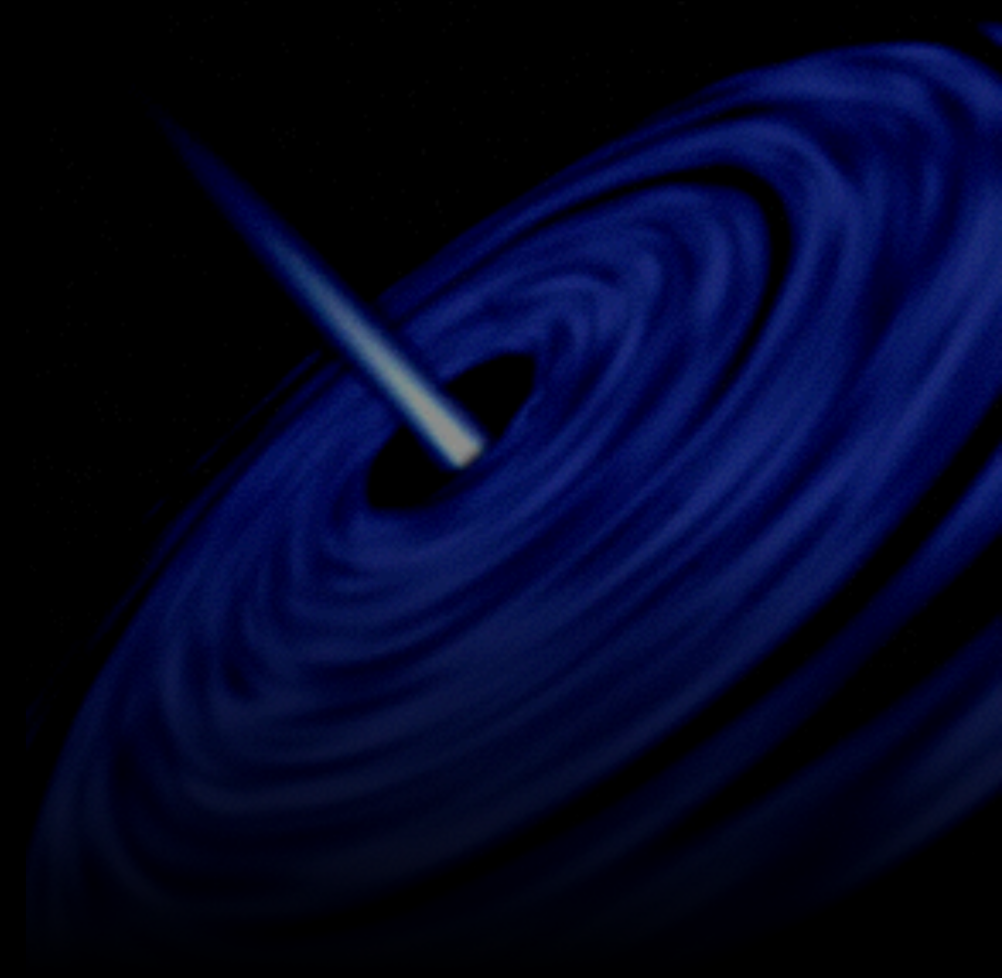
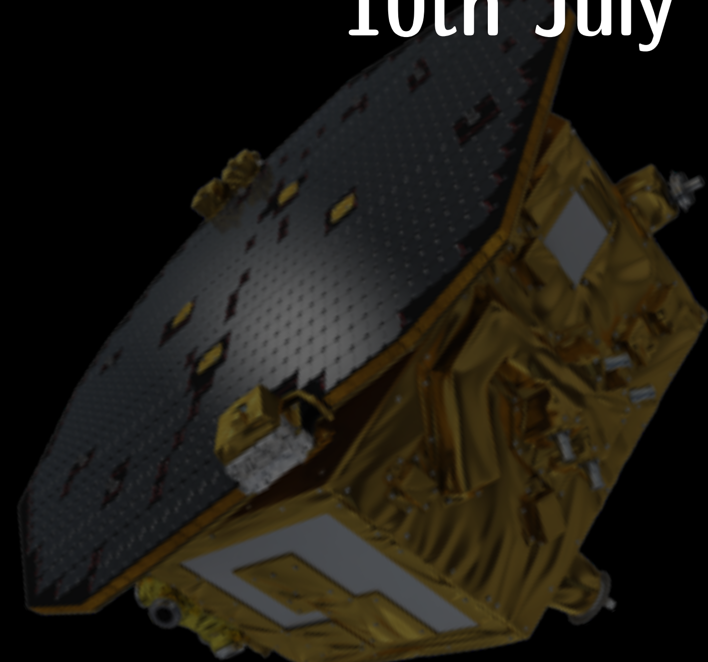
LISA DPC France



10th July 2017



Context & Goals of the day

- LISA: ESA mission, accepted, in phase 0
- Contribution France: Data Processing Center (+ AIVT)

=> Start to organise the French community for the DPC

- Introduce LISA DPC and update on its current status
- Inform about the current and future organisation for LISA
- Identify interests & expertises of each participant
- Include all interested persons in the correct loops for work packages: science & computing
- Identify potential contributors for current and future activities: definition of the DPC, infrastructure, tests, ...

Program

- 10h30 - 12h00 : LISA Overview
- 12h00 - 12h30 : Tour de table ...
- 12h30 - 14h00 : Lunch
- 14h00 - 16h15 : ... Tour de table
- 16h15 - 17h00 : Discussions

10:30 - 11:00	LISA overview: LISA mission 15' + 15' Responsable: Mr. Antoine Petiteau (APC - Université Paris-Diderot)
11:00 - 11:30	LISA overview: DPC projet definition 15' + 15' Responsable: Mrs. Laurence Chaoul (CNES)
11:30 - 12:00	LISA overview: DPC status 15' + 15' Responsable: Ms. Maude LE JEUNE (APC)

Program

12:00 - 12:15	Points of view: CEA 10'+5' Responsable: Gautier Hamel de Monchenault (CEA-Saclay/IRFU-SPP)
12:15 - 12:30	Points of view: CC IN2P3 10'+5' Responsable: Rachid LEMRANI (CC-IN2P3)
12:30 - 14:00	Lunch
14:00 - 14:15	Points of view: ARTEMIS 10'+5' Présidents de session: Prof. Nelson Christensen (Carleton College), Dr. Nicoleta Dinu (LAL/IN2P3)
14:15 - 14:30	Points of view: LAL 10'+5' Responsable: Mrs. marie anne bizouard (LAL)
14:30 - 14:45	Points of view: LPC Caen 10'+5' Présidents de session: Mr. yves Lemiere (LPCCaen, ENSICAEN, Unuiversité de Caen, CNRS/IN2P3, Caen, France), M. François MAUGER (LPC Caen)
14:45 - 15:00	Points of view: IAP 10'+5' Responsable: Dr. Jean-Marc Delouis (IAP)
15:00 - 15:15	Points of view: LAM 10'+5' Responsable: Dr. christian surace (Laboratoire d'Astrophysique de Marseille)
15:15 - 15:30	Points of view: ONERA 10'+5' Responsable: M. Manuel RODRIGUES (ONERA)
15:30 - 15:45	Points of view: CPPM 10'+5' Responsable: Mrs. Anne Ealet (CPPM)
15:45 - 16:00	Points of view: DINO 10' + 5' Responsable: Prof. Themis Palpanas (LIPADE - Paris Descartes University)
16:00 - 16:20	Points of view: IN2P3 10'+5' Présidents de session: Dr. Volker Beckmann (CNRS / IN2P3), Dr. Volker Beckmann (CNRS / IN2P3)

LISA Overview
LISA Data Processing Center

Antoine Petiteau

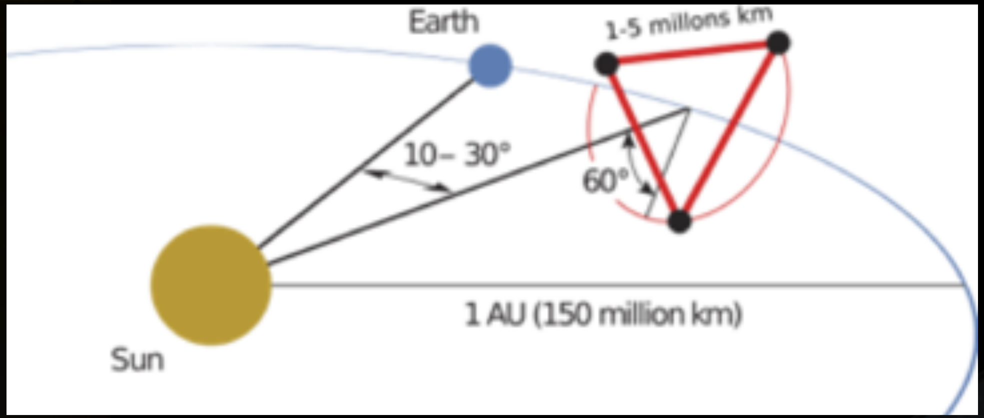
(APC – Université Paris-Diderot/CNRS)

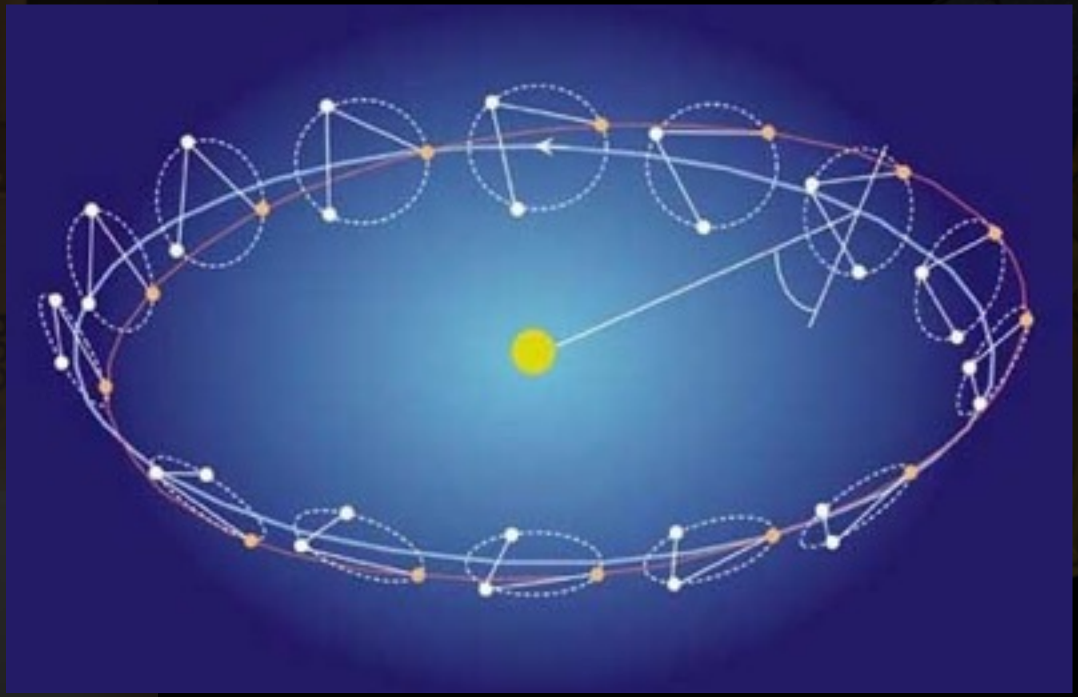
LISA France DPC meeting

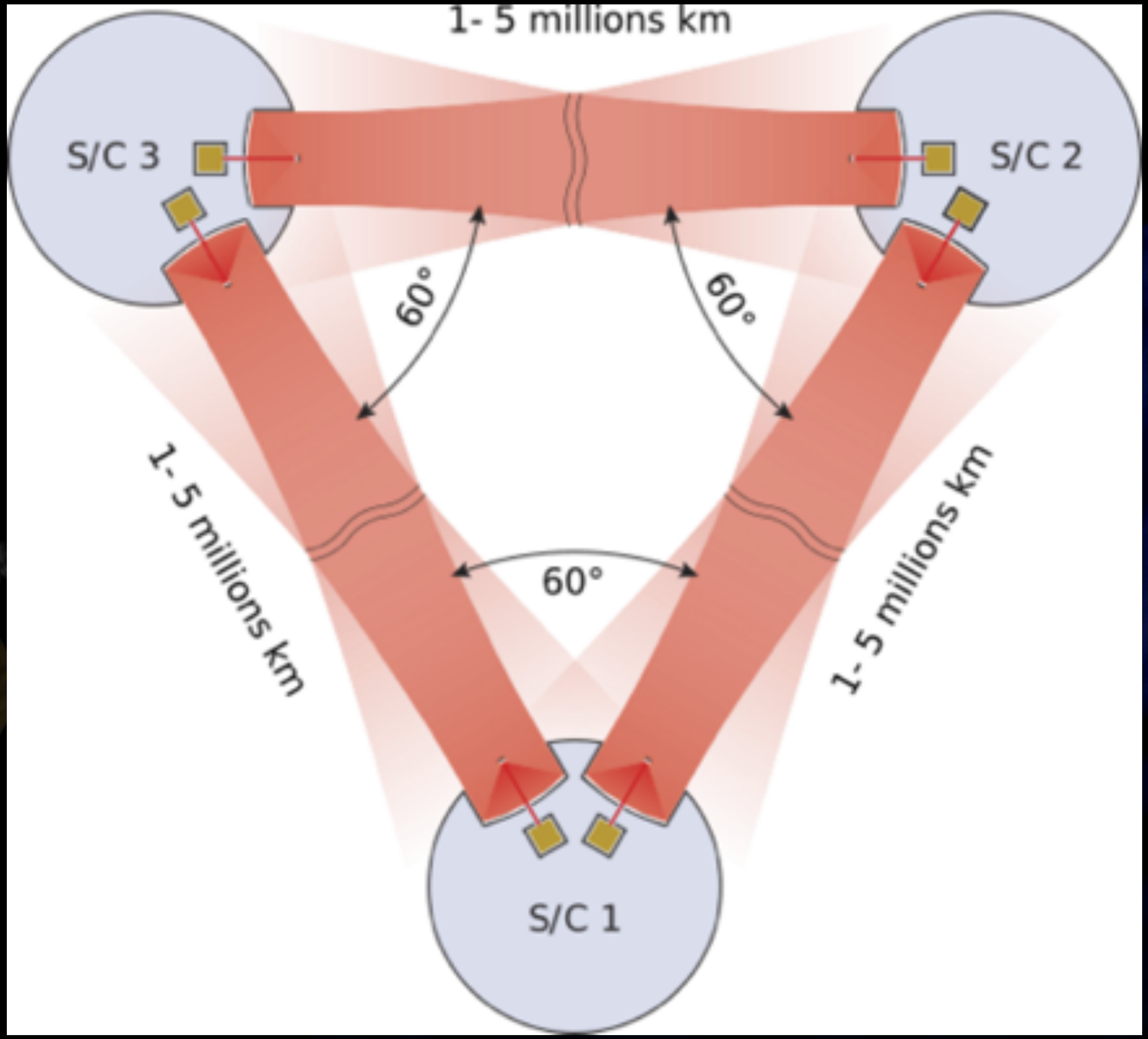
10 July 2017

LISA

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



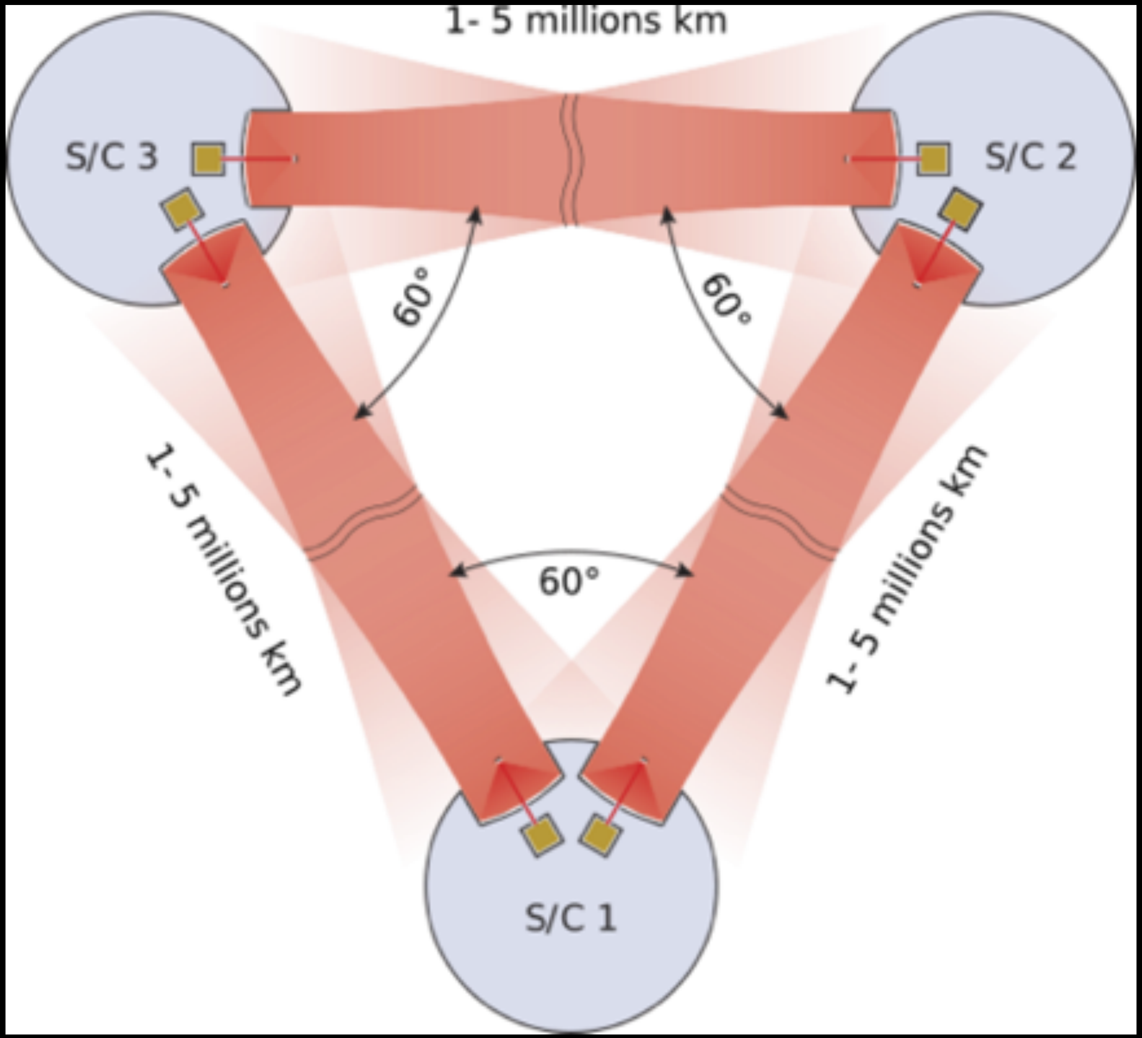




LISA

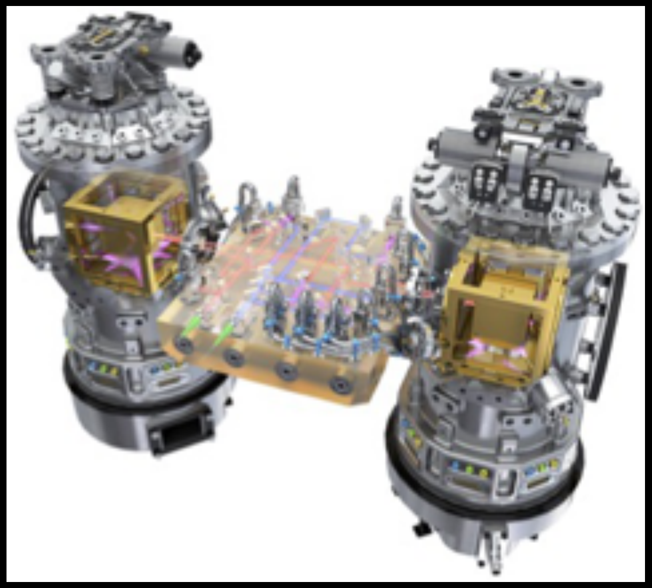
LISA

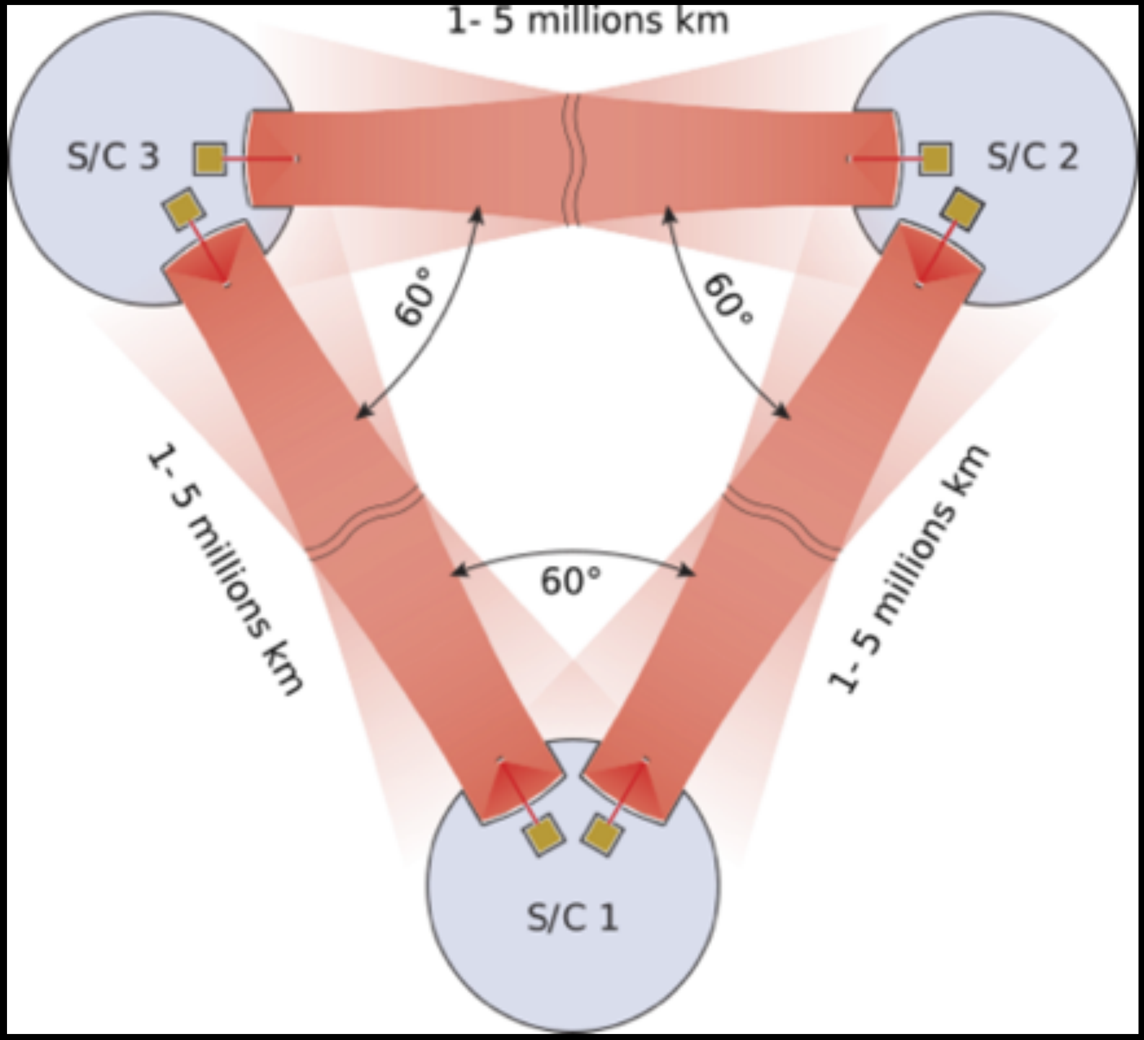
- Photon flight time measurement between free-floating objects:



LISA

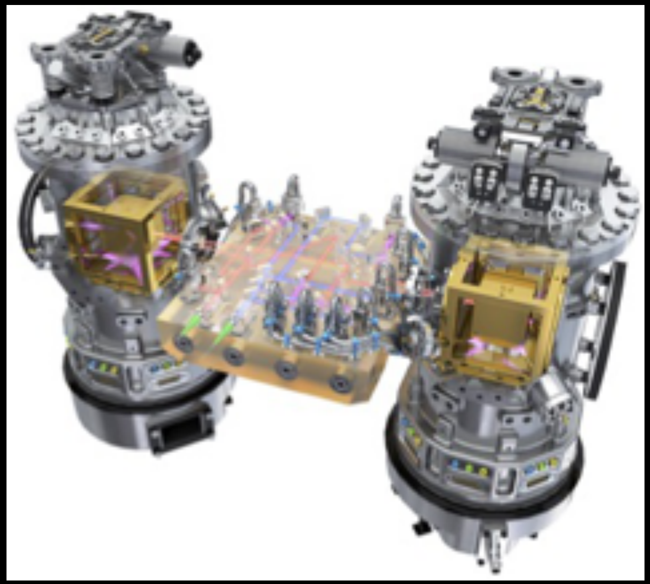
- Photon flight time measurement between free-floating objects:
  - Reference masses in each spacecraft only sensitive to gravity along measurement axis (follow geodesics)

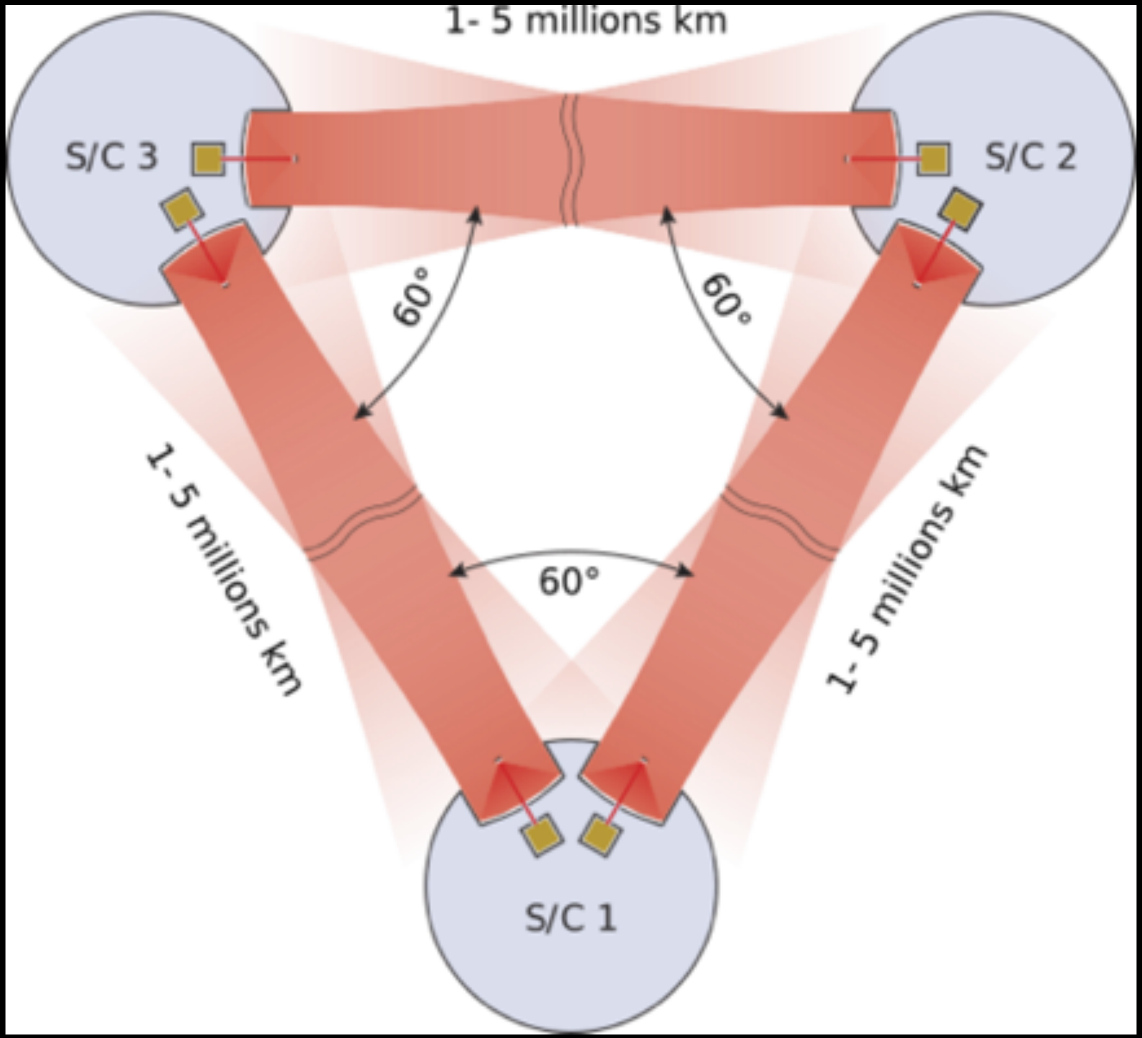


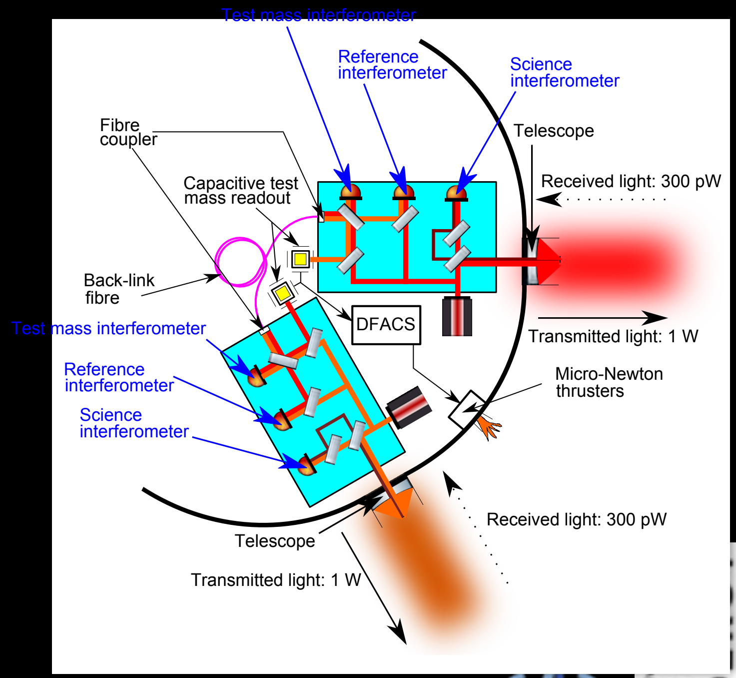


LISA

- Photon flight time measurement between free-floating objects:
  - Reference masses in each spacecraft only sensitive to gravity along measurement axis (follow geodesics)
  - Exchange of laser beam between spacecraft
  - Interferometry at the picometer precision

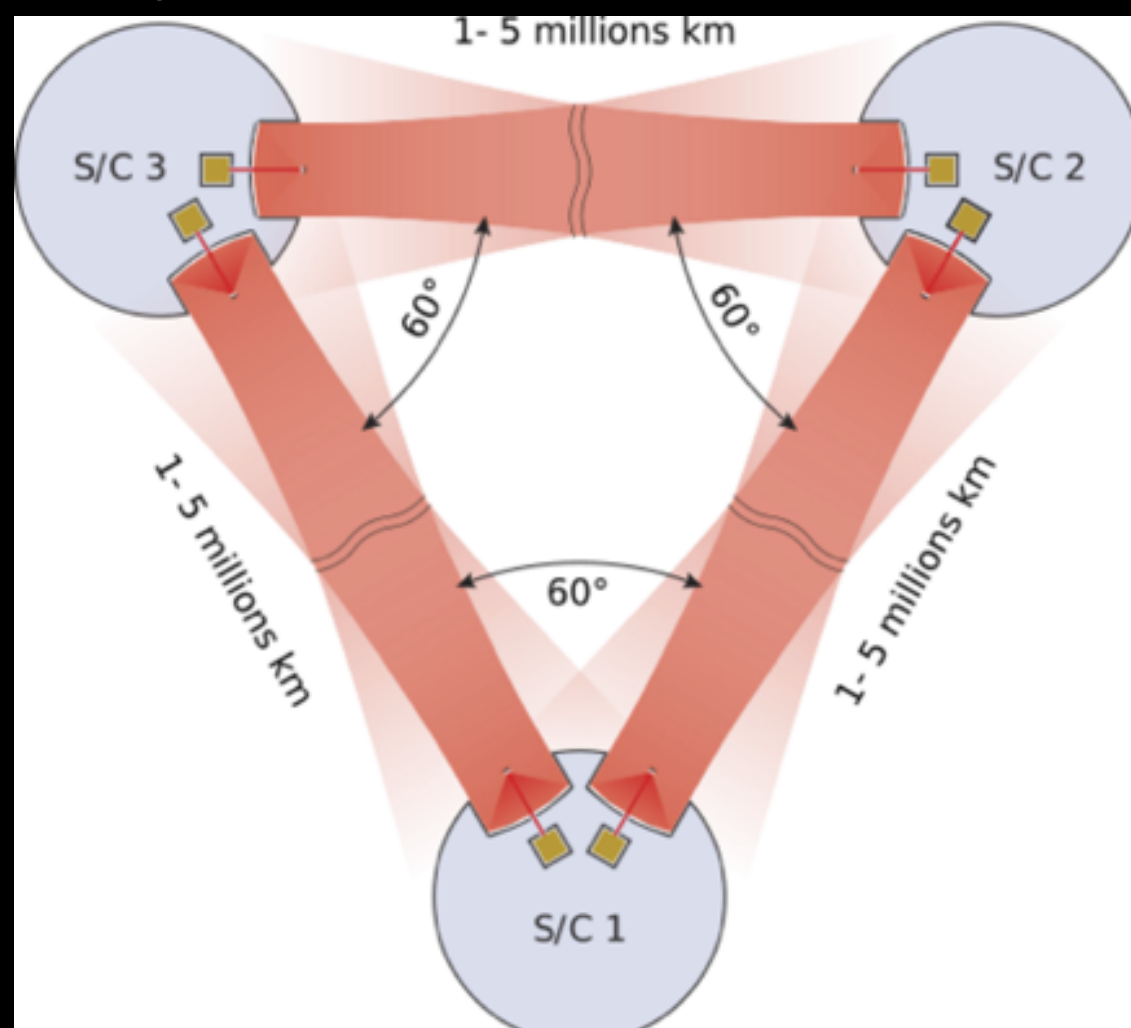


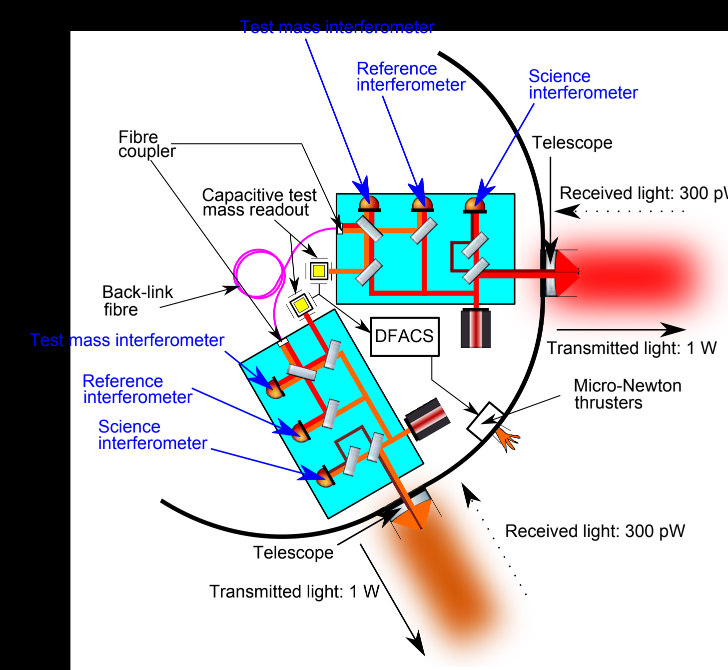




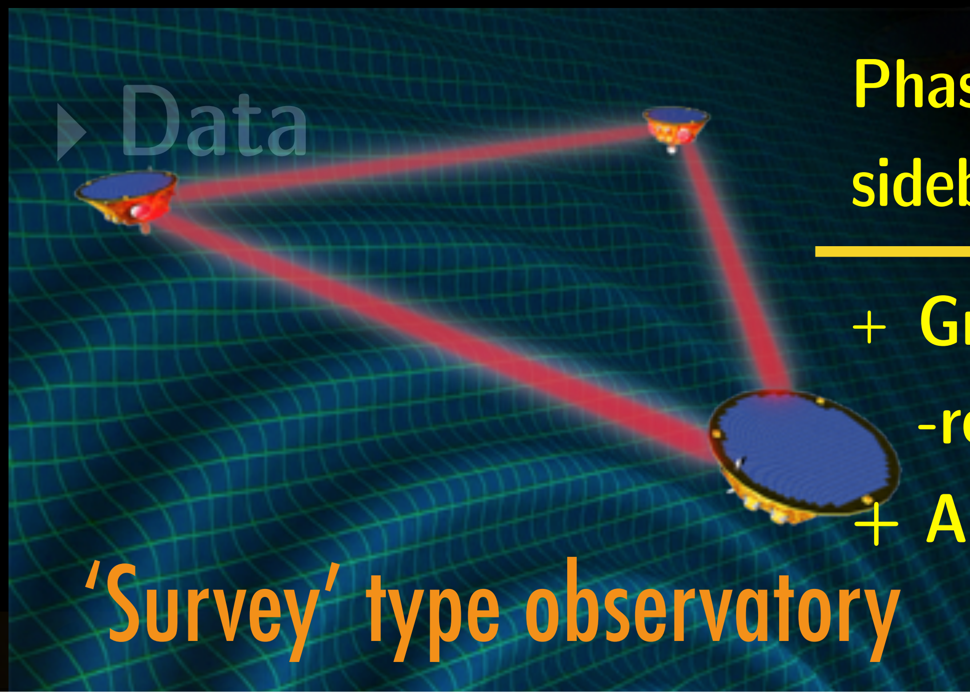
LISA

- Photon flight time measurement between free-floating objects:
  - Reference masses in each spacecraft only sensitive to gravity along measurement axis (follow geodesics)
  - Exchange of laser beam between spacecraft
  - Interferometry at the picometer precision
  - Extracting GW signals in the data





LISA data



Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe-
-rence Sensor

+ Auxiliary channels

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

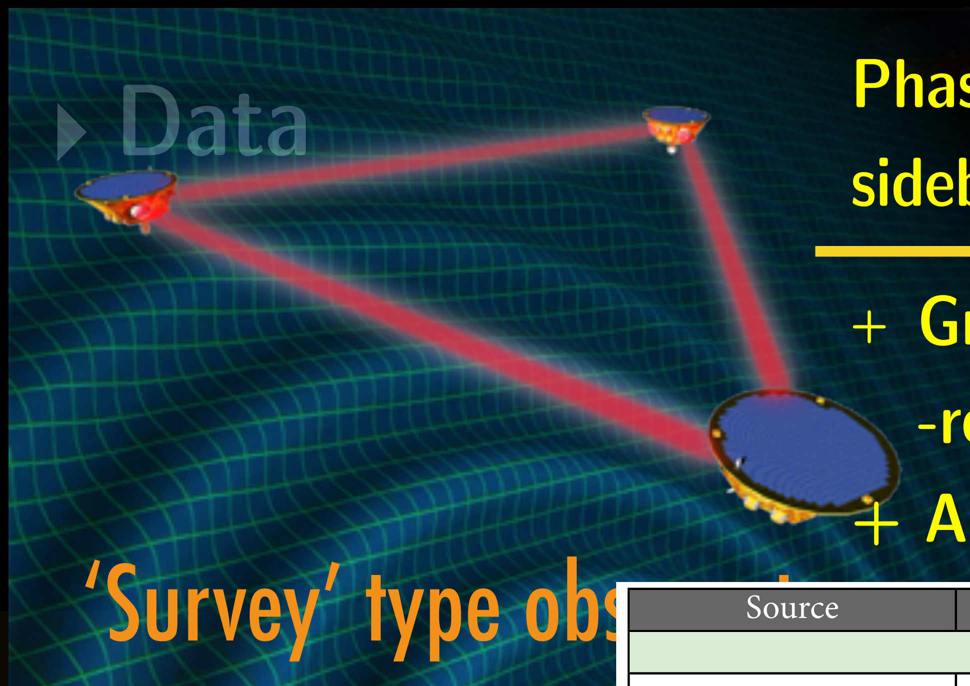
L1 — 2 data channels TDI non-correlated

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 100 mHz

LISA data



Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe--rence Sensor

+ Auxiliary channels

L0

Calibrations corrections

'Survey' type obs

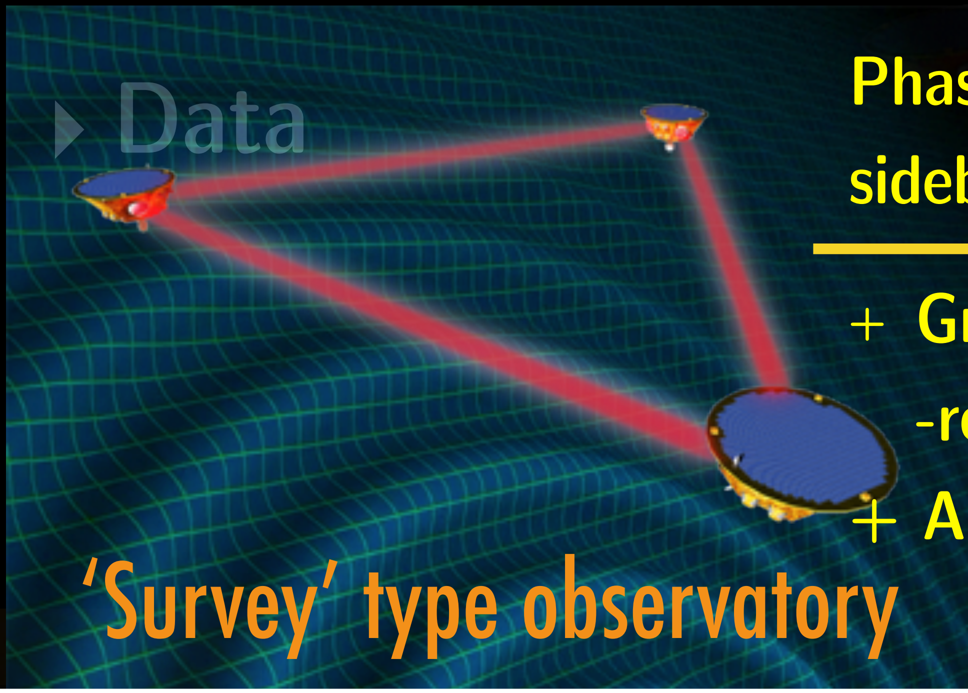
Source	Class	Measurement	Count	Sampling Rate [Hz]	Bits / channel	Rate [bits/s]
Payload						
Phasemeter	IFO Longitudinal	Science IFO	2	3.3	32	213.3
		Test Mass IFO	2	3.3	32	213.3
		Reference IFO	2	3.3	32	213.3
		Clock Sidebands	2	3.3	32	213.3
	IFO Angular	S/C θ,η	4	3.3	32	426.6
		TM θ,η	4	3.3	32	426.6
	Anciliary	Time Semaphores	2	3.3	96	639.9
	Optical Monitoring	PAAM Longitudinal	2	3.3	32	213.3
		PAAM Angular	4	3.3	32	426.6
		Optical Truss	6	3.3	32	639.9
GRS FEE	GRS Cap. Sensing	TM x,y,z	6	3.3	24	480.0
		TM θ,η,ϕ	6	3.3	24	480.0
Payload Computer	DFACS	TM applied torques	6	3.3	24	480.0
		TM applied forces	6	3.3	24	480.0
		S/C applied torques	3	3.3	24	240.0
		S/C applied forces	3	3.3	24	240.0
	Payload HK	e.g. Temperature, Power Monitors *etc.*				2613
	Total Payload					8639
Platform						
	Housekeeping (based on LPF)					1189
	Total Platform					1189
Totals						
	Raw rate per S/C					9828
	Paketisation overhead [10%]					983
	Packaged rate per S/C					10811
	Packaged rate for Constellation					32433

Gravitational w

emitting betwee

and 100

LISA data



'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor

+ Auxiliary channels

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

L1

2 data channels TDI non-correlated

L2

Data Analysis of GWs

L3

Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 100 mHz

LISA data level

- **Level L0 data**: raw science telemetry and housekeeping data.
- **Level L1 data**: TDI variables, all calibrated science data streams and auxiliary data.
- **Level L2**: intermediate waveform products such as partially regressed observable series (i.e., dataset obtained by progressively deeper subtraction of identified signals).
- **Level L3**: catalogs of identified sources, with faithful representations of posterior parameter distributions.

LISA data volume

- Data volume to be stored:
  - Level L0: about 300 Mo per day
  - Level L1: about 600 Mo per day
  - Sub-product of the analysis: fews Go per day
  - Level L2 and L3: about 6 Go per day

=> Storages and archives are not problematic

- Complexity for the DPC is mainly in data analysis because the goal is to extract the parameters for a maximum number of sources.

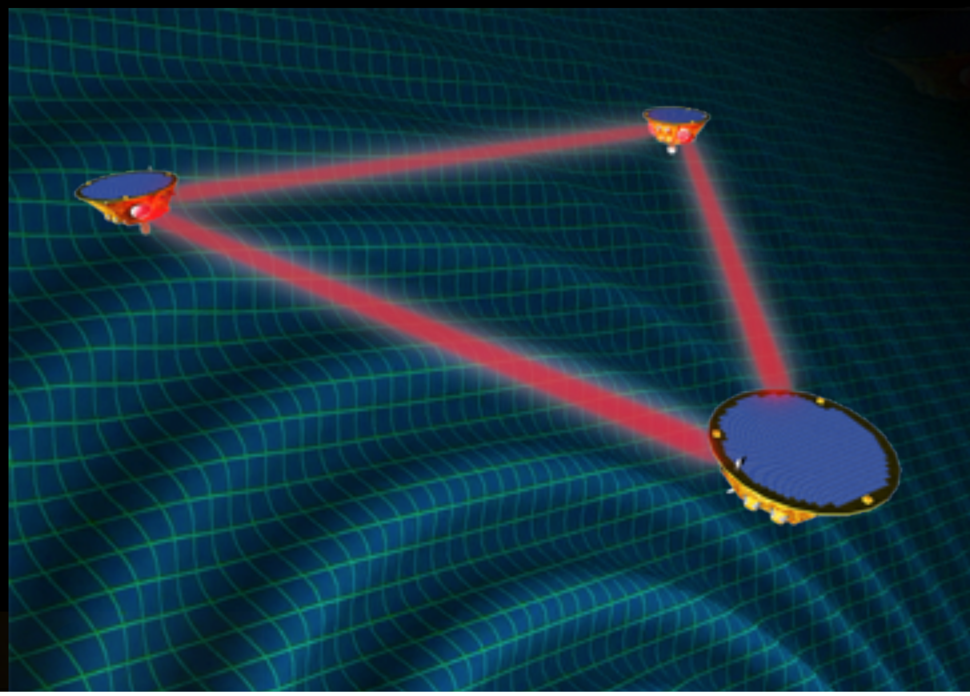
Particularities LISA data

- **First** data of this kind
  - Discovery mission; no previous expertise on this kind of data
- Event rate is **uncertain**
  - Depending on the type of sources but typically from few tens to few thousands per year
- Potential **unknown** sources
- **Transient** sources + continuous sources

=> Constrains on data processing:

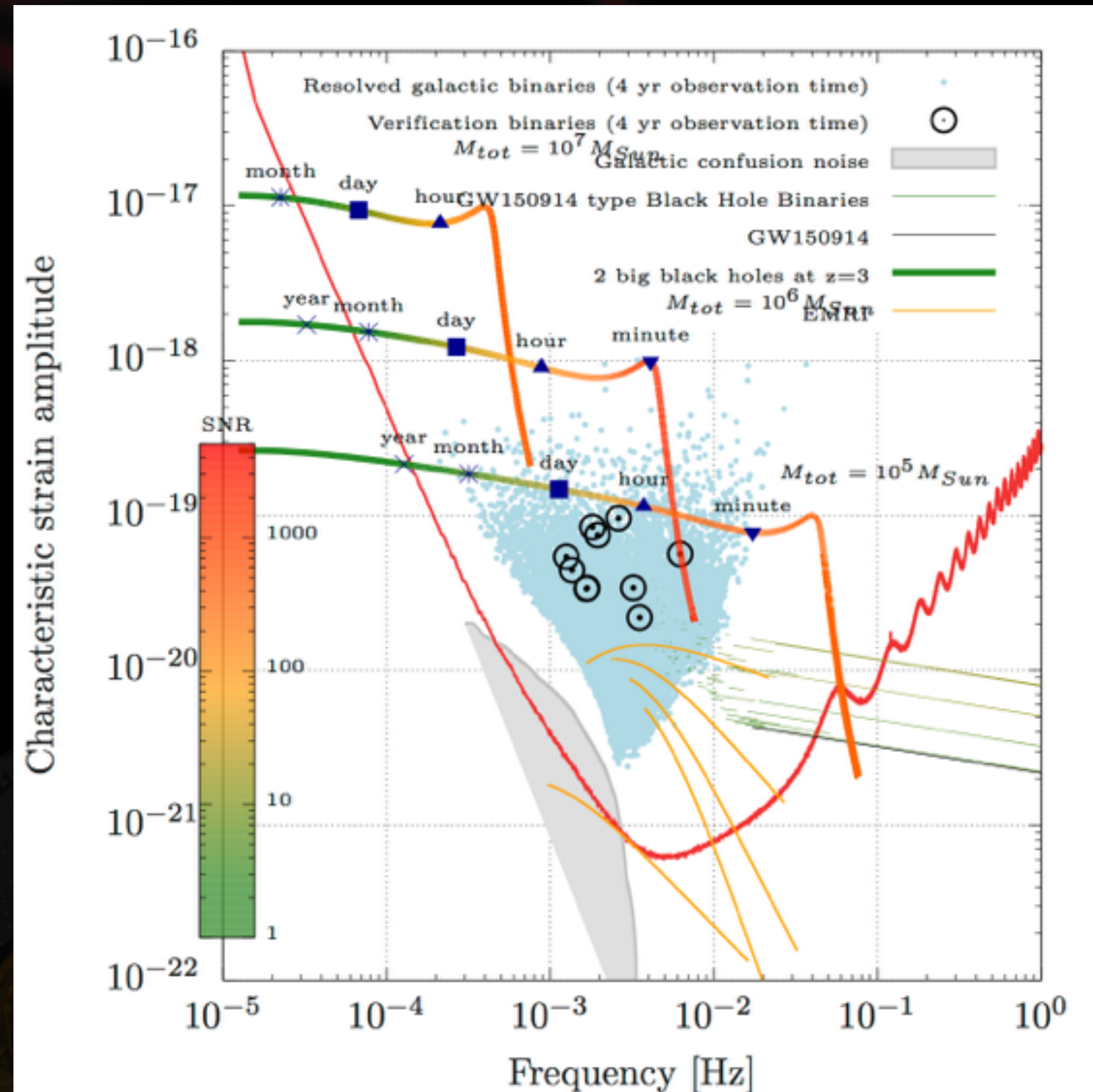
- **Large fluctuation** of computation needs
- **Continuous evolution** of the pipelines

LISA data



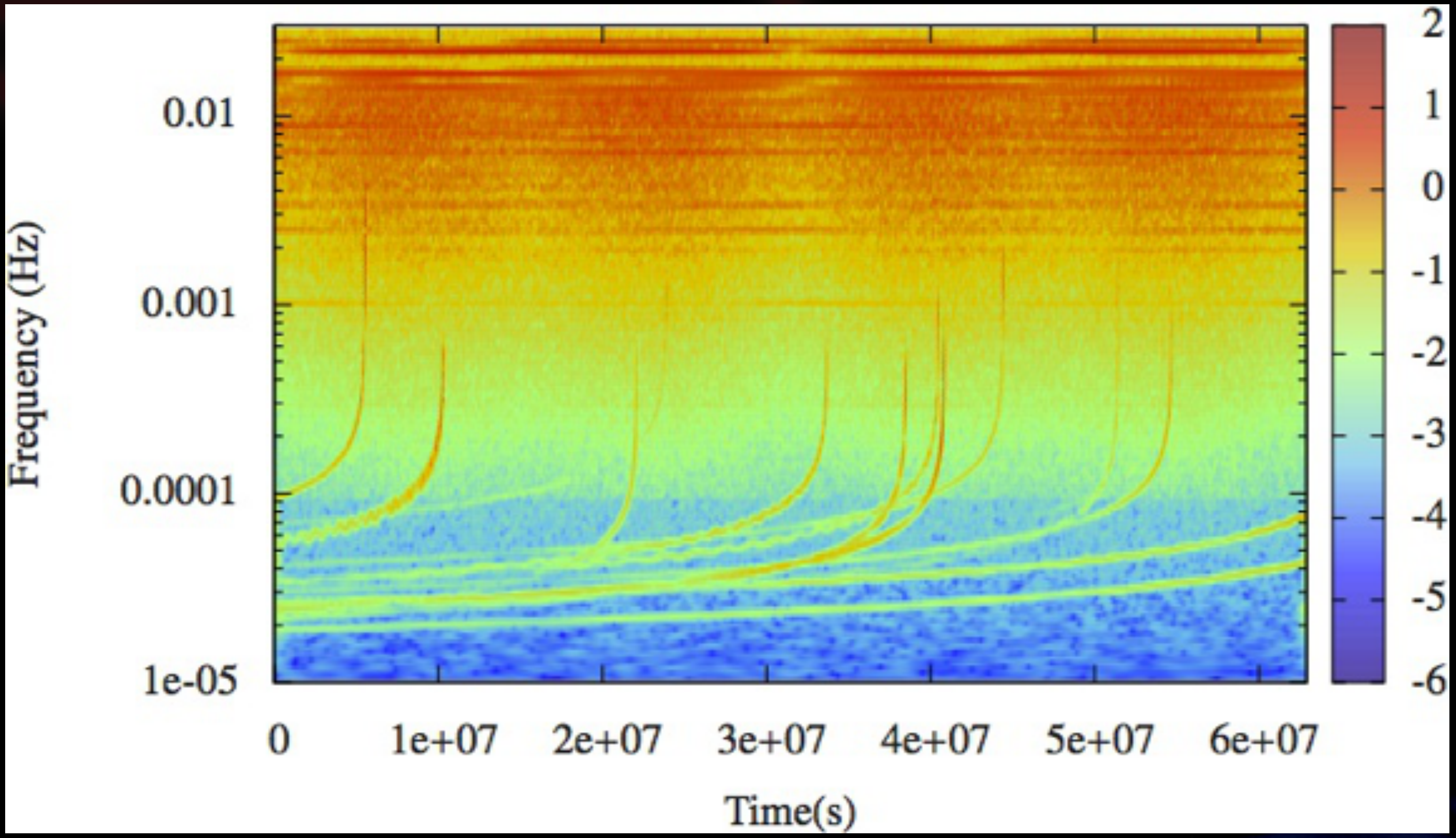
GW sources

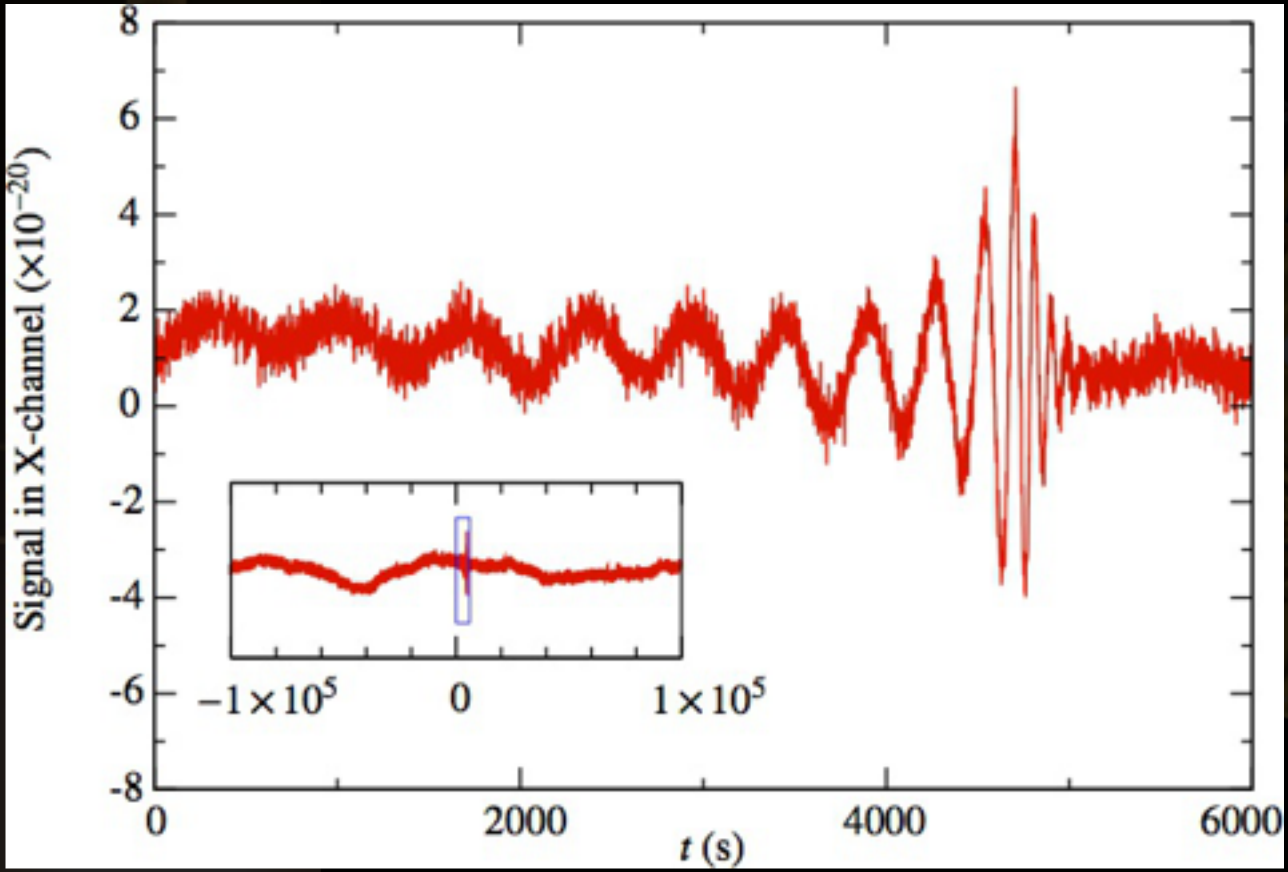
- 6 x10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources

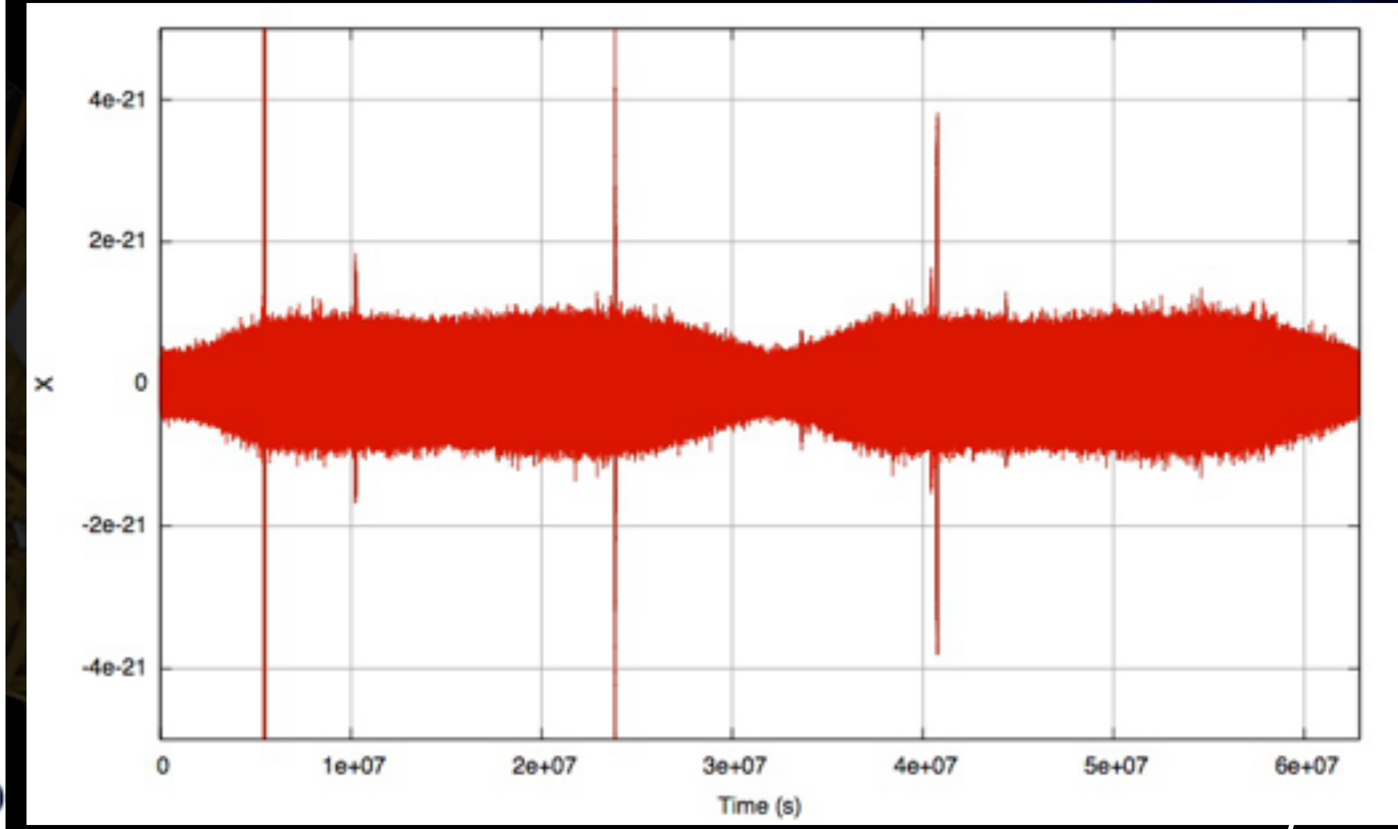


GWs in LISA data

- Example of simulated data (LISACode):
  - about 100 SMBHs,
  - Galactic binaries



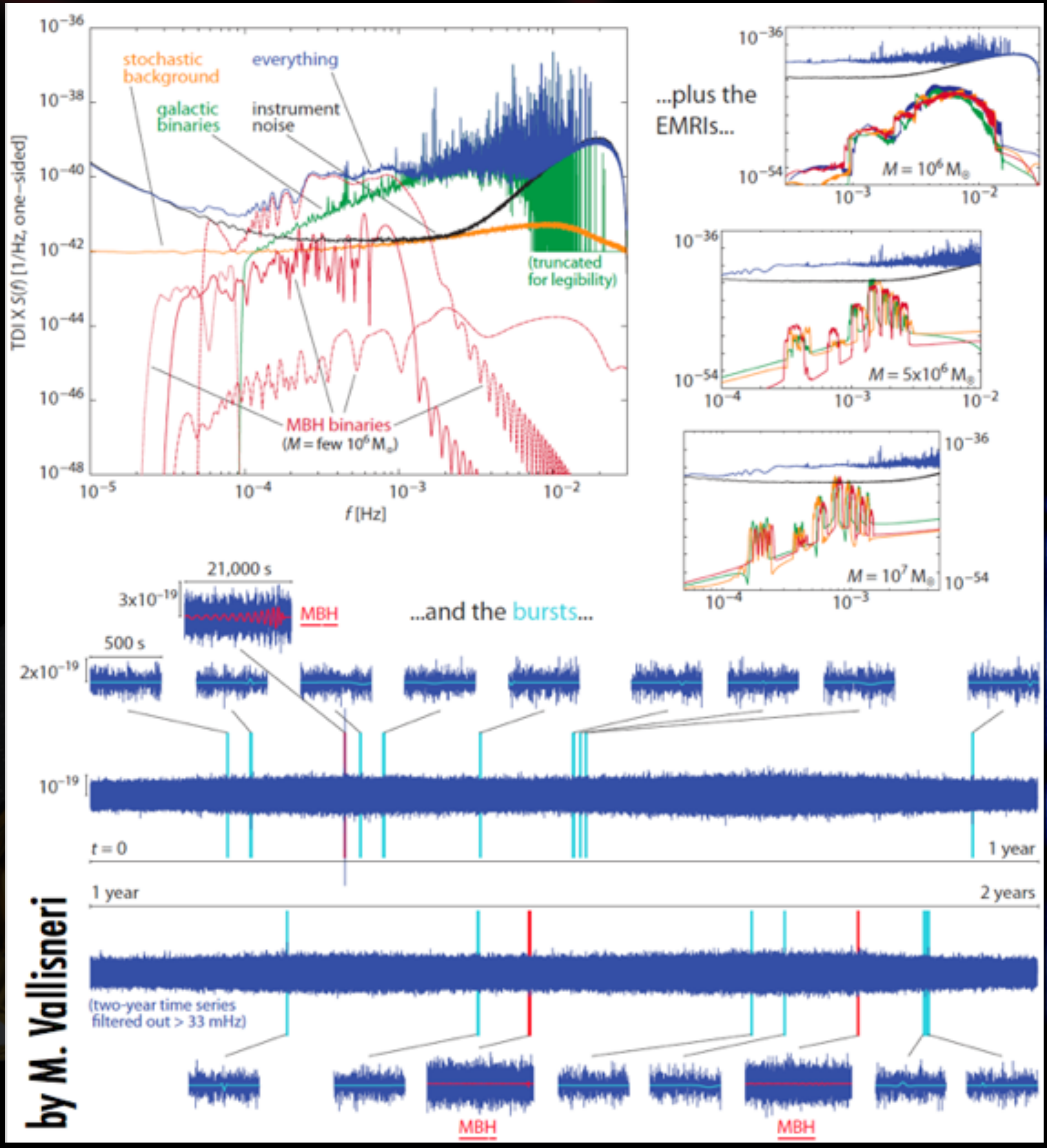




LISA Data Challenges

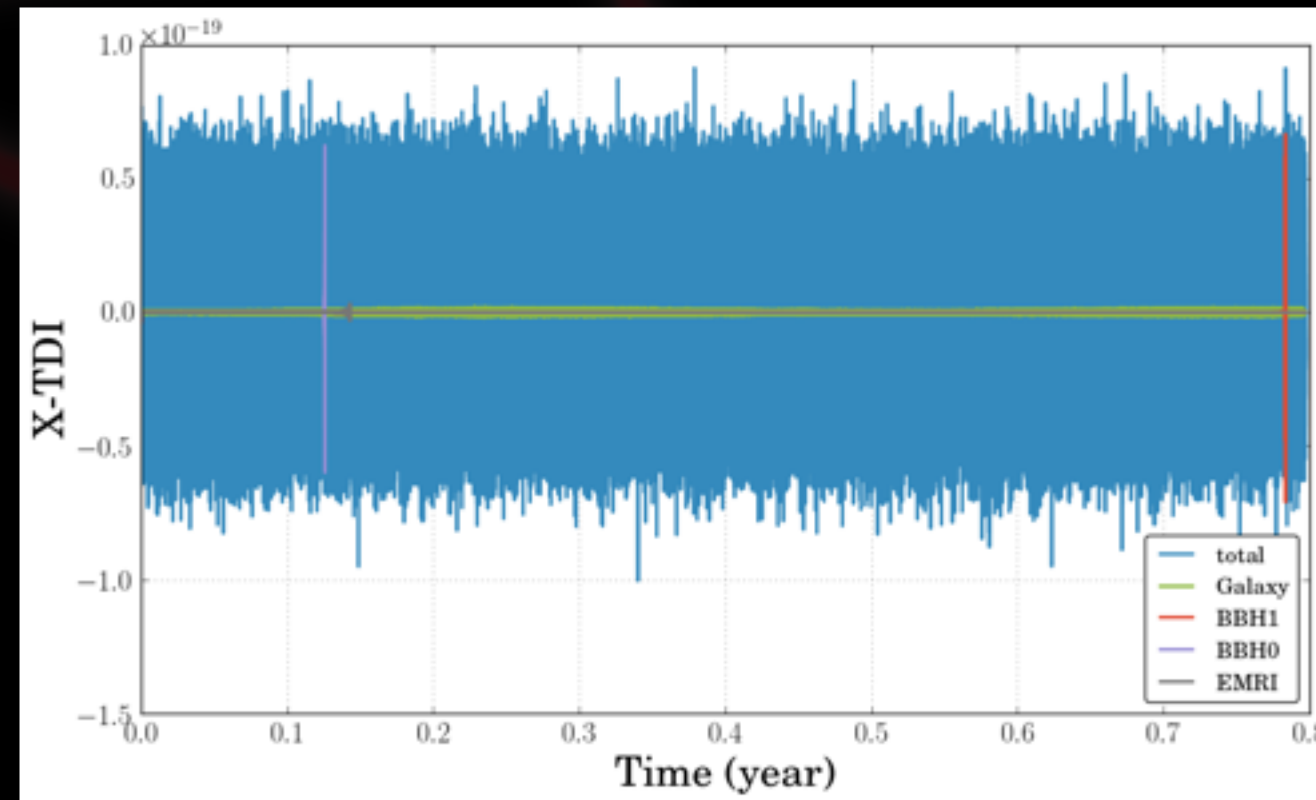
- Mock LDC: 2005→2011
- Data: few sources + simplified noises
- Challenges of increasing complexities
- Goals of the MLDC:
  - Check the feasibility of LISA data analysis
  - Develop data analysis
- now (2017): start of the LDC

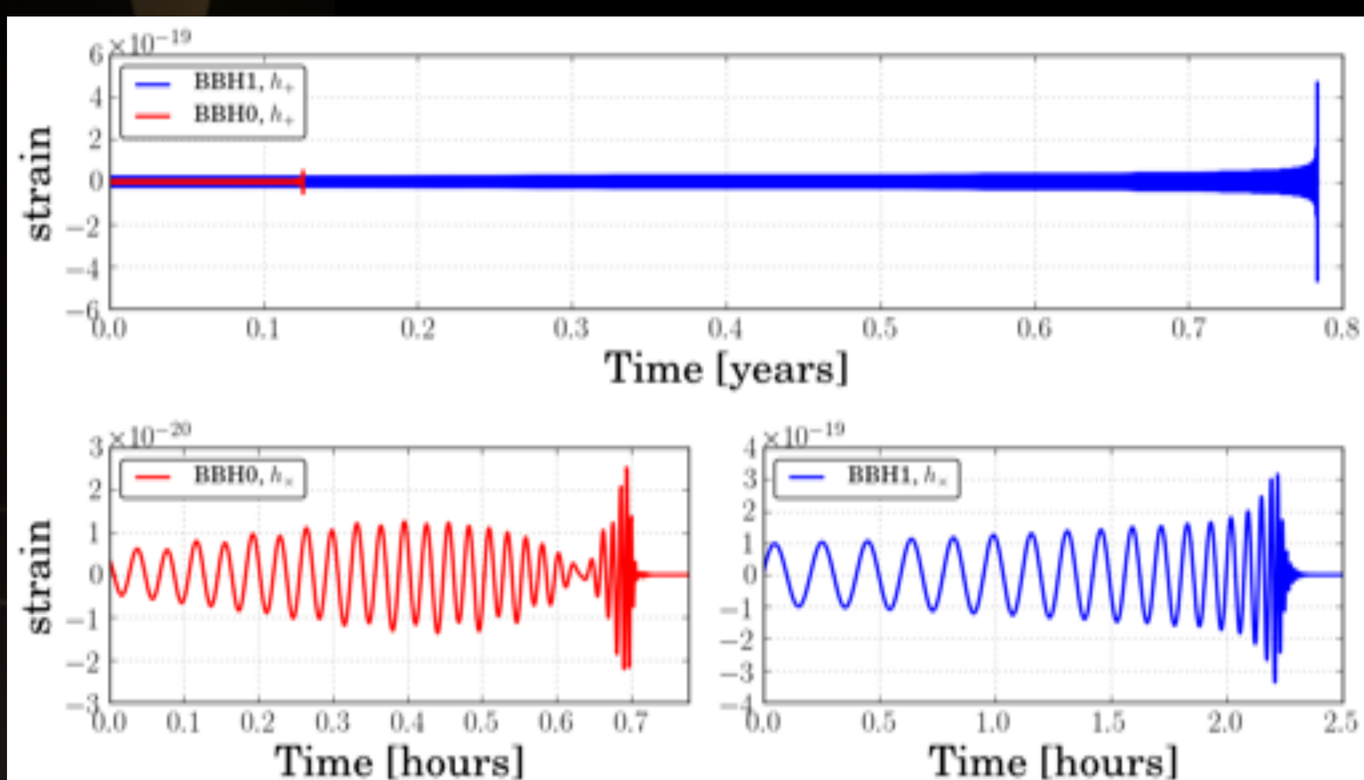
MLDC 4

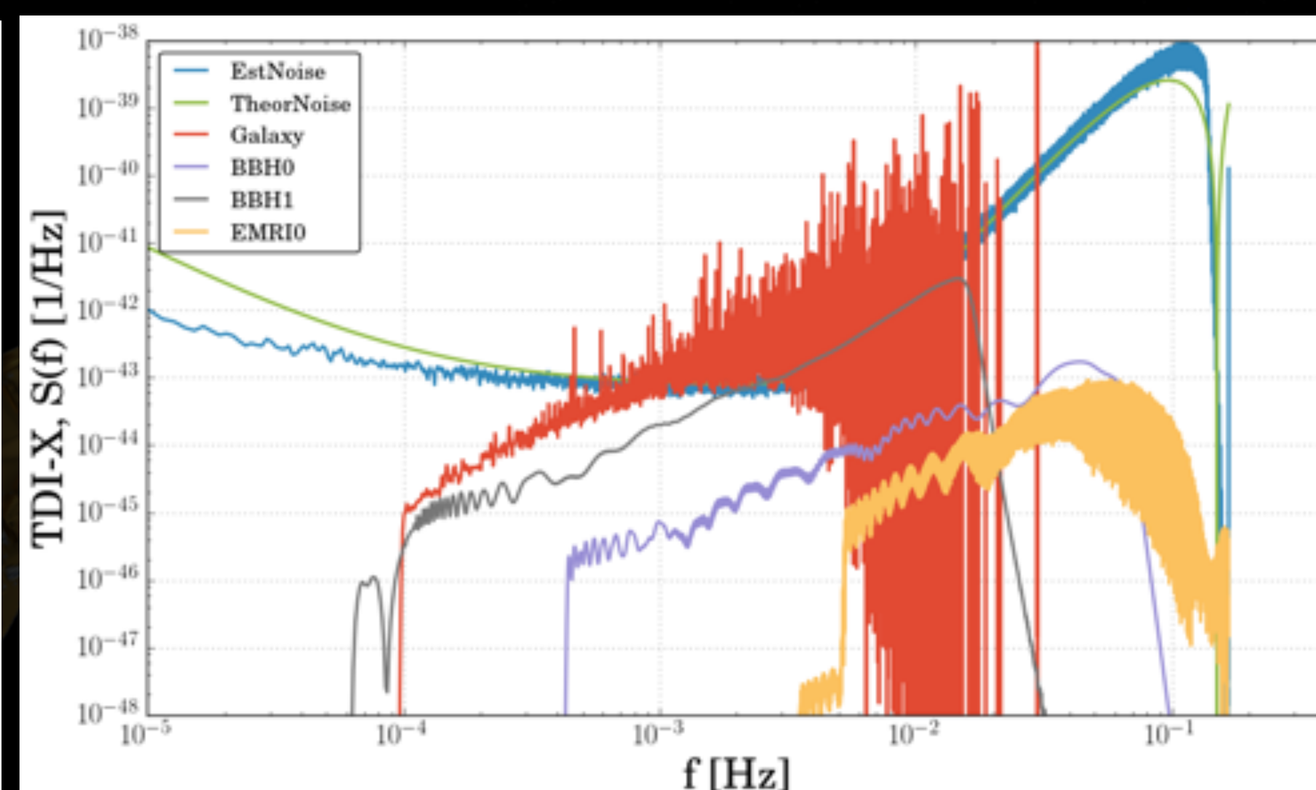


LISA Data Challenges

- 2017: start of the LDC
- Additional goal:
  - Design the pipelines of the mission
- Example of the potential data for LDC1 (from S. Babak)



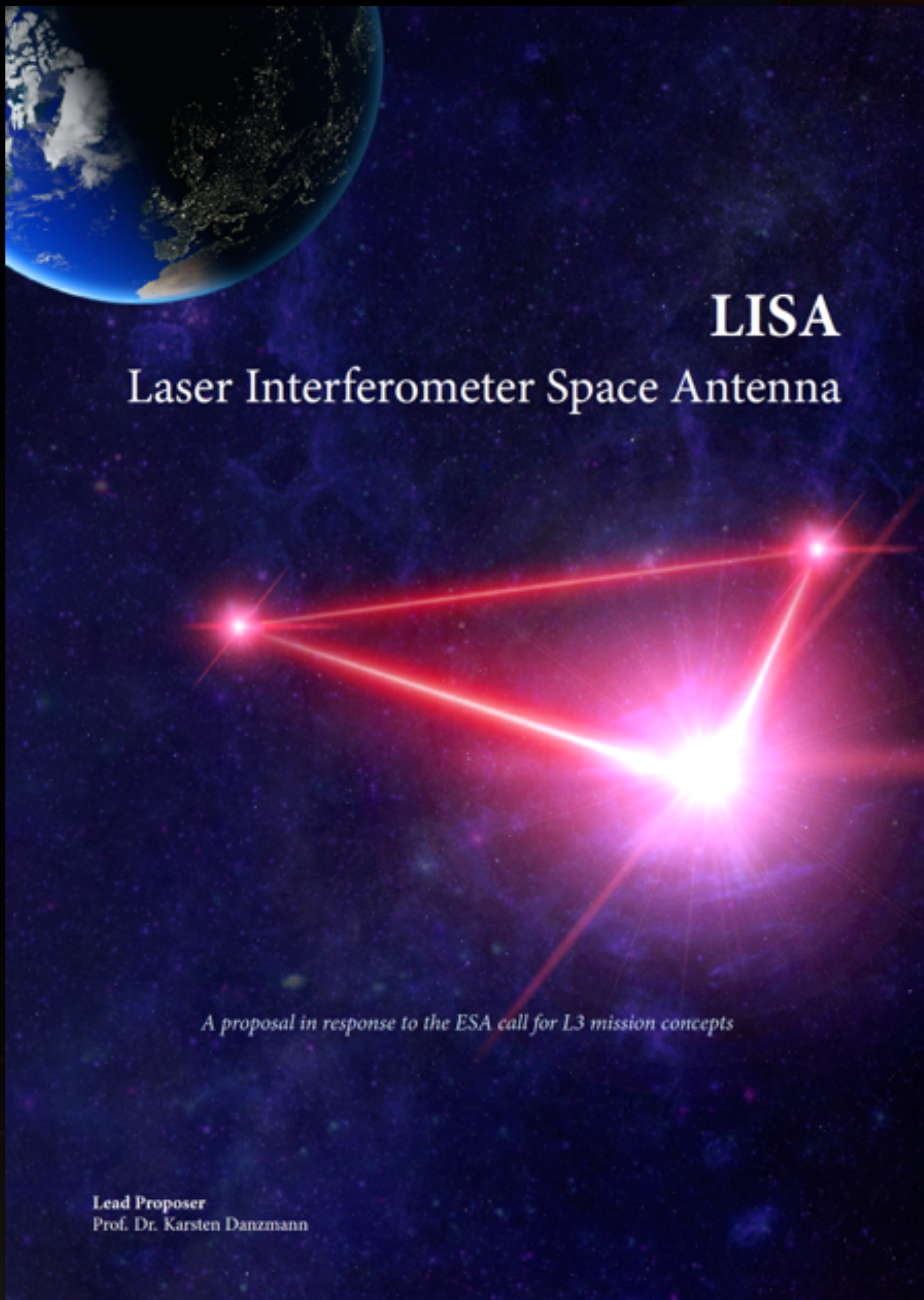




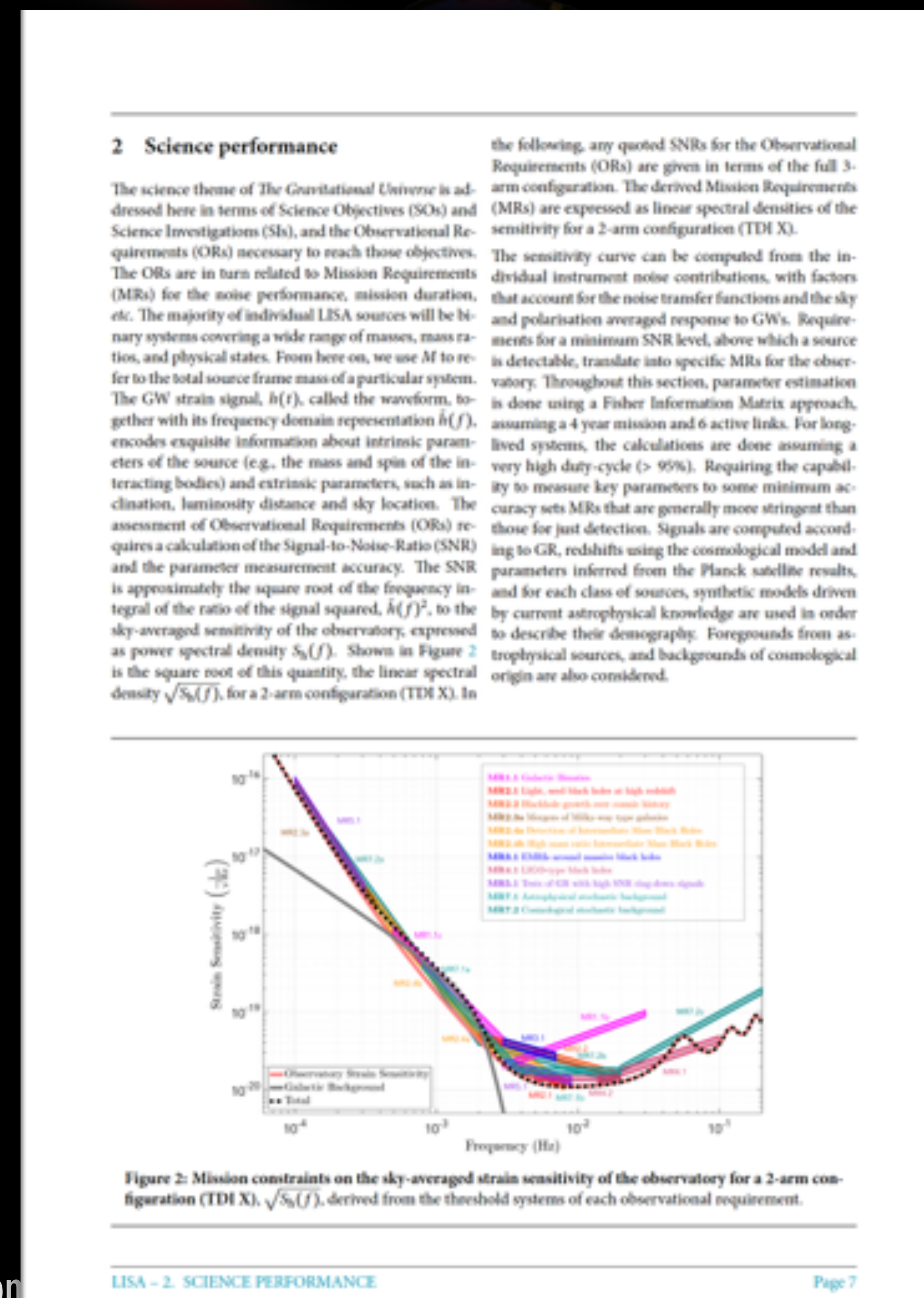
LISA at ESA

- 25/10/2016 : Call for mission
- 13/01/2017 : submission of «LISA proposal» (LISA consortium)
- 8/3/2017 : Phase 0 mission (CDF 8/3/17 → 5/5/17)
- 20/06/2017 : LISA mission approved by SPC
- 8/3/2017 : Phase 0 payload (CDF June → November 2017)
- 2018→2020 : competitive phase A : 2 companies compete
- 2020→2021 : B1: start industrial implementation
- 2021-2022 : mission adoption
- During about 8.5 years : construction
- 2030-2034 : launch Ariane 6.4
- 1.5 years for transfert
- 4 years of nominal mission ⇒ GW observations !
- Possible extension to 10 years

« The LISA Proposal »



https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf



2 Science performance

The science theme of *The Gravitational Universe* is addressed here in terms of Science Objectives (SOs) and Science Investigations (SIs), and the Observational Requirements (ORs) necessary to reach those objectives. The ORs are in turn related to Mission Requirements (MRs) for the noise performance, mission duration, *etc.* The majority of individual LISA sources will be binary systems covering a wide range of masses, mass ratios, and physical states. From here on, we use M to refer to the total source frame mass of a particular system. The GW strain signal, $h(t)$, called the waveform, together with its frequency domain representation $\tilde{h}(f)$, encodes exquisite information about intrinsic parameters of the source (e.g., the mass and spin of the interacting bodies) and extrinsic parameters, such as inclination, luminosity distance and sky location. The assessment of Observational Requirements (ORs) requires a calculation of the Signal-to-Noise-Ratio (SNR) and the parameter measurement accuracy. The SNR is approximately the square root of the frequency integral of the ratio of the signal squared, $\tilde{h}(f)^2$, to the sky-averaged sensitivity of the observatory, expressed as power spectral density $S_h(f)$. Shown in Figure 2 is the square root of this quantity, the linear spectral density $\sqrt{S_h(f)}$, for a 2-arm configuration (TDI X). In the following, any quoted SNRs for the Observational Requirements (ORs) are given in terms of the full 3-arm configuration. The derived Mission Requirements (MRs) are expressed as linear spectral densities of the sensitivity for a 2-arm configuration (TDI X).

The sensitivity curve can be computed from the individual instrument noise contributions, with factors that account for the noise transfer functions and the sky and polarisation averaged response to GWs. Requirements for a minimum SNR level, above which a source is detectable, translate into specific MRs for the observatory. Throughout this section, parameter estimation is done using a Fisher Information Matrix approach, assuming a 4 year mission and 6 active links. For long-lived systems, the calculations are done assuming a very high duty-cycle (> 95%). Requiring the capability to measure key parameters to some minimum accuracy sets MRs that are generally more stringent than those for just detection. Signals are computed according to GR, redshifts using the cosmological model and parameters inferred from the Planck satellite results, and for each class of sources, synthetic models driven by current astrophysical knowledge are used in order to describe their demography. Foregrounds from astrophysical sources, and backgrounds of cosmological origin are also considered.

Strain Sensitivity
Frequency (Hz)

Figure 2: Mission constraints on the sky-averaged strain sensitivity of the observatory for a 2-arm configuration (TDI X), $\sqrt{S_h(f)}$, derived from the threshold systems of each observational requirement.

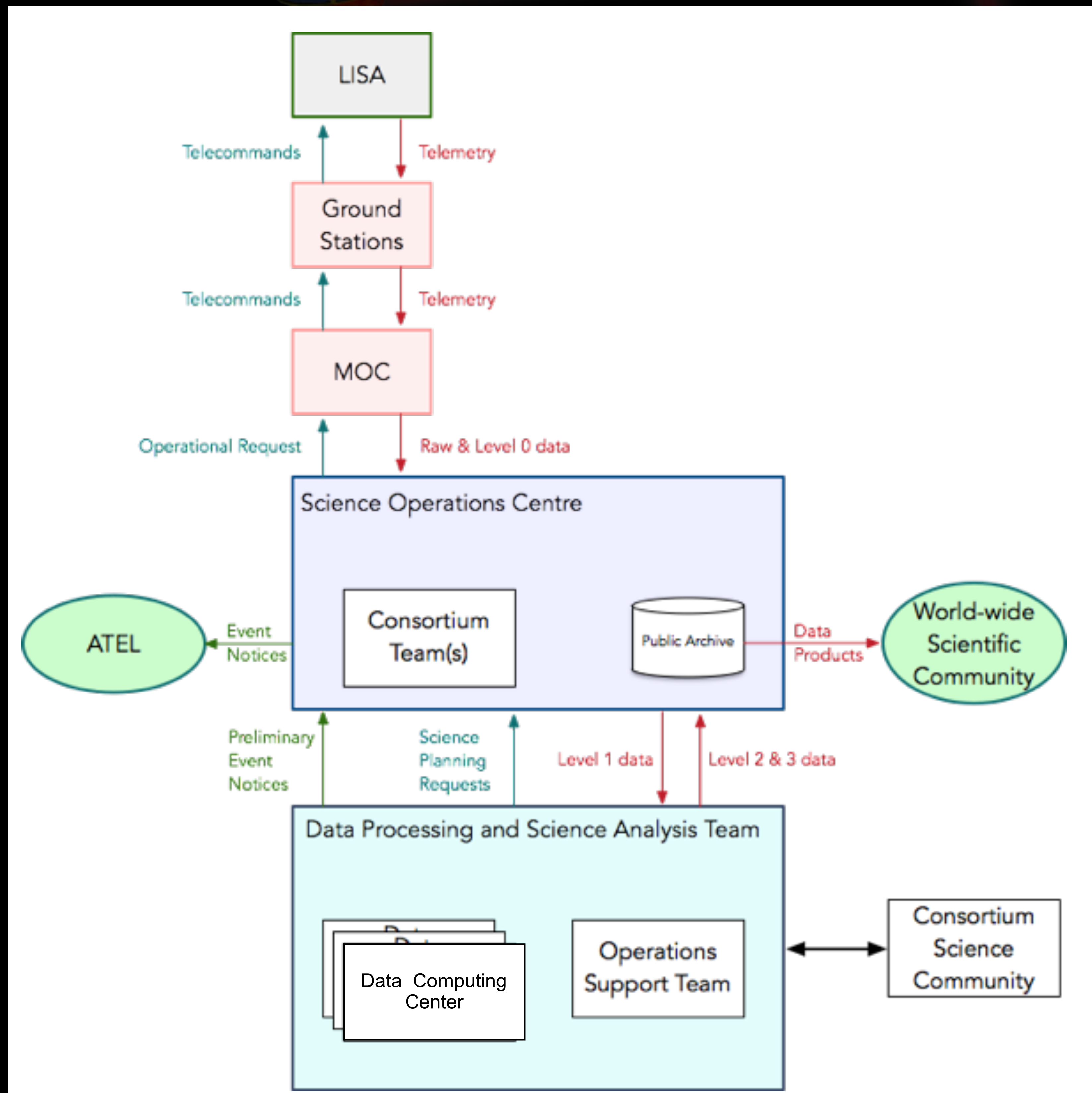
LISA – 2. SCIENCE PERFORMANCE Page 7

DPC in LISA proposal

section 6: science operations and archiving

- Activities of scientific operations, data processing, dissemination and archives share between:
  - The Science Operation Center (SOC): ESA + Consortium
  - The unique Consortium DPC:
    - « Direct and supervise data analysis and processing activities »
    - Organise Data Computing Centers (DCCs): member states, ESA and/or NASA)
- SOC:
  - Operations: science planning (update config., calibrations, ...)
  - Pre-processing: ingestion of L0 data from MOC, calibration, monitoring, quicklook and production of L1 data

GS in LISA proposal

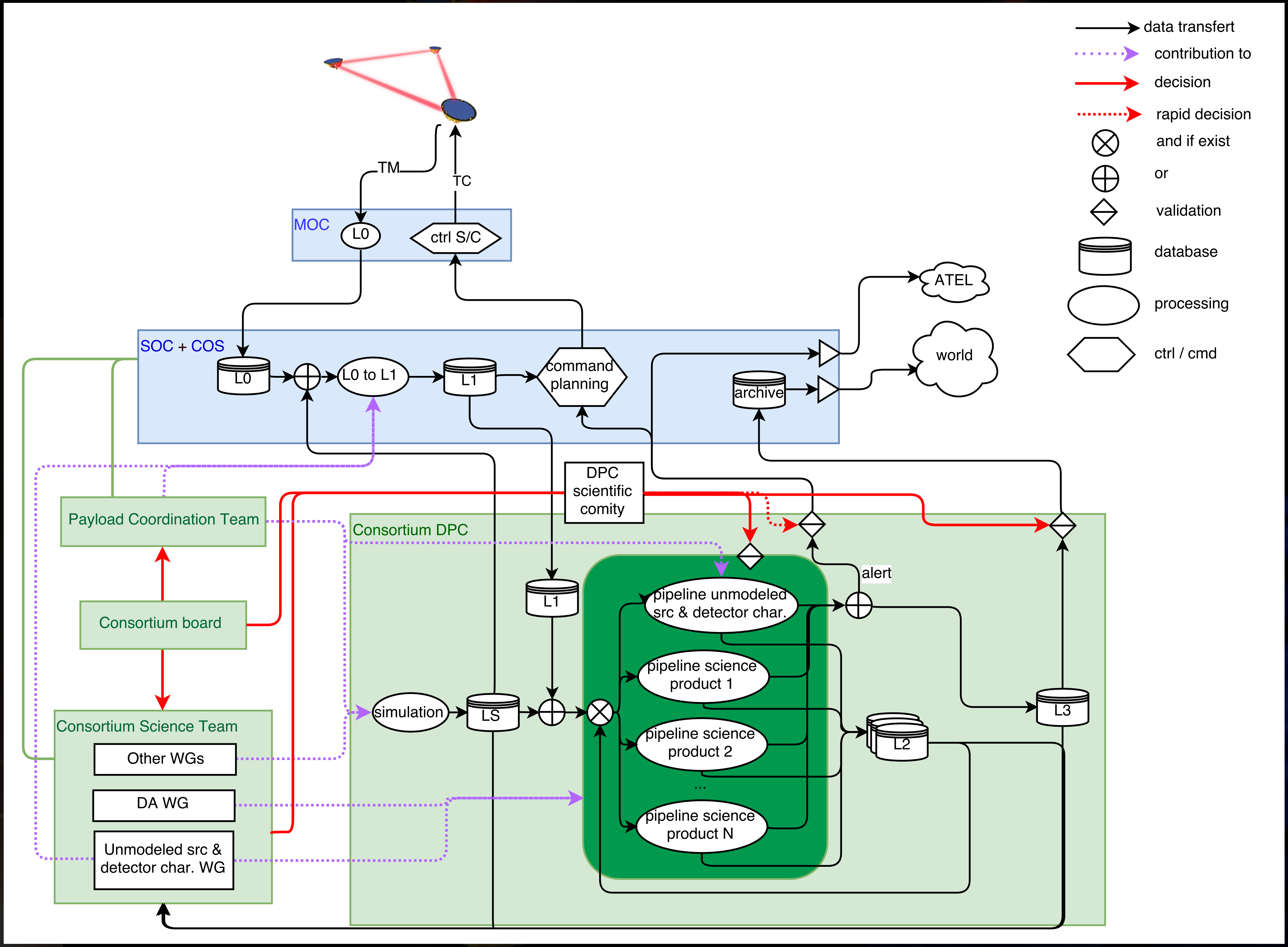


DPC in LISA proposal

section 6: science operations and archiving

- DPC activities:
  - Receive L1 data from the SOC;
  - Identify and extract waveforms;
  - Build the catalogs of sources;
  - Create L2 et L3 science products;
  - Analyse the quality of science data products;
  - Distribute data to SOC and to the scientific community of the Consortium
  - Produce periodic releases of science data products
  - Generate alerts for upcoming transients, such as mergers

LISA Ground Segment



Current vision of the DPC

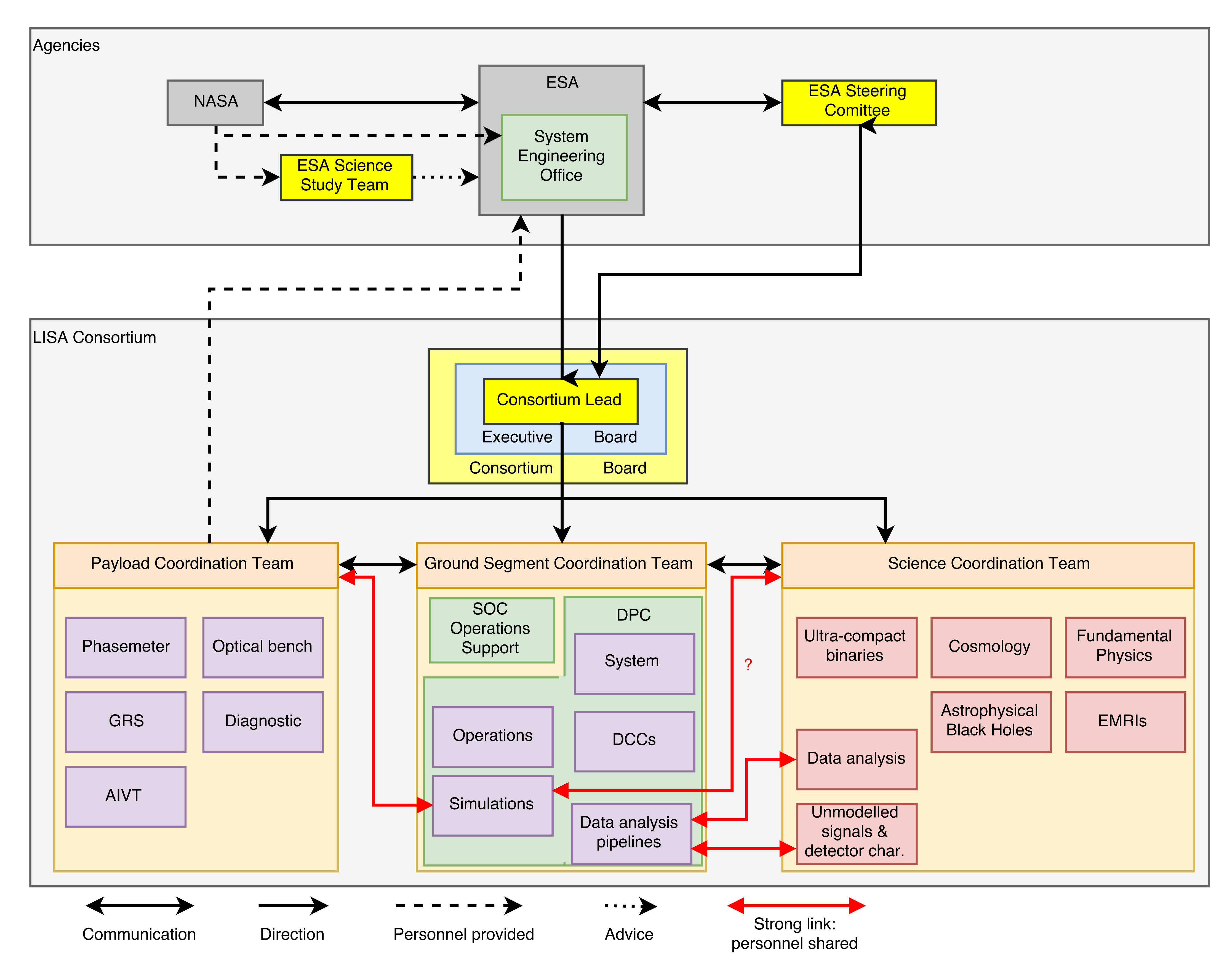
- DPC: unique entity responsable for the data processing (driving, integration of software block, ...)
- DPC in charge of delivering L2 & L3 products + what's necessary to reproduce/refine the analysis (i.e. input data + software + its running environment + some CPU to run it).
- Data Computing Centres (DCC): hardware, computer rooms (computing and storage) taking part to the data processing activities.
- The DPC software « suite » can run on any DCC.
    - Software: codes (DA & Simu.) + services (LDAP, wiki, database) + OS.
- First solutions:
    - Separation of hardware and software: ligth virtualization, ...
    - Collaborative development: continuous integration, ...
    - Fluctuations of computing load: hybrids cluster/cloud

(see next talks by Laurence and Maude)

History & status

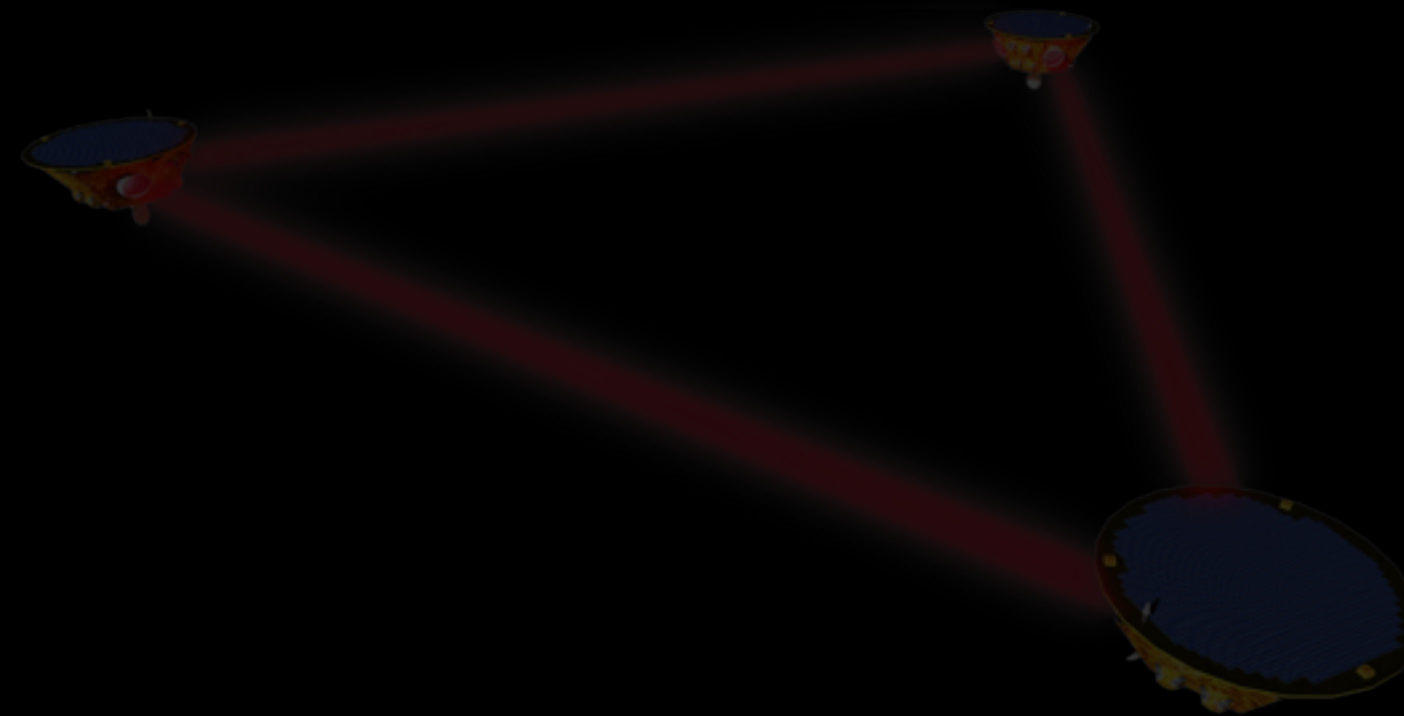
- Previous studies:
  - Before 2011, LISA yellow books
  - eLISA/NGO yellow book
  - 2014: CNES Phase 0 for eLISA/NGO
- 2015: Start of the proto-DPC
- 2017: Proposal LISA
- 2017: DPC kickoff meeting
- In progress:
  - DPC Definition Document
  - Definition of the LISA Ground Segment with ESA

Consortium organisation



Conclusion

- First mission of this kind => some uncertainties (number of sources, data quality, unknown sources ...) => flexibility + continuous evolution + computation load fluctuations
- Existing expertises (MLDCs, LPF, other missions)
- LISA DPC in the LISA proposal
  - Extract gravitational wave sources from TDI data (L1) to produce catalogs and waveform (L2 & L3)
- Our vision of the DPC at the moment (see next talks):
  - French responsibility but collaboration with other partners
  - Continuous integration, virtualization, hybrid computing
  - DA methods and pipeline design by the scientists using the DPC
- Activities started in 2015 in France: development of a proto-DPC



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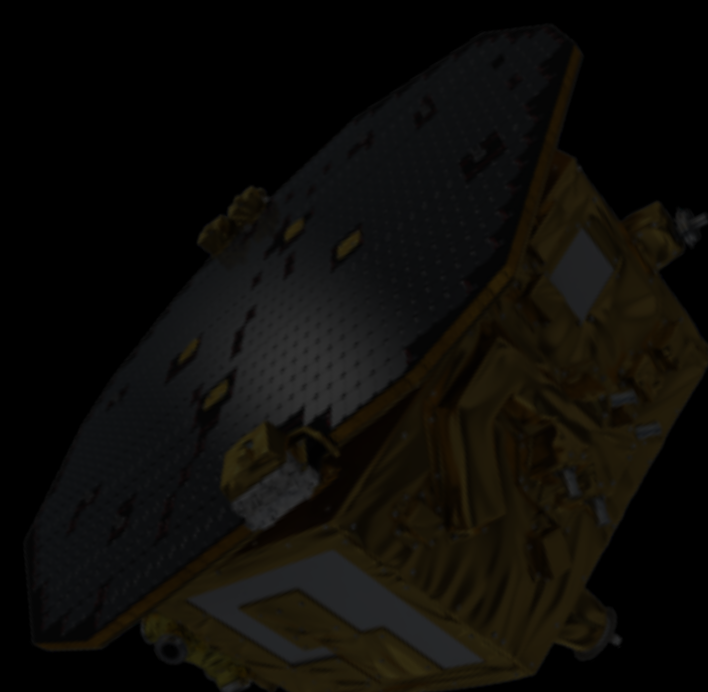
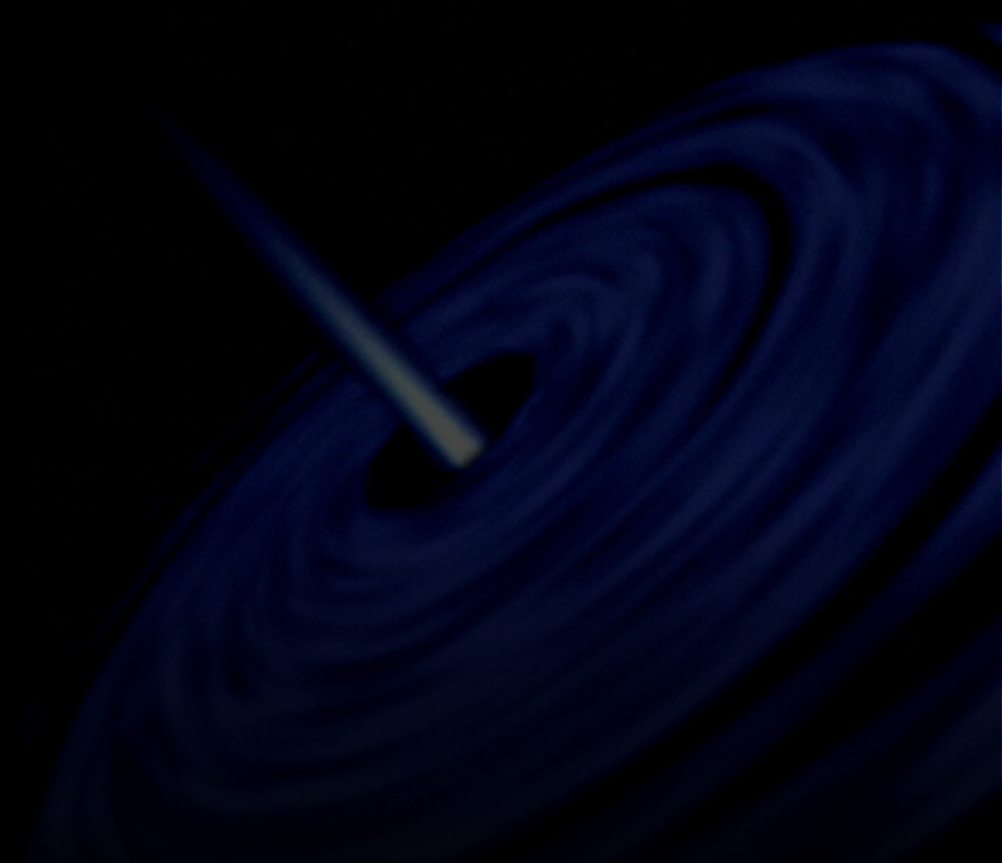
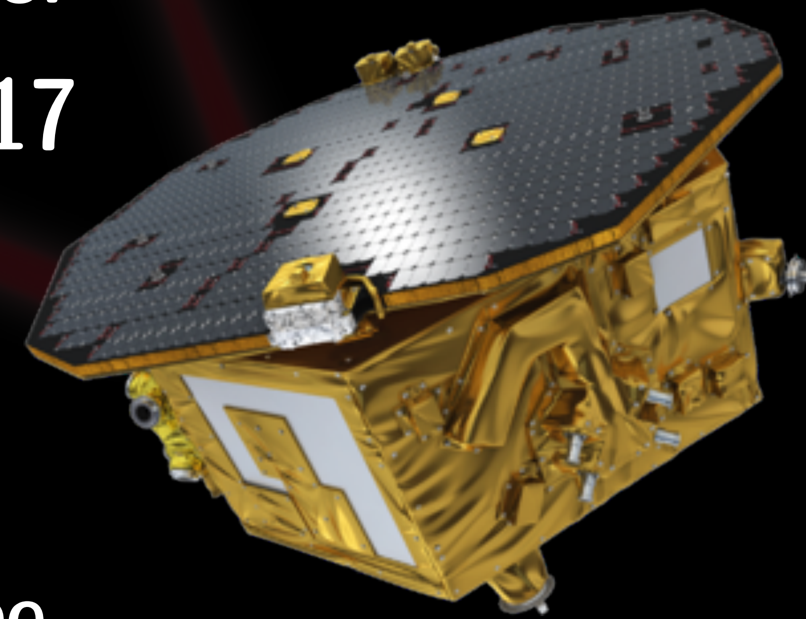


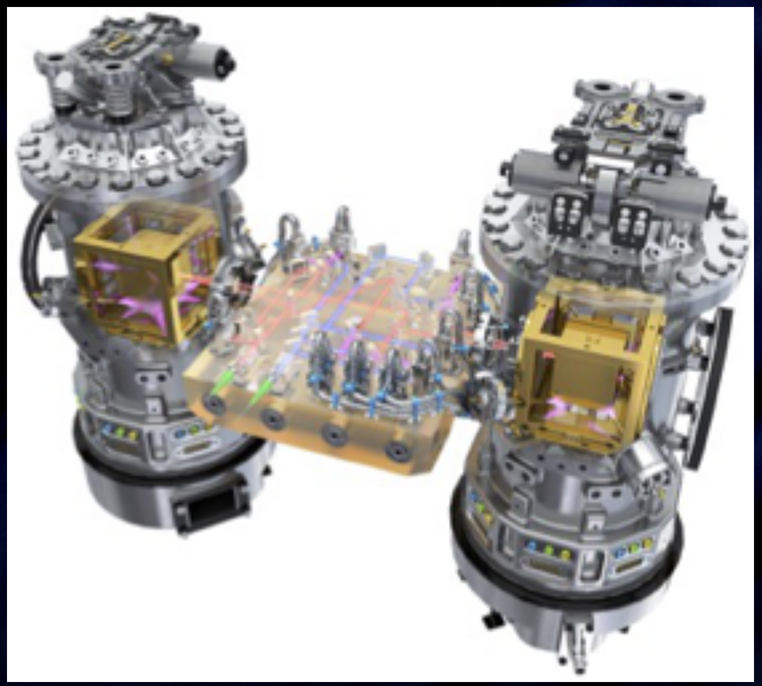


LISAPathfinder

- LISAPathfinder: technological demonstrator operating from March 2016 until June 2017



- Better understanding of noises:
  - Noise sources in particular at low-frequency
  - Coupling effects (temperature, others degree of freedom, ...)



- Data processing for calibrating and correcting the data:
  - remove commanded force, correct cross-talk effect
  - Data analysis toolbox: LTPDA

Others experiments

- Others GW observatories: LIGO/Virgo
  - Similarity in some type of sources (binaries, stochastic background, etc) and some type of noises
  - But difference in SNR, data volumes, available channels, etc

=> some data analysis methods & processing strategies can be updated for LISA

- Space-based observatories: Planck, GAIA, Euclid, …
  - Several examples for ground segment organisation
  - Space qualified data processing for operation
  - Not possible to modify the instrument in space
  - …

DPC in LISA proposal

section 6: science operations and archiving

- Before archiving, high level products of the DPC have to be validated and consolidated by the consortium
- Data Computing Centres (DCCs):
  - essentially hardware
  - at least one DCC in Europe (France) and in US, but probably several in Europe => one of the topic of this meeting!
- «CNES has performed a Phase 0 study on LISA DPC, and will be funding, in collaboration with other participating countries, the development of the Consortium DPC for central coordination of data analysis at all DCCs. »

DPC in LISA proposal

section 6: science operations and archiving

- Transient events processing:
  - Quick notifications by the SOC to the astronomer community
  - DPC should quickly establish the quality of the events:
    - Produce and assess preliminary events notices
    - Provide detailed transient parameters to the science planning team
  - Powerful events: latency of about one day requires at the SOC.
  - Other events: longer latency at SOC+DPC

DPC in LISA proposal

section 6: science operations and archiving

- Developments needed on data analysis:
  - detection multiple signals overlapping and parameter estimations => challenge
  - Number of previous studies with MLDCs
  - « Although some data processing and waveform generation details remain, the data analysis is considered to be tractable »
  - Restart MLDC in the futur

=> DPC can have a role in these activities in coordination with the scientists defining the waveform and pipeline (Data Analysis WG, ...). In fine, we would to run MLDCs within the DPC.

DPC in LISA proposal

section 8: management

- <u>Ground Segment:</u> Ground Segment element includes all Mission Operations during Low Earth Operations (LEOP), and later during nominal operations and Science Operations under ESA responsibility, that is raw science data pre-processing and calibration, leading to level-1 data (TDI combinations). This task will be performed with support from France, Italy, the United Kingdom, Switzerland, Spain, Germany and the US (algorithm development) and the instrument providers (calibration during operation).

Our (french) vision of the DPC

Our = APC DPC team with CNES (Phase0 + LISA review)

Proposal to be discussed

- Solutions to LISA Data Processing:
  - Keep a maximum flexibility
  - Constant evolution and continuous integration with functional verifications (compilation), tests low and high level and quality checks.
  - Regular reprocessing
  - Hybrid system to absorb large fluctuation of computing load: cluster standard + Cloud(s)

Our (french) vision of the DPC

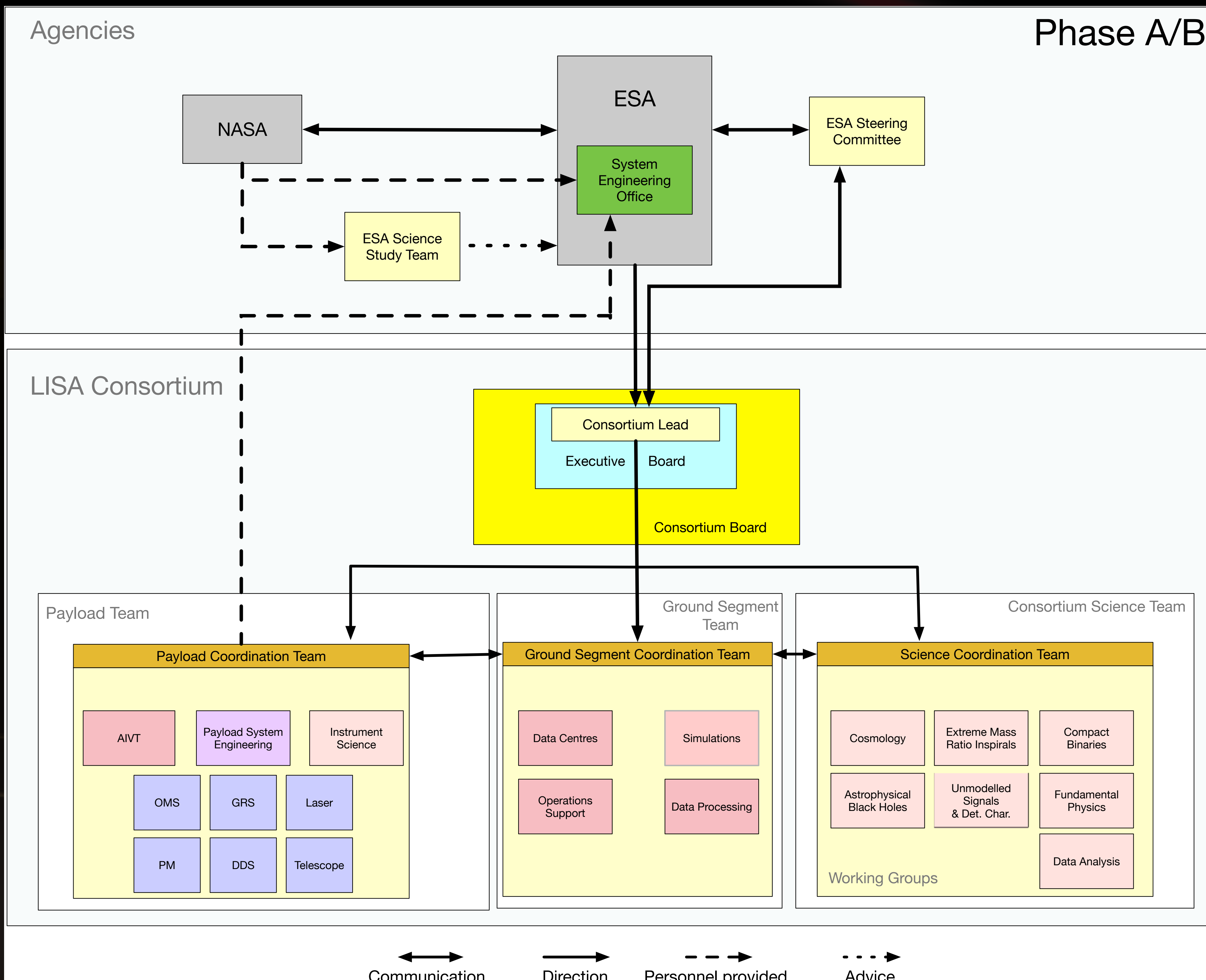
- Main DPC interactions:
  - Consortium Board (decision taking),
  - Ground Segment Coordination Team (integrated ?)
  - Working Groups
- DPC under French responsibility & one of the main DCC in France
- Possible contributions of other partners: National DCC(s) + Contribution to the DPC software
- French coordination of activities distributed between partners in order to guaranteed the completeness of the analysis, the reproducibility and the validation:
  - Need of team management and decision taking

Our (french) vision of the DPC

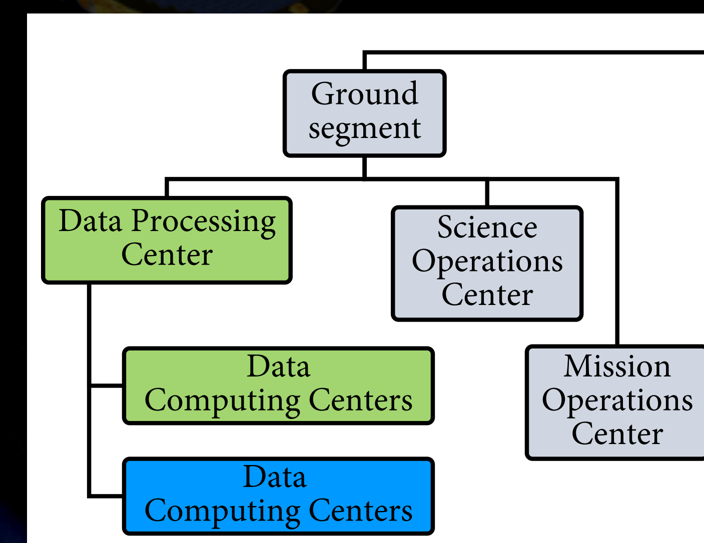
- The DPC is a tools for the consortium
- To avoid reintegration in the pipeline of blocks developed separately (ex: difficult in GAIA), our idea is:
    - to develop with scientists the tools that fulfill their needs,
    - to adapt « DPC tools » (i.e. required tools for having consolidated DA pipelines,) to the scientists,
    - to make scientists and developers used to all these tools and to the way of working with them.
- In 2015, we started at APC with the support of CNES the development of a proto-DPC
    - See talk of Maude Le Jeune

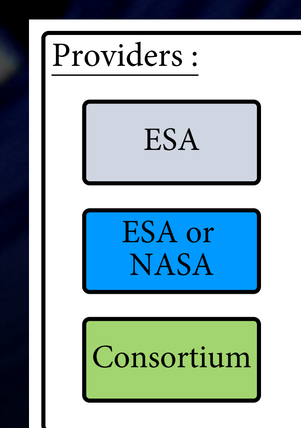
DPC in LISA proposal

section 8: management



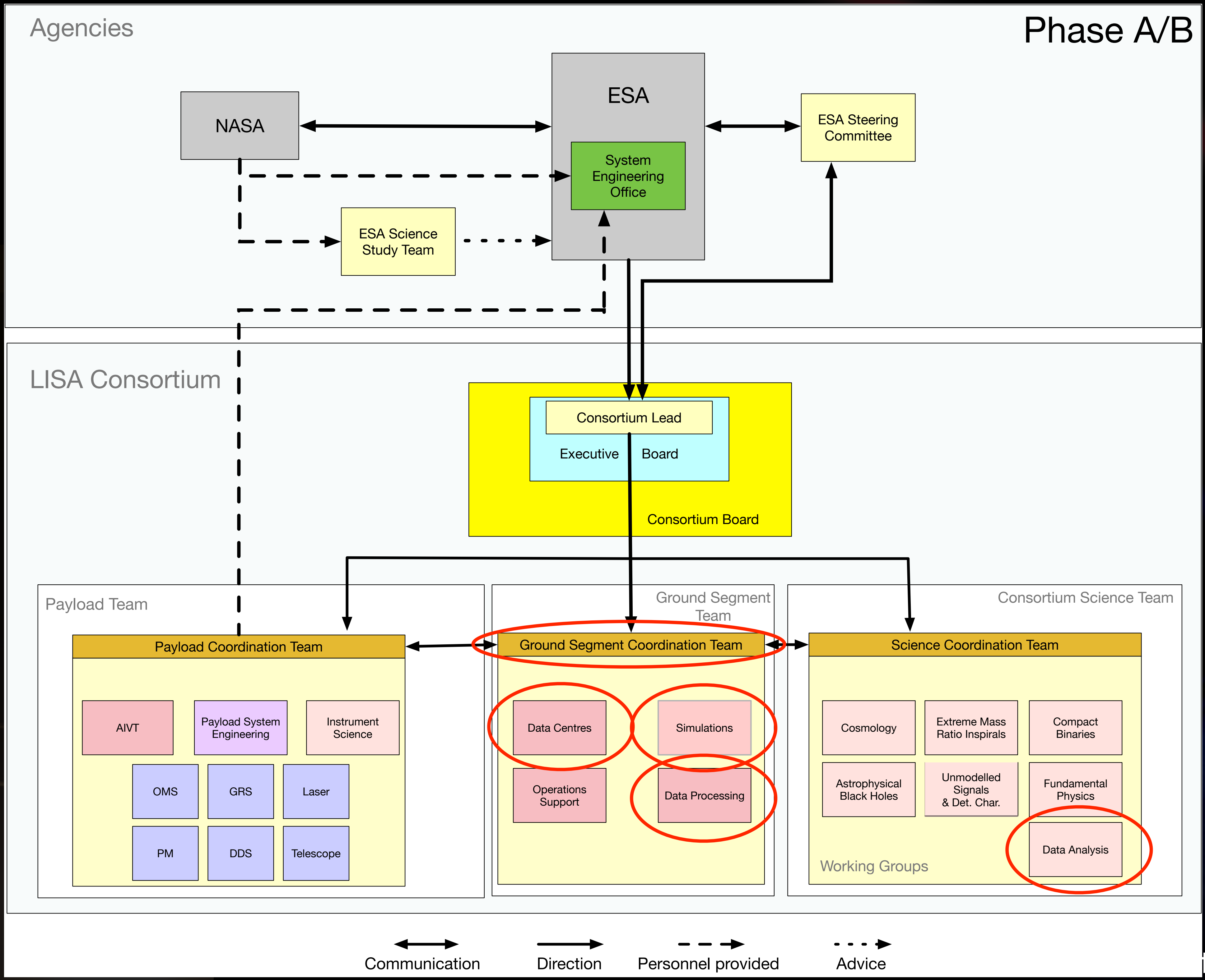
In product tree





DPC in LISA proposal

section 8: management



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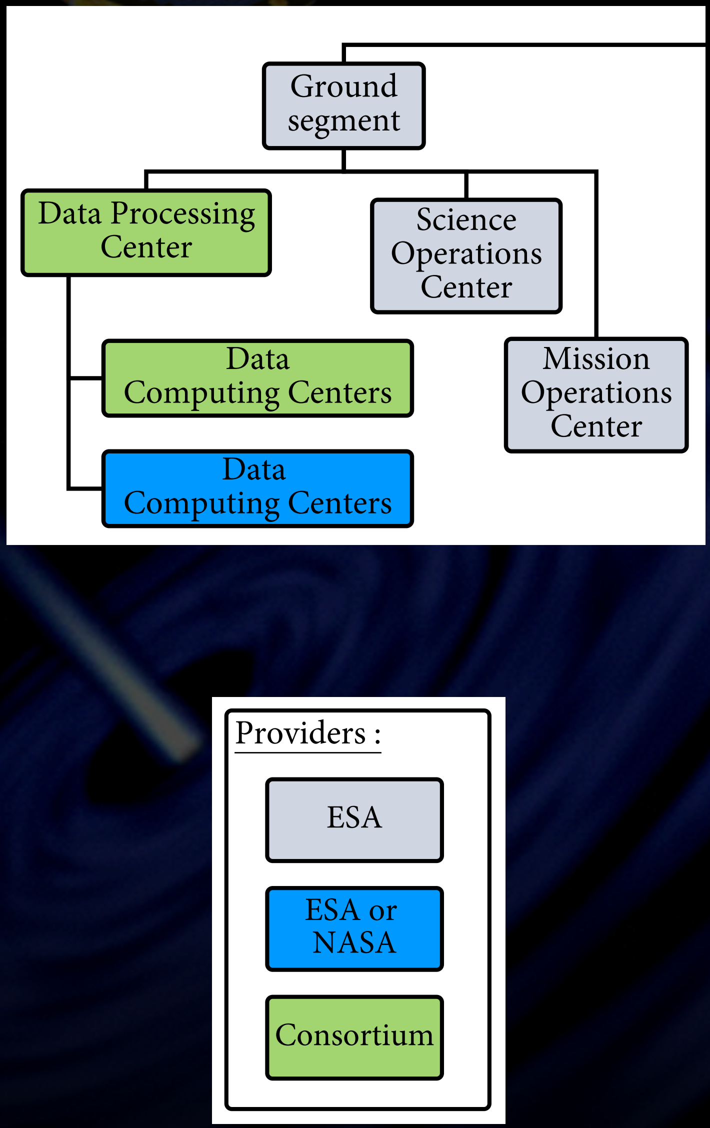
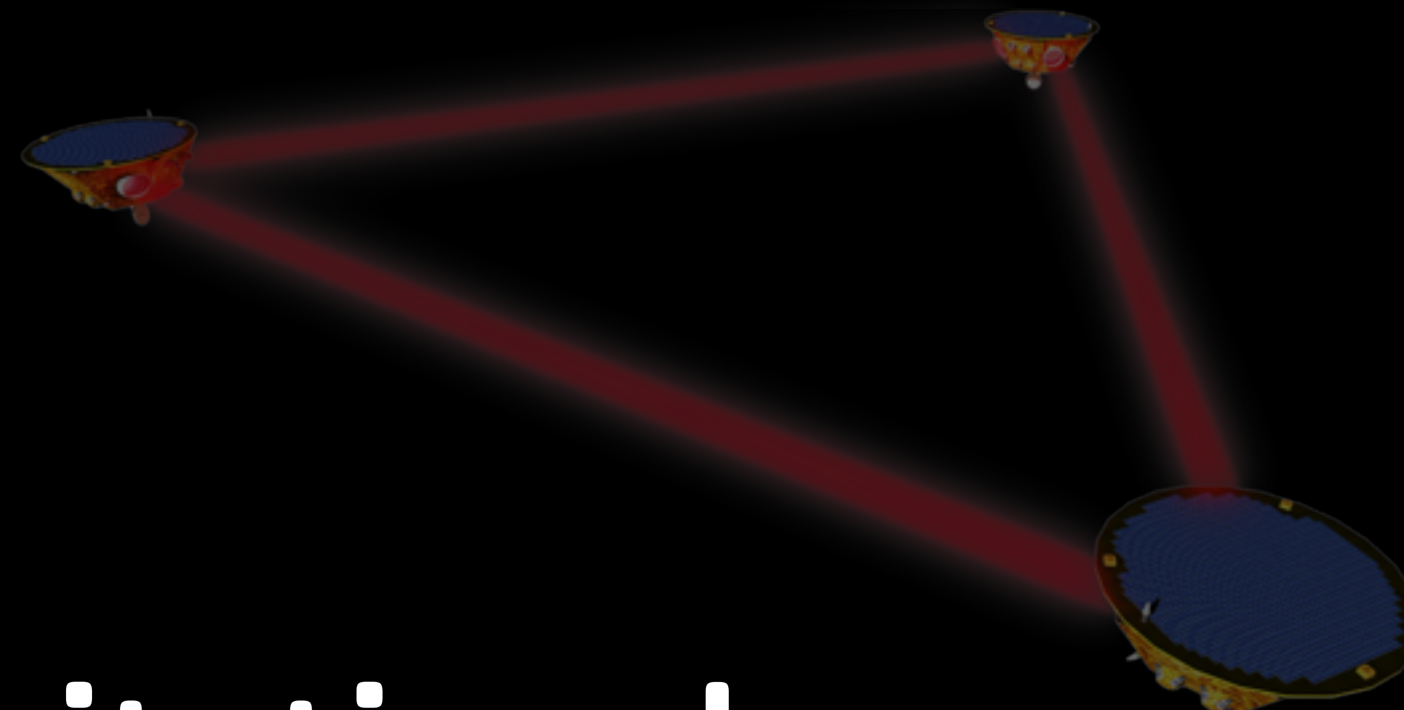
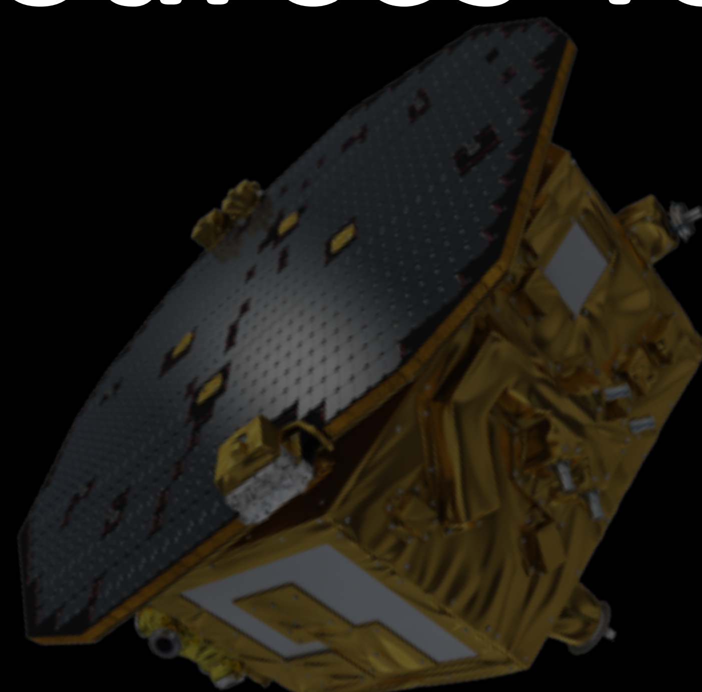
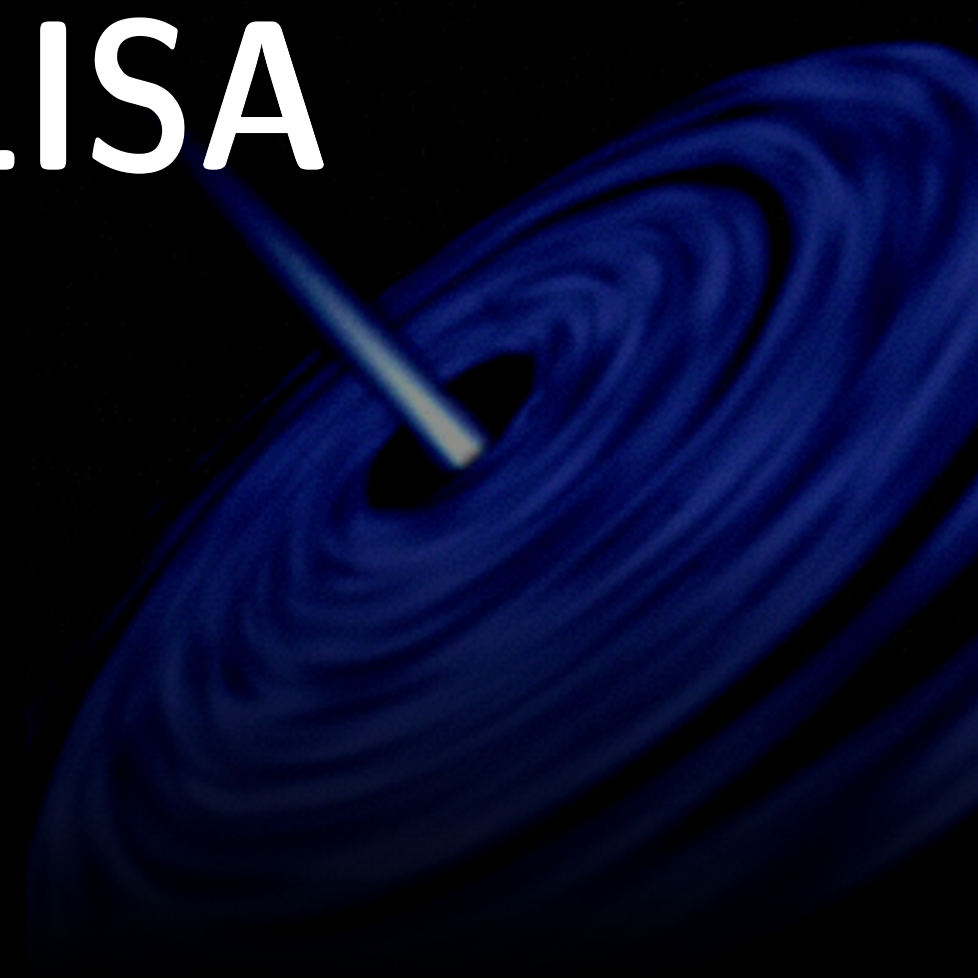


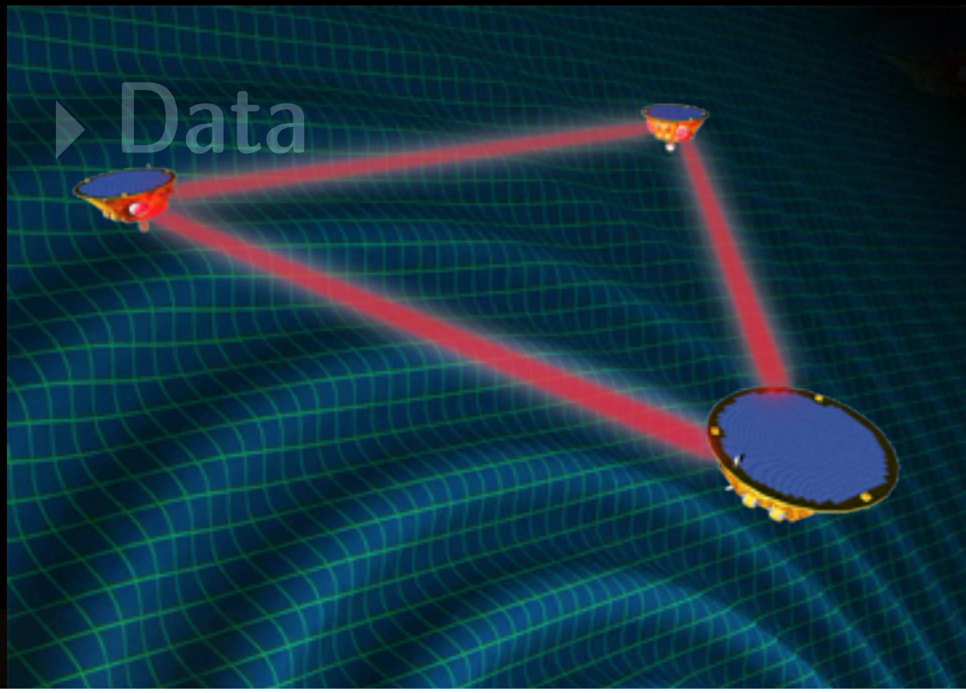


Gravitational wave sources for LISA



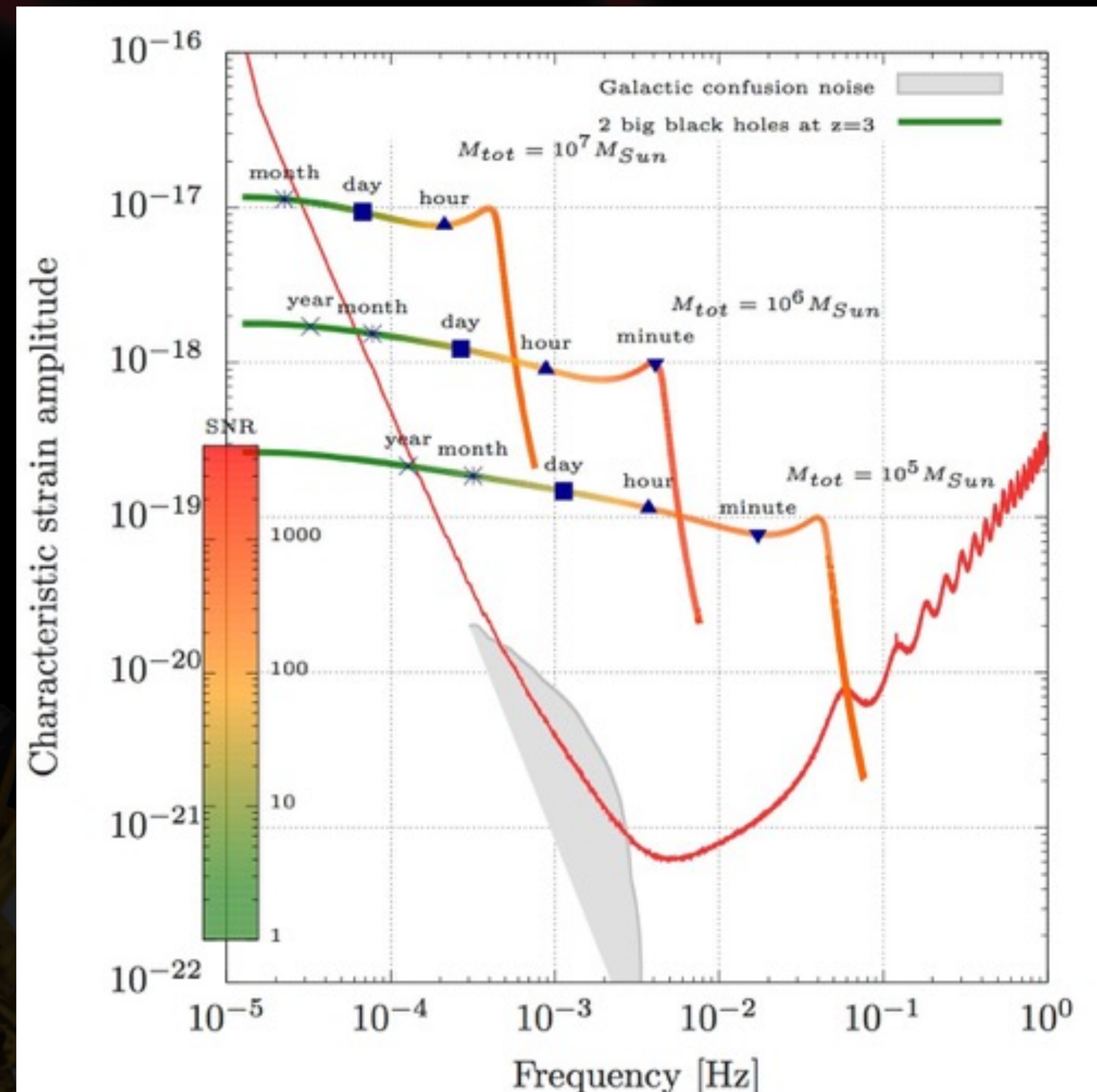


Galactic binaries



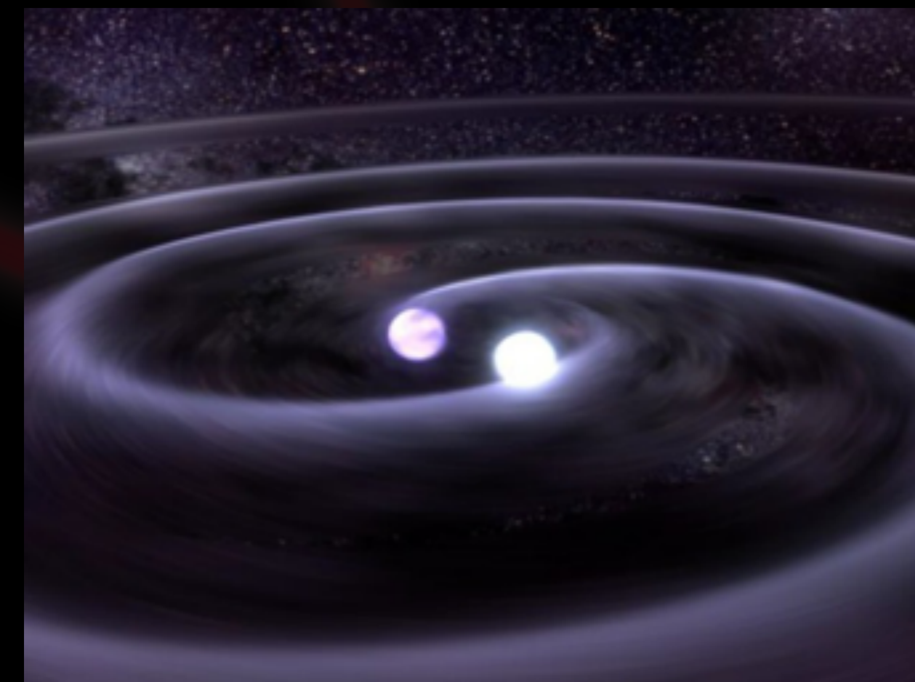
GW sources

- 6 x10^7 galactic binaries

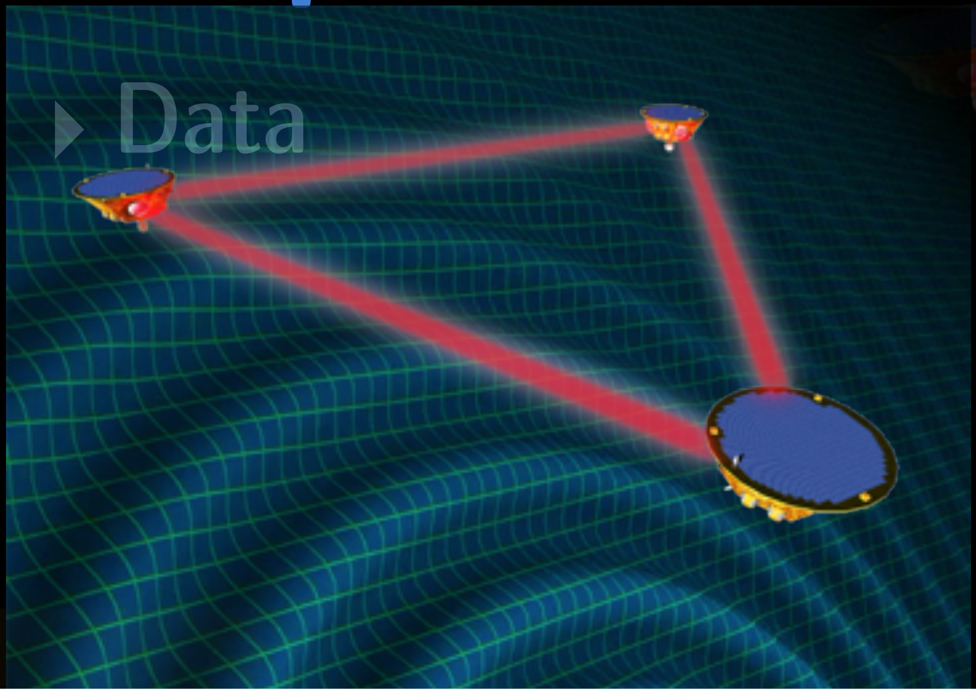


Galactic binaries

- 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
  - more than 10 guarantied sources (verification binaries)

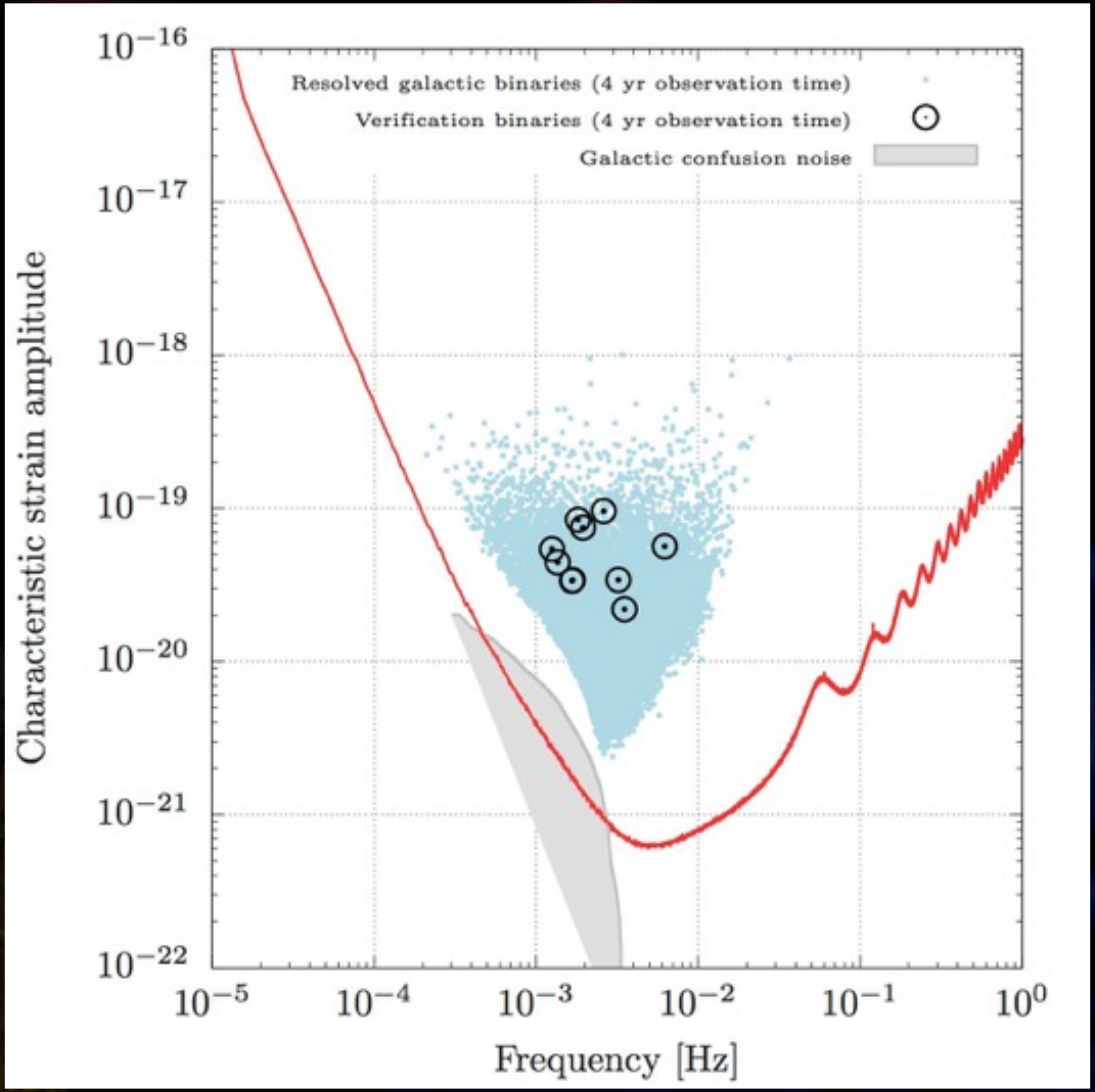


Super Massive Black Hole Binaries



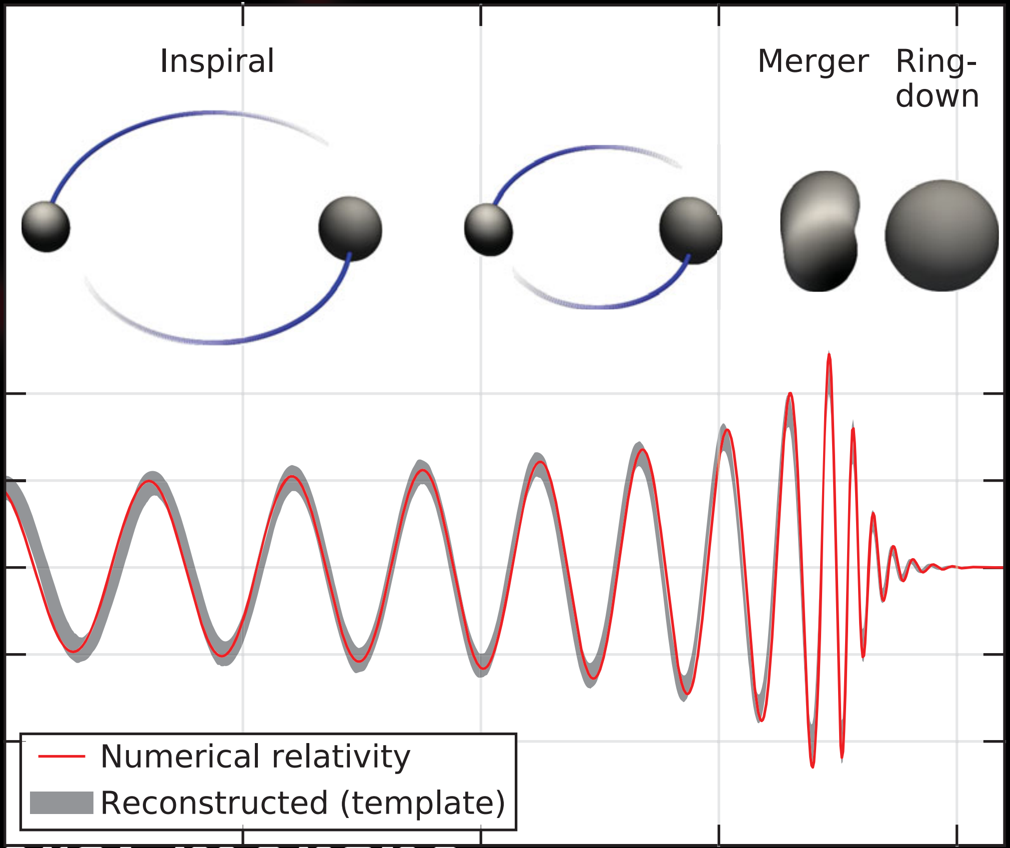
OG sources

- 6×10^7 galactic binaries
- 10-100/year SMBHBs



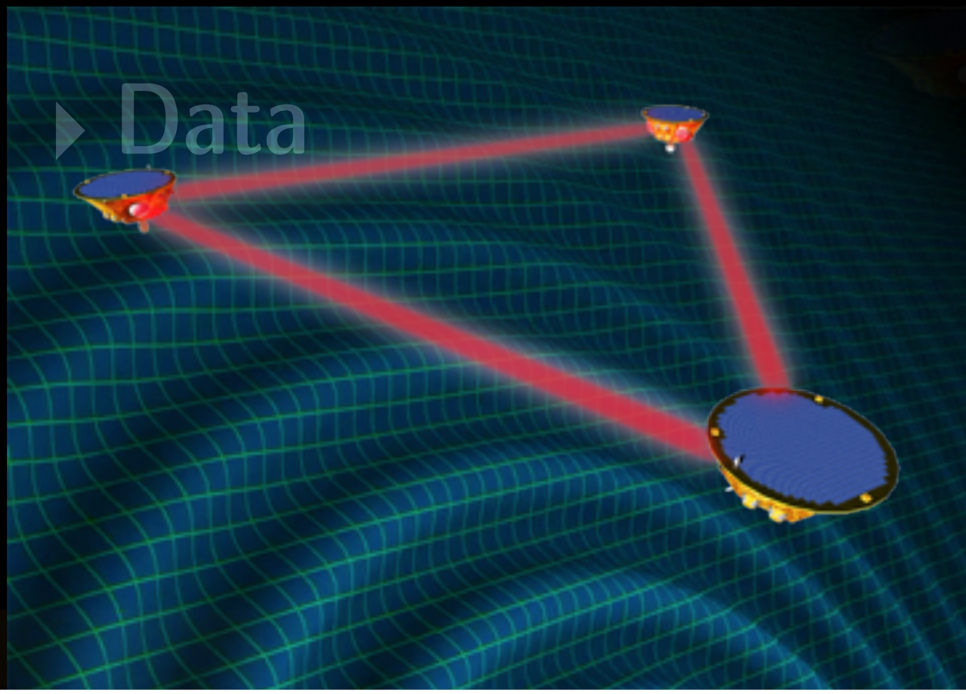
Super Massive Black Hole Binaries

- 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

EMRIs



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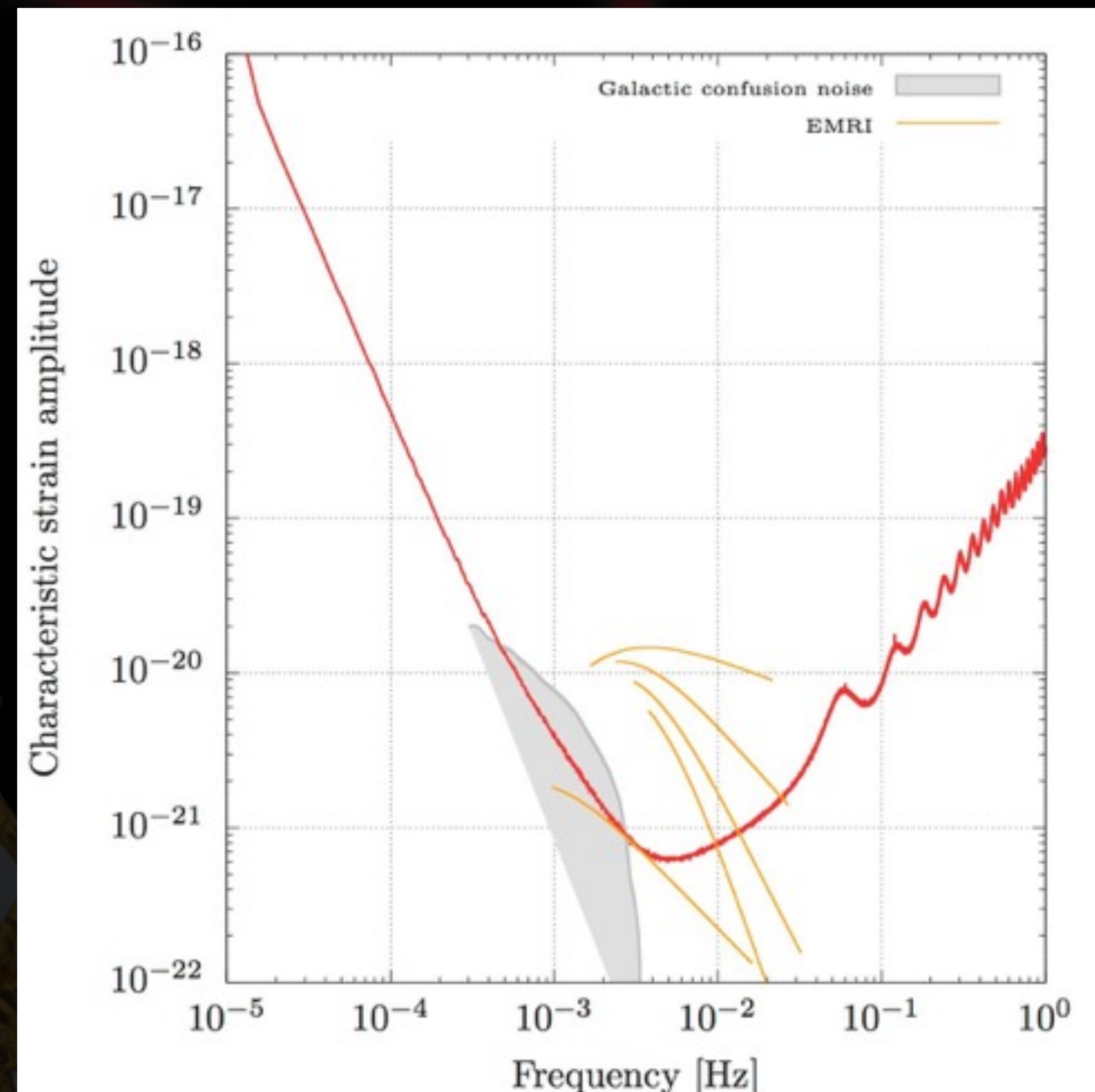
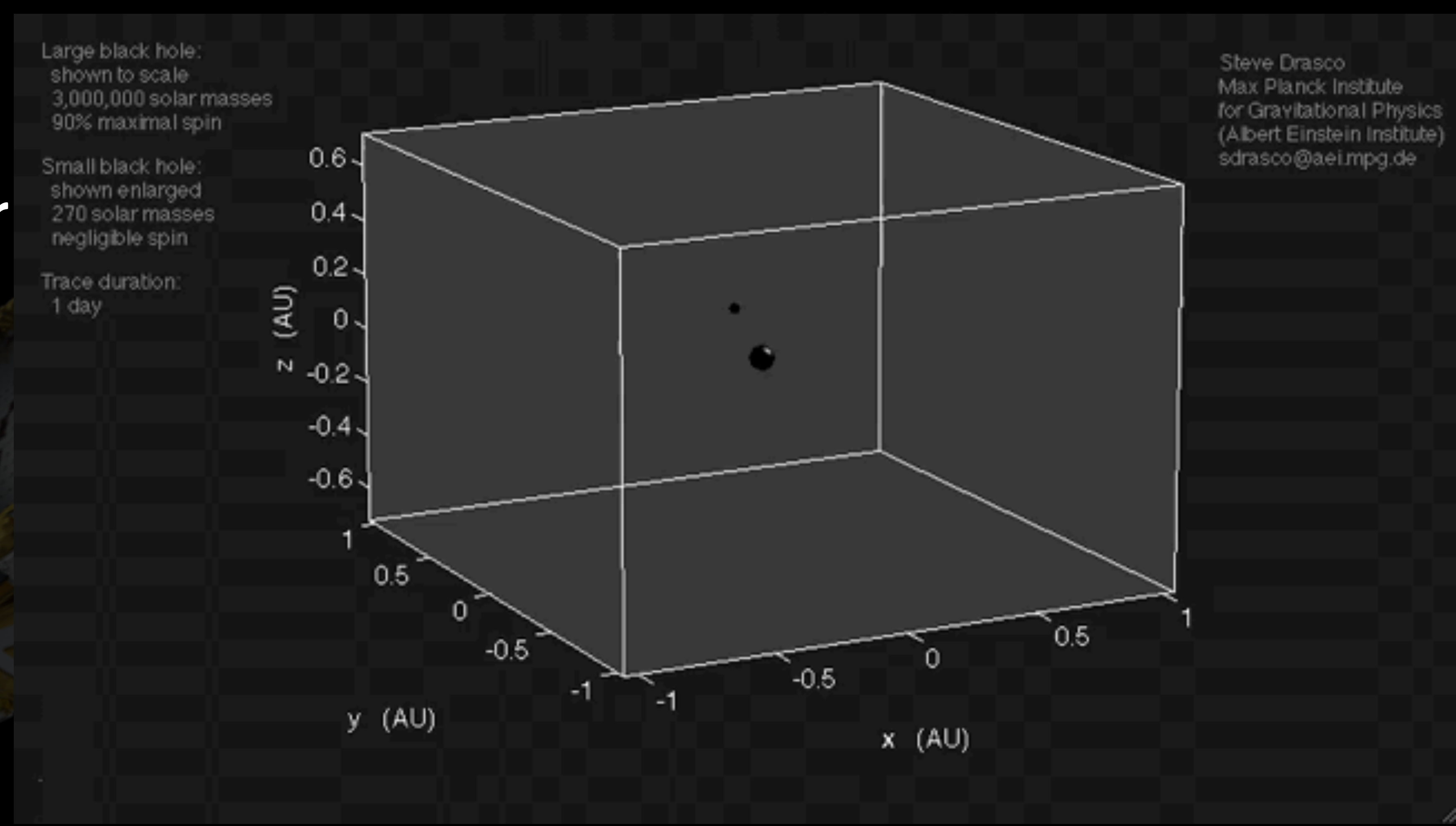
- 10-1000/years EMRIs



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



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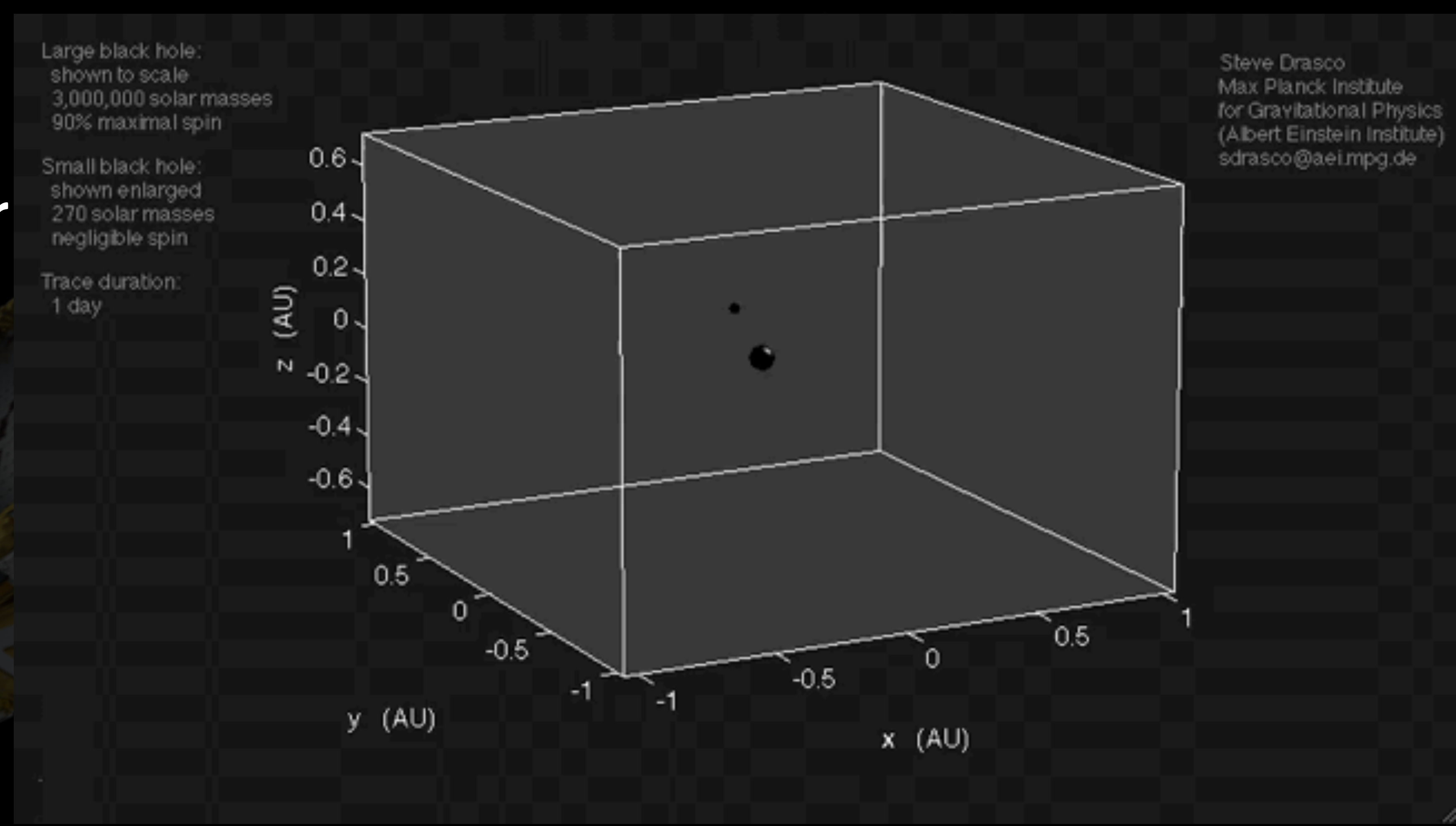
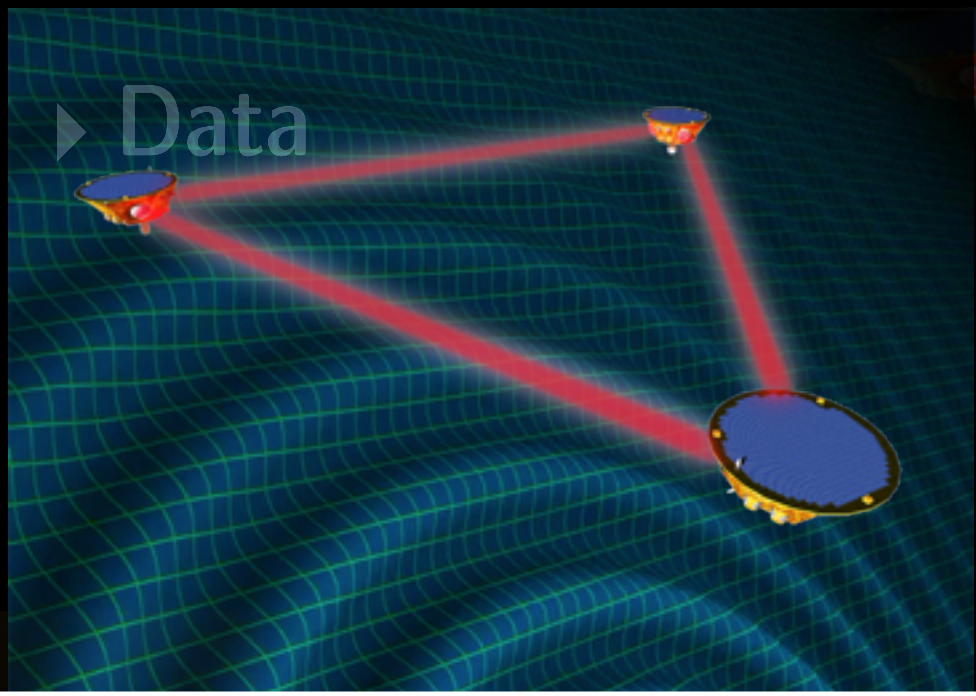
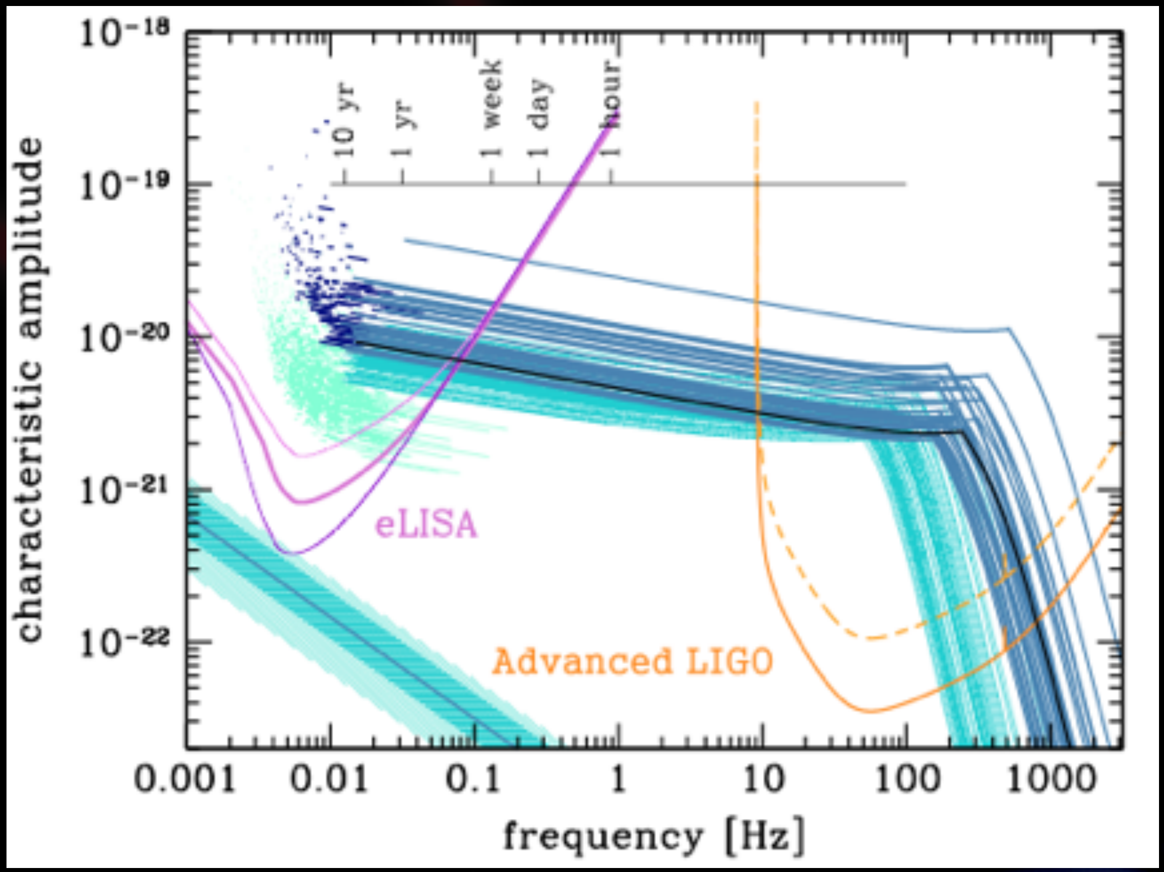


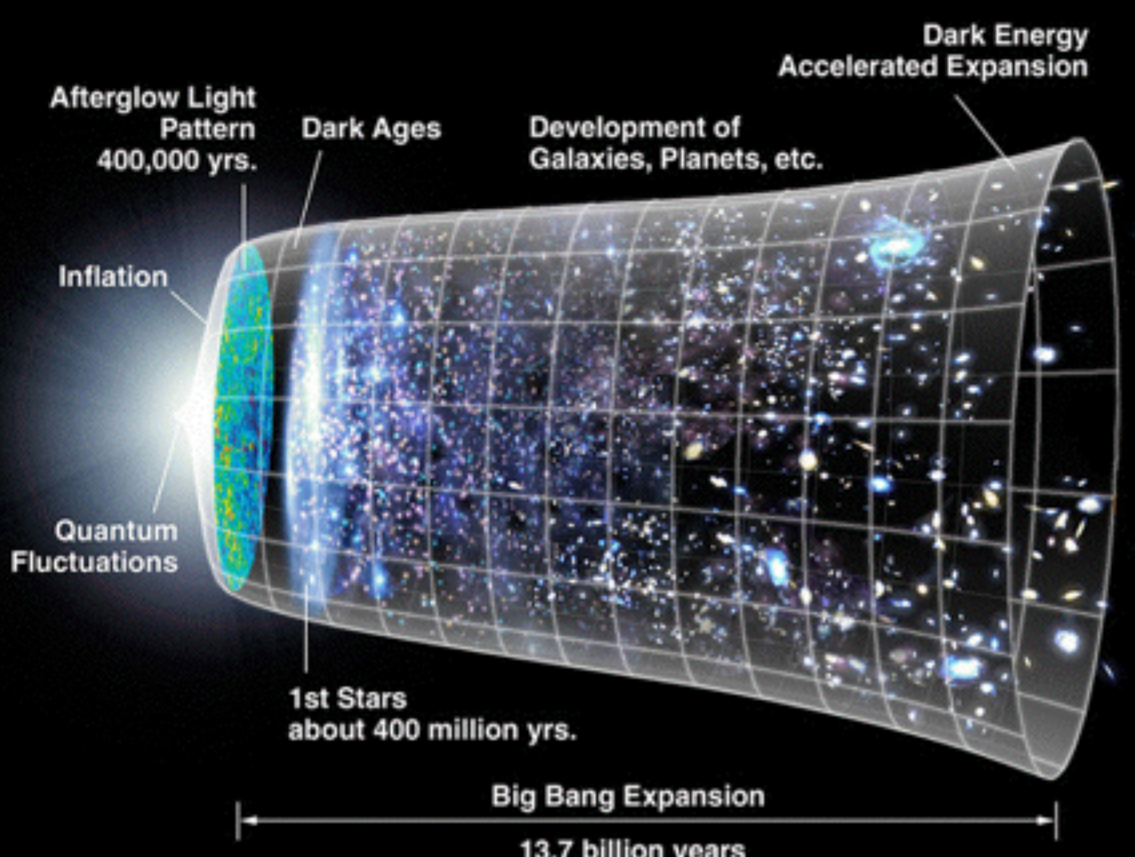
Others sources



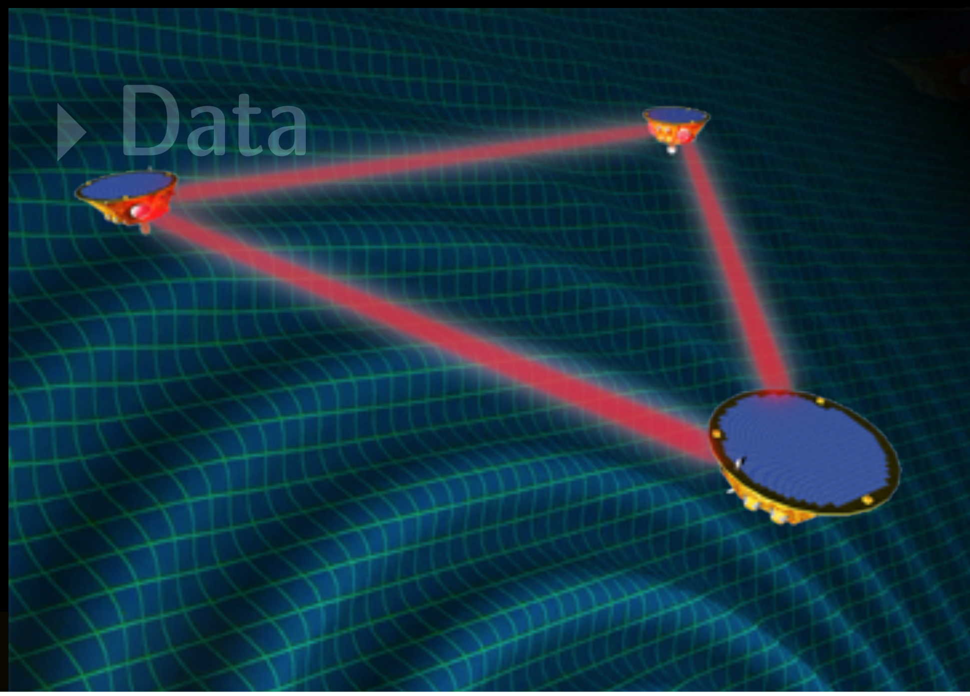


GW sources

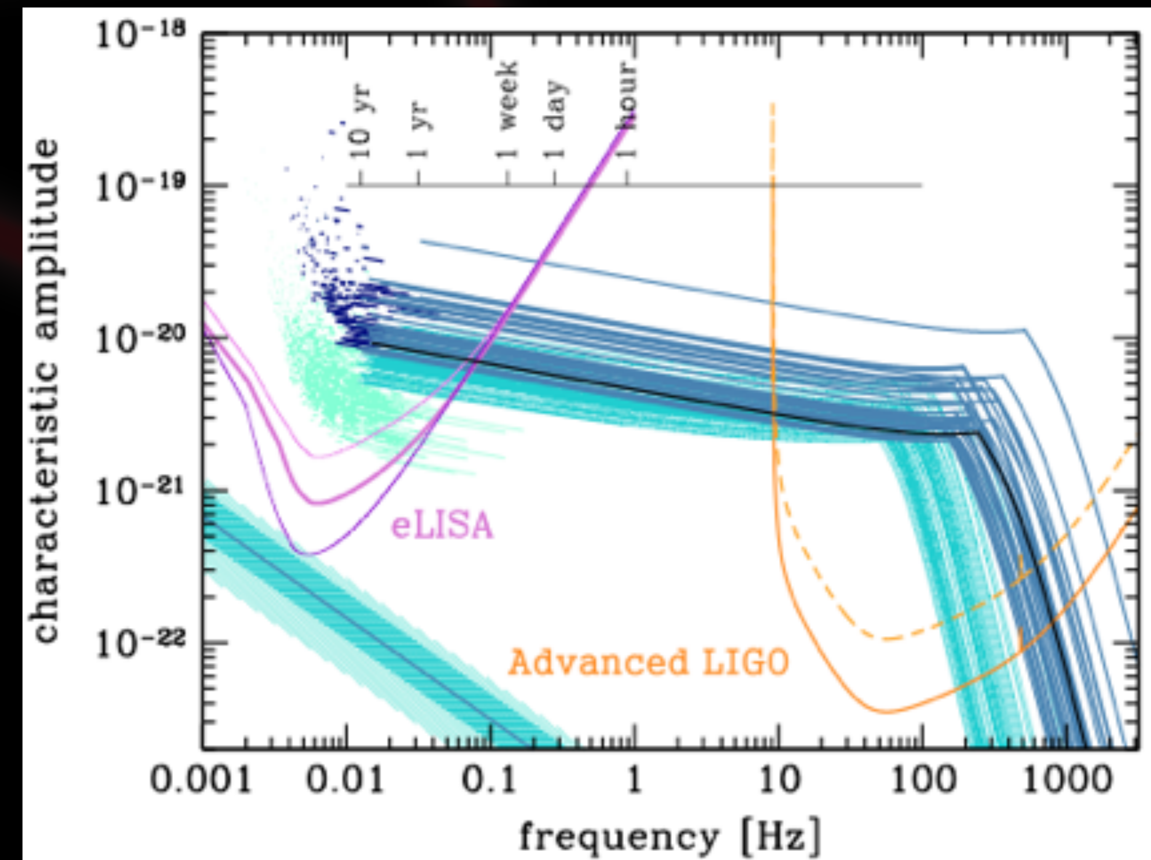
- 6 x10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources



Others sources



?



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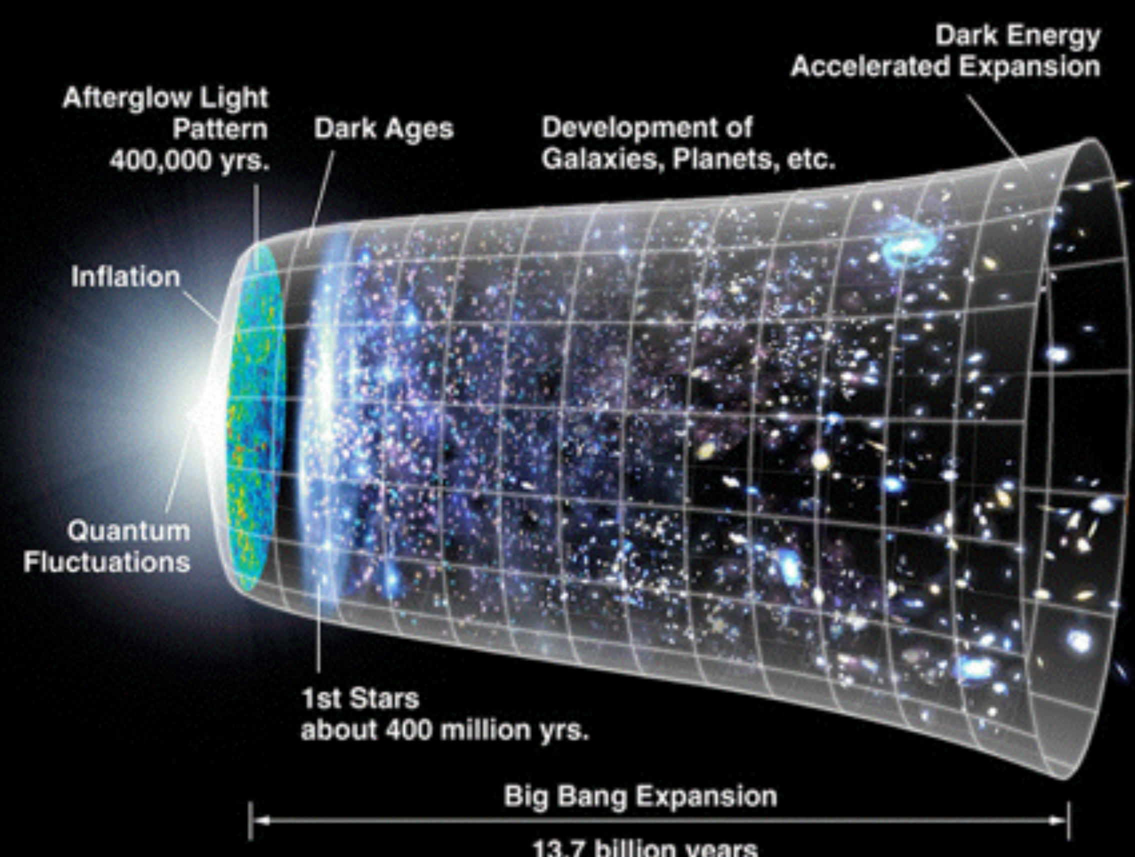
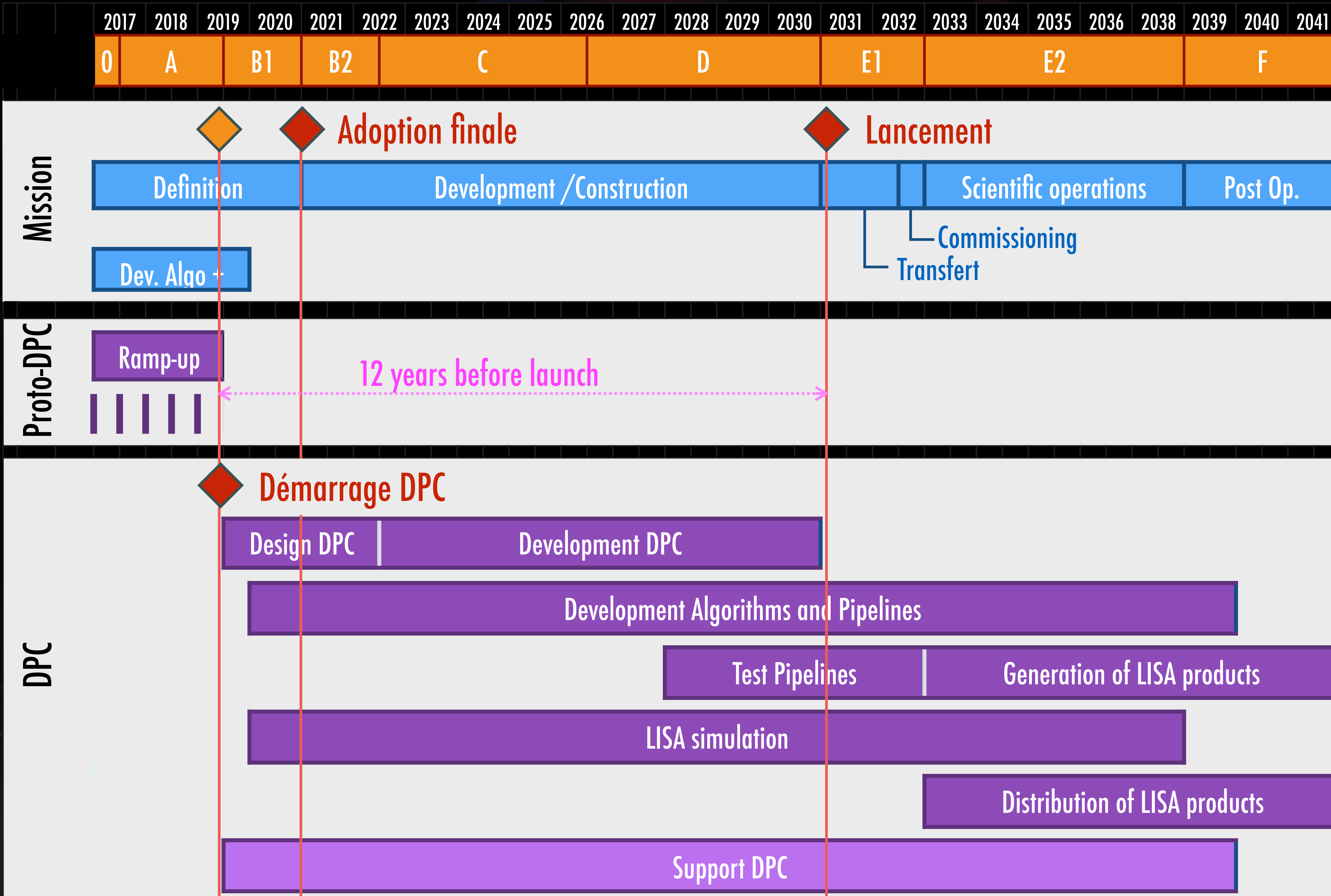
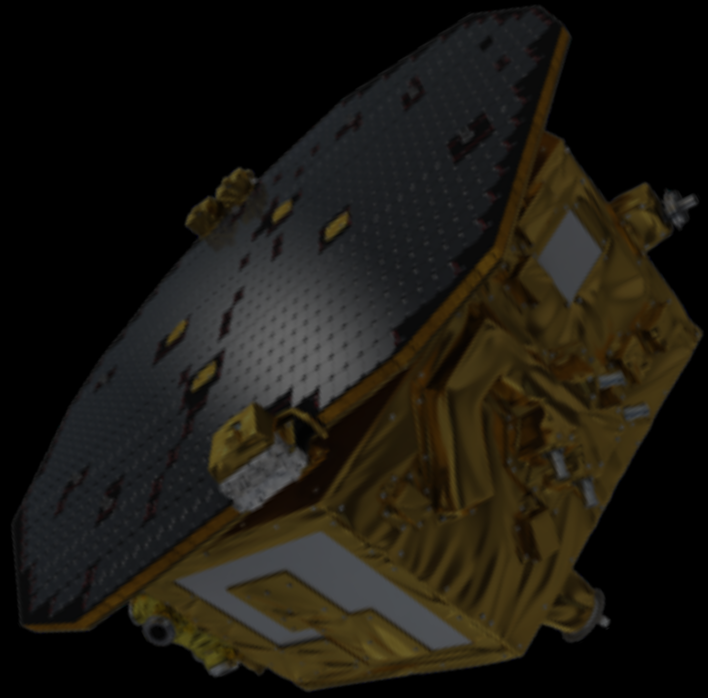
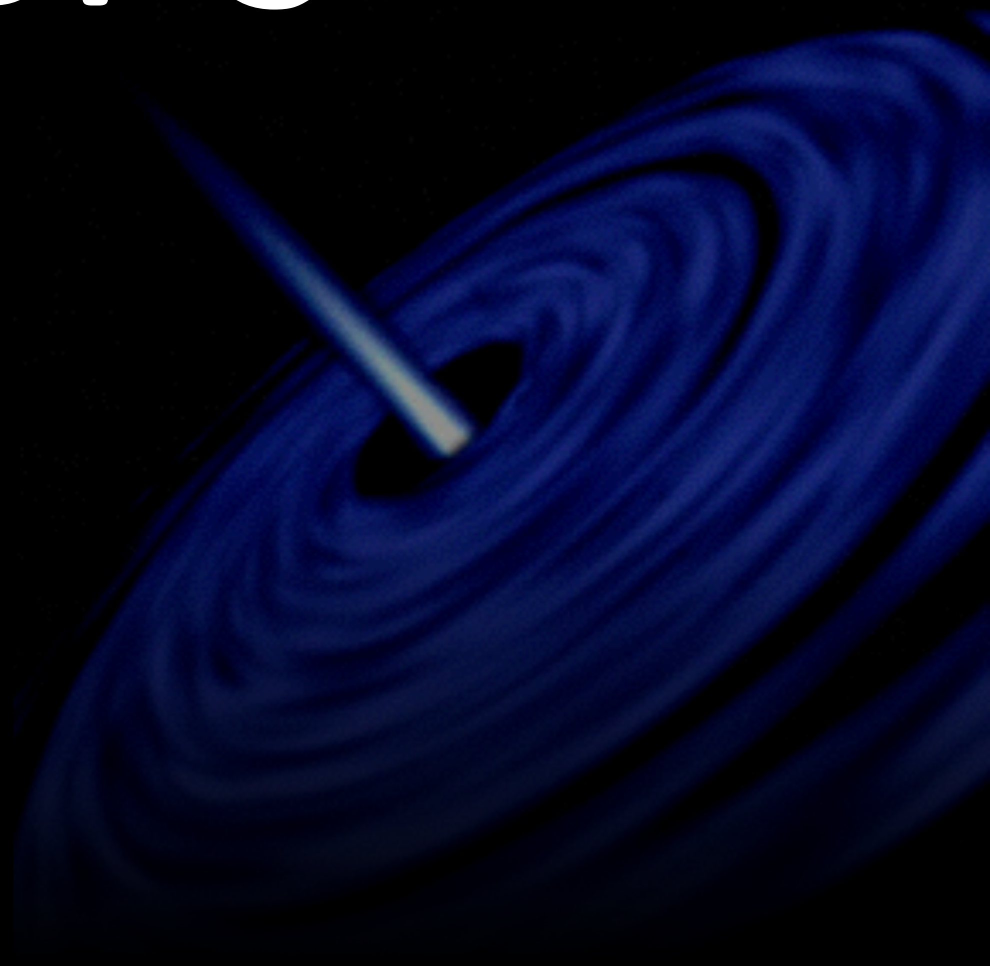


Planning of development



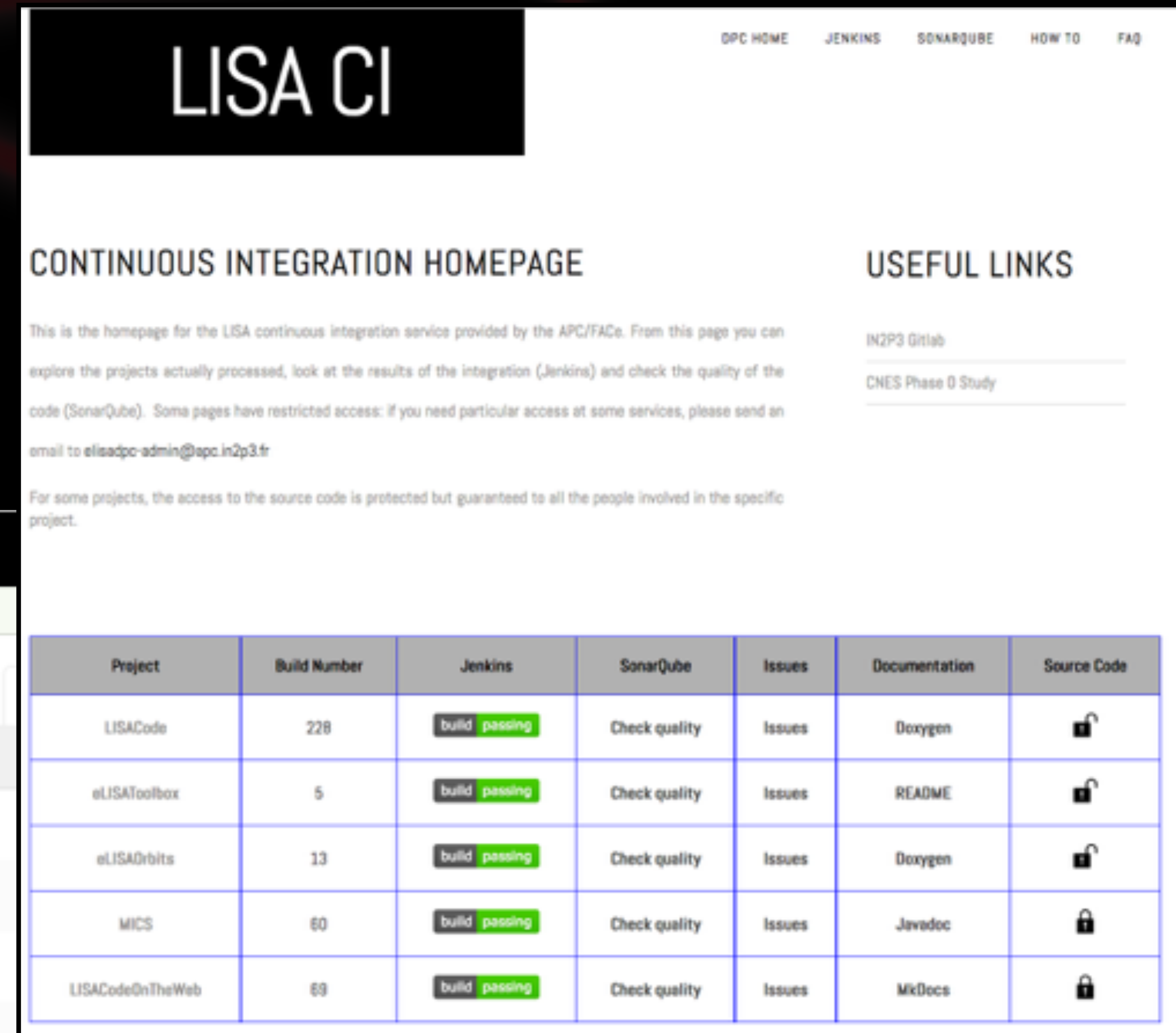
LISA proto-DPC





LISA proto-DPC

- https://elisadpc.in2p3.fr/home



Project	Build Number	Jenkins	SonarQube	Issues	Documentation	Source Code
LISACode	228	build passing	Check quality	Issues	Doxygen	
eLISAToolbox	5	build passing	Check quality	Issues	README	
eLISAOrbits	13	build passing	Check quality	Issues	Doxygen	
MICS	60	build passing	Check quality	Issues	Javadoc	
LISACodeOnTheWeb	69	build passing	Check quality	Issues	MkDocs	

Continuous integration

developer

branch develop

User

- last version
- documentation

light virtual machine with codes installed: ready to use

docker

Machine LISADPC

jenkins: compile test

documentation

performance quality

interface web

git repository

branch develop

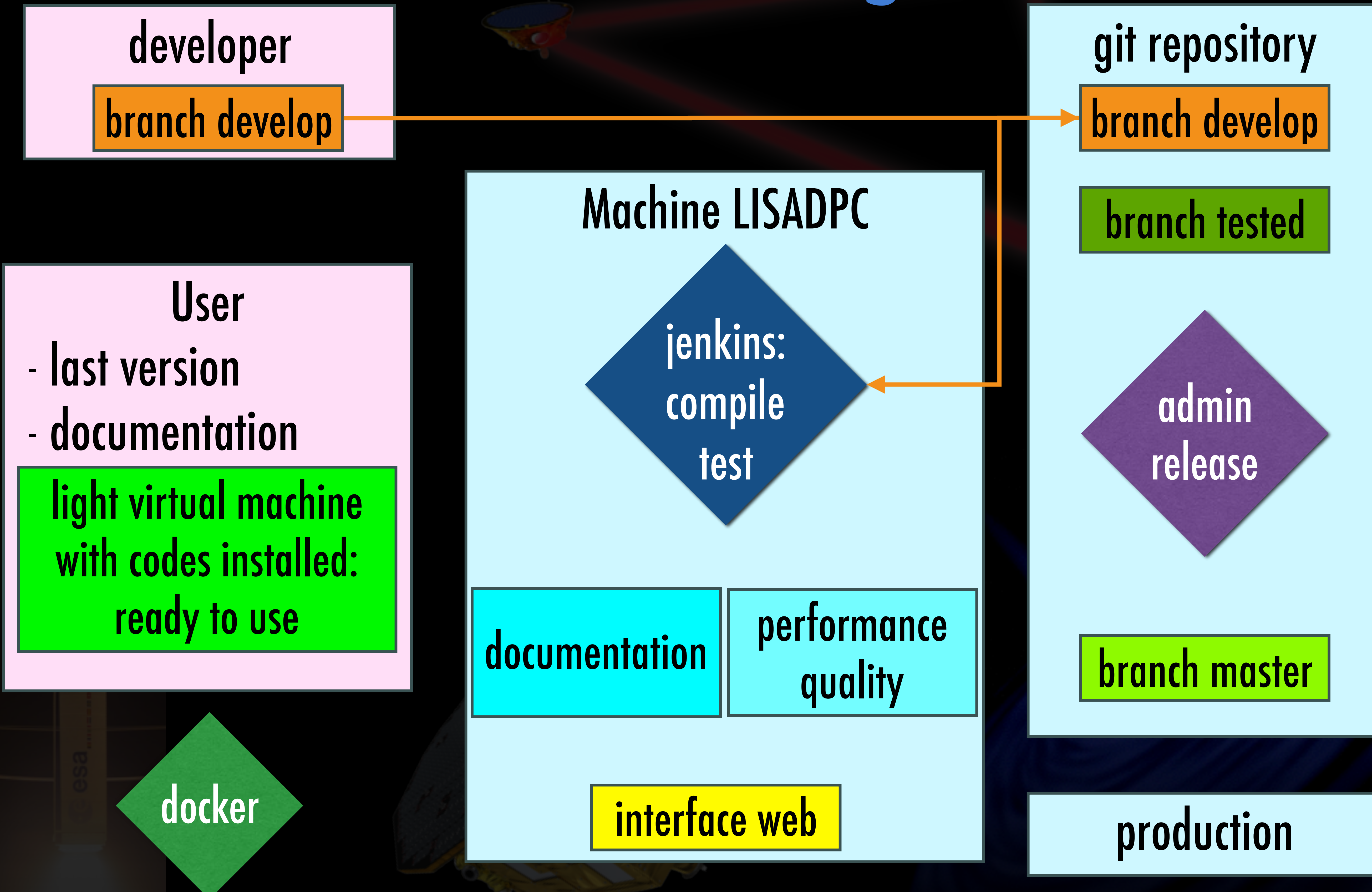
branch tested

admin release

branch master

production

Continuous integration



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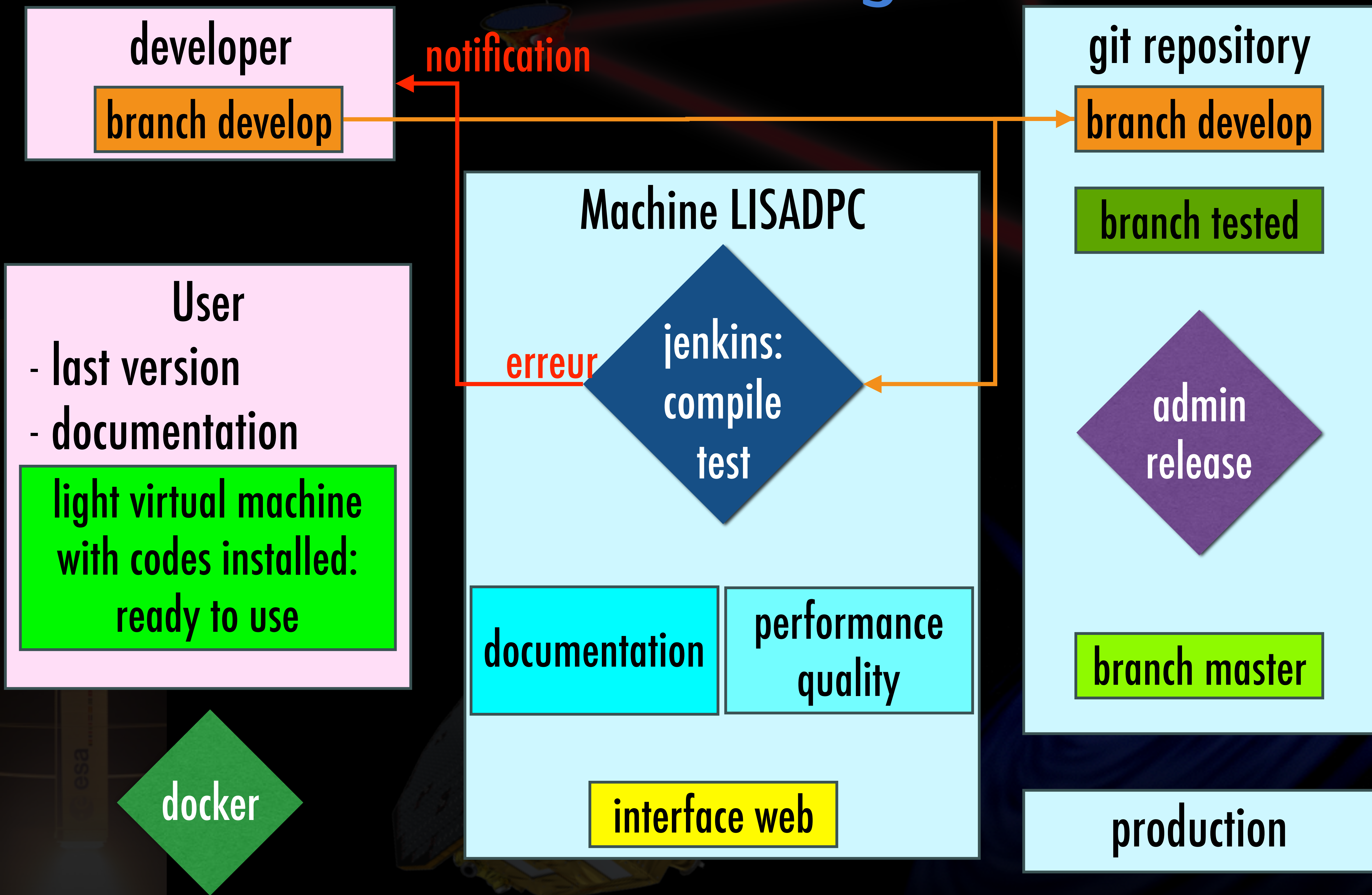

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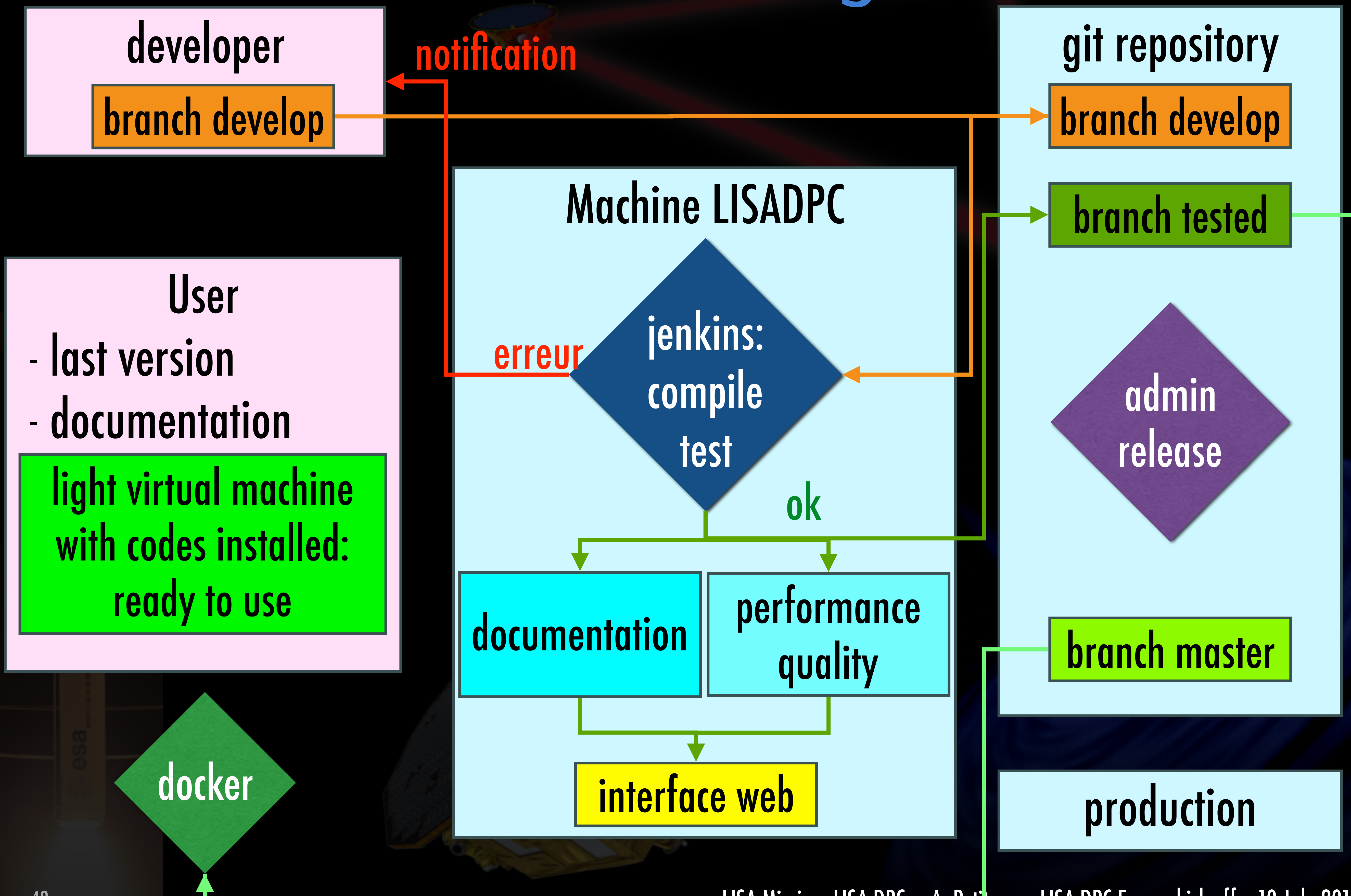

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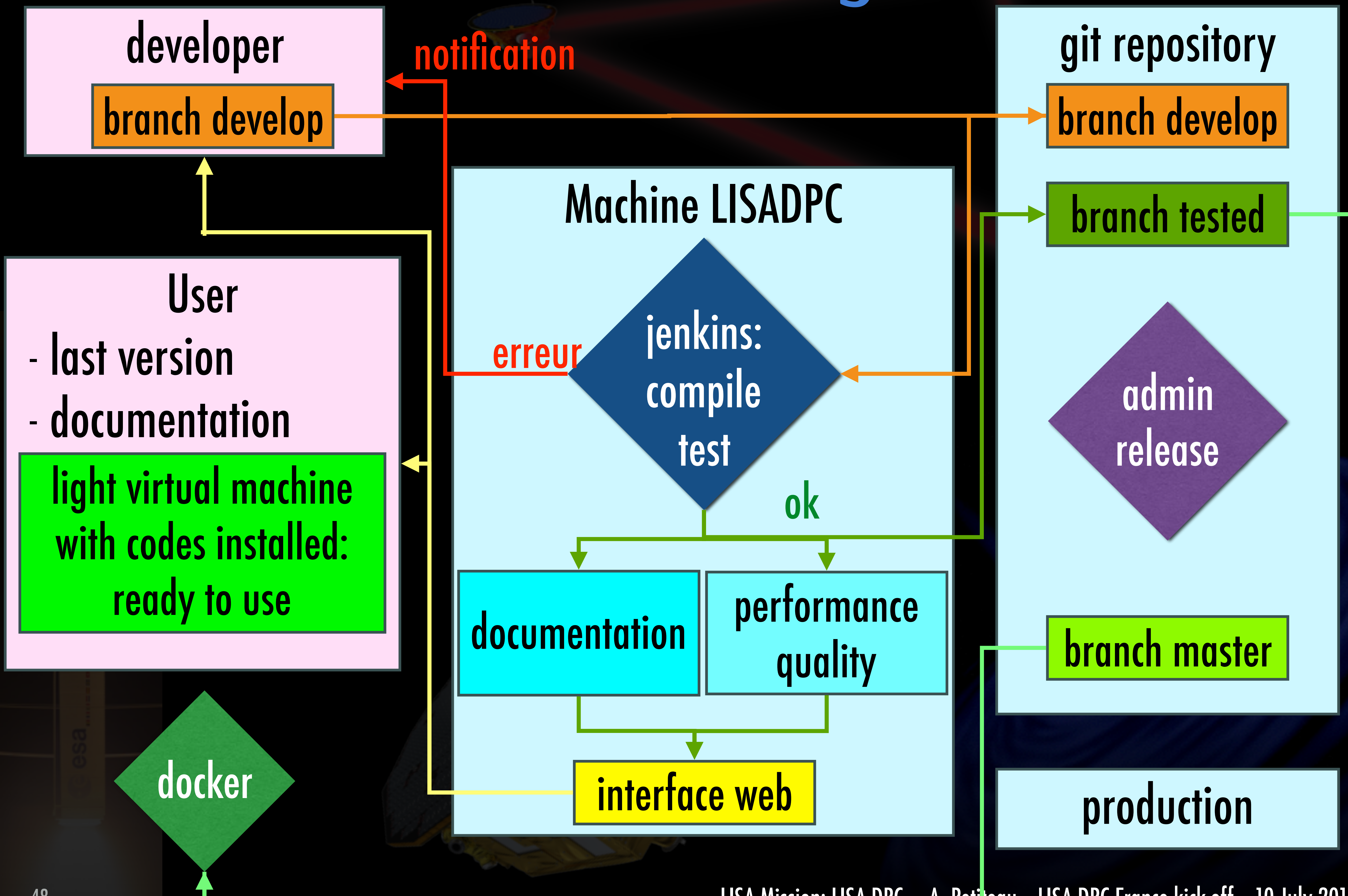

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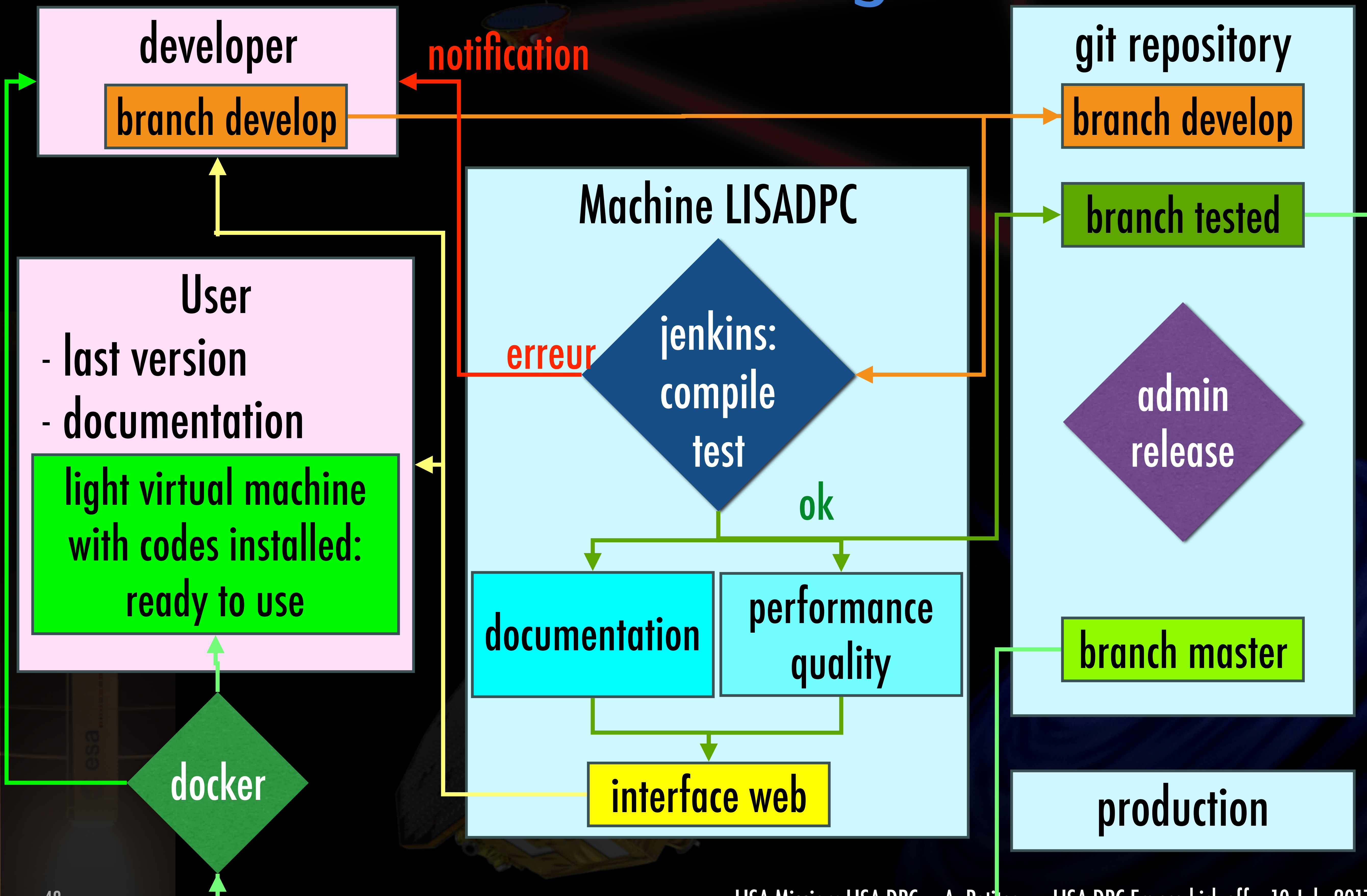

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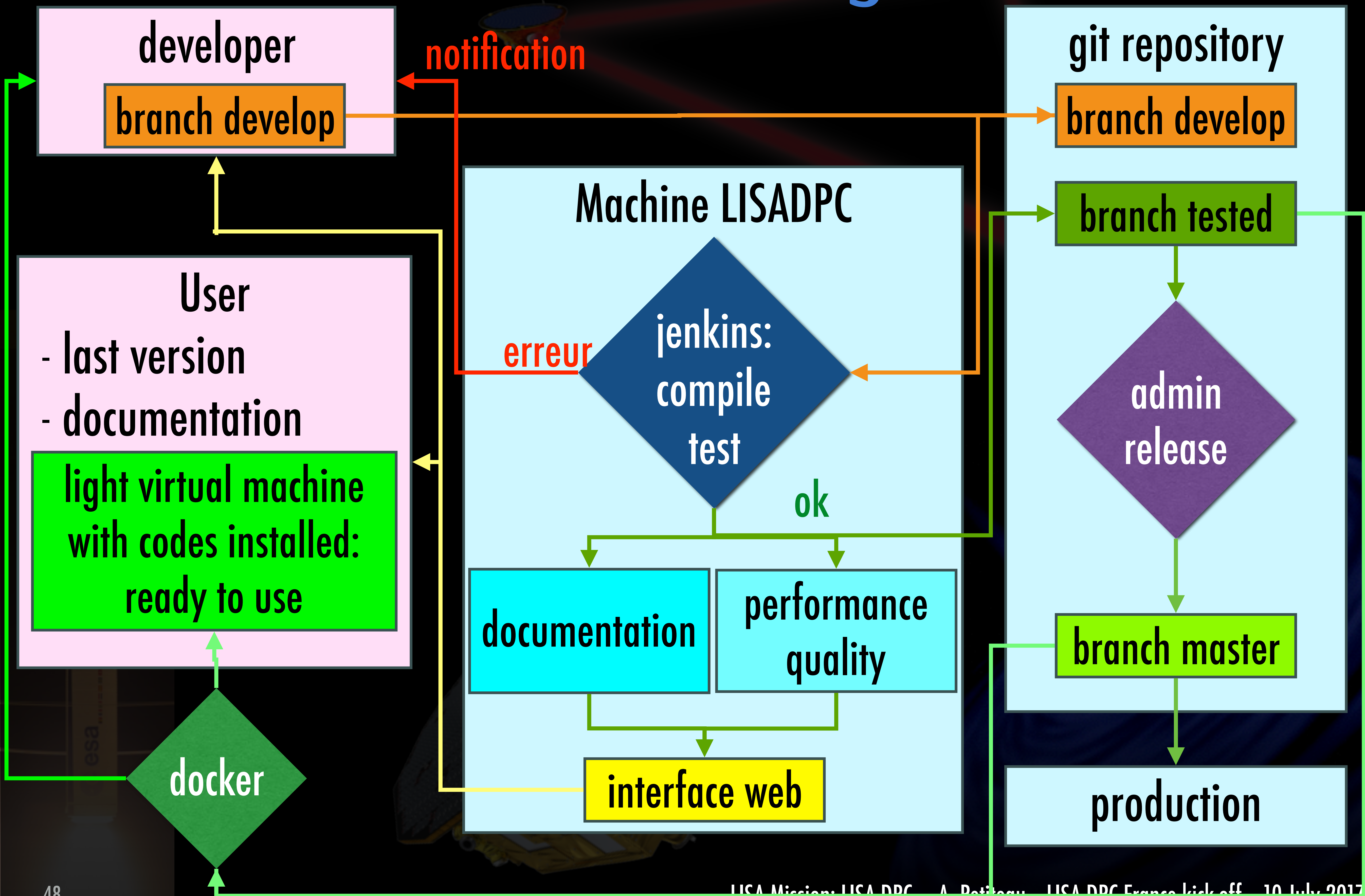
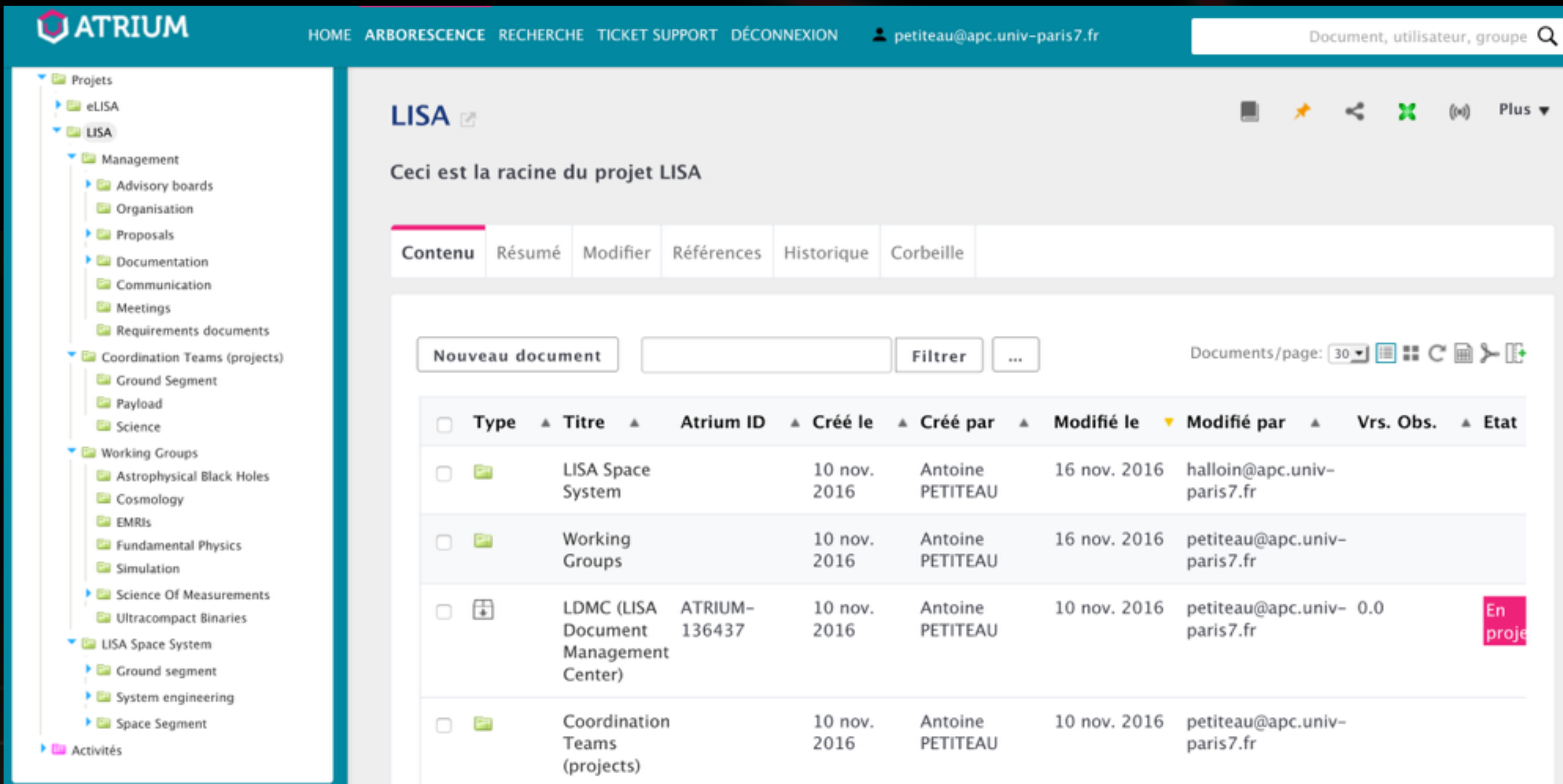
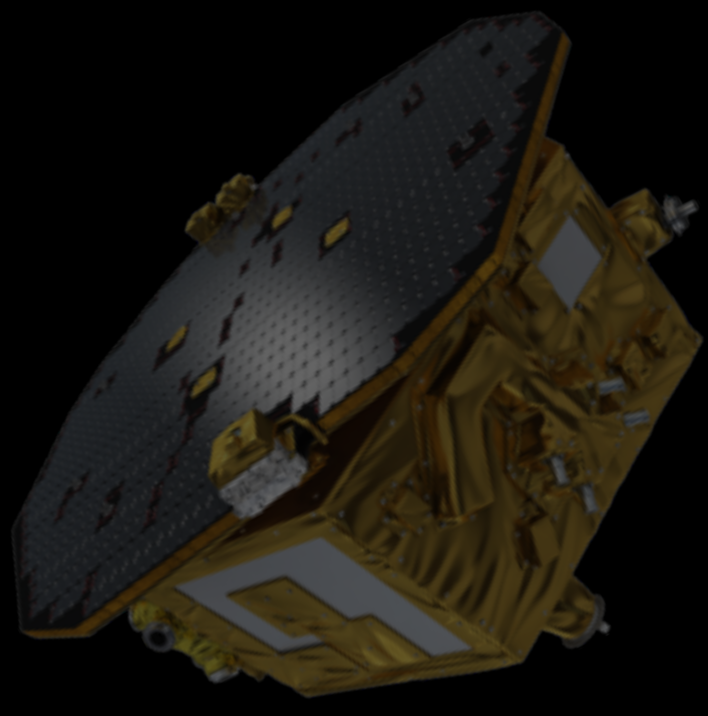


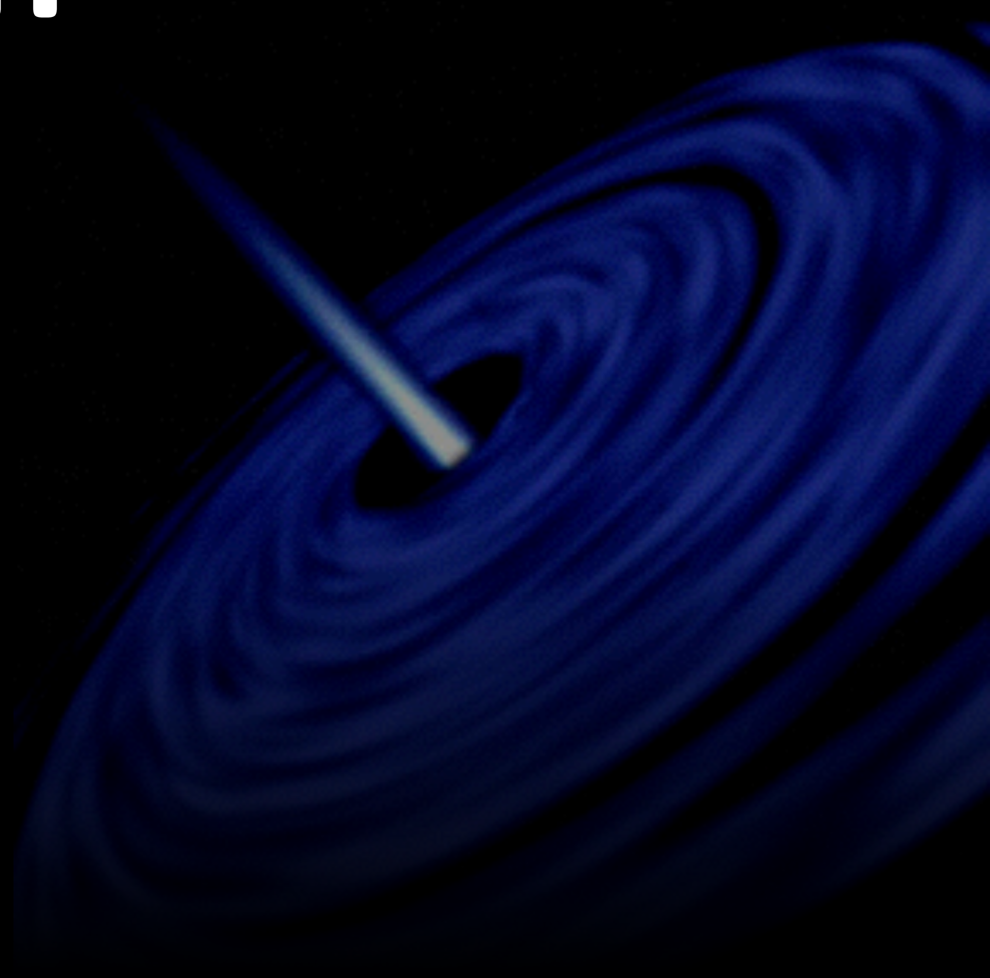
LISA Doc. Management Center

- In parallel mise en place du centre de documentation pour



Simulation





Simulateur de la mission

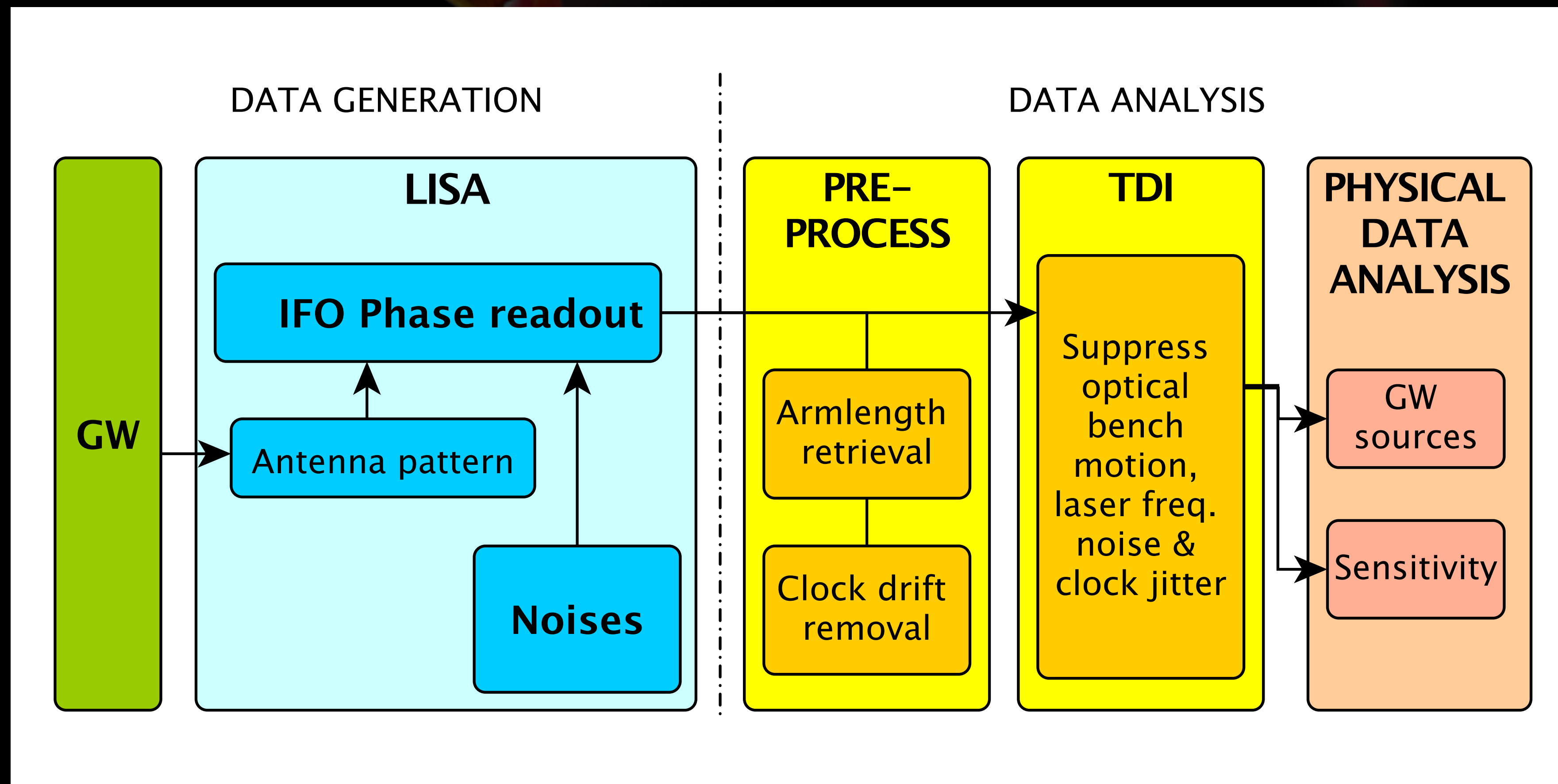
Goals:

- End-to-end simulation → the mission simulator
- "Quick performance" study for various configurations → final design (required for phase A)
- Accompany the hardware developments (industries & labs.)
- Tool(s) for performance controls

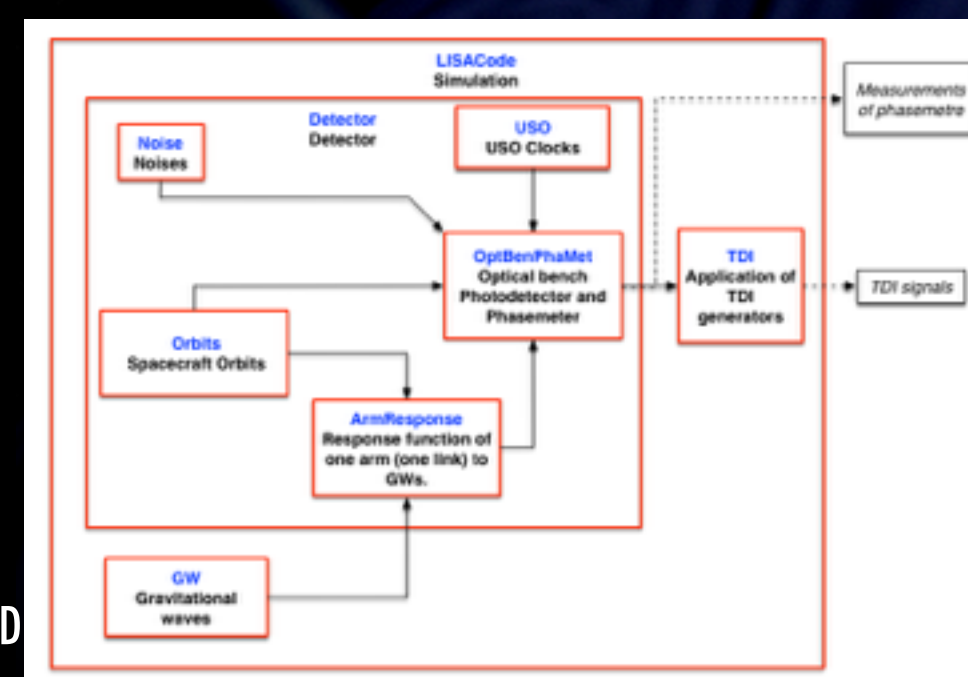
First requirements:

- Close modeling of the instrument subsystems
- Waveform generation for various GW sources
- Noise generation using various types of representation
- Data pre-processing (distinct from simulation)
- Modularity
- Computation speed (> 10-100 times faster than reality)
- Open-source

Simulation



- LISACode is the starting point of the end to end simulator
- 2 complementary simulators:
  - TDISim (check TDI)
  - LISADyn (3D dynamic)



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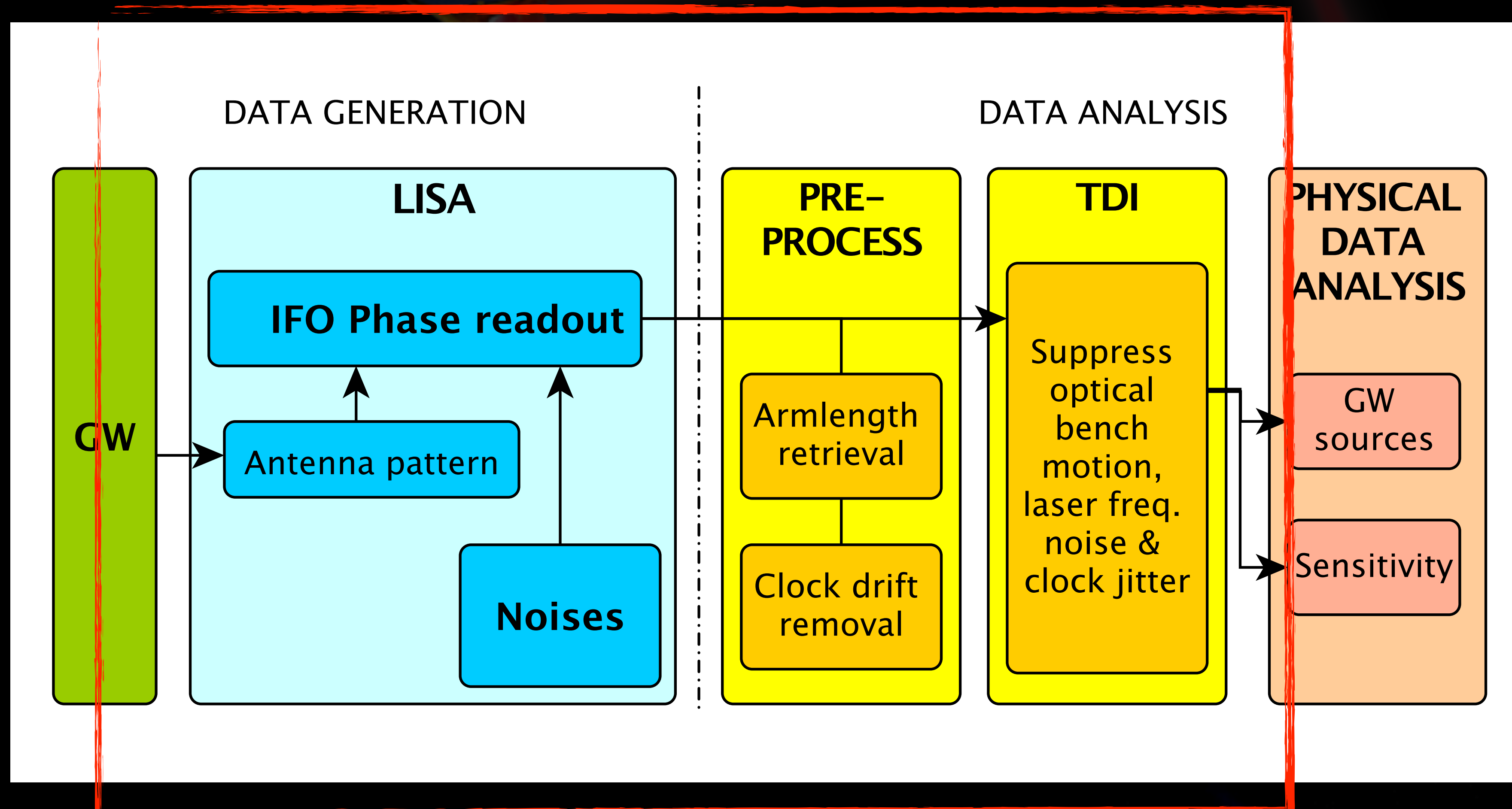

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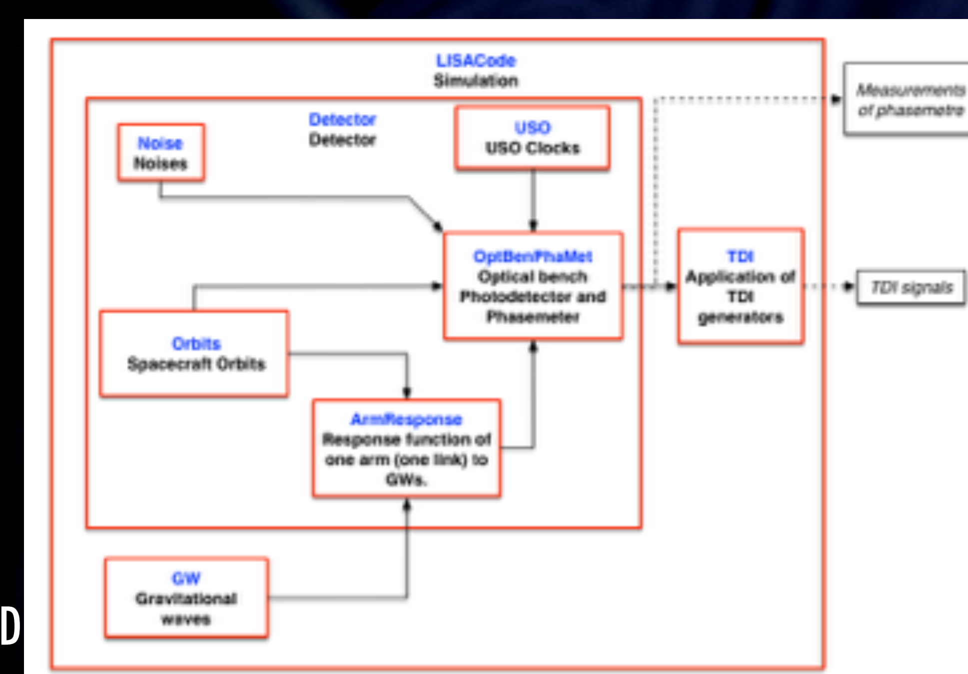
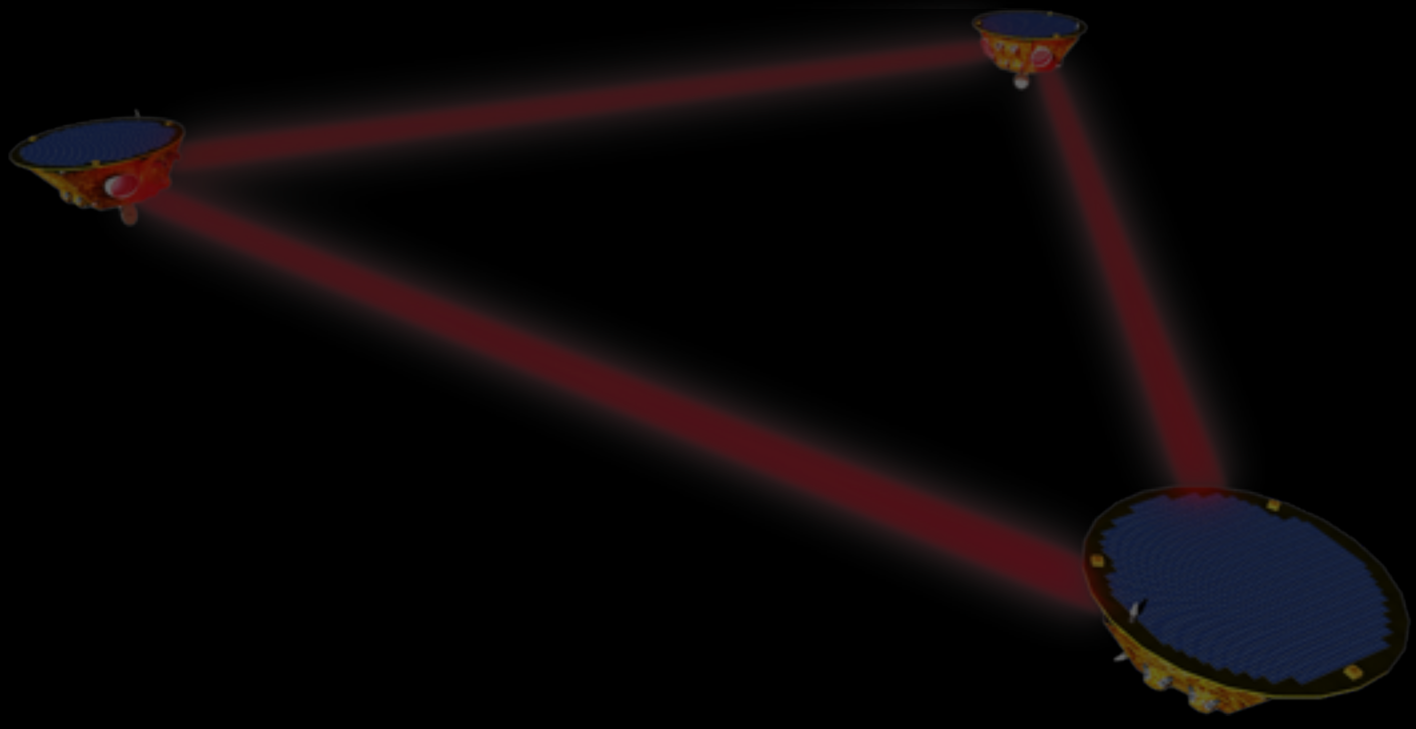
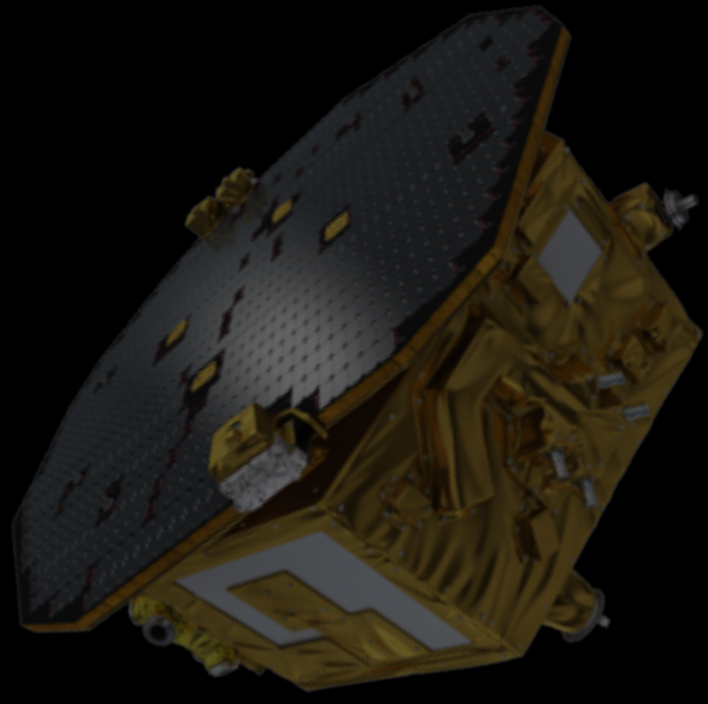
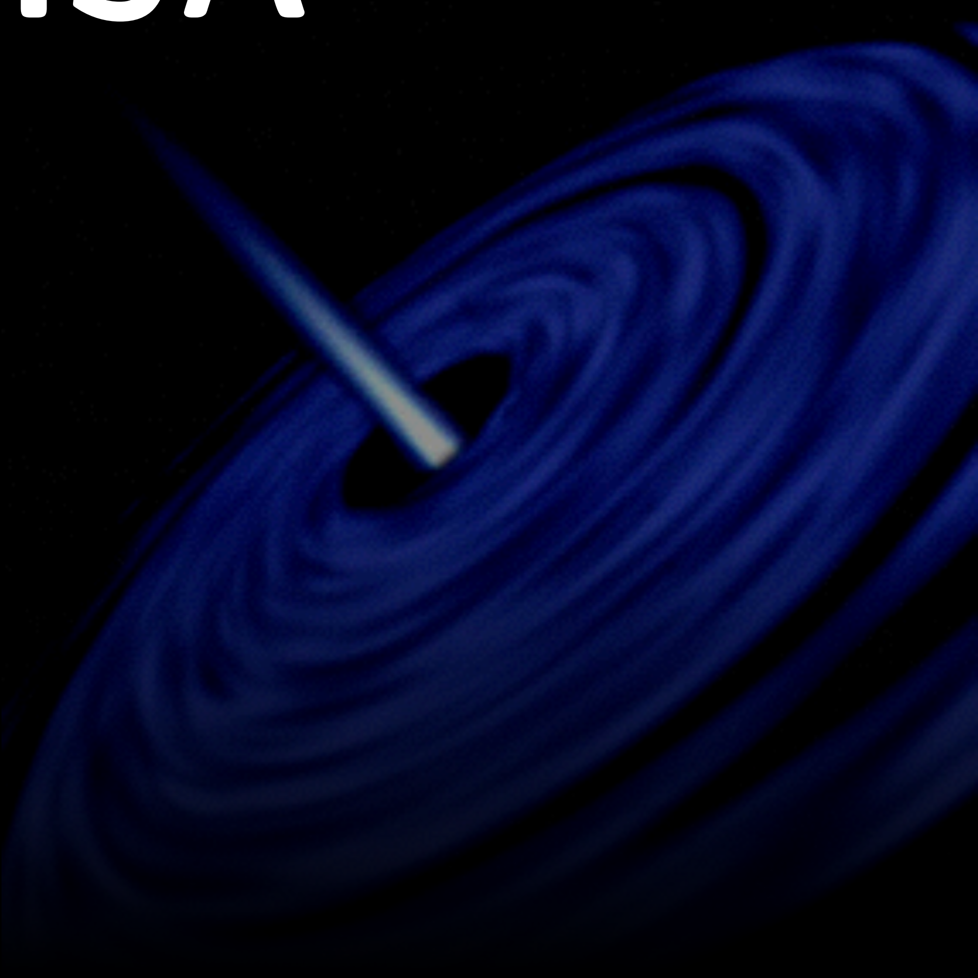




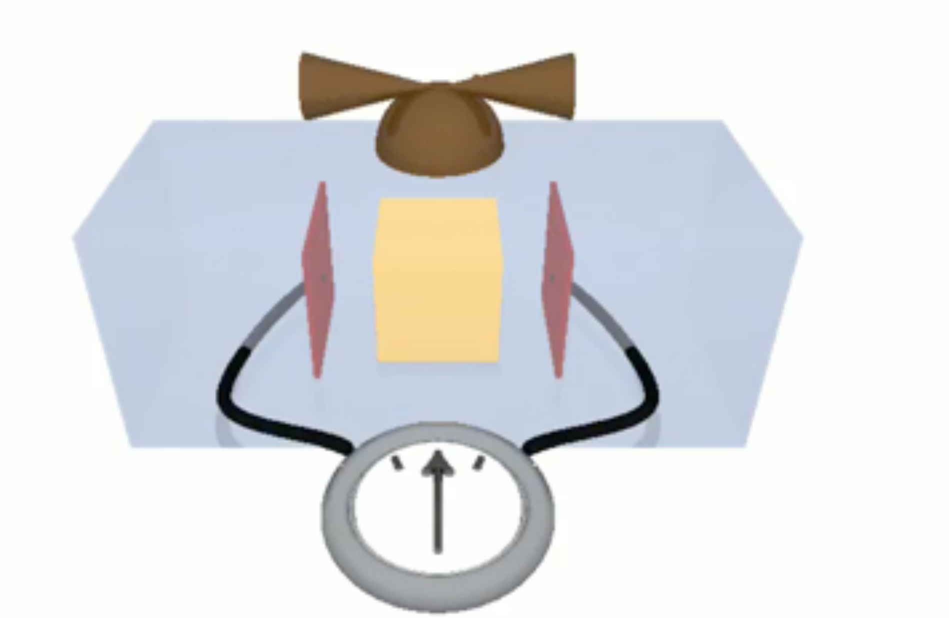
Instrument LISA

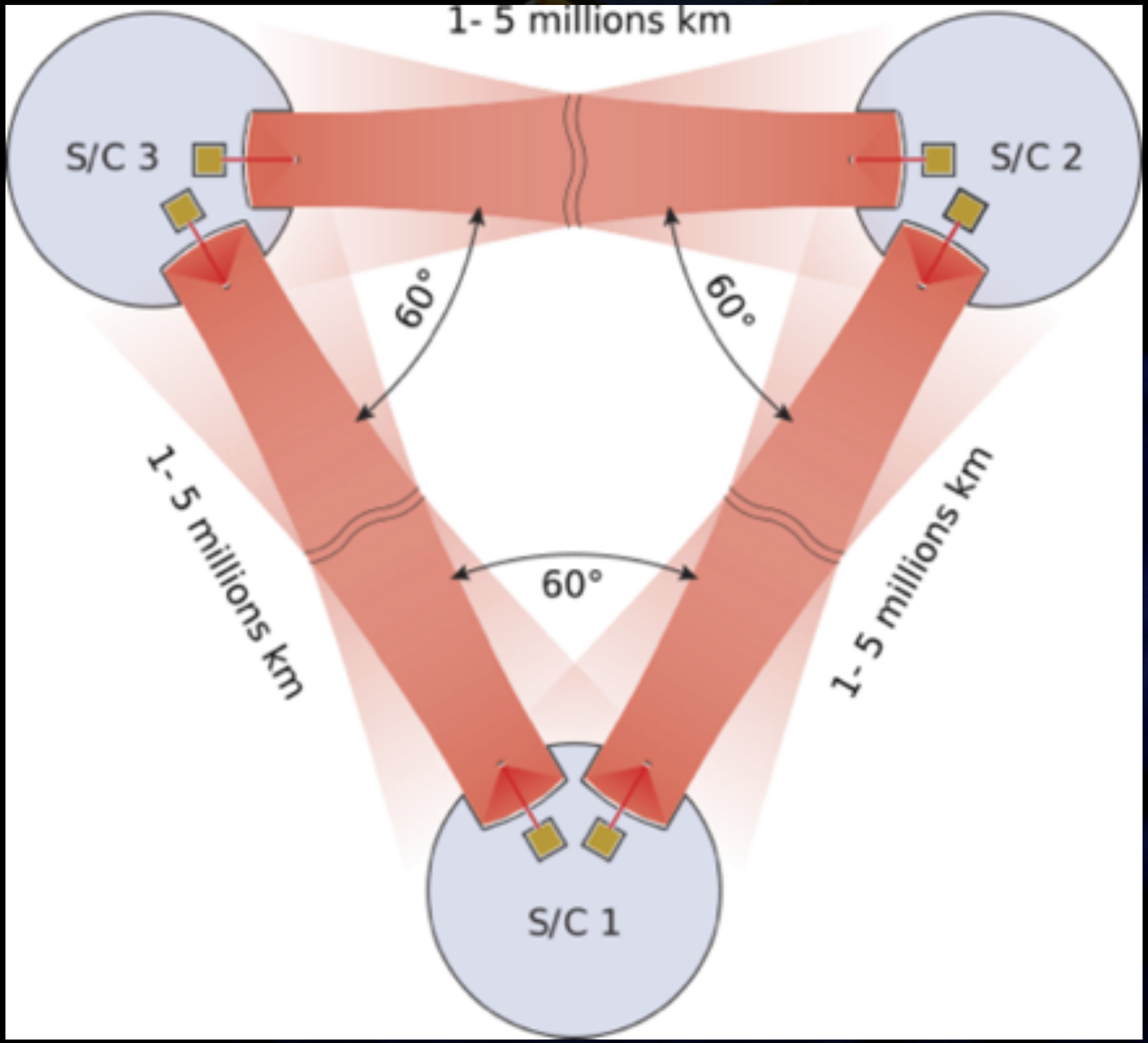




LISA

- 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





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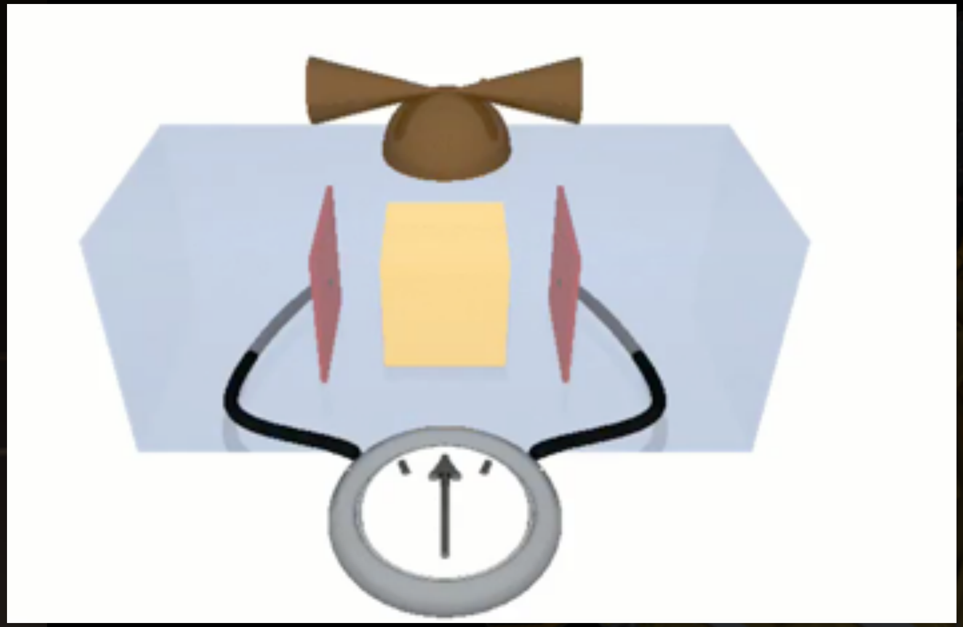
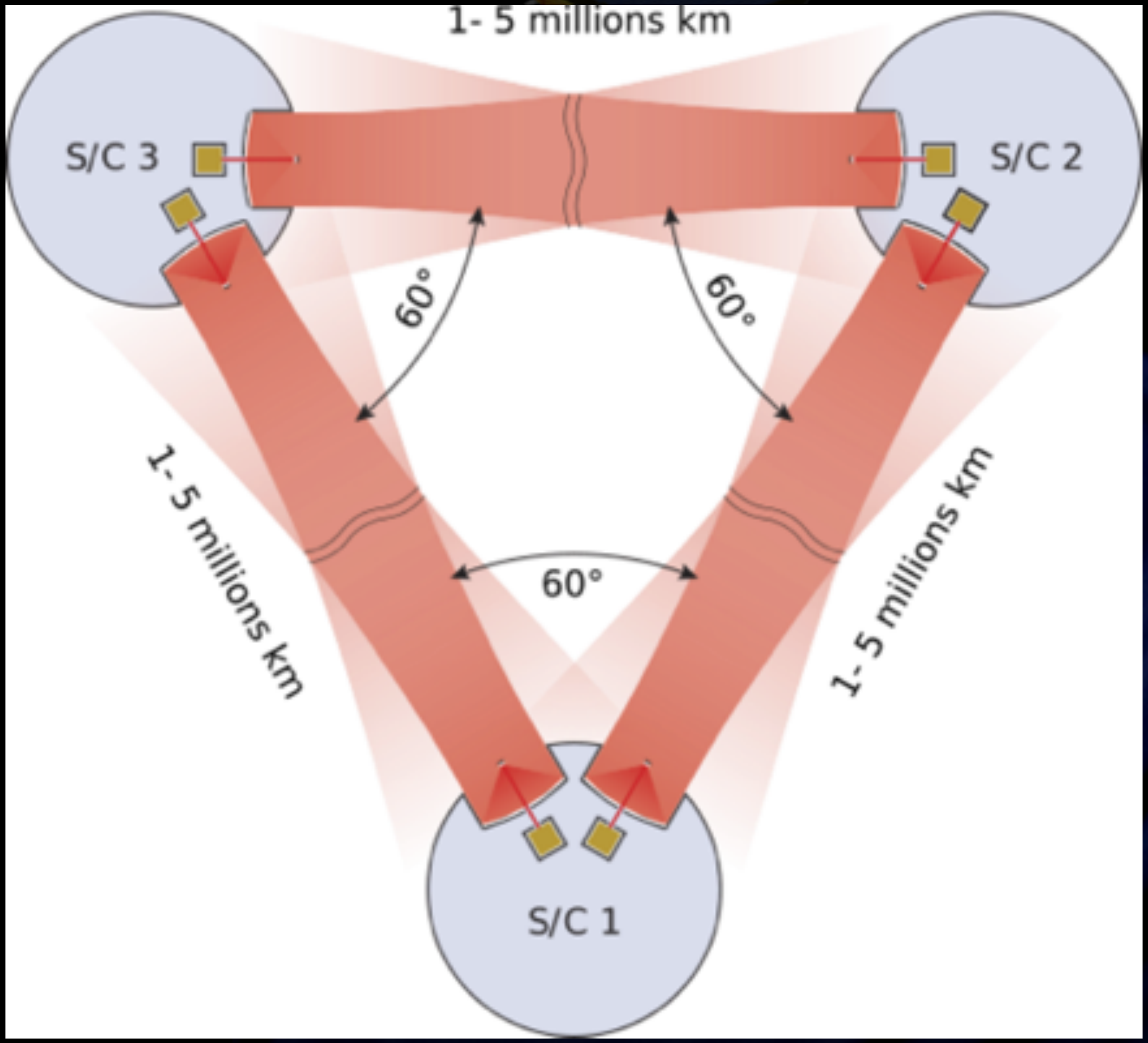
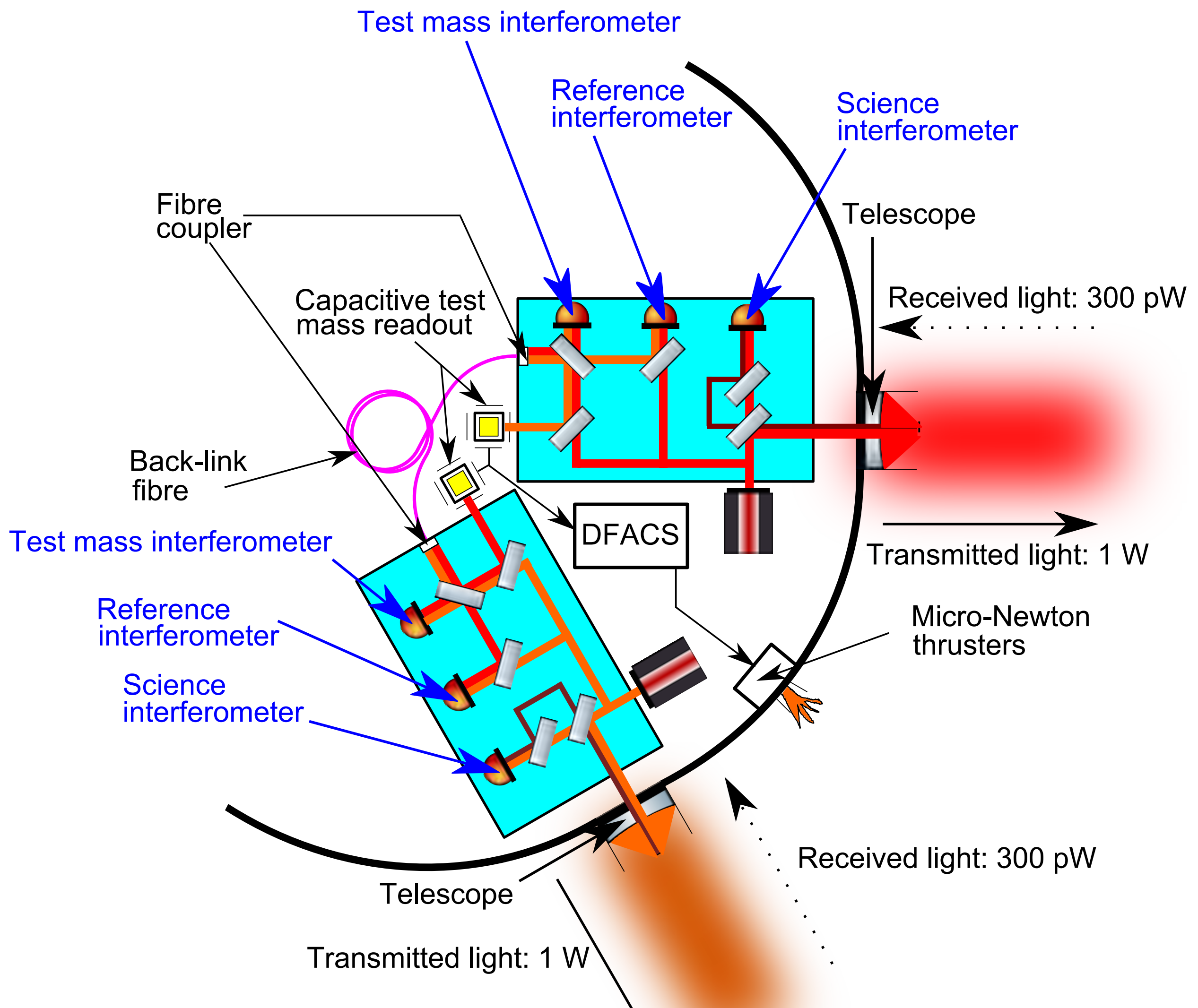




LISA

- Exchange of laser beam 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
- Noises sources:
  - Laser noise : 10^{-13} (vs 10^{-21})
  - Clock noise (3 clocks)
  - Acceleration noise (see LPF)
  - Read-out noises



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LISA

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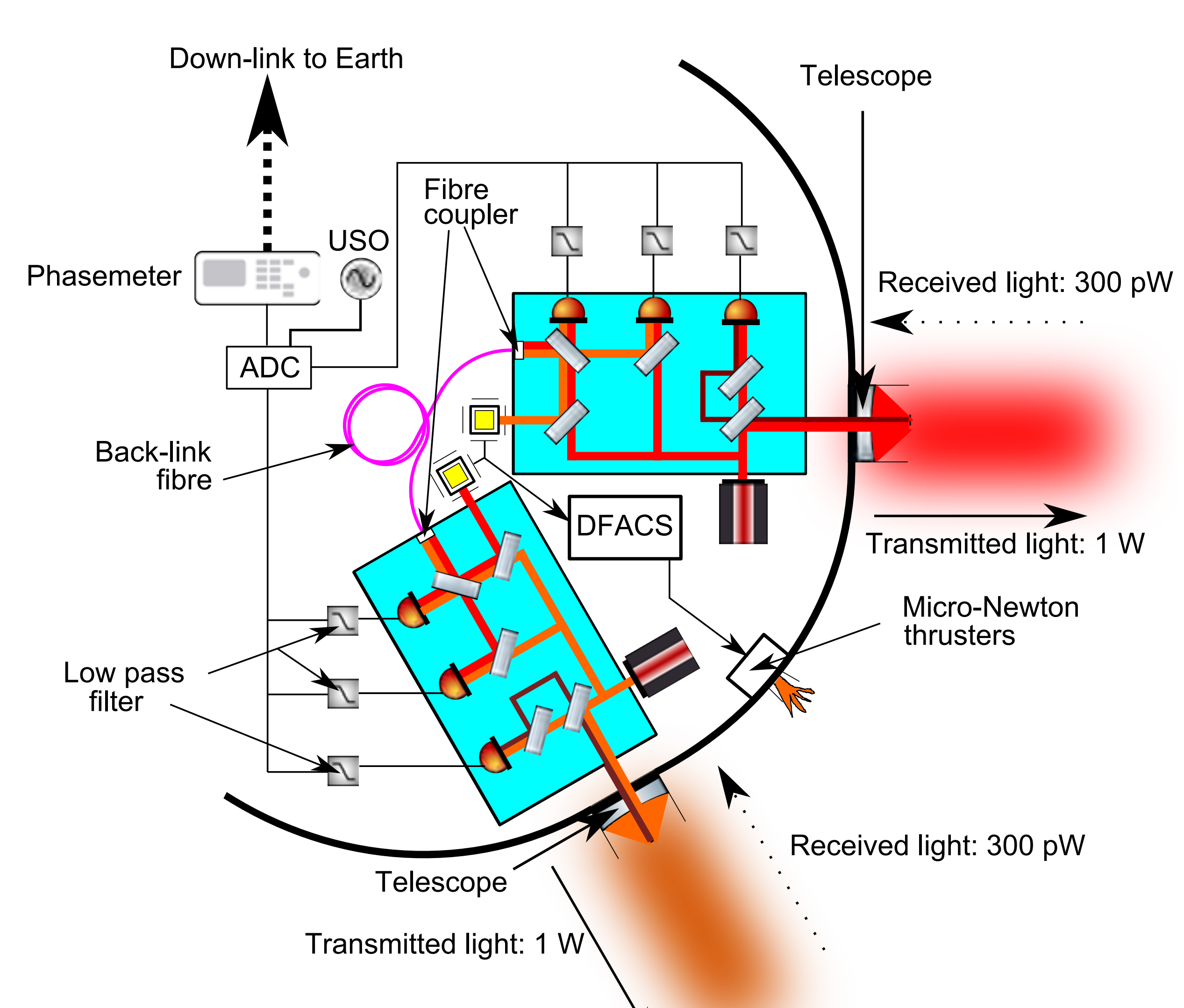

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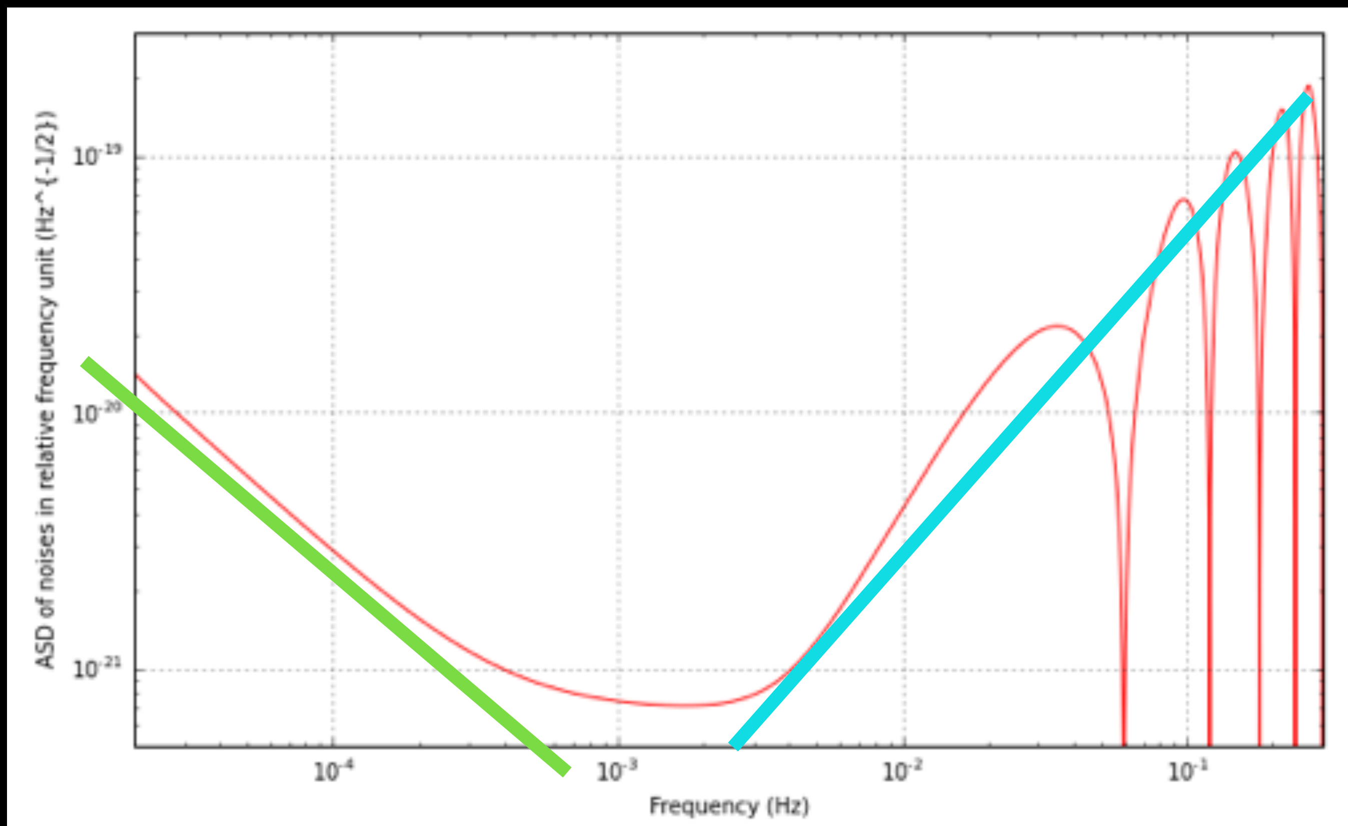
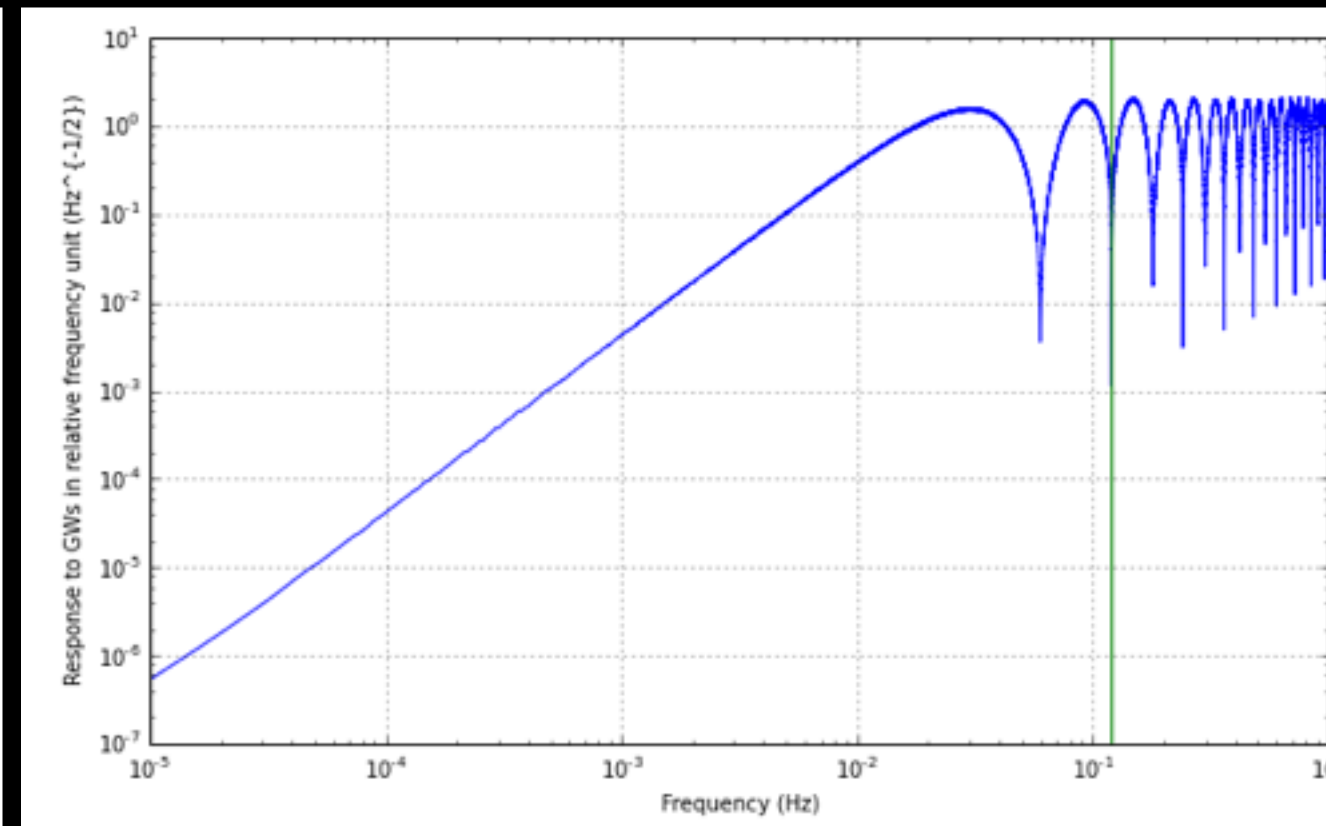
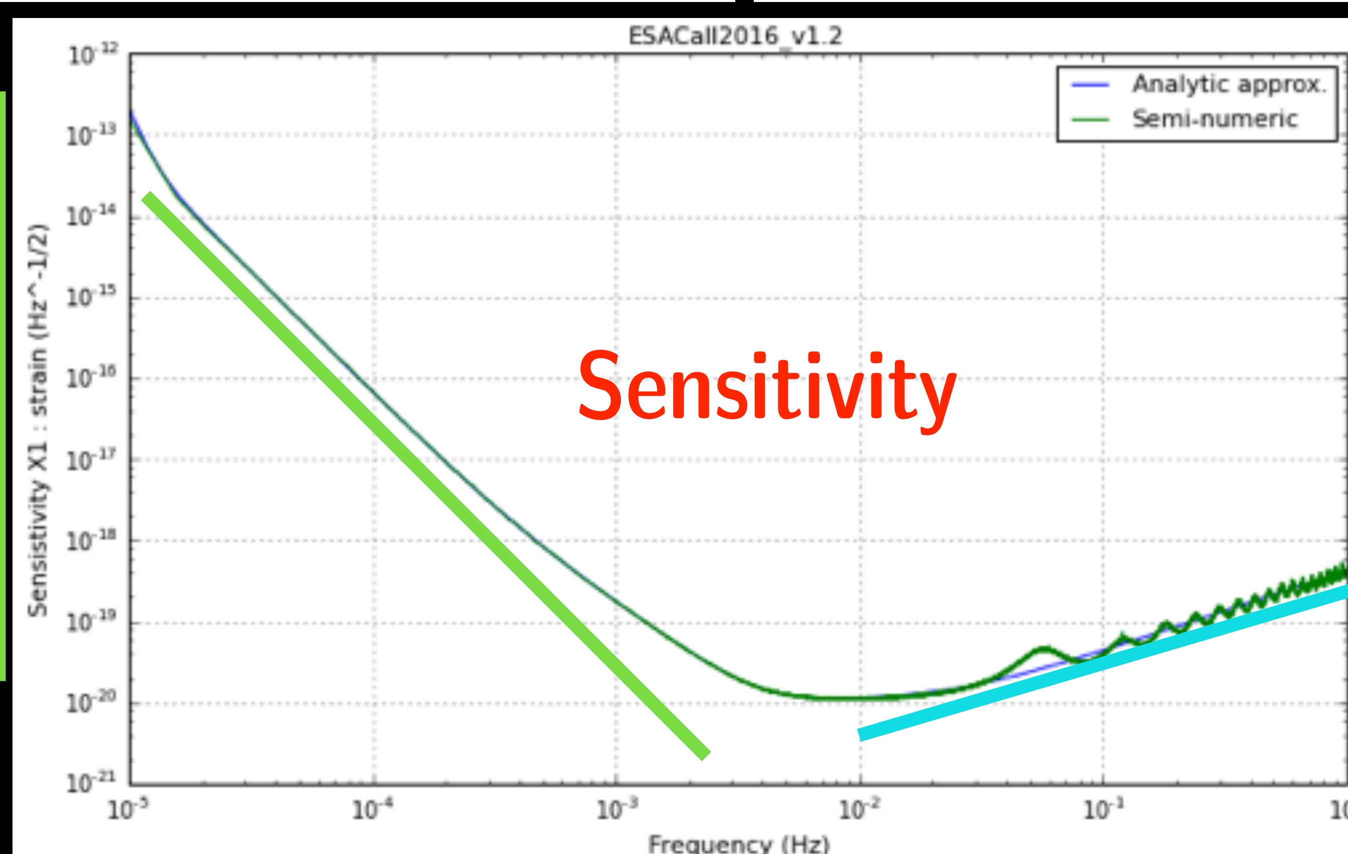
LISA

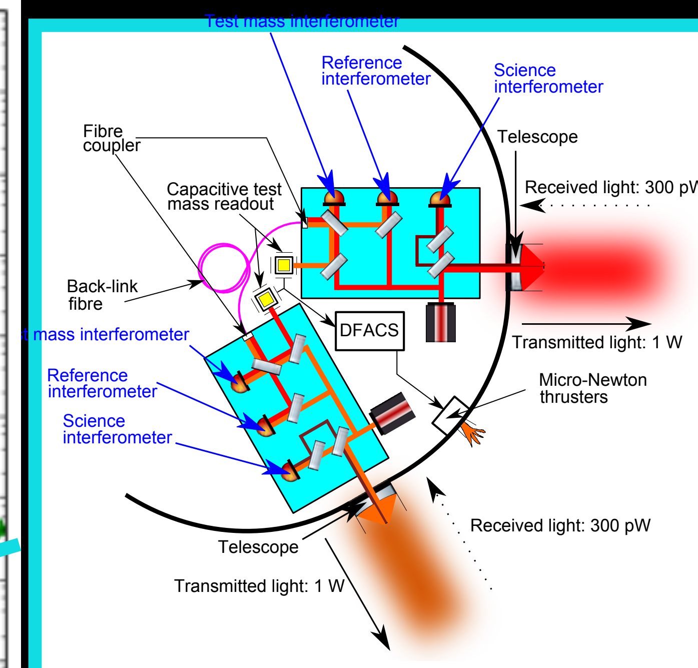
Noises

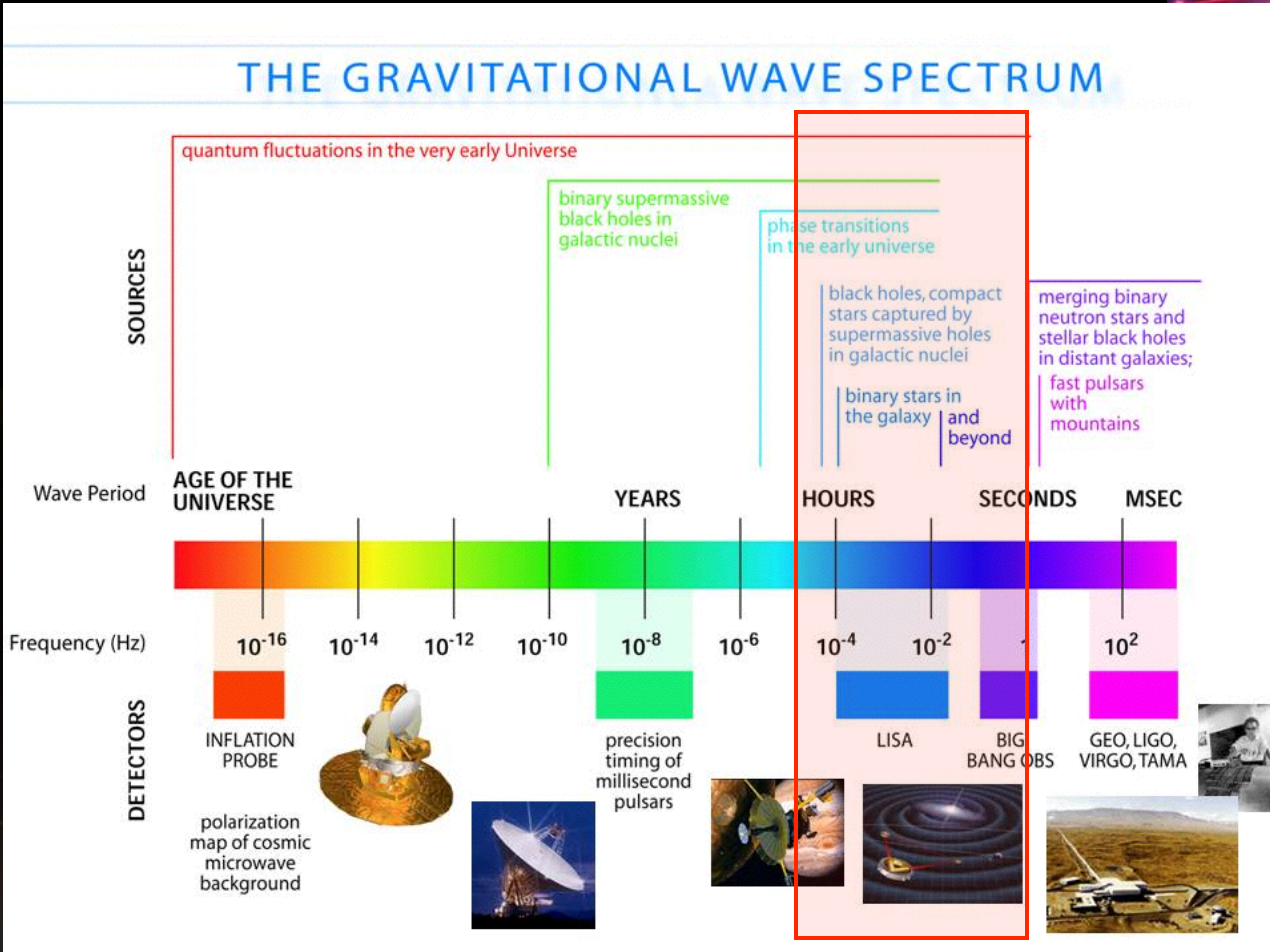


Response of the detector to GWs








THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{2}
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA