LISA Ground Segment

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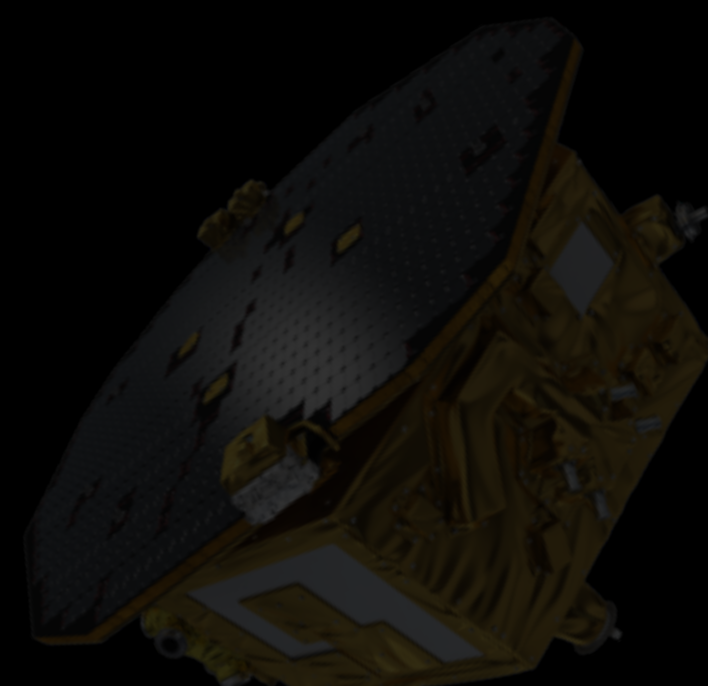
in collaboration with L. Chaoul (CNES), M. Le Jeune (APC)

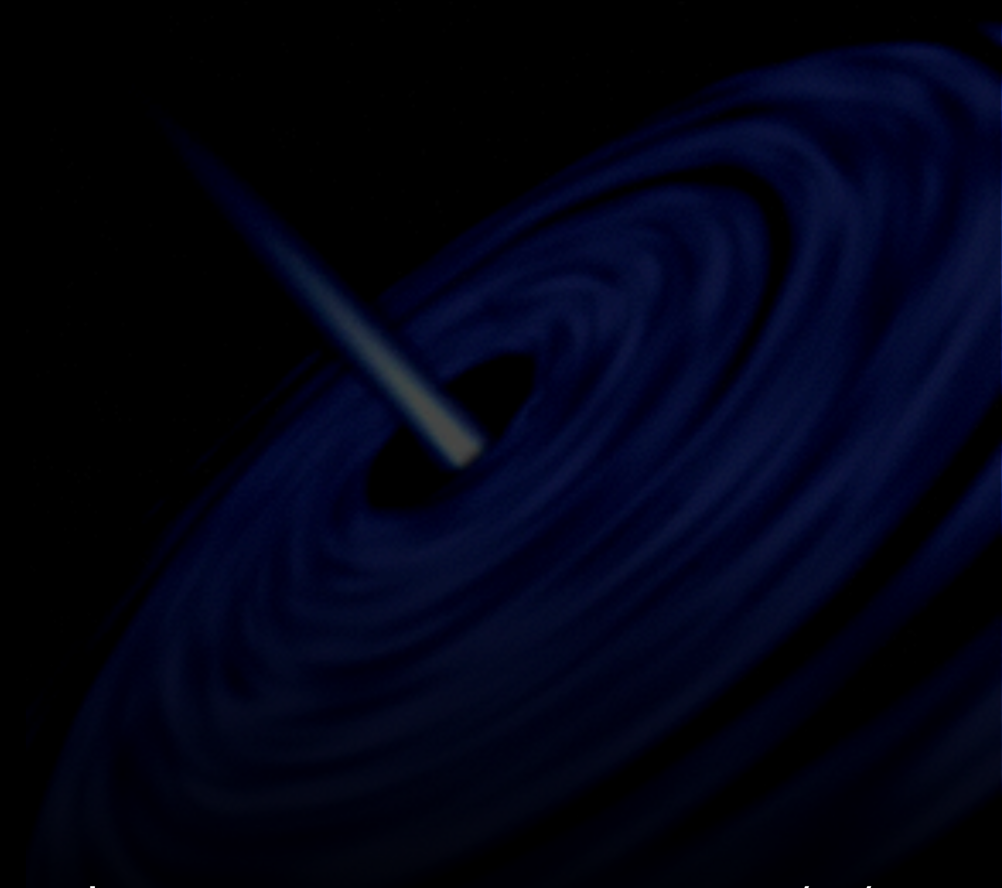
and with the inputs/feedbacks from LISA Consortium and ESA

SciOps 2017 - ESAC

20 October 2017

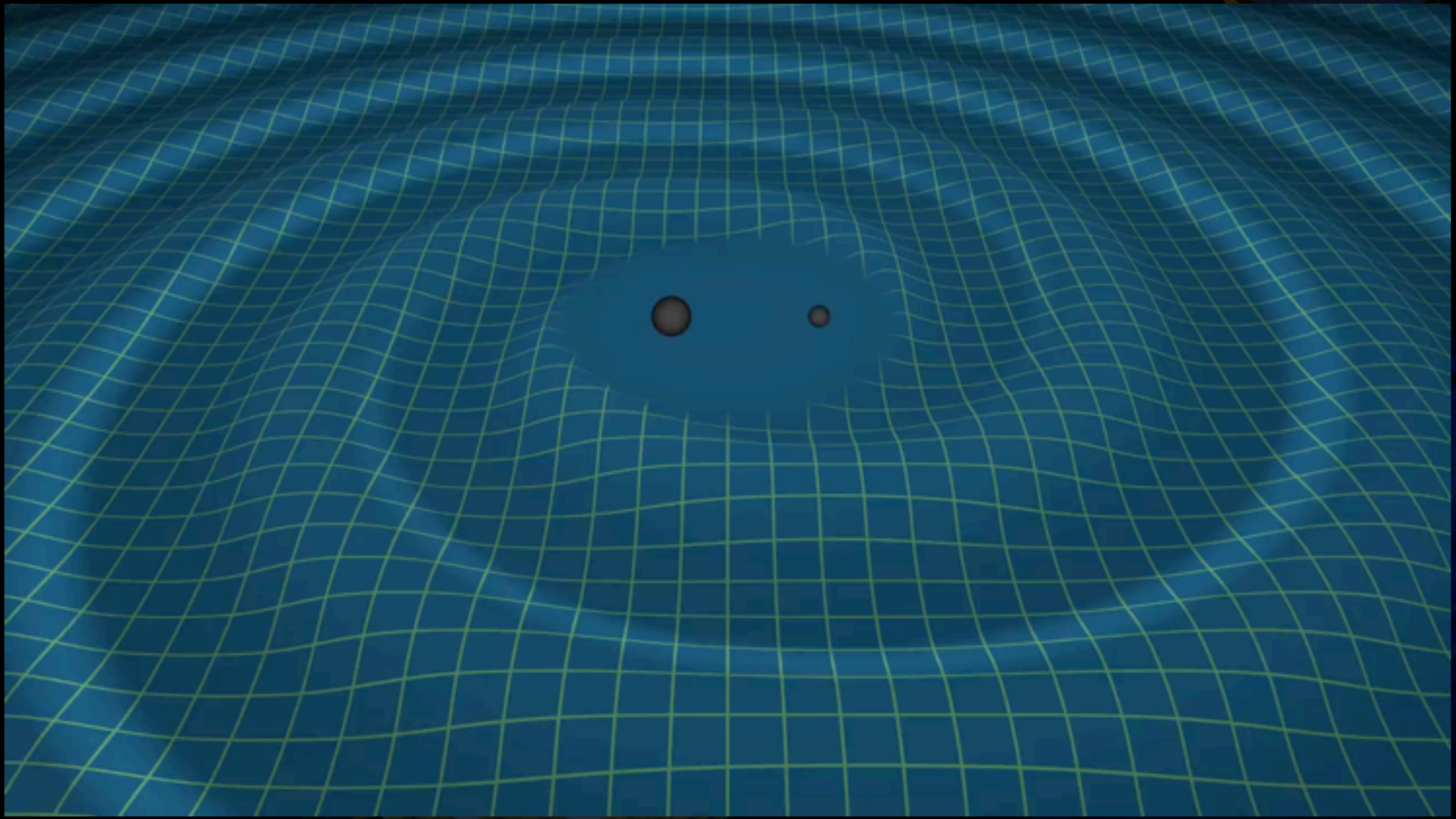
Gravitational waves (GWs)





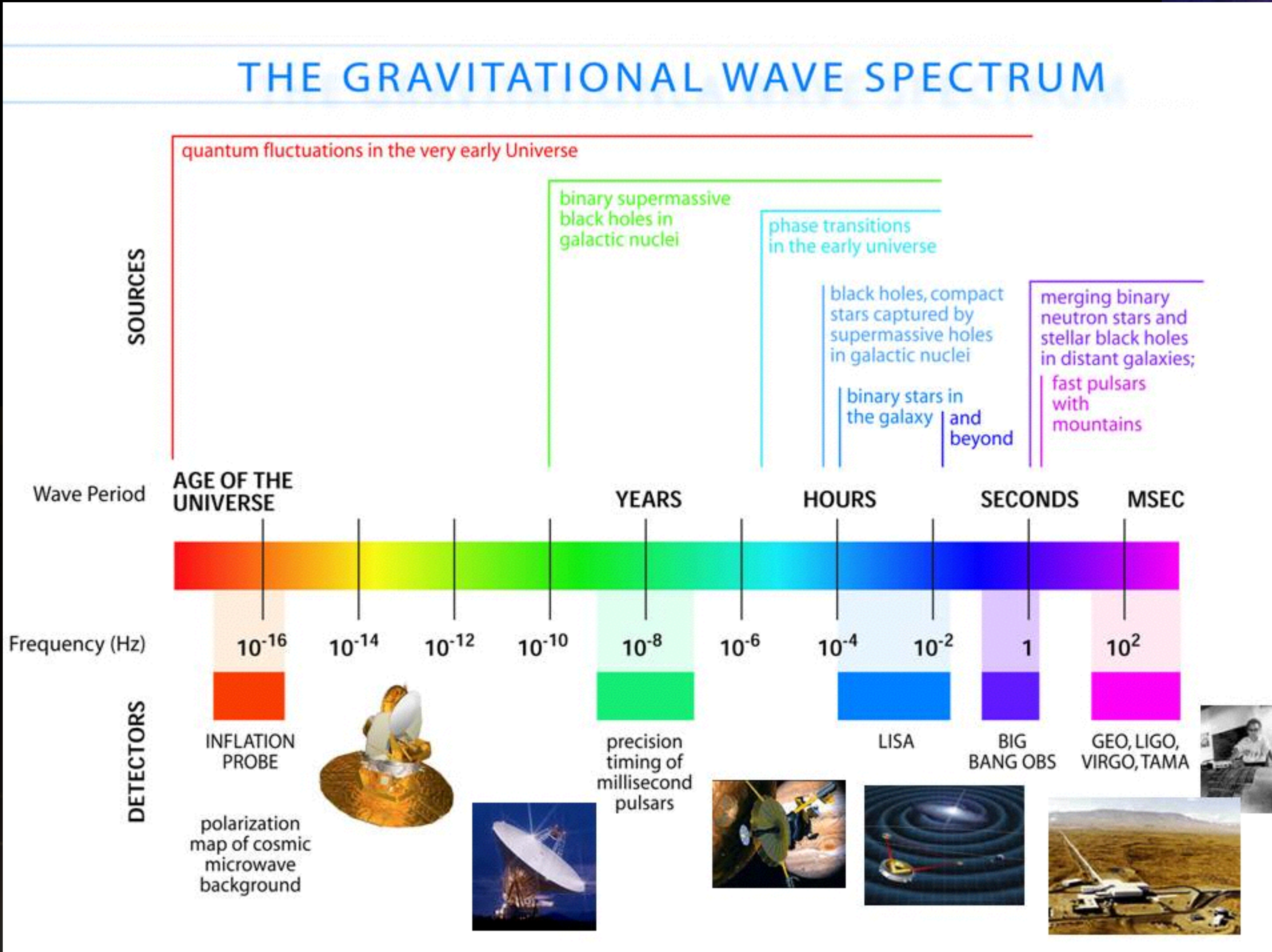
Gravitational waves (GWs)

- General relativity: GW are created by non-spherical acceleration of one or several massive objects (asymetric collapse, bodies in orbits or coalescing)



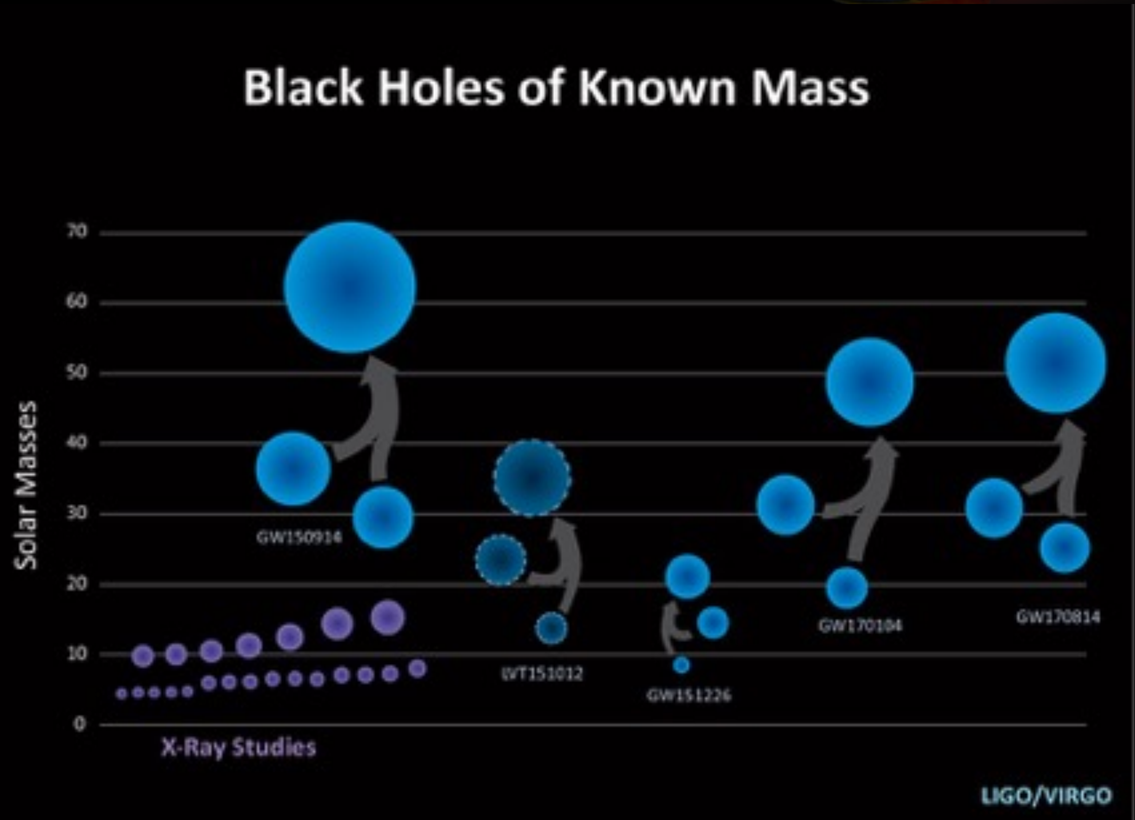
Gravitational waves (GWs)

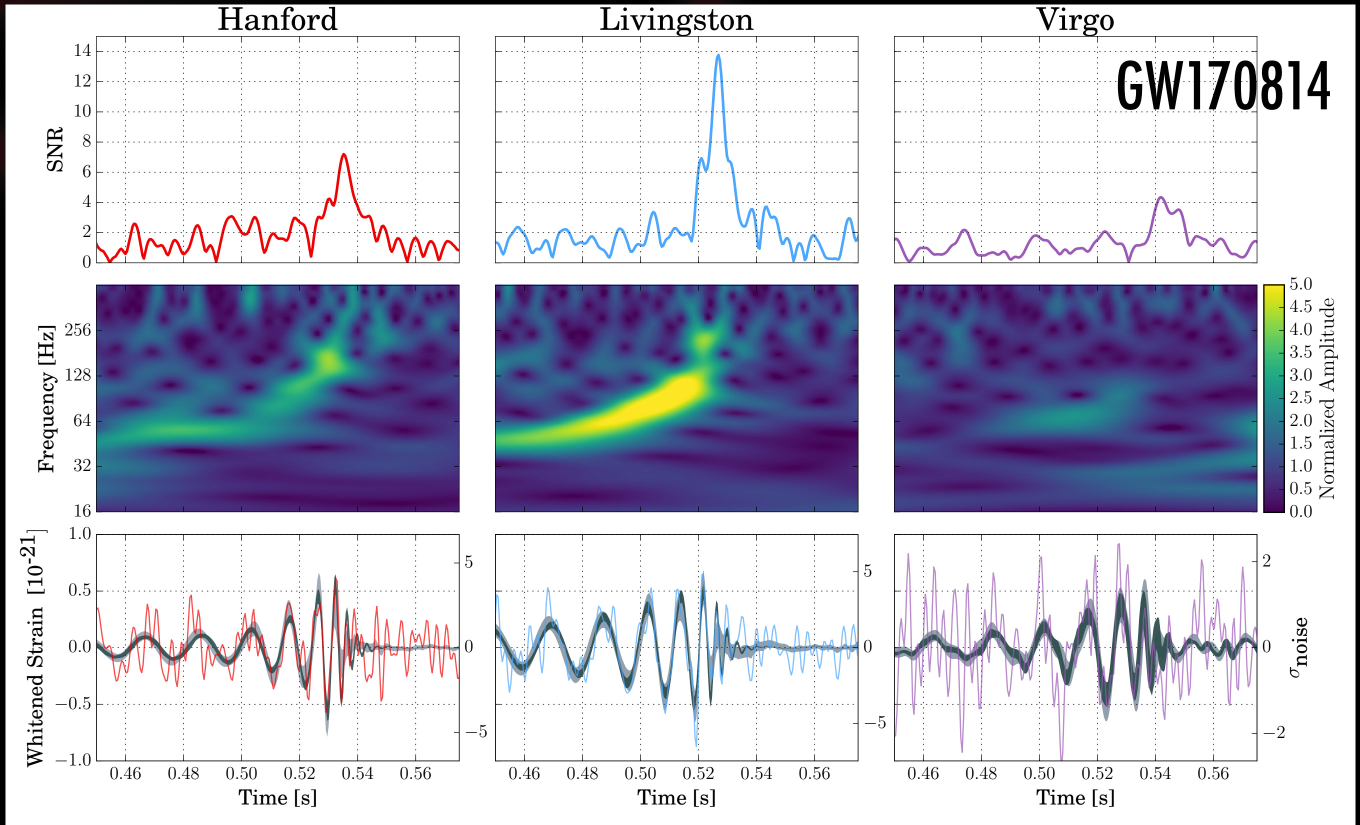
- General relativity: GW are created by non-spherical acceleration of one or several massive objects (asymetric collapse, bodies in orbits or coalescing)
- Modification of distance between 2 objects:
  - Elastic deformation proportional to the distance between the 2 obj.,
  - Transverse deformation: perpendicular to the direction of propagation (different from ripples on water !),
  - Two components of polarisation : h_+ and $h_\times$



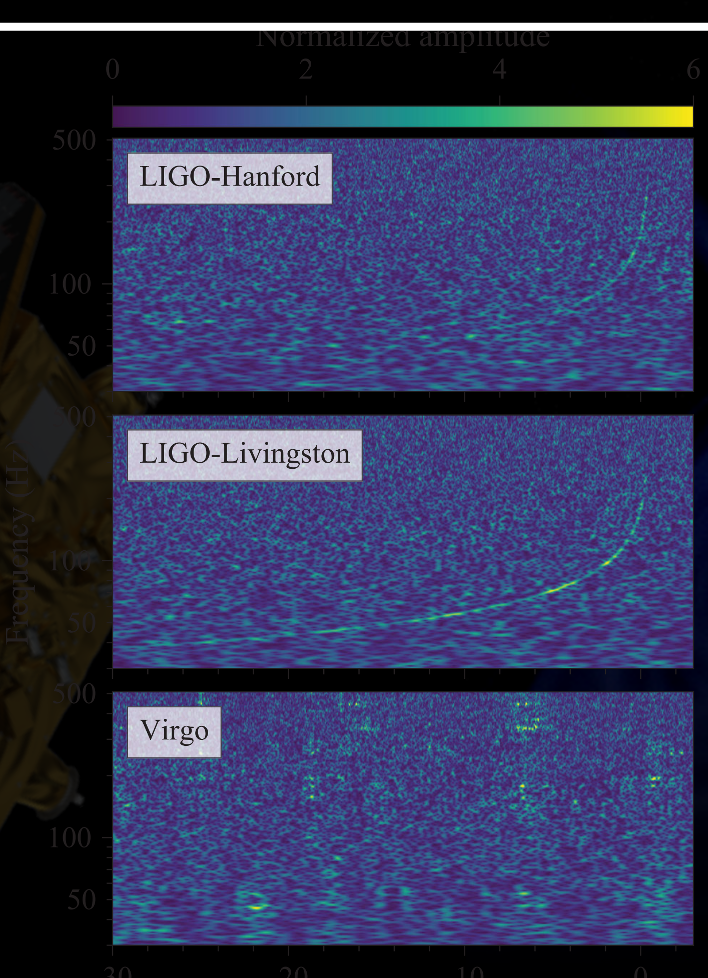
THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging 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}
1
10^{2}
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA

GWs detected



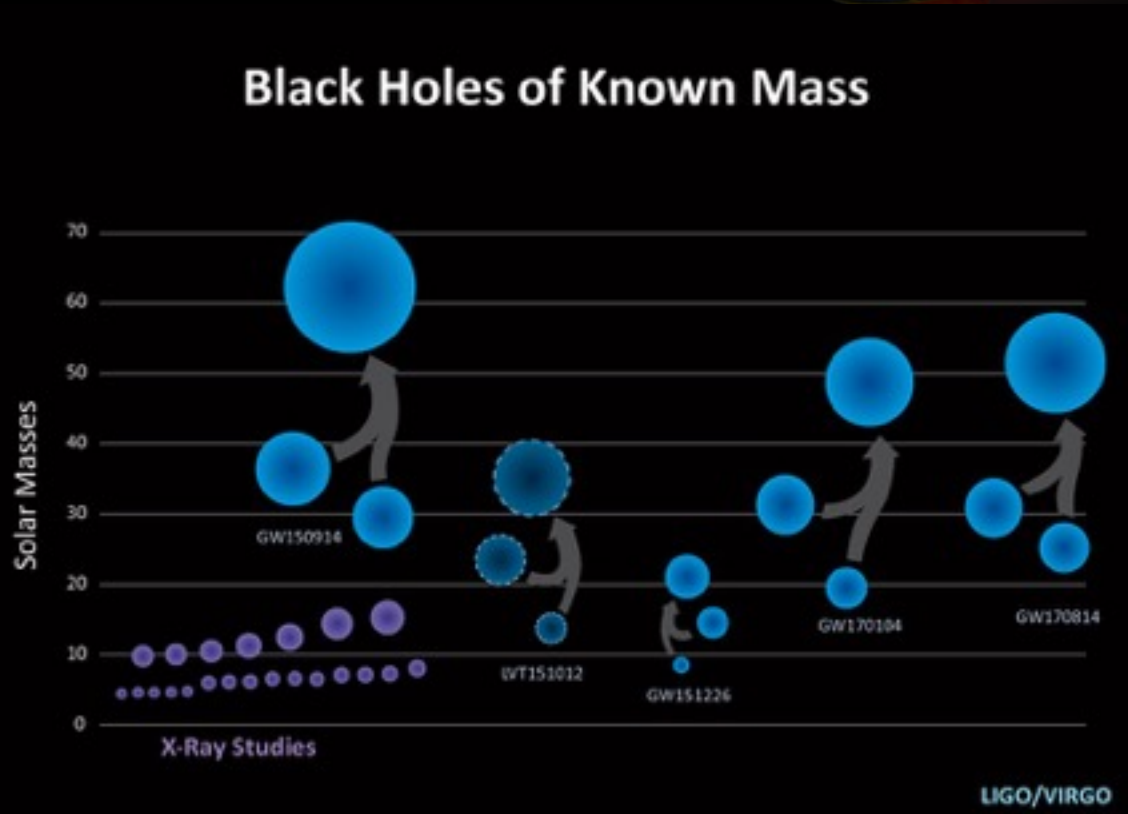


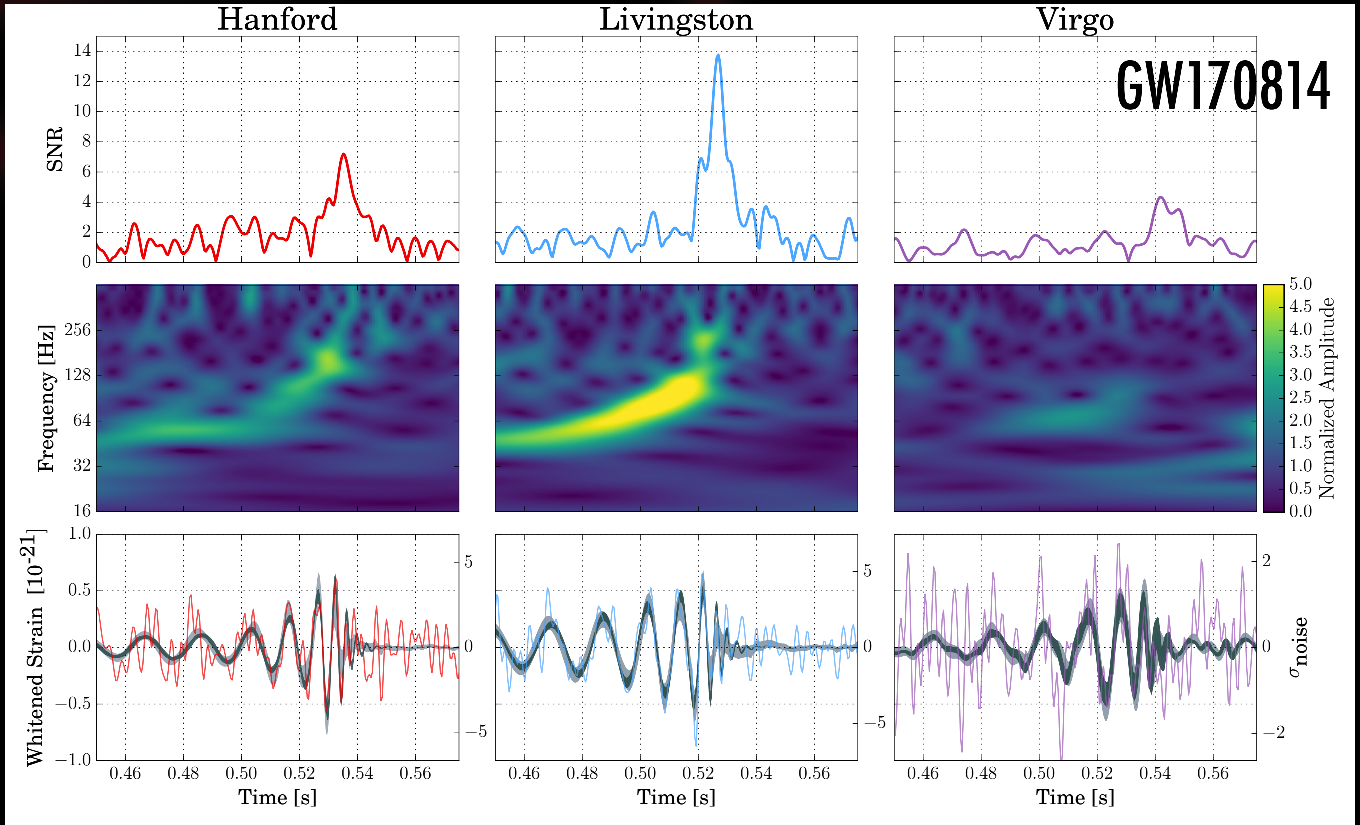
Binary Neutron Star - GW170817



NASA

GWs detected





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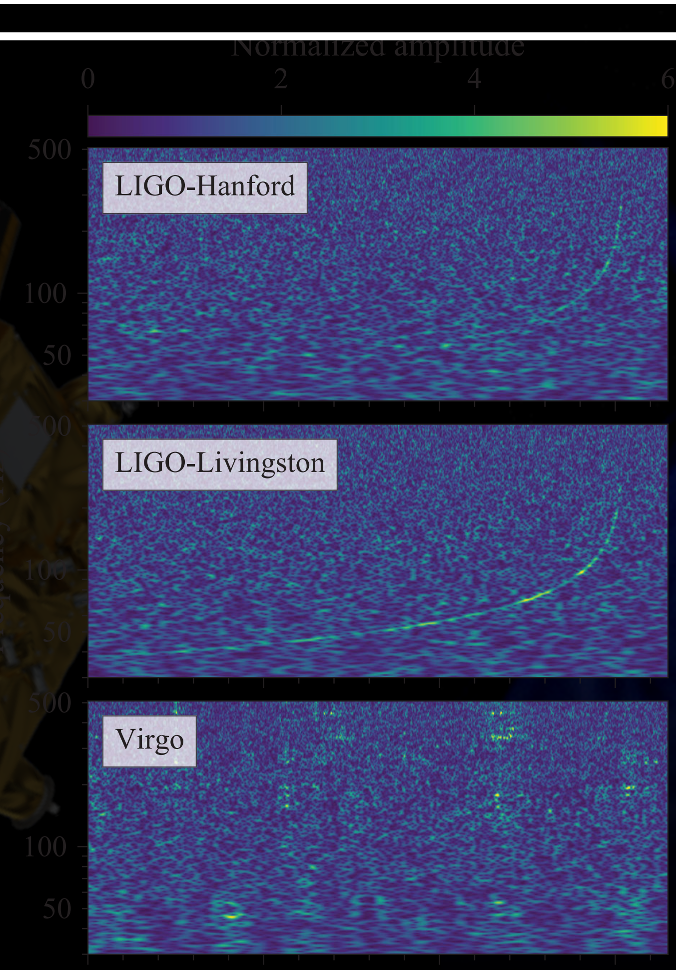
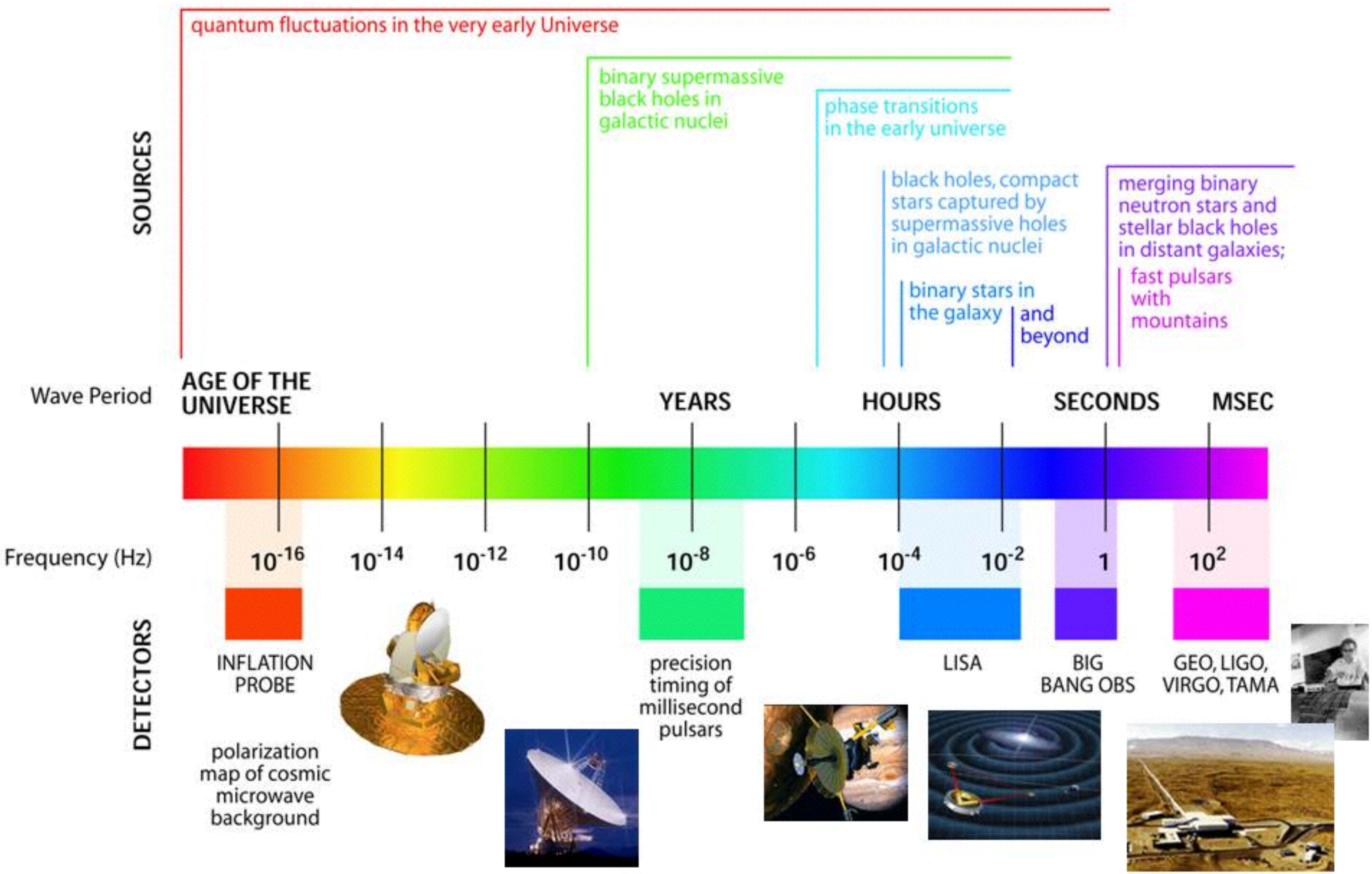
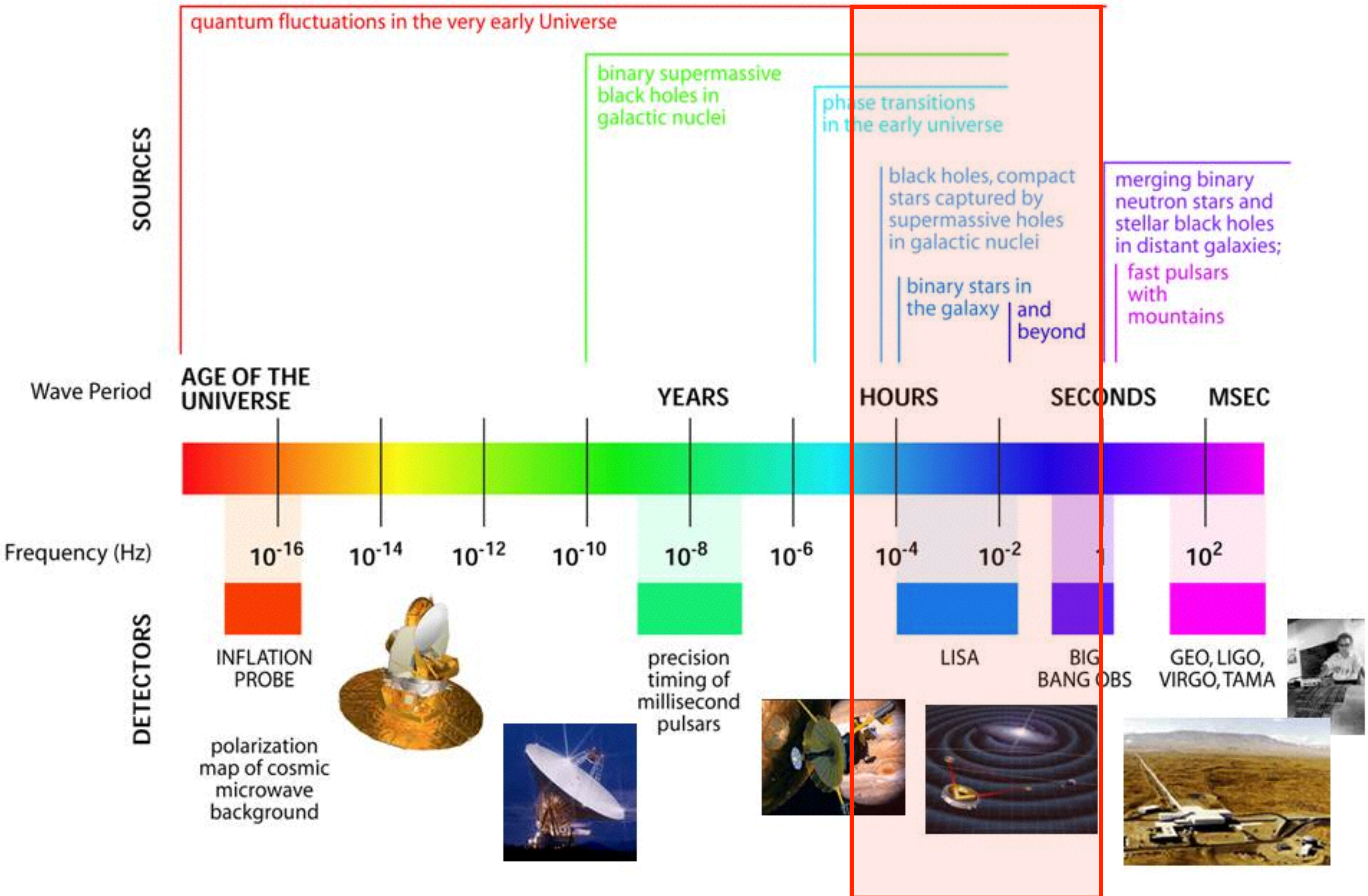


NASA

THE GRAVITATIONAL WAVE SPECTRUM



THE GRAVITATIONAL WAVE SPECTRUM



History of LISA

- 1978: first study based on a rigid structure (NASA)
- 1980s: studies with 3 free-falling spacecrafts (US)
- 1993: proposal ESA/NASA: 4 spacecrafts
- 1996-2000: pre-phase A report
- 2000-2010: LISA and LISAPathfinder: ESA/NASA mission
- 2011: NASA stops => ESA continue: reduce mission
- 2012: selection of JUICE L1 ESA
- 2013: selection of ESA L3 : « The gravitational Universe »
- 2015-2016: success of LISAPathfinder + detection GWs

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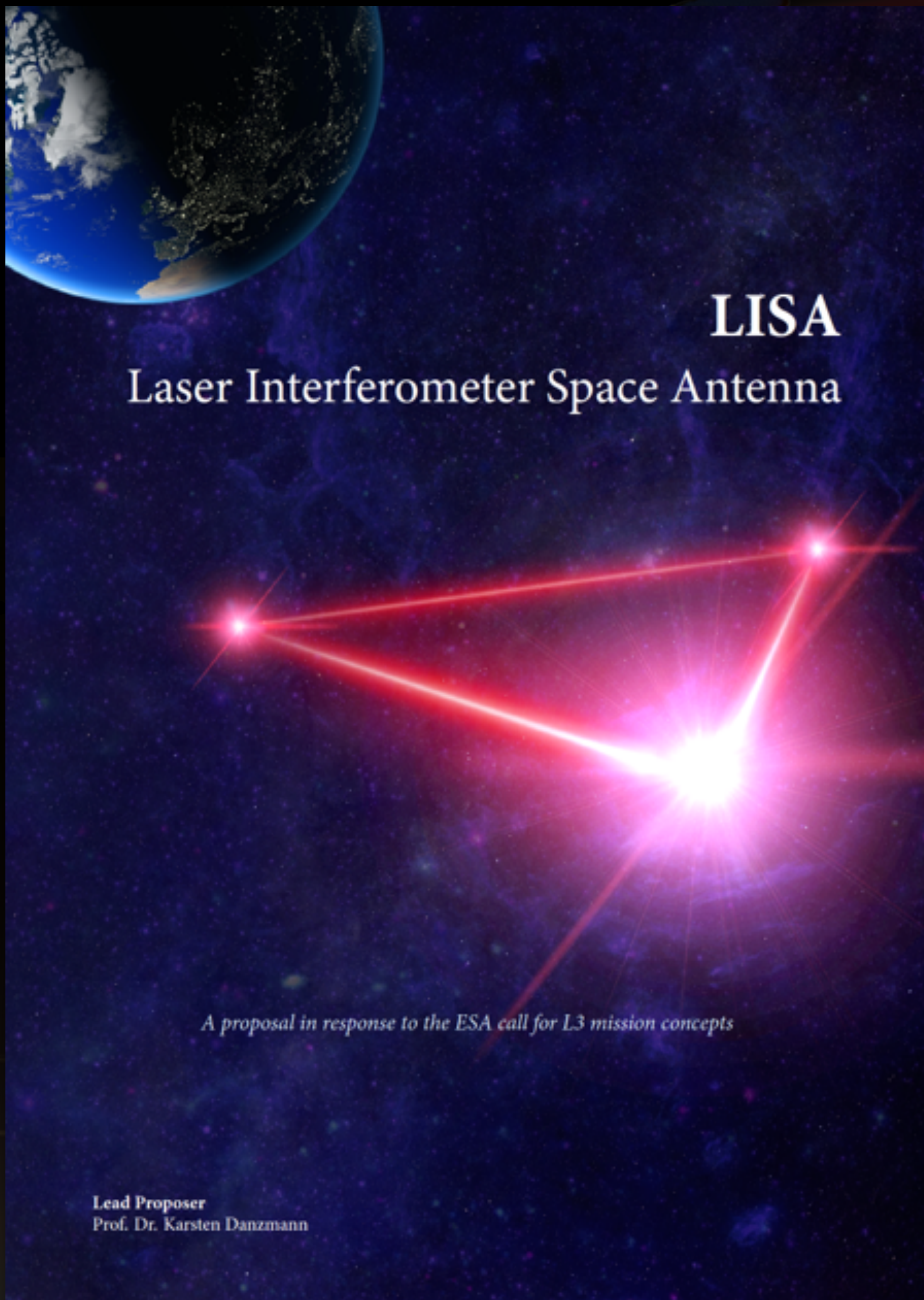
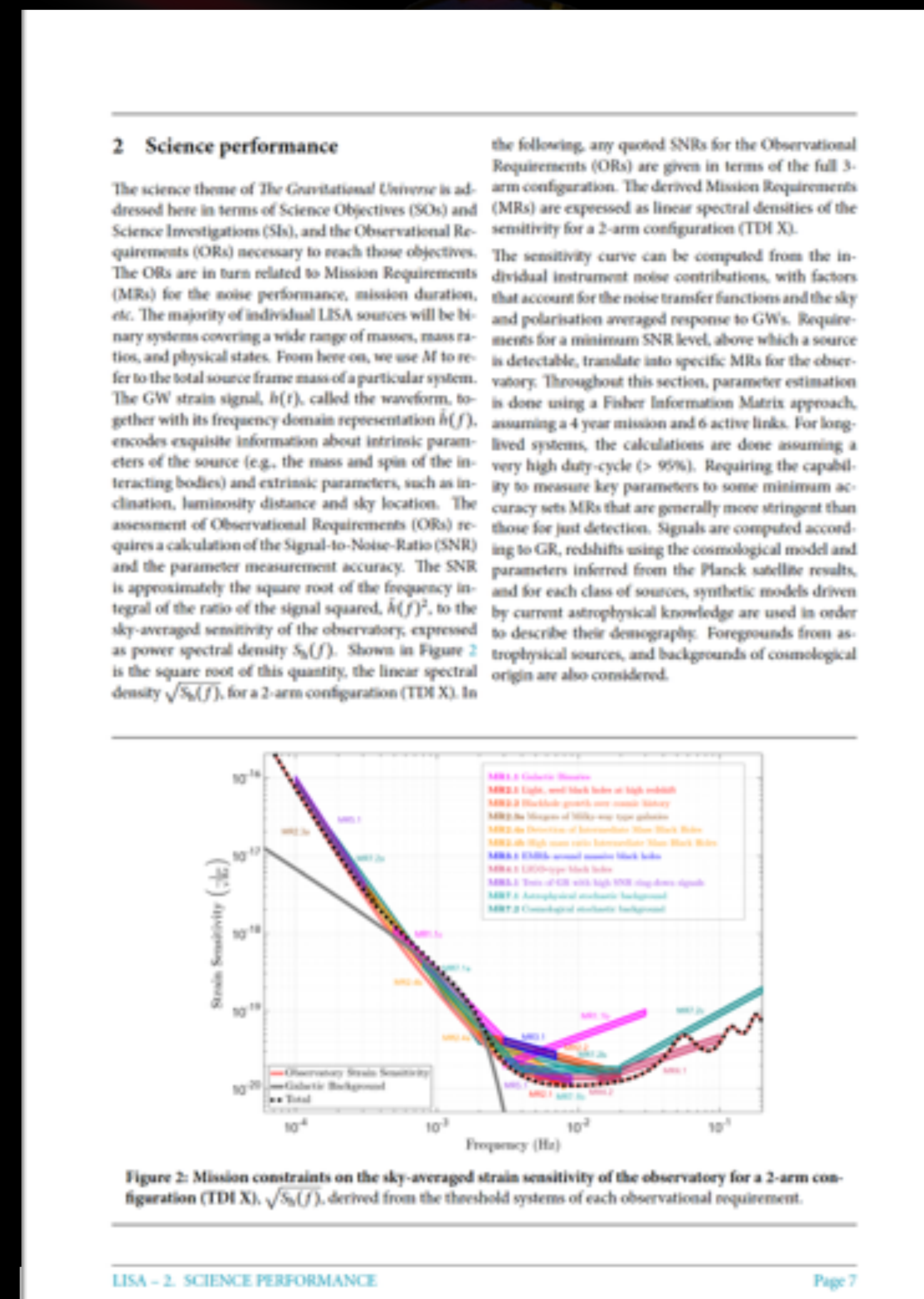
Call for mission at ESA

The LISA Proposal

https://www.lisamission.org/proposal/LISA.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.

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 science objectives

- SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages
- SO3: Probe the 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
- SO8: Search for GW bursts and unforeseen sources

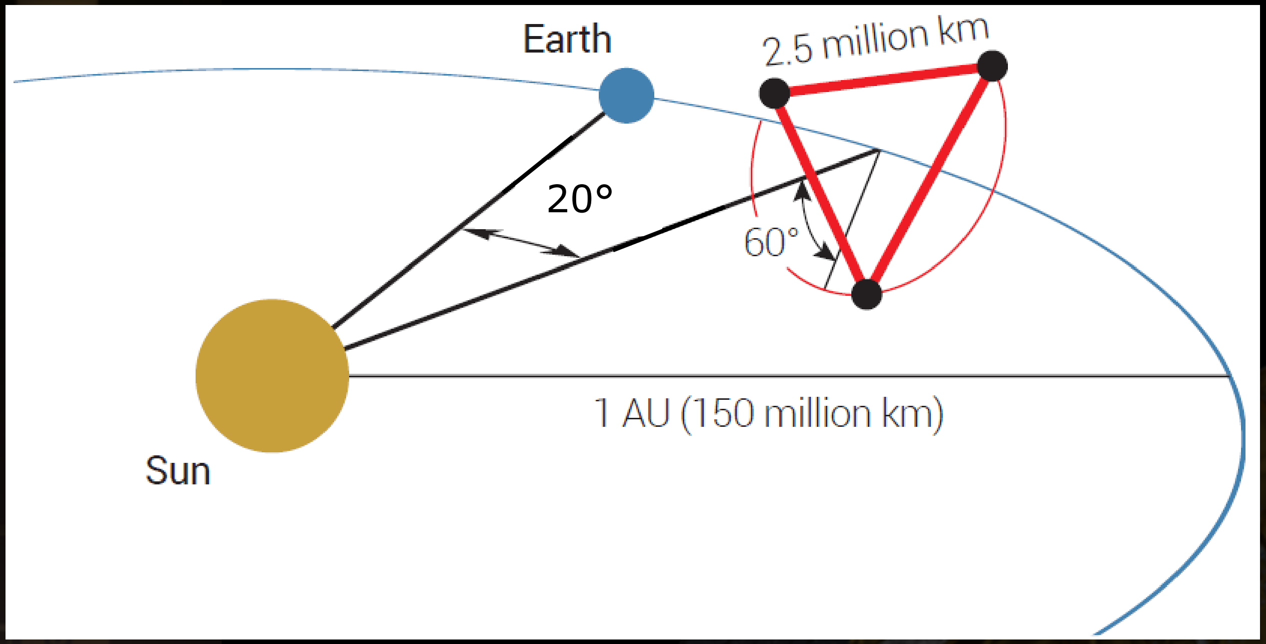
LISA at ESA

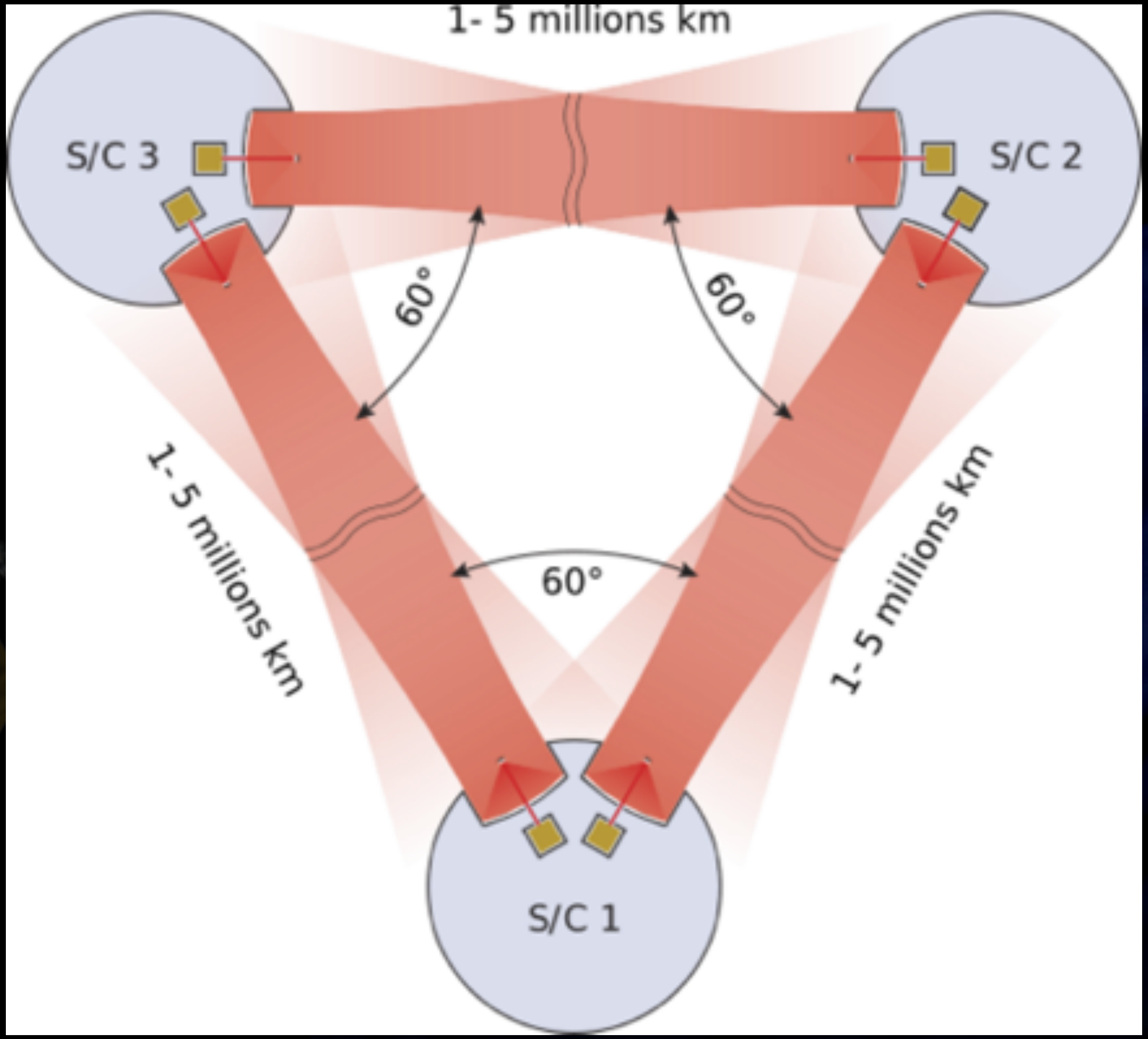
- 25/10/2016 : Call for mission
- 13/01/2017 : submission of «LISA proposal» (LISA consortium)
- 8/3/2017 : Phase 0 mission (CDF 8/3/17 → 5/5/17)
- 20/06/2017 : LISA mission approved by SPC
- 8/3/2017 : Phase 0 payload (CDF June → November 2017)
- 2018→2020 : competitive phase A : 2 companies compete
- 2020→2022 : B1: start industrial implementation
- 2022-2024 : mission adoption
- During about 8.5 years : construction
- 2030-2034 : launch Ariane 6.4
- 1.5 years for transfert
- 4 years of nominal mission
- Possible extension to 10 years

GW observations !

LISA

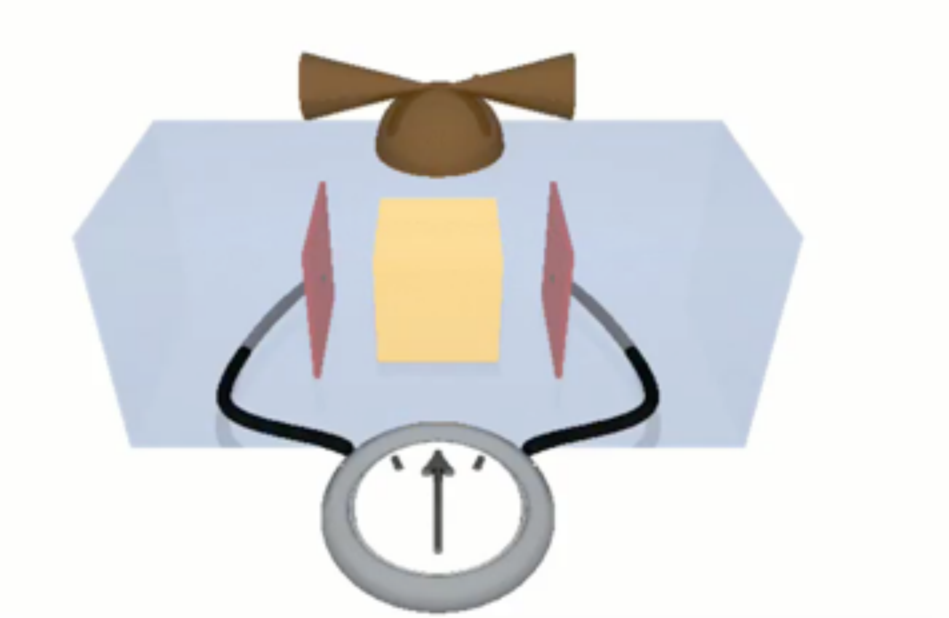
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of 10^{-21}: few picometers

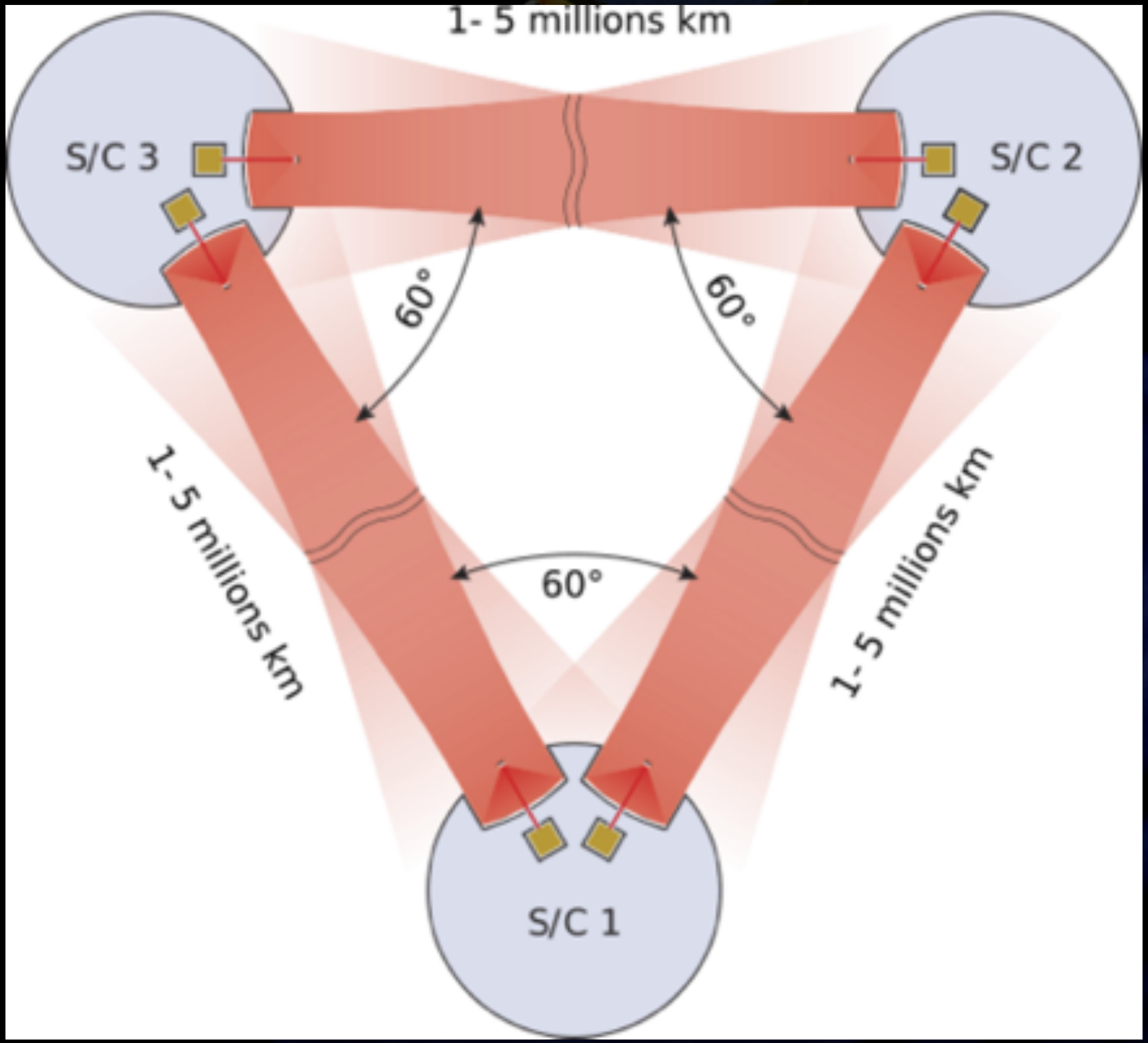




LISA

- 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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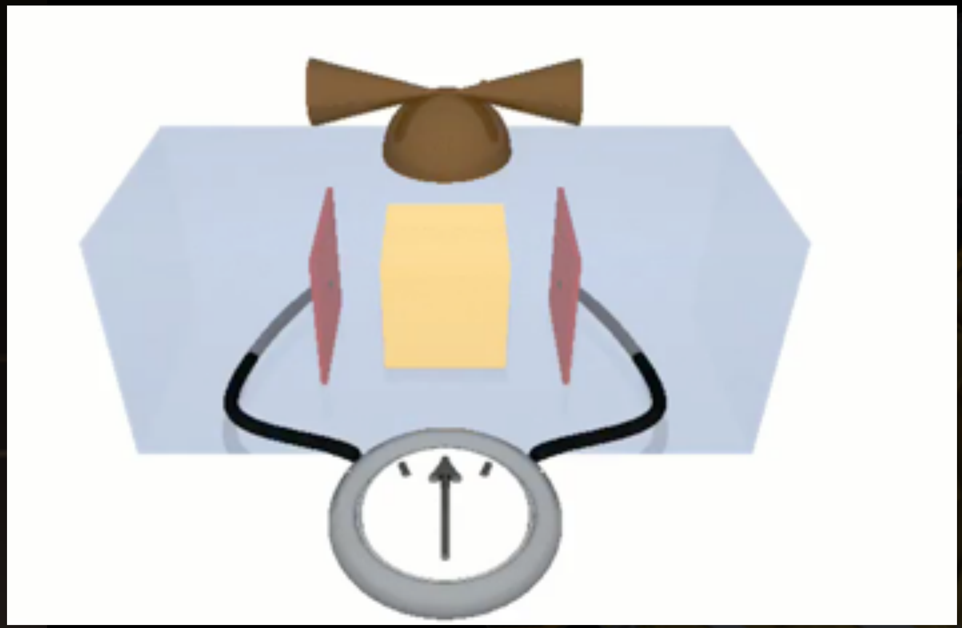
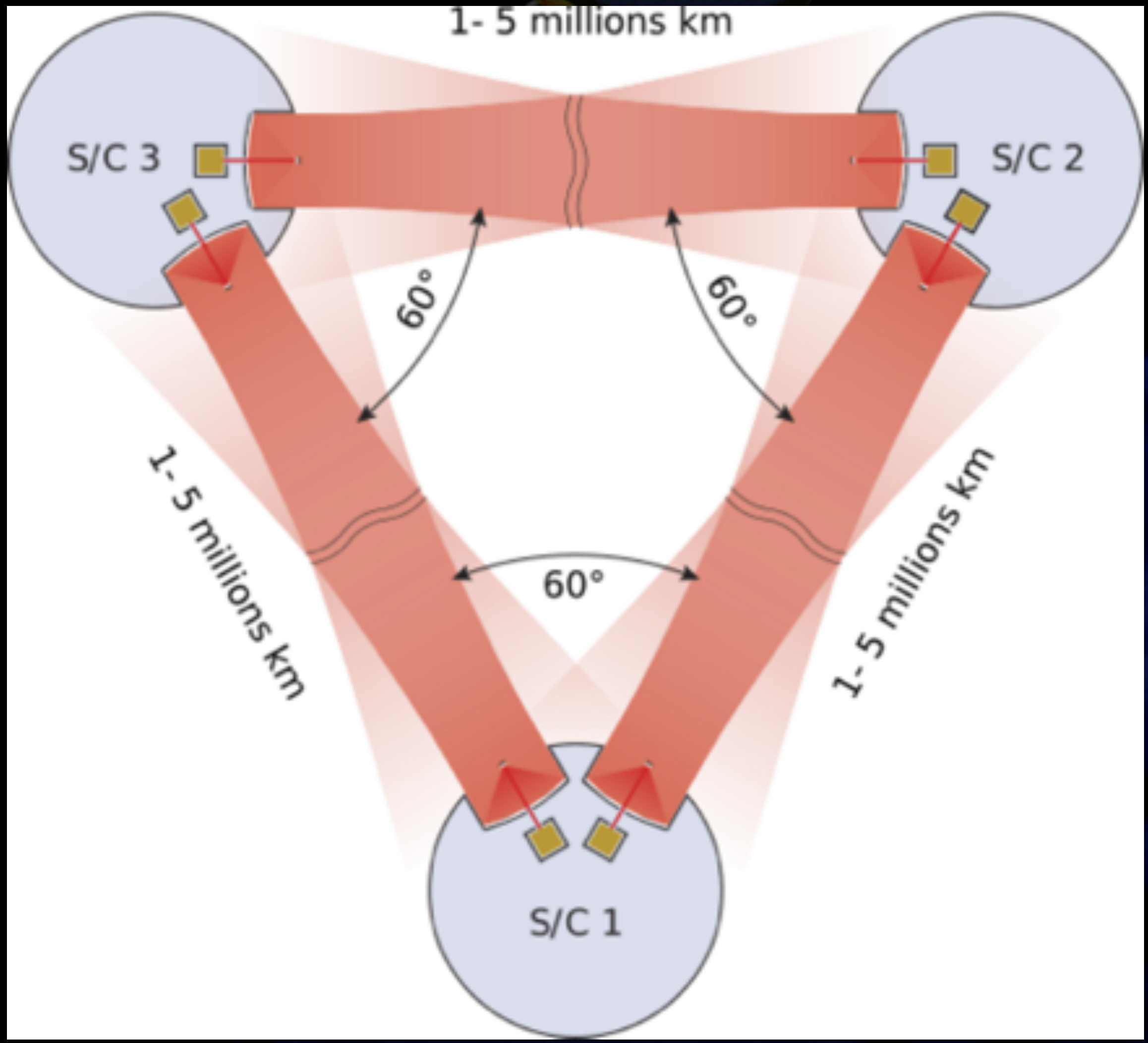
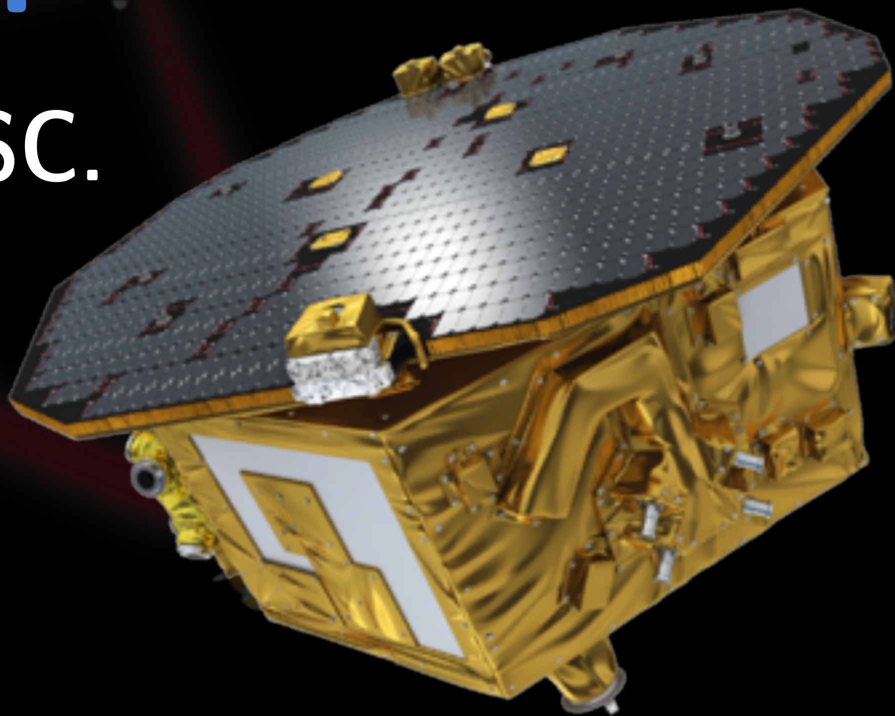
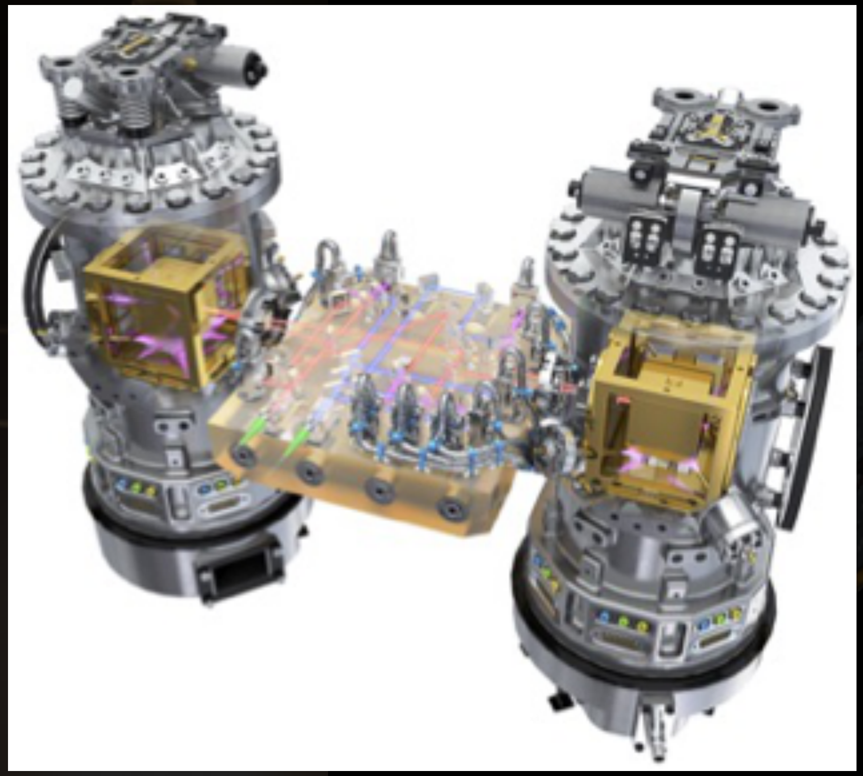


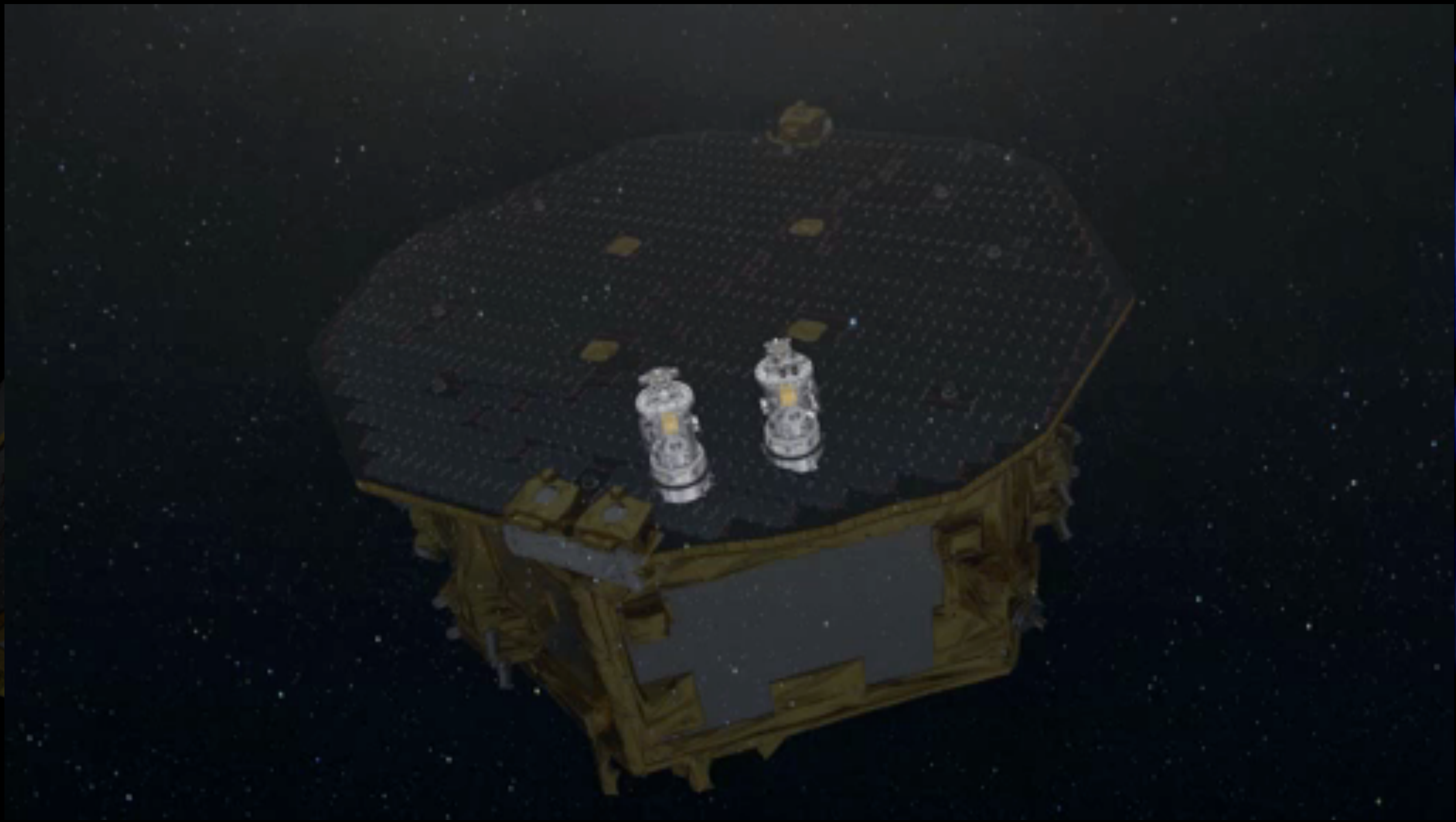


LISAPathfinder

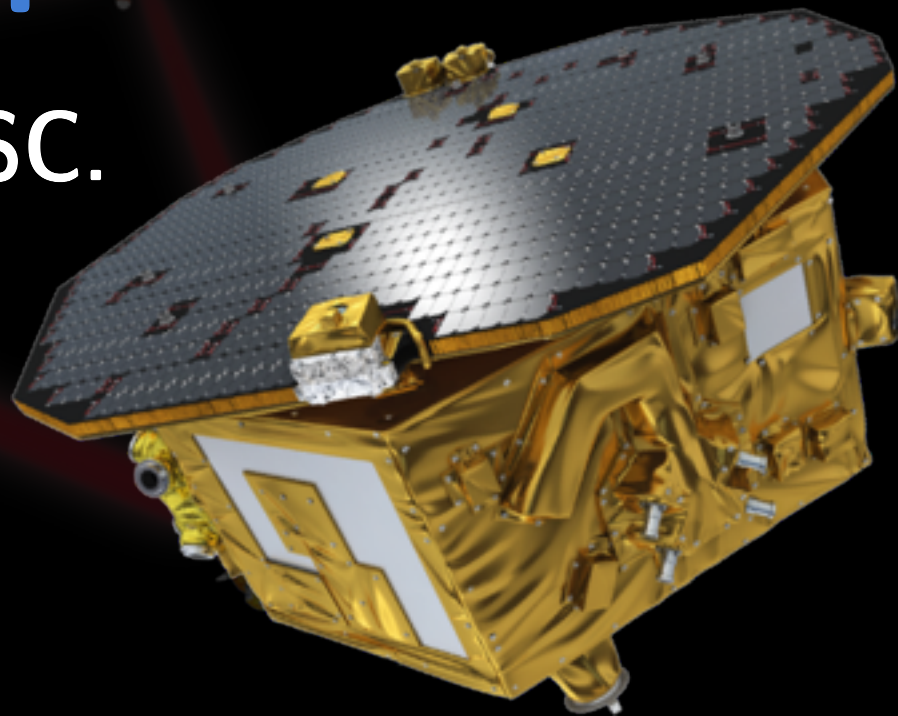


- Basic idea: Reduce one LISA arm in one SC.
- LISAPathfinder is testing :
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
  - Micro-thrusters





LISAPathfinder



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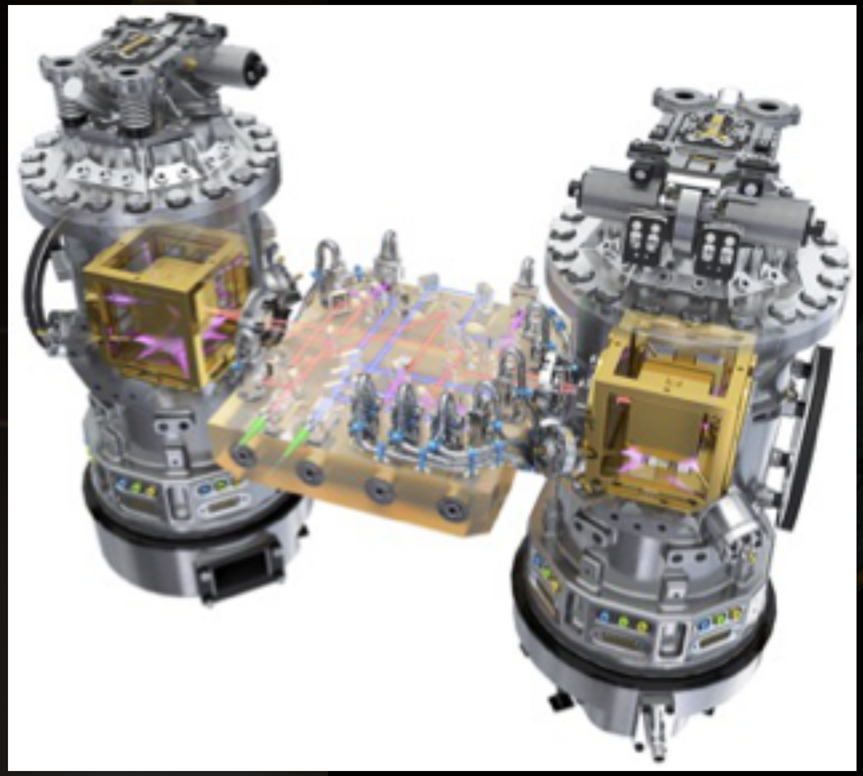
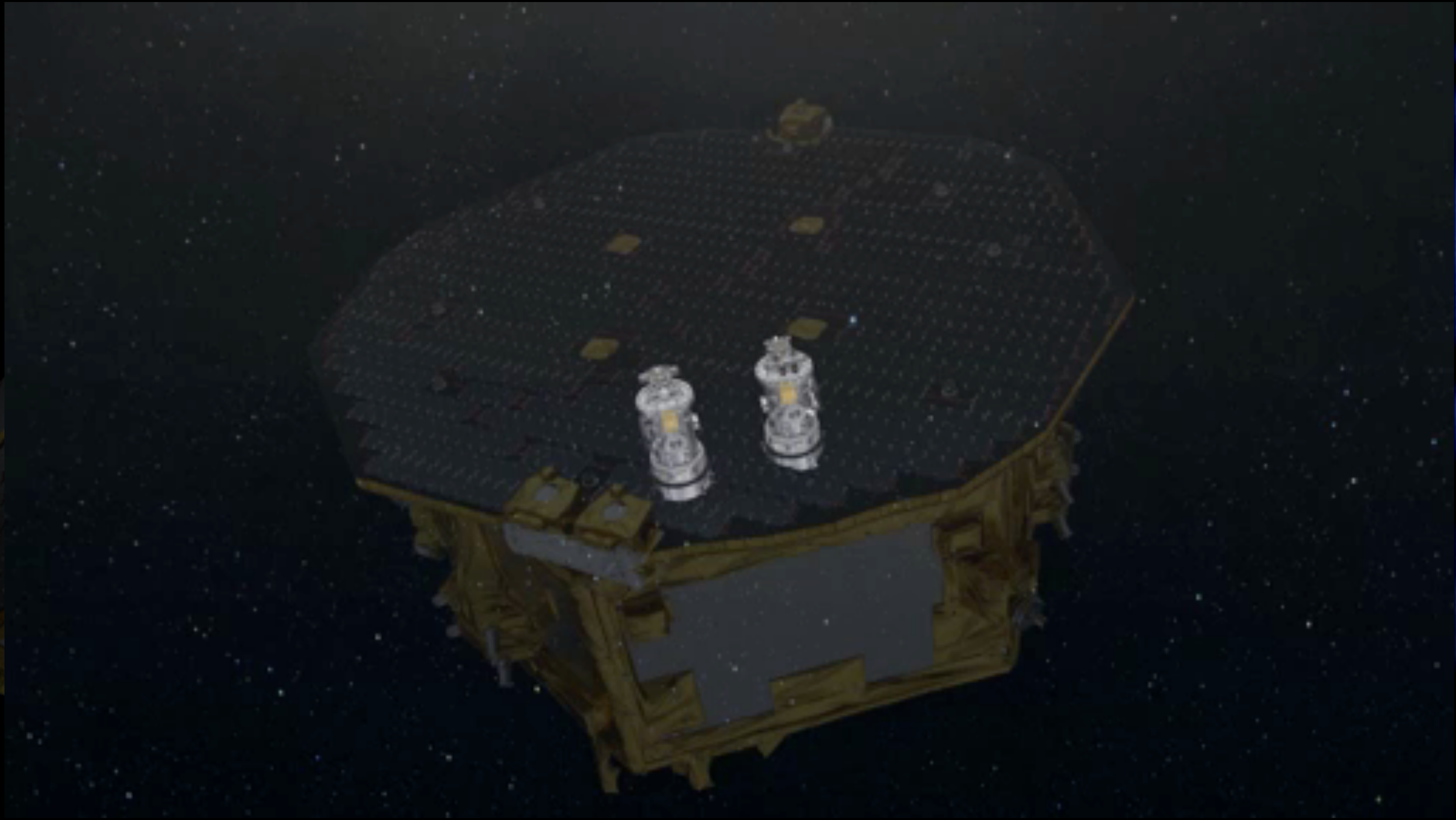
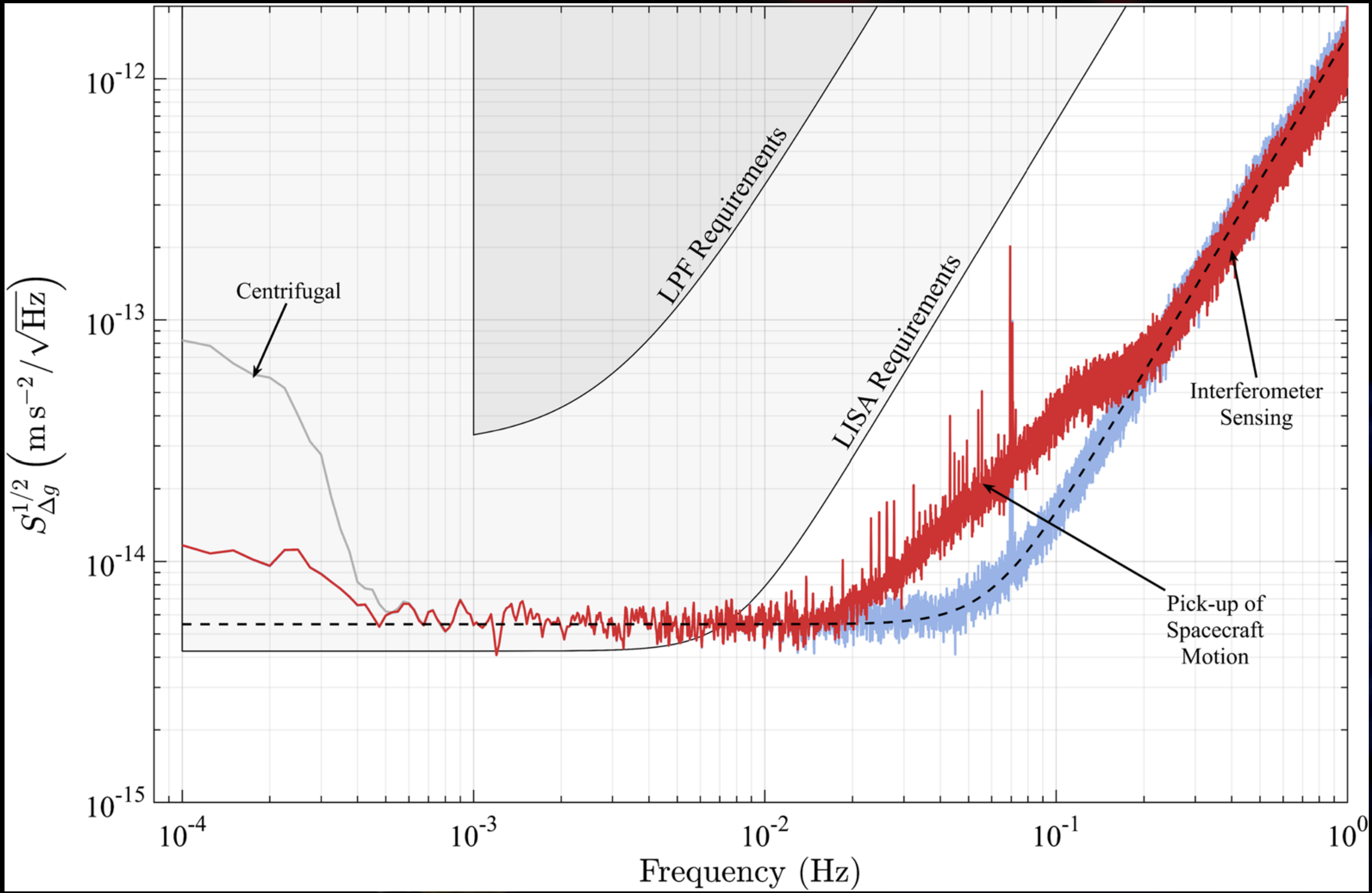




LISAPathfinder first results

- Results after 45 days of operations ...

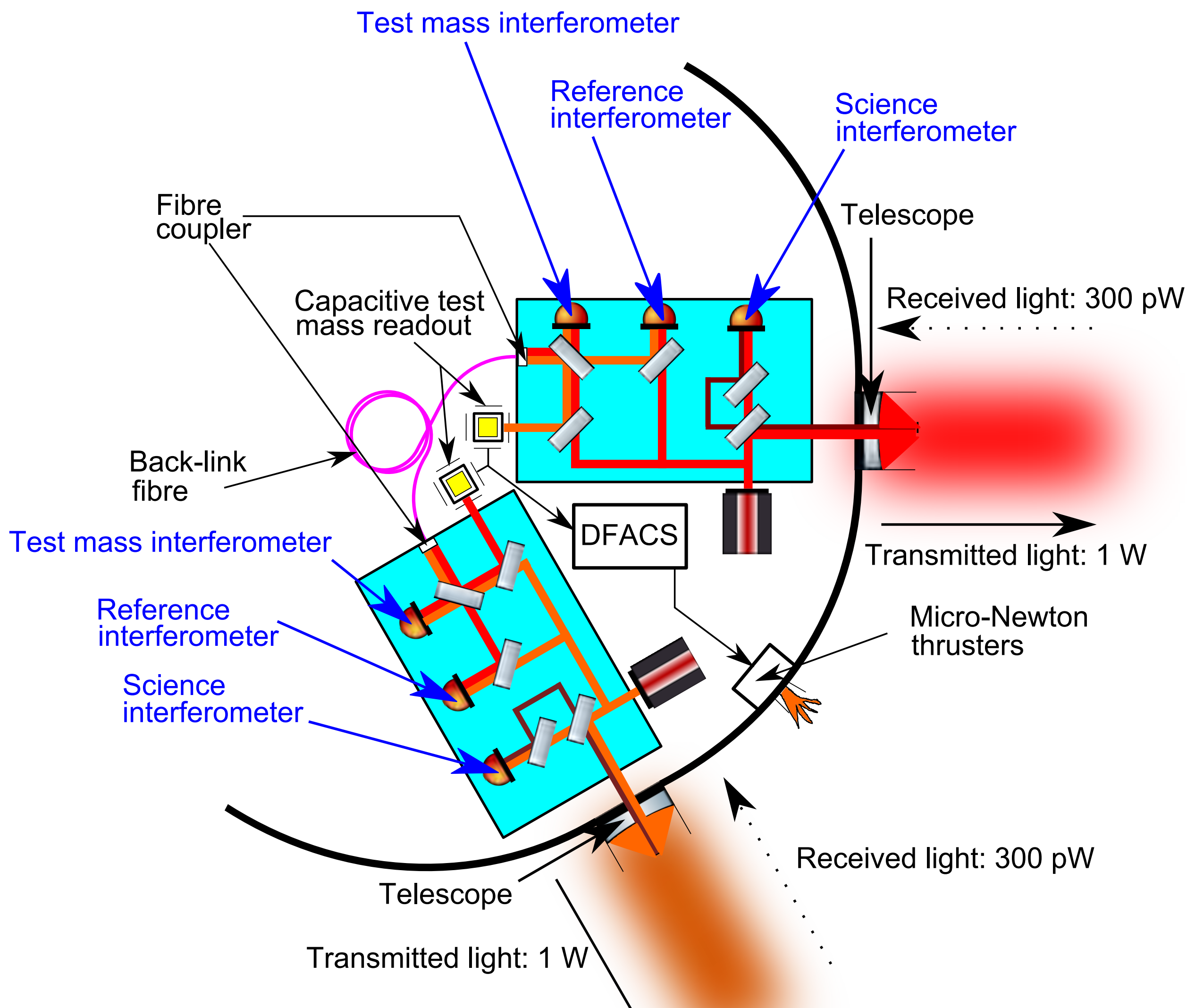
  and after 1.5 years, better than LISA requirements



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

LISA

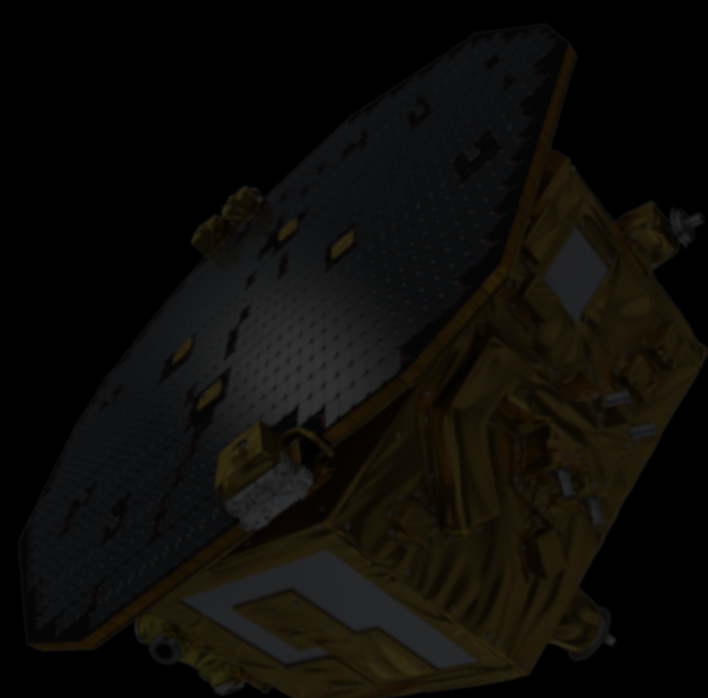
- Exchange of laser beam to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts

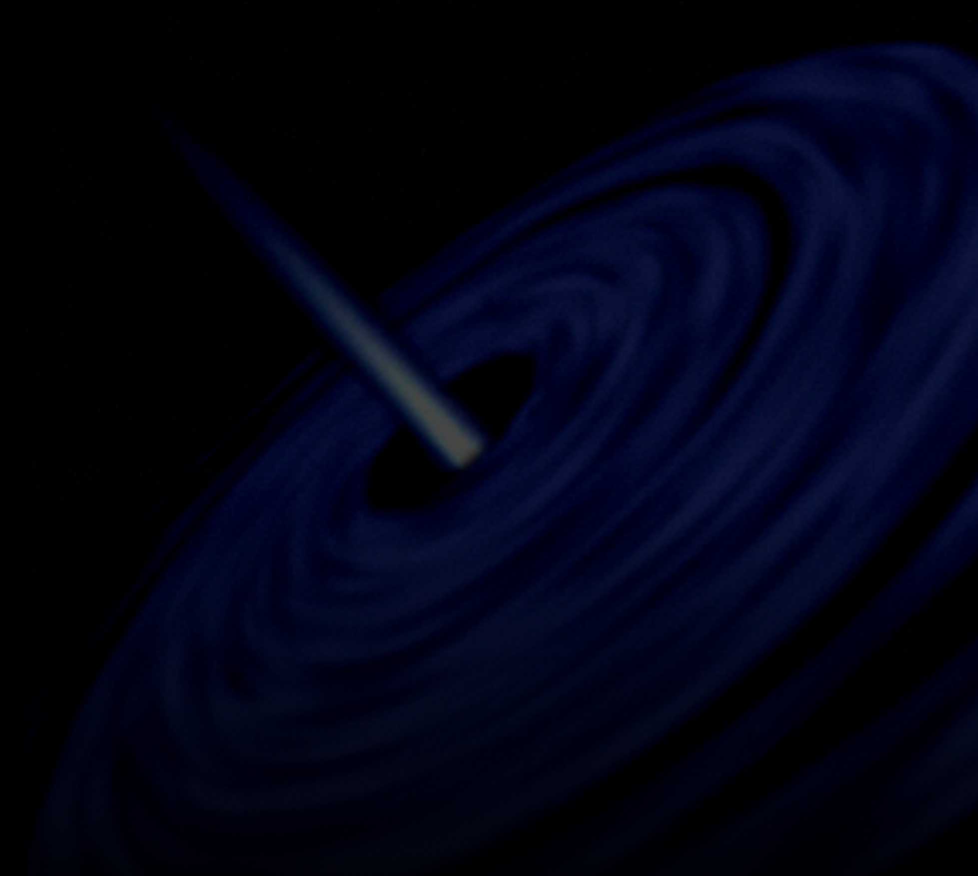


© M. Otto, PhD thesis (2016)

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

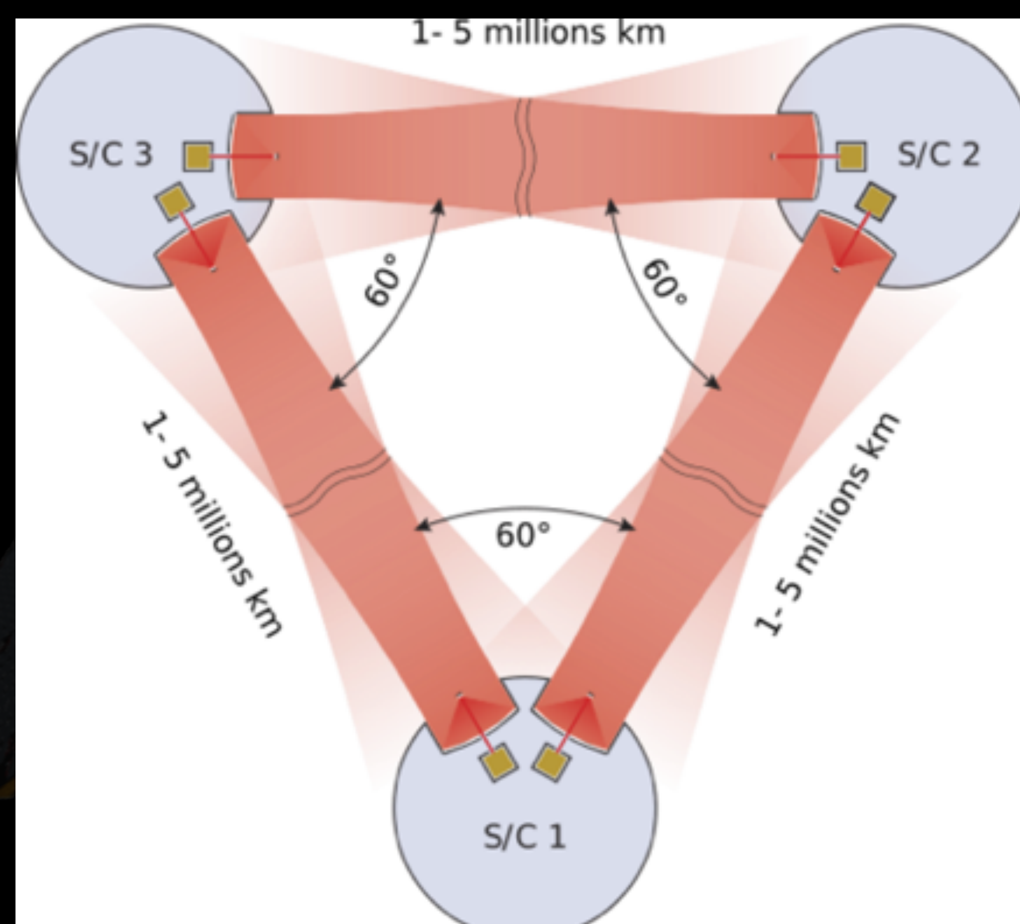
LISA





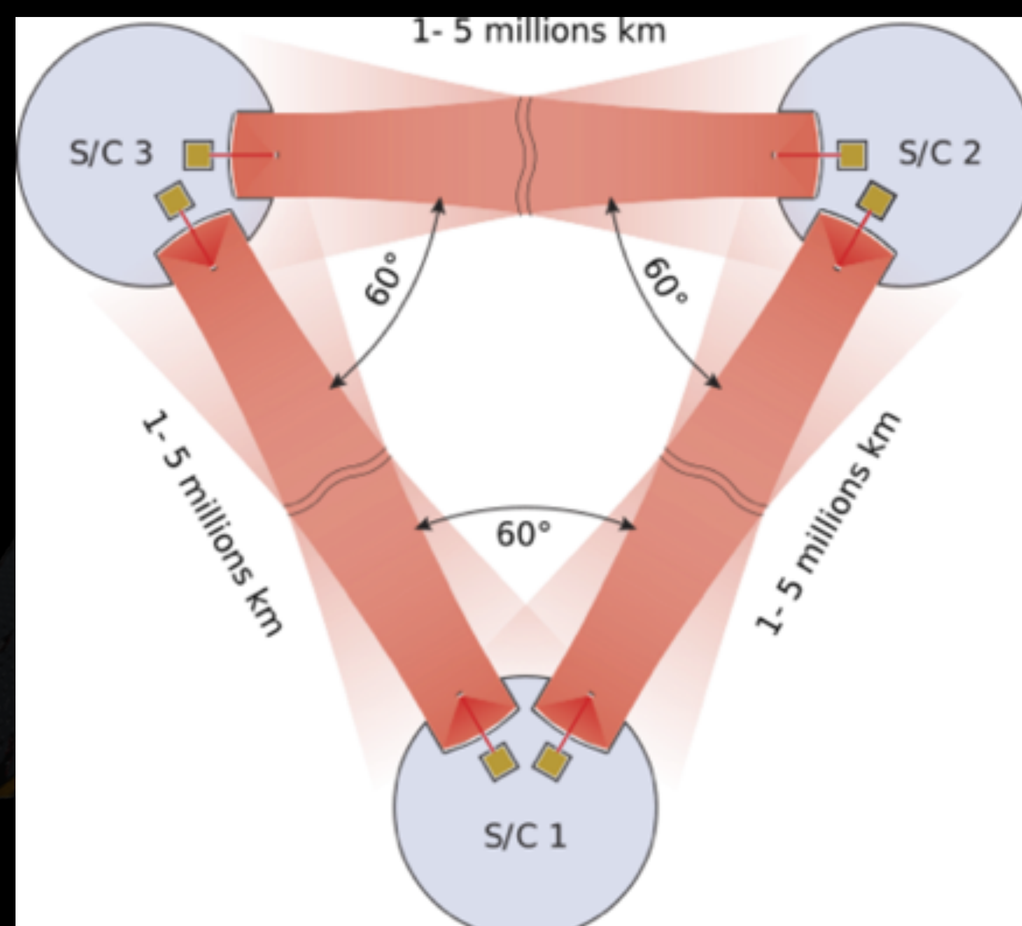
LISA

- Photon flight time measurement between free-floating objects:



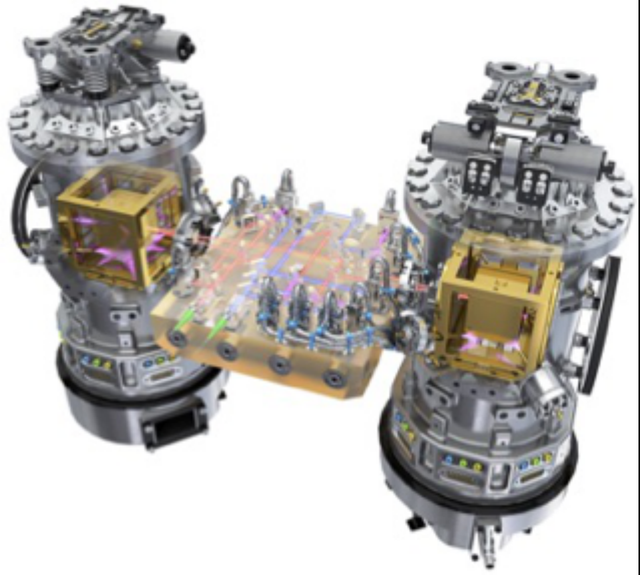
LISA

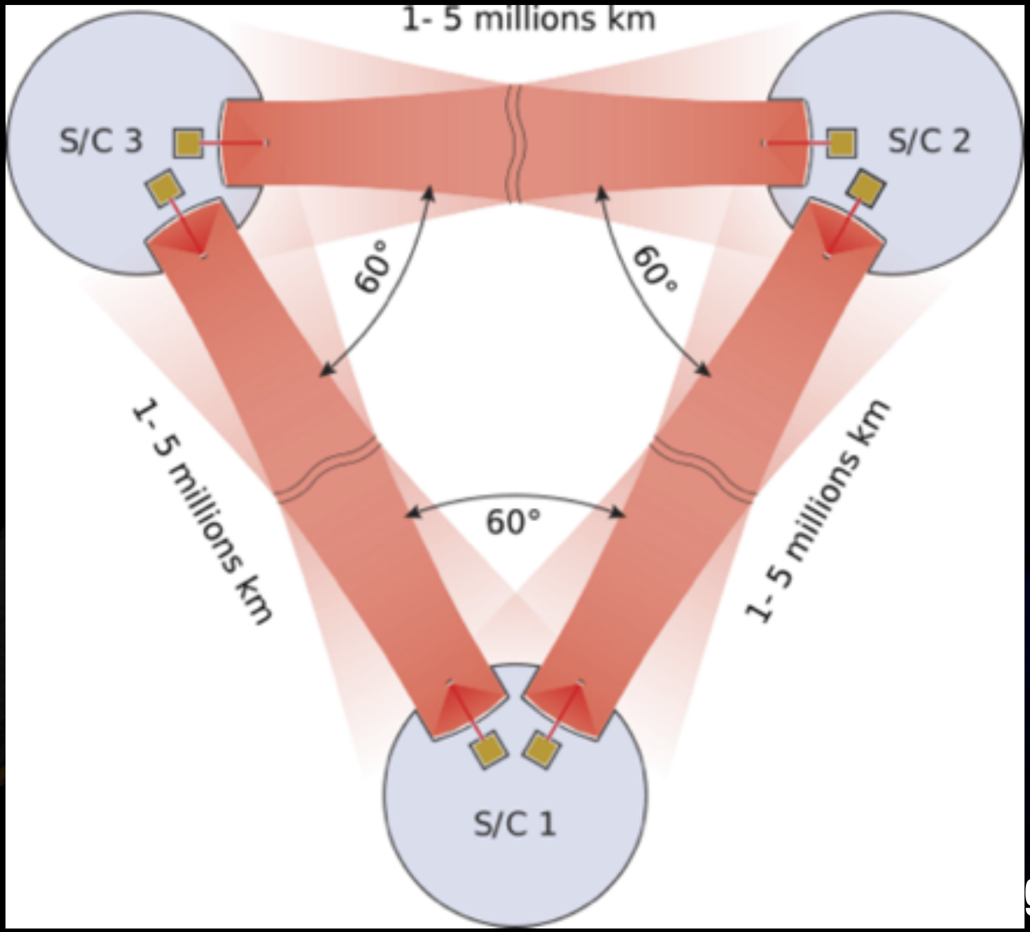
- Photon flight time measurement between free-floating objects:
  - Reference masses in each spacecraft only sensitive to gravity along measurement axis (follow geodesics)

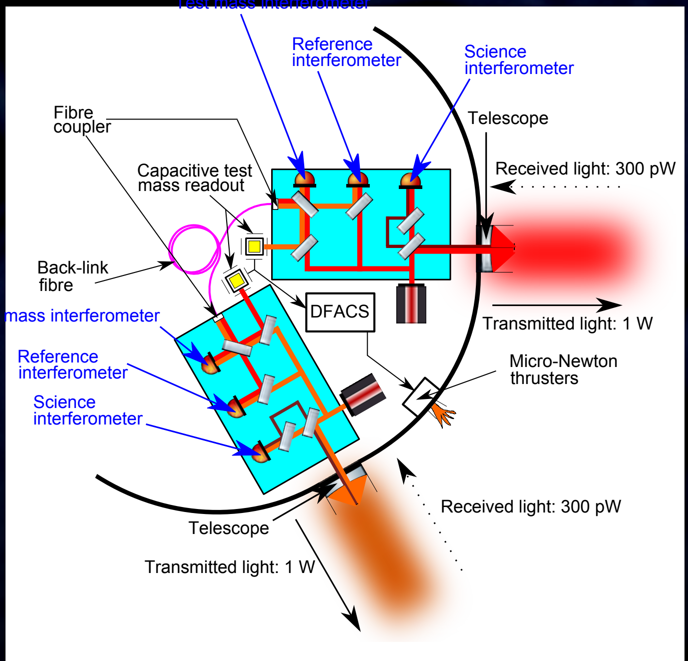


LISA

- 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

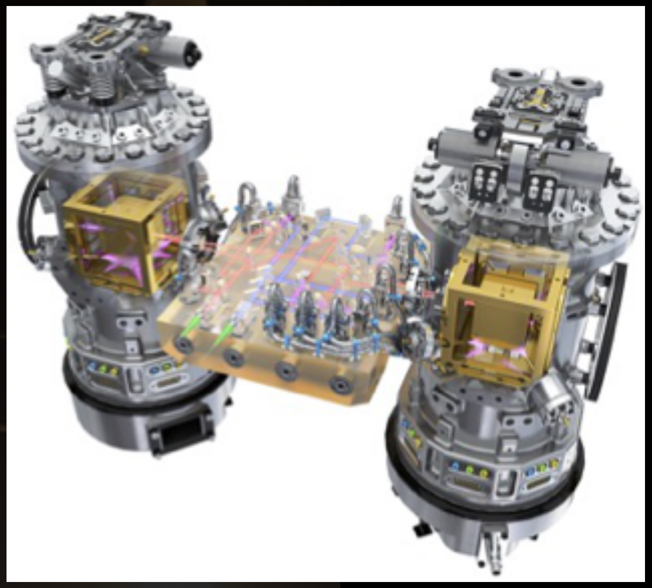


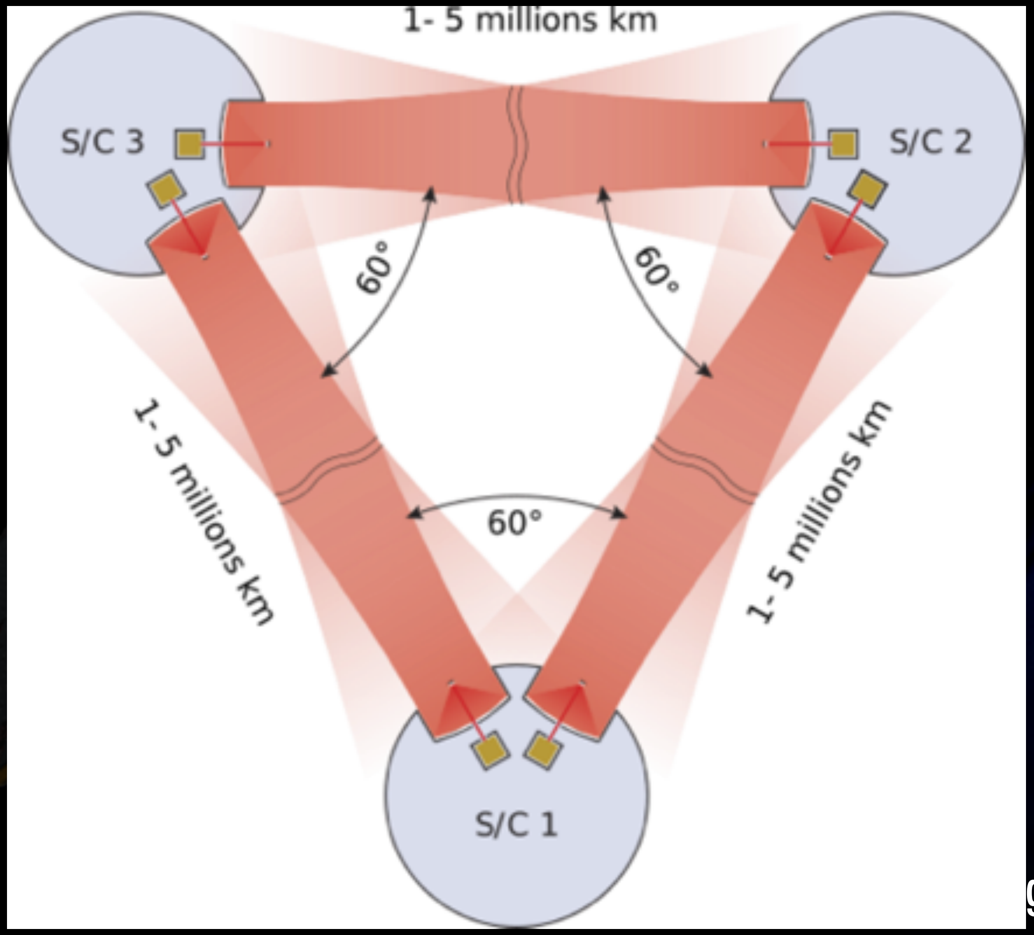


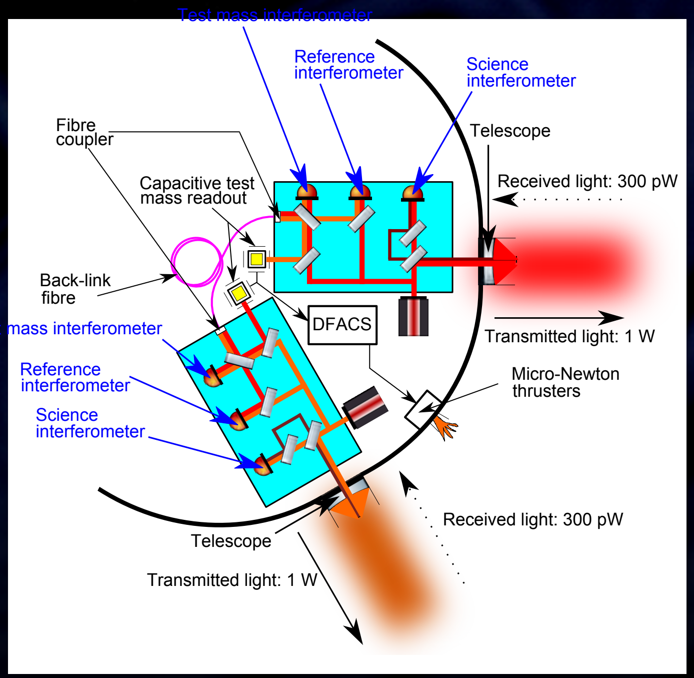


LISA

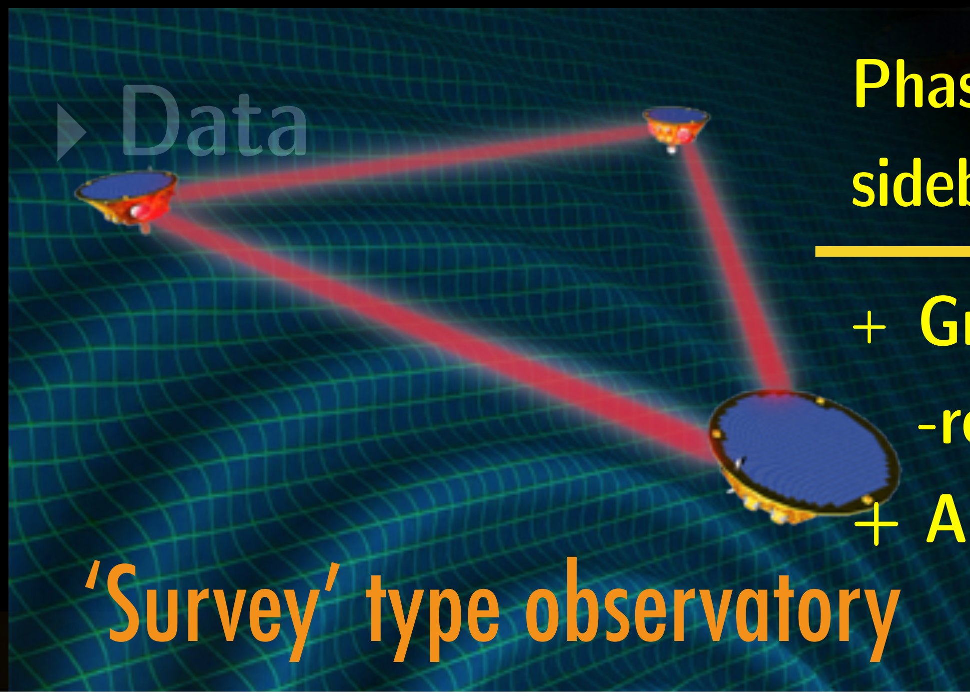
- Photon flight time measurement between free-floating objects:
  - Reference masses in each spacecraft only sensitive to gravity along measurement axis (follow geodesics)
  - Exchange of laser beam between spacecraft
  - Interferometry at the picometer precision
  - Extracting GW signals in the data







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

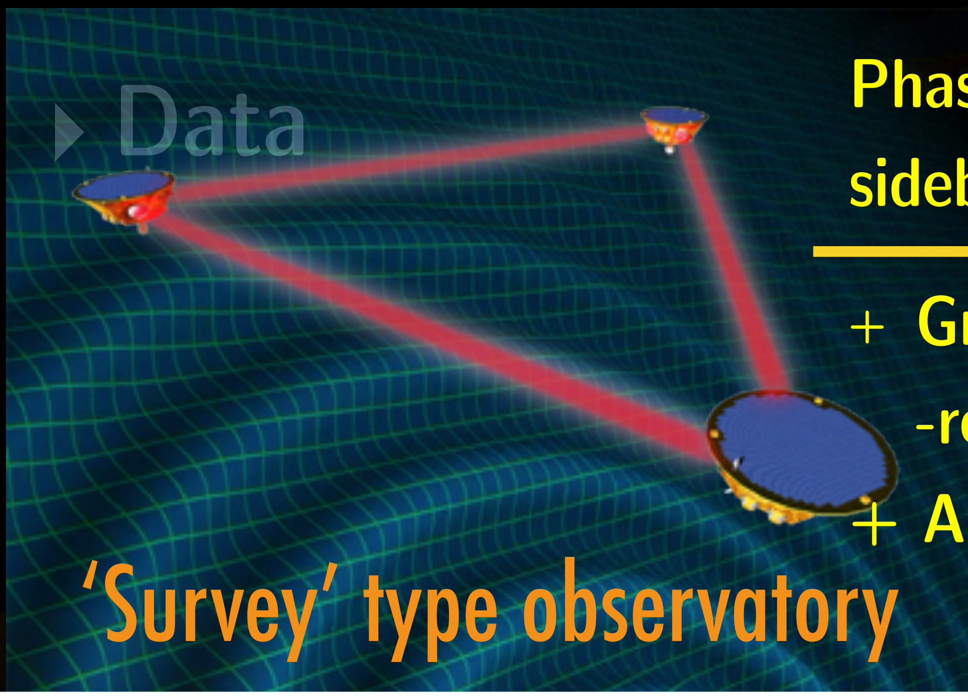
Data Analysis of GWs

L2

L3 — Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 100 mHz

LIS



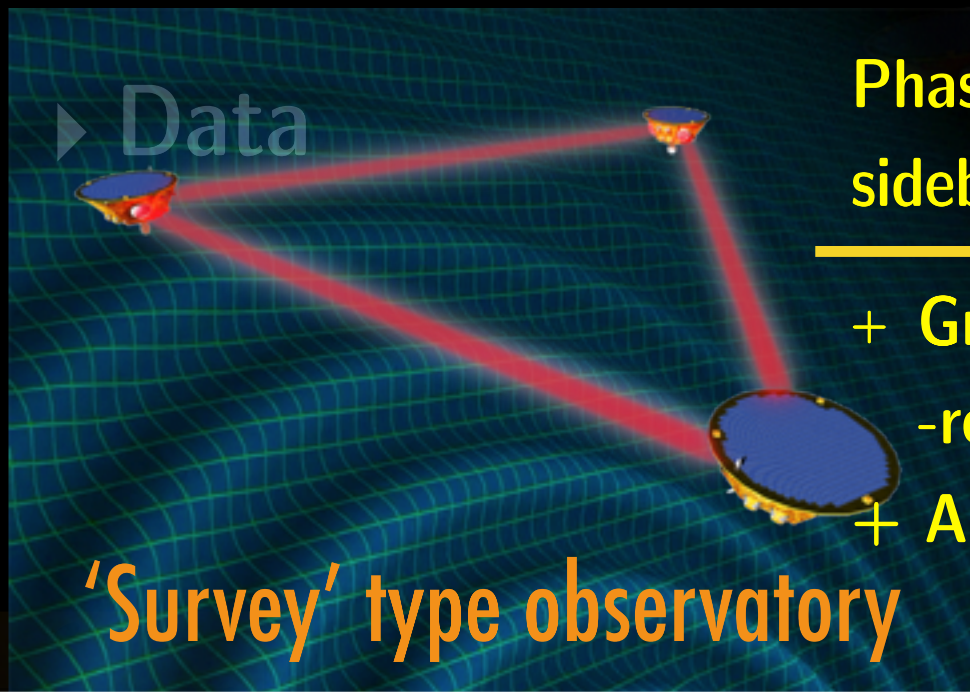
Phasemeter
sidebands, c

+ Gravitatio
-rence Se
+ Auxiliary

Source		Measurement	Channel Count	Sample Rate [Hz]	Bits per Channel	Rate [bits/s]
Payload						
IFO Longitudinal		Inter-S/C IFO	2	3,0	64	384,0
		Test Mass IFO	2	3,0	64	384,0
		Test mass y IFO	0	3,0	64	0,0
		Reference IFO	2	3,0	64	384,0
		Clock Sidebands	4	3,0	64	768,0
Freq reference		error point	1	3,0	32	96,0
		feedback	2	3,0	32	192,0
		clock sidebands monitoring (local pilot tone beat)	1	3,0	32	96,0
IFO Angular		SC η,φ	4	3,0	32	384,0
		TM η,φ	4	3,0	32	384,0
		TM θ (from y IFO)	0	3,0	32	0,0
Ancillary		Time Semaphores	4	3,0	64	768,0
Optical Monitoring		PRDS metrology	4	3,0	32	384,0
			0	3,0	32	0,0
		Optical Truss	0	3,0	32	0,0
DFACS / GRS Cap. Sens.		TM x,y,z	6	1,0	32	192,0
		TM θ,η,φ	6	1,0	32	192,0
DFACS		breathing errorpoint	0	1,0	32	0,0
		breathing actuator	2	1,0	32	64,0
		TM applied torques	12	1,0	24	288,0
		TM applied forces	12	1,0	24	288,0
		SC applied torques	3	1,0	24	72,0
		SC applied forces	3	1,0	24	72,0
Science Diagnostics	Themometers	EH	16	0,1	32	51
		OB	20	0,1	32	64
		Telescope	10	0,1	32	32
		interface	10	0,1	32	32
	Magnetometers	TM	12	0,1	32	38
	radiation monitor		1			30
	FIOS output powers (Inloop and Out of Loop)		6	3,0	32	576
	pressure sensor		0	0,1	32	0
	body mic	CGAS tanks	0	3,0	32	0
		breathing mechanism	0	3,0	32	0
	RIN monitoring	2 lasers, 2 frequencies, 2 quadratures	8	3,0	32	768
				0,0		0
				0,0		0
Payload HK						1000
Total Payload						***7984***
Platform						
Housekeeping [Based on LPF]						4000
Total Platform						***4000***
Totals						
Raw Rate per SC						11984
Packetisation Overhead [10%]						1198
Packaged Rate per SC						**13182**
Packaged Rate for Constellation						**39546**

Gravitational wave sources emitting between 0.02mHz and 100 mHz

LISA data



'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor
+ Auxiliary channels

L0

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L1 — 2 data channels TDI non-correlated

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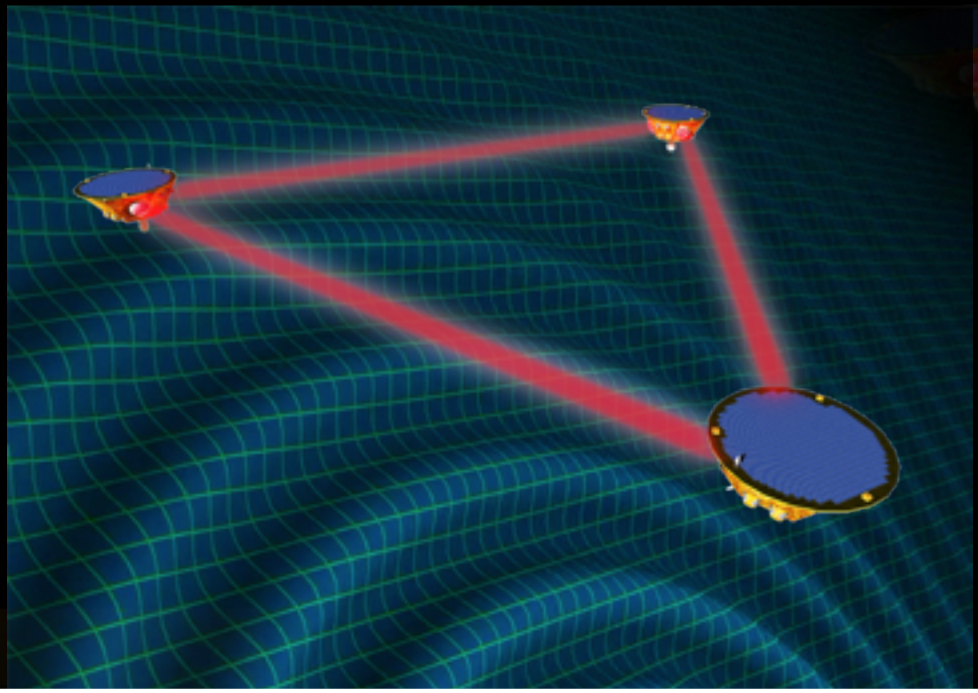
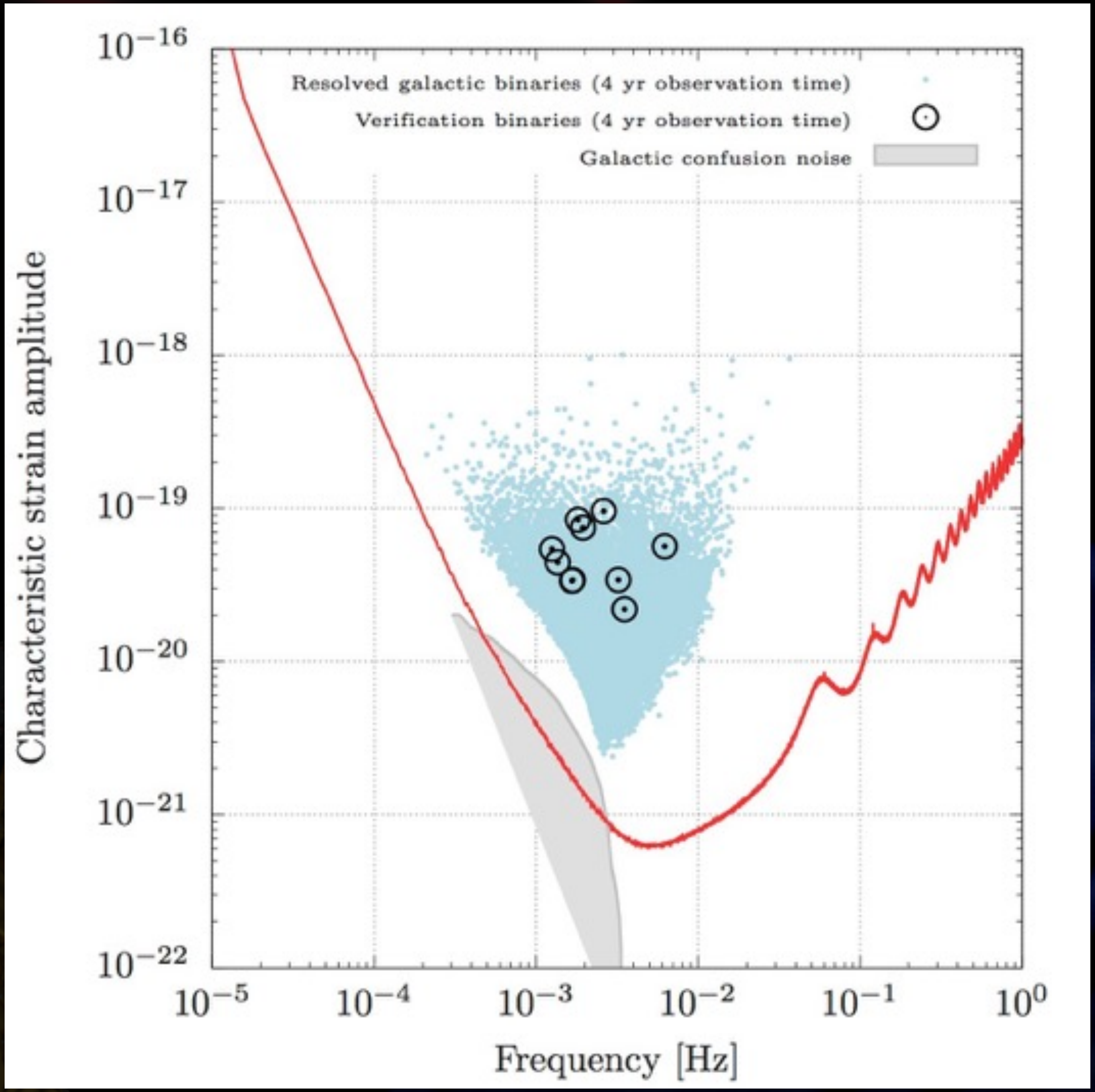
Gravitational wave sources emitting between 0.02mHz and 100 mHz

Galactic binaries

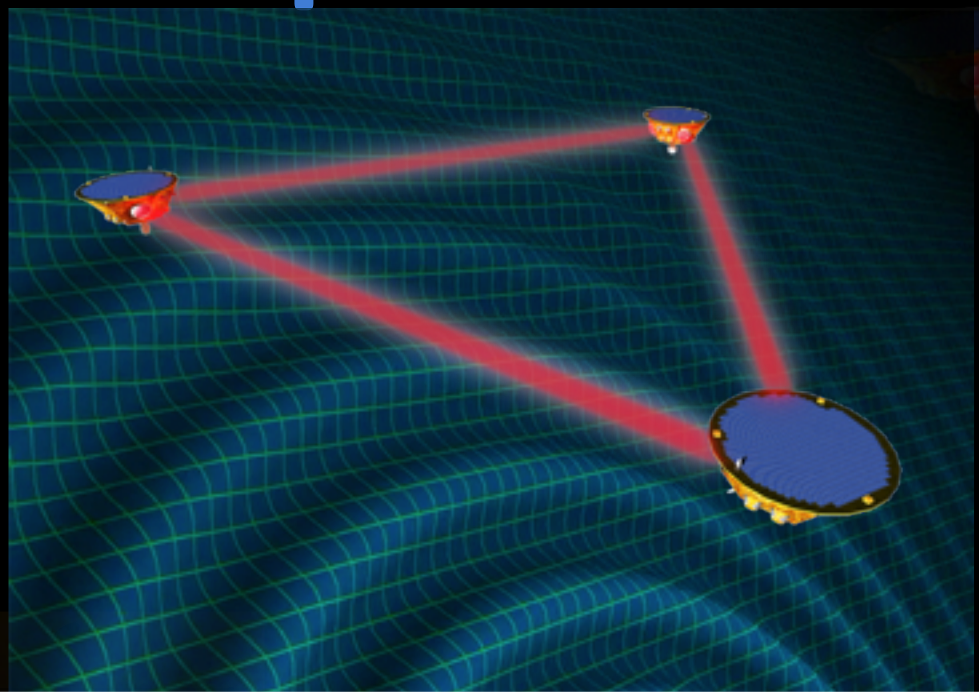




GW sources

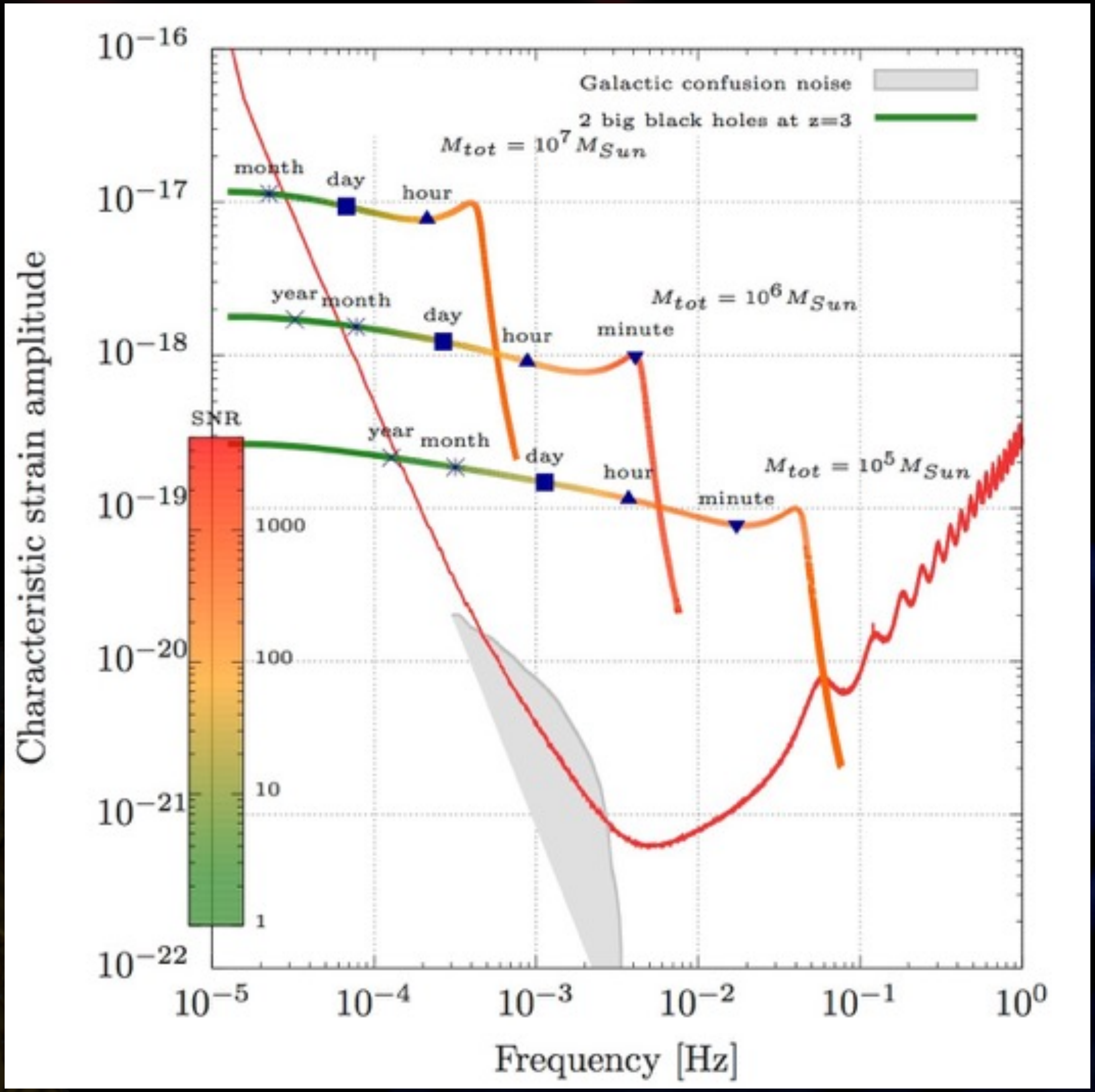
- 6×10^{7} galactic binaries

Super Massive Black Hole Binaries

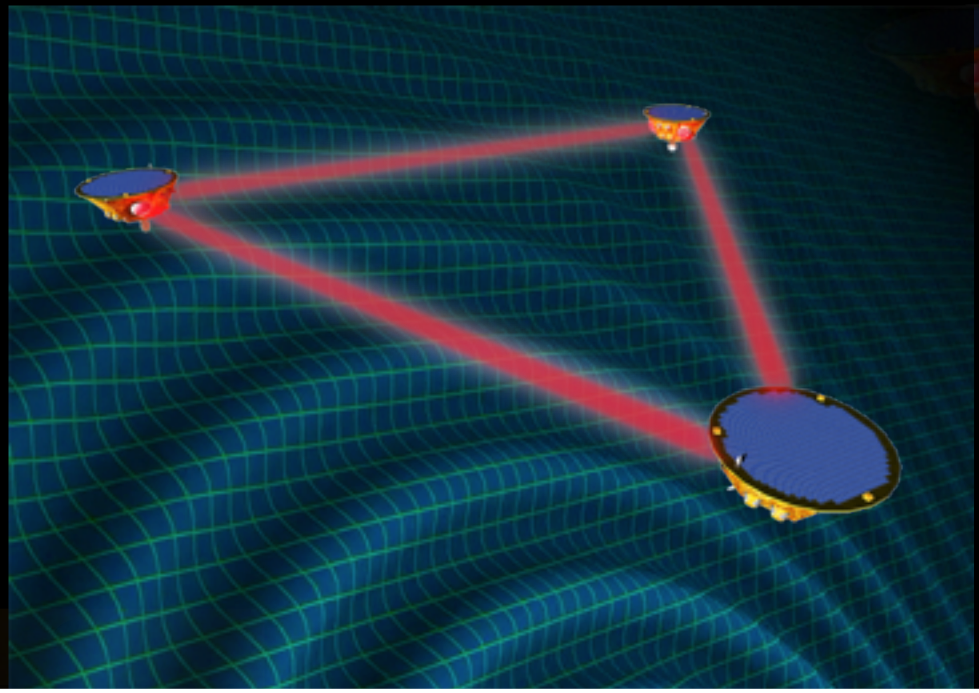


GW sources

- 6 x10^7 galactic binaries
- 10-100/year SMBHBs



EMRIs



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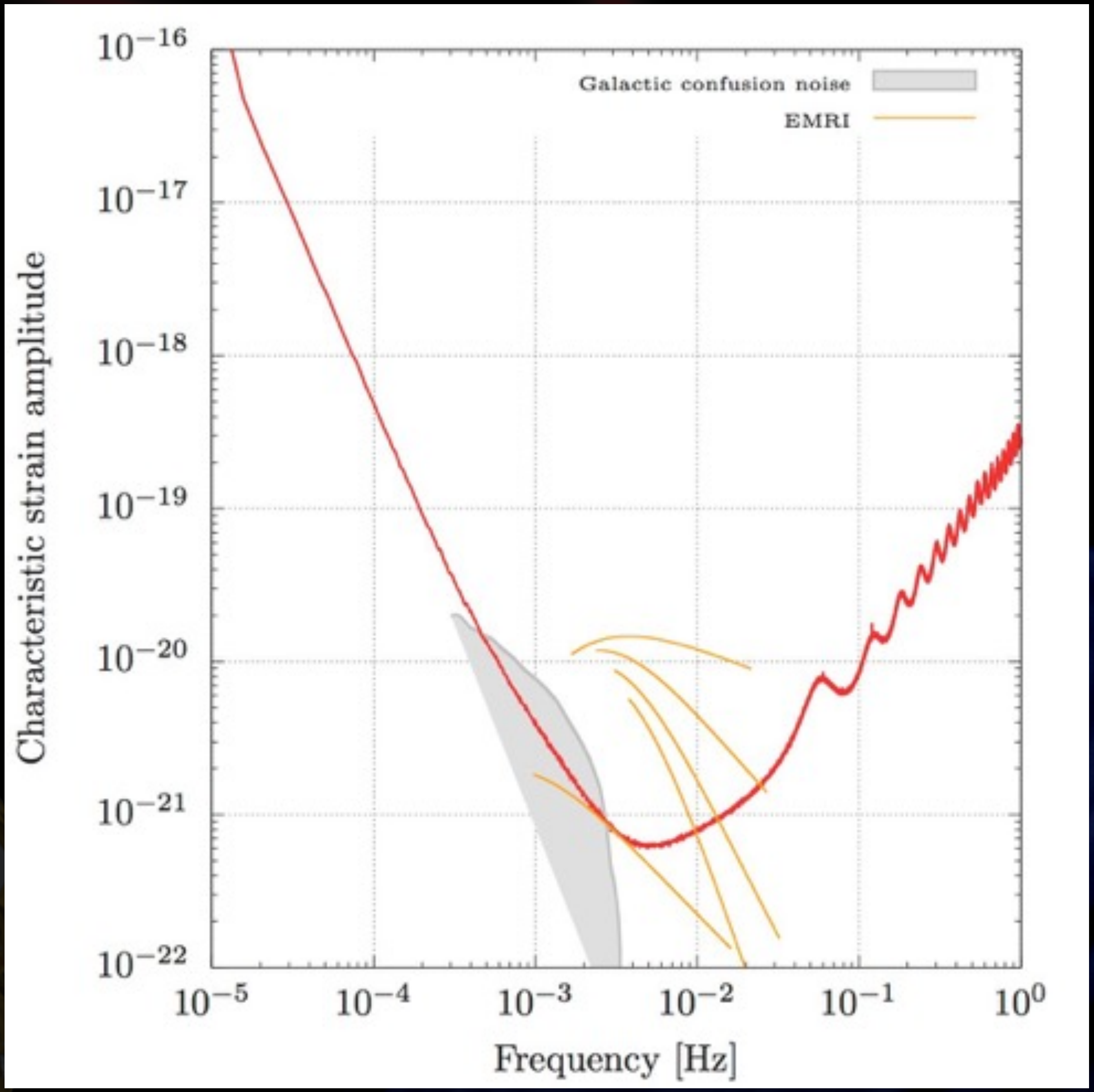
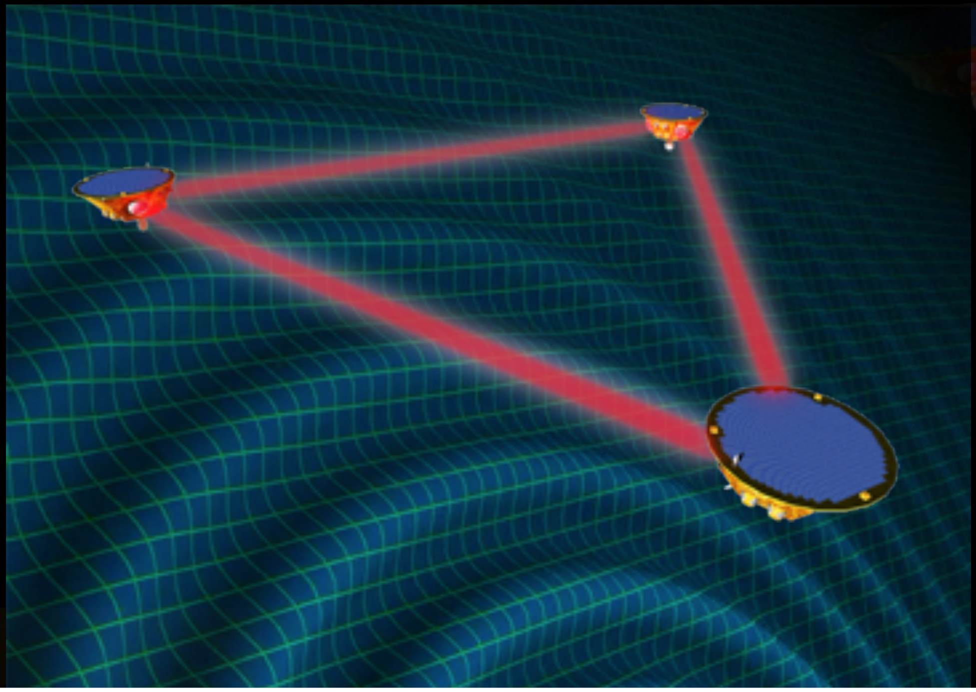
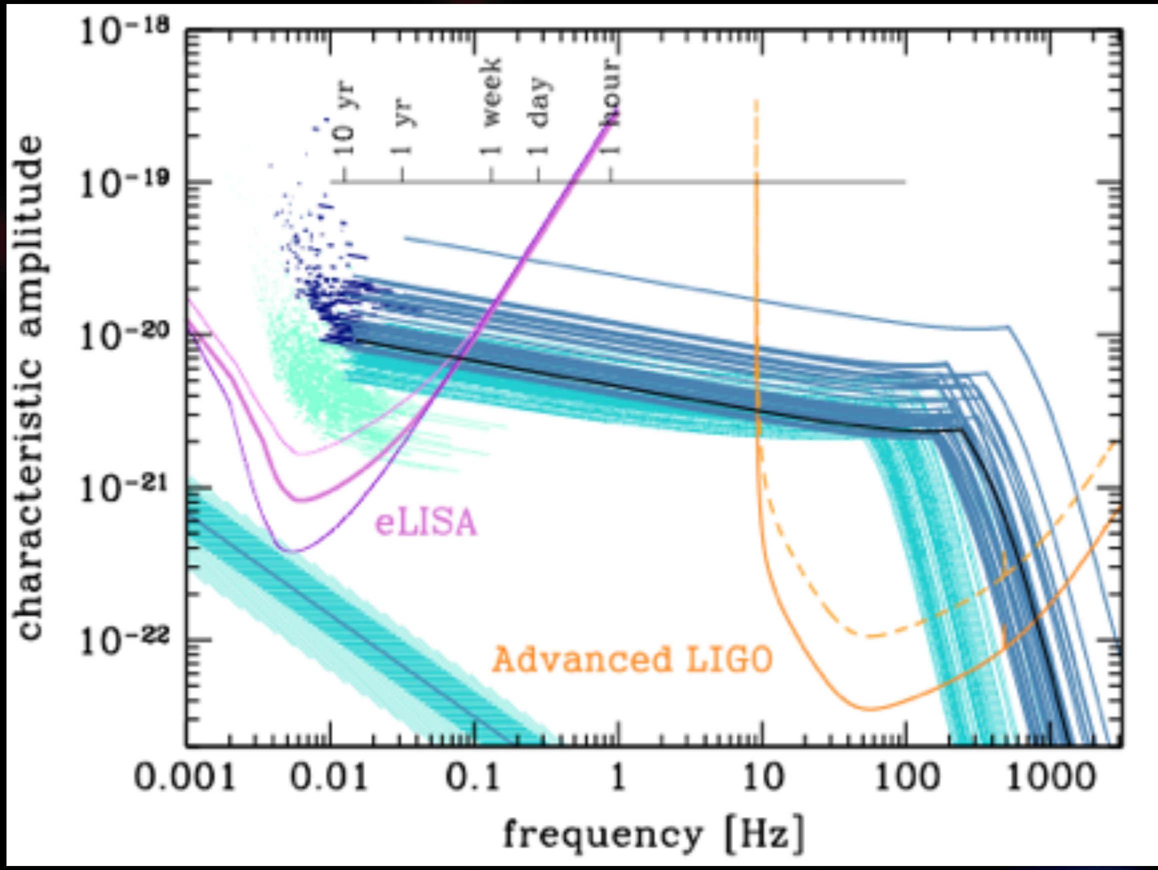
- 6 x10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/years EMRIs



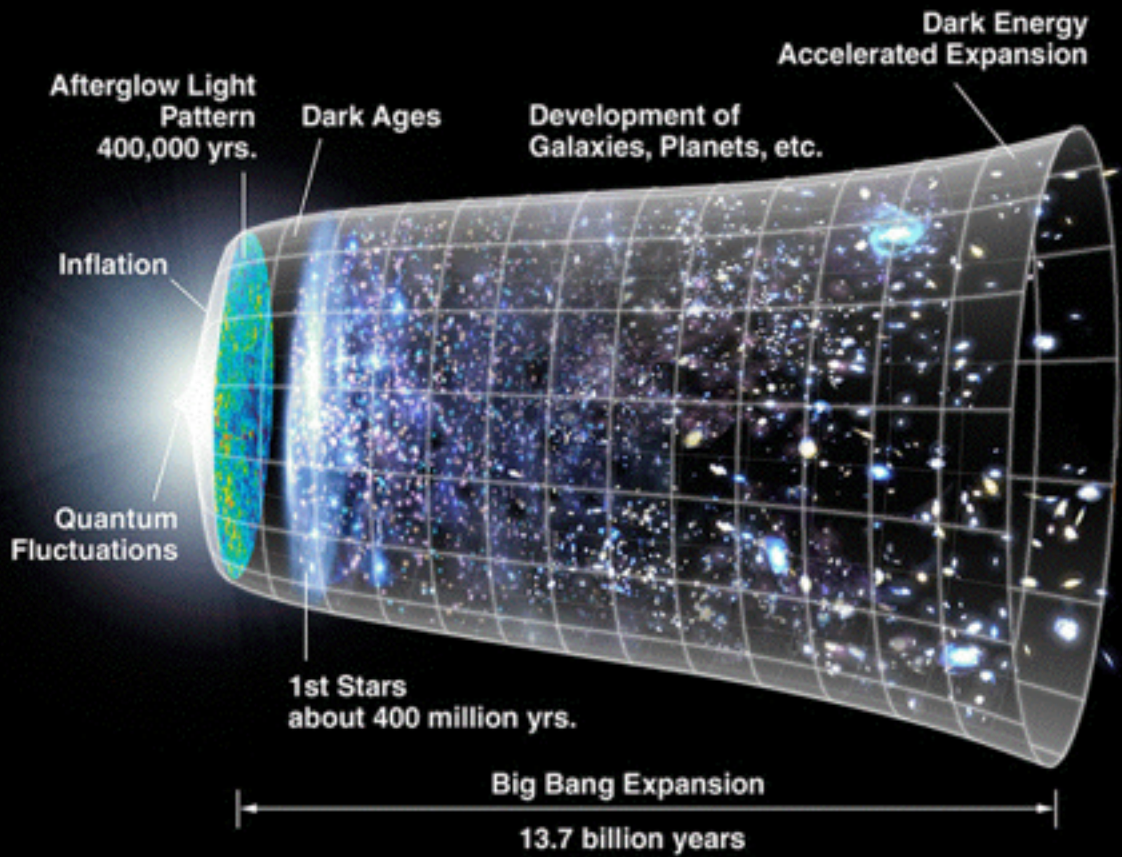
Others sources





GW sources

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



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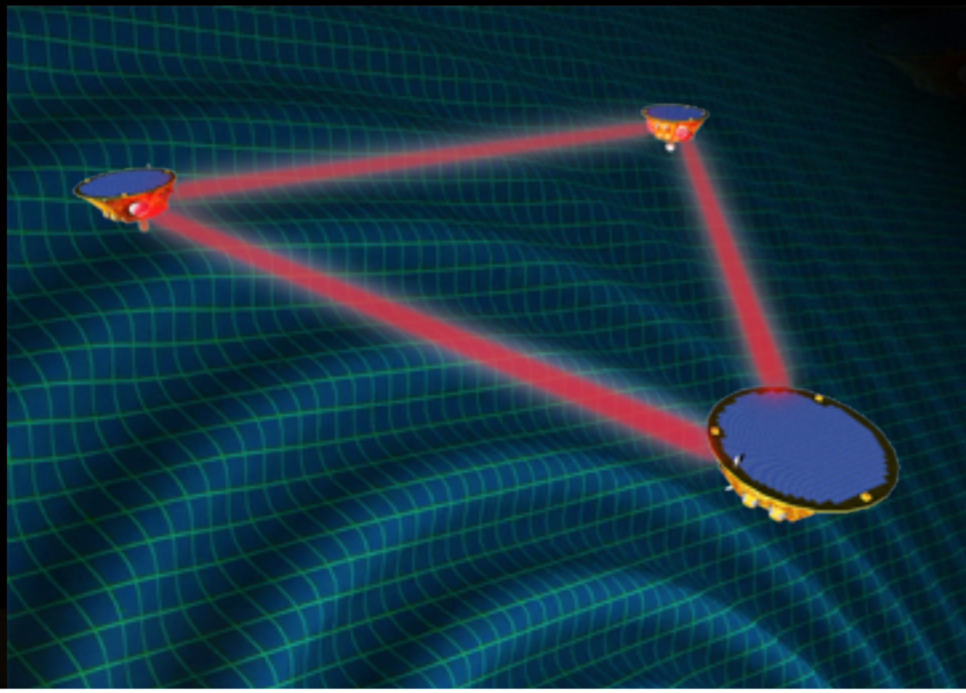

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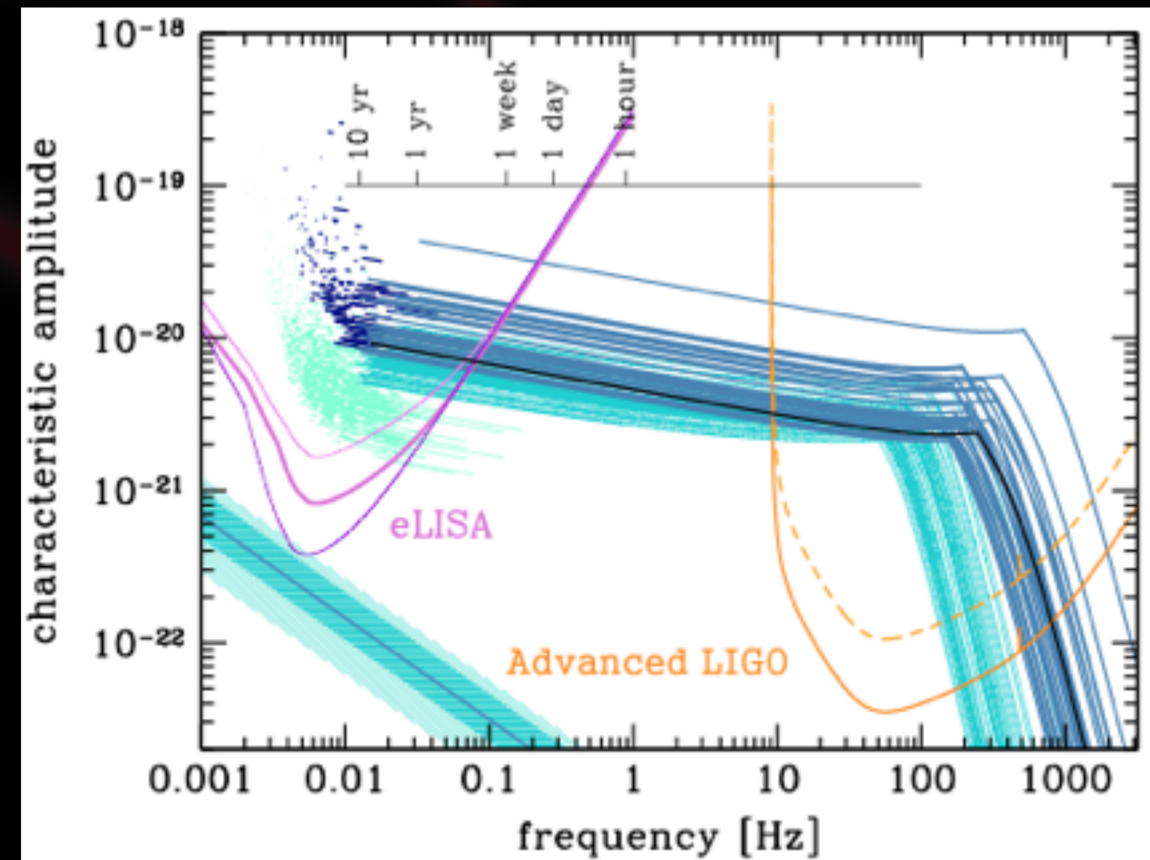

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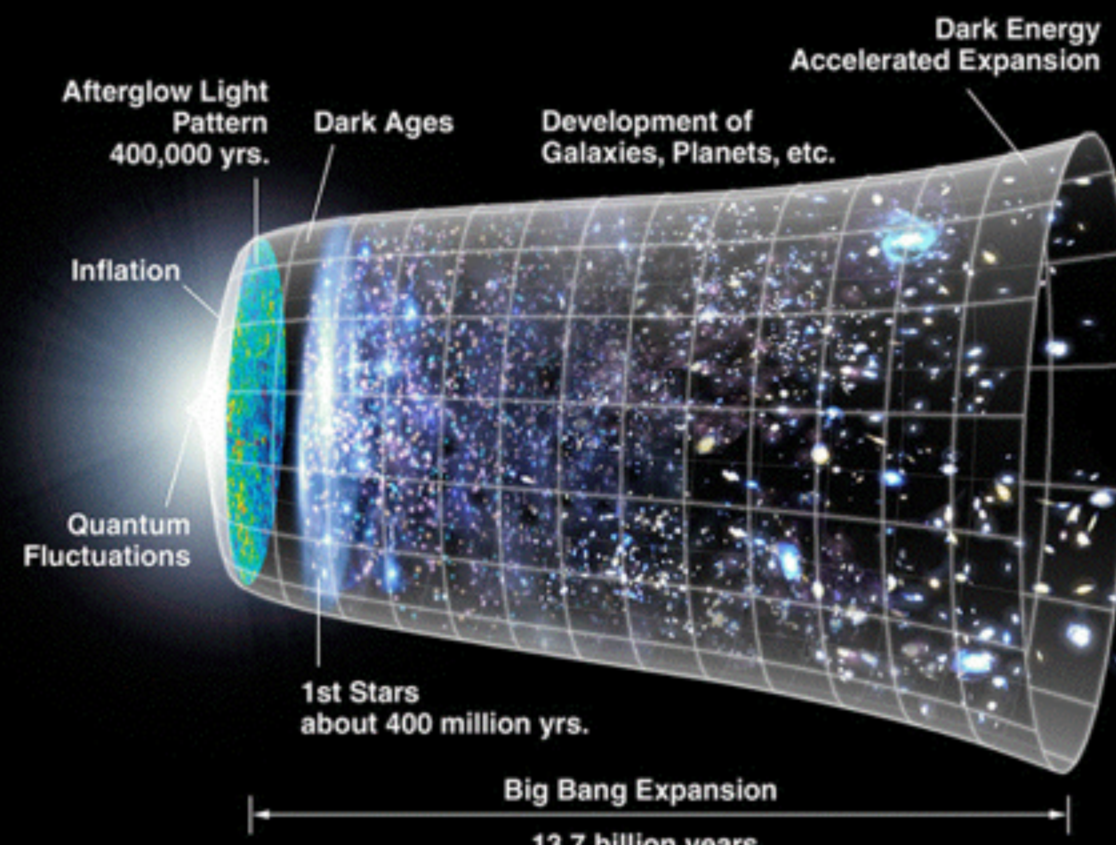
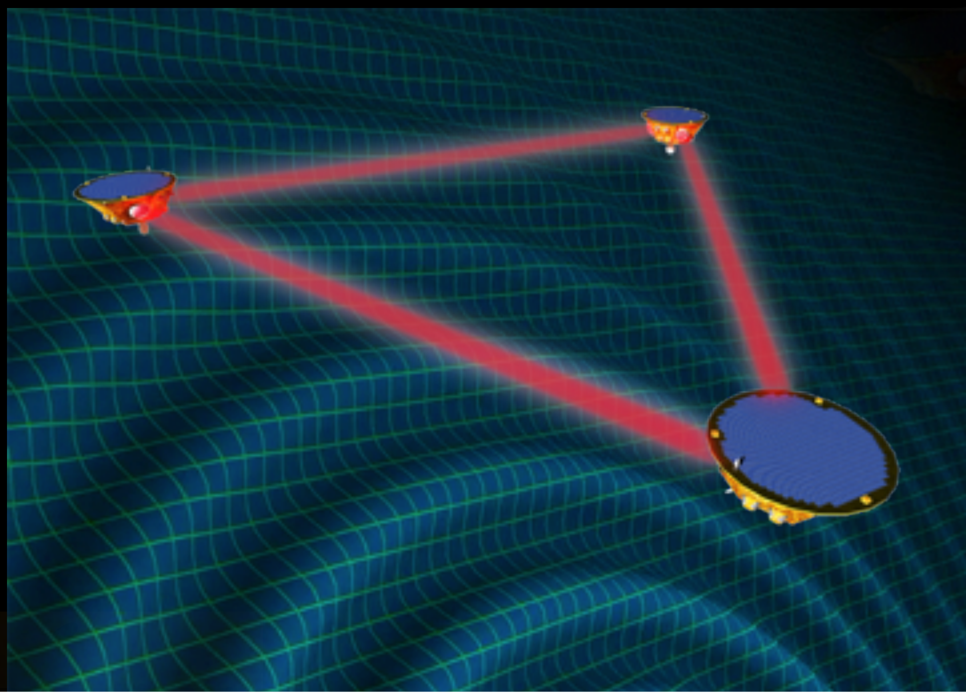
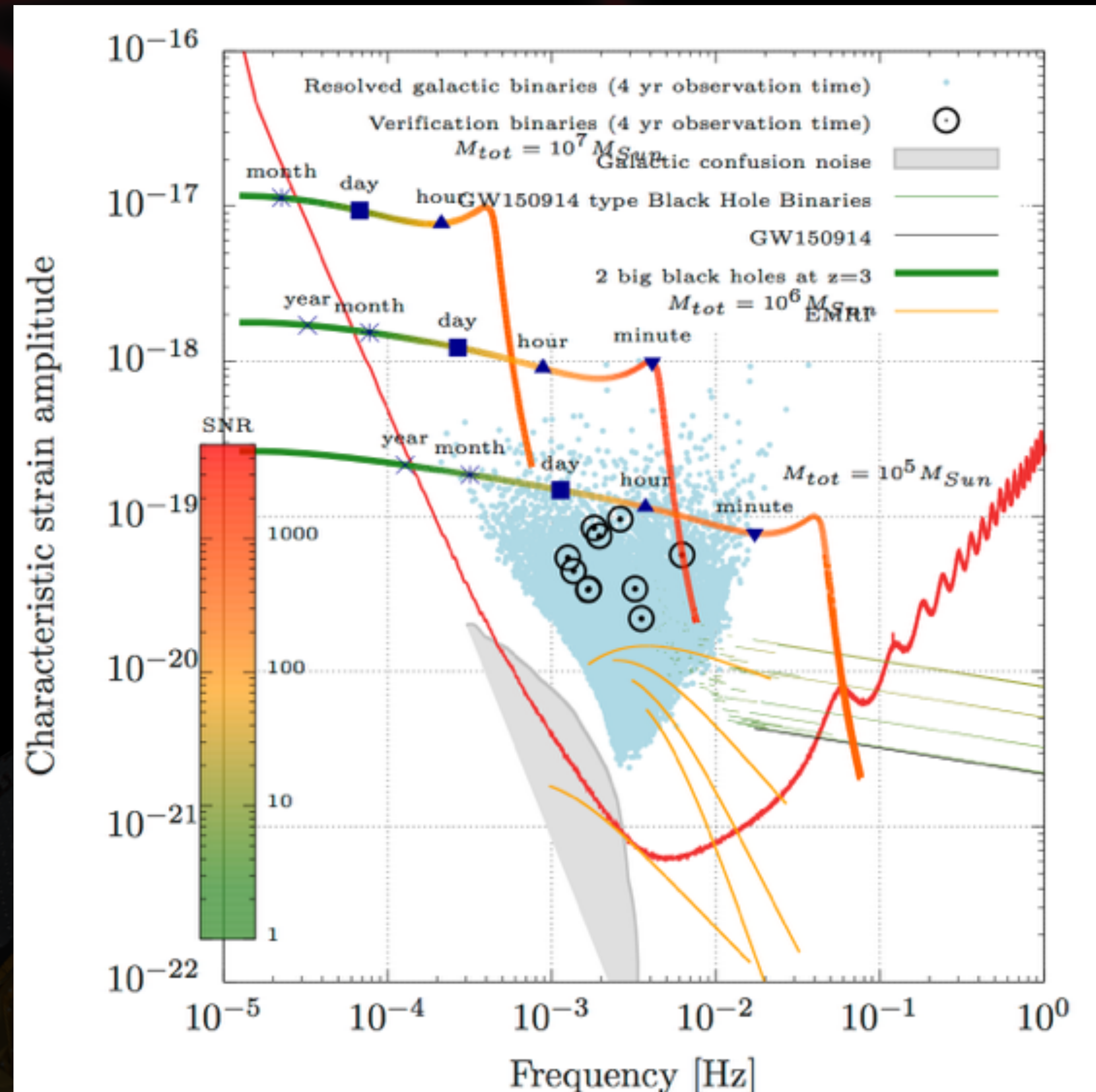


LISA data





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- Cosmological backgrounds
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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

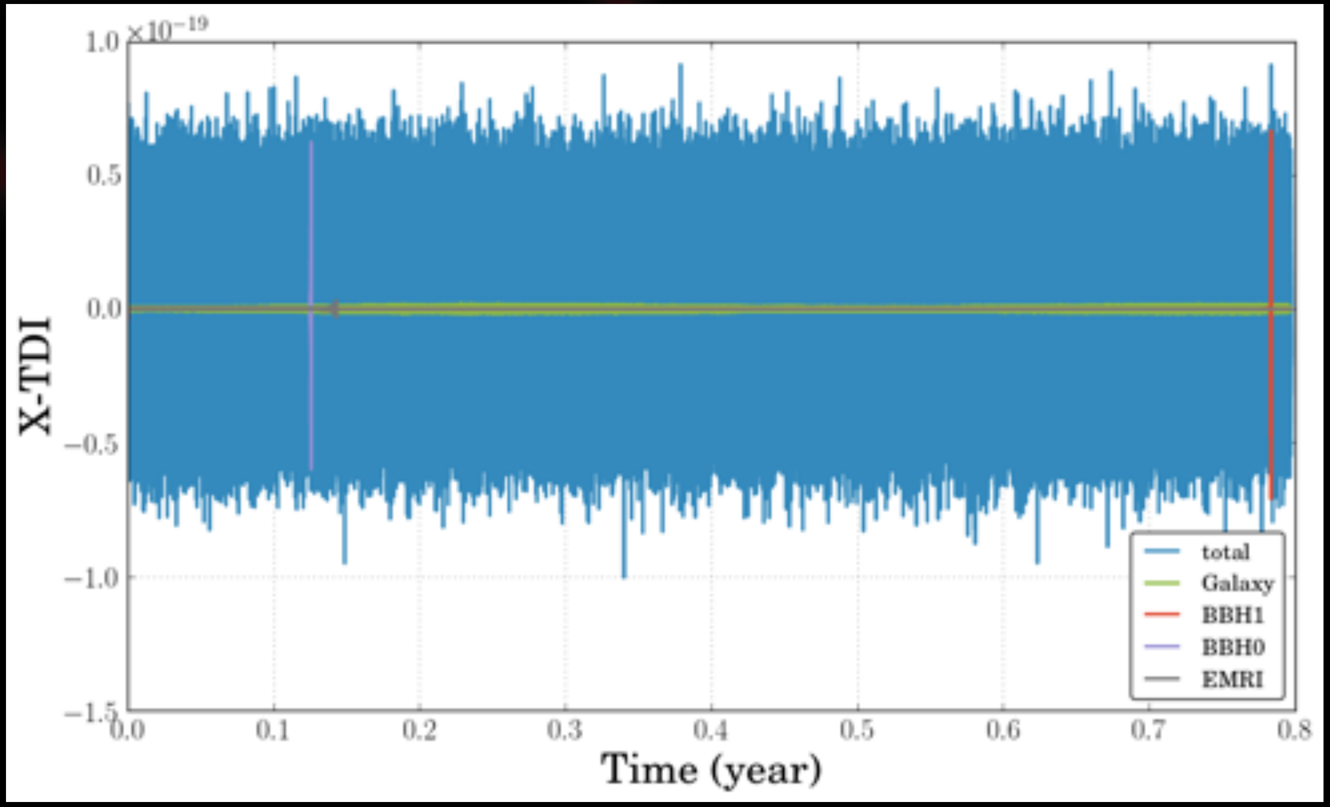
=> Storages and archives are not problematic

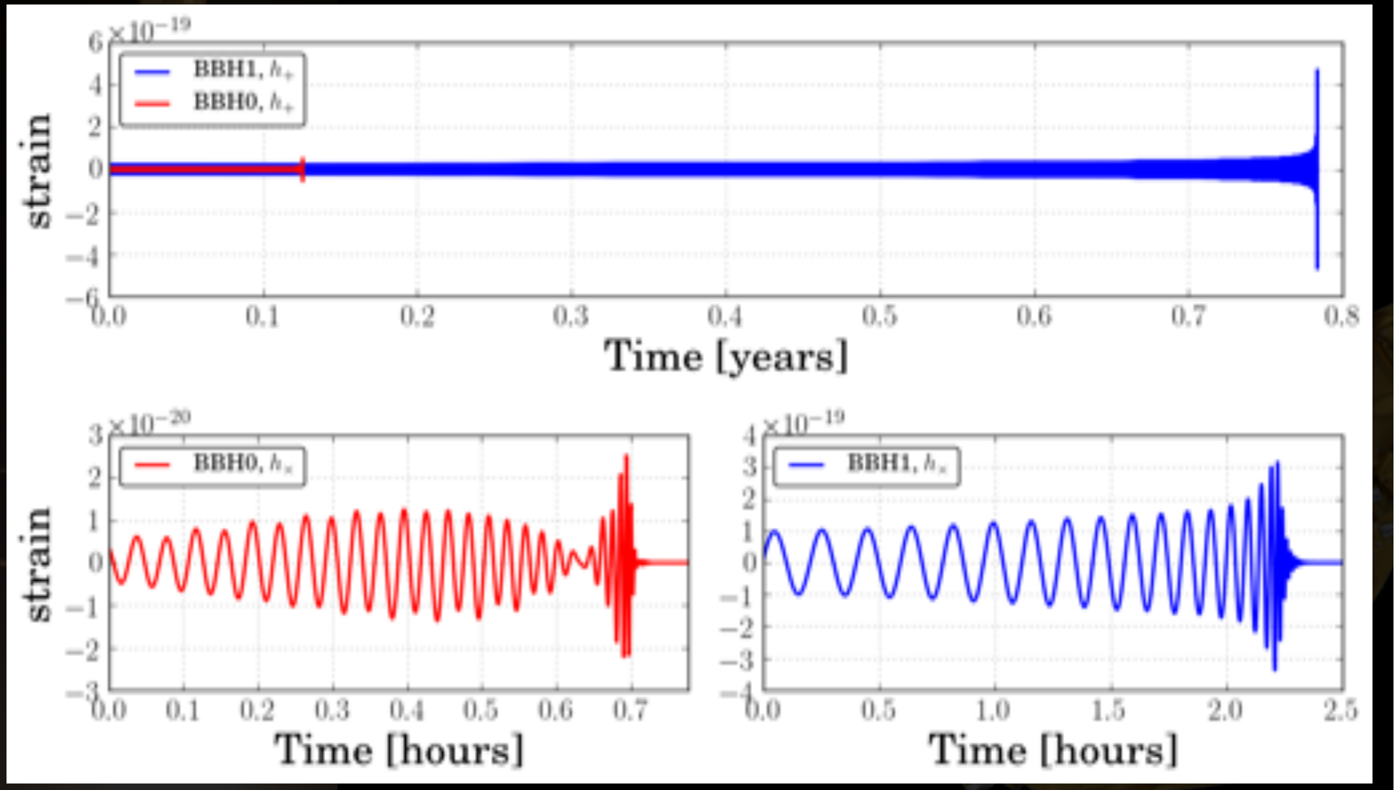
- But simulations will require some storage to be properly sized

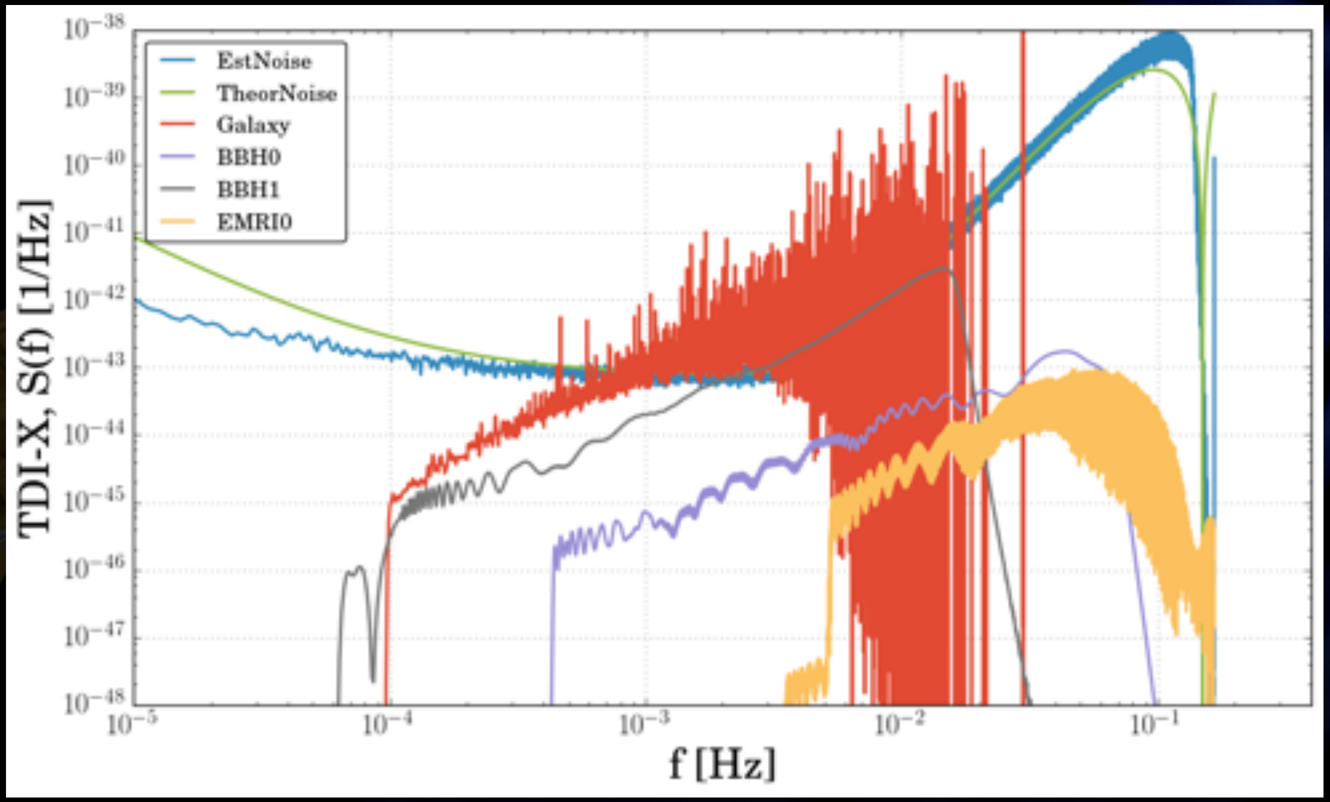
- Complexity for the DPC is mainly in data analysis because the goal is to extract the parameters for a maximum number of sources.

LISA Data Challenges

- Mock LDC: 2005→2011
- 2017: start of the LDC
  - Develop data analysis
  - Design the pipelines of the mission
- Example of the potential data for LDC1







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

Ground Segment (LISA proposal)

- 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

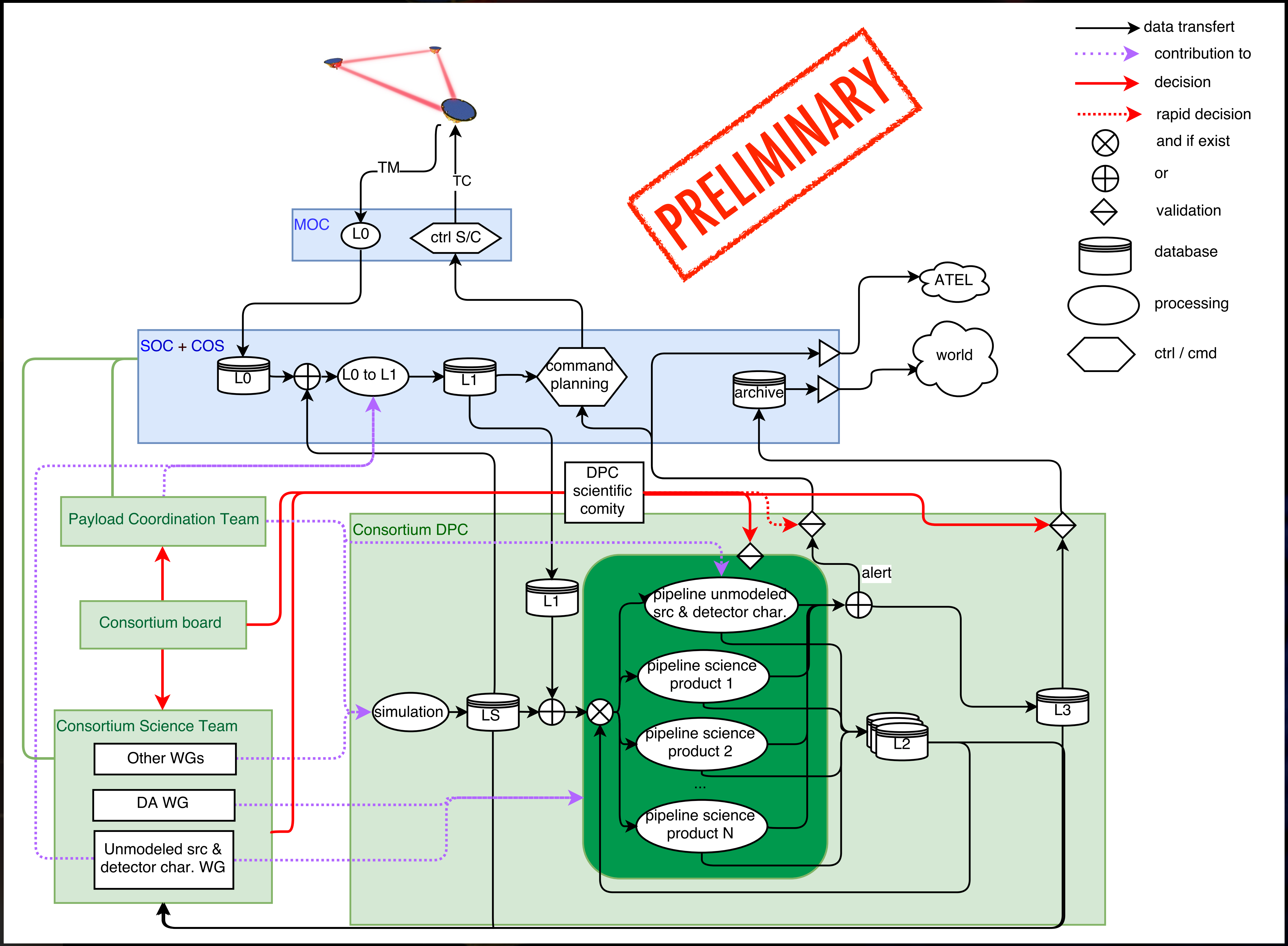
Ground Segment (LISA proposal)

- 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 & to the scientific community of the Consortium
  - Produce periodic releases of science data products
  - Generate alerts for upcoming transients, such as mergers

Ground Segment (LISA proposal)

- 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 (time span) to the science planning team => protected period
  - Powerful events: latency of about one day requires at the SOC.
  - Other events: longer latency at SOC+DPC

LISA Ground Segment



Current vision of the DPC

- DPC: unique entity responsable for the data processing
- 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).
- Distributed DPC:
  - 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

DPC: 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
- Next: detailed definition in phase A

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- Support LISA developments (simulation, data analysis - LISA Data Challenge)
- Prototyping future DPC

LISA proto-DPC

- The DPC is a set of tools provided to ease the challenging data analysis tasks of LISA:
  - Hardware (CPU and disk) usage not a major concern
  - Data Analysis itself is challenging: lot of unknowns, complex noises and pre-processing

=> Keep a simple and easy to use DPC infrastructure.

  - How IT will look like in 10 years ? Will virtualization be the next standard ?

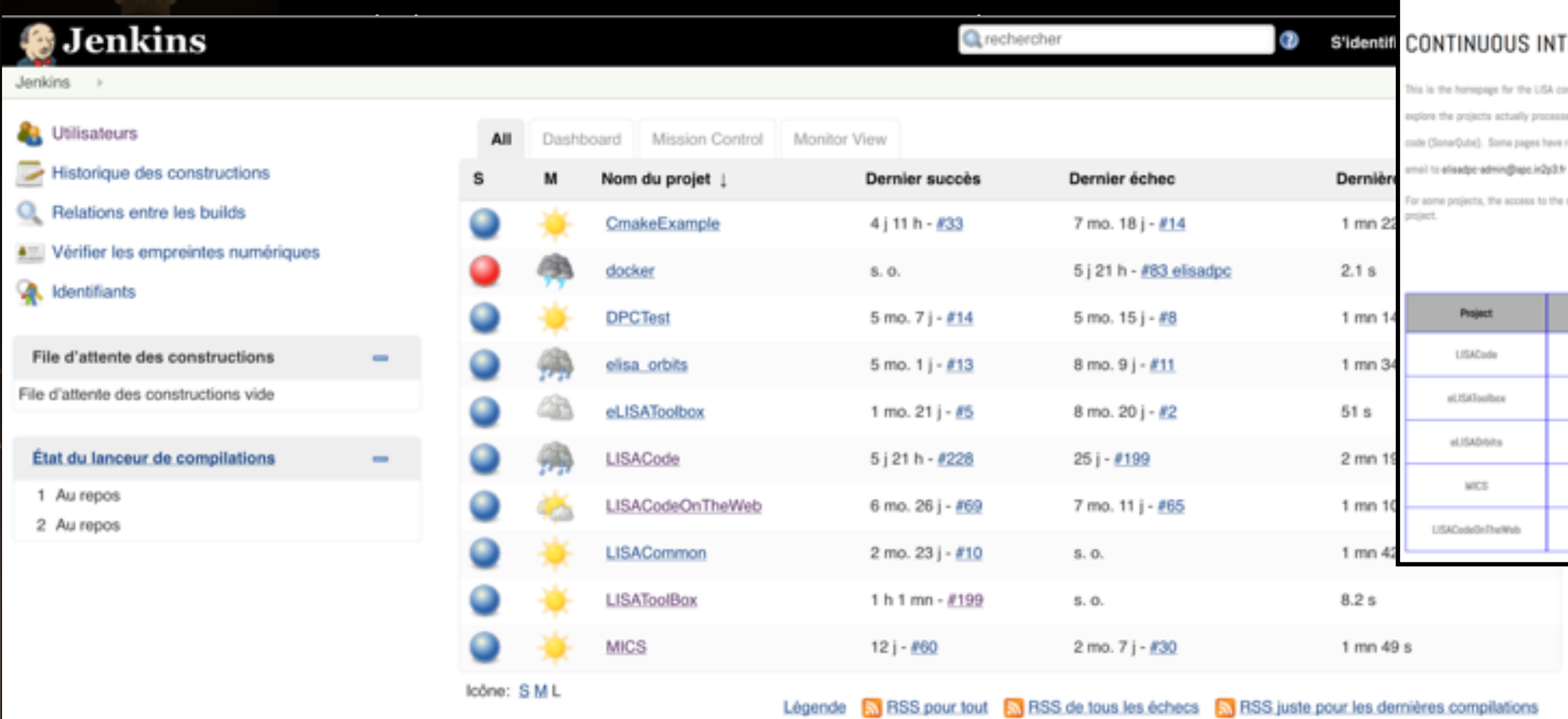
- Our guideline : The DPC has to be easy-to-use, simple, flexible and easily upgradeable until the end of the mission.

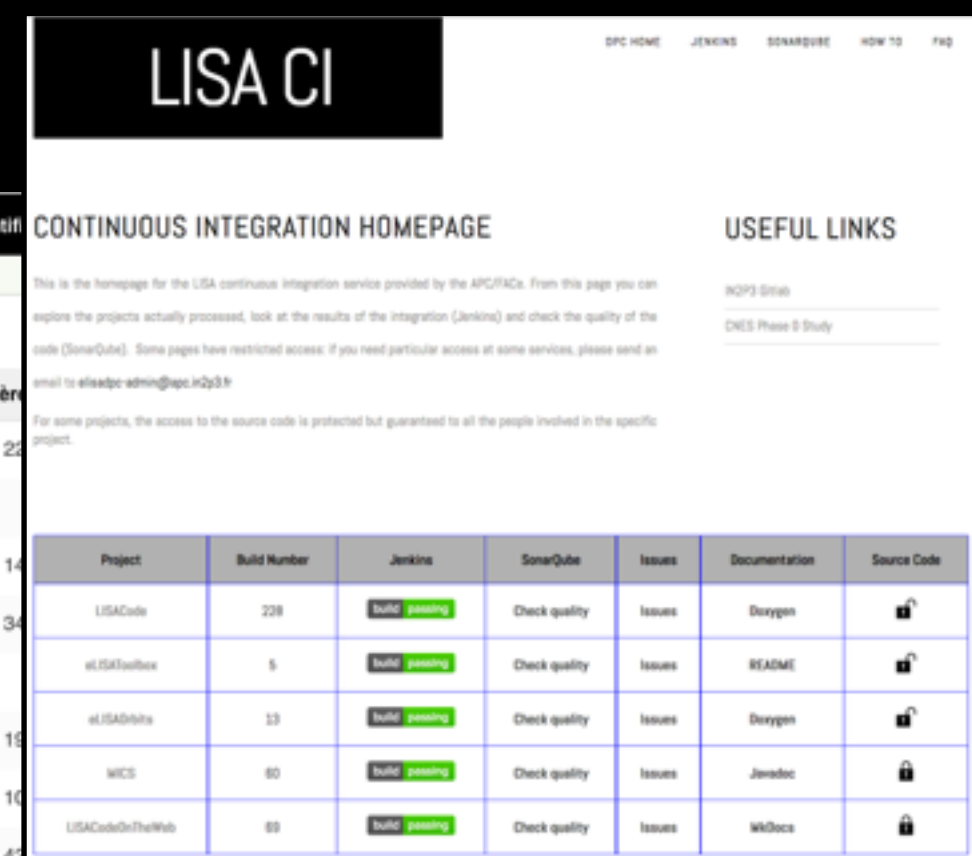
LISA proto-DPC

- Development environment: in production
  - Goals
    - Ease the collaborative work: reason why it's already started
    - During the operation: guarantee reproducibility of a rapidly evolving and composite DA pipeline
    - In fine: keep control of performance, precision, readability, etc
  - Use existing standard tool
    - Control version system to keep track of code revision history, manage teams and workflows.
    - Continous integration (like in Euclid, LSST): suite of non-regression tests automatically run after each commit
    - Docker image: a way to encapsulate source code + its execution

LISA proto-DPC

- Development environment: in production
  - Done:
    - Simple install of open and standard tools: Jenkins, SonarQube, gitlab CI
    - Worked on moving from 'simple' to 'automatic' using Docker
    - More projects, more users to come.





LISA proto-DPC

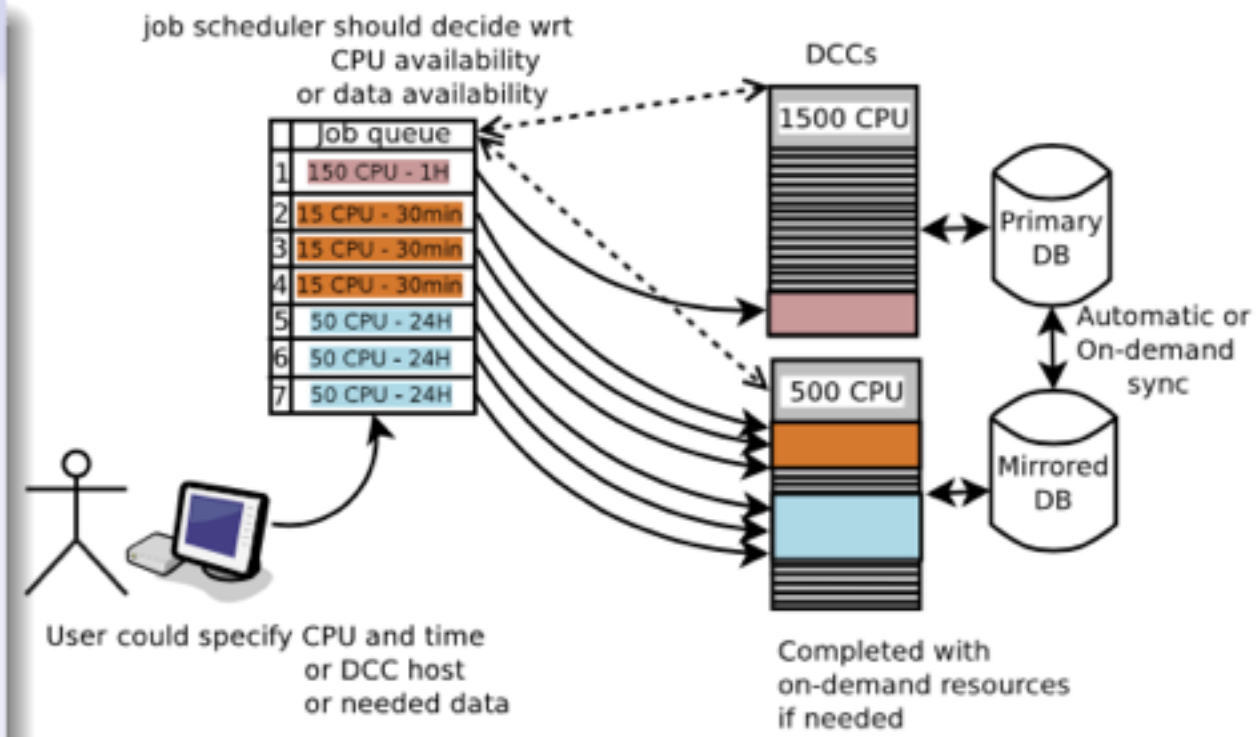
- Data basis & data model: in R&D
  - Motivations
    - Data sharing among people and computing centers
    - Mainly processed, temporary or intermediate data: need meta data management to use them
    - A lot of information: a web 2.0 (intuitive) interface is mandatory (search engine, DB request, tree view to show data dependancies, etc)
  - Context
    - Not big LISA data volume
    - But still implies some specific developments even if using standard data format. One has to define LISA data model first …
      - LDC, simulations, LPF data
      - Django website + its sqlite DB: first version ready

LISA proto-DPC

- **Execution environment**: in R&D

Objectives: a composite computer center

- Pooling of CPU resources with a single scheduler for all DCCs
  - the user-friendly way to go
  - a dynamic CPU pool to adapt the resources to the actual needs (the economic way)
  - transfering data if needed
- Assumptions
  - it's easy to plug new hardware
  - it's easy to transfer data



same principles than grid computing with a shorter learning phase.

R&D activities

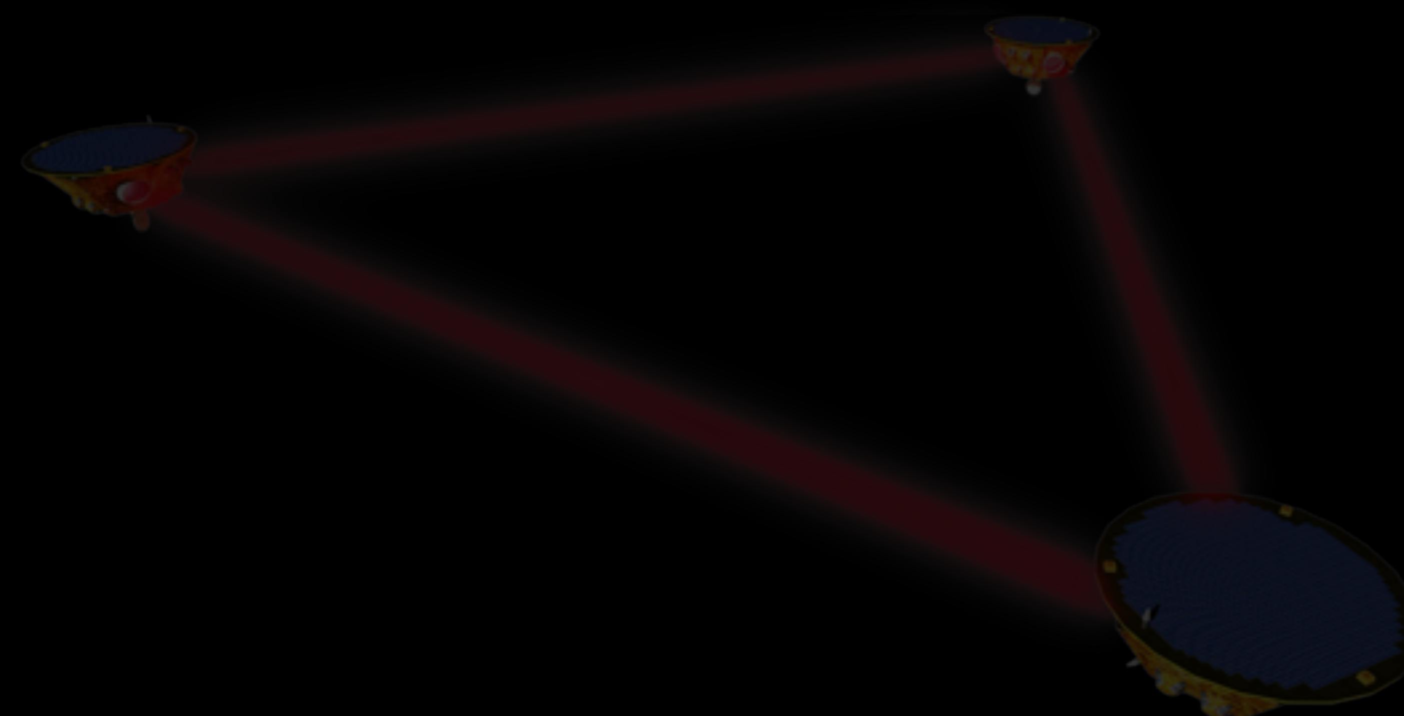
- Docker ochestrator R&T study performed by CNES
- APC involved in the French cloud network
- Doing some actual testing of cloud platform and containers orchestration (singularity).

From M. Le Jeune

Conclusion

- LISA in phase 0/A : Ground Segment in definition
- First mission of this kind => some uncertainties (number of sources, data quality, unknown sources ...) => flexibility + continuous evolution + computation load fluctuations
- Distributed Ground Segment: MOC + SOC + DPC running on DCCs
  - SOC: L0 → L1: calibration, pre-processing reducing noises
  - DPC: L1 → L2,L3 : extract GW sources from TDI data (L1) to produce catalogs and science products (L2 & L3)

  => Same shared software running on distributed infrastructure
- Existing LISA proto-DPC to:
  - Support LISA developments: simulations, data analysis (LISA Data Challenge)
  - Prototype for the future DPC



Thank you