From LISAPathfinder to LISA: space-based observatory for gravitational waves

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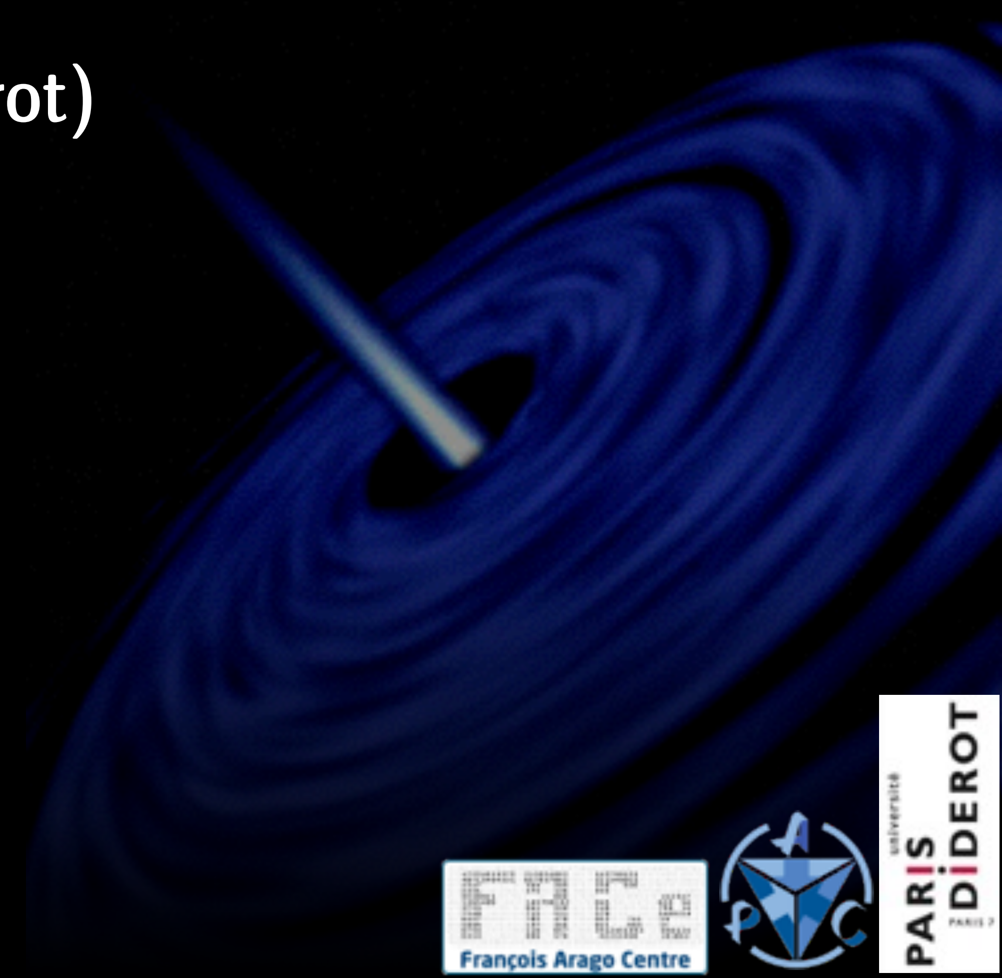
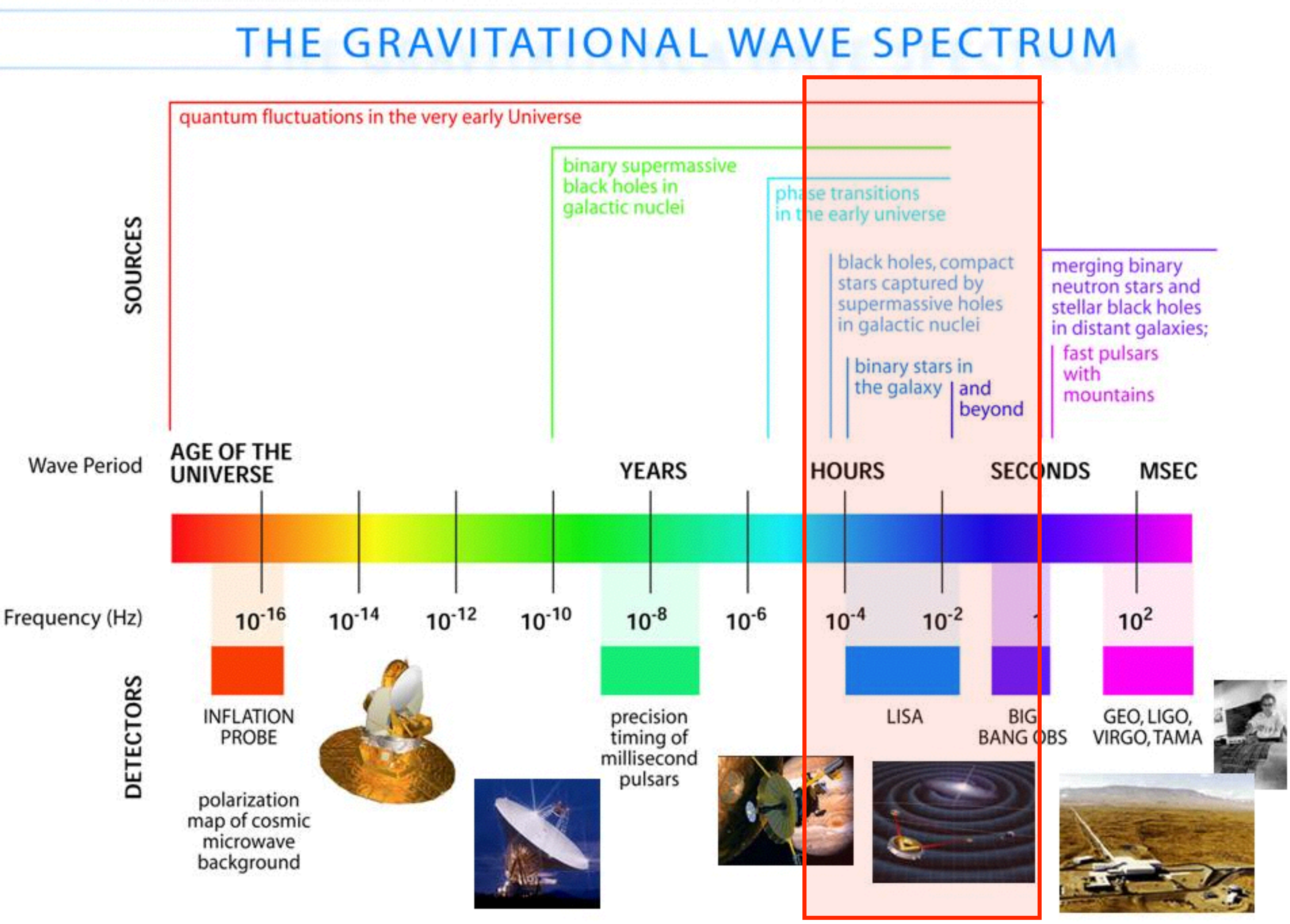
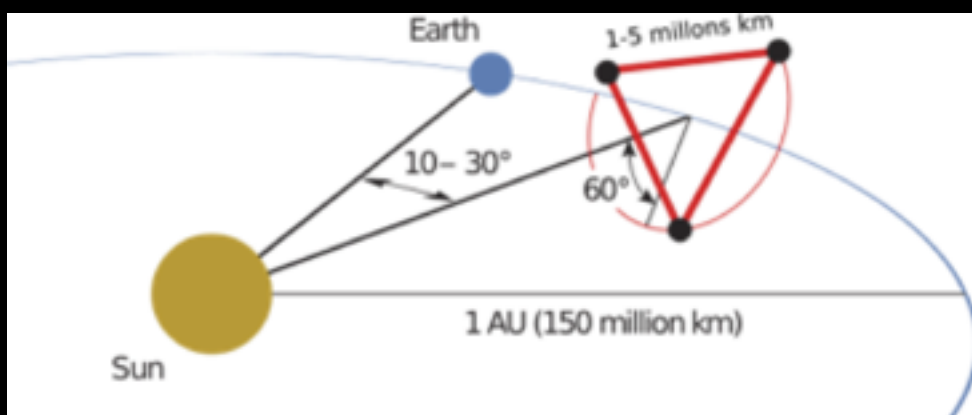


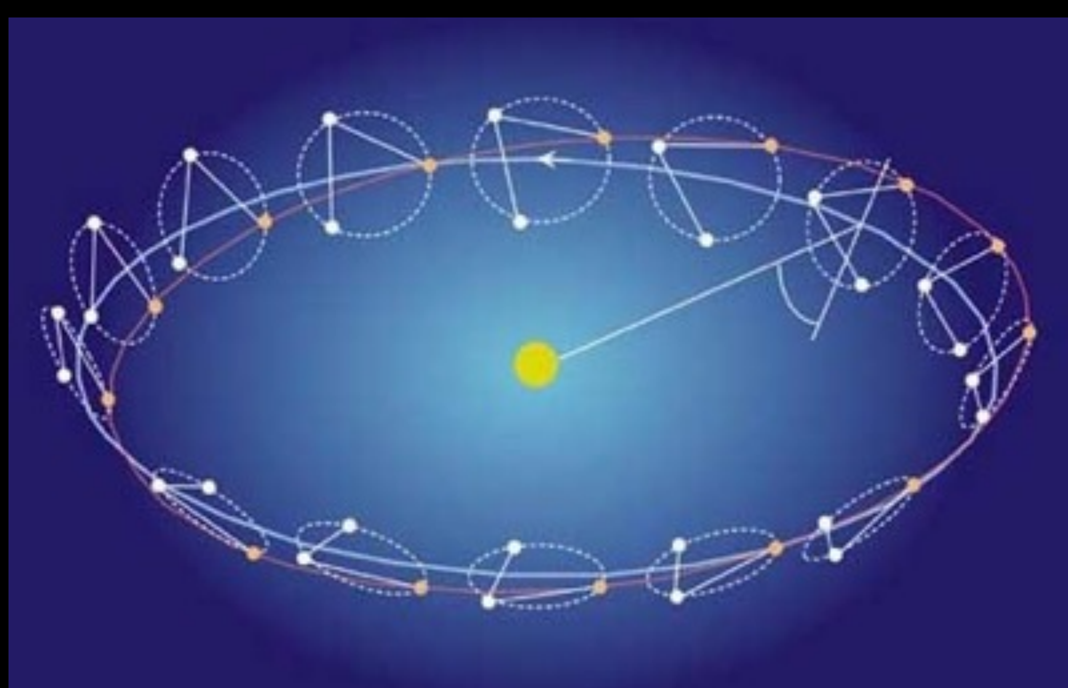
SF2A
Paris
4 Juillet 2017

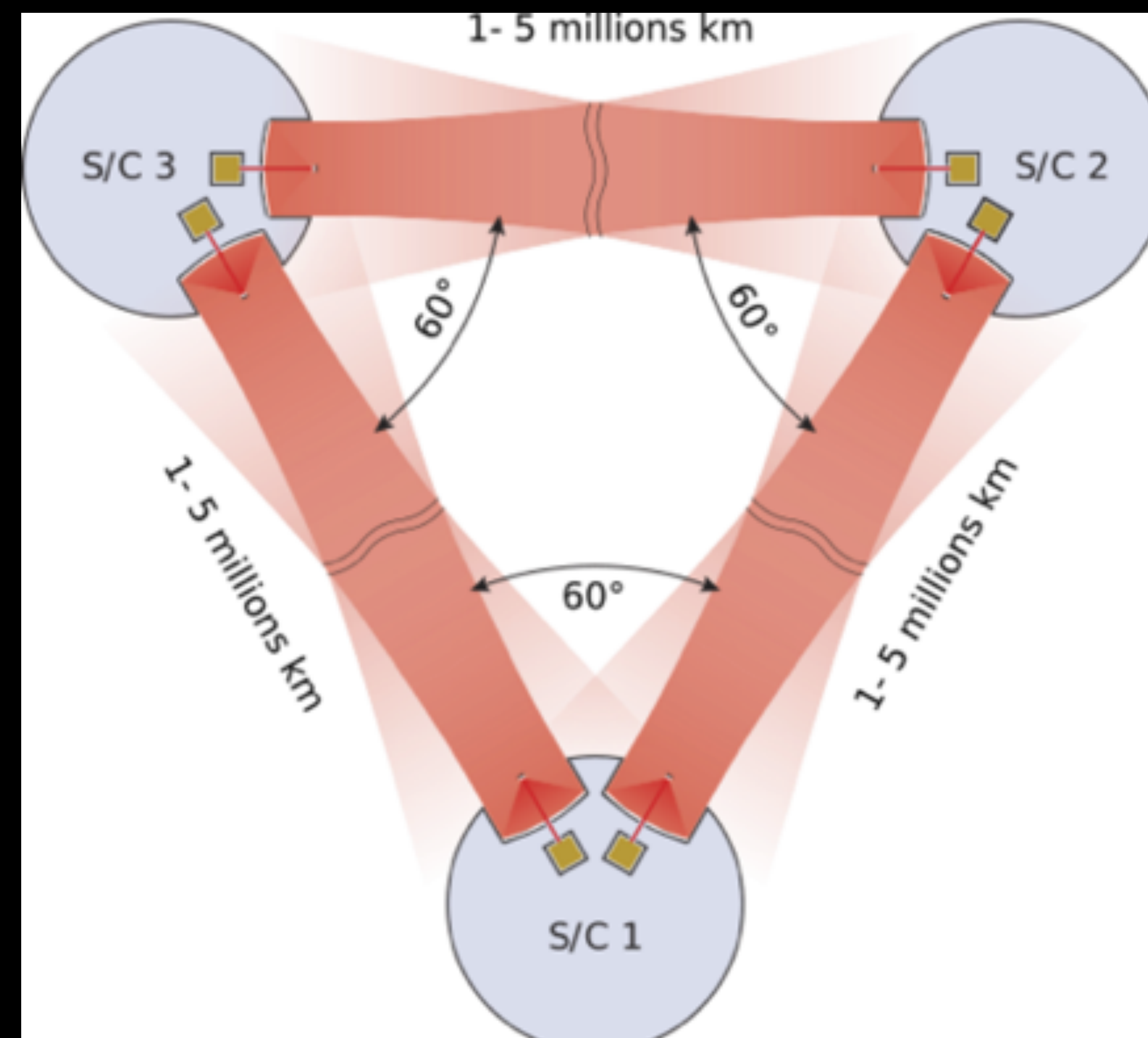

THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging 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
102
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA

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

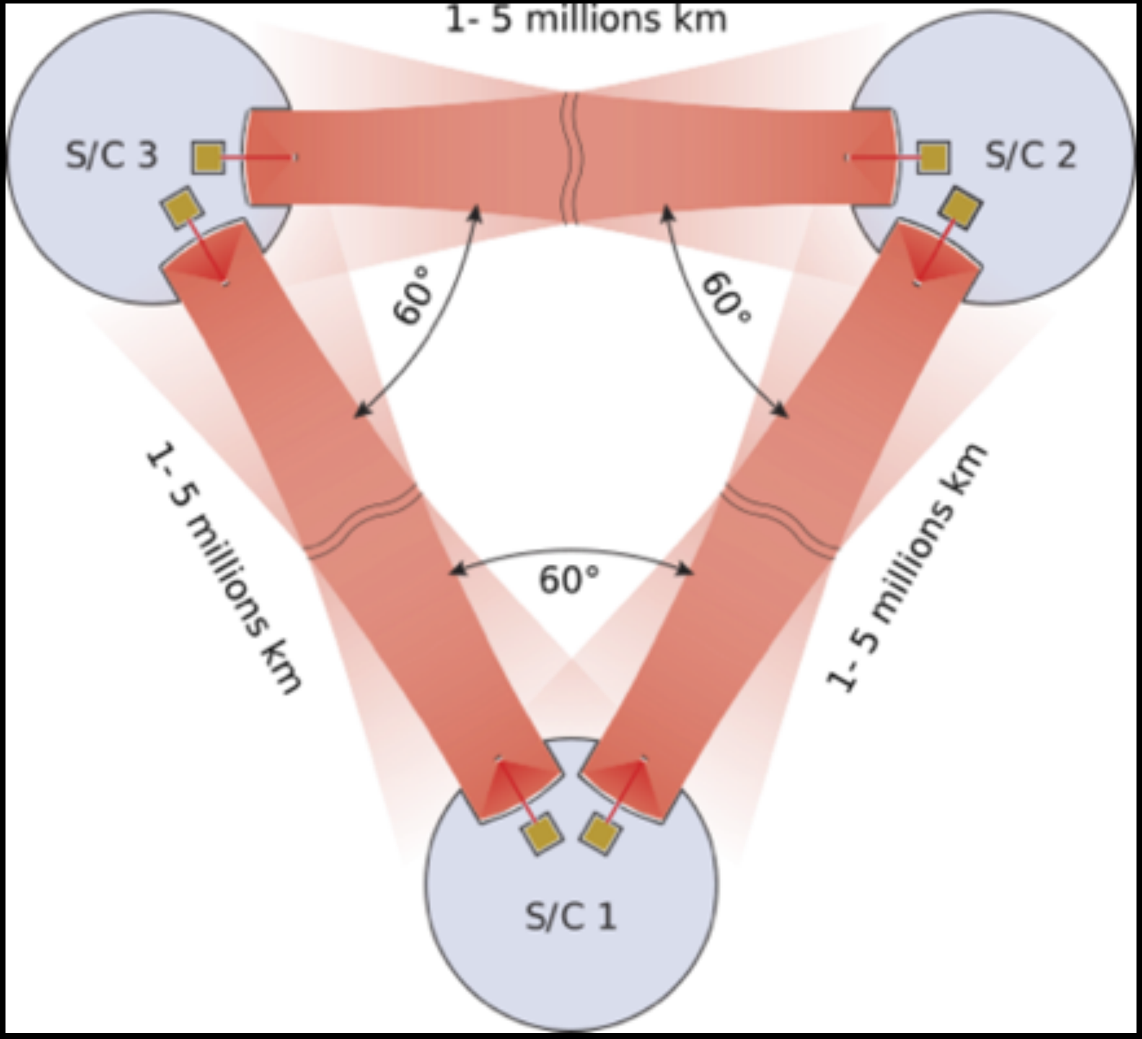






LISA

- 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

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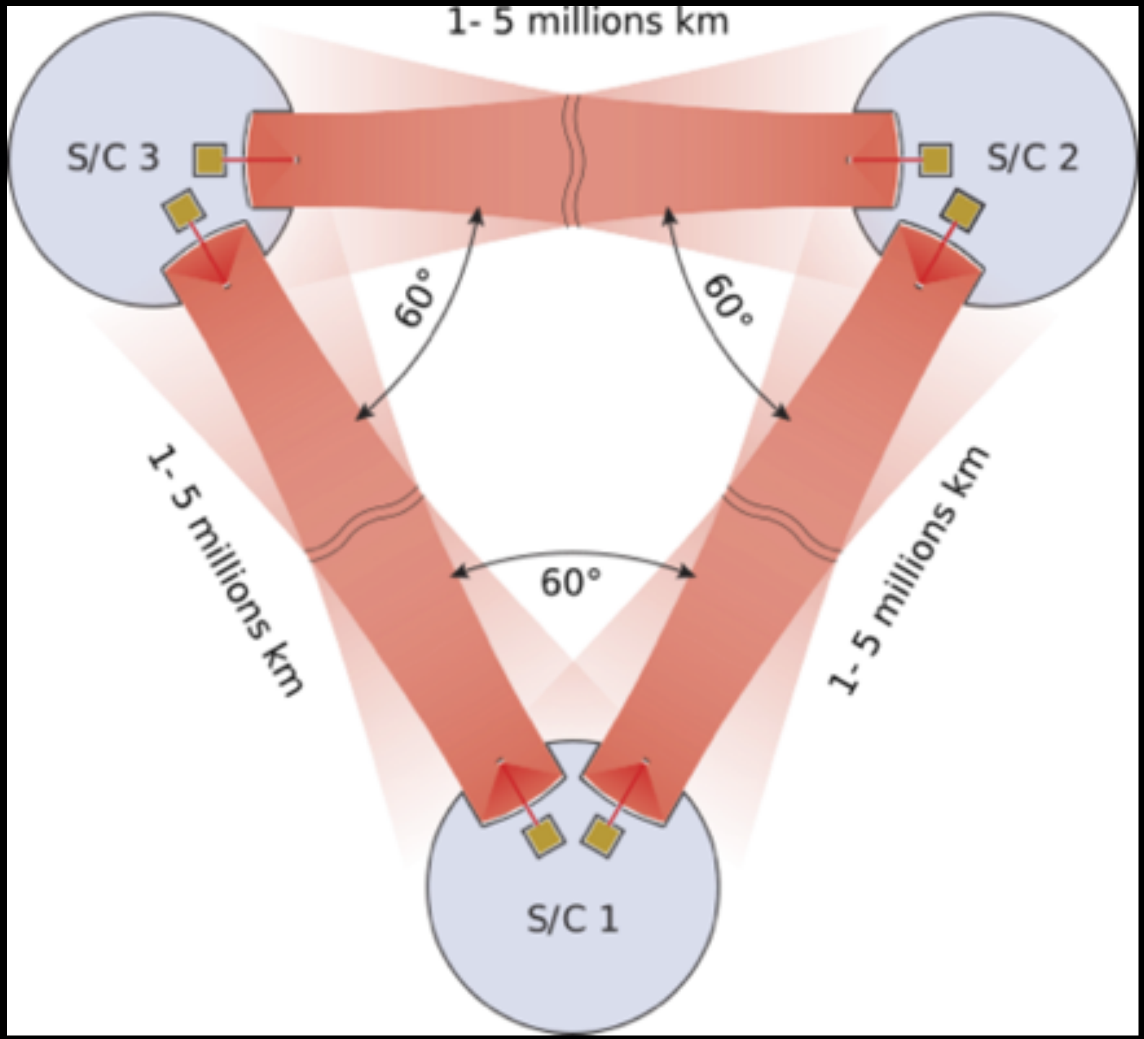
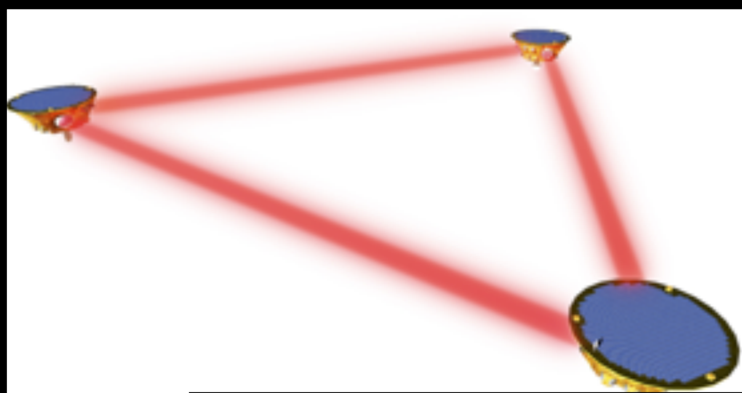
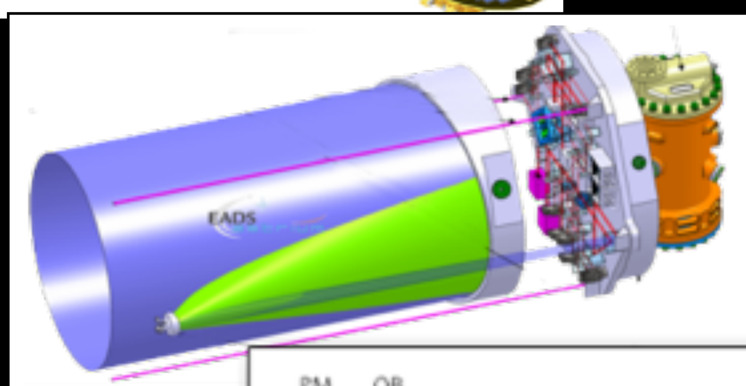


LISAPathfinder

- Technological demonstrator for LISA





LISA :

- Measure distance along using laser interferometry

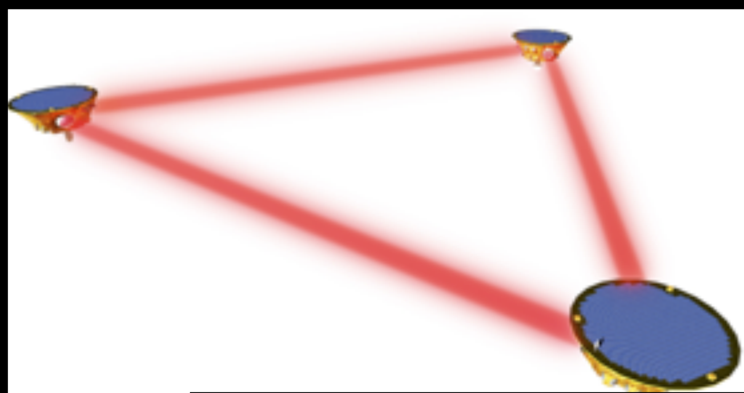
$$(TM1 \rightarrow SC1) + (SC1 \rightarrow SC2) + (SC2 \rightarrow TM2)$$

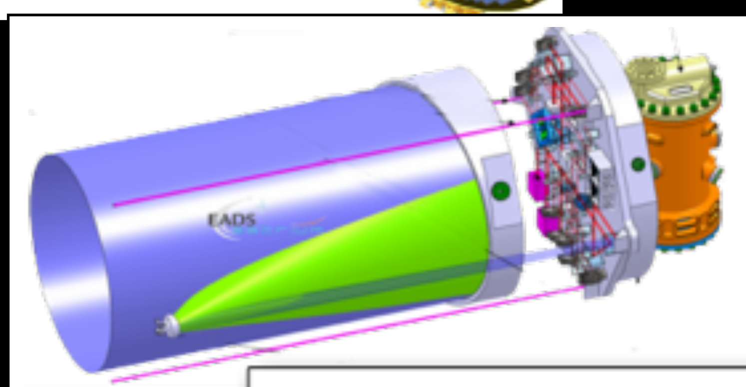
LISAPathfinder

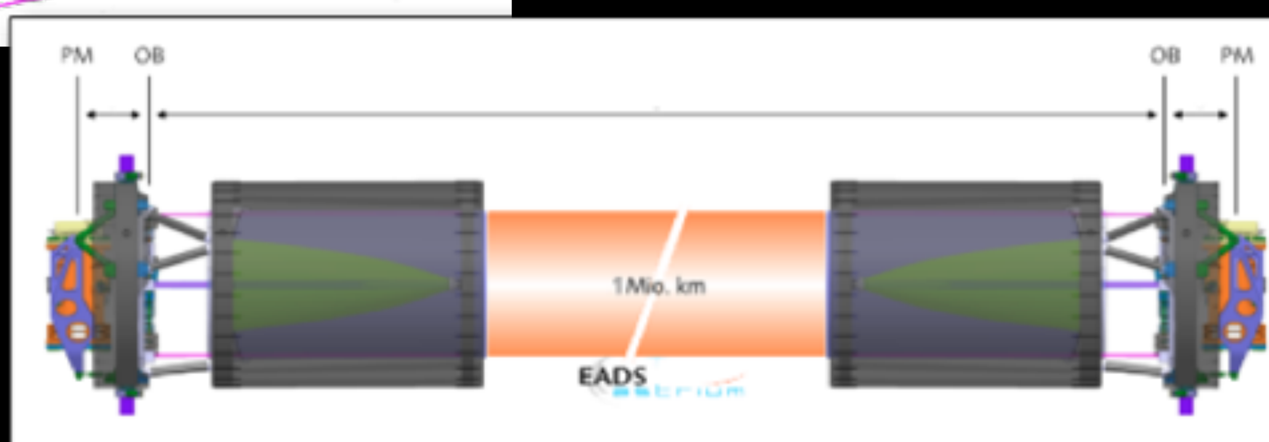
- Technological demonstrator for LISA

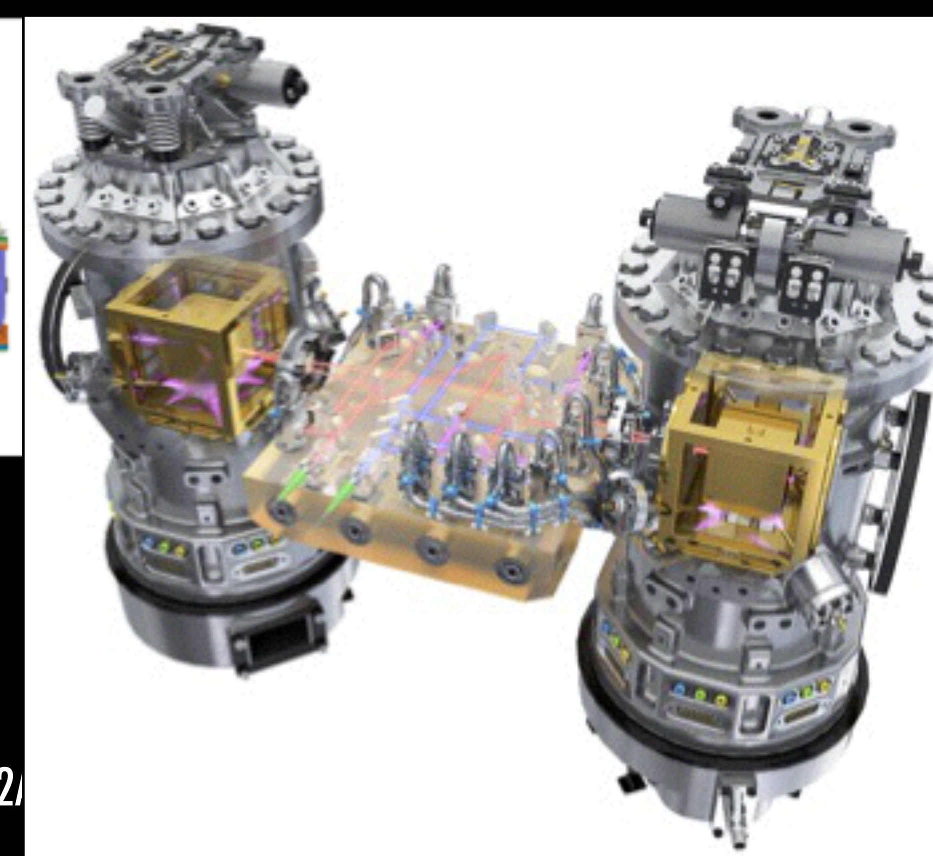
LISAPathfinder:

- 2 test masses / 2 inertial sensors
- Laser readout of TM1 → SC and TM1 → TM2
- Capacitive readout of all 6 d.o.f. of TM
- Drag-Free and Attitude Control System
- Micro-newton thrusters



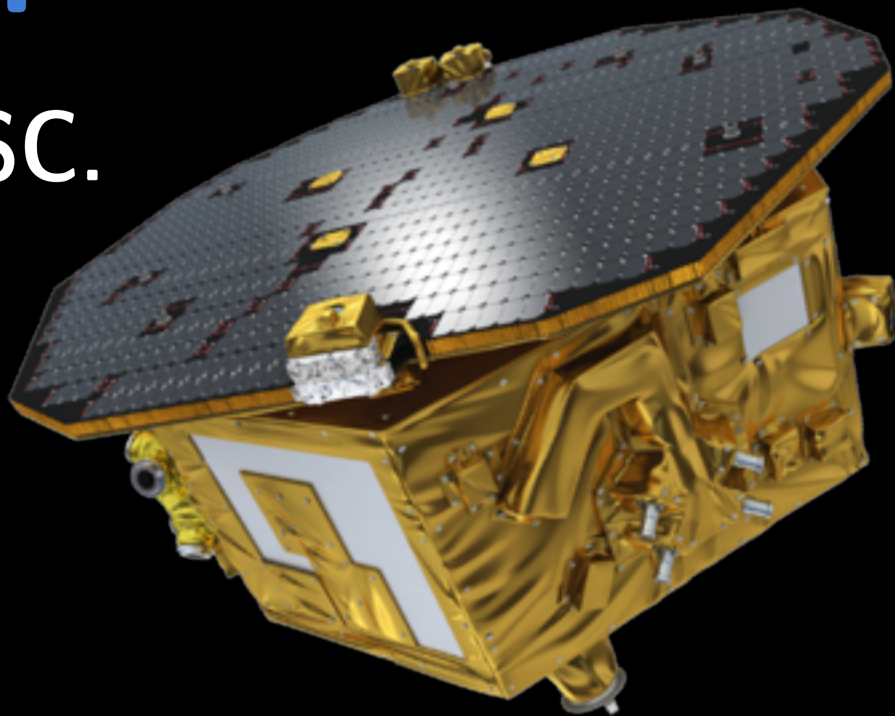


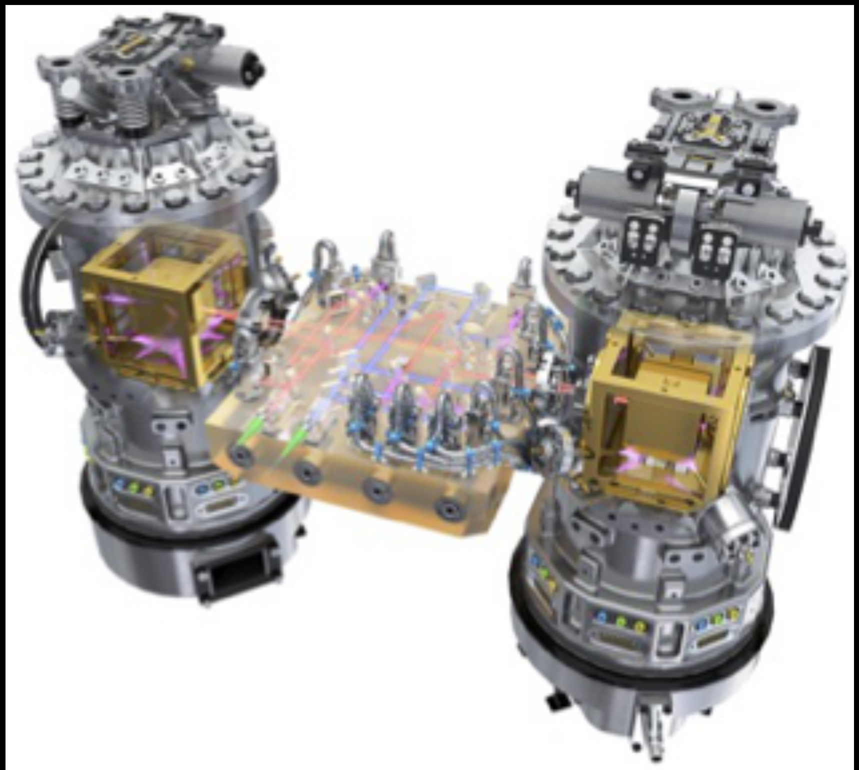




LISAPathfinder

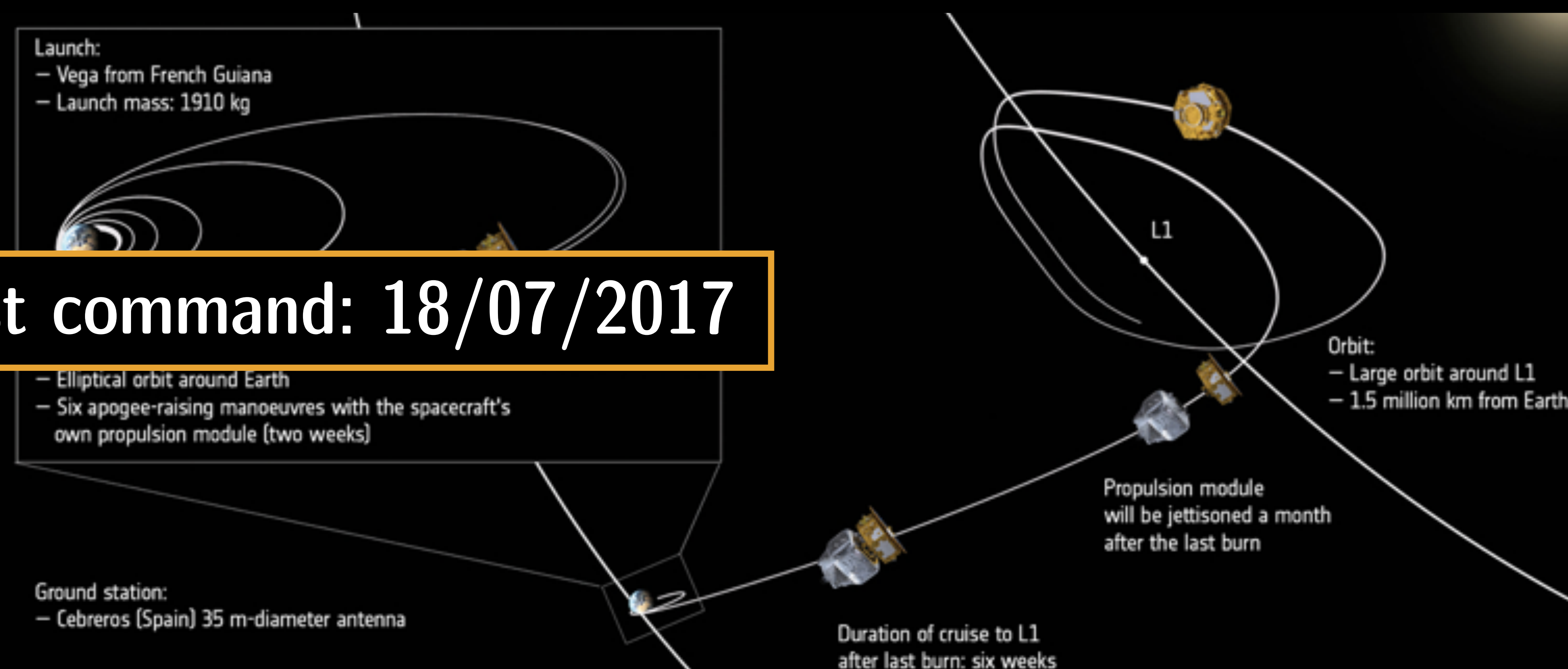
- Basic idea: Reduce one LISA arm in one SC.
- LISAPathfinder is testing :
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
  - Micro-thrusters





LISAPathfinder timeline

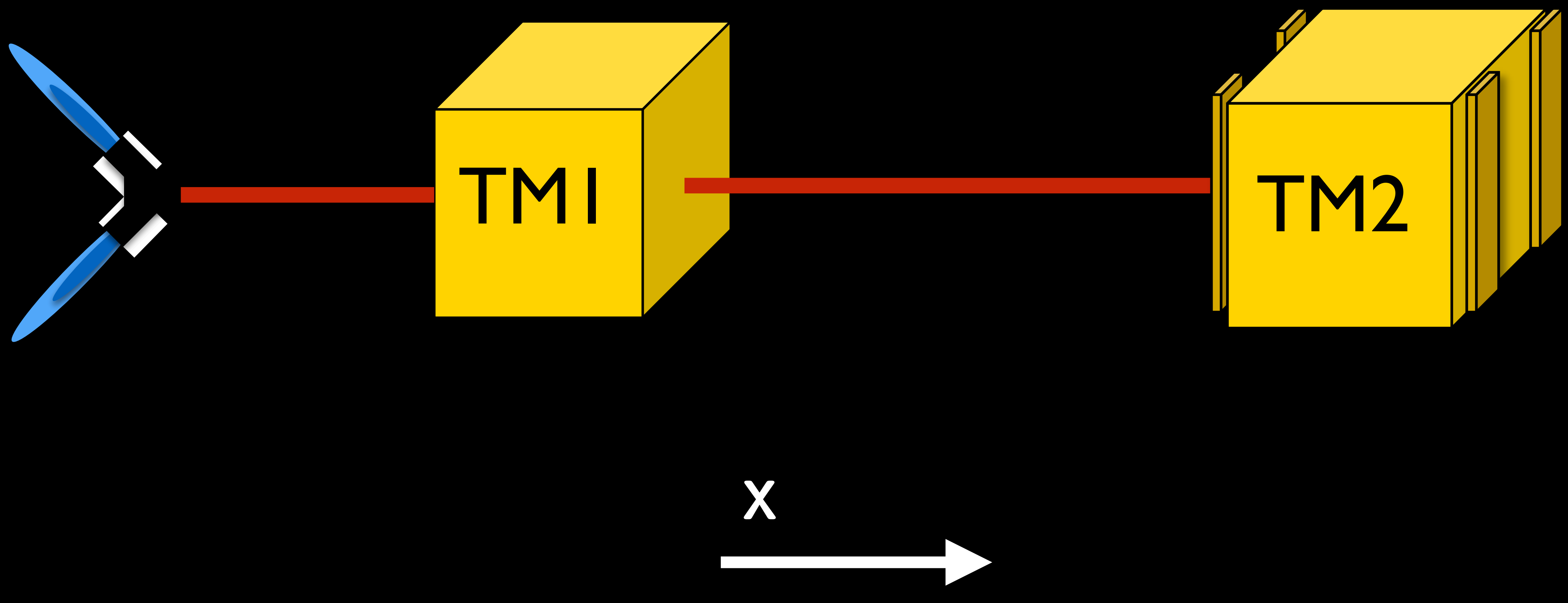
- 3/12/2015: Launch from Kourou
- 22/01/2016: arrived on final orbit & separation of propulsion module
- 17/12/2015 → 01/03/2016: commissioning
- 01/03/2016 → 27/06/2016: LTP operations (Europe)
- 27/06/2016 → 11/2016: DRS operations (US) + few LTP weeks
- 01/12/2016 → 31/06/2017: extension of LTP operations



Last command: 18/07/2017

The measurement - deltaG

Suspension (f<1mHz)

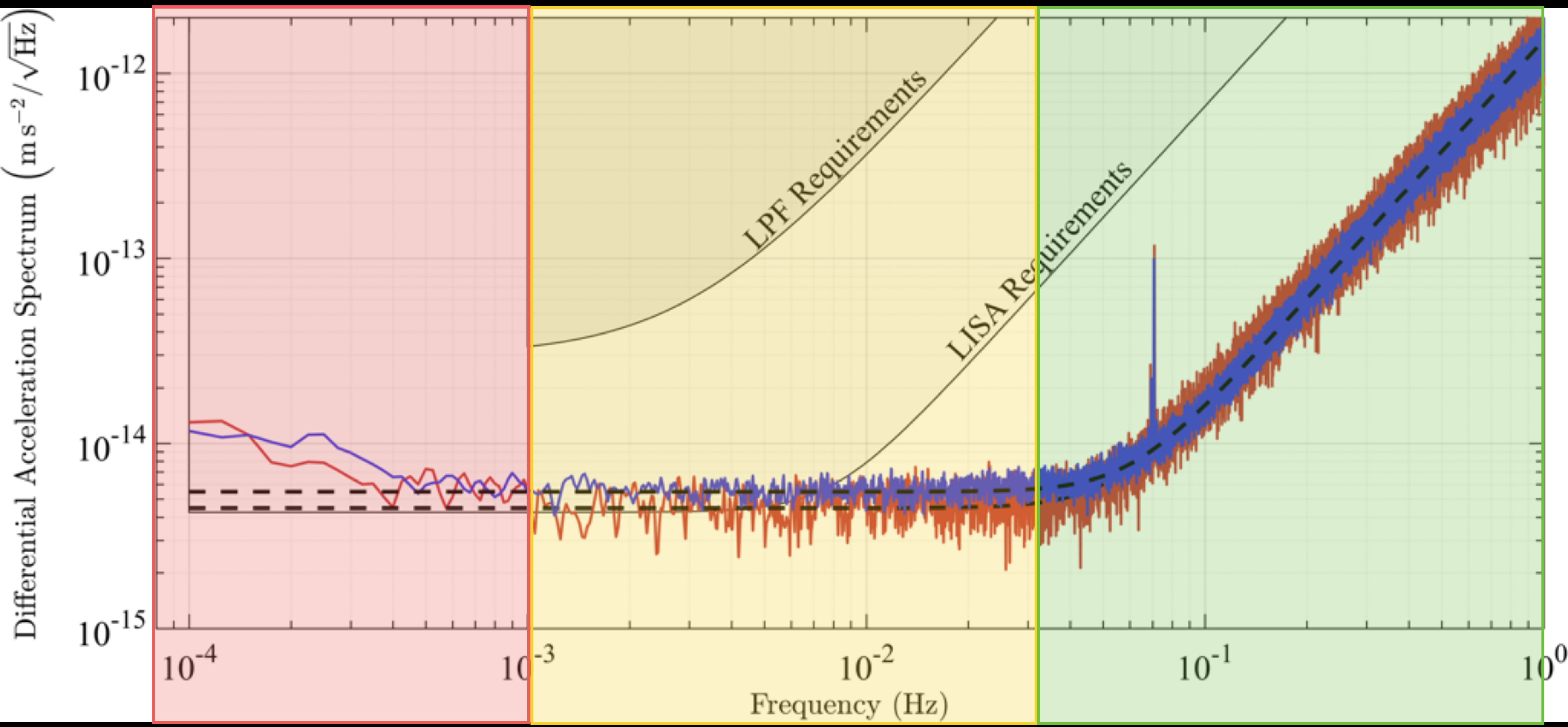


$$deltaG = d^2(o12)/dt^2 - Stiff * o12 - Gain * Fx2$$

First results

- Results

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



Low frequency noise: actuation noie + ...

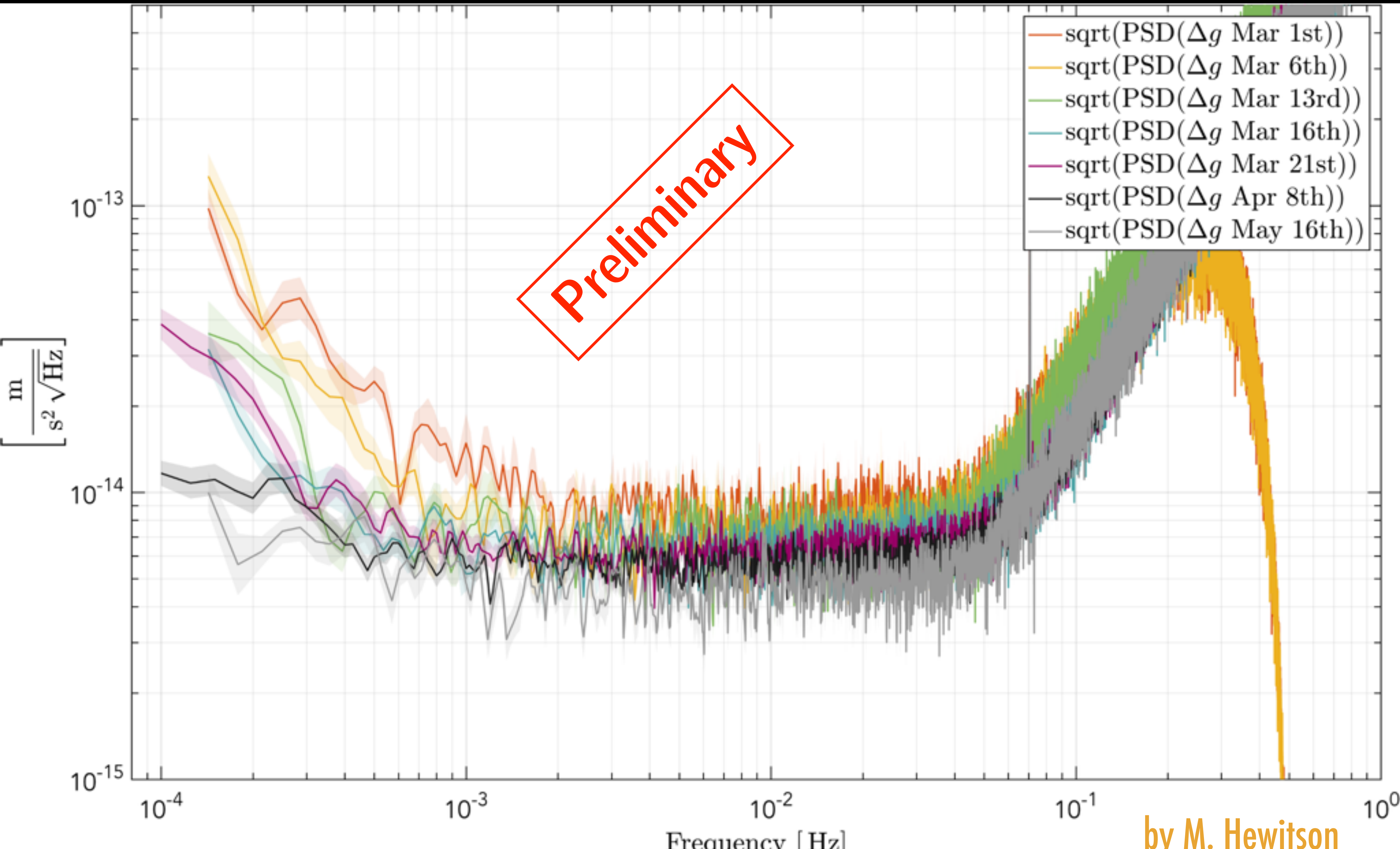
Brownian noise
Molecules within the noise hit test-masses

Interferometric noise
Not real test-mass motion

François Arago Centre

université PARIS DIDEROT

Time evolution of noises



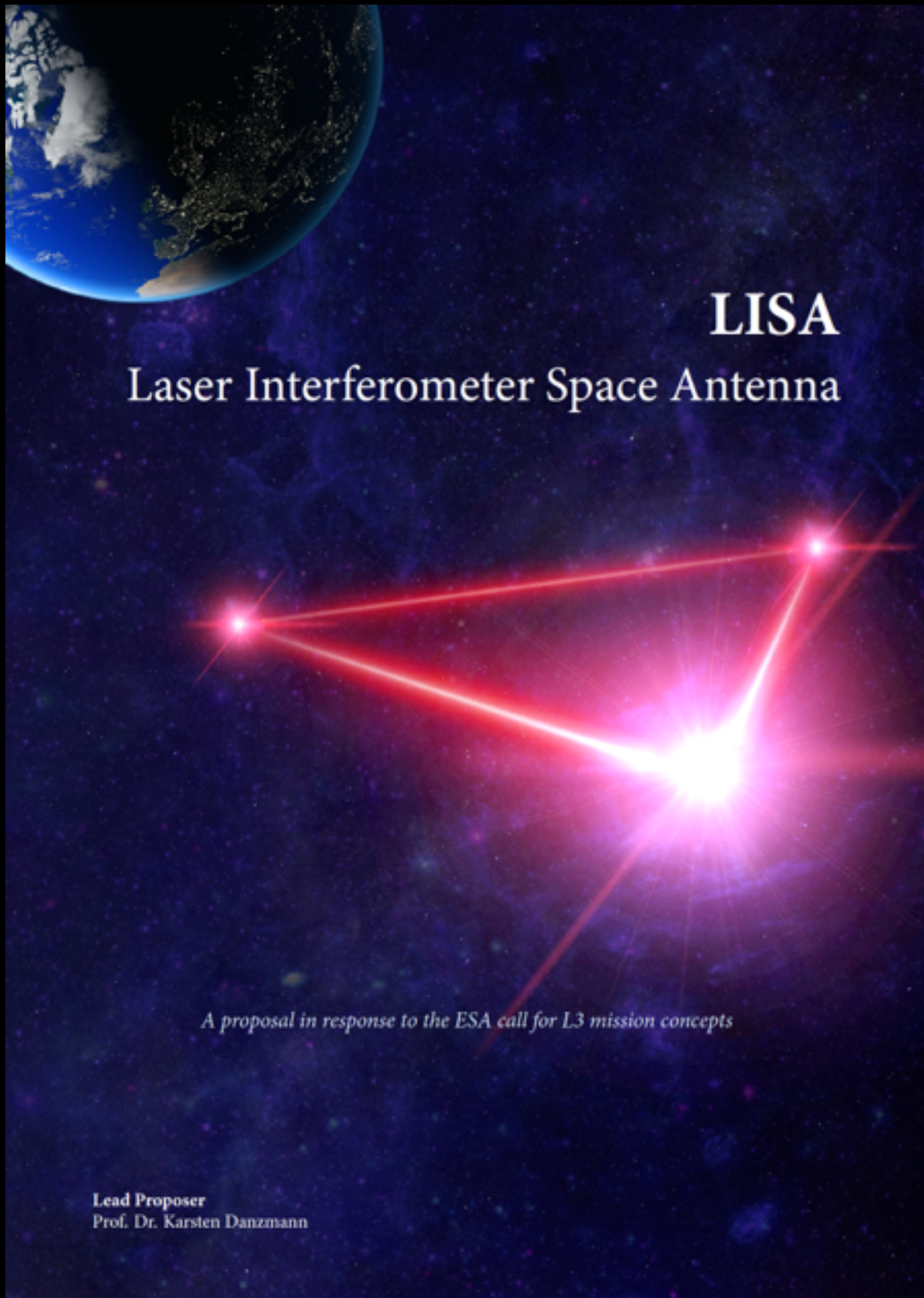
by M. Hewitson

LISA at ESA

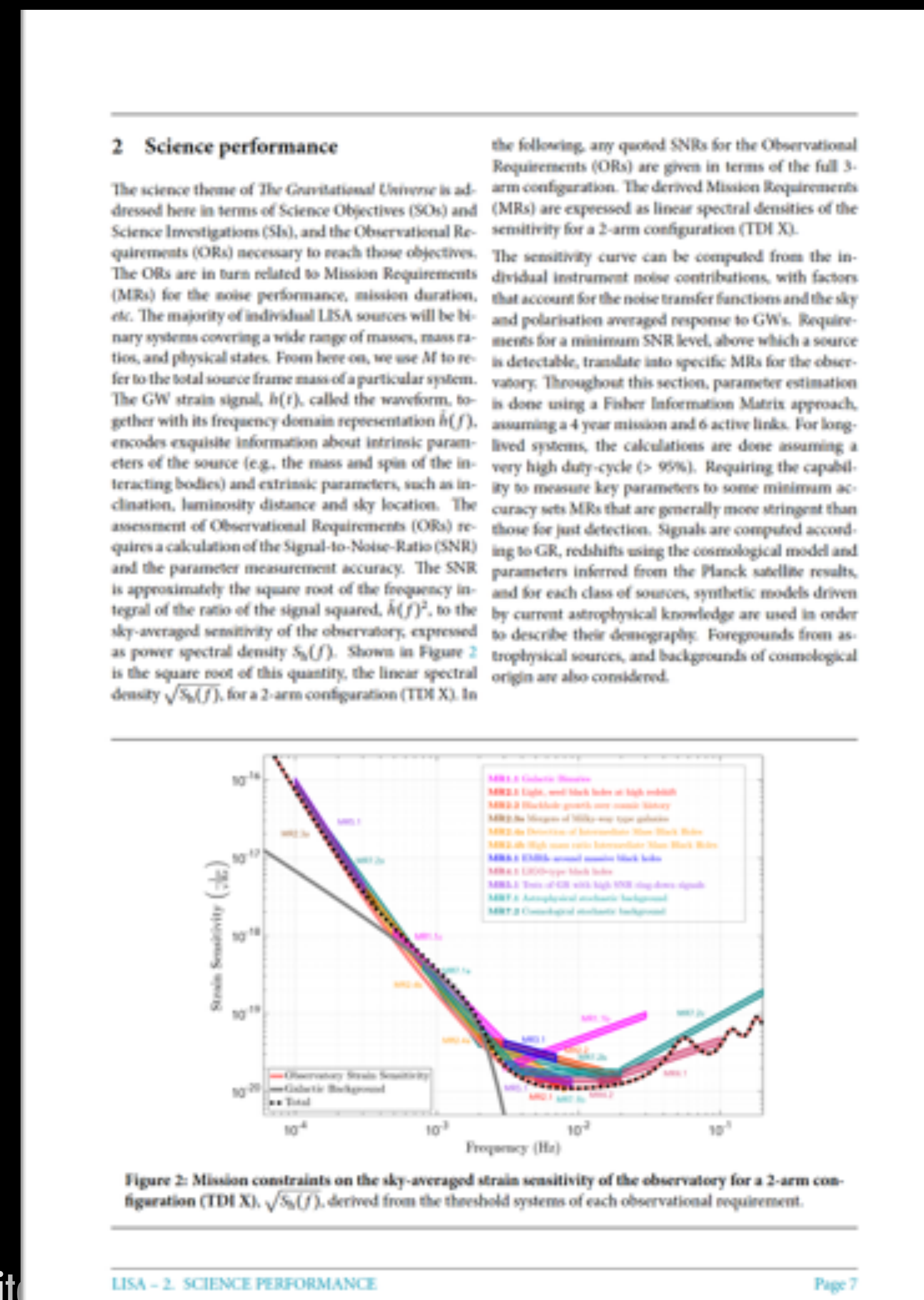
- 25/10/2016 : Call for mission
- 13/01/2017 : submission of «LISA proposal» (LISA consortium)
- 8/3/2017 : Phase 0 mission (CDF 8/3/17 → 5/5/17)
- 20/06/2017 : LISA mission approved by SPC
- 8/3/2017 : Phase 0 payload (CDF June → November 2017)
- 2018→2020 : competitive phase A : 2 companies compete
- 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
- Possible extension to 10 years

GW observations !

« The LISA Proposal »



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



2 Science performance

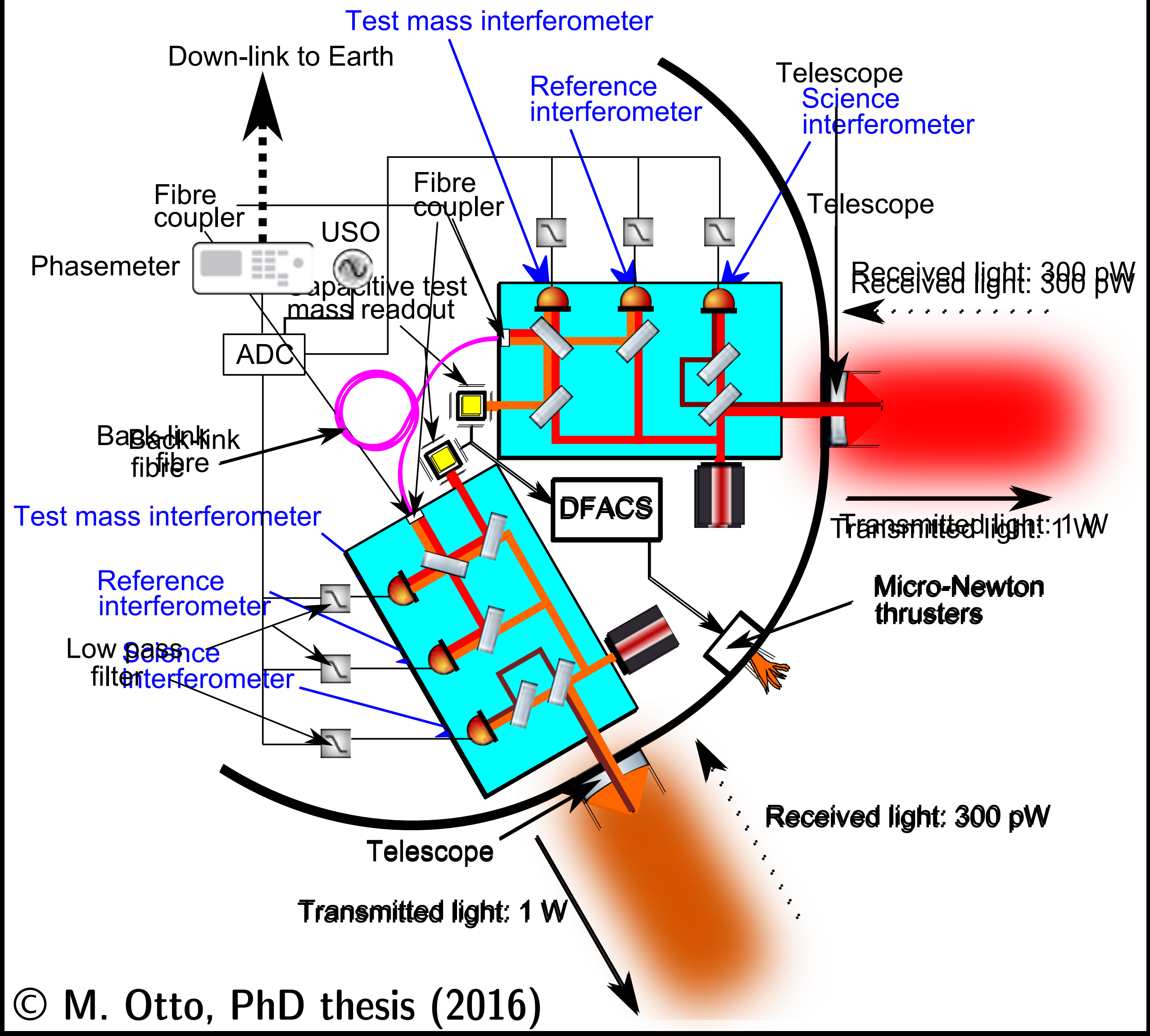
The science theme of *The Gravitational Universe* is addressed here in terms of Science Objectives (SOs) and Science Investigations (SIs), and the Observational Requirements (ORs) necessary to reach those objectives. The ORs are in turn related to Mission Requirements (MRs) for the noise performance, 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 expessed 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.

Current design

- 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

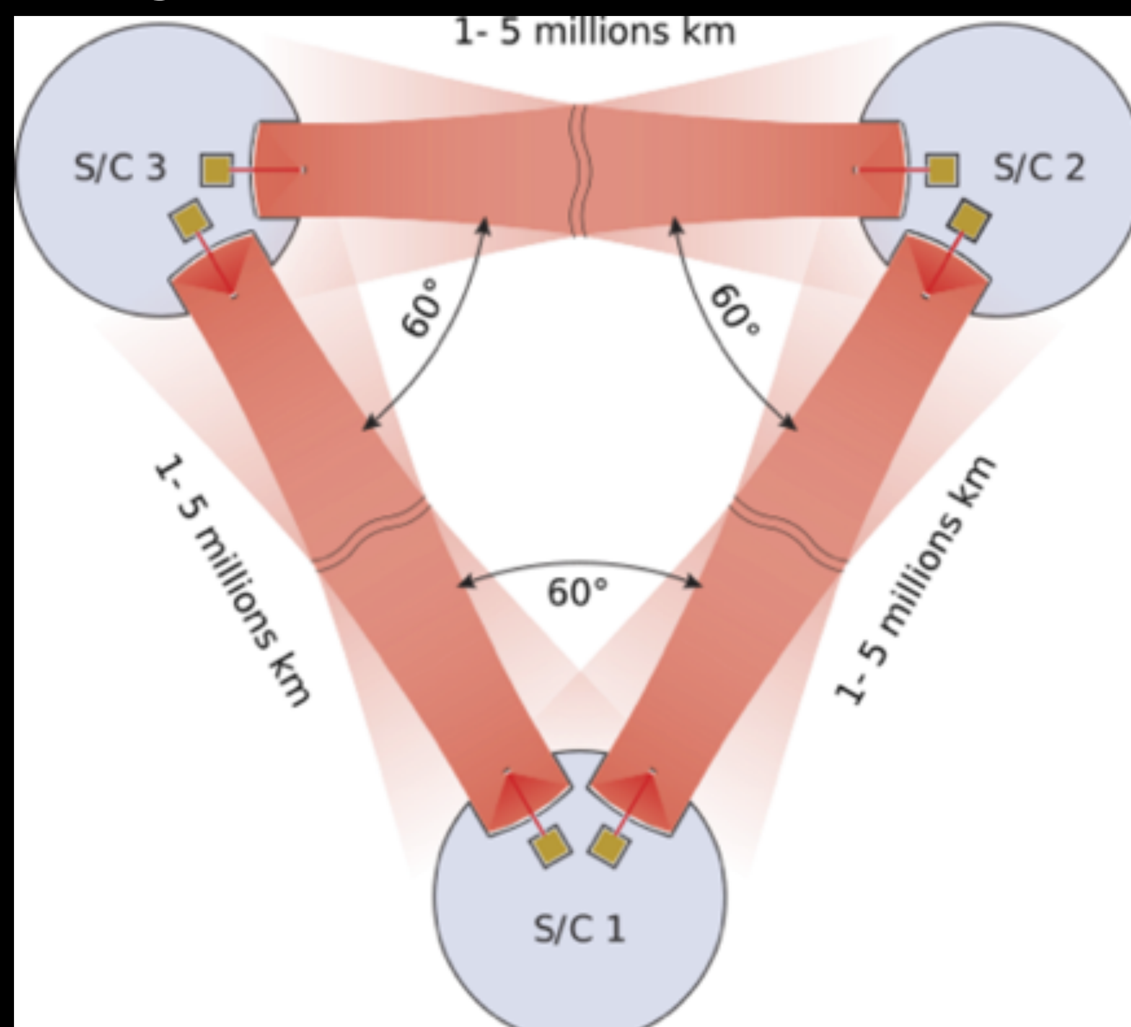


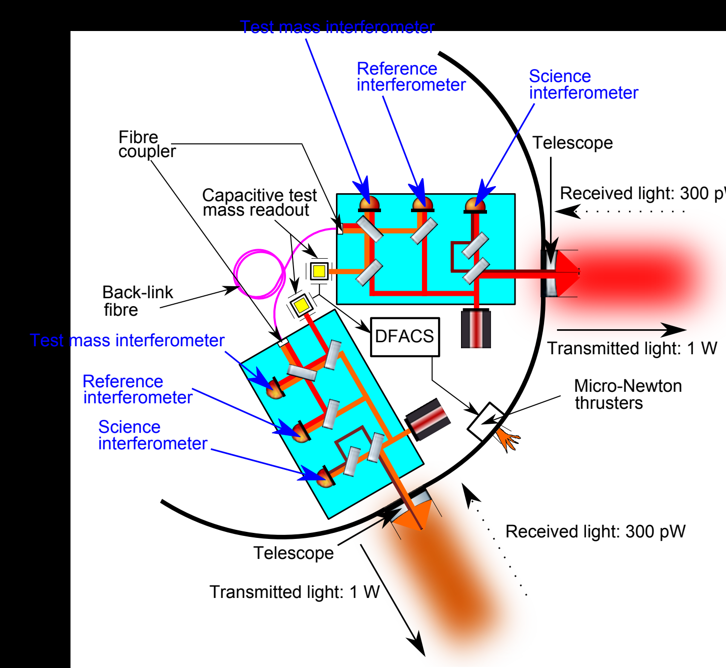
© M. Otto, PhD thesis (2016)

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

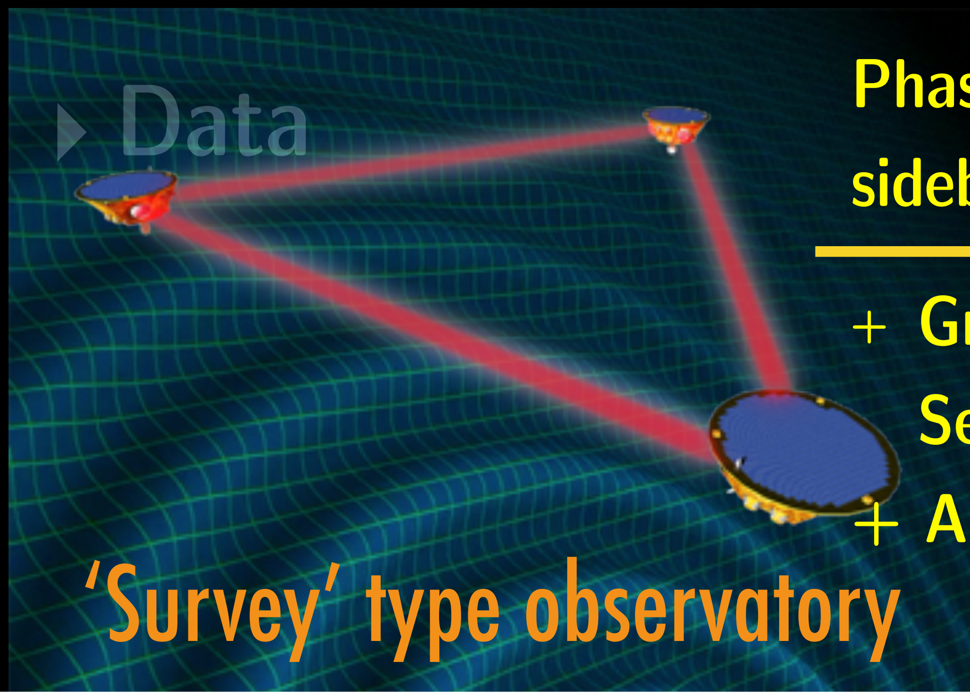
LISA

- 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 Reference Sensor

+ Auxiliary channels

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

L1 — 2 data channels TDI non-correlated

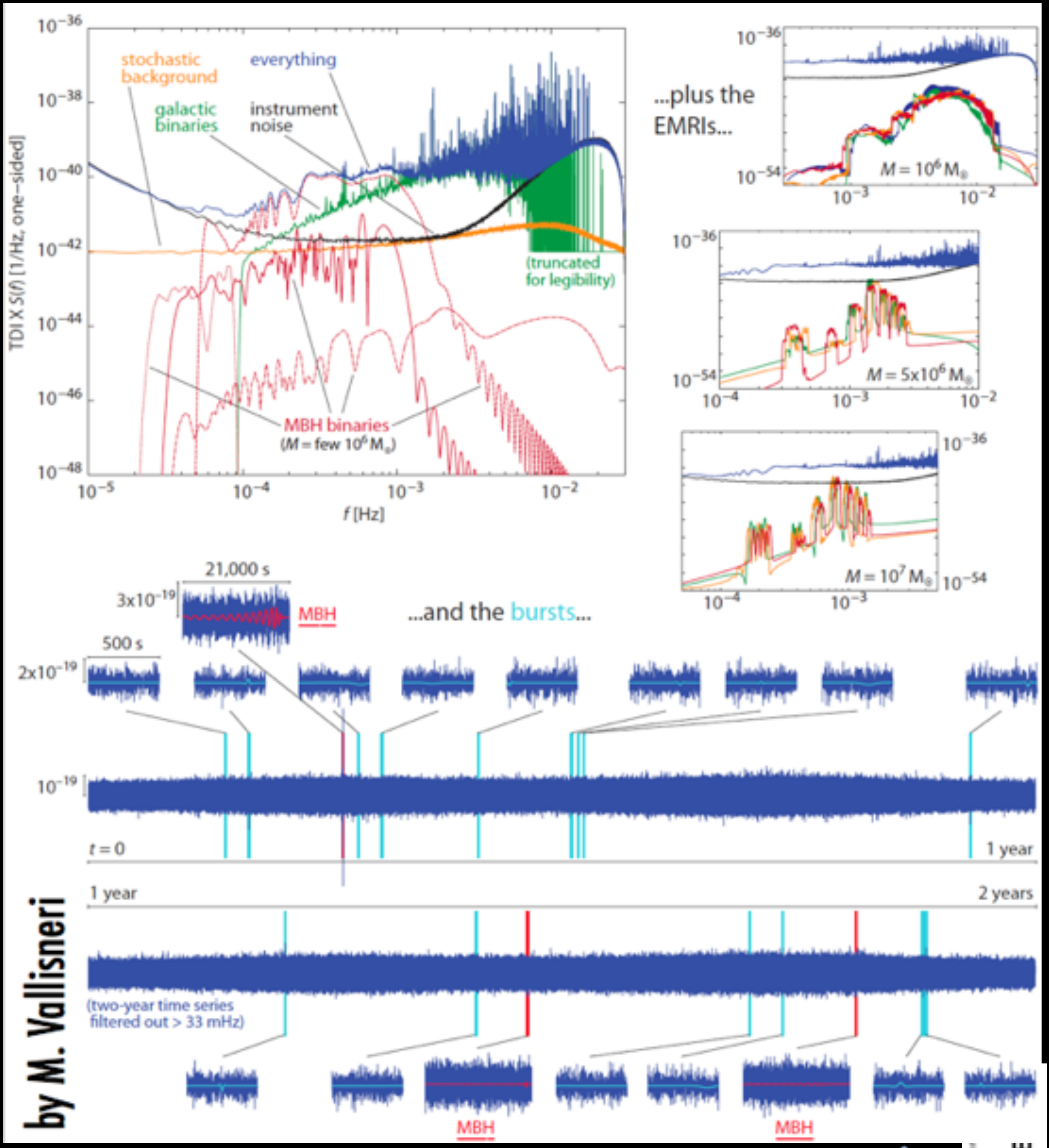
L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 100 mHz

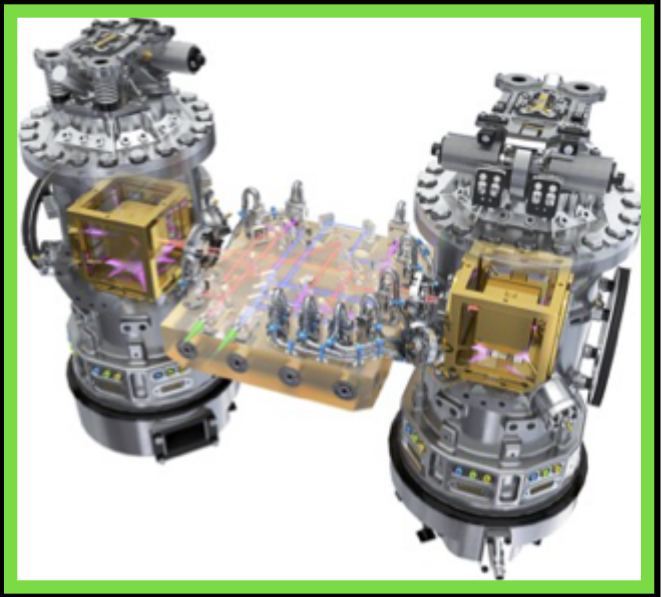
LISA Data Challenges

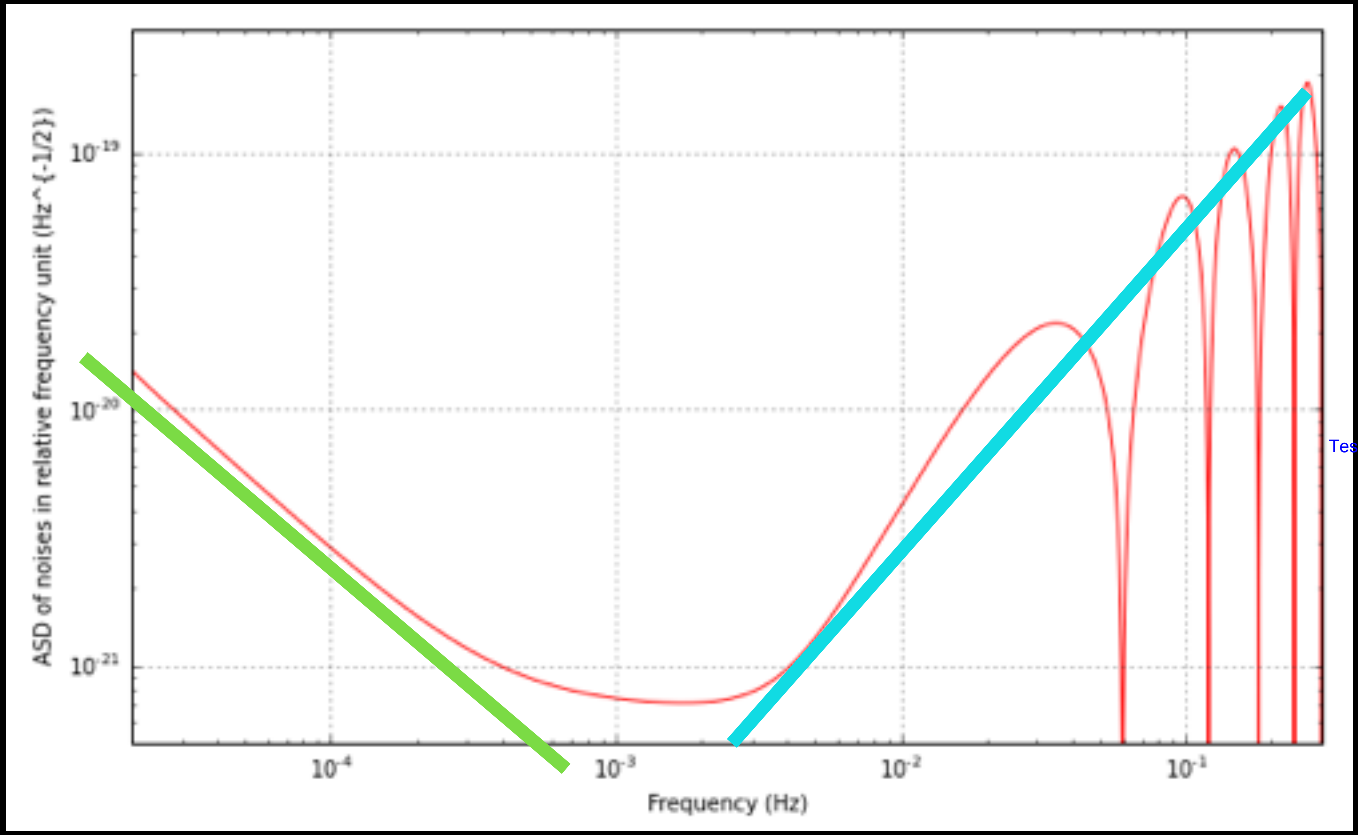
- Mock LDC : 2005 → 2011
- 2017: start LDC
- Data: few sources + simplified noises
- Challenges of increasing complexities
- Goals :
  - Check the feasibility of LISA data analysis
  - Develop data analysis
  - Make the pipelines for the mission

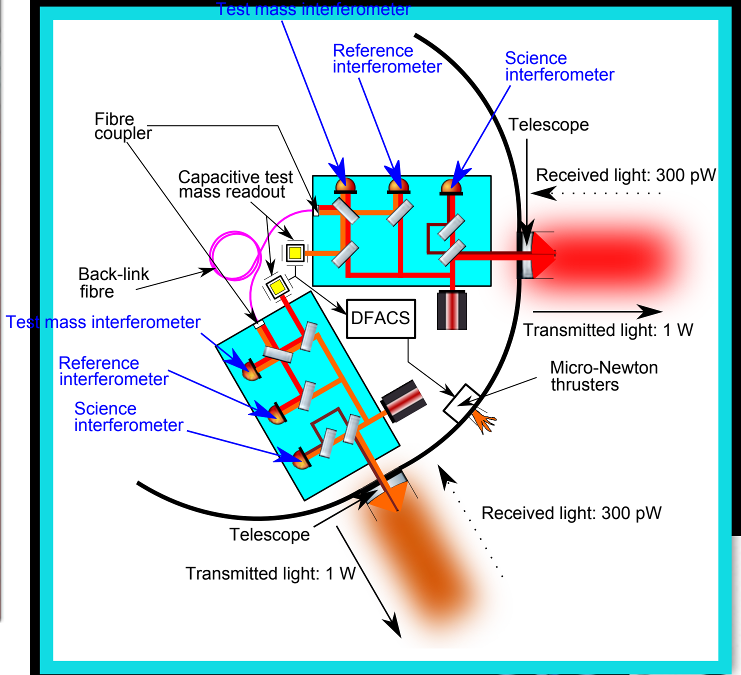


LISA

- Quick noise budget:
  - Low-frequency: acceleration noises (reference test-masses)
  - High frequency: interferometric mesurent system
  - Pre-processing for reducing part of the noises (TDI)



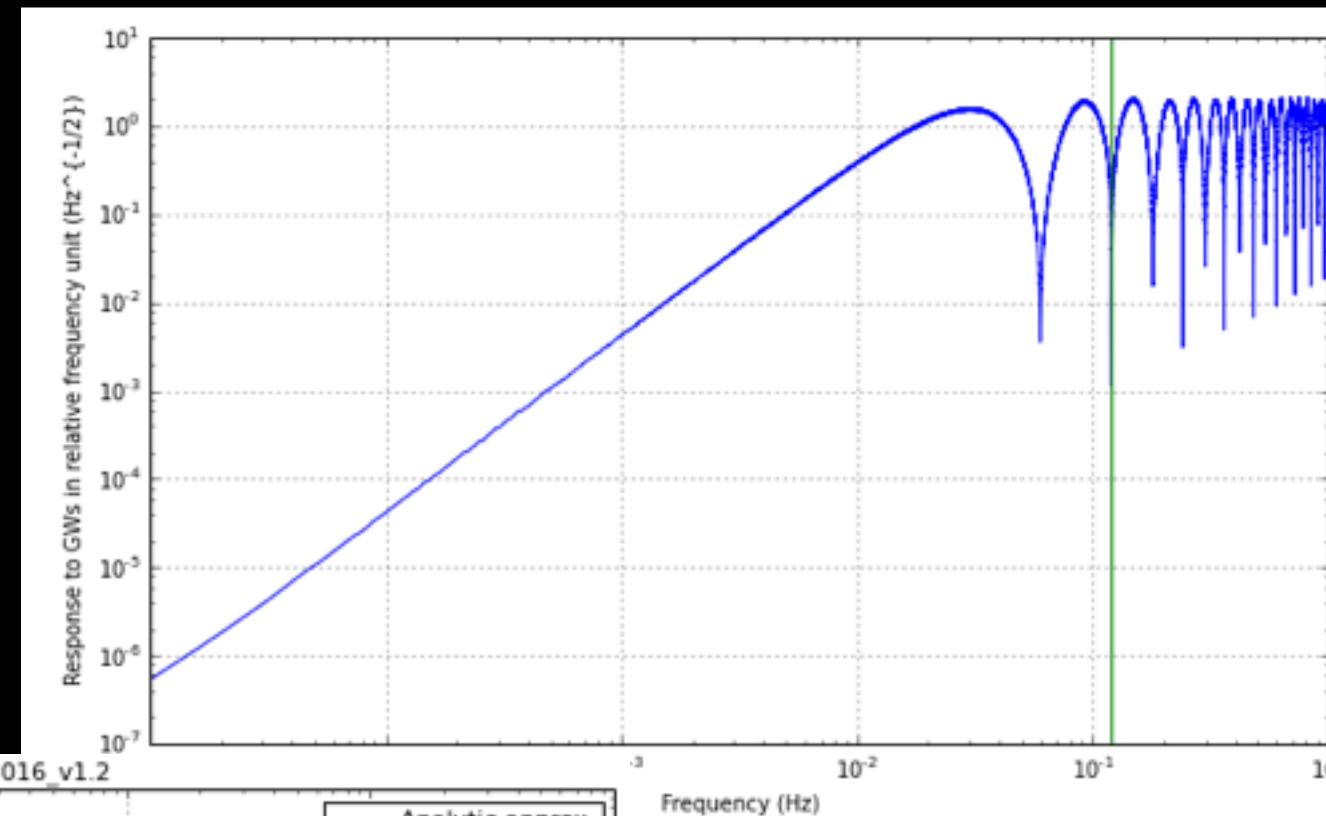


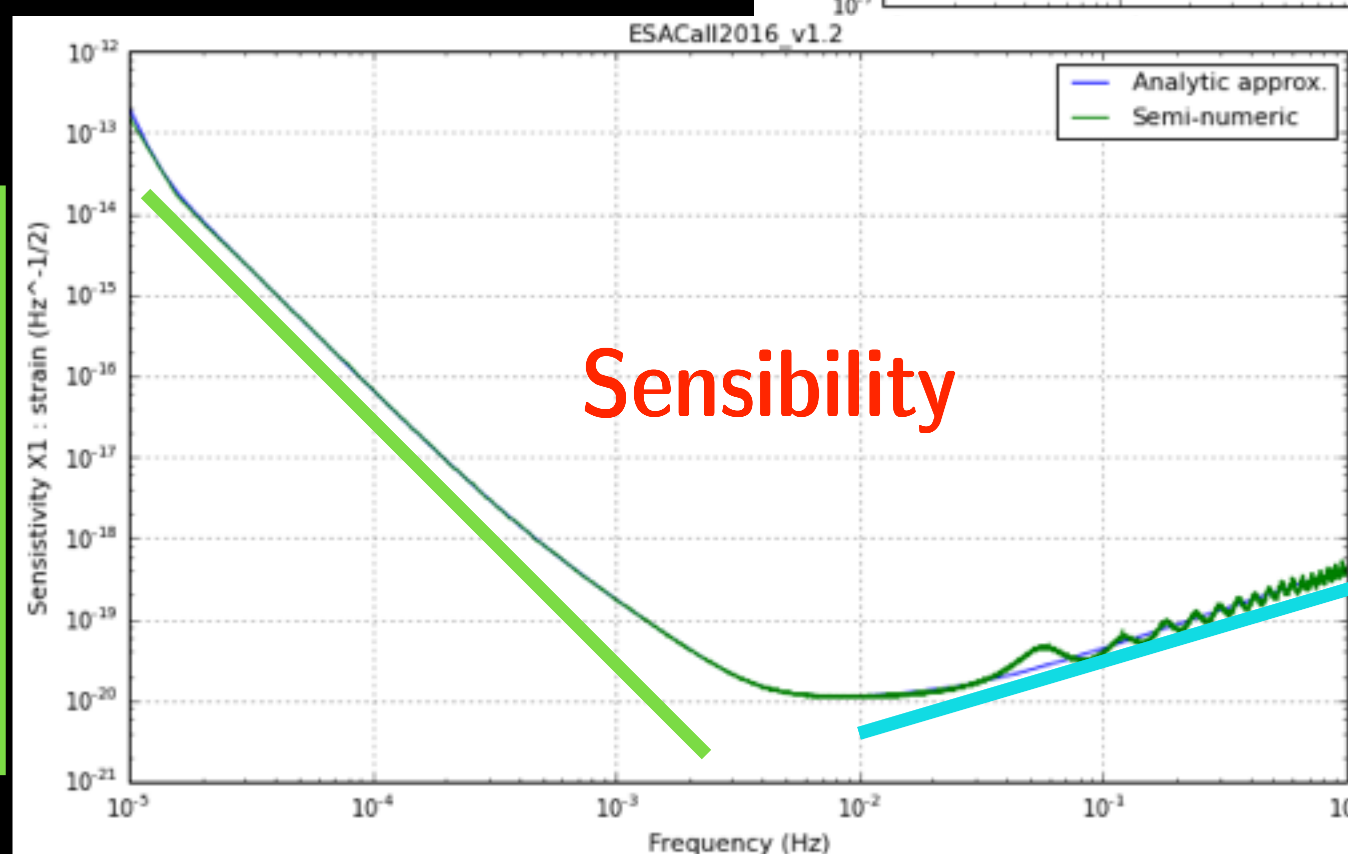


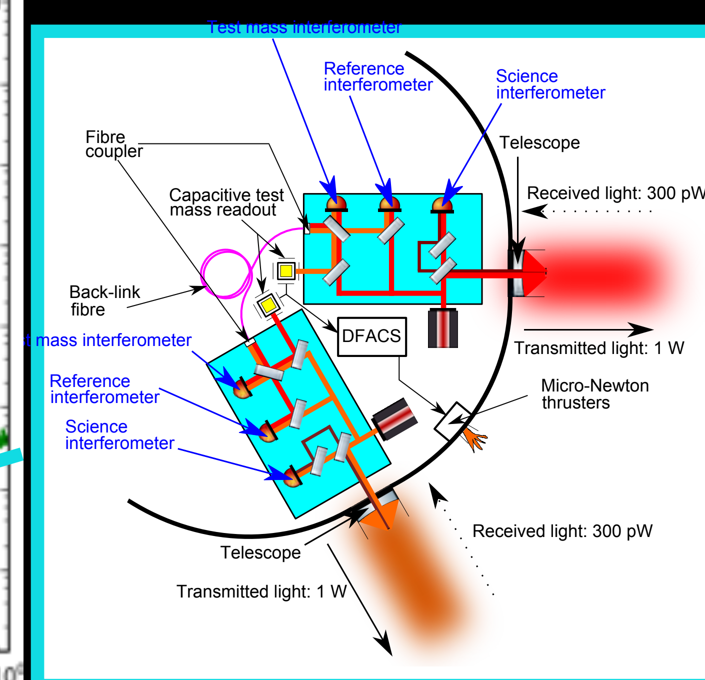
LISA

Noises

Response of the detector to GWs

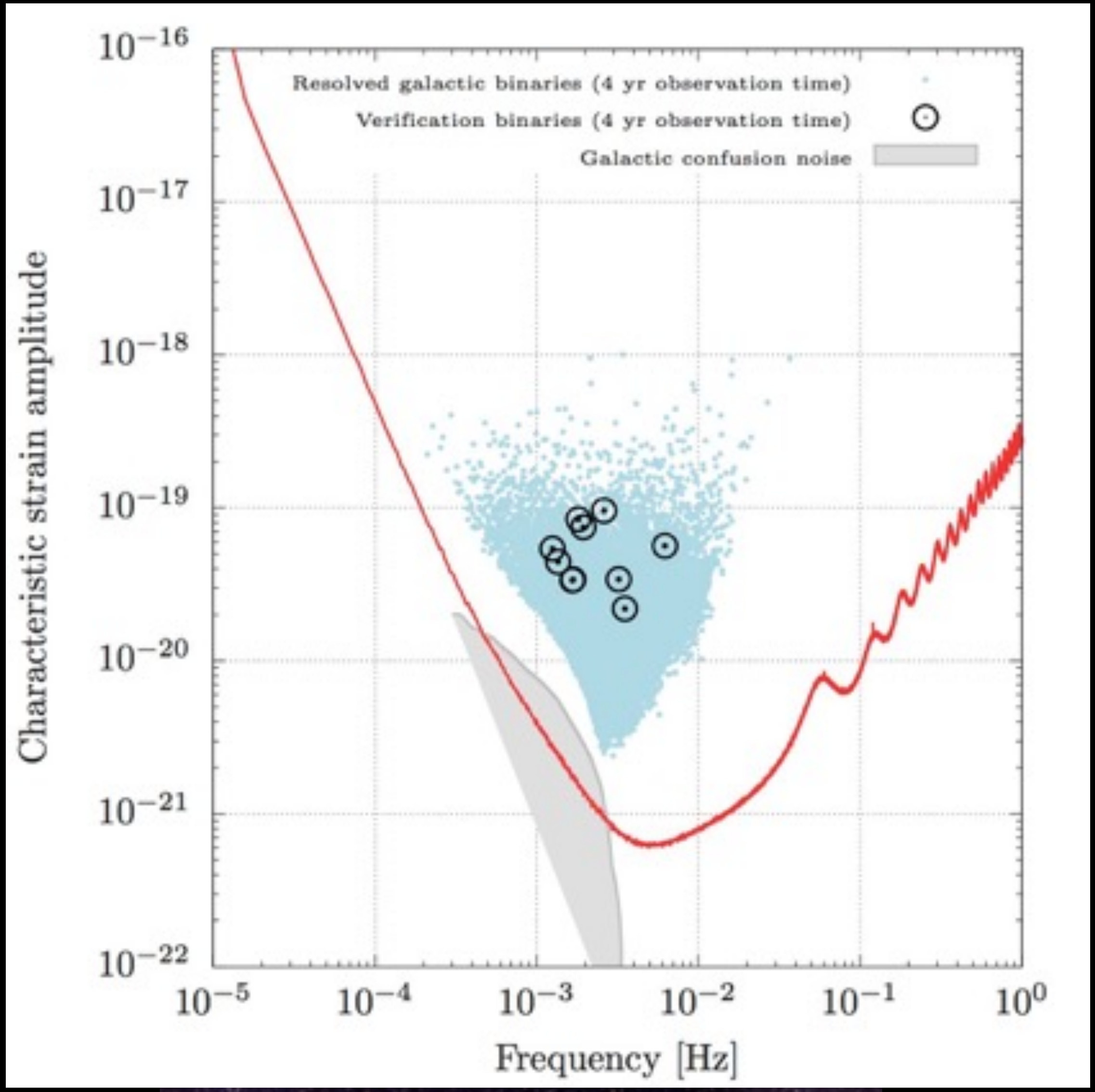


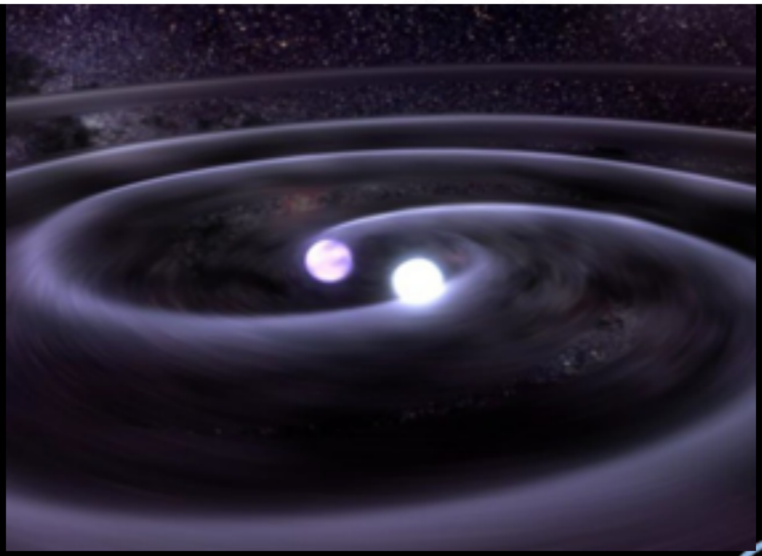




Galactic Binaries

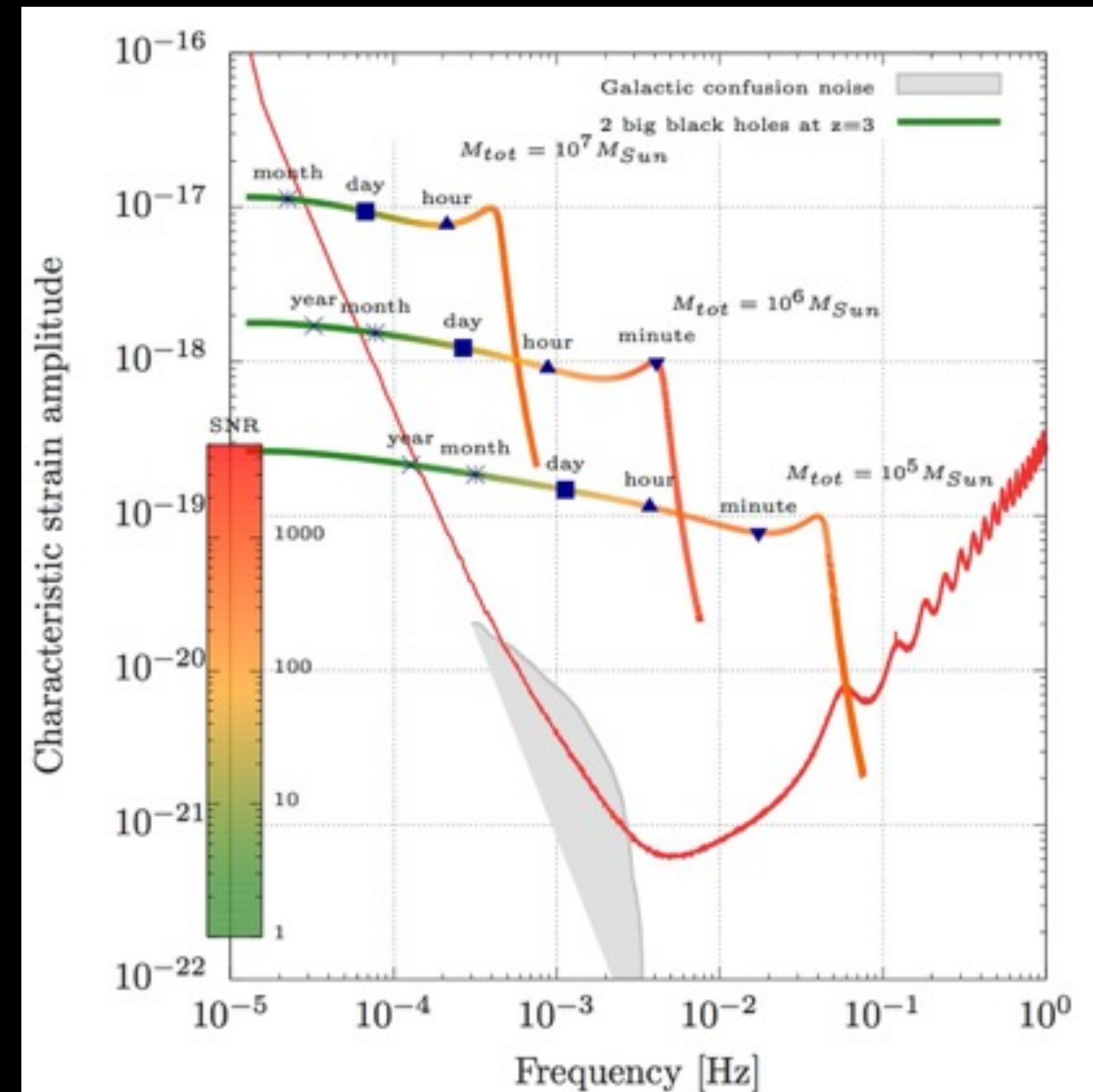
- Gravitational wave:
  - quasi monochromatic
- Duration: permanent
- Signal to noise ratio:
  - detected sources: 7 - 1000
  - confusion noise from non-detected sources
- Event rate:
  - 25 000 detected sources
  - more than 10 guarantied sources (verification binaries)

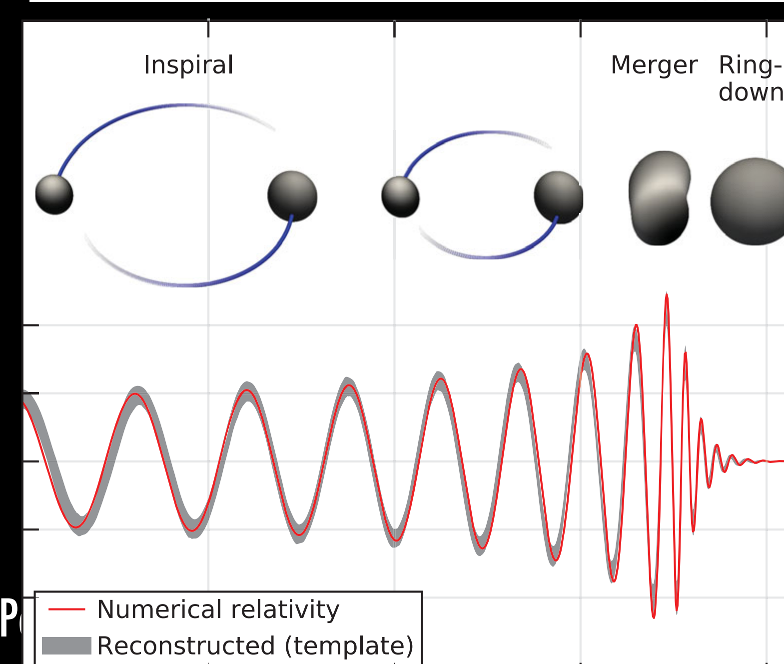




Super Massive Black Hole Binaries

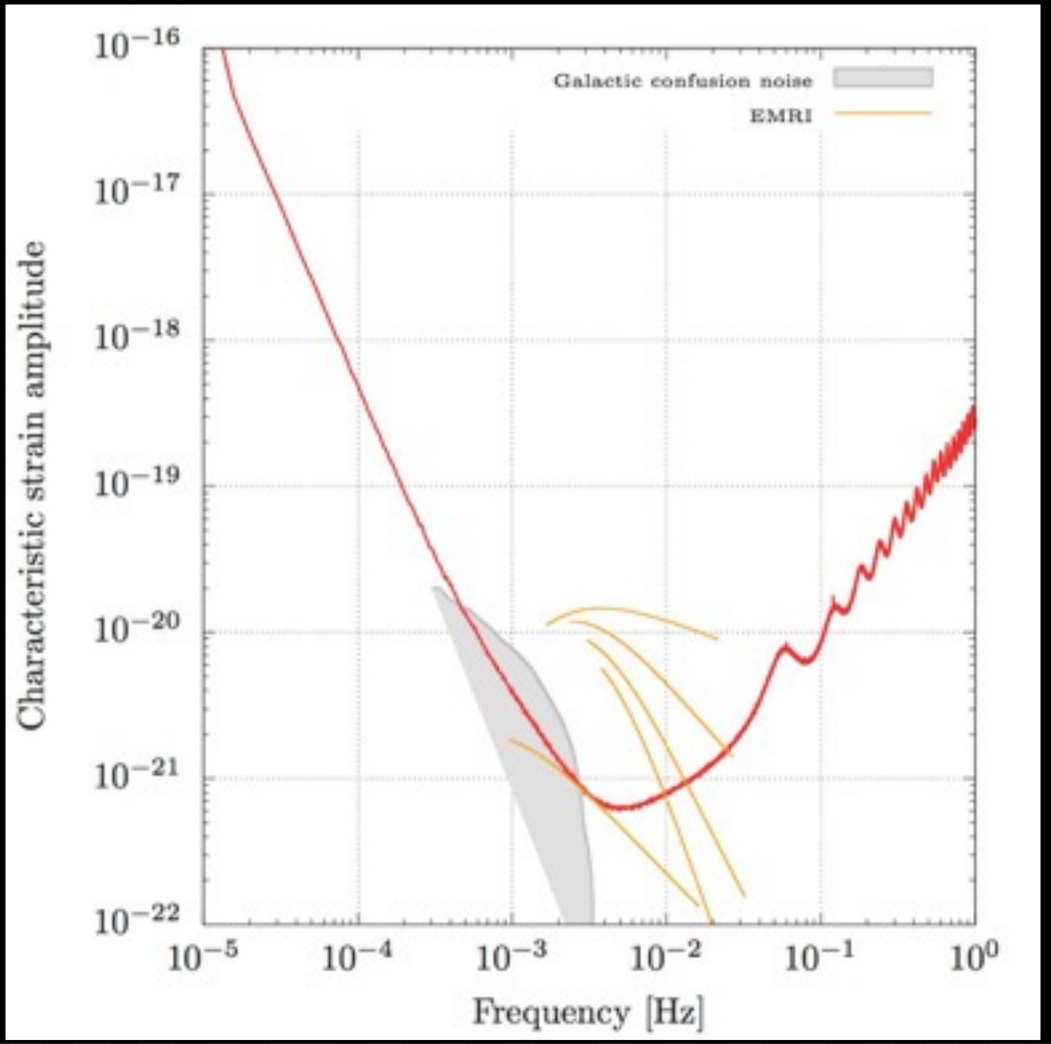
- Gravitational wave:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.
- Duration: between few hours and several months
- Signal to noise ratio: until few thousands
- Event rate: 10-100/year

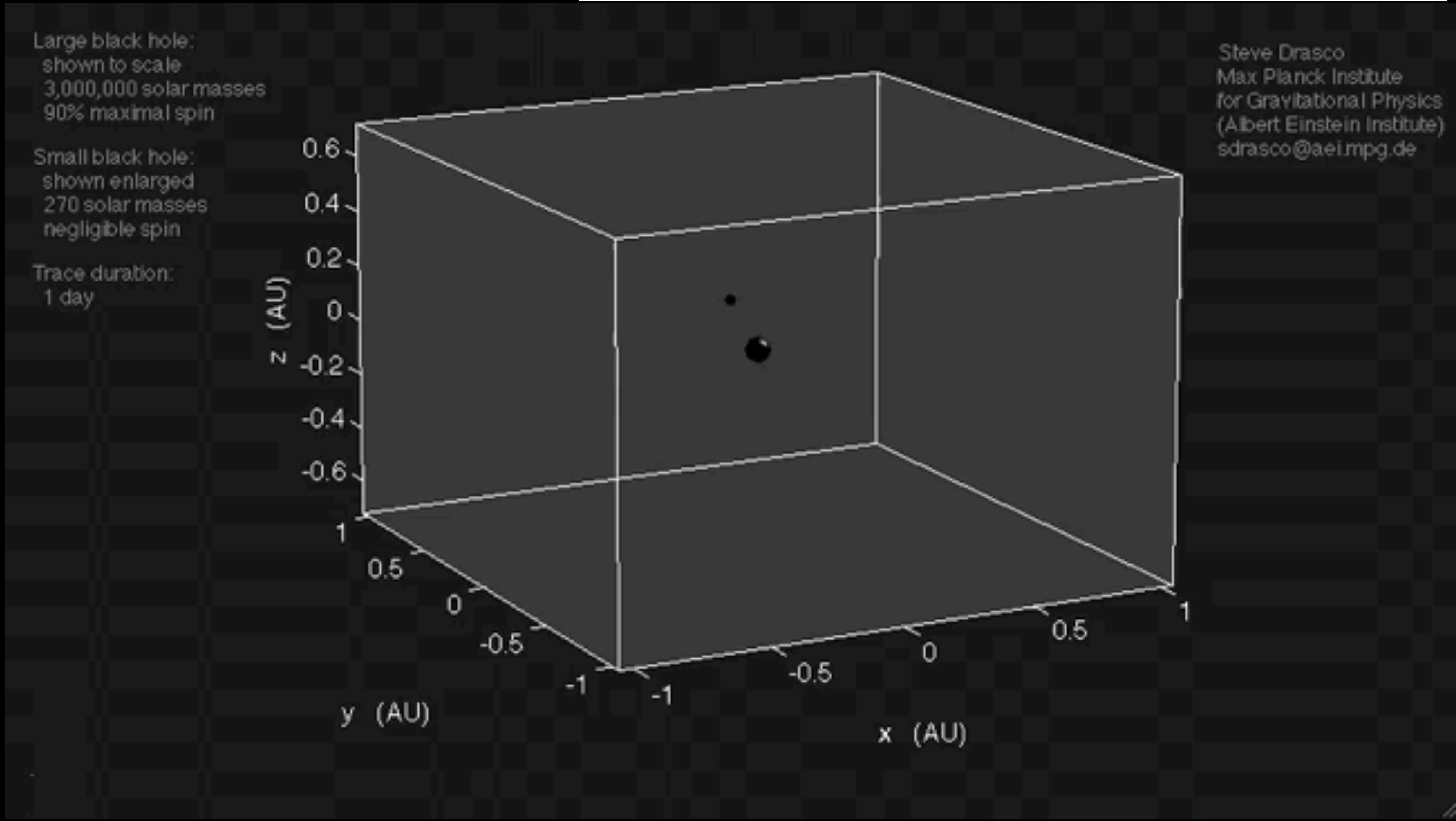




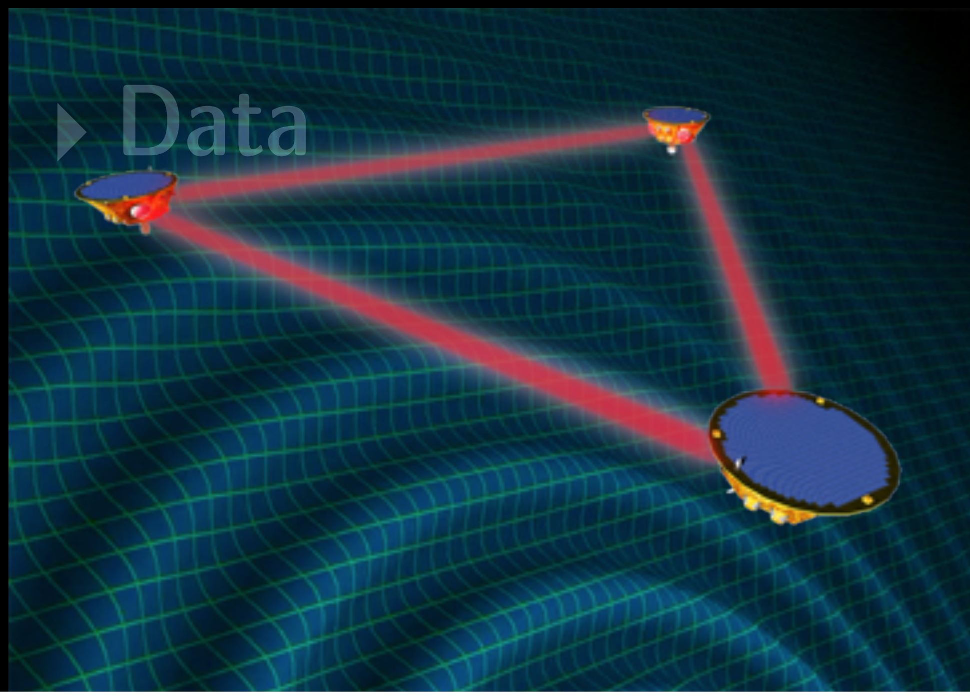
EMRIs

- 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





Others sources



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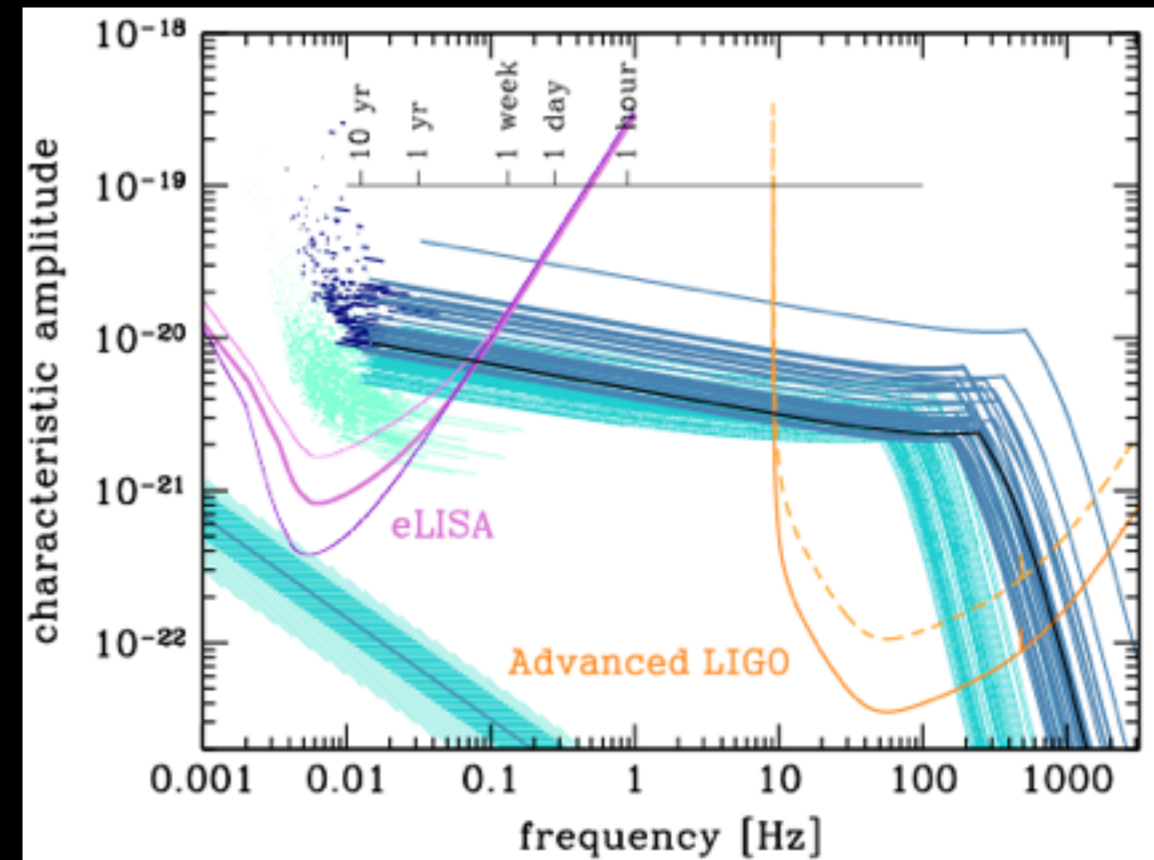
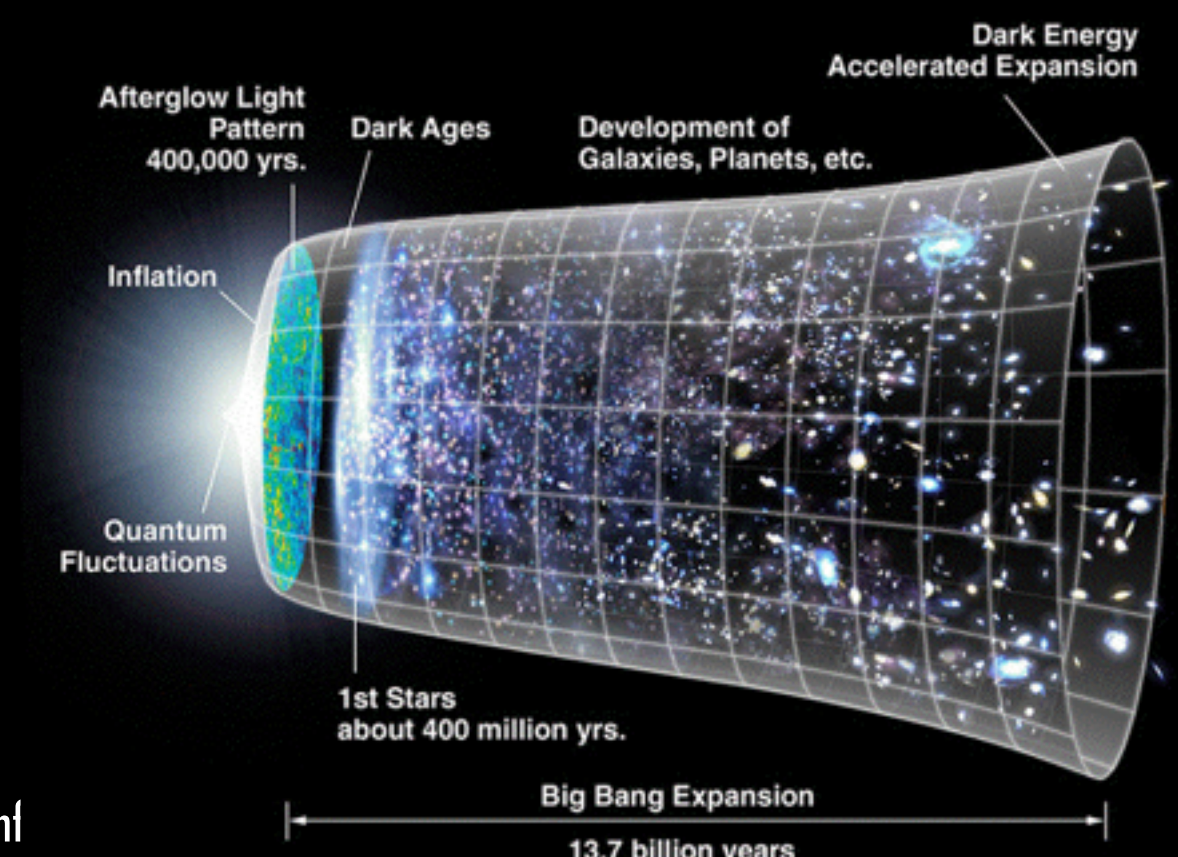
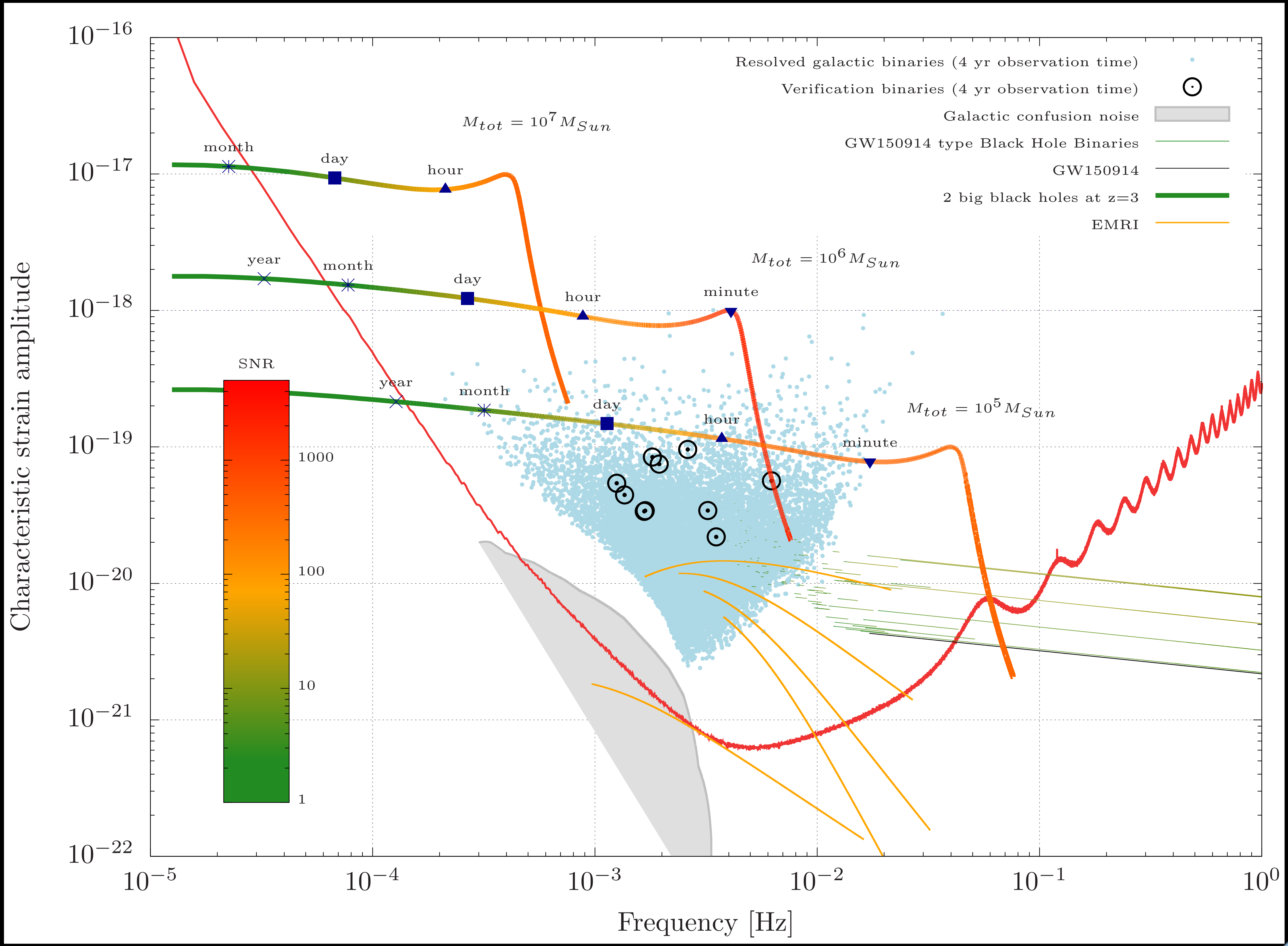


GW sources

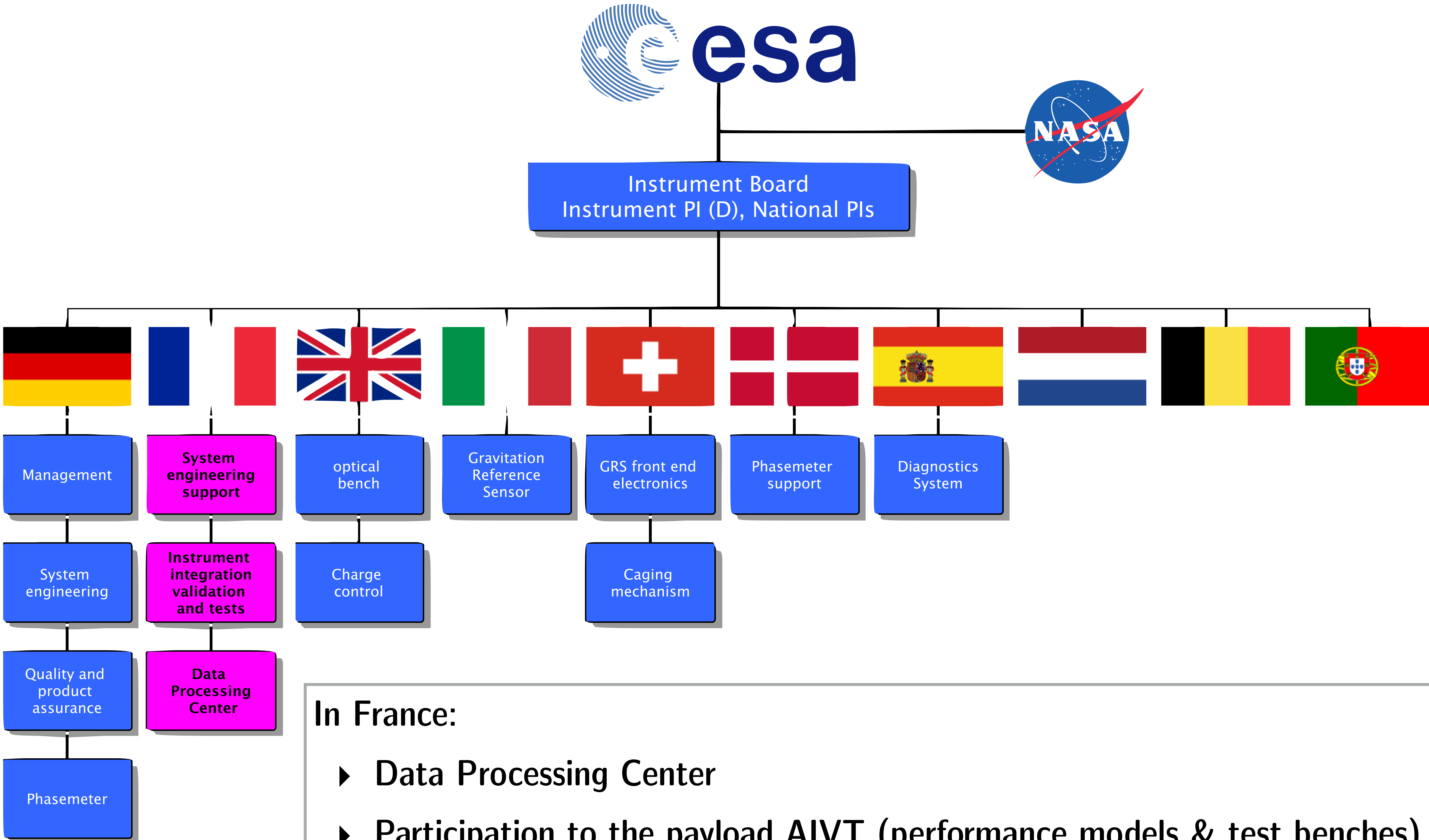
- 6 x10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources



LISA: sensitivity



LISA consortium



In France:

- Data Processing Center
- Participation to the payload AIVT (performance models & test benches)
- Support in system engineering

Conclusion

- After 1.5 years in space and a large number of experiments, LISAPathfinder provides extremely good results
  - Noises sources understood except one component at low freq.

  => green light for LISA

- LISA: 3 spacecraft exchanging laser over 2.5 Mkm to measure relative distance changes at the picometer level.

- Will observe GW sources between 0.02 - 100 mHz: large number of existing and potential sources

- LISA proposal accepted by ESA => LISA officially started !
  - Now: phase 0 in progress until Nov. 2017
  - Scientists gets quickly organise to form a solid consortium