The LISA mission at the IN2P3

Presentation to the IN2P3 Scientific Council
27.10.2020

H. Halloin on behalf of the LISA IN2P3 collaboration

LISA France | APC | CCIN2P3 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules | CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM | IP2I | LPC Caen laboratoire de physique corpusculaire | L2IT

LISA France

Outline

- LISA Science Objectives
- Mission Description and Proposed French Contribution
- The IN2P3 within LISA
- Conclusion

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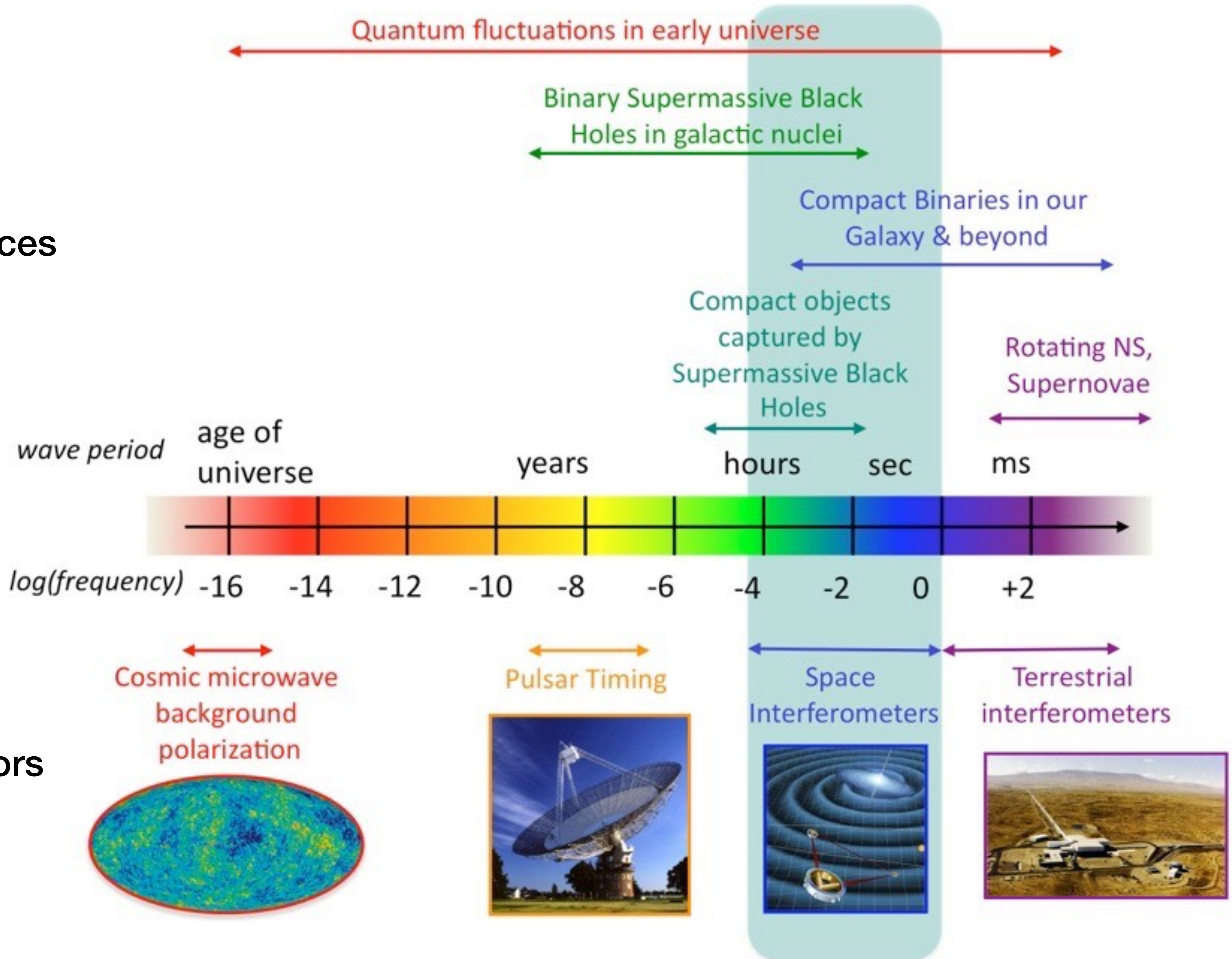
The GW spectrum

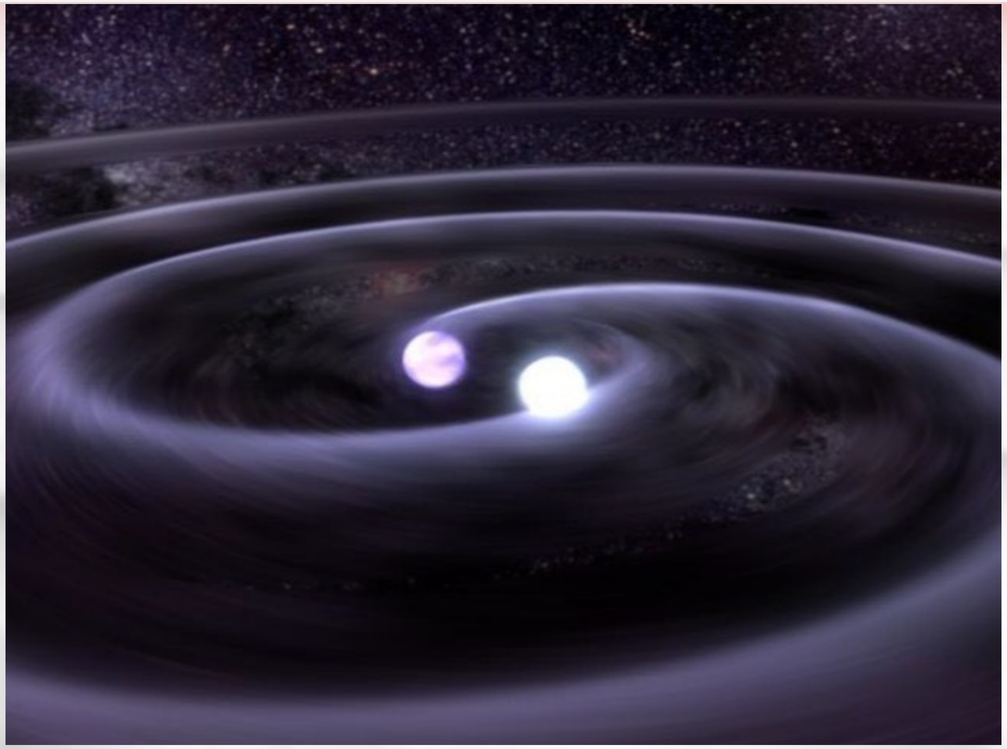
Sources

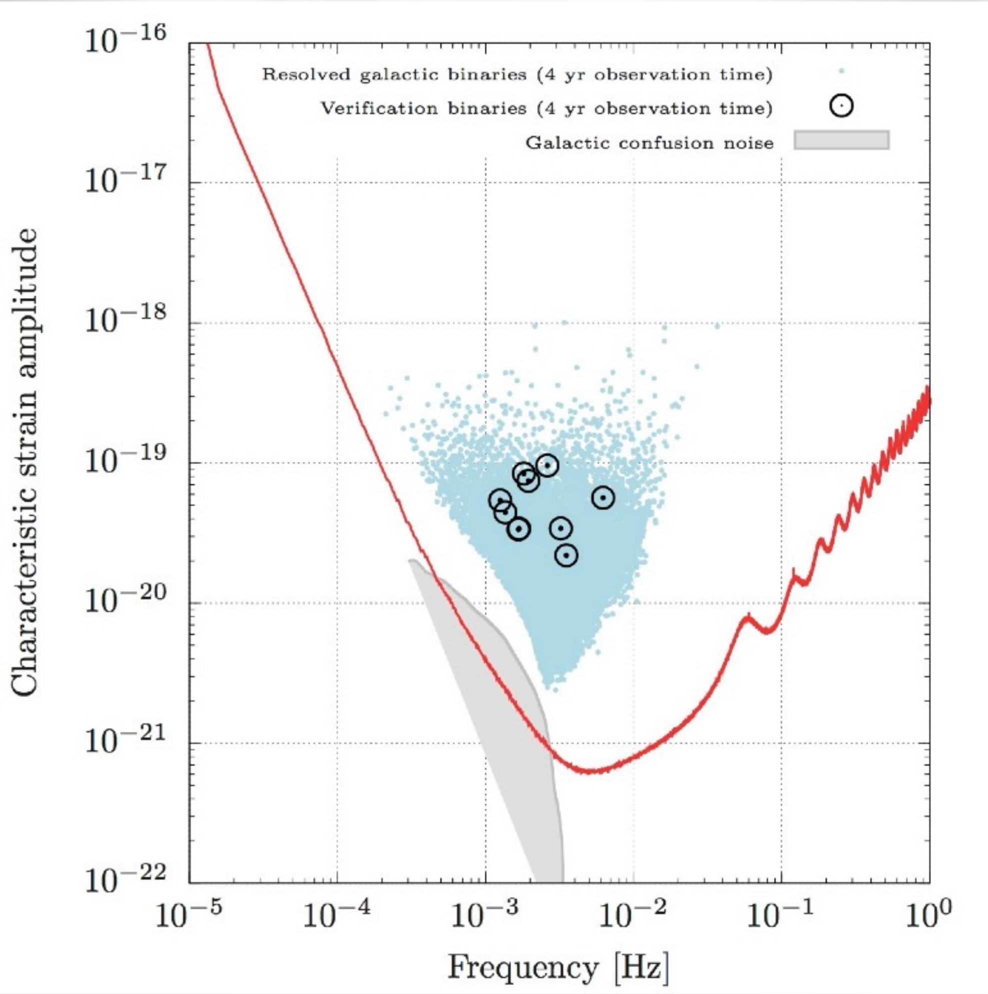


Detectors

Study the formation and evolution of compact binary stars in the Milky Way Galaxy.

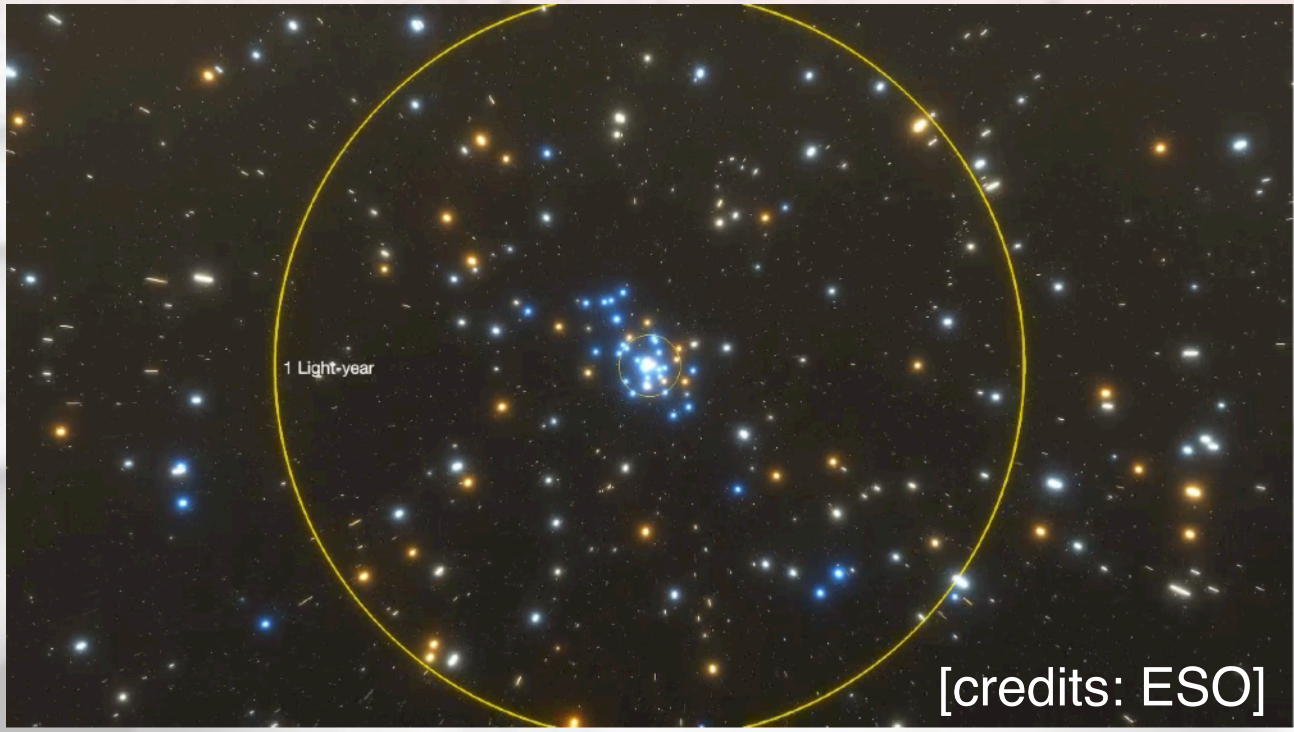
- Large number of stars are in binary systems
- Evolution in white dwarf (WD) and neutron stars (NS).
  - Existence of WD-WD NS-WD and NS-NS binaries
  - Estimated population for the Galaxy : ~10^7.
- Monochromatic sources for LISA (far from coalescence)
- Three categories
  - Joint EM - GW sources (Gaia, LSST)
    - Already ~10 known verification binaries in the LISA band
  - Individually detected : ~10^4
  - Stochastic GW signal
    - foreground 'noise'

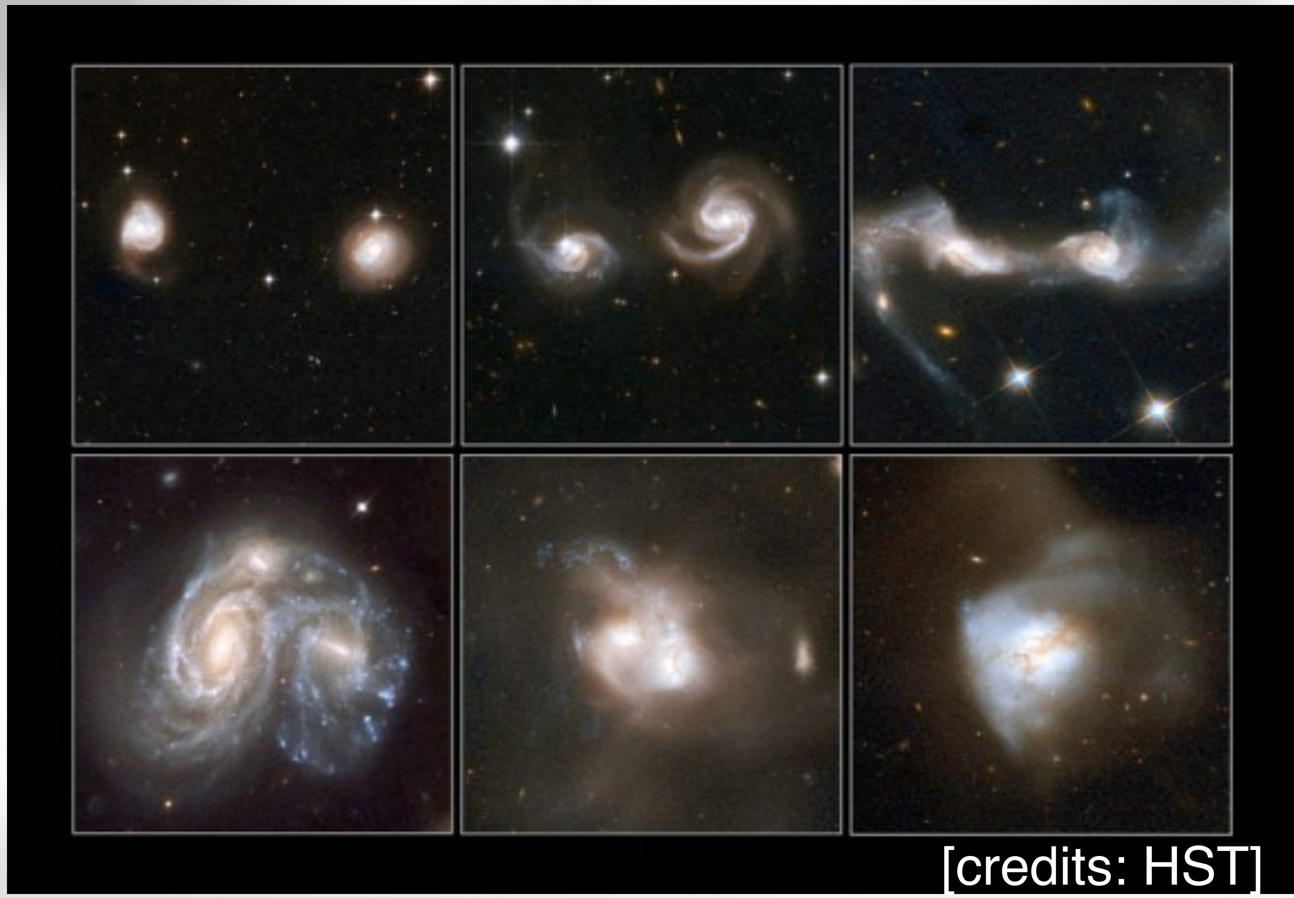




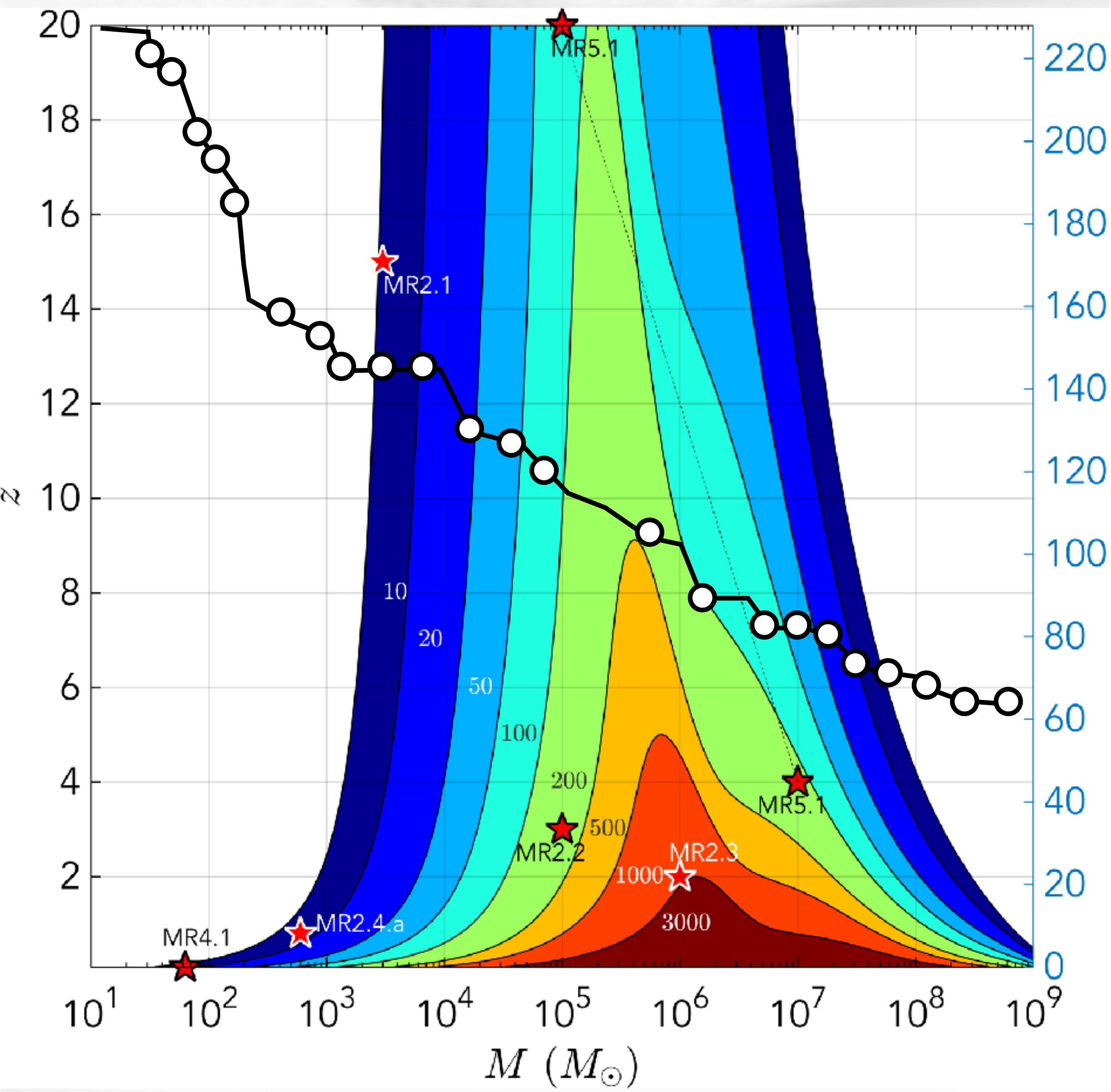
Massive BH binaries

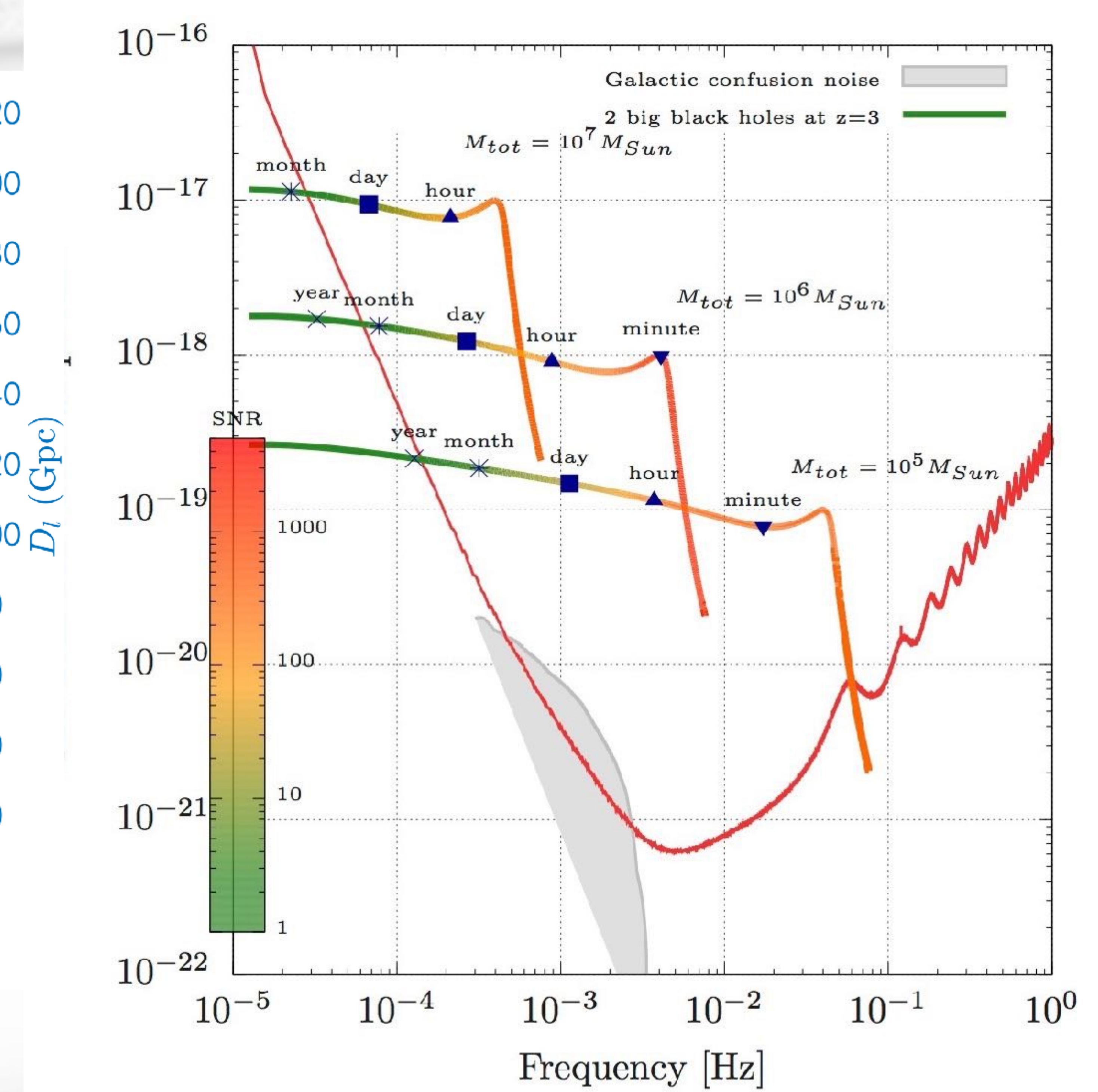
- Massive BHs in the nucleus of every Galaxy
  - $4\ 10^6\ M_{sun}$ at the center of the Milky Way
- MBHs accumulate mass
  - gas accretion
  - merging with other BHs
- Galaxies merge
  - observed…
  - may result in a MBH binary which could merge in a reasonable time
    - Stars and/or gas required to dissipate orbital momentum and bring it in GW driven regime





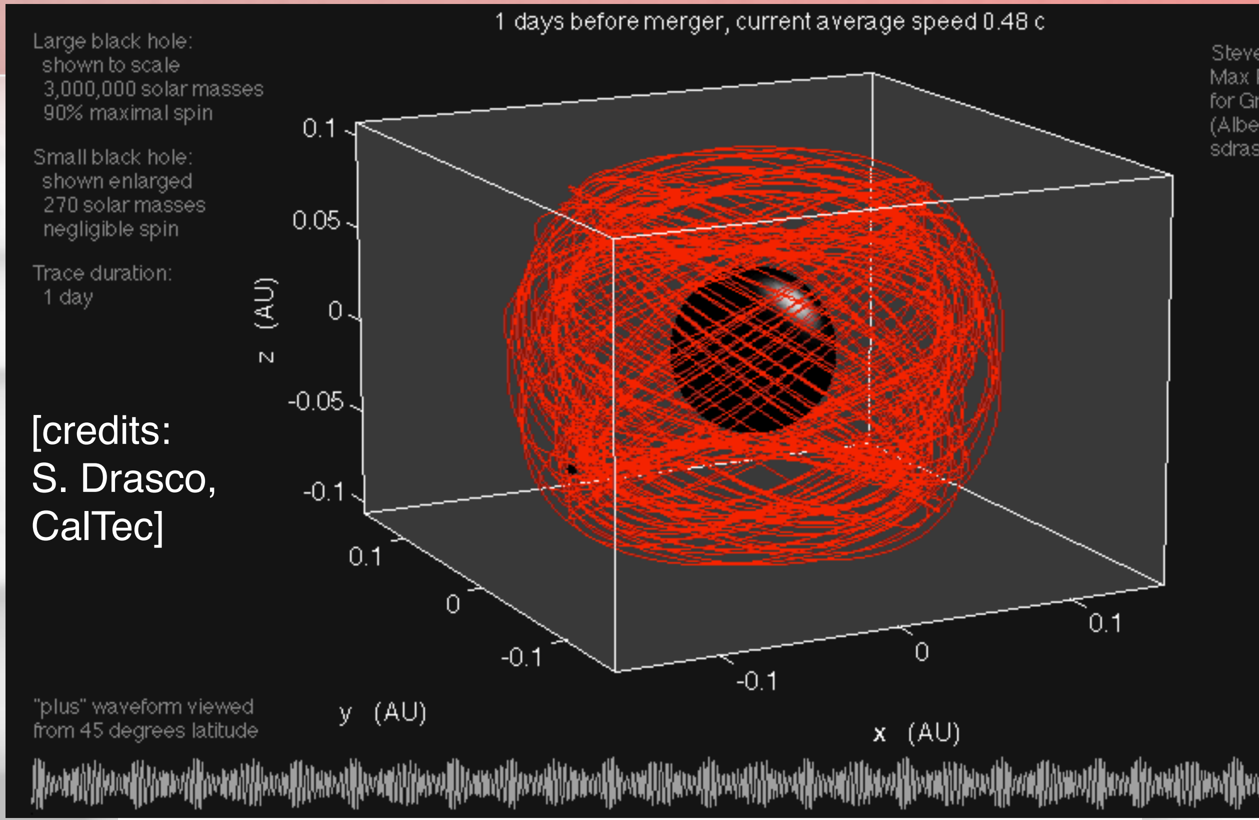
Origin, growth and merger history of massive black holes across cosmic ages

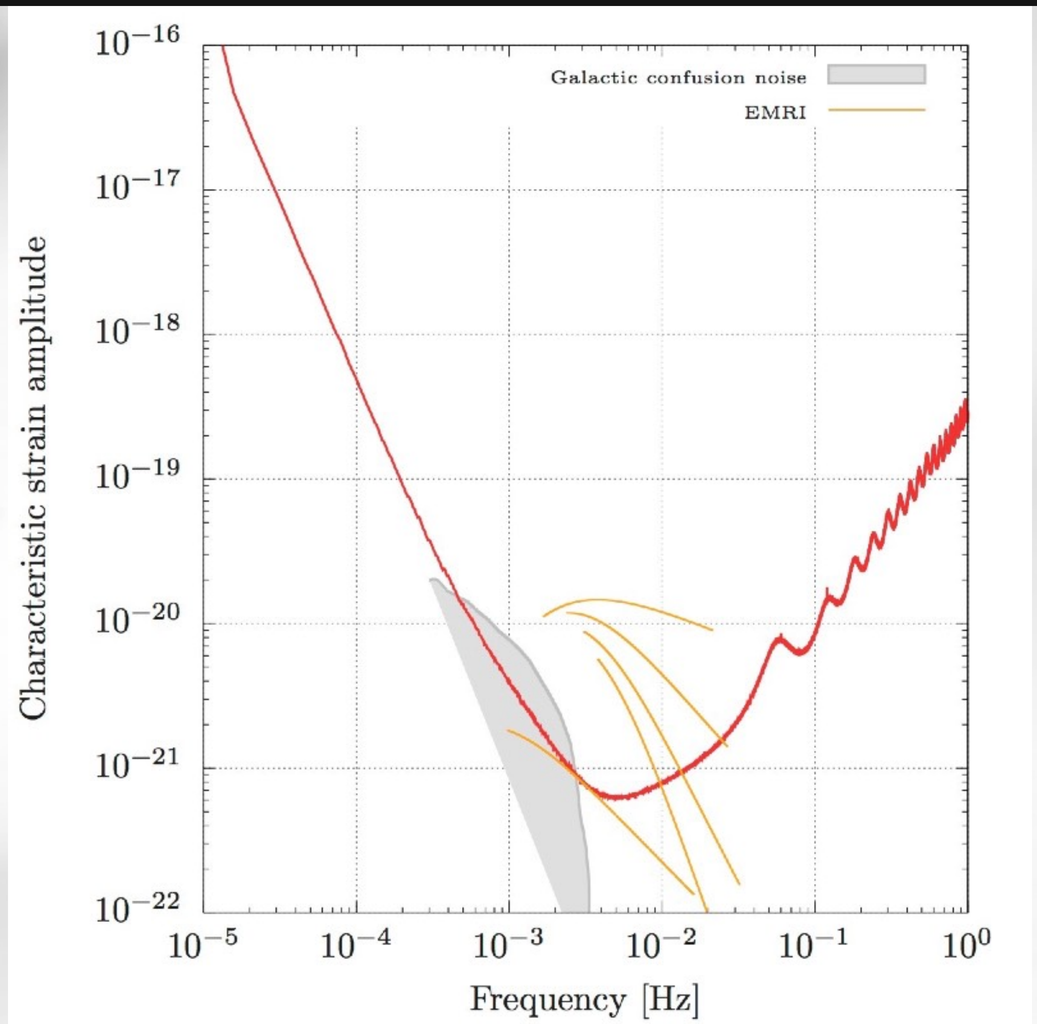




EMRIs (extreme mass ratio inspirals)

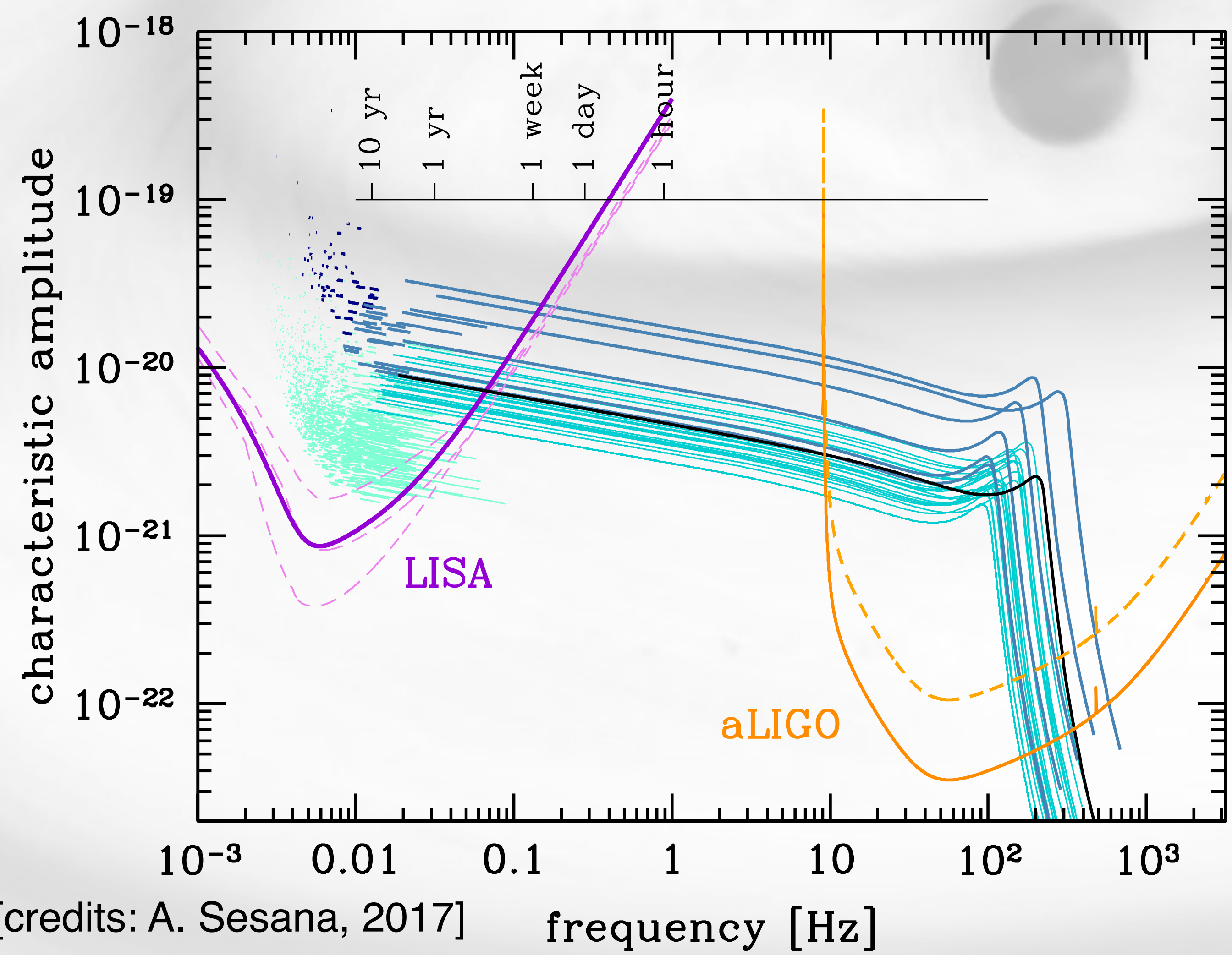
- Massive BHs could be embedded in stellar cusps
  - high density stellar environment
- Massive BH could capture a compact object
  - companion : NS, stellar mass BH
  - very eccentric orbit shrinking under GW radiation
- EMRI: Binary system with an extreme mass ratio: 10^{-7} - 10^{-5}
  - ~10^6 orbits of the compact object close to the MBH before the plunge
- Companion as 'test particle'
  - Strong relativistic effects
  - Complex (and very informative…) waveforms



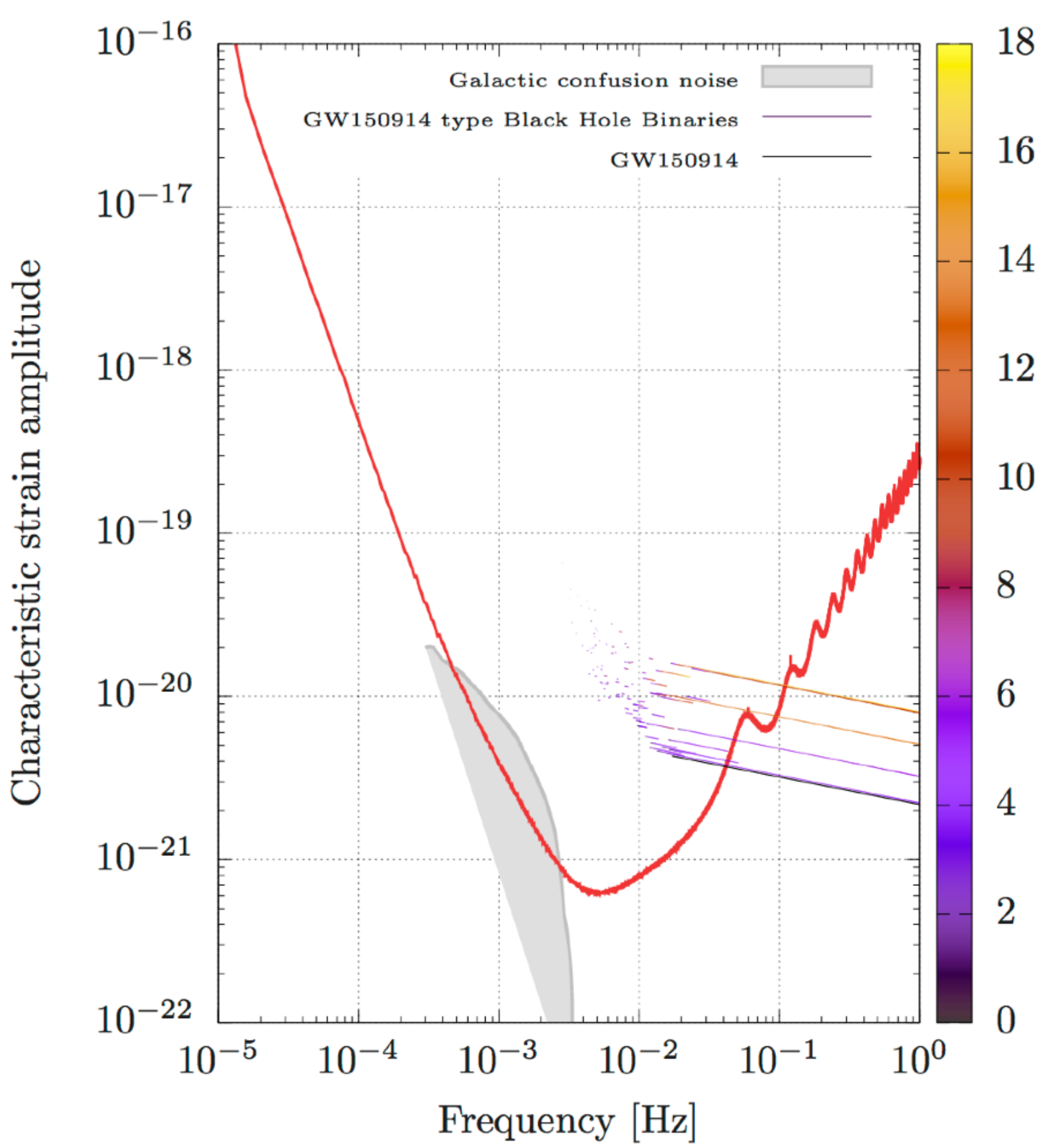


Multiband GW astronomy

- Stellar BH may be detectable by LISA prior coalescing in the ground based detectors band
  - Observed for ~years in LISA until ~days before merger
- Possible pre-warning
  - Time of coalescence at ~10s accuracy
  - Sky localisation : 0.1 - 1 deg²

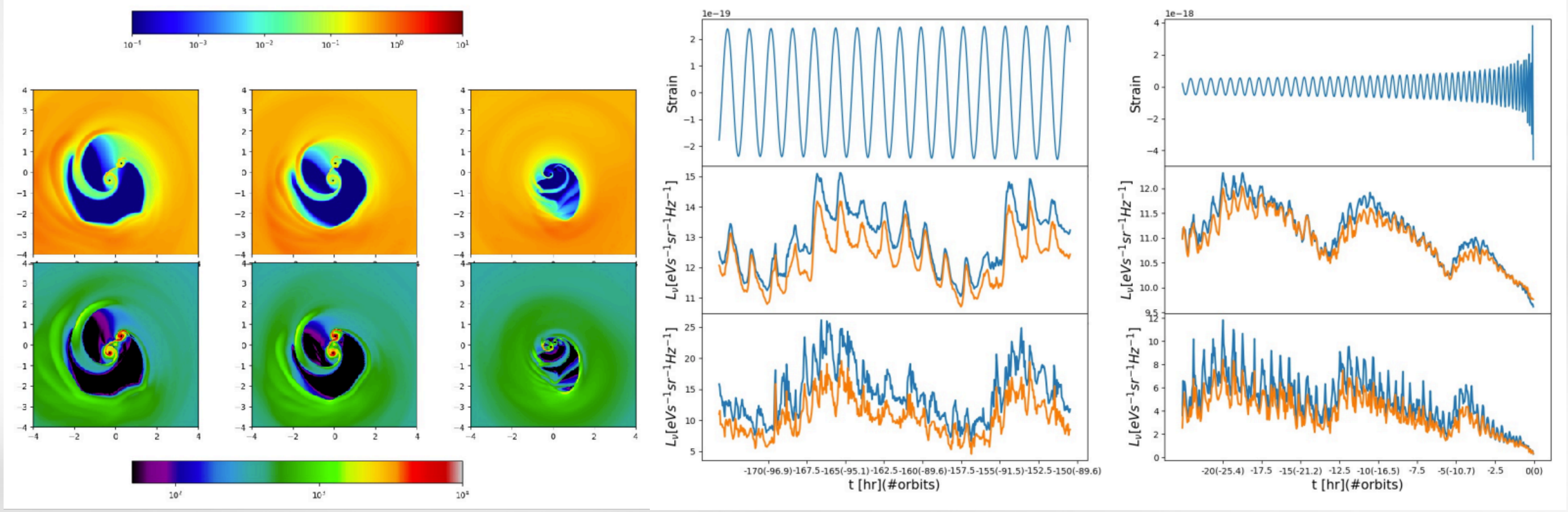


[credits: A. Sesana, 2017]



Possible e/m counterparts

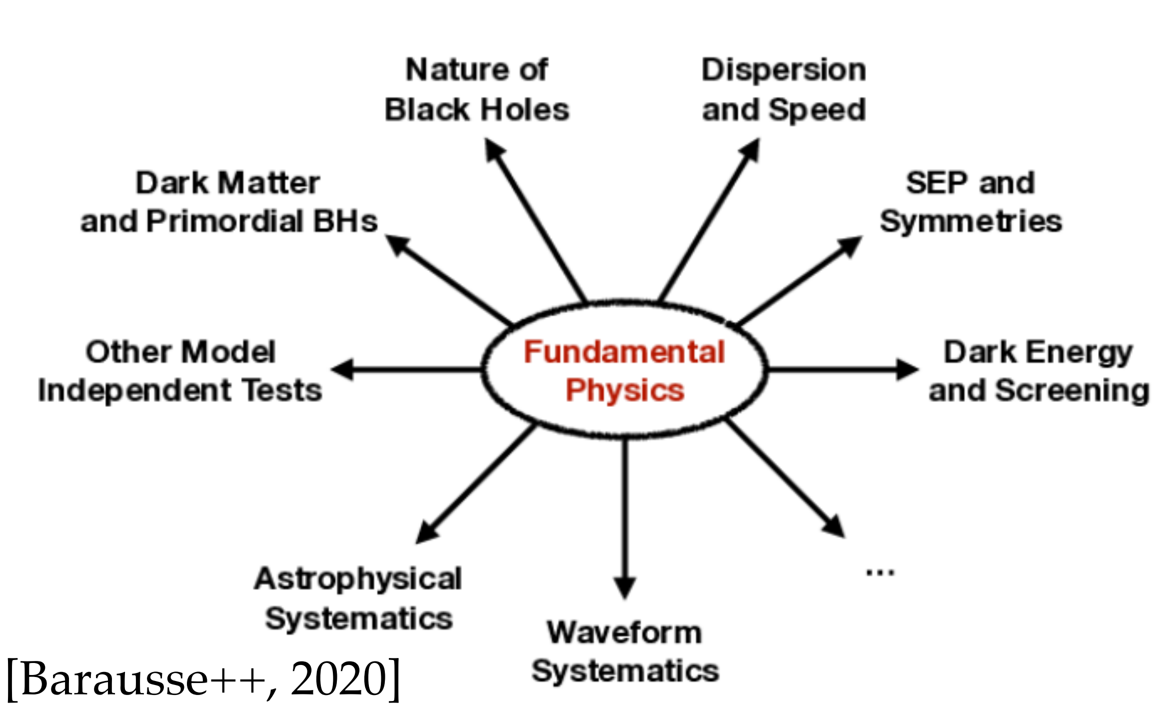
- Possible X-ray emission during the late stages of the SMBH inspiral (days to hours before final merger) comes from:
  - Circumbinary disc:
    - X-ray emission in soft x-rays (≤1keV)
  - Mini-discs around black holes
    - Hard x-ray emission (≥10keV) from accretion of minidiscs individually onto each black hole
  - Interaction of circumbinary and mini discs:
    - Accretion of circumbinary disc onto mini-discs via optically thick streams
    - Thermal radiation dominated by the inner edge of the circumbinary disc, producing soft x-rays (~2keV)
  - X-ray emission shows clear modulation on timescales as short as a few hours



Y. Tang+, MNRAS 2018

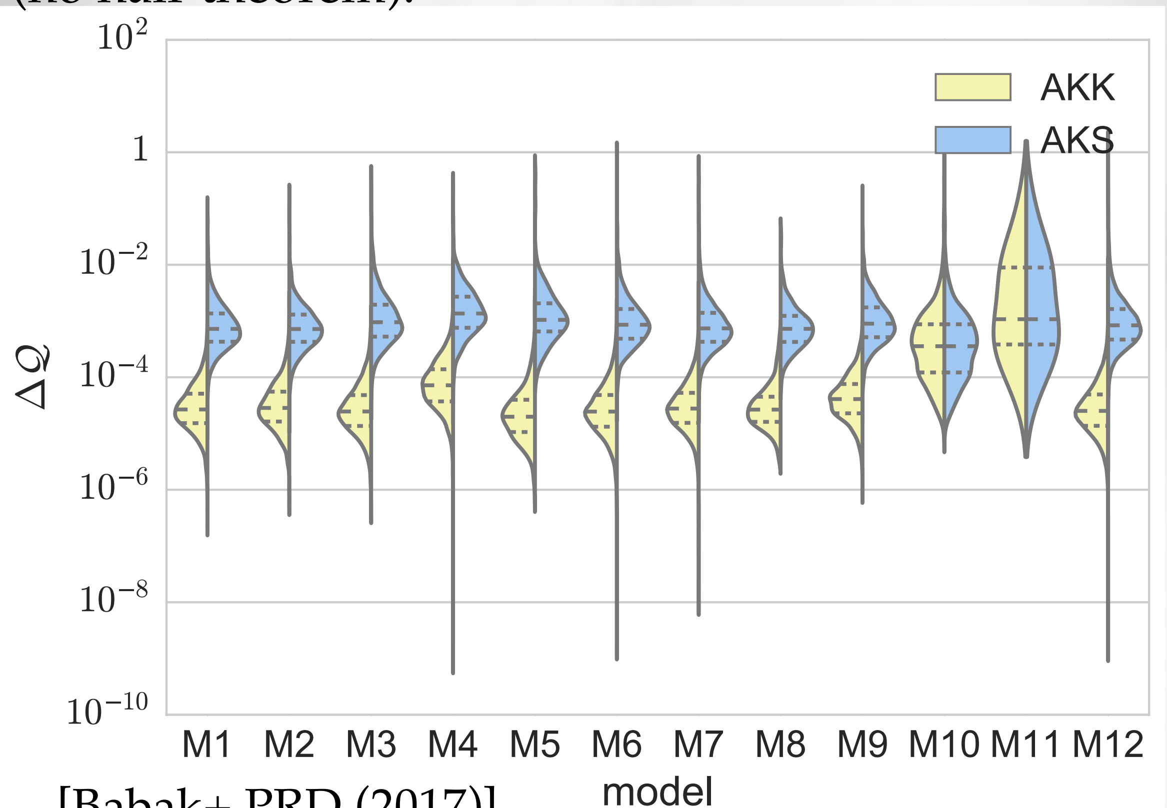
Fundamental physics with LISA

- Using emitted GW to map the spacetime structure
- Tests of GR
  - Fundamental principles and symmetries of GR
  - Testing GR with compact objects
- Tests of the Nature of Black Holes
- Dark matter and Primordial Black Holes
- Model-independent tests
  - Consistency of GR vs constraining Modified Gravity
  - Parameterised tests
  - Other tests including: Polarisation, GW propagation, Stochastic GW Background
- Astrophysical and Waveform systematics



[Barausse++, 2020]

Deviation in quadrupole moment from Kerr value (no hair theorem):



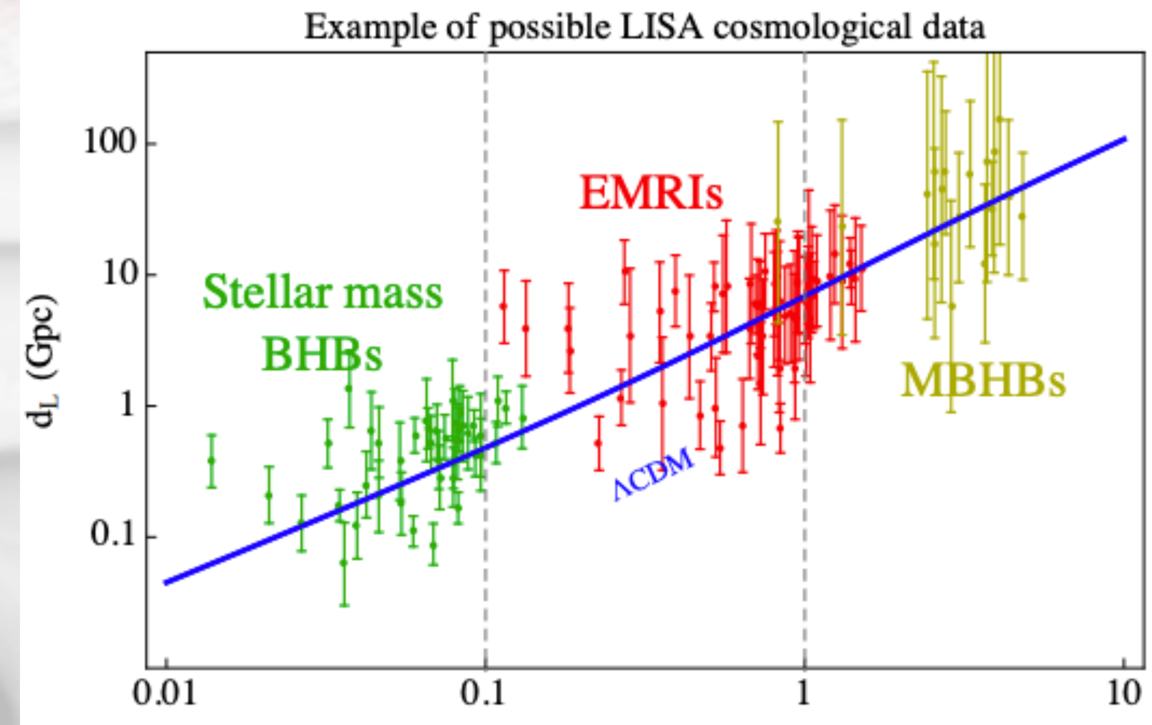
[Babak+ PRD (2017)]

Cosmography with LISA

LISA France

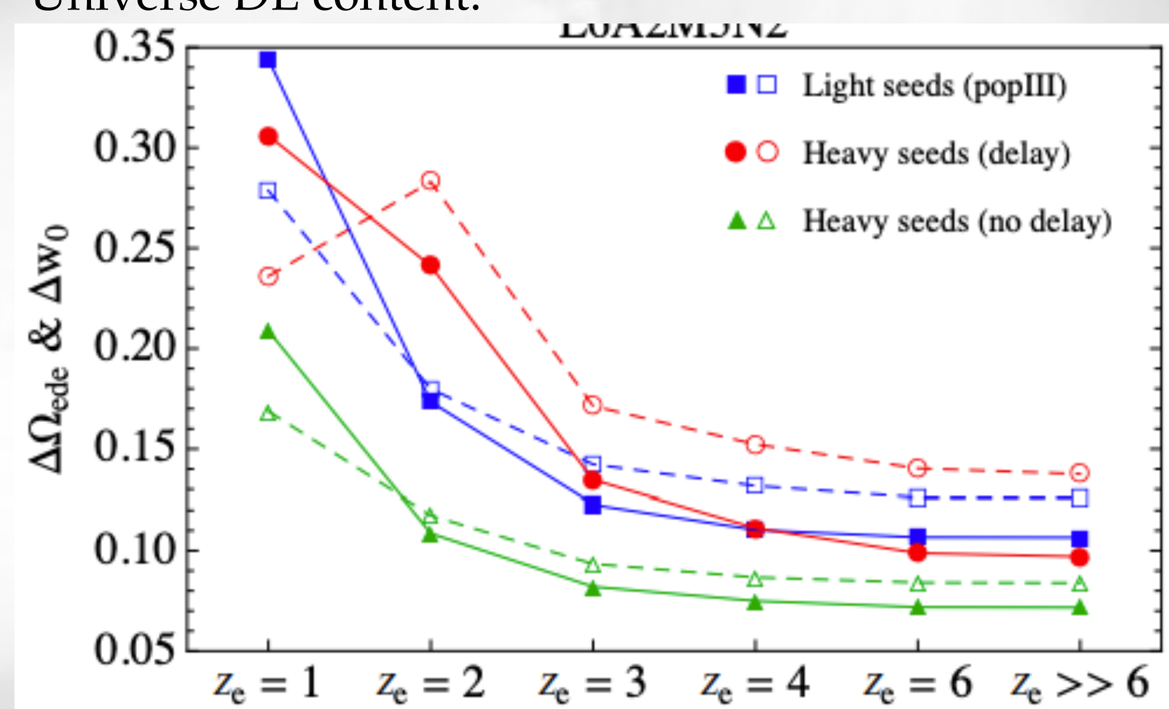
- LISA may help on many cosmological problems
  - Expansion rate of the Universe : late acceleration ?
    - CMB : $H_0 = 66.93 \pm 0.62$ km.s^{-1}.Mpc^{-1}
    - SN Ia : $H_0 = 73.5 \pm 1.4$ km.s^{-1}.Mpc^{-1}
  - Dark energy
    - Cosmological constant ?
    - Early dark energy: DE evolves with redshift and contributes to rate of expansion at z>1
  - Modification of GR on large scale
- LISA can probe the Universe at different scales
  - Use BHBs merger events as standard sirens
  - Requires the knowledge of the redshift
    - from e/m counterpart of the host galaxy
    - or from statistical inference

Universe expansion rate from GW events :



N. Tamanini J. Phys. CF 2016

Universe DE content:



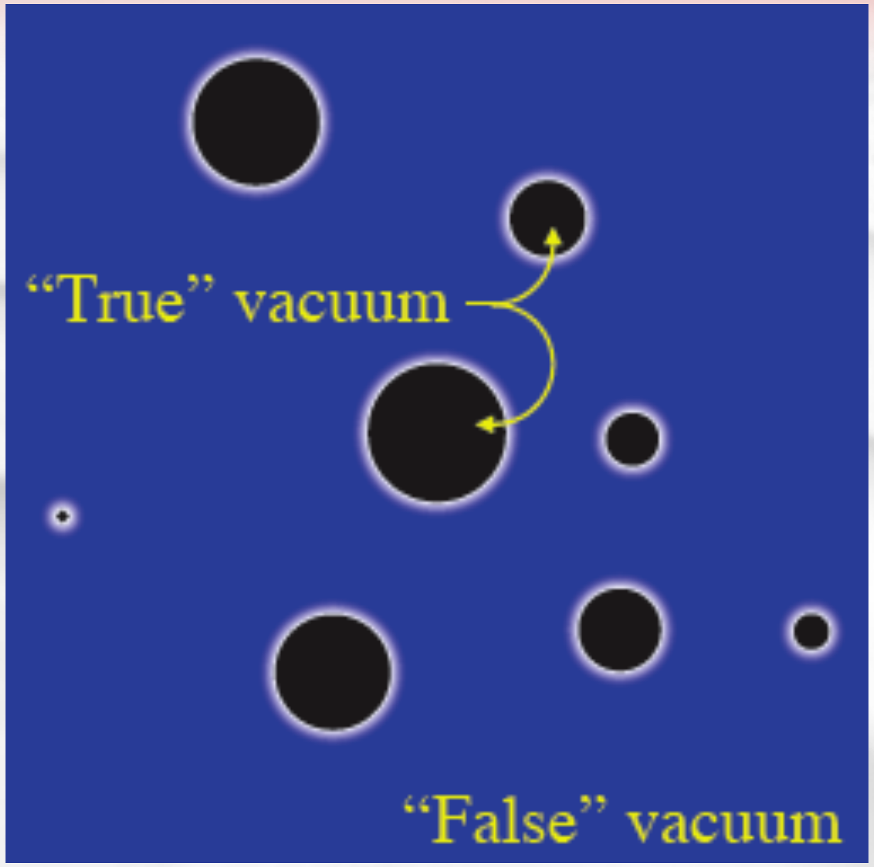
Ch. Caprini, N. Tamanini JCAP 2016

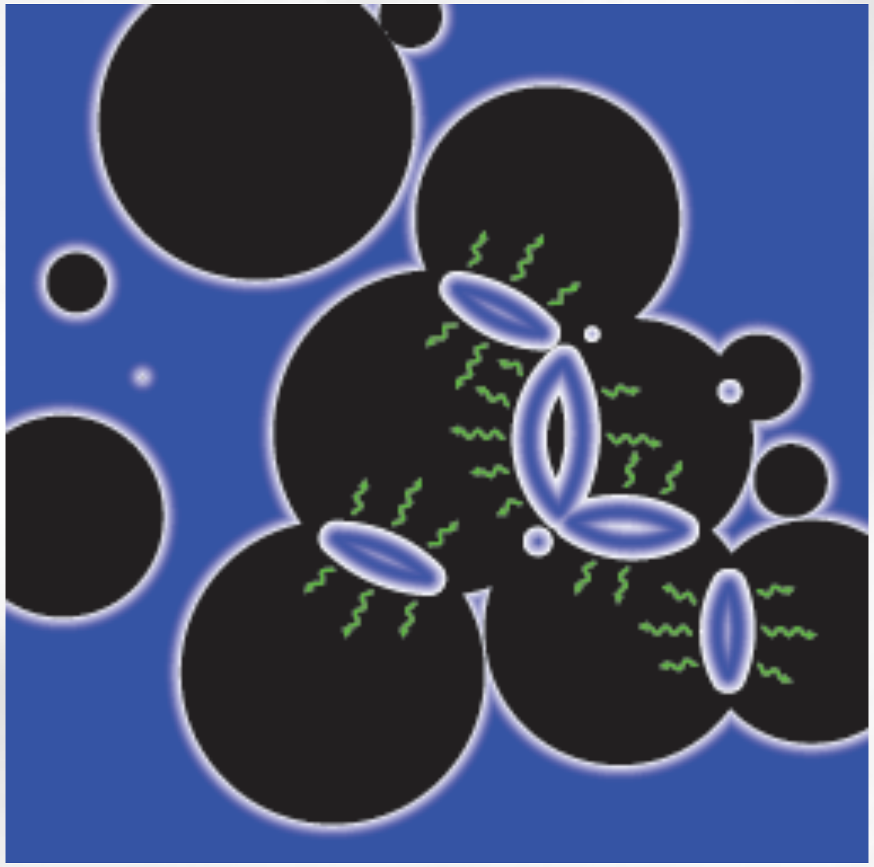
Early Universe in GWs

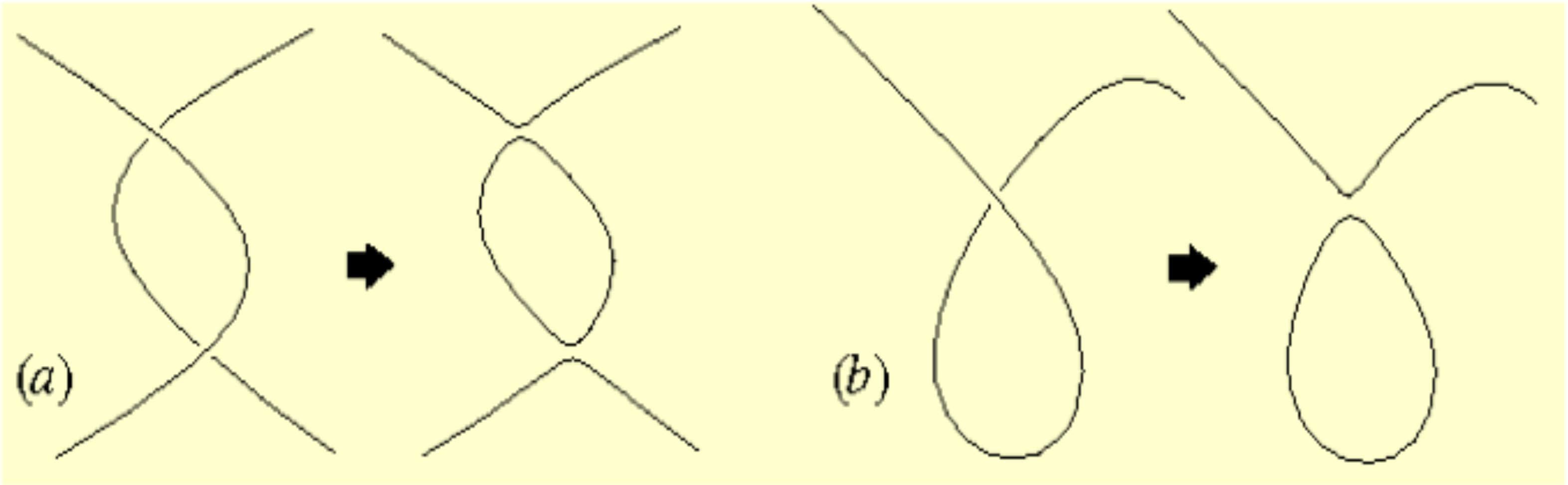
- Violent processes in the early Universe may produce stochastic GW background (SGWB)

- First order phase transition
  - Collision of true vacuum bubbles and conversion to the symmetry-broken phase accompanied with anisotropic stresses.
  - The LISA band (10^{-4} - 0.1 Hz) corresponds to the energy scale of the EW (electroweak) phase transition (up to 10^{4} TeV).
  - Formation of sound wave, shocks and turbulence in the plasma

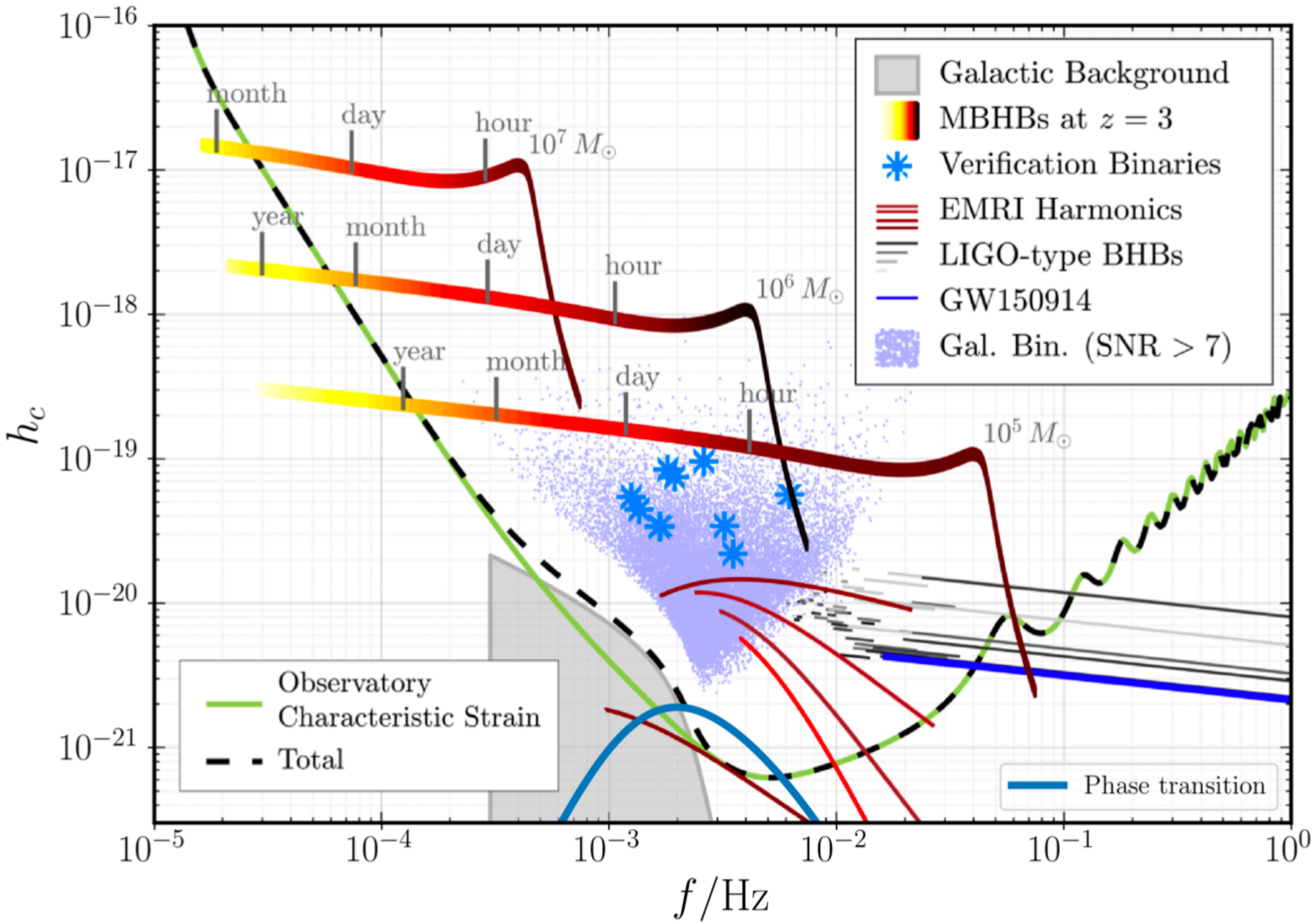
- Cosmic strings:
  - A network of strings formed in the early Universe generates SGWB (as superposition of many uncorrelated sources) and (possibly) individual bursts







Potential sources for LISA: summary



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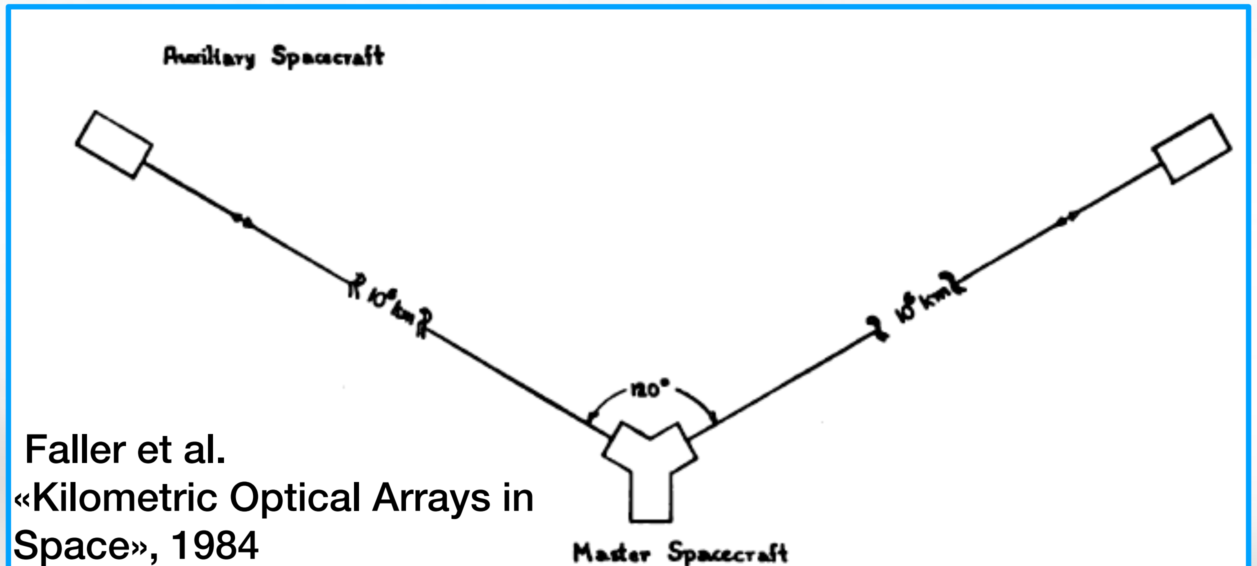
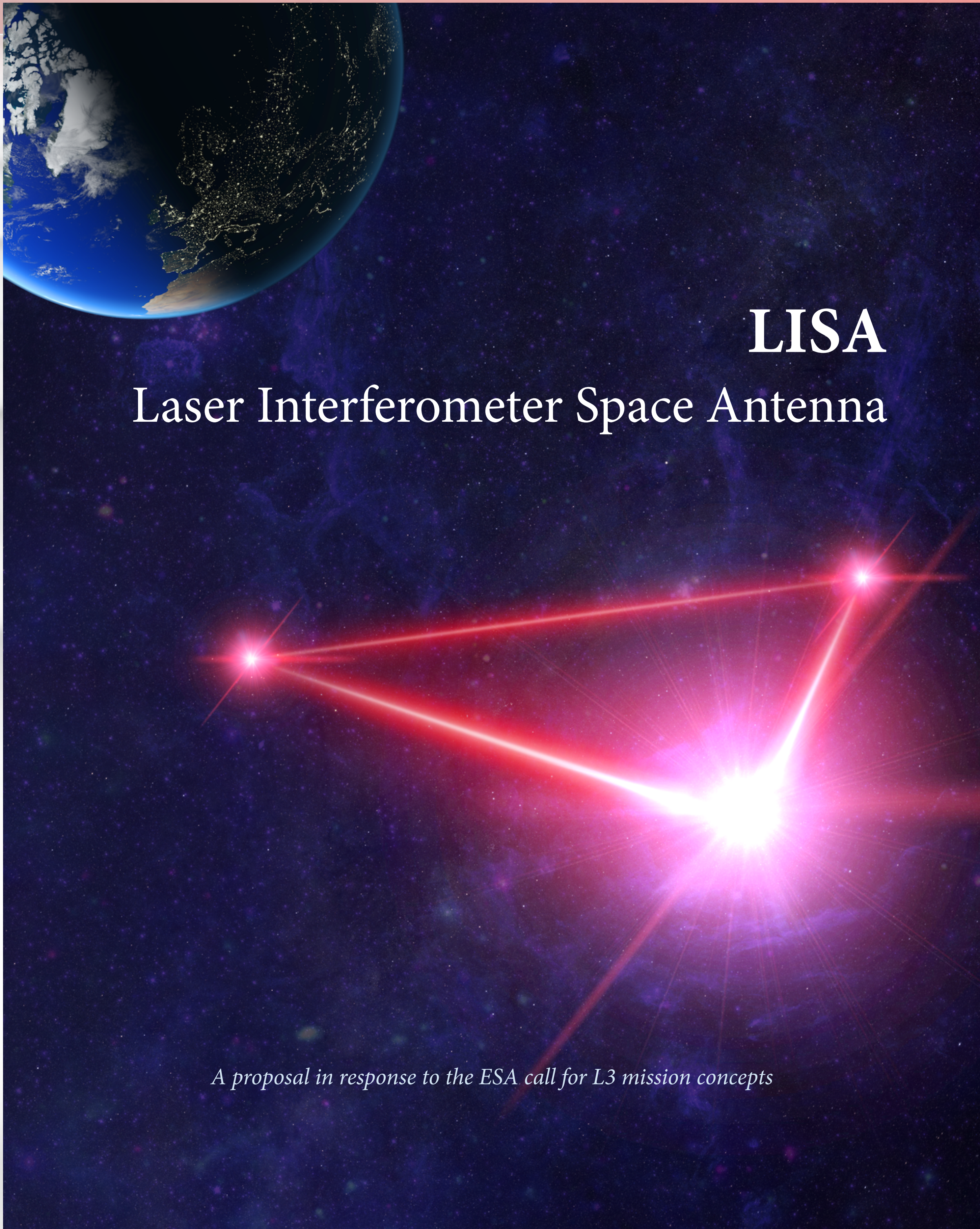
Towards a space-borne GW detector !

- LISA selected as L3 mission in spring 2017
  - Launch expected in 2034/2035
- Proposal :
  - https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf
- First concepts in the 1970s…

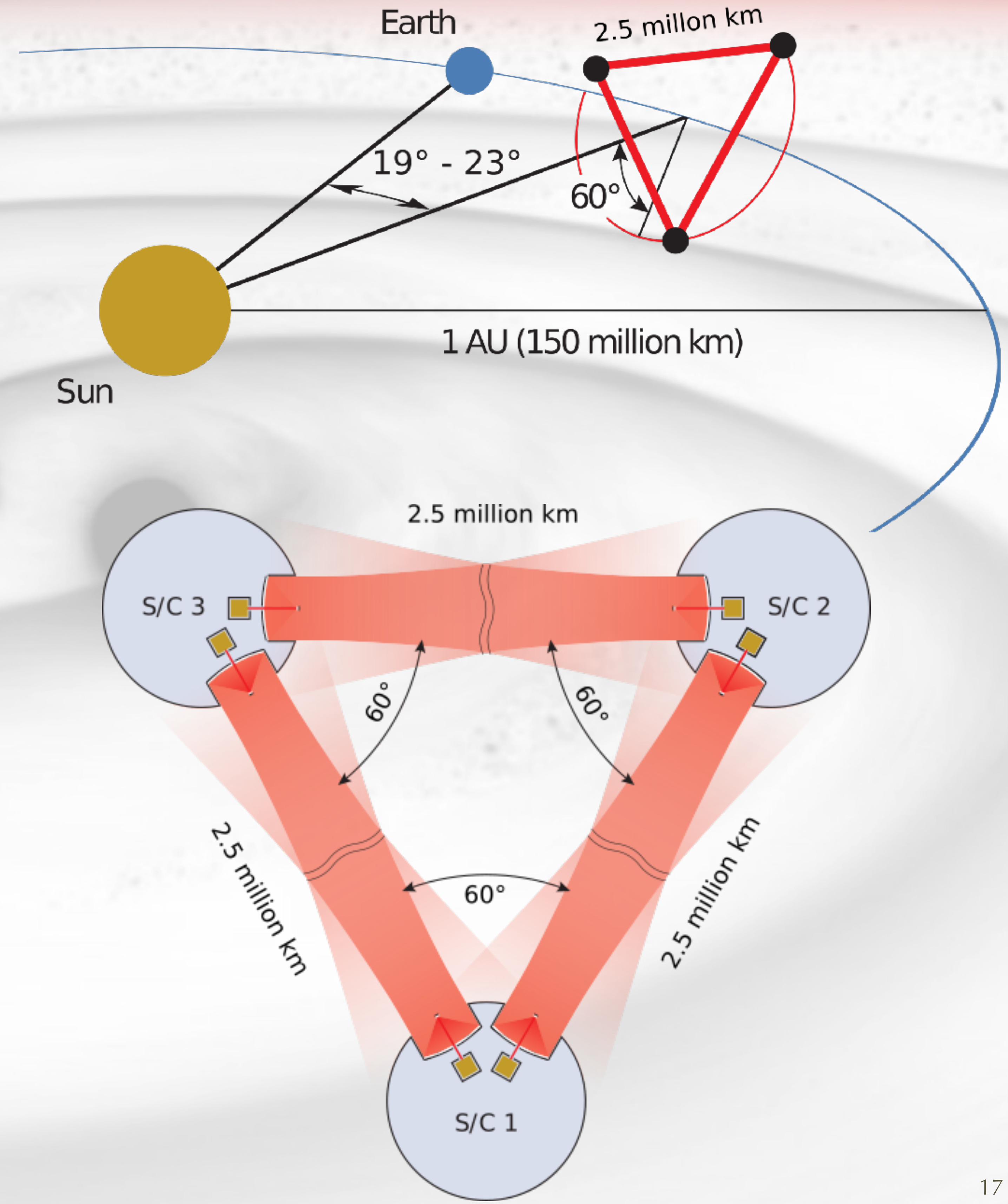


Faller et al. «Kilometric Optical Arrays in Space», 1984



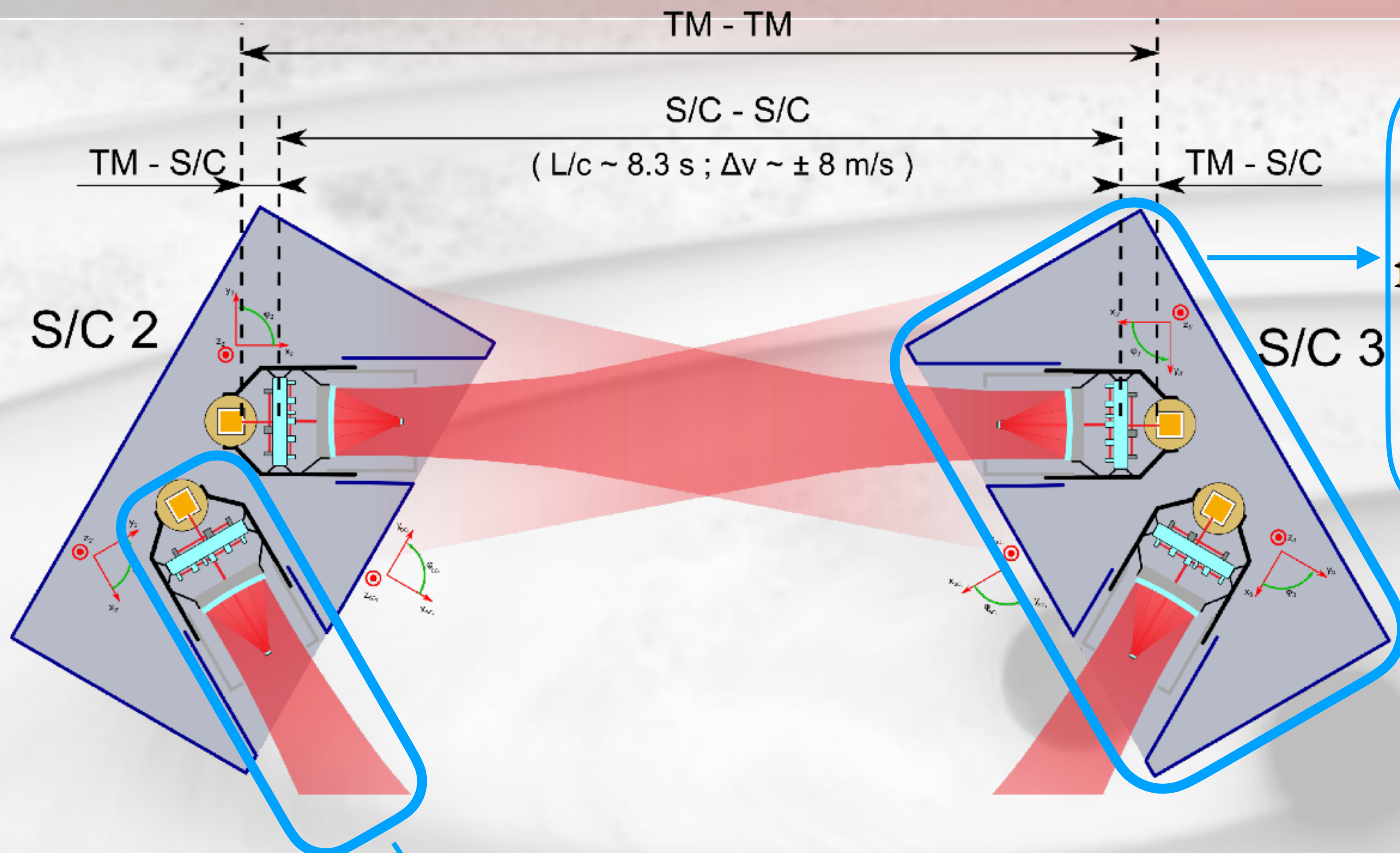
LISA Interferometer

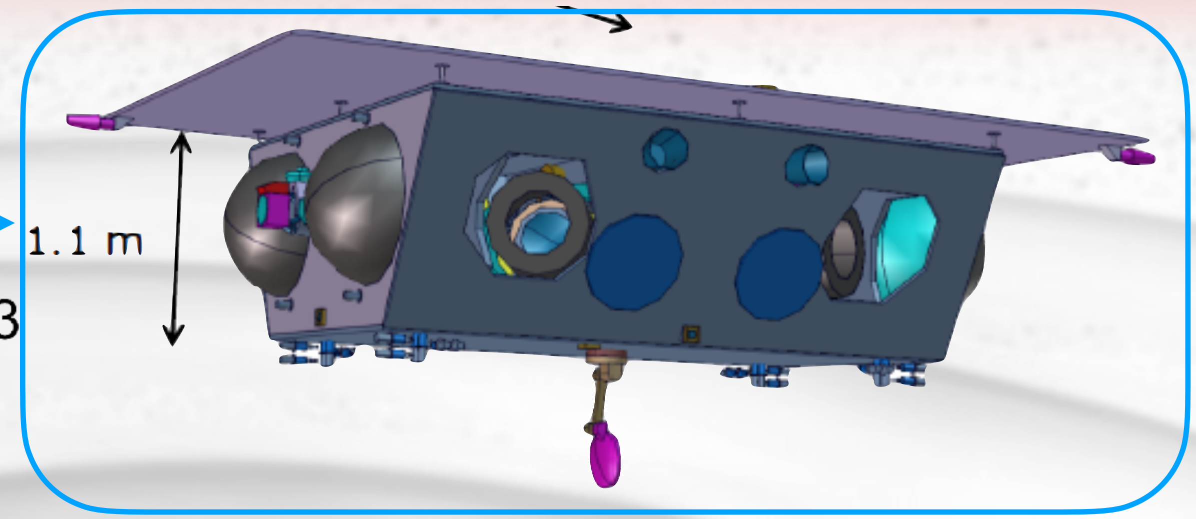
- Equilateral configuration
  - 3 arms / 6 links ; 2.5 Mkm
  - Earth-like orbit, 19° to 23° trailing
  - Science mission duration : minimum 6 years (consumables for 10 years)
- Drag free-flying
  - Heritage from LISA Pathfinder
- Typical metrology requirement : **~10 pm/√Hz @ 1 mHz**

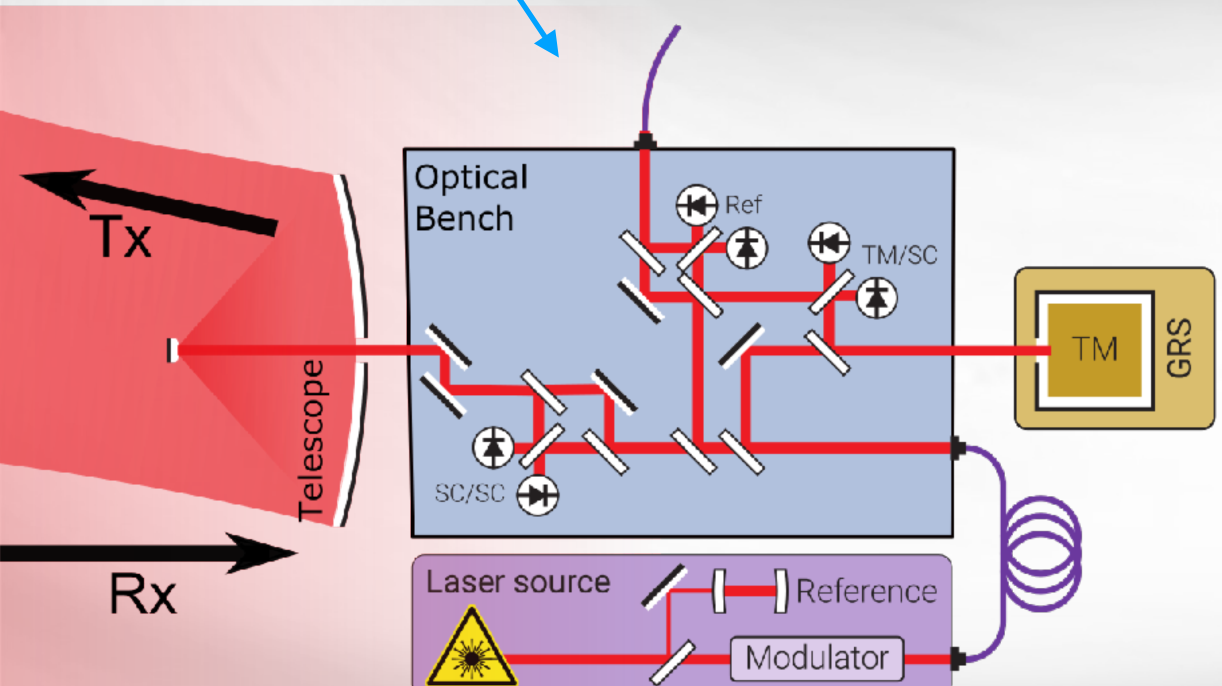


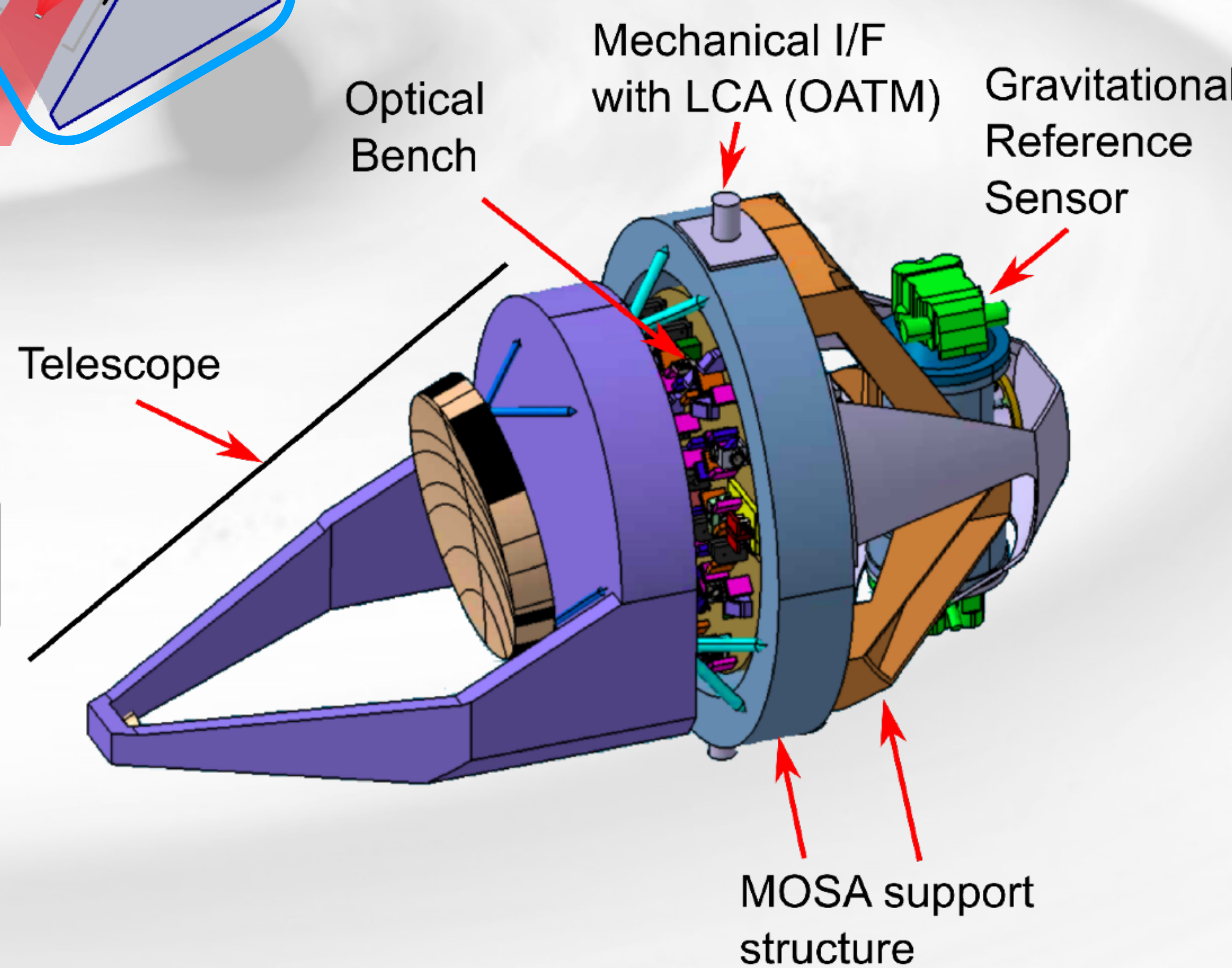
LISA instrument

LISA France





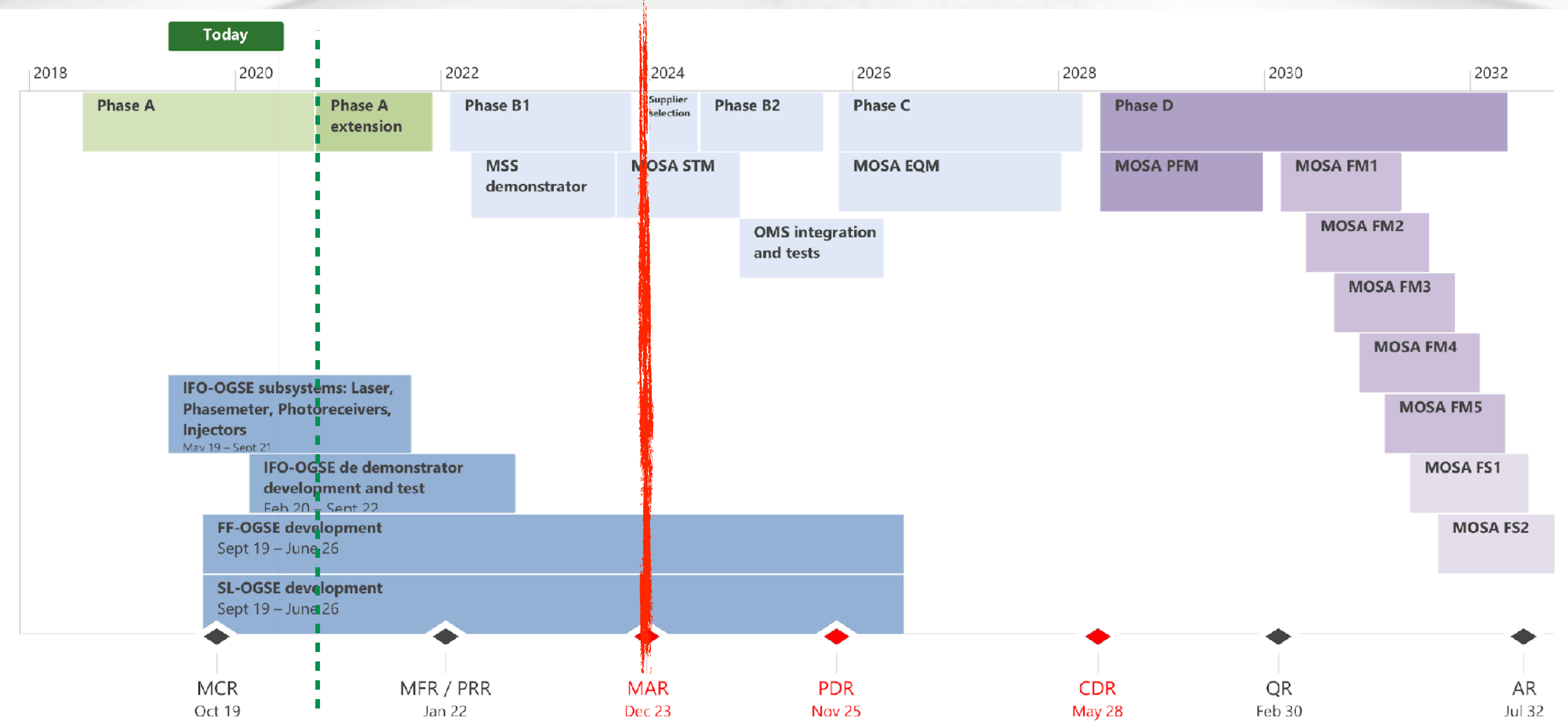




LISA deuelopment schedule

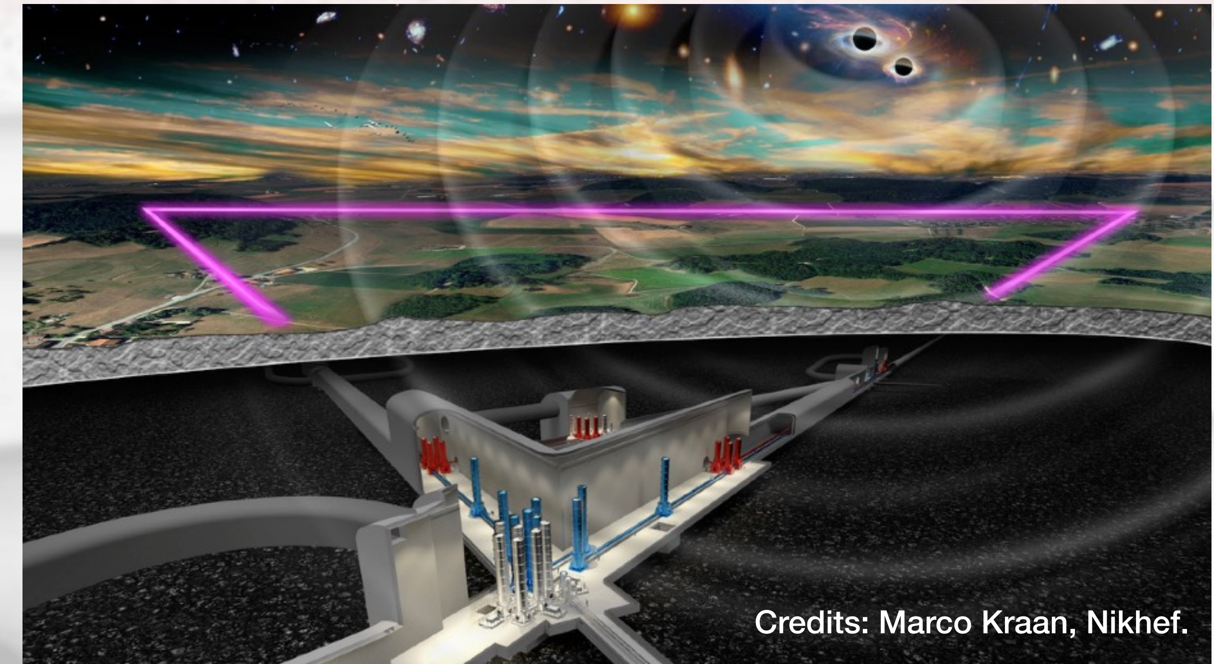
LISA France

- Major milestone : adoption end 2023 / early 2024
- Launch : 2034/2035
- In-flight operations : up to 12.5 years
  - 2.5 years cruise + commissioning
  - 6 years science mission, extendable to 10 years

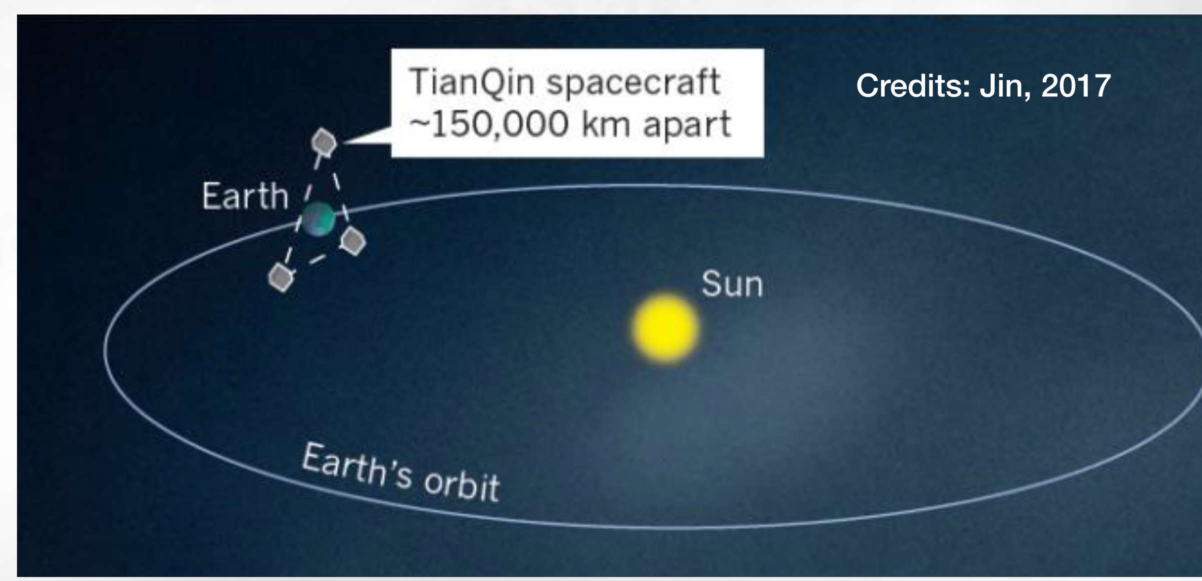


Science context in 2035

- LISA will be complementary of other operational instruments in 2035 - 2045
  - 3rd generation of interferometric GW ground-based detectors (Einstein Telescope, Cosmic Explorer) and Pulsar Timing Array
    - Broad simultaneous coverage of the GW spectrum from nHz to kHz
    - LISA as early (years in advance…) detection system for some binary sources coalescing in the ET/CE band
    - Detection or constraints on the GW backgrounds from the early Universe (at 10^{10} GeV)
  - Multimessenger astronomy
    - With ATHENA for observing the X-ray emission emitted by discs around coalescing massive black holes.
    - With wide field telescopes (e.g. LSST, SKA) for identifying e/m counterparts and host galaxies
    - With large telescopes on ground (ELT, TMT, GMT) and in space (JWST) for the measurement of redshifts at cosmological distances
  - Particle physics
    - LISA may be complementary to future colliders to identify physical processes at the TeV scale: constraints on cosmic strings, inflation, …

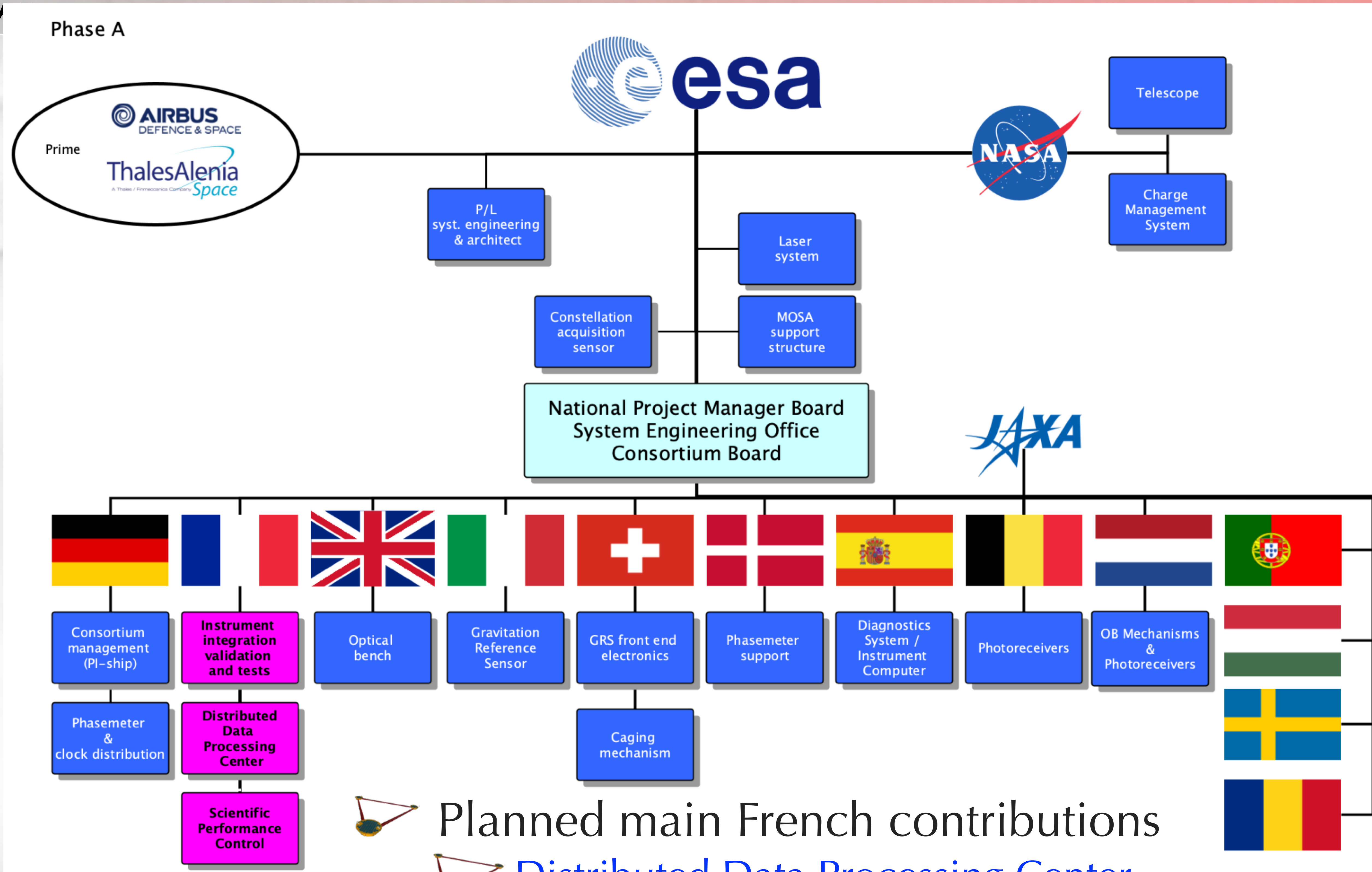

Credits: Marco Kraan, Nikhef.

- No equivalent mission with the same objectives in the same time frame
  - Active development of the TianQin mission by the Chinese Academy of Science
    - Rapidly progressing but still a lot of technologies to master
    - Launch of TianQin in the same timeframe as LISA difficult to assess



Credits: Jin, 2017

What contribution for France ?



- Planned main French contributions
  - Distributed Data Processing Center
  - MOSA AIVT & Perf. Control

LISA France research institutes

- Presently 19 laboratories / research institutes participate to the LISA France collaboration
  - **@IN2P3 : APC, CPPM, L2IT, LPCC, LMA/IP2I, CC-IN2P3**
  - @INSU : LAM, IAP, LPC2E
  - @INSIS : Institut Fresnel
  - @Obs de Paris / INSU : SYRTE, LUTh
  - @Obs. de la Côte d'Azur / INSIS : ARTEMIS
  - @CEA : IRFU (DEDIP, DIS, DPhN, DPhP, DAP), IPhT

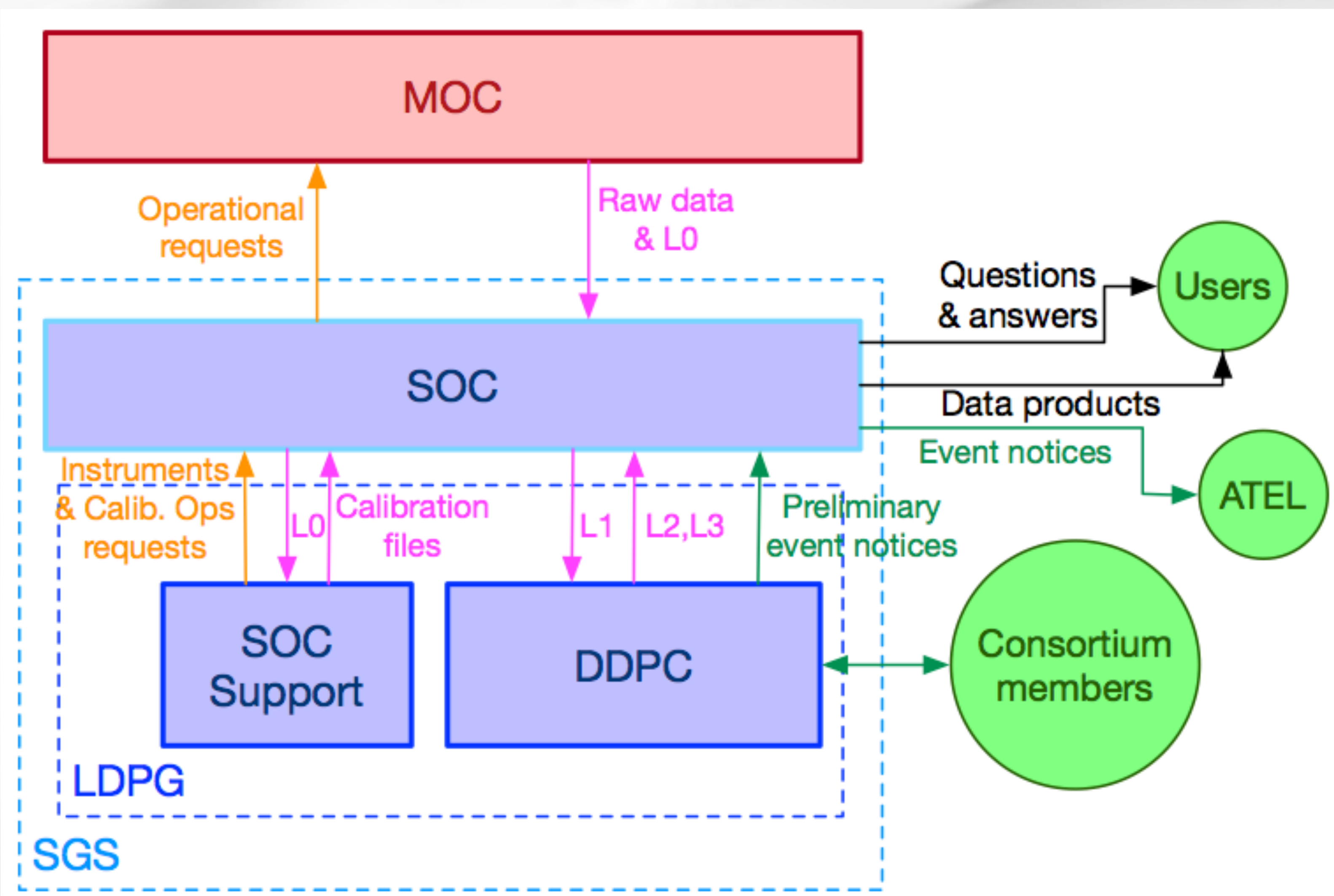
- CNES is managing and supporting the project activities with engineers and financial ressources (incl. short-term contracts).

- Members from French institutes in the LISA Consortium
  - 130 Full members (43 from IN2P3 labs)
    - 63 FTEs (incl 18 at IN2P3)
    - 1358 members in the LISA Consortium
  - 68 Associates (7 from IN2P3 labs)

LISA France

Distributed Data Processing Center

- Development of a Distributed Data Processing Center for LISA
  - Produces scientific L2&L3 data and supports ESA on L0 to L1 software
  - Will implement, maintain and operate simulations and data analysis
  - Supports the LISA community for SW and collaborative tools
  - Prototype architecture based on virtualisation and continuous integration



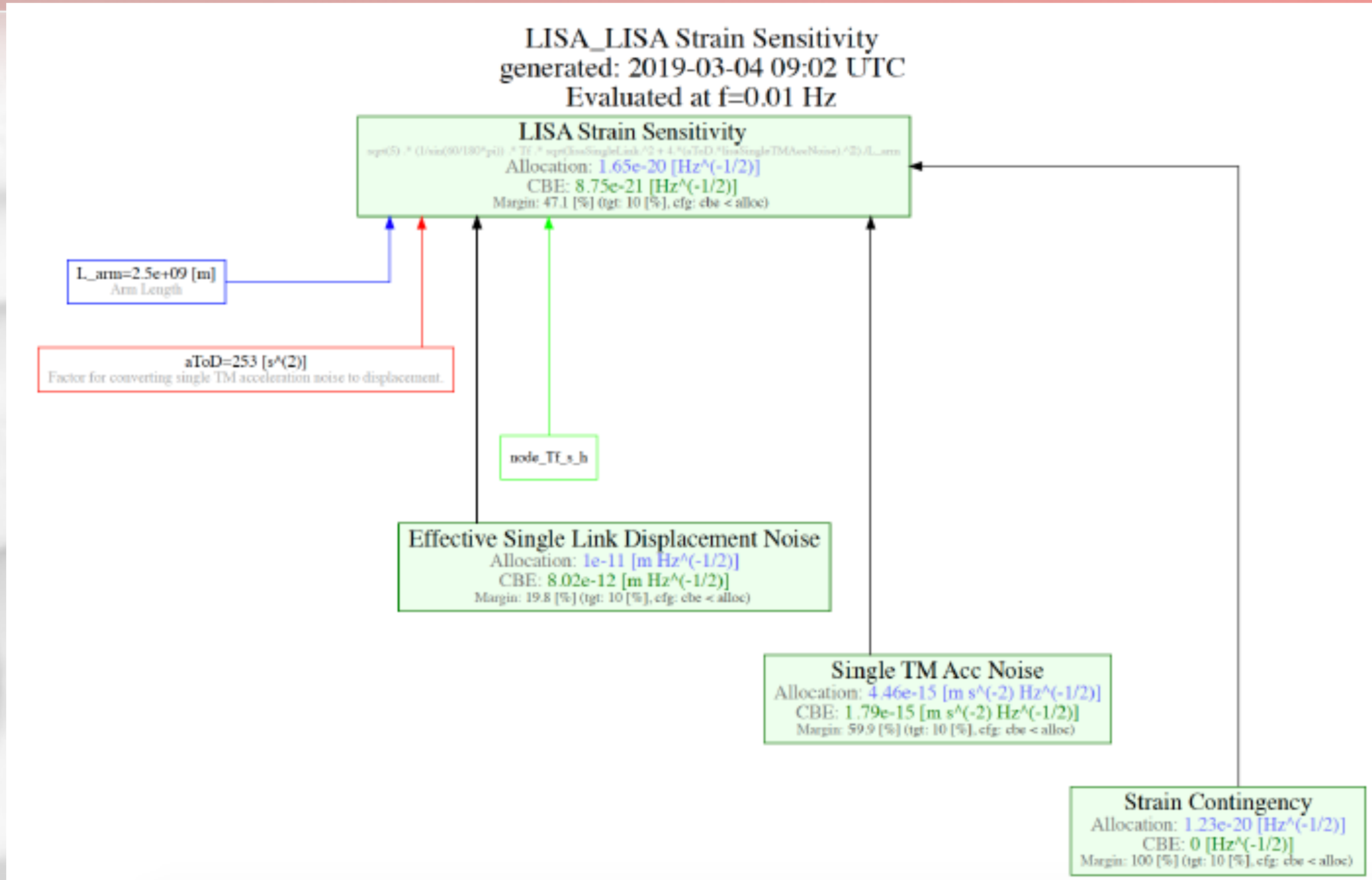
docker GitLab jupyter

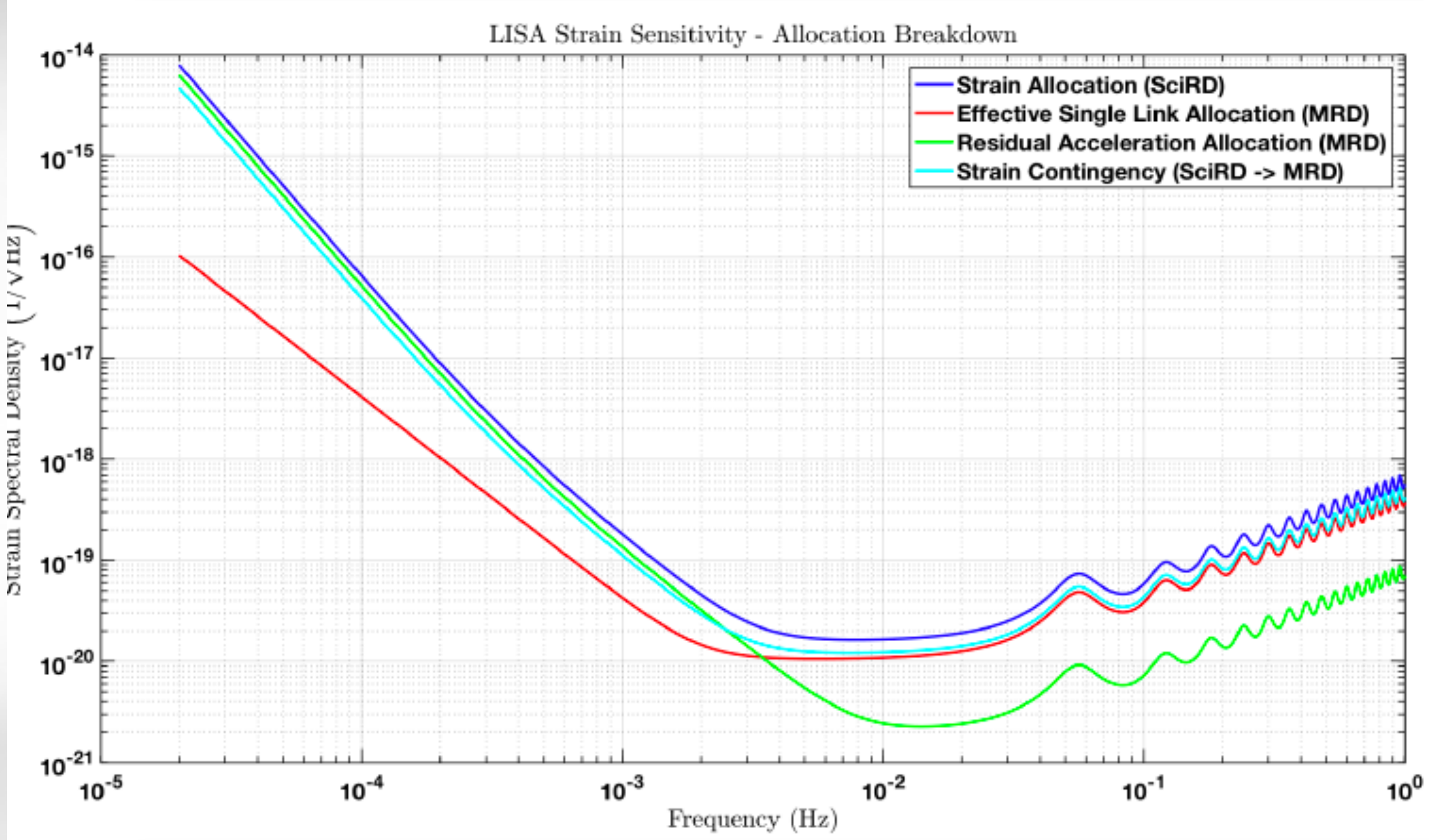
Scientific Performance Budget

LISA France

- Objective : build a 'simplified', system-level, performance model
  - Identify critical items
  - Unified view of the system performance from science requirement to sub-systems level.
  - Support the allocation breakdown for each sub-system
  - Sensitivity analysis to support design trade-off
- Different sources of information
  - Specific or 'end-to-end' simulations
  - Mathematical & physical models
  - Lab experiments

Interface with all stakeholders – Consortium, Agencies, Industry.

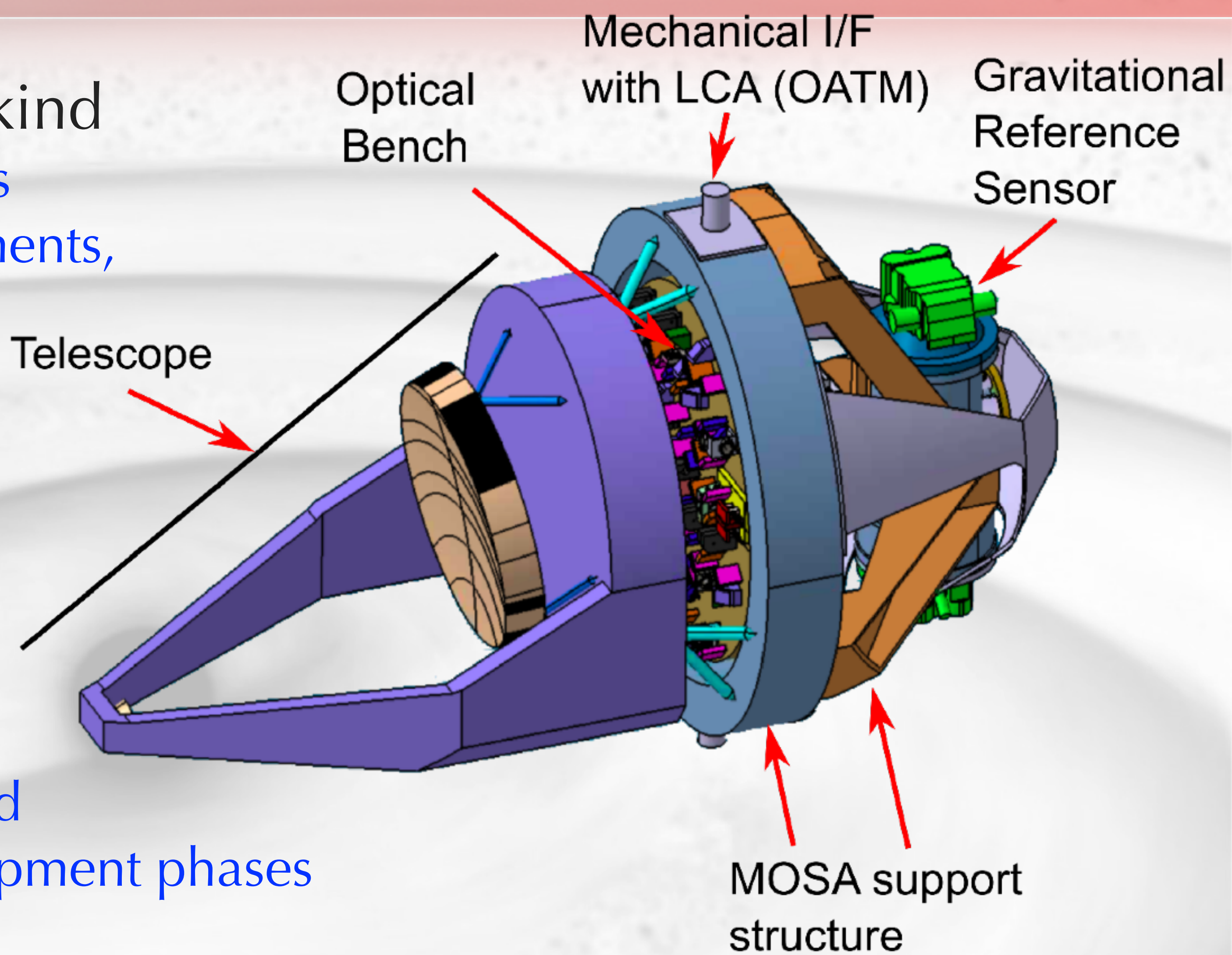




MOSA AIVT
Assembly, Integration, Validation and Tests

LISA France

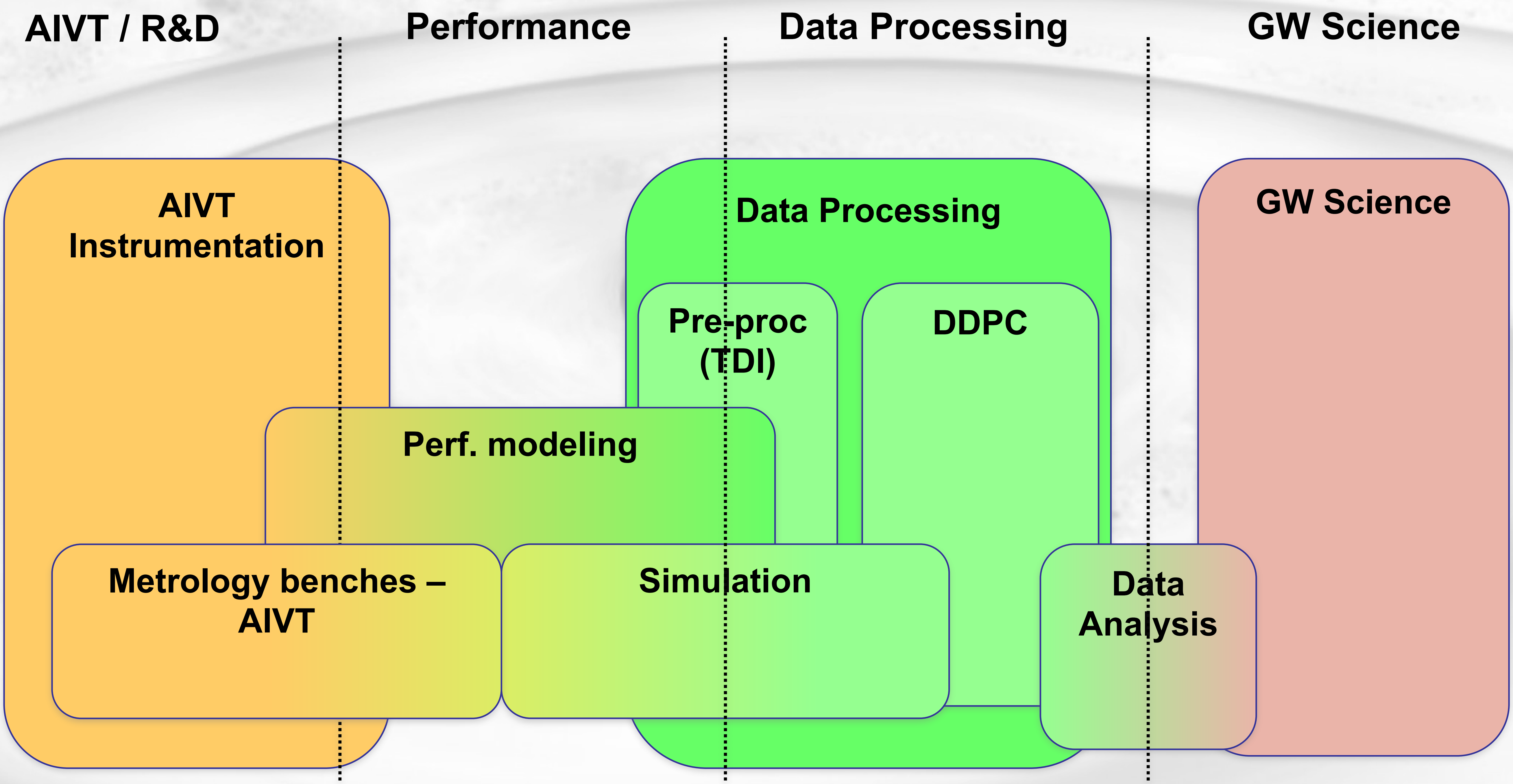
- LISA will be the first instrument of its kind
  - Not a collection of separate instruments
  - Combination of finely designed equipments, forming a Mkm-scale instrument
- LISA science return depends on the in-depth performance characterisation of the metrology core
  - Importance of the AIVT and scientific performance modelling
  - Crucial activity giving high visibility and involvement in early instrument development phases



- Integration and tests in close collaboration with industries
  - 10 MOSAs to integrate and validate (1 STM, 1 EQM, 1 PFM, 5 FMs, 2 spares)
  - Research institutes : development of optical metrology test benches and strong involvement in the EQM characterisation
    - Experience on MOSA testing transferred to industry with PFM
  - Industries : integration procedures and semi-serialisation of FMs & spares AIVT
    - The research institutes still follow the process and interpret the measurements

French LISA activities landscape

Broad and continuous coverage, from instrument to GW science



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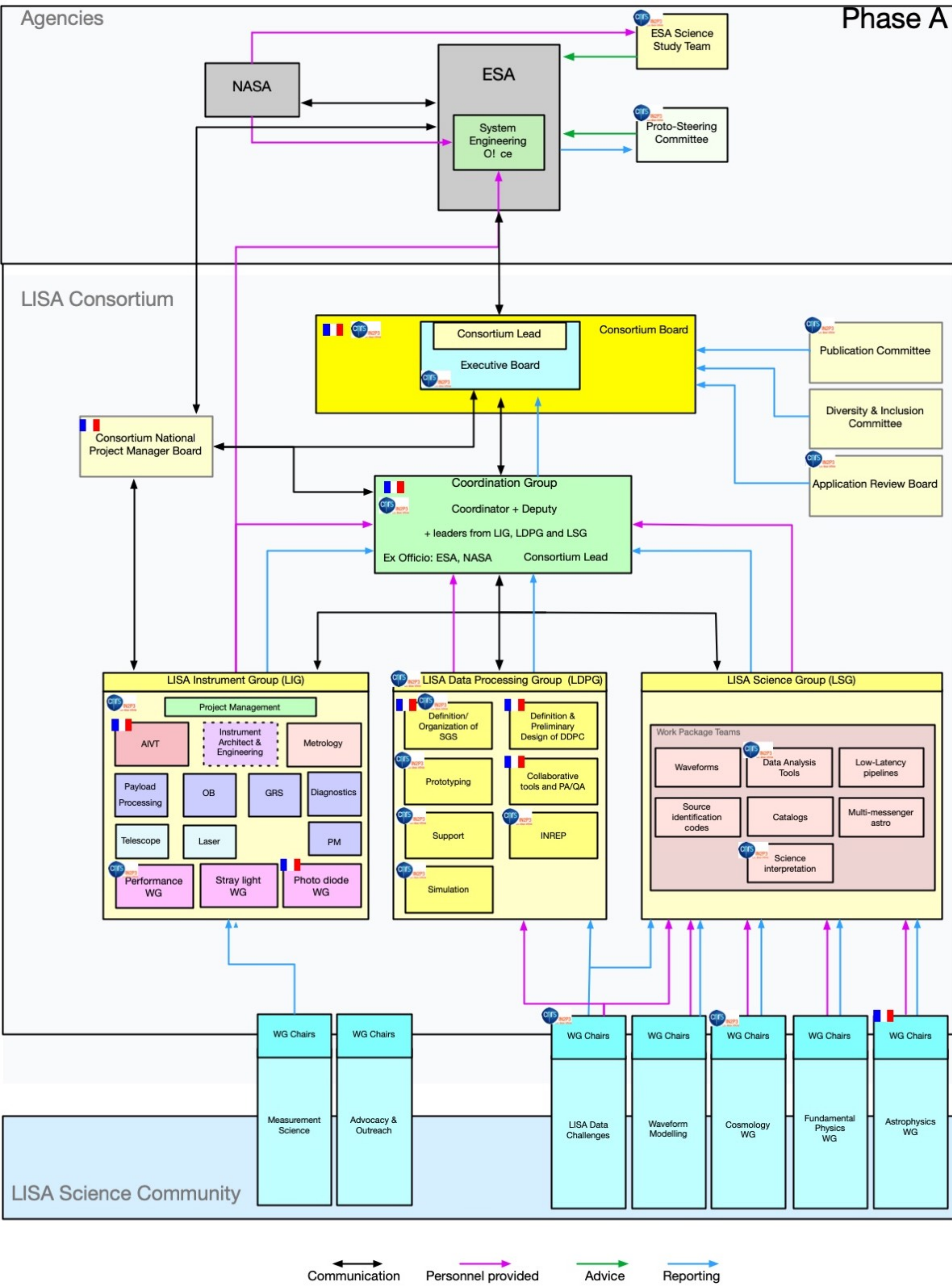


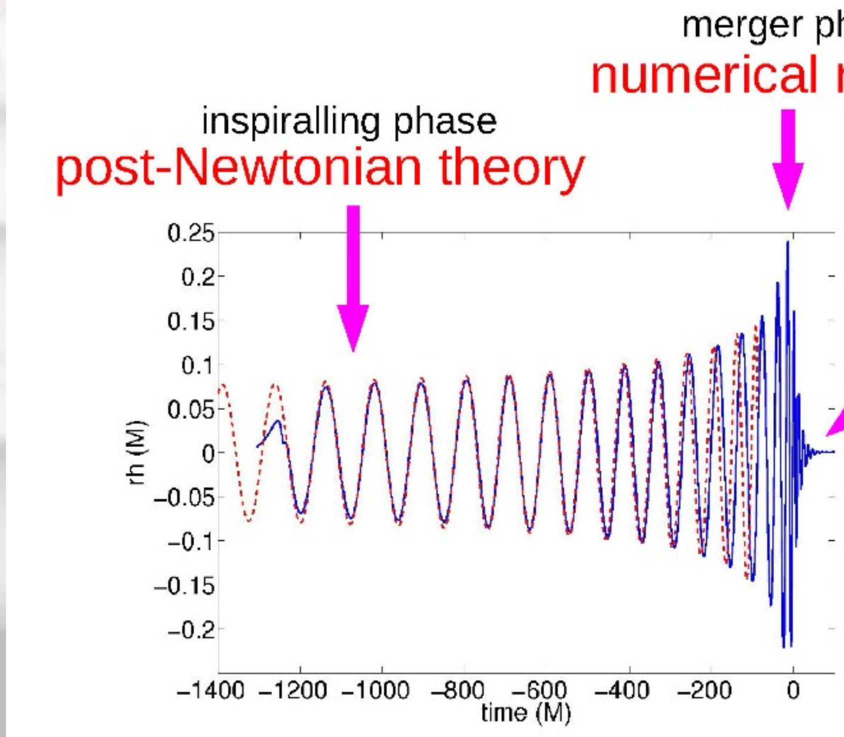
Key roles of IN2P3 members in the LISA Consortium

- ESA committees
  - Science Study Team
  - System Engineering Office
- LISA Consortium Management
  - Executive Board
  - Coordination Team
- LISA Instrument Group
  - Core team
  - Performance Working Group
- LISA Data Processing Group
  - Lead
  - SGS Definition and organisation
  - SGS prototyping
  - SGS support
  - Simulation
  - Initial Noise Reduction Pipeline
- LISA Science Group
  - Data Analysis
  - Science Interpretation
- Working Groups
  - LISA Data Challenges
  - Cosmology

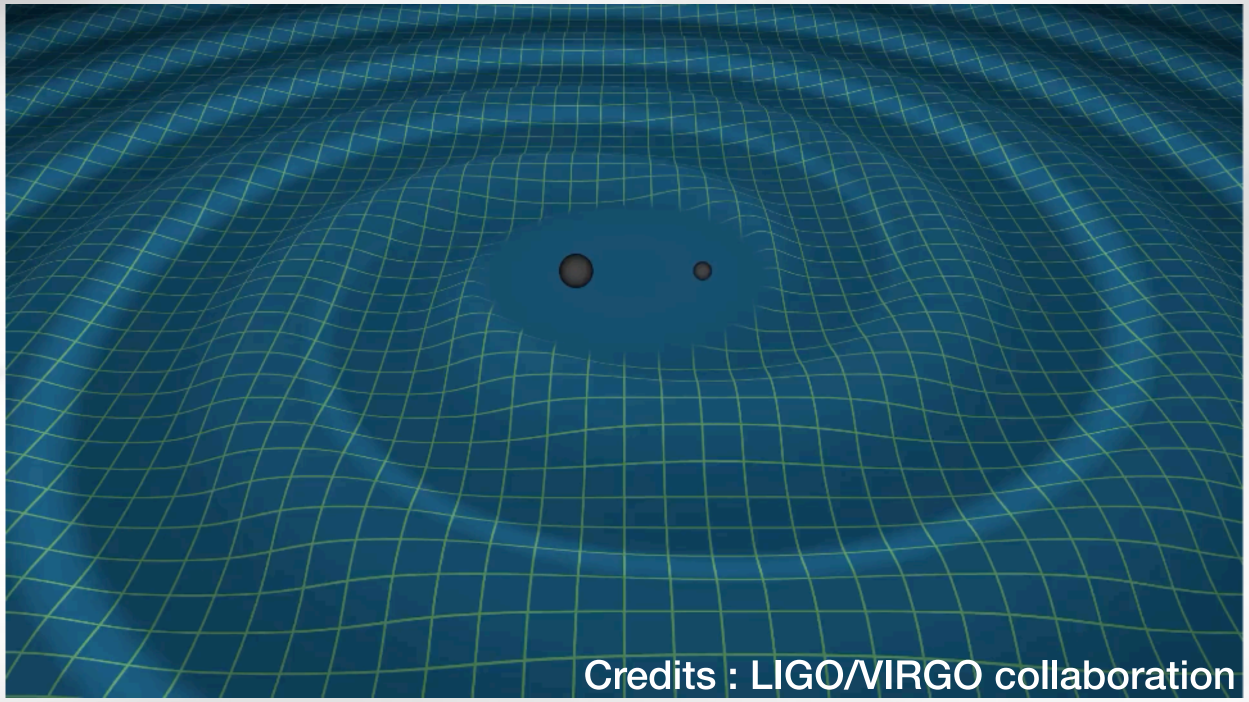
Science activiities summary

LISA France

- Modelling GW sources
  - Matched filtering requires very good knowledge of GW signals.
  - Biases and 'false' GR deviations to arise from mismodelled GW
- Testing GR with coalescing binaries
  - Very tight constraints on GR deviations from GW waveform details
  - Multiband observations of stellar mass BBHs
- GW signals from the early Universe
  - Modelling the signals of first-order transitions
  - Study on detection prospects with LISA
  - Cosmic strings signal modelling (burst and stochastic background)
- Using GW sources as "standard sirens"
  - LISA localisation compatible with e/m identification?
  - Constraints on Hubble constant, dark energy equation of state, etc.
- Participating institutes : ***APC***, ***L2IT***, IAP



Credits : IAP



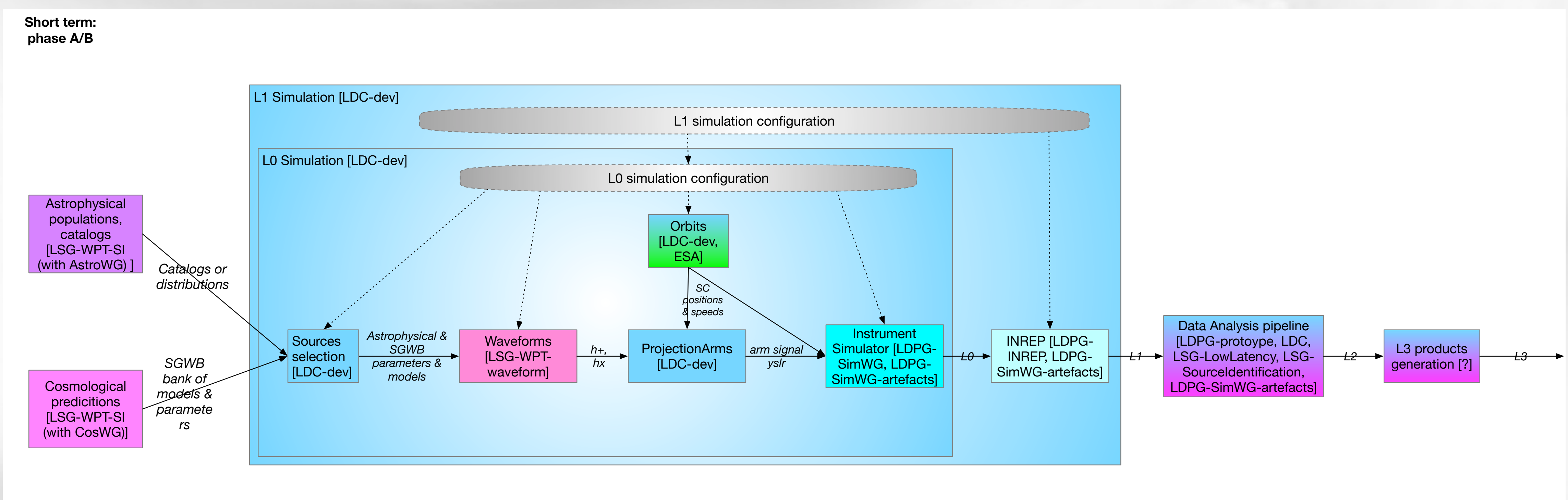
Credits : LIGO/VIRGO collaboration

Distributed Data Processing Center
Science Ground Segment

- Definition and organisation of the SGS
  - Led by ESA and LDPG (LISA Data Processing Group)
  - Definition of organisation, responsibilities, interfaces, …
    - Organisation for generating and processing LISA data

- Definition and preliminary design of the DDPC
  - Led by CNES
  - Logical design of the analysis for extracting GWs (L1 -> L2 -> L3)
    - Functional tree and product tree
    - Development plan

- Participating institutes
  - ***APC, LPCCaen***



Distributed Data Processing Center
Science Ground Segment

- Instrument Simulation
  - Realistic simulation of the instrument: noises, beam propagation, dynamics, on-board processing, artefacts (glitches, gaps, …), etc
  - Current simulator: LISANode:
    - time domain, C++/python, modular
    - mainly developed at APC
  - Key tool for:
    - validating instrumental concept
    - identifying correlations or particular effects
    - producing realistic data for INREP & LDC

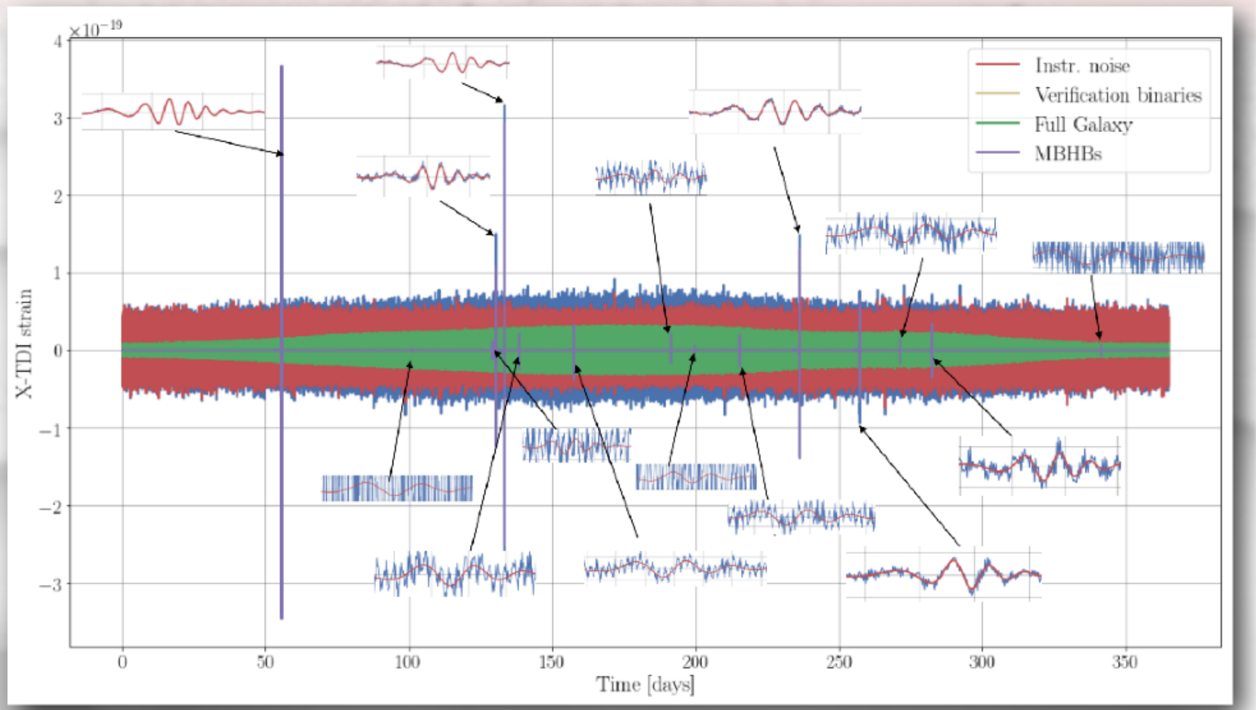
- INREP (INitial Noise REduction Processing)
  - Main objective: to deliver level-1 (L1) data
    - i.e. reduced raw observations with dominant noises suppressed (mostly laser frequency noise)
  - Signal calibration: from gain correction to time synchronisation of signals
  - Kalman filtering for estimating absolute armlength
  - Correction of laser frequency noise, clock jitter noise with application of Time-Delay-Interferometry

- Participating institutes
  - ***APC***, ***LPCCaen,*** SYRTE, CEA

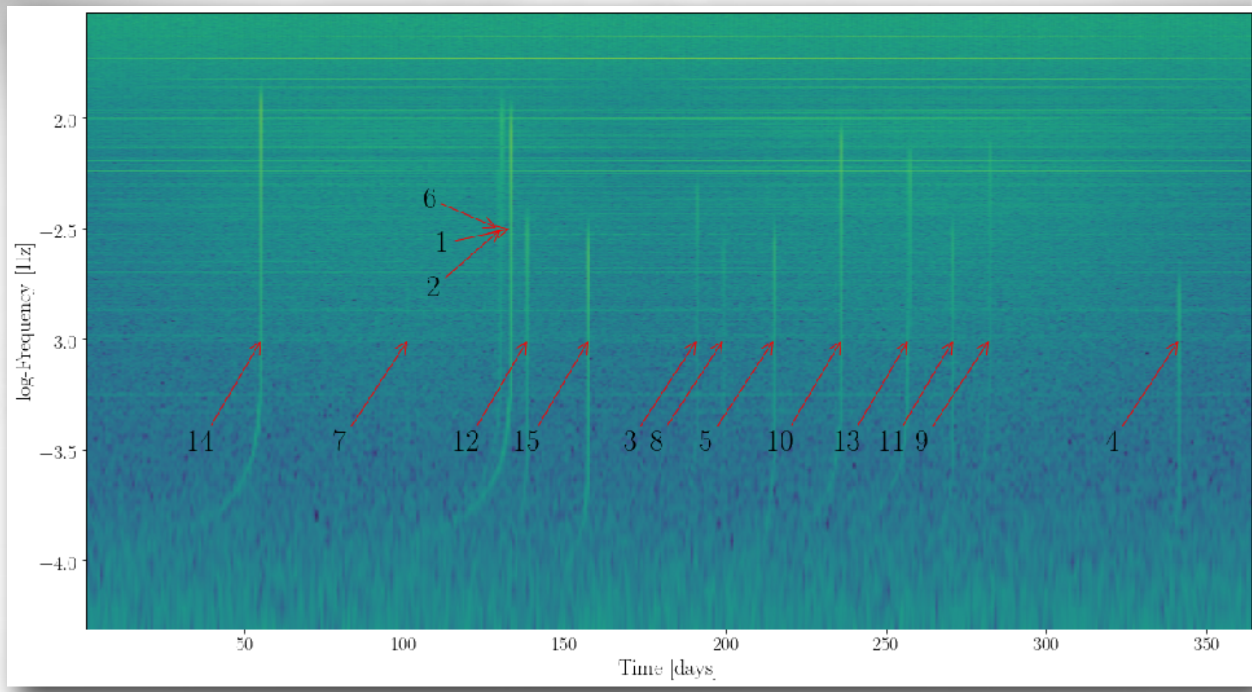
LISA Data Challenges

LISA France

- Objectives:
  - Establish a common playground to evaluate algorithms
  - Foster data-analysis research and community involvement
  - Prototype and develop end-to-end data-analysis pipelines



- 2 released challenges
  - LDC-1
    - Idealized noise and separated sources
    - ‘Training’ data set
  - LDC-2
    - LDC2a: source confusion (MBHBs and Gal. binaries)
    - LDC2b: realistic instrumental noise (gaps, non-stationarity) but simple GW signals



- Participating institutes
  - ***APC***, SYRTE/Obs. de Paris, ARTEMIS/OCA, CEA

Collaborative tools

LISA France

- LDPG WG to support Consortium activities
  - Common development environment based on containers (docker, singularity)
  - CCIN2P3 tools at the core of LISA Consortium tools
    - gitlab
    - Atrium
    - continuous integration
    - wiki
  - Computing ressources
    - Mainly CC-IN2P3
    - Preliminary DCC (Data Computing Center)

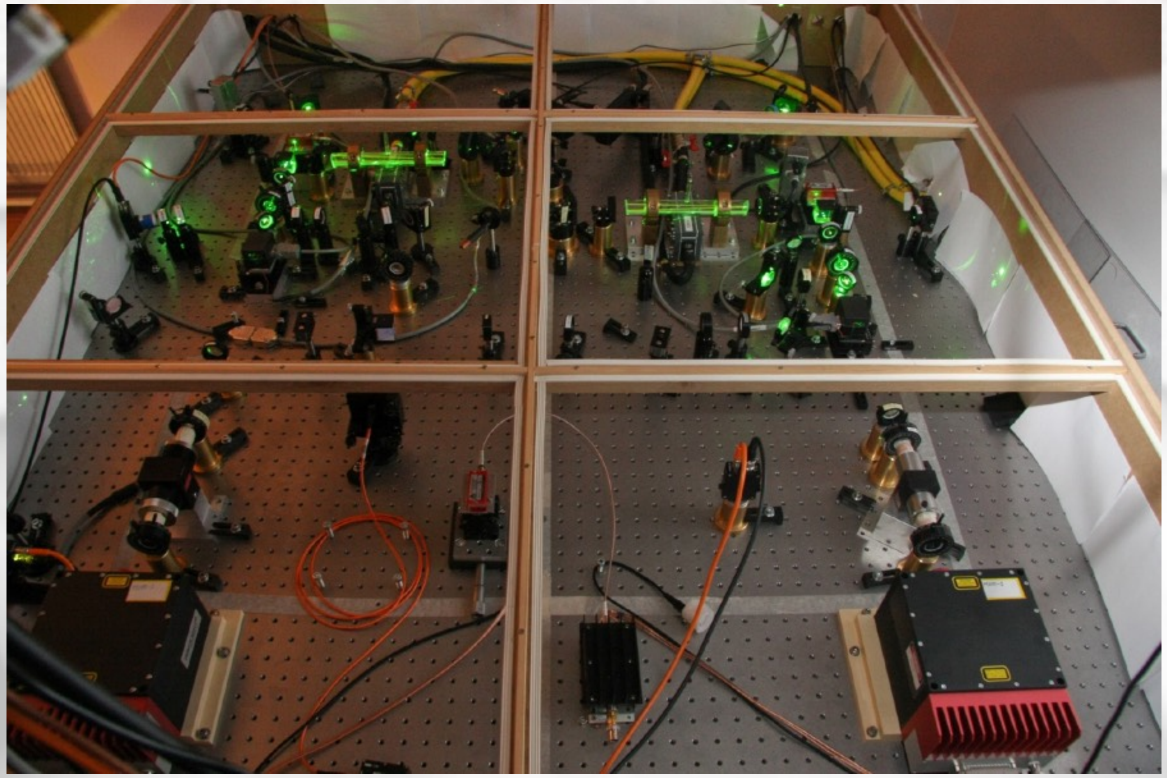
- Participating institutes
  - ***CCIN2P3, APC***

Performance modelling: from subsystems to LISA sensitivity

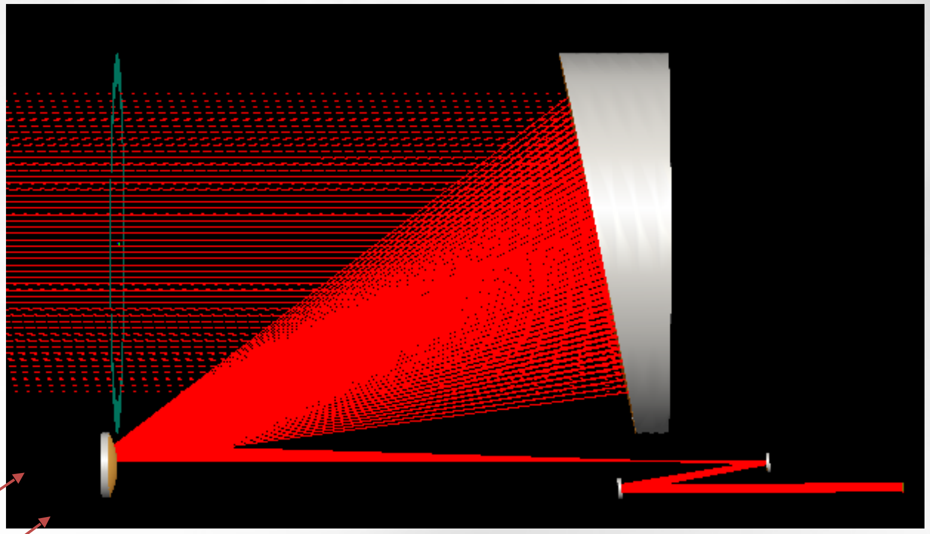
- Performance Modelling activities
  - Co-chair of the performance modelling working group
    - Coordination of periodical releases to ESA.
    - Information and data management with the industrial primes
  - Models development on specific items
    - Data processing impact on noise (TDI)
    - Telescope stray-light noise
    - Impact of correlations on the noise budget.
  - Development of the performance model software
    - incl. web interface
- Figures of merit
  - Assessing ability of LISA to fulfill the science objectives
  - Evaluation of a given LISA configuration to deliver the expected science
- Setting requirements on the performance
  - Duty cycle, minimum mission duration, science frequency range
  - Impact of gaps, glitches, calibration uncertainties
- Participating institutes
  - ***APC***, CEA, IAP, ***L2IT***

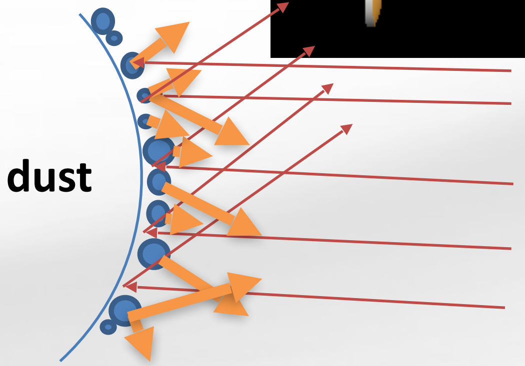
Instrument science : past R&D activities

- Laser frequency stabilisation [***APC***, ARTEMIS, SYRTE]
  - R&T activity funded by CNES
  - Objective of $10^{-13}/\sqrt{Hz}$ above 3 mHz
  - Based on molecular iodine spectroscopy, first ideas in ARTEMIS/OCA
  - **Successful demonstration at APC, considered as alternative technique to nominal Fabry-Perot solution**
  - **Developments pursued at SYRTE, to be used in optical benches prototypes**



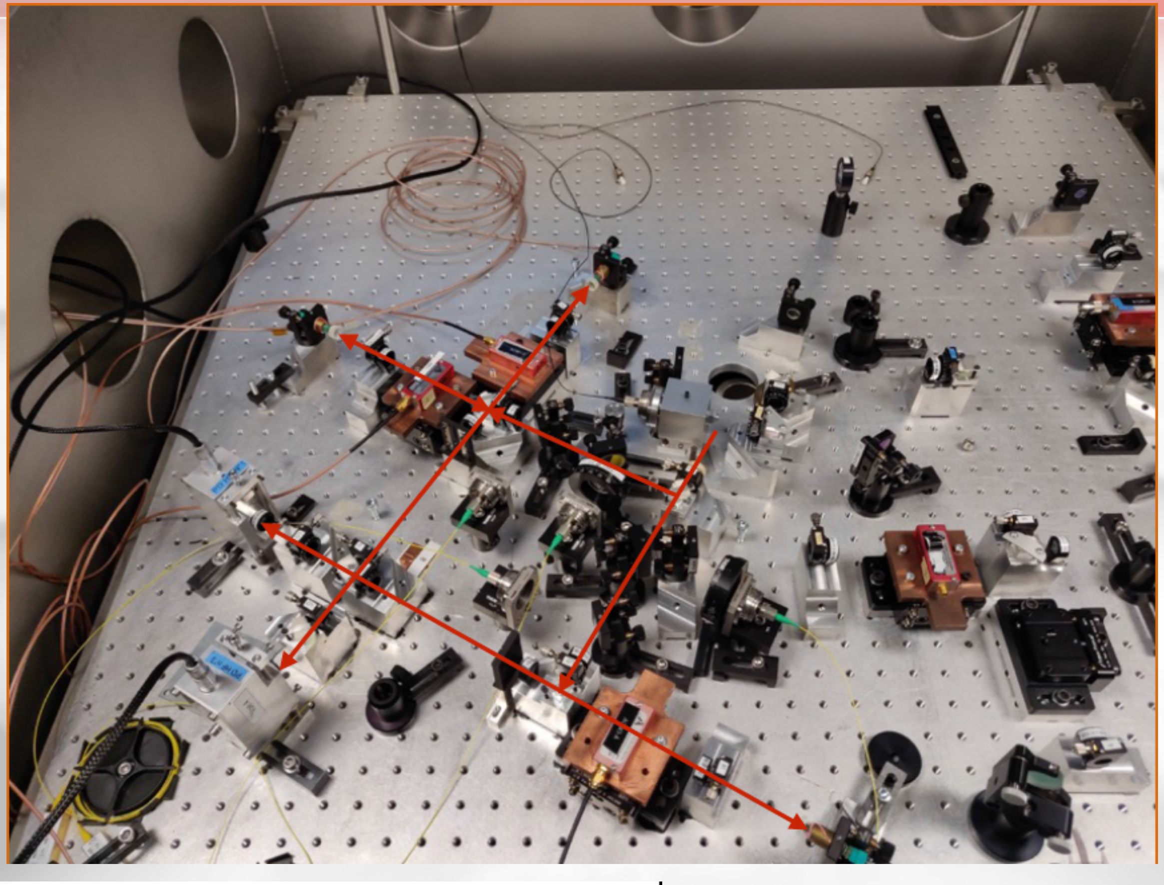
- Telescope design studies [***APC***, ARTEMIS, INRIM, ***LMA***, TAS]
  - Answer to an ESA ITT (Invitation To Tender) in 2016
  - Collaboration of research institutes with TAS for a (backup) design of a telescope for LISA
  - @APC : study of back-scattered light and impact on the phase measurements
  - @LMA : expertise in components characterisation, straylight modelling and coating design
  - **Expertise and models still used and applied on the NASA telescope design for LISA performance modelling**

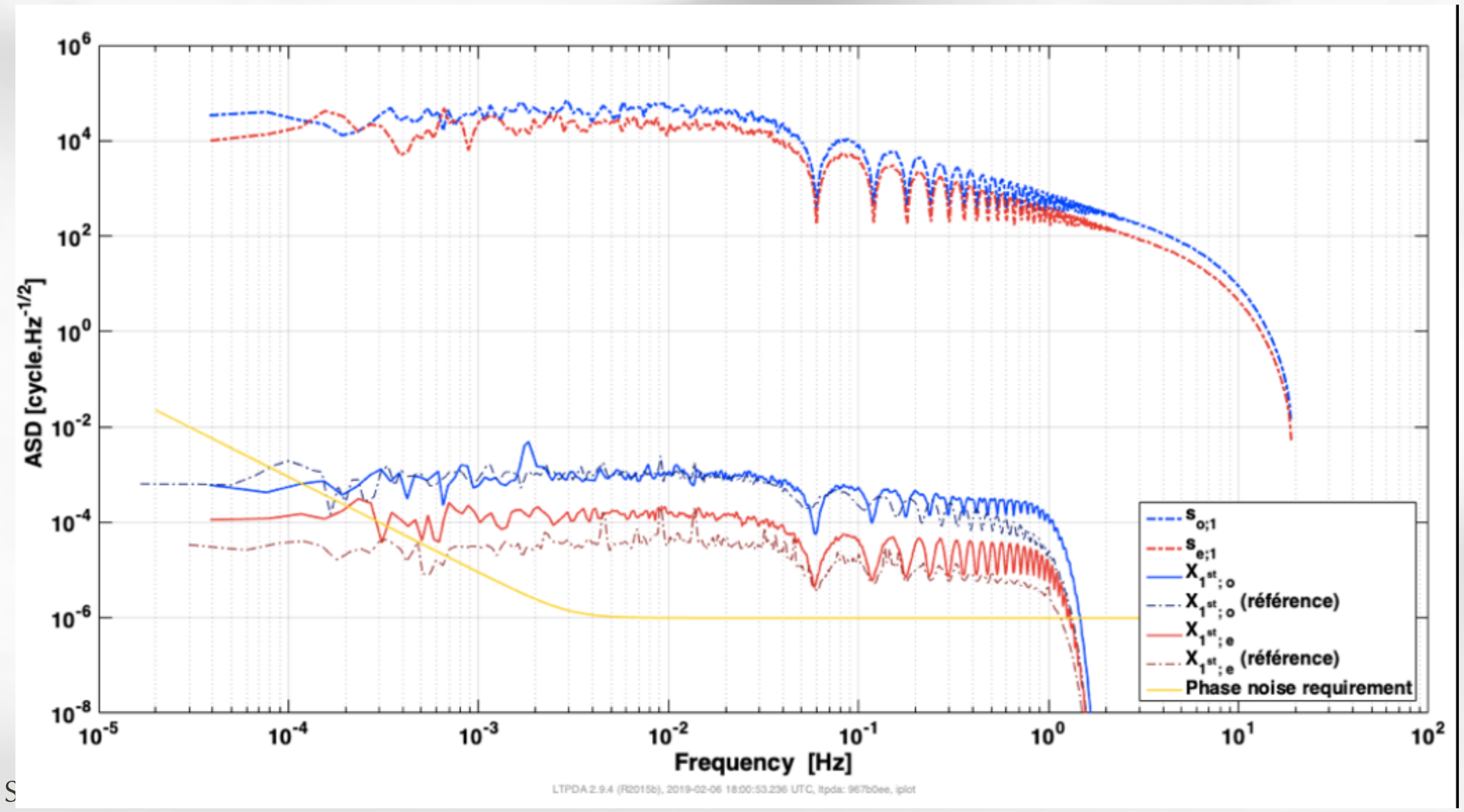




Current R&D activities

- LISA On Table [***APC***]
  - Objectives: Generation of LISA-like beat notes for testing noise reduction algorithms with representative data
  - Optical and electronically interferometers
  - **Demonstration of a noise reduction factor >10^8 with instrumental data using TDI**





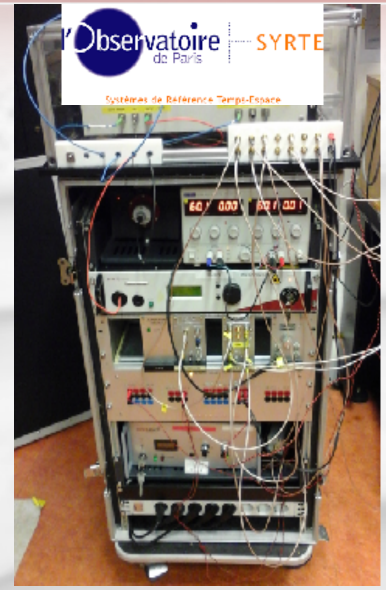
OGSE prototyping: MIFO/ZIFO demonstrators

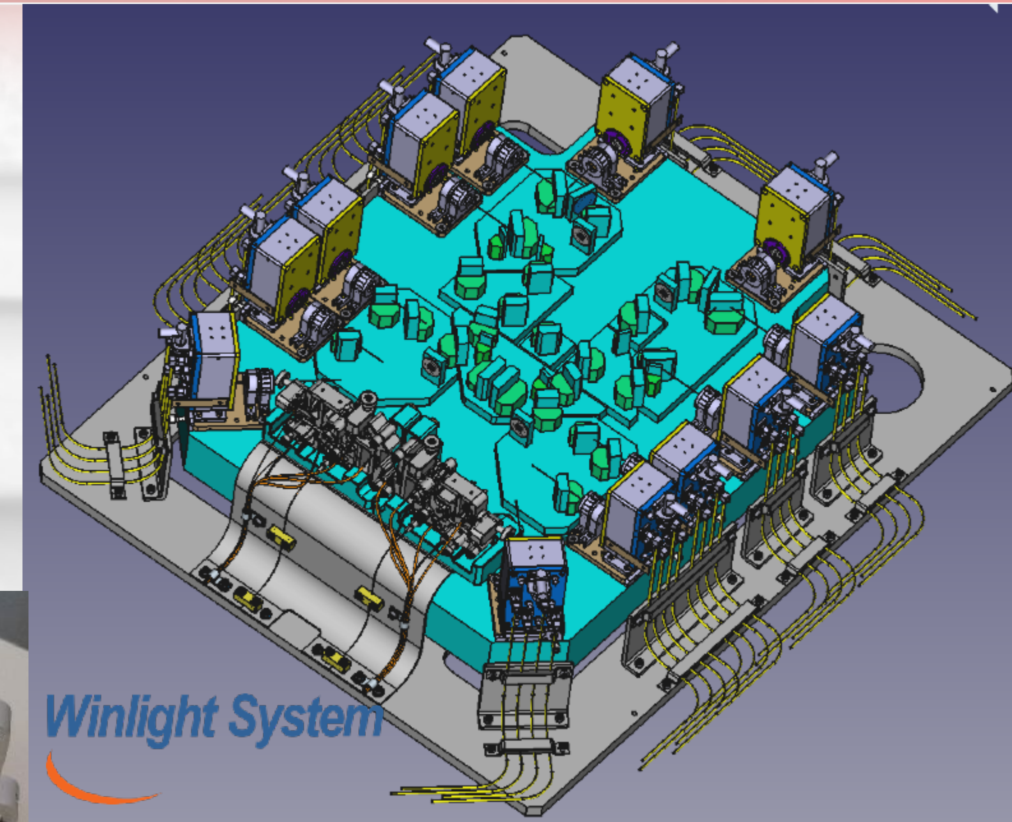
LISA France

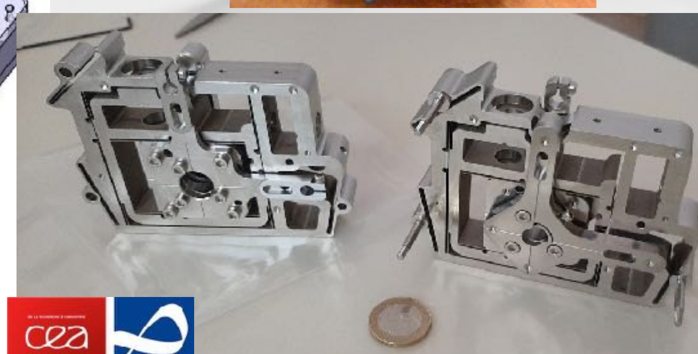
- Purpose
  - Development of an ultra-stable optical bench for demonstrating the on-ground characterisation capabilities
- Goals
  - Pathlength stability of ~10 pm/√Hz in [10 mHz:1 Hz]
  - Organise the French community in view of the development of the MOSA GSEs (including private companies, e.g. on optical contacting)
  - Identify and quantify the main noise sources in a relevant environment
  - Evaluate the complexity (+cost, duration, etc) of MOSA performance tests
- 2 steps approach
  - 'Metallic' bench (MIFO) with an invar base plate
    - Integrated and tested in a 'lab' vacuum chamber
    - Validation of the mounting and tuning procedures, acquisition chain, analysis tools and performance model
    - Final results expected end 2021
  - Zerodur bench (ZIFO) with optically contacted components
    - Designed and integrated by Winlight (except photoreceivers and injectors)
    - Tested and characterised in a vacuum chamber representative of AIVT environment
    - Final results expected end 2022
- Participating institutes :
  - ***APC***, ARTEMIS/OCA, CEA/IRFU, CNES, ***CPPM***, ***L2IT***, LAM, SYRTE/Obs. de Paris

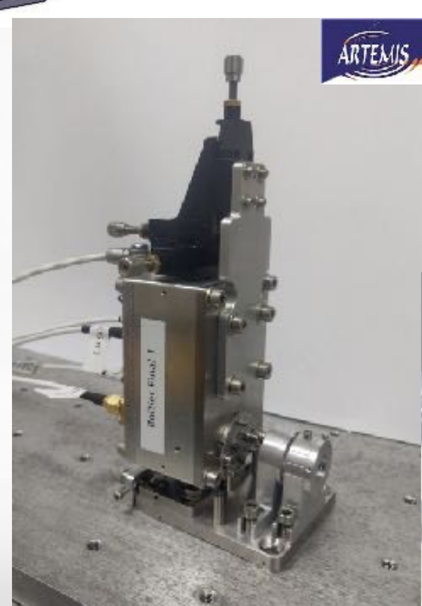
MIFO/ZIFO current status

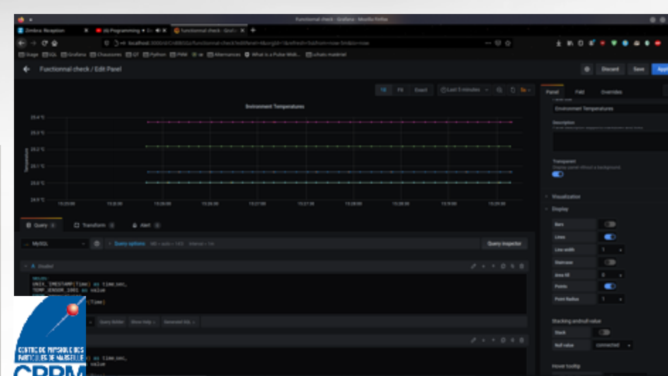
- Magt. + ing. système : APC
- Design optique : L2IT + APC
- Blindage thermique : LAM

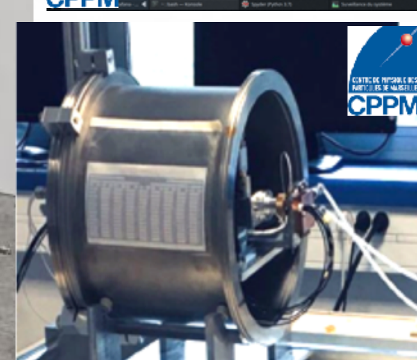






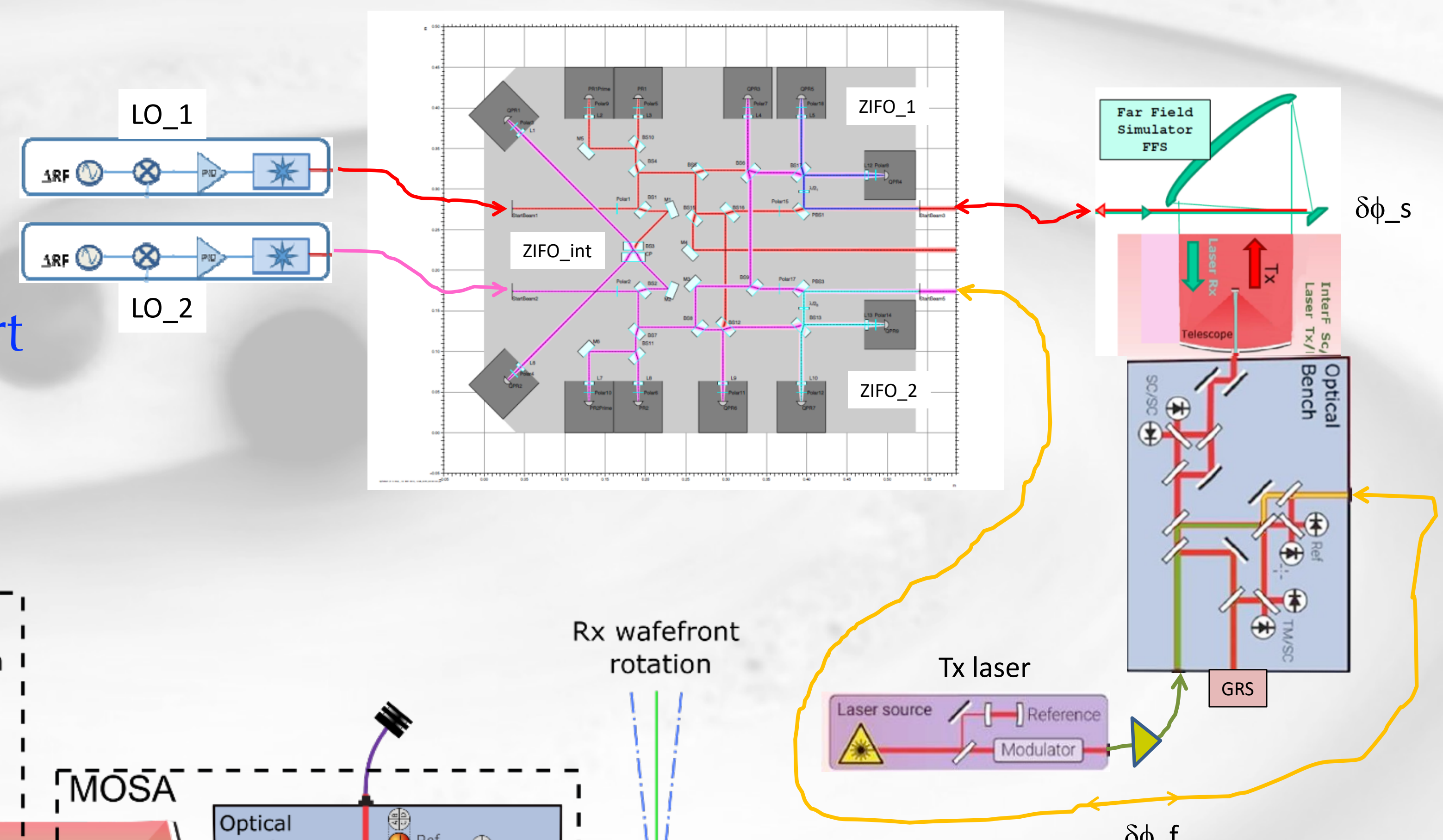


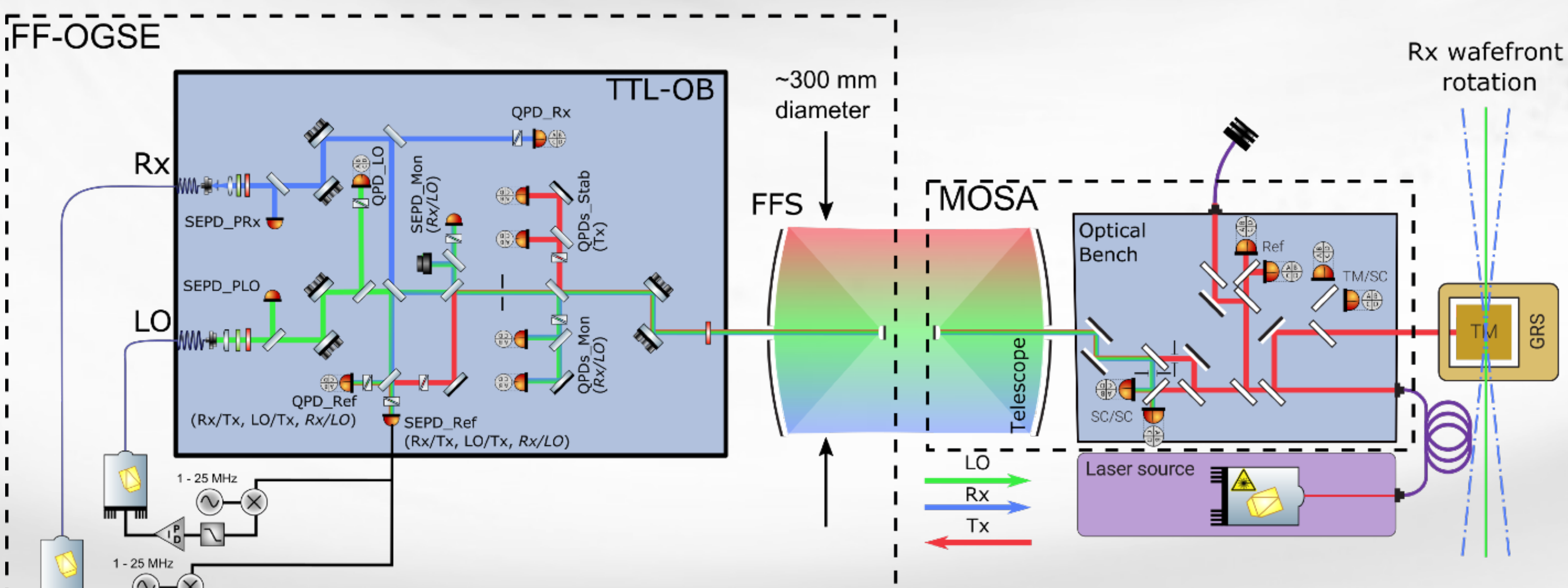




Design of the future AIVT GSEs

- Design requirements and key technologies prototyping for critical Optical Ground Support Equipments for LISA
- Participating institutes :
  - ***APC***, ARTEMIS/OCA, CEA/IRFU, CNES, ***CPPM***, Institut Fresnel, ***L2IT***, LAM, ***LMA***, SYRTE/Obs. de Paris
- 5 main OGSEs identified :
  - Beam wavefront measurement
  - Beam centring measurement
  - Far-Field Optical Ground Support Equipment
  - Differential and global interferometric tests (2 OGSEs)





Outline

- *LISA Science Objectives*
- *Mission Description and Proposed French Contribution*
- *The IN2P3 within LISA*
- **Conclusion**

LISA France

Highlights and conclusion

- LISA schedule for launch in 2034 / 2035
  - major milestones in end 2021 (end of Phase A) and end 2023 (adoption)
  - LISA will be complementary to future ground based GW detectors and e/m observatories

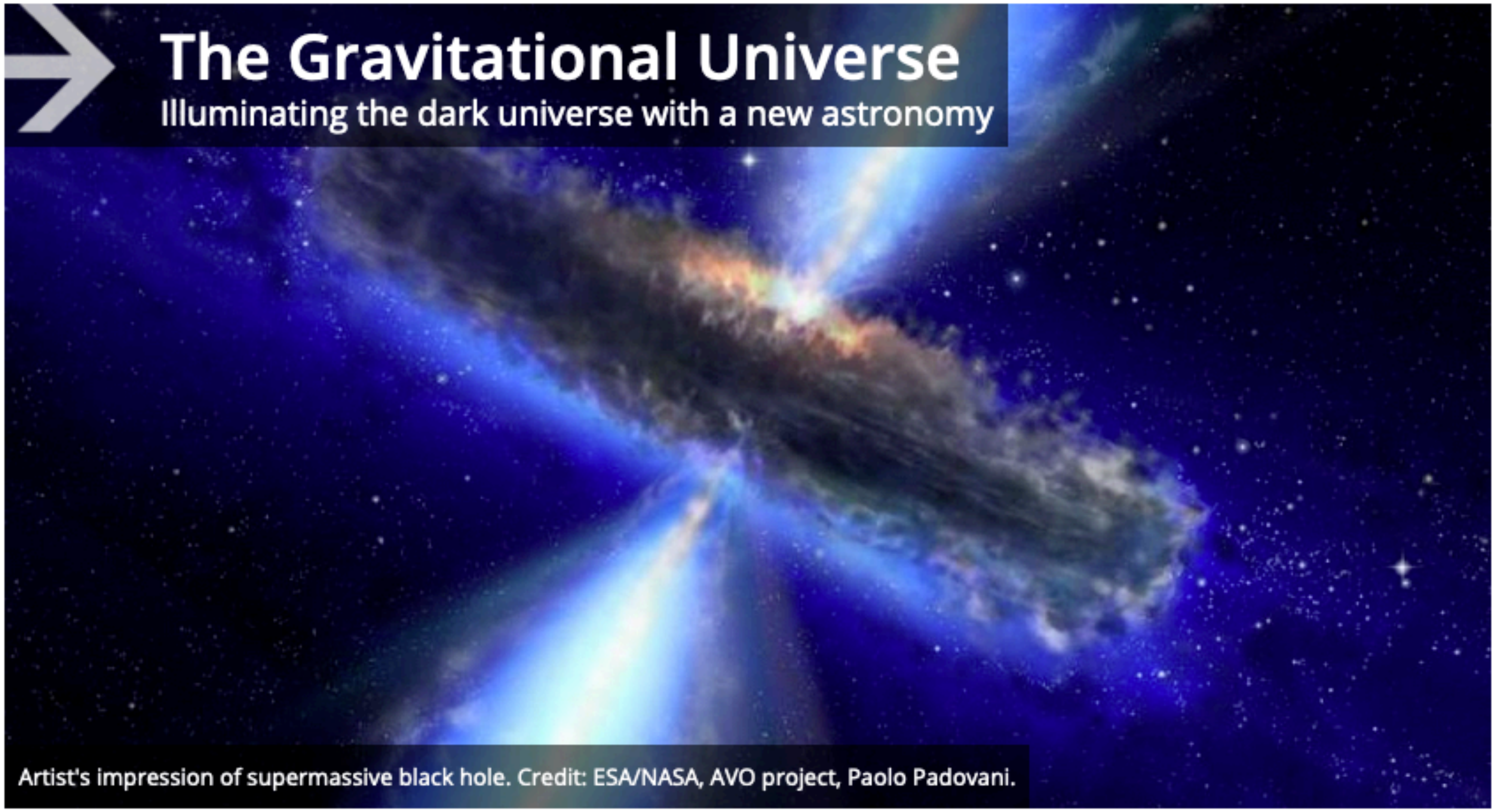
- Foreseen French contributions
  - Science Ground Segment / Distributed Data Processing Center
  - Scientific Performance Model
  - Instrument core AIVT

- The IN2P3 laboratories are actively involved in LISA
  - IN2P3 expertise based on LIGO/VIRGO developments, computing infrastructures, previous space missions and LISA Pathfinder
  - The community is presently prototyping the contributions
  - Close collaborations with other institutes: CNES, CEA, INSU, INSIS, OCA, Obs. de Paris

- Very strong support from CNES (financial, short term contracts and engineering)
  - Deliverables and support to science exploitation

- IN2P3 is the driving research institute involved on LISA in France
  - Participation in GW space detectors started with LISA more than 15 years ago
  - Important contributions, recognition and responsibilities in the LISA Consortium

- The continuing support of IN2P3 is crucial
  - permanent positions for securing the expertise brought by young engineers and researchers
  - regular reviews and project status reports



Artist's impression of supermassive black hole. Credit: ESA/NASA, AVO project, Paolo Padovani.

Against racism and discrimination

We have been deeply touched by the brutal and senseless killing of George Floyd in Minneapolis, the recent appalling episode of violence against Black Americans, which brought into relief systemic issues of racism and discrimination that pervade our communities worldwide in a Privacy settings and blatant forms. The

LISA Consortium Internal

Register as scientist

Code of conduct

Newsflash

Join the LISA Consortium
If you are a scientist and wish to contribute to the LISA mission, use this **scientist registration form**.

Images