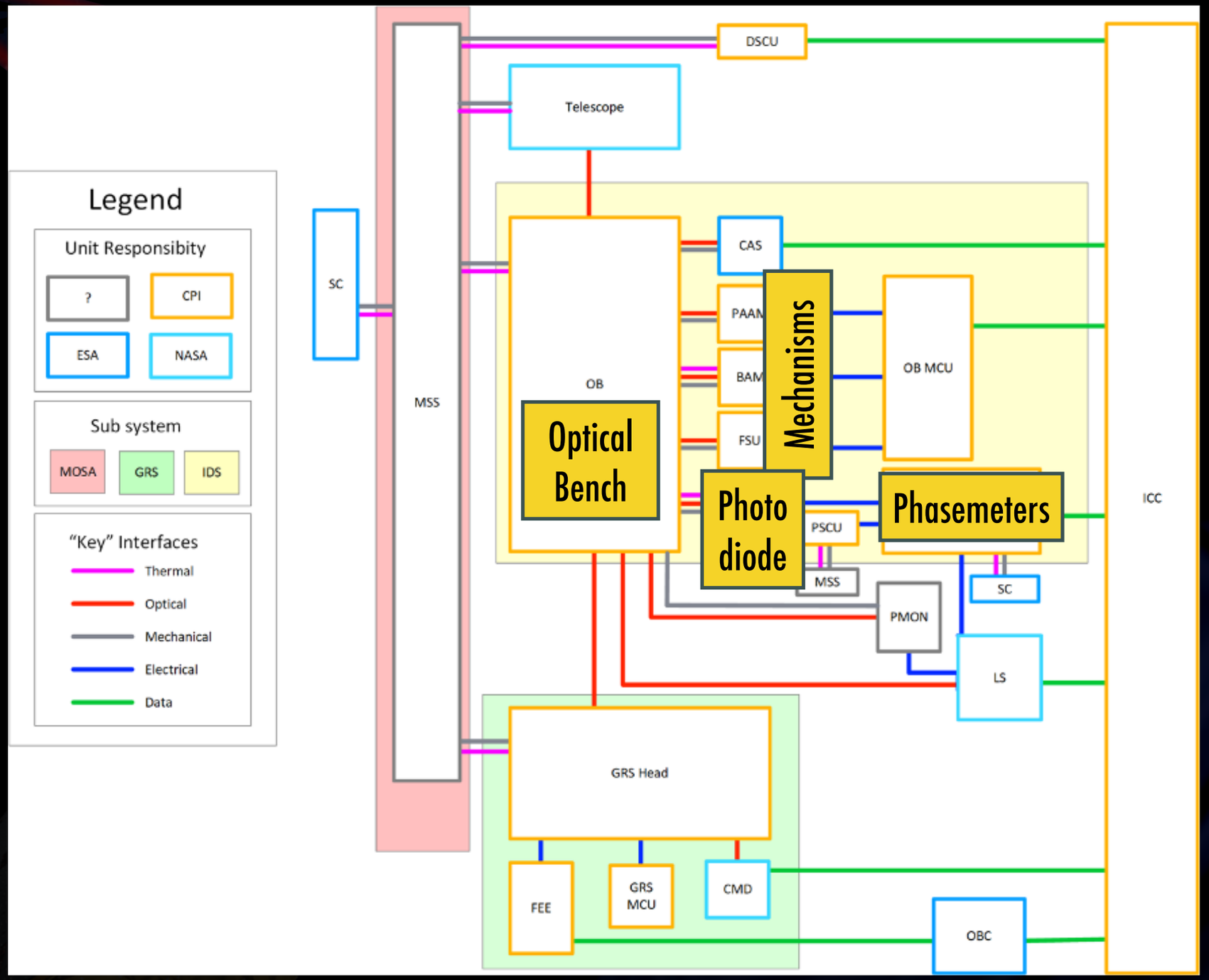
- IDS (Interferometric Detection Subsystem)
- GRS (Gravitational Reference Sensor Subsystem)
- Optical Metrology Qualification & Verification Ground Support Equipment
- Science Diagnostics & Control Subsystem



Consortium: Space Segment

4 main CPI Consortium Provided Items:

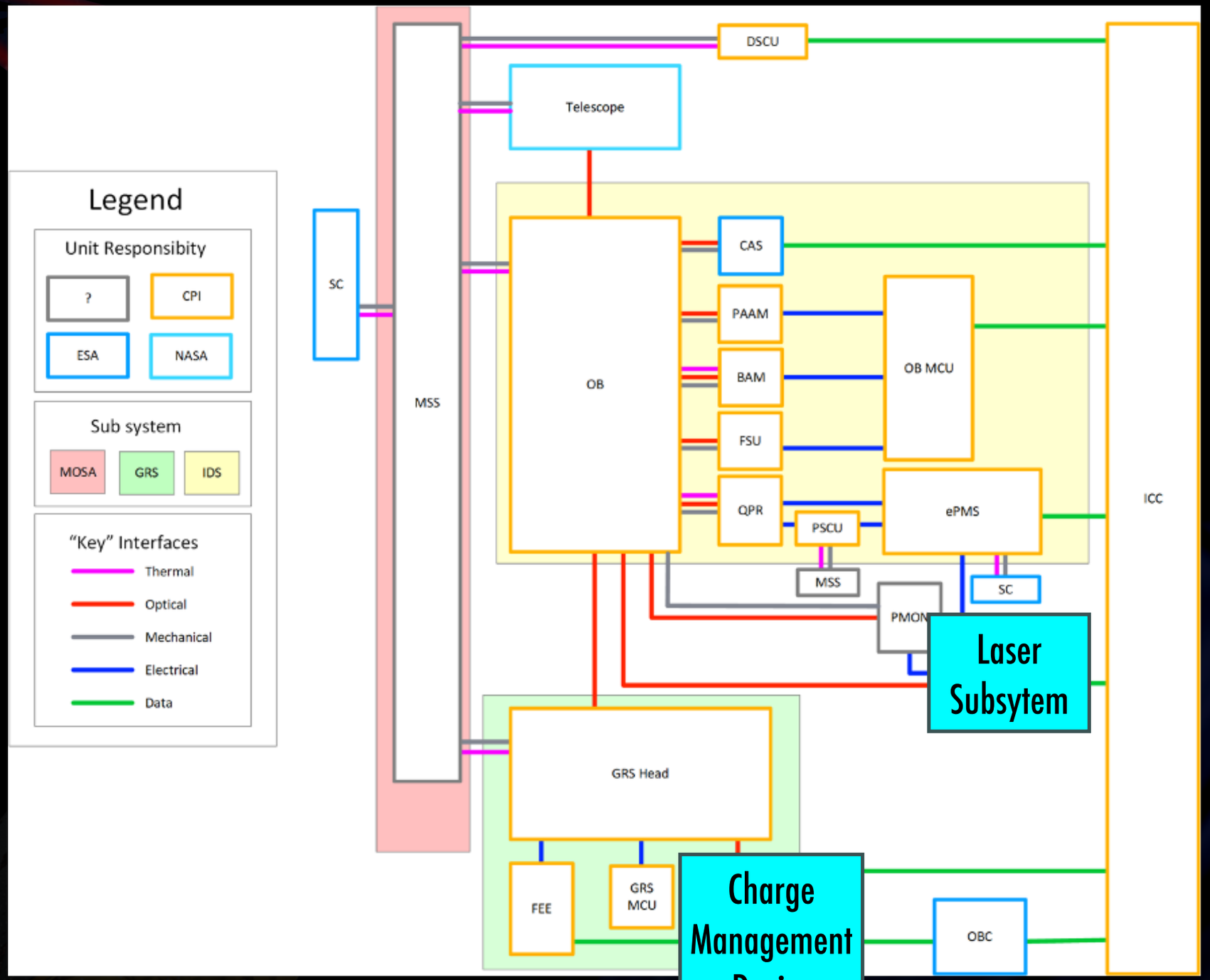
- IDS (Interferometric Detection Subsystem)
- GRS (Gravitational Reference Sensor Subsystem)
- Optical Metrology Qualification & Verification Ground Support Equipment
- Science Diagnostics & Control Subsystem



Consortium: Space Segment

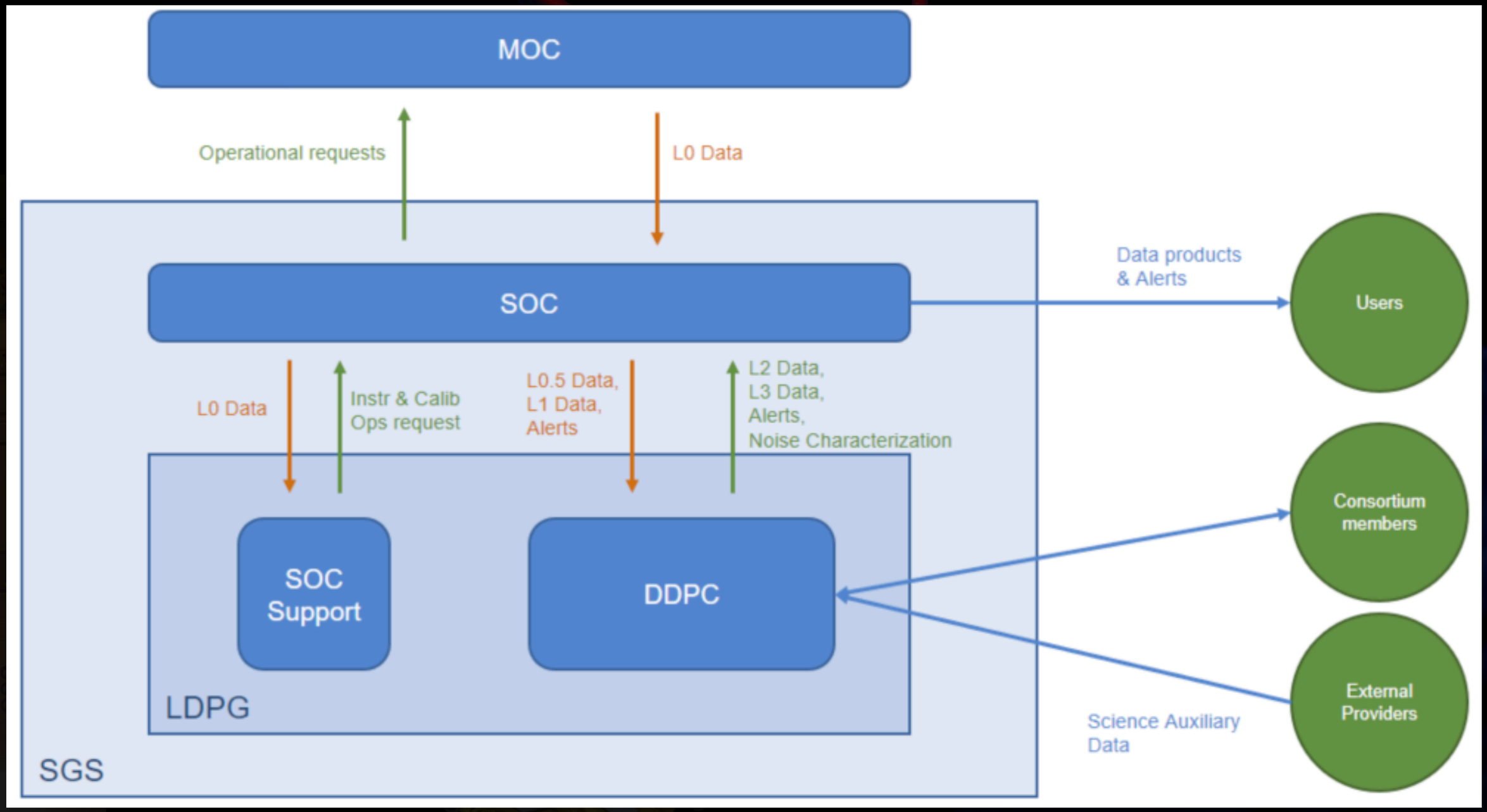
4 main CPI Consortium Provided Items:

- IDS (Interferometric Detection Subsystem)
- GRS (Gravitational Reference Sensor Subsystem)
- Optical Metrology Qualification & Verification Ground Support Equipment
- Science Diagnostics & Control Subsystem



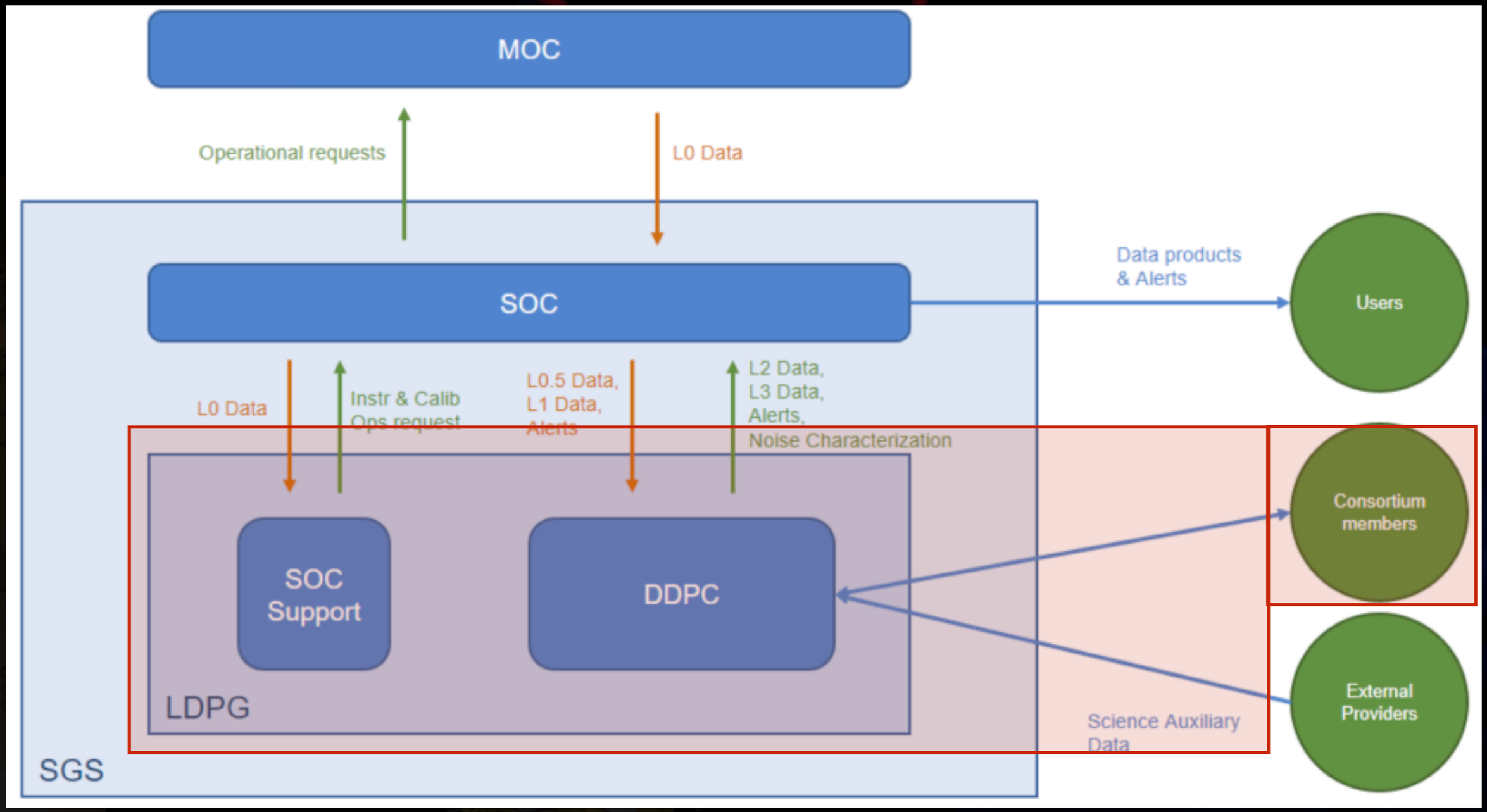
Consortium: Ground

- Global organisation



Consortium: Ground

- Global organisation



Consortium: Ground Segment

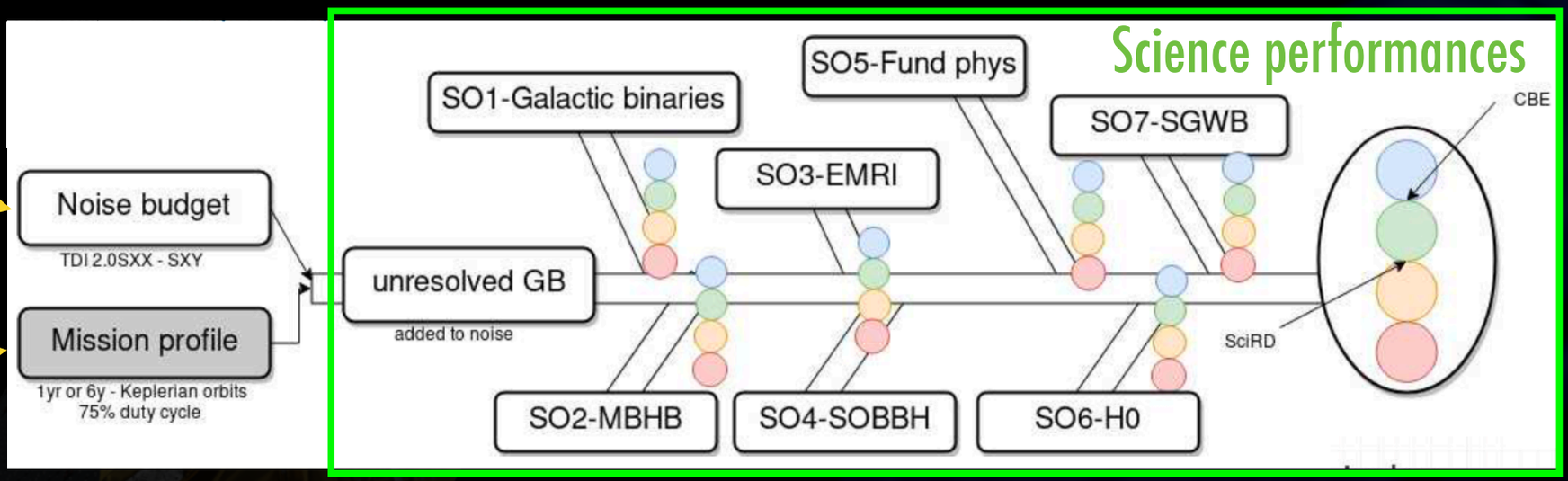
- Support ESA with the development of the mission ground segment, specifically:
  - by providing a Distributed Data Processing Centre
  - by providing a data processing software including TDI routines
  - by supporting the design of science operations
- DDPC WBS (preliminary)
  - Science softwares:
    - L0 -> L1: INReP
    - L1 -> L2 Alerts
    - L1 -> L2 Deep Analysis
    - L1 -> L2 Mono-blocks
    - L2 -> L3 SW
    - Simulation
    - Common SW & Tools
  - System softwares:
    - Software Development kit
    - Prototyping Framework
    - Expertise Lab Framework
    - Data Management
    - DDPC Framework
    - DevOps
    - DDPC Deployment
    - Pipeline Management
  - Infrastructure

Figures of merits

- Infrastructure to derive Science Performance (detection of sources, parameter estimation, etc) from any configuration of the mission (linked via noise budget / performance model and mission profile)
- 30 Fig. of Merits defined by Science Group (LSG) for 7 Science Objectives (SciRD)
- 1 hour (on a small cluster) to evaluate the performance of a configuration

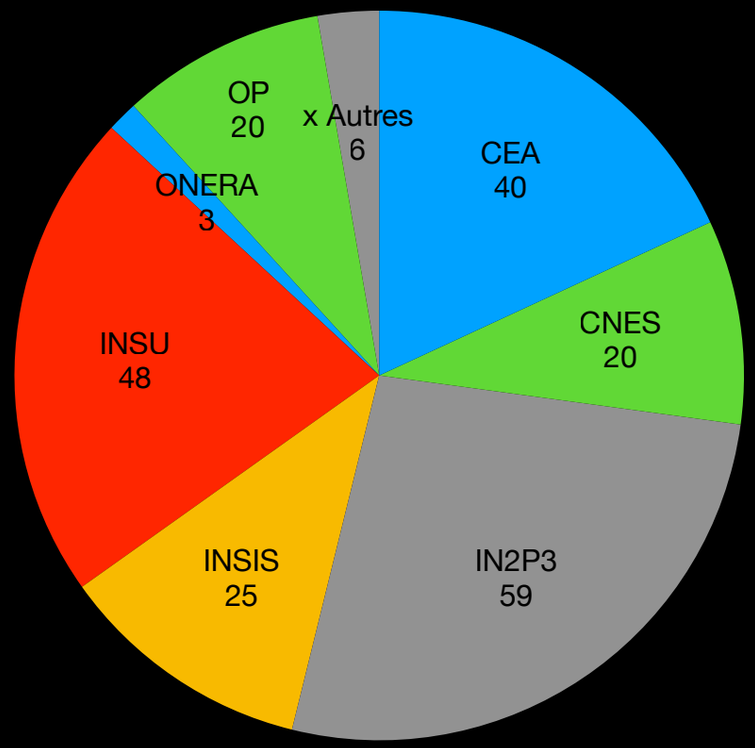
Performance model

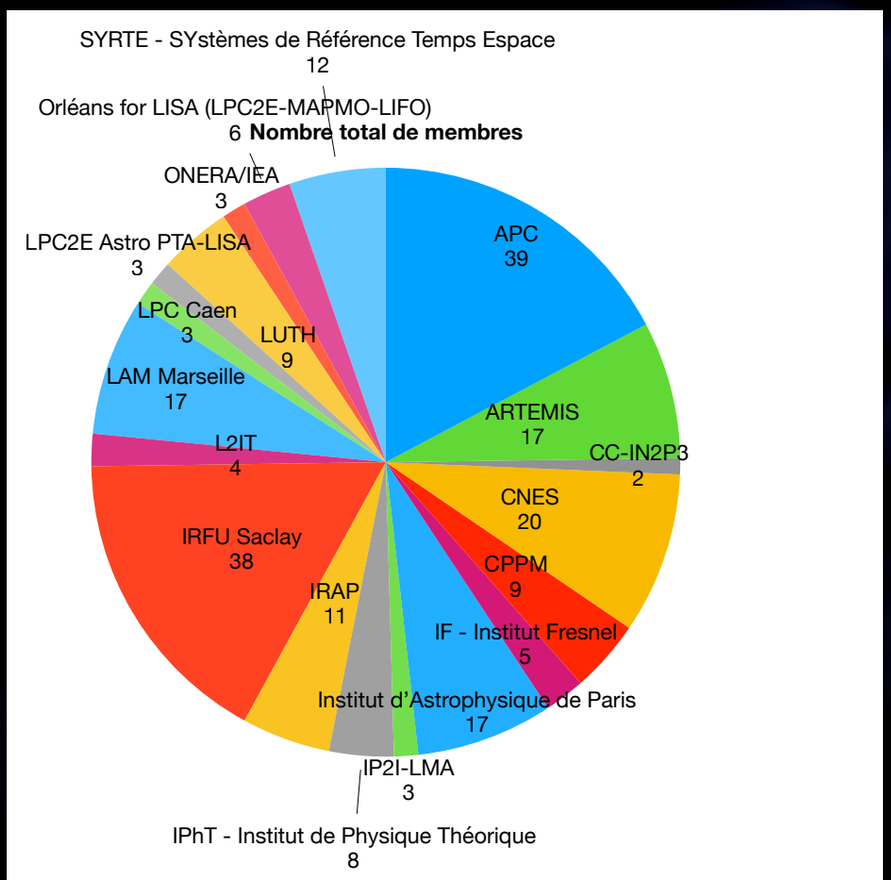
Mission configuration



LISA France

- About 220 members of the LISA Consortium are from French institutes: 140 full members
- Contribution:
  - Science:
    - All topics: Astrophysics, Cosmology, Fundamental Physics, Data Processing, ...
  - Project:
    - Managed by CNES with contributions of 11 laboratories





LISA France

- Contribution to "project":
  - IDS: System Engineering and AssemblyIVT:
    - Ground Segment Equipement (GSE): Optical, Electrical and Mechanical
  - MOSA: development of complex GSE
  - Performance model
  - Distributed Data Processing Center:
    - Important role of France in the Science Ground Segment

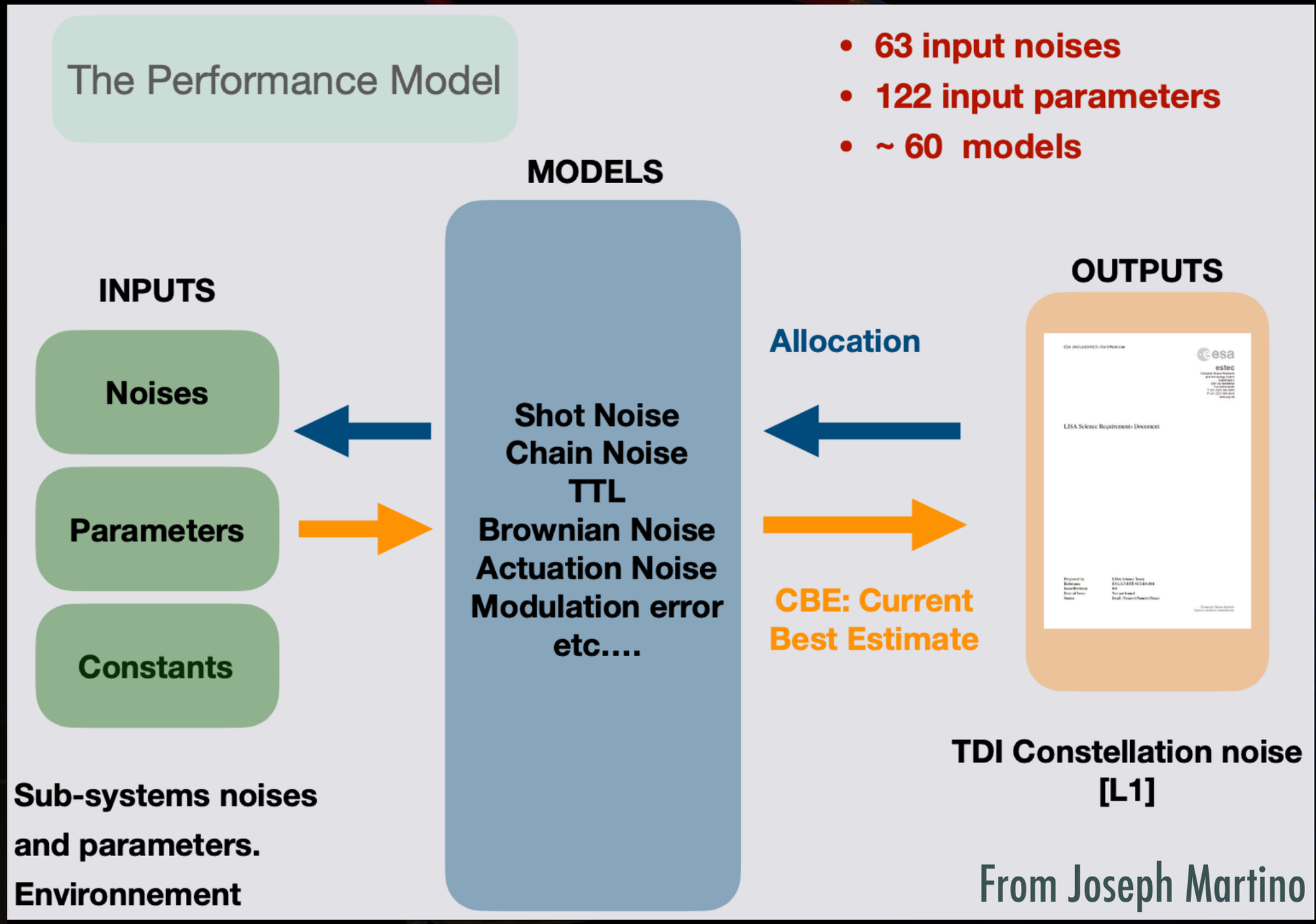
LISA France: IDS

Work Breakdown Structure

- Facility (CNES)
- Ground Segment Equipement:
  - Optical GSE:
    - Test mass simulator
    - Beam simulators
    - Lasers
  - Electrical GSE:
    - Command & control
    - Phasemeters
  - Mechanical GSE:
    - Stable structure
    - Thermal set
    - Hoisting
- Engineering Model (EM) Campaign:
  - EM Test Specification
- Qualification Model (QM) Campaign:
  - QM Test Specification

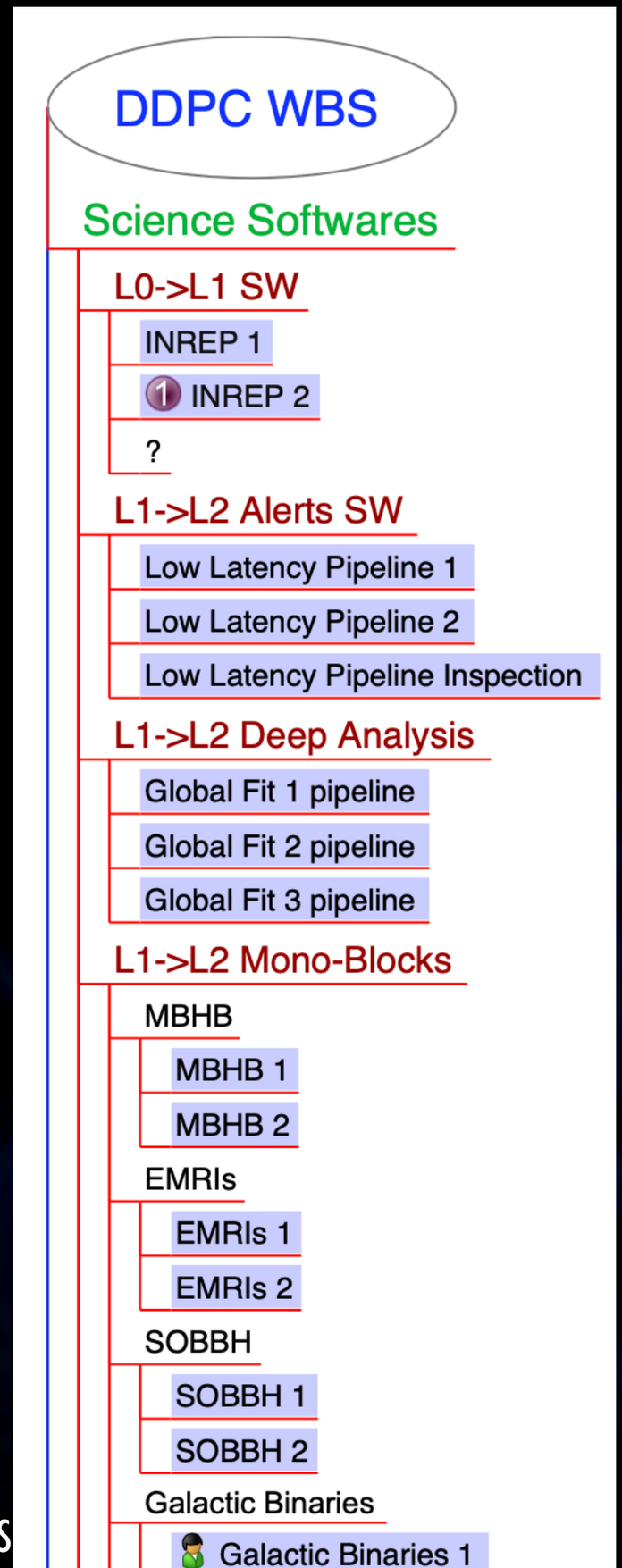
LISA France: Performances

- Performance Model



LISA France: SGS

- Science Ground Segment in France
  - Leading role of France on the Distributed Data Processing Center
  - On-going discussion between CNES and French laboratories to define the possible contribution from each laboratories and then the French contribution
  - Similar discussion will start at the Consortium level



Overview

- Gravitational wave sources in the mHz band and LISA science objectives
- The mission
  - Space segment (hardware)
  - Ground segment (data analysis & science exploitation)
- Science performances
- Status: end of phase A (MFR) and Phase B1
- Organisations: Consortium & LISA France
- LISA at Paris Observatory

OP & LISA Consortium

- 20 members / 2 laboratories in the LISA Consortium
- SYRTE (9 full members / 2 associates)
  - Laser for MIFO (laser iode) and for OGSE
  - Alternative INReP
  - Galactic binaries (collab. IRFU):
    detectability of magnetic & tidal effects for WD-WD
- LUTh (9 associates)
  - Waveforms: numerical relativity, perturbation theory & self-force, ...
  - GW sources
  - General Relativity and Fundamental Physics

Science Objectives

Define in the Science Requirements Doc.:

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

Astrophysics

Funcdamental physics

Cosmology

LISA & Obs. Paris

- "Forces" of Observatoire de Paris:
  - "Lois de la gravitation, Objets compacts et hautes énergies" (GW, physics of compact objects, high energy environments and modelling, tests gravitation laws, ...)
    => direct and indirect connexion with many scientific fields of LISA in particular via compact objects binaries (SO1, SO2, SO3, SO4, SO5 - astrophysics & fundamental physics)
  - "Les galaxies: des étoiles aux grandes structures": (dynamical evolution of galaxies, large scale structures, Milky Way modelling, ...)
    => connexion with SO1, SO2, SO3 and SO4:
    - Trace the origin, growth and merger history of SMBHB
    - Milky Way structure via binaries WD, NS, BH
    - Dense nuclear cluster
    - Astrophysics of Stellar mass BH binaries

LISA & Obs. Paris

- "Forces" of Observatoire de Paris:

  - "Instrumentation: recherche & ingénierie" (optics, metrology, data processing, system engineering, ...)
    => IDS AIVT and MOSA GSE: high precision alignment, optics, lasers, noise reduction, ...

  - "Pipelines de traitement de données"
    => leading role of France on the DDPC, development of data analysis pipelines

  - "De la planétologie aux systèmes exoplanétaires"
    => small connexion via the detection of planets around compact galactic binaries

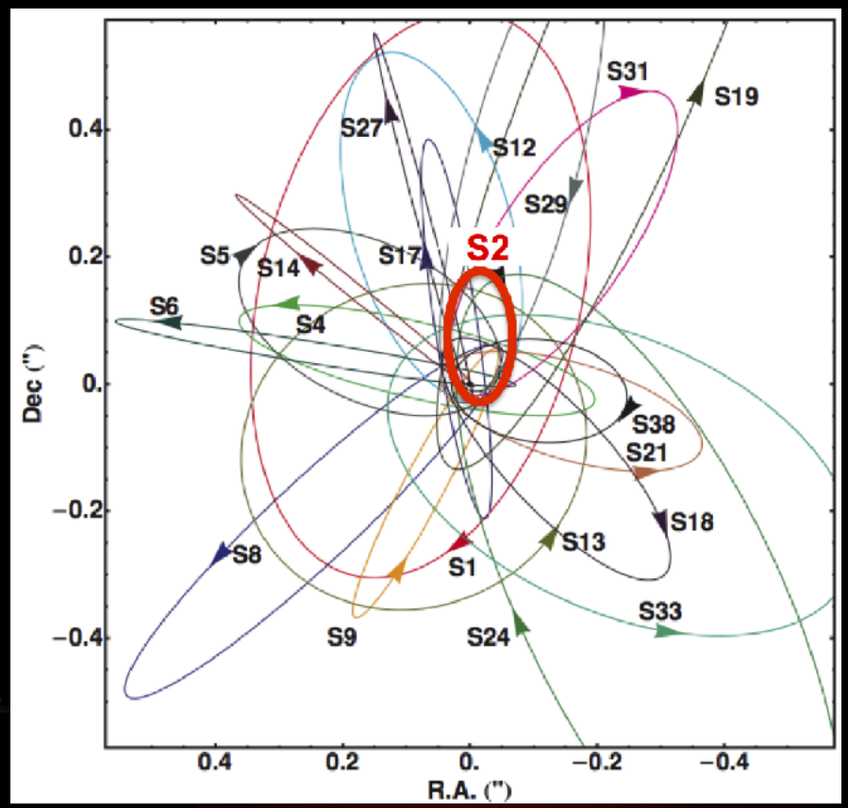
Conclusion

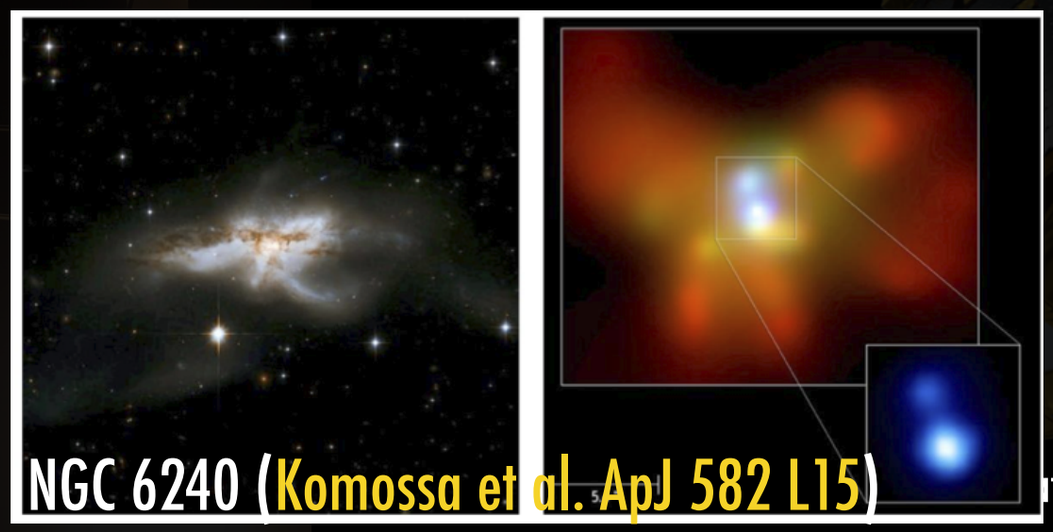
- LISA: space-based interferometer to observe the Universe with GWs
- Will observe a large number and variety of GW sources in the frequency band 10^{-5} to 1 Hz
- Huge scientific potential: astrophysics, cosmology, fundamental physics
- ESA led mission: end of phase A, adoption in 2023 and launch mid-2030s
- Very integrated system with an extremely high precision in metrology
- Large scientific Consortium with important French contributions
- Observatoire de Paris
  - Already involved in LISA (SYRTE, LUTh)
  - But also has expertises in many fields relevant for LISA

Supermassive Black Holes

- Observations:
  - Sgr A* : 4.5x10^6 M_{Sun} at the center of the Milky Way (VLT - Gravity)
  - M87: 6.5x10^9 M_{Sun} (picture EHT)
- Supermassive Black Hole are indirectly observed in the centre of a large number of galaxies (Active Galactic Nuclei).
- Observations of galaxy mergers =>

  => SuperMassive BH Binaries (SMBHB) should exist.




NGC 6240 (Komossa et al. ApJ 582 L15)

Antennae galaxies

© Vincent, Paumard, Gourgoulhon, Perrin (2011)

© EHT (2019)