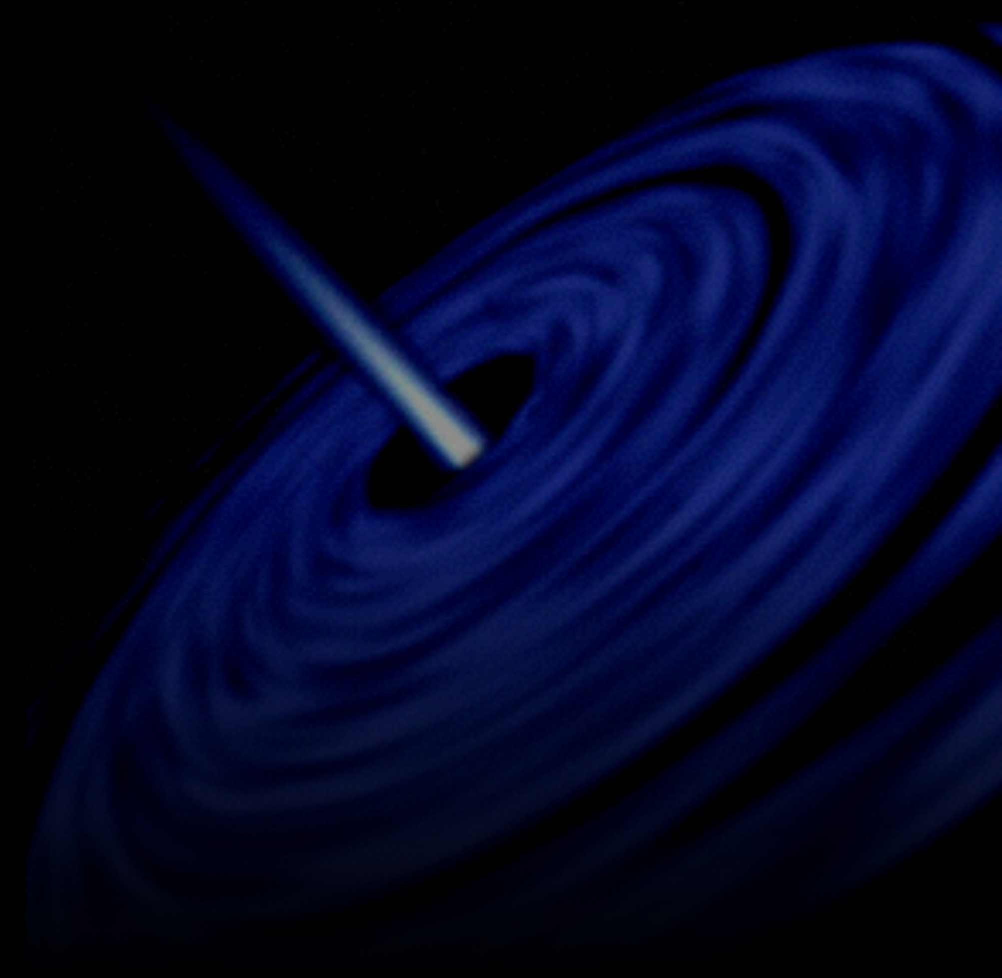
LISA status:
ESA, Consortium, LISAFrance

Antoine Petiteau

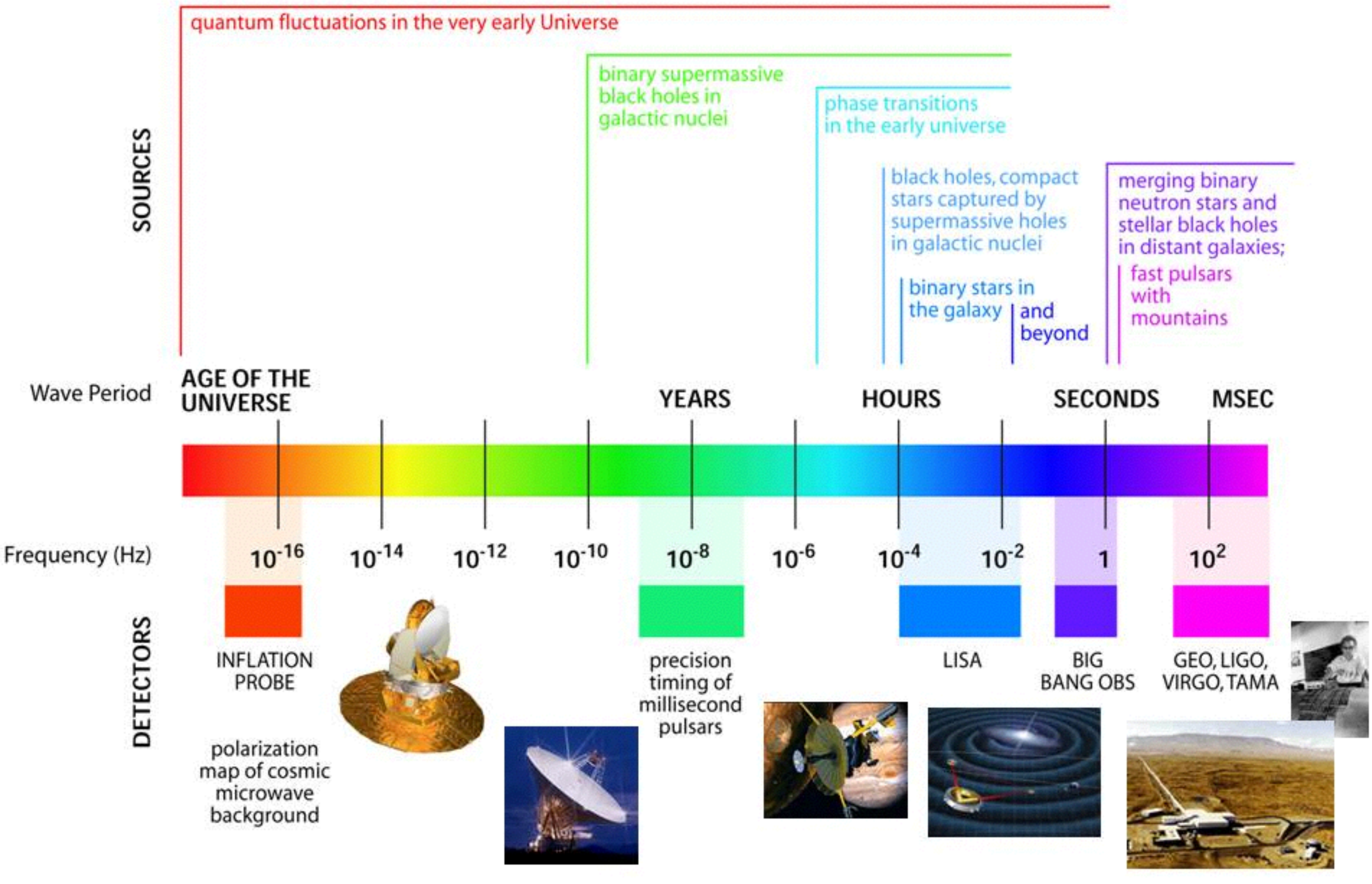


Journée LISAFrance

APC - France

12-13 October 2017

THE GRAVITATIONAL WAVE SPECTRUM



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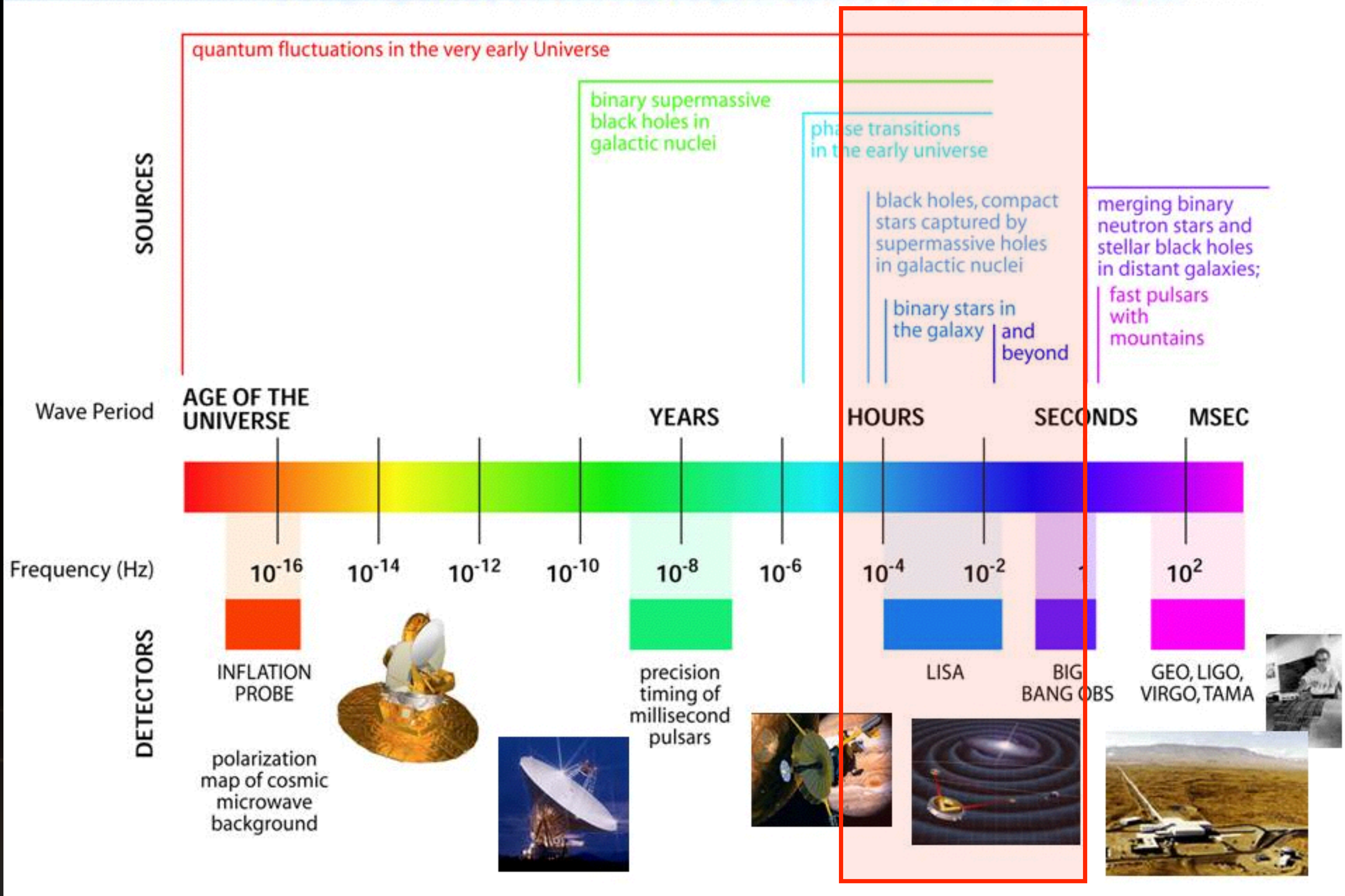

History of LISA

- 1978: first study based on a rigid structure (NASA)
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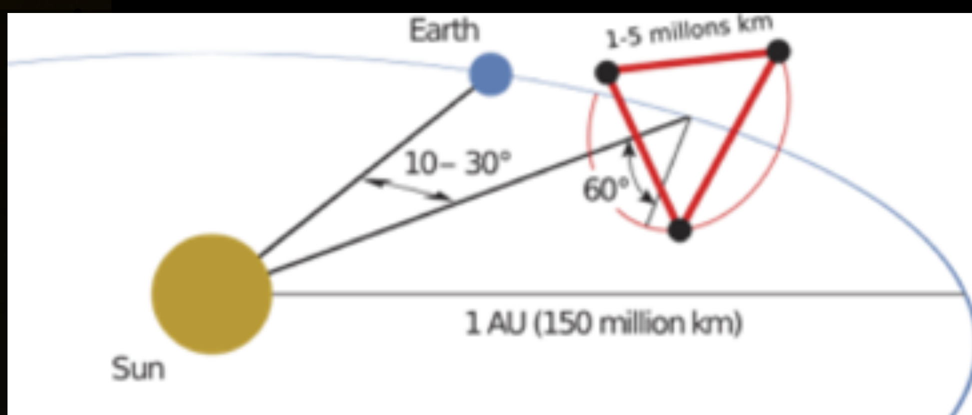
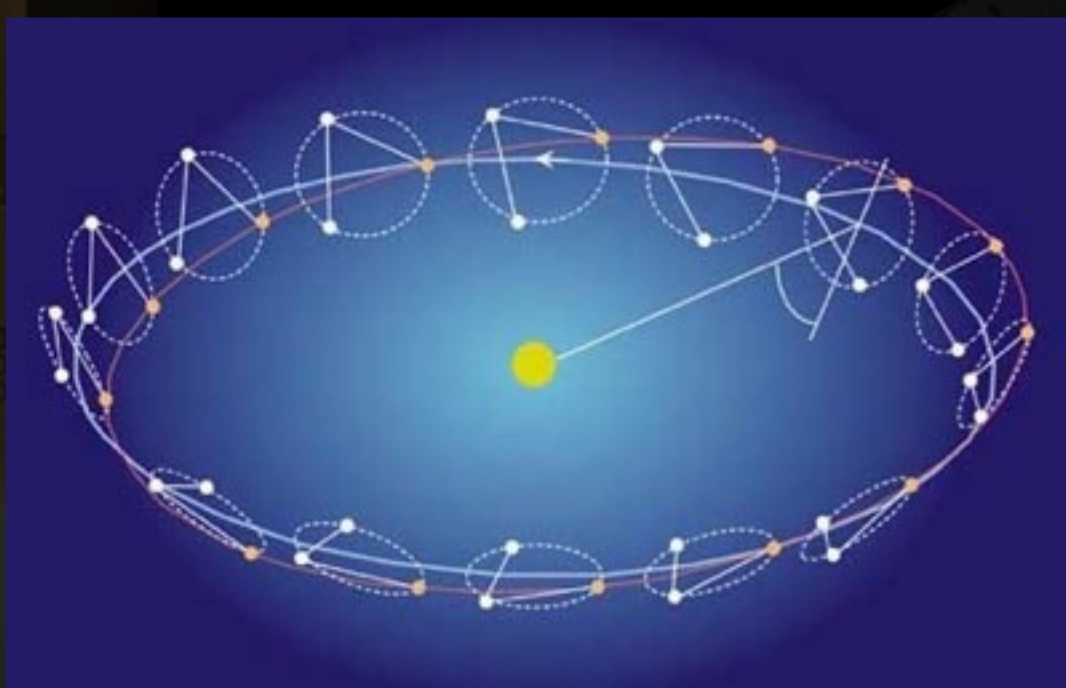
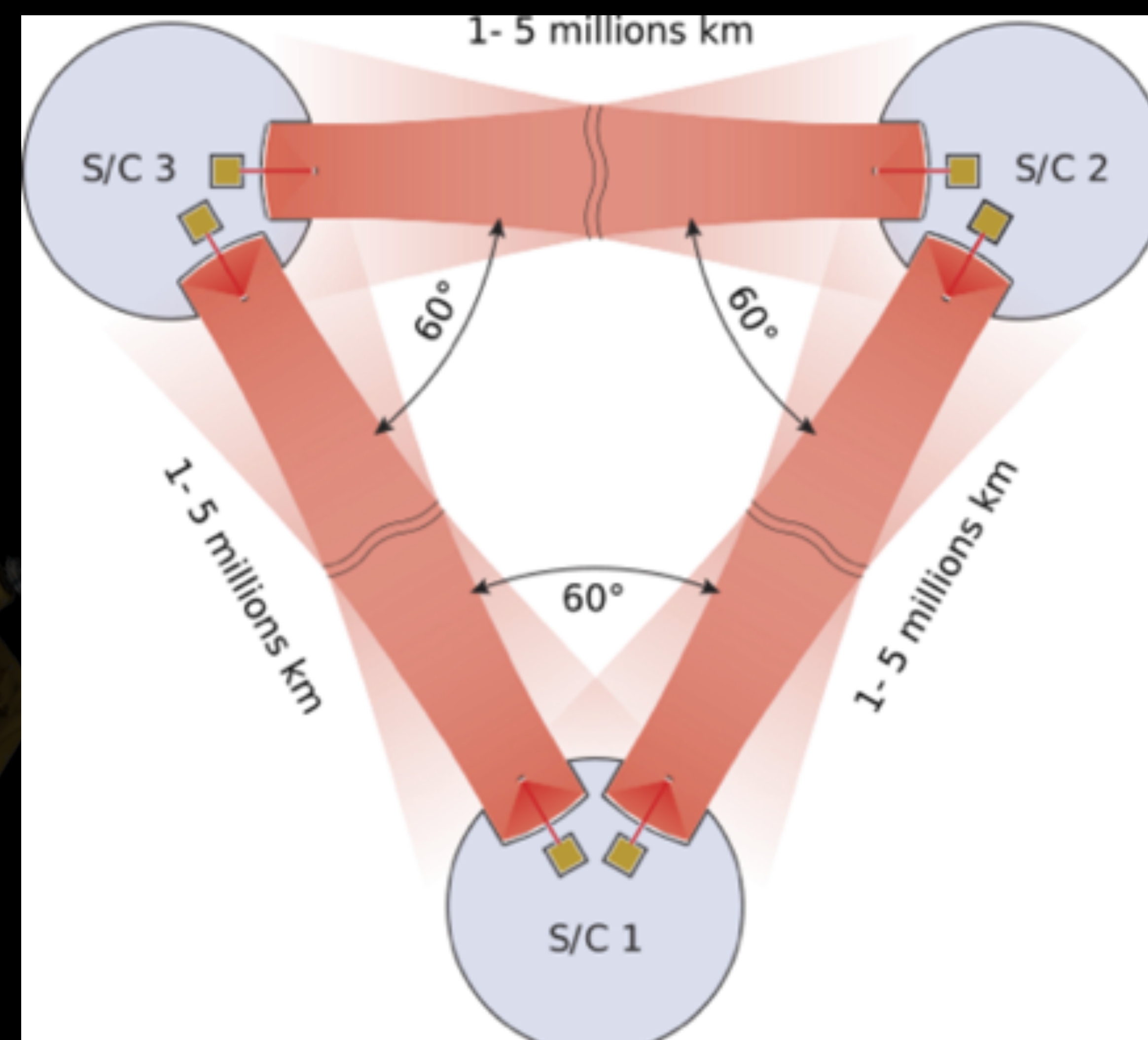
- 2013: selection of ESA L3 : « The gravitational Universe »

LISA

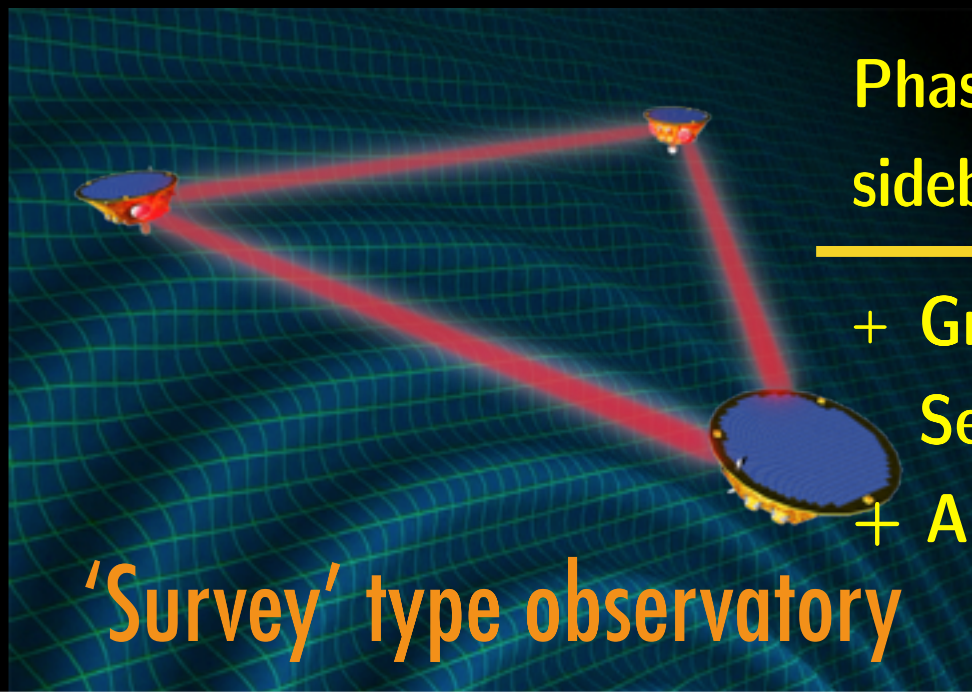
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from few millions kilometers (2.5 millions km in the proposal L3)
- Goal: detect relative distance changes of 10^{-21}: few picometers







LISA data



Phasemeters (carrier, sidebands, distance)

+ Gravitational Refer… Sensor

+ Auxiliary channels

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry
reduction of laser noise

L1 — 2 data channels TDI non-correlated

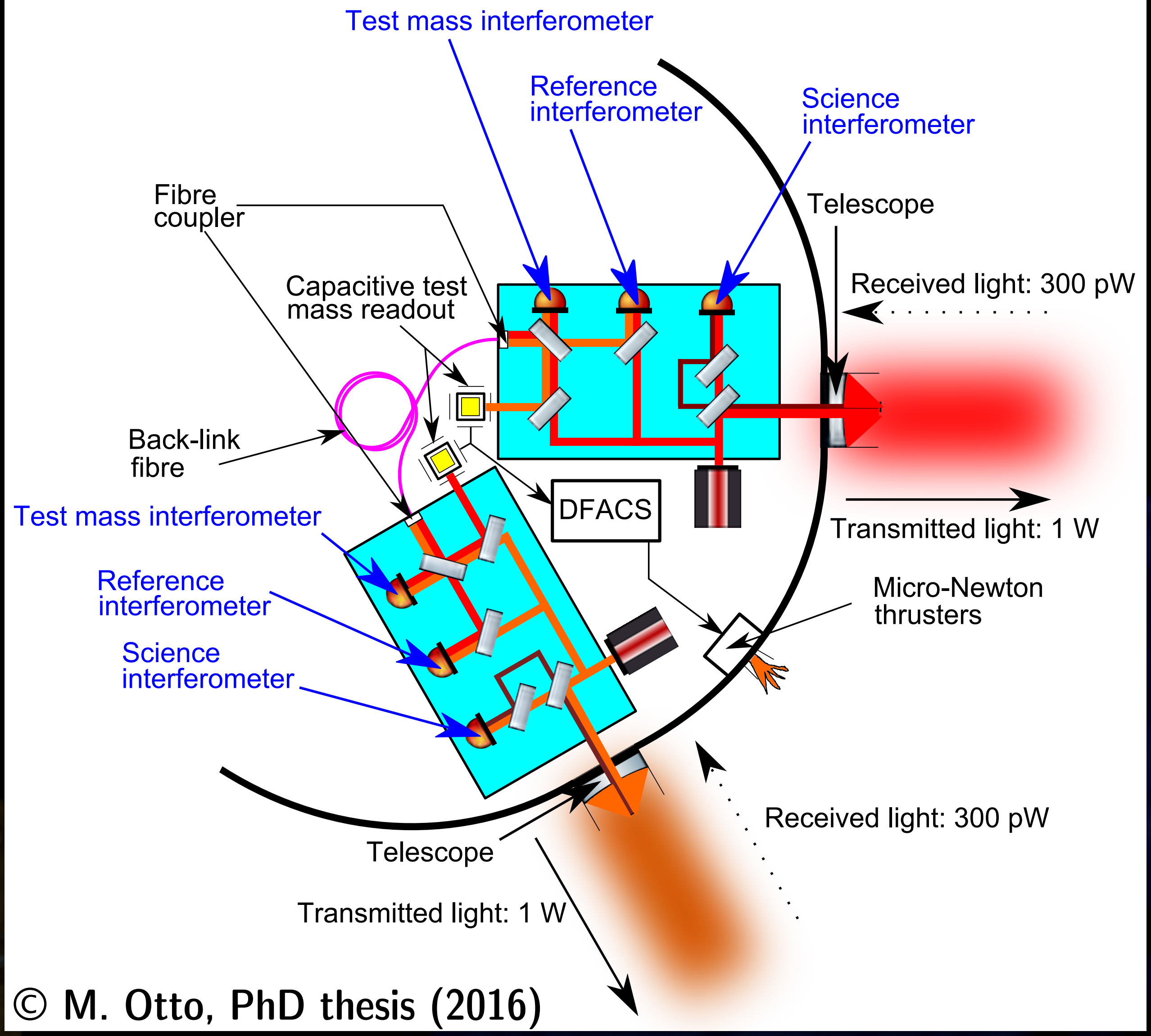
L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 100 mHz

LISA

- 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

LISA

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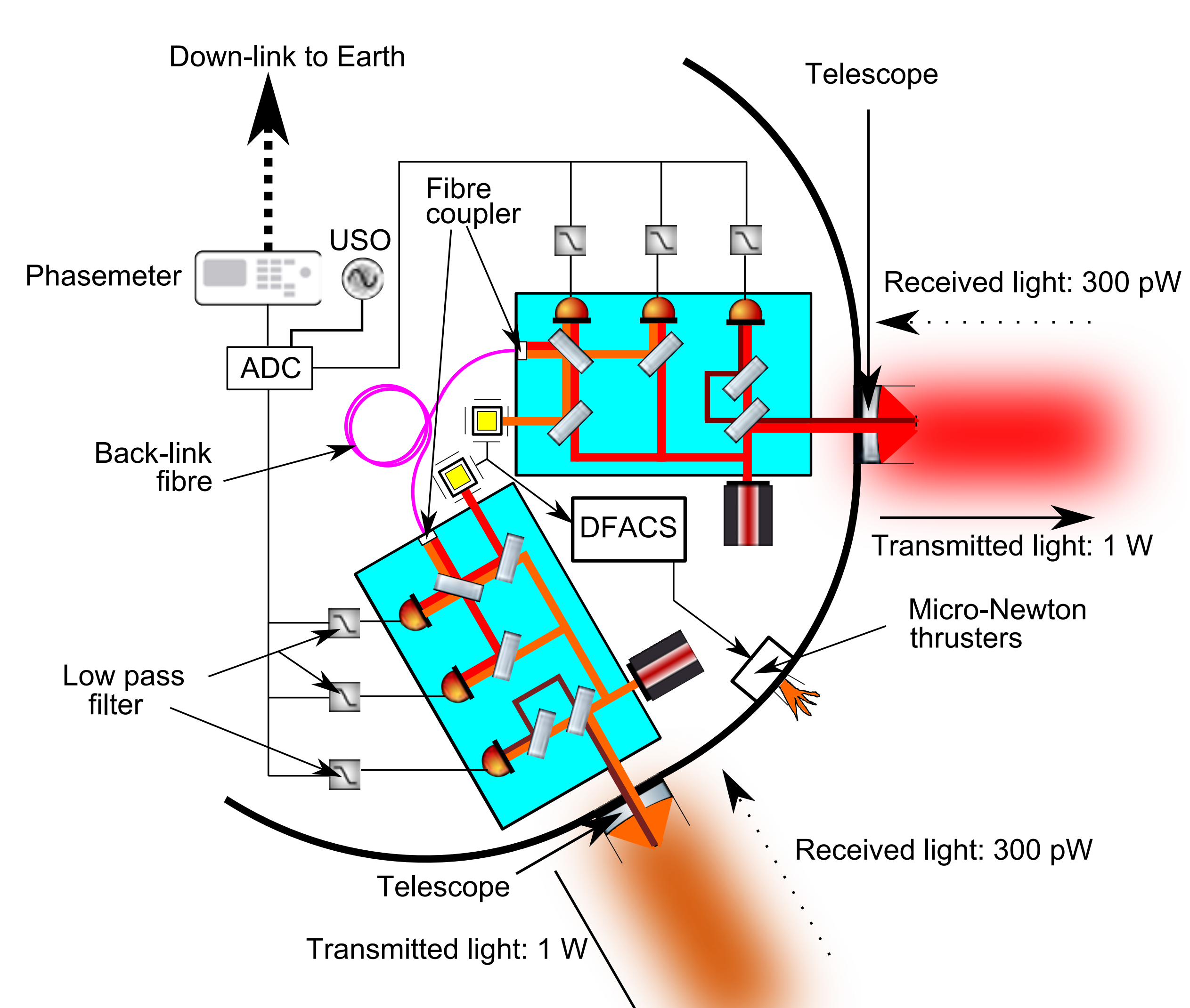
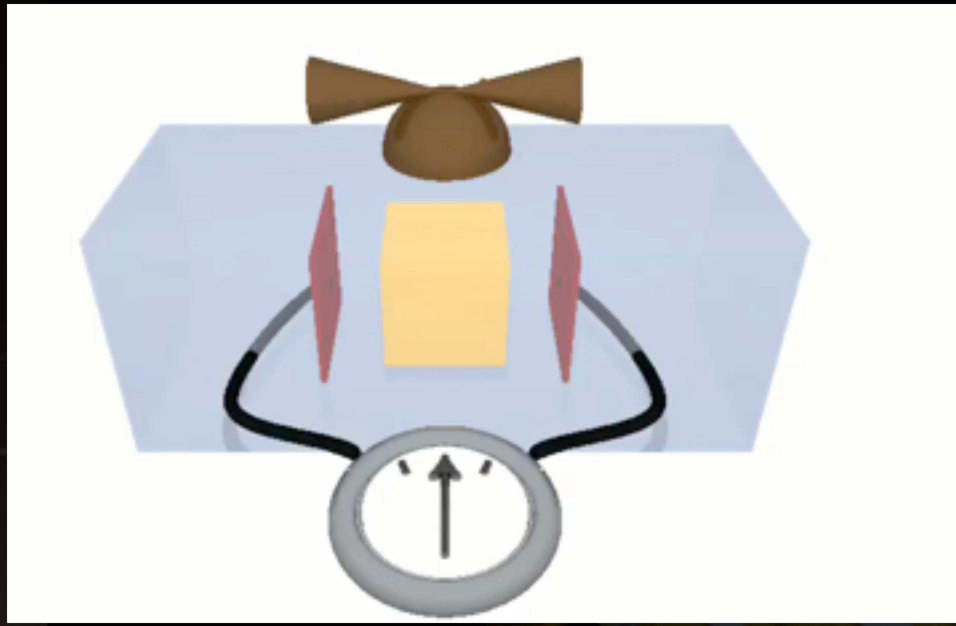
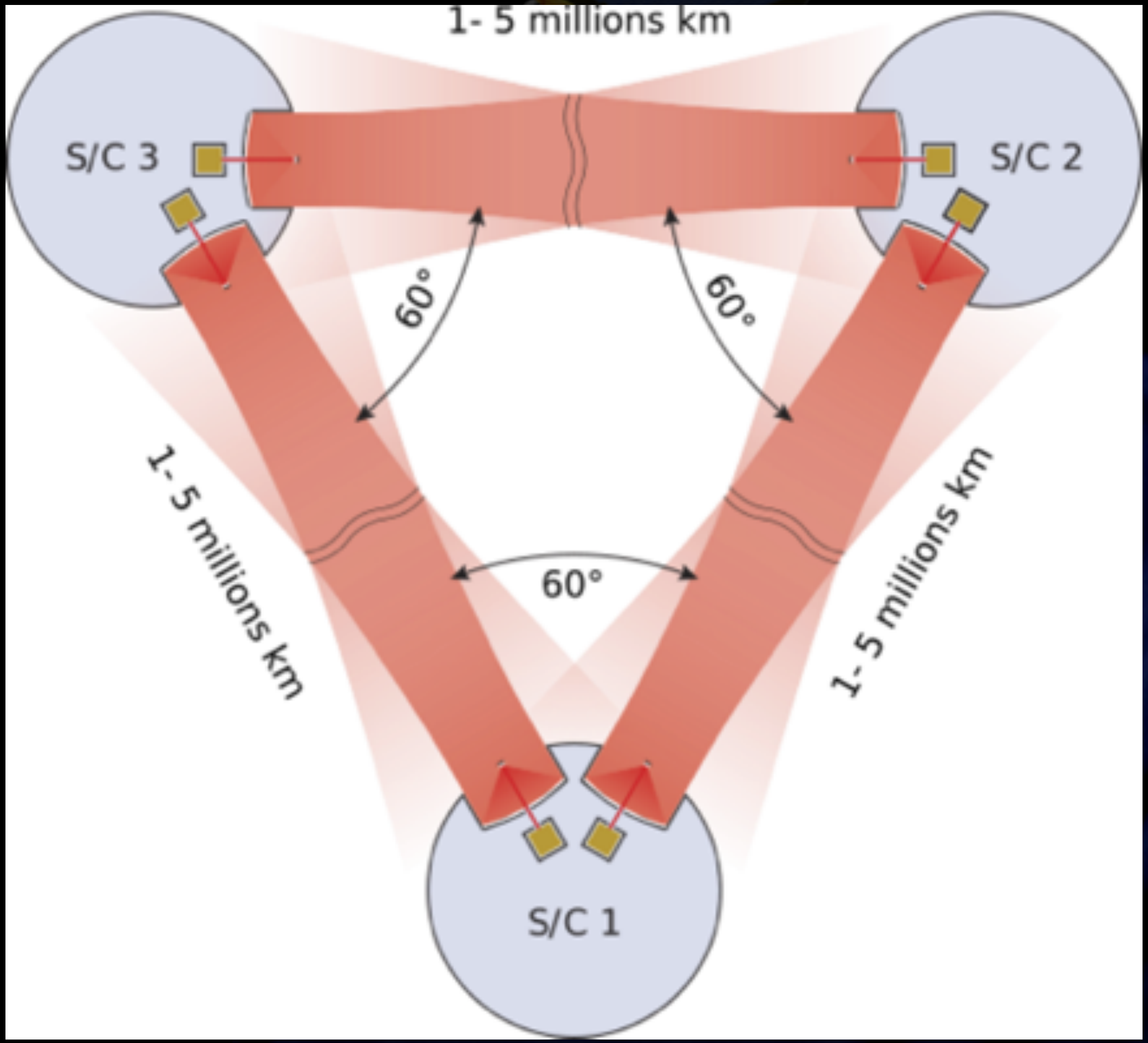


© M. Otto, PhD thesis (2016)

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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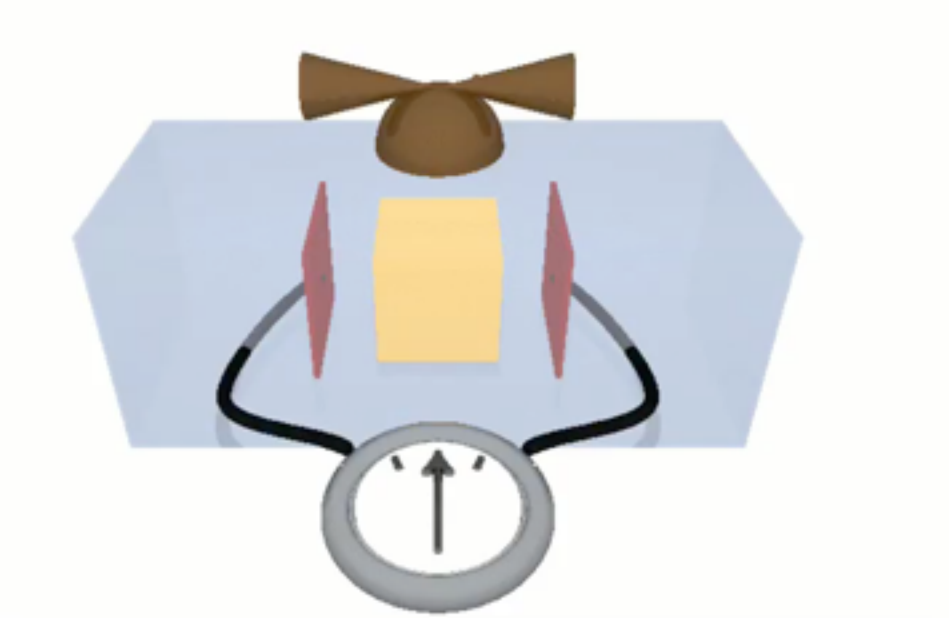
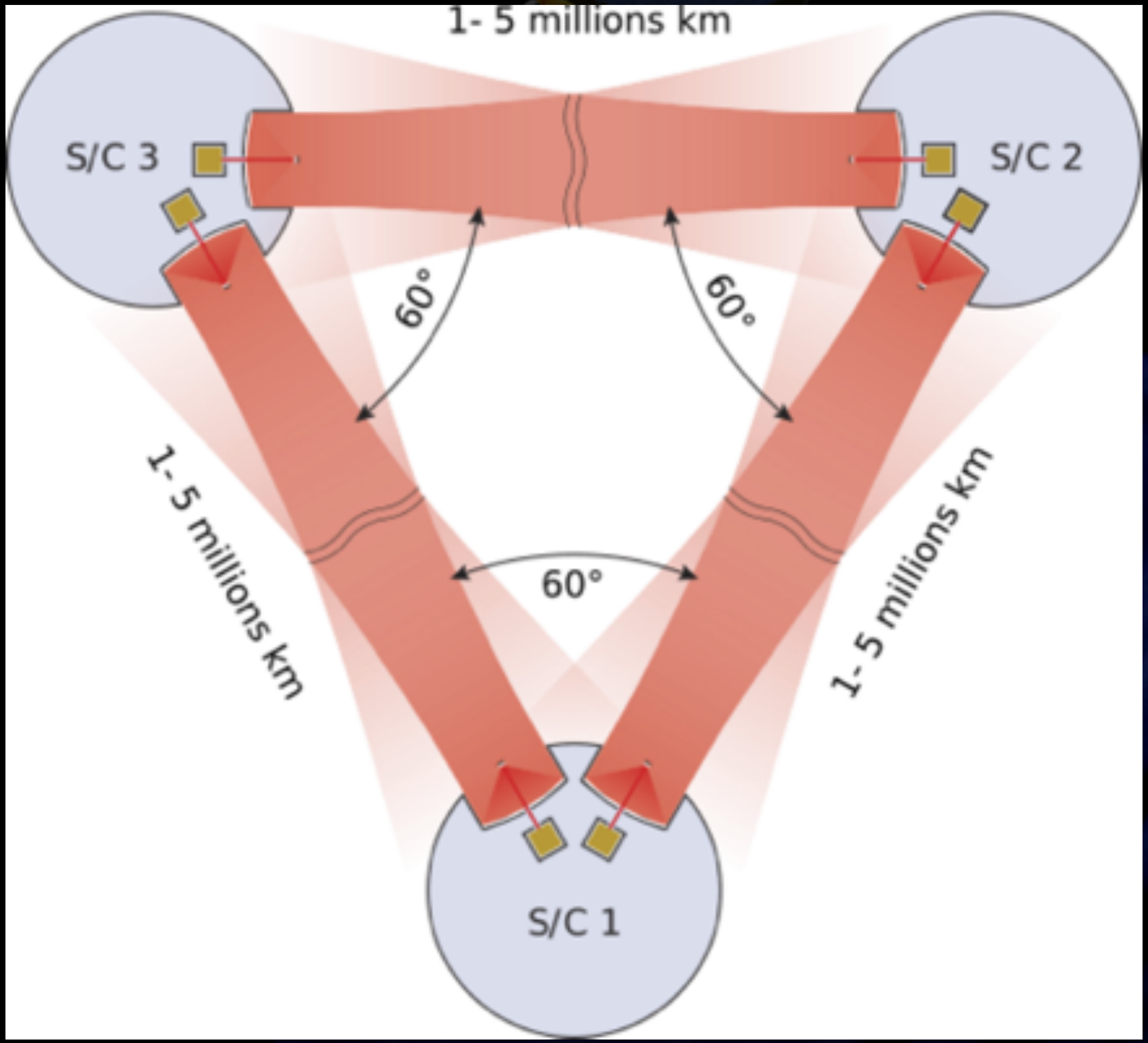
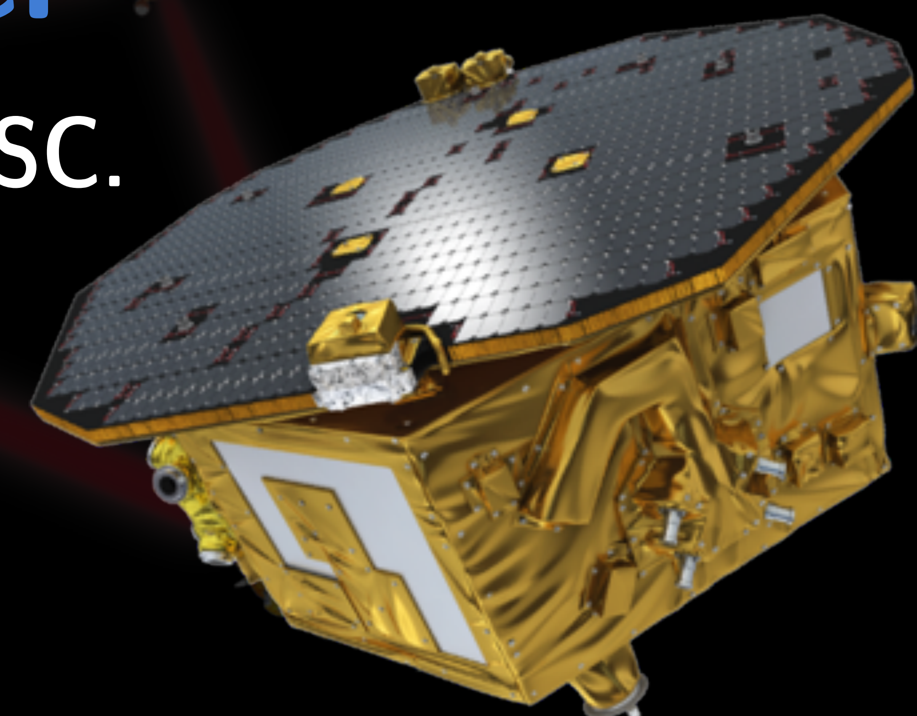
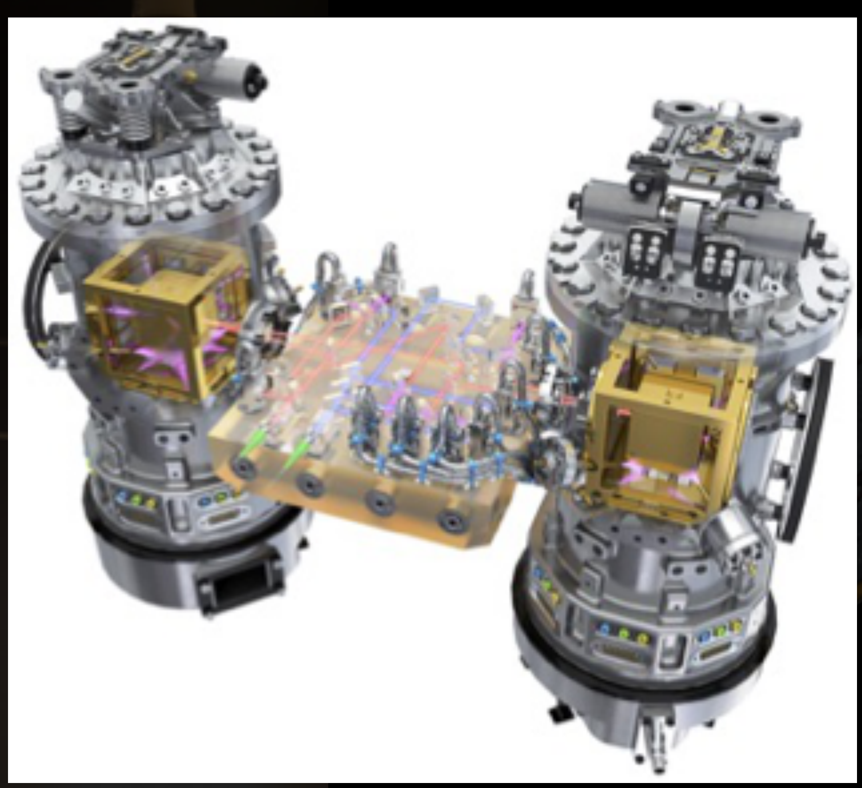




LISAPathfinder



- 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



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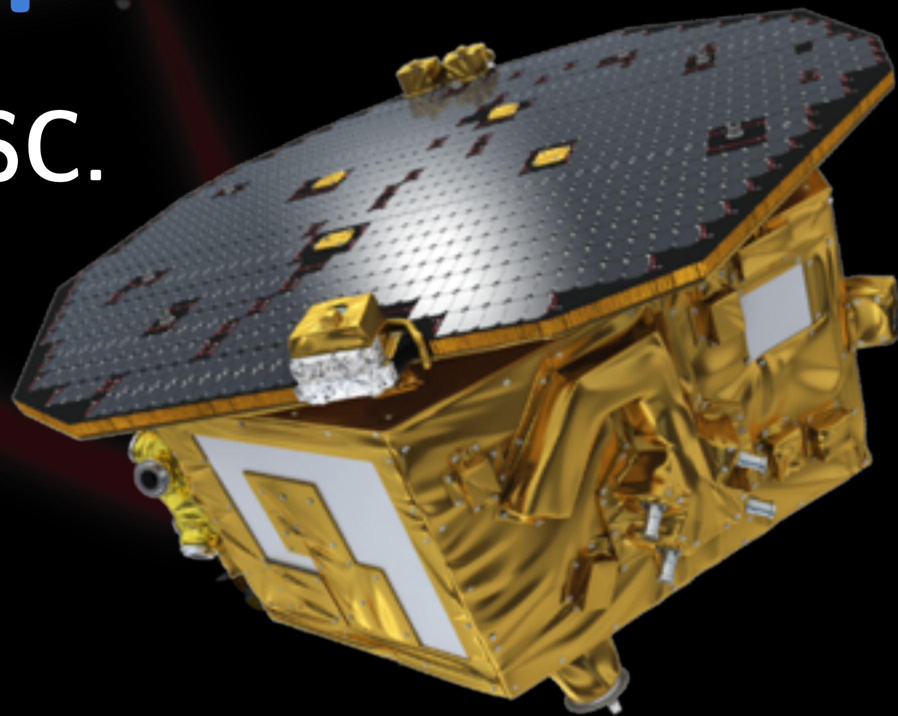

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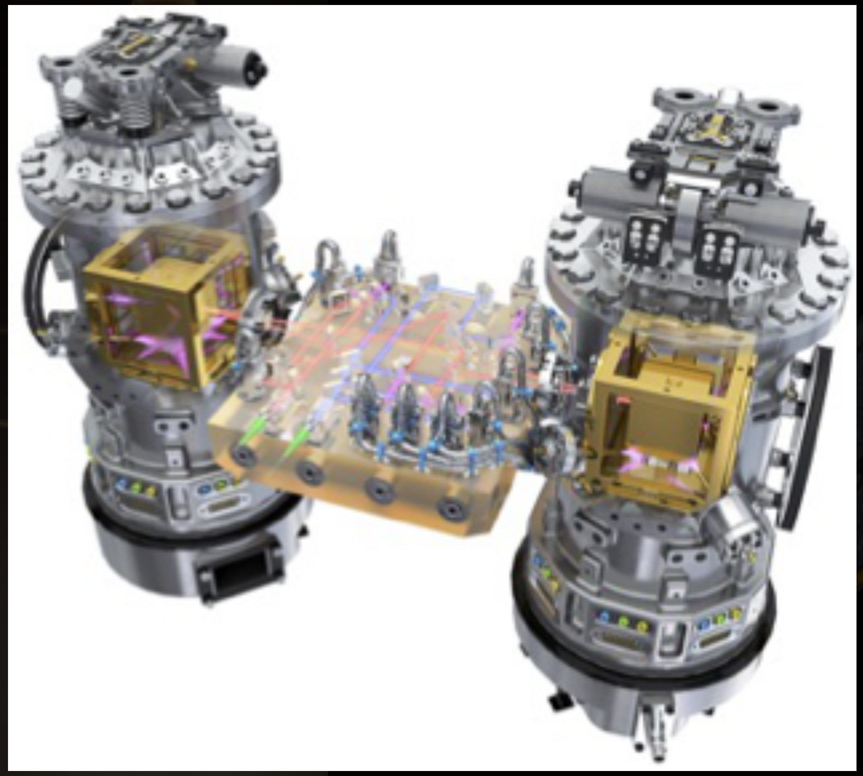
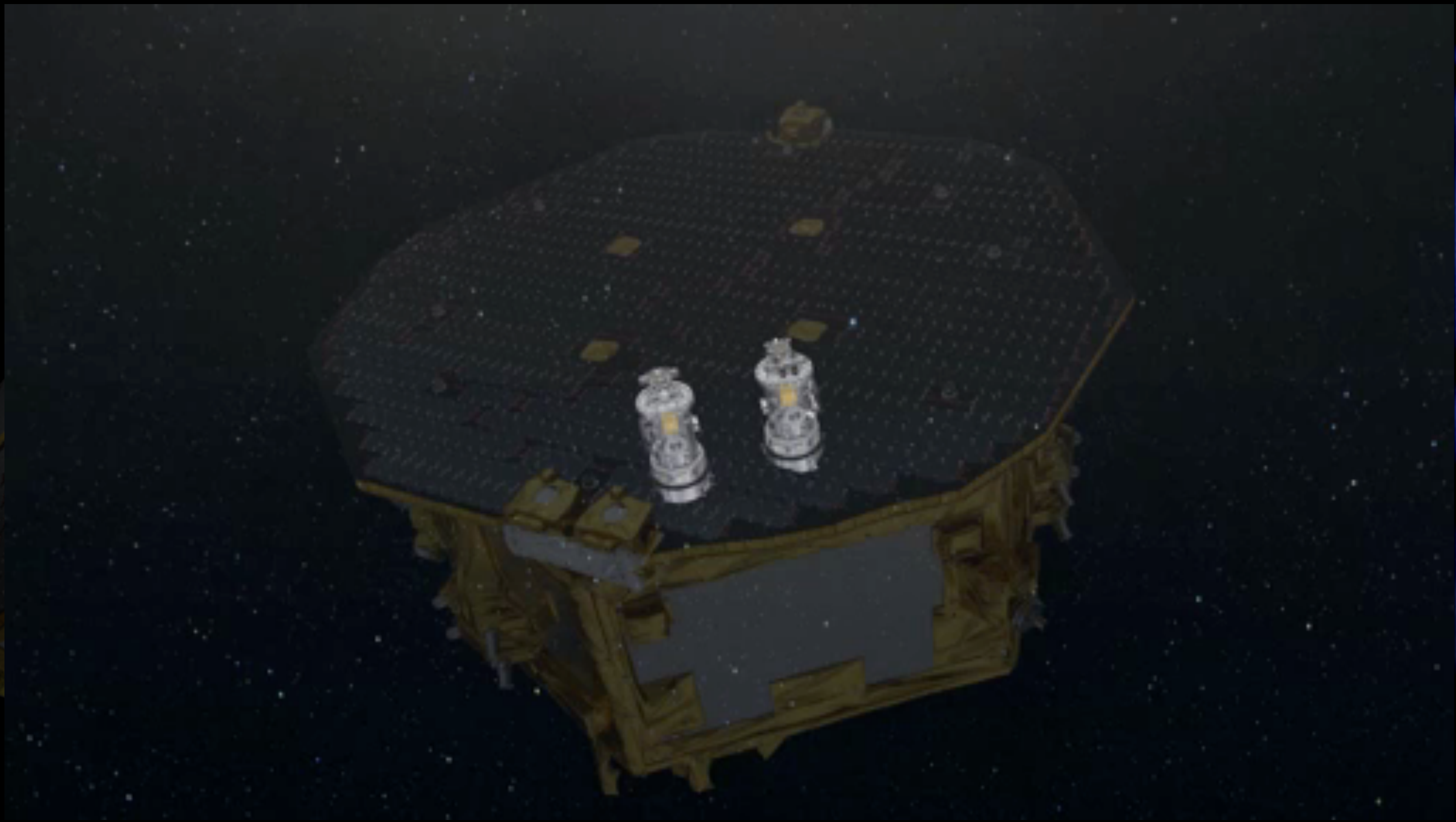
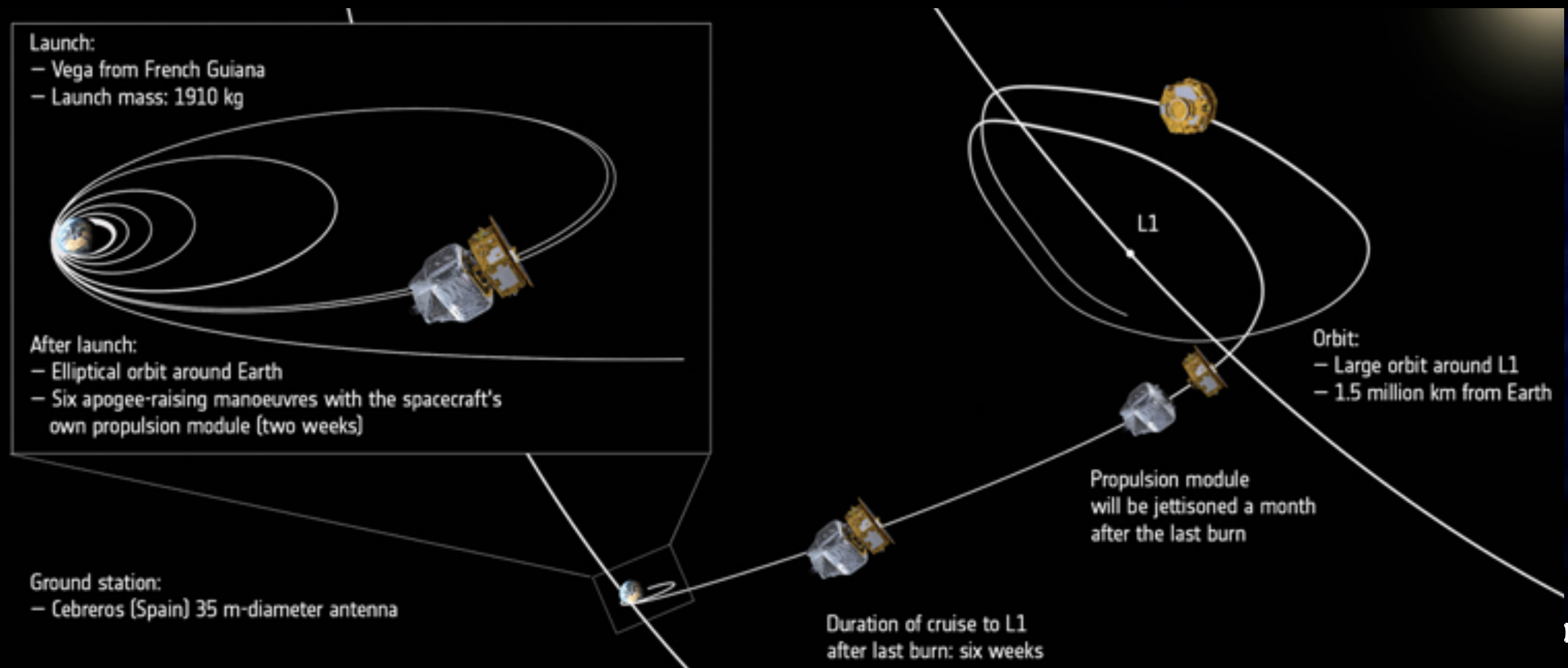




LISAPathfinder timeline

- 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



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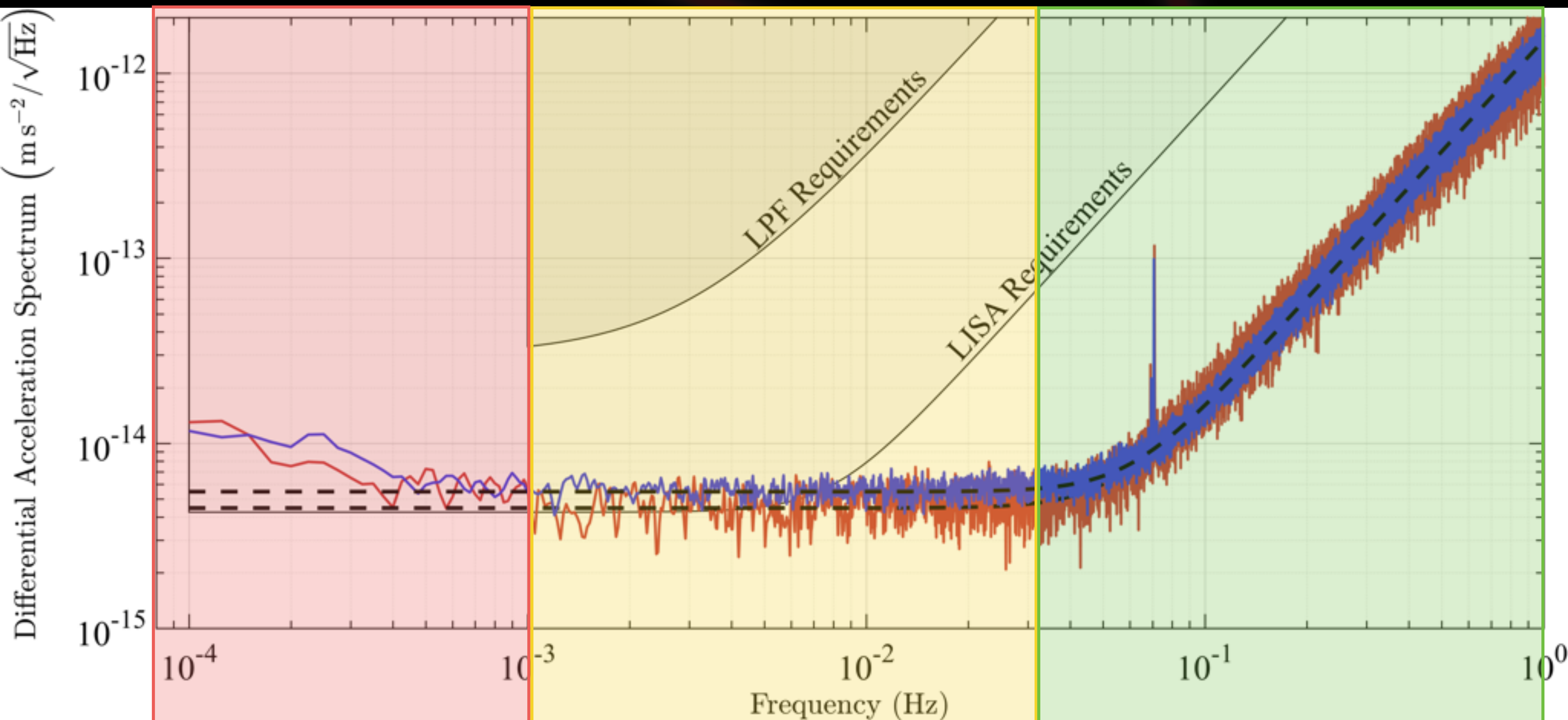
First results

- 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

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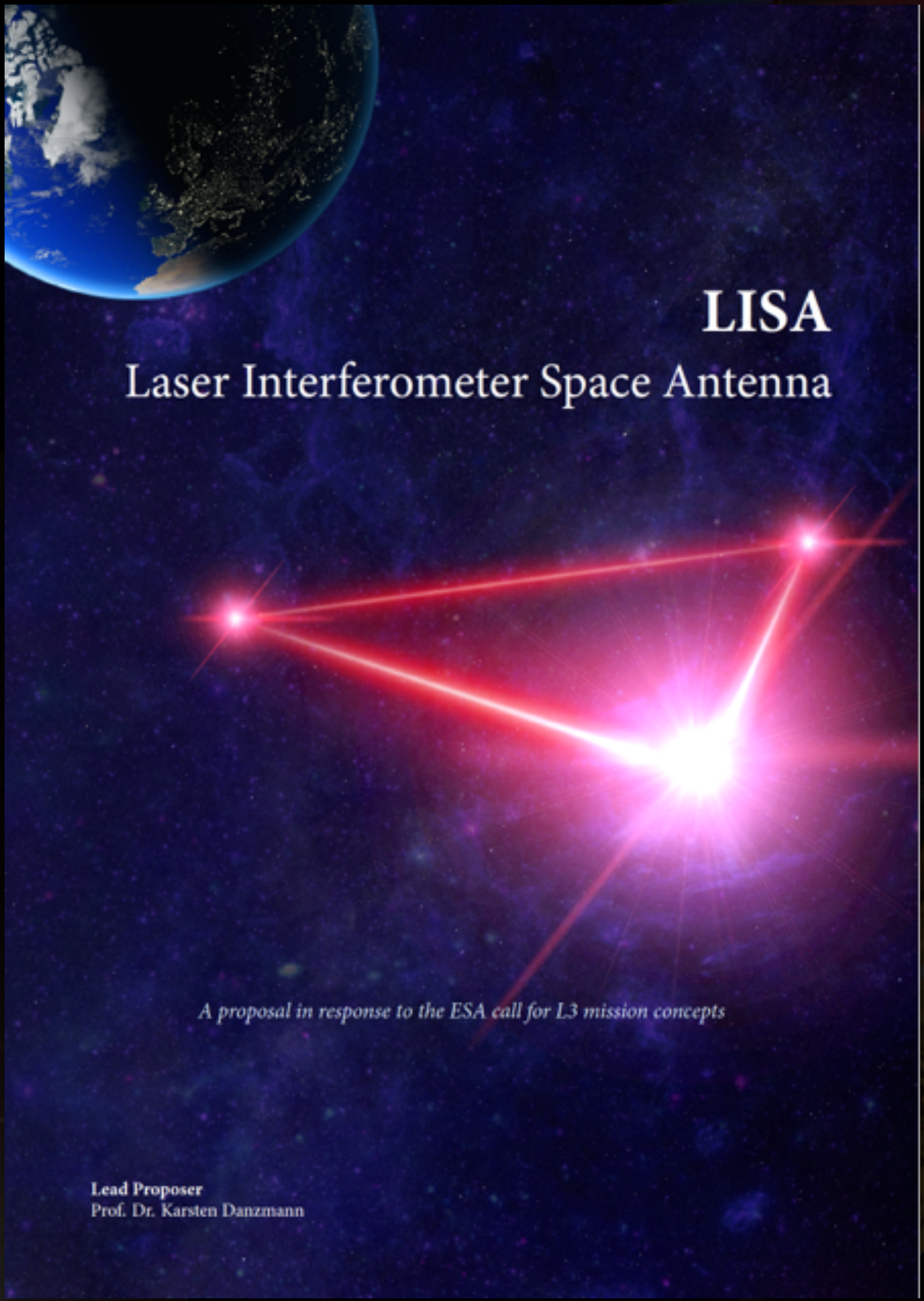
→ Call for mission at ESA

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.

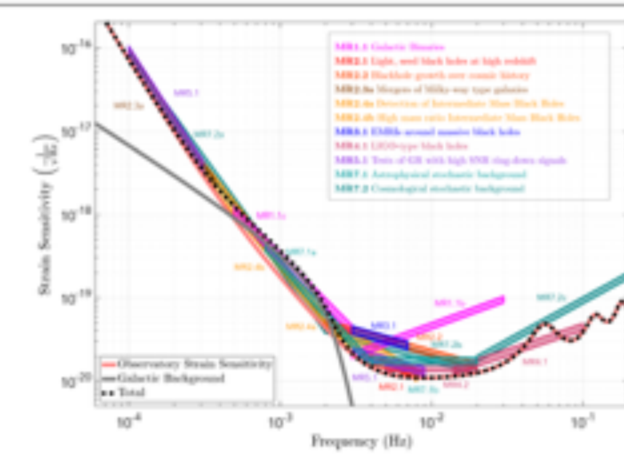


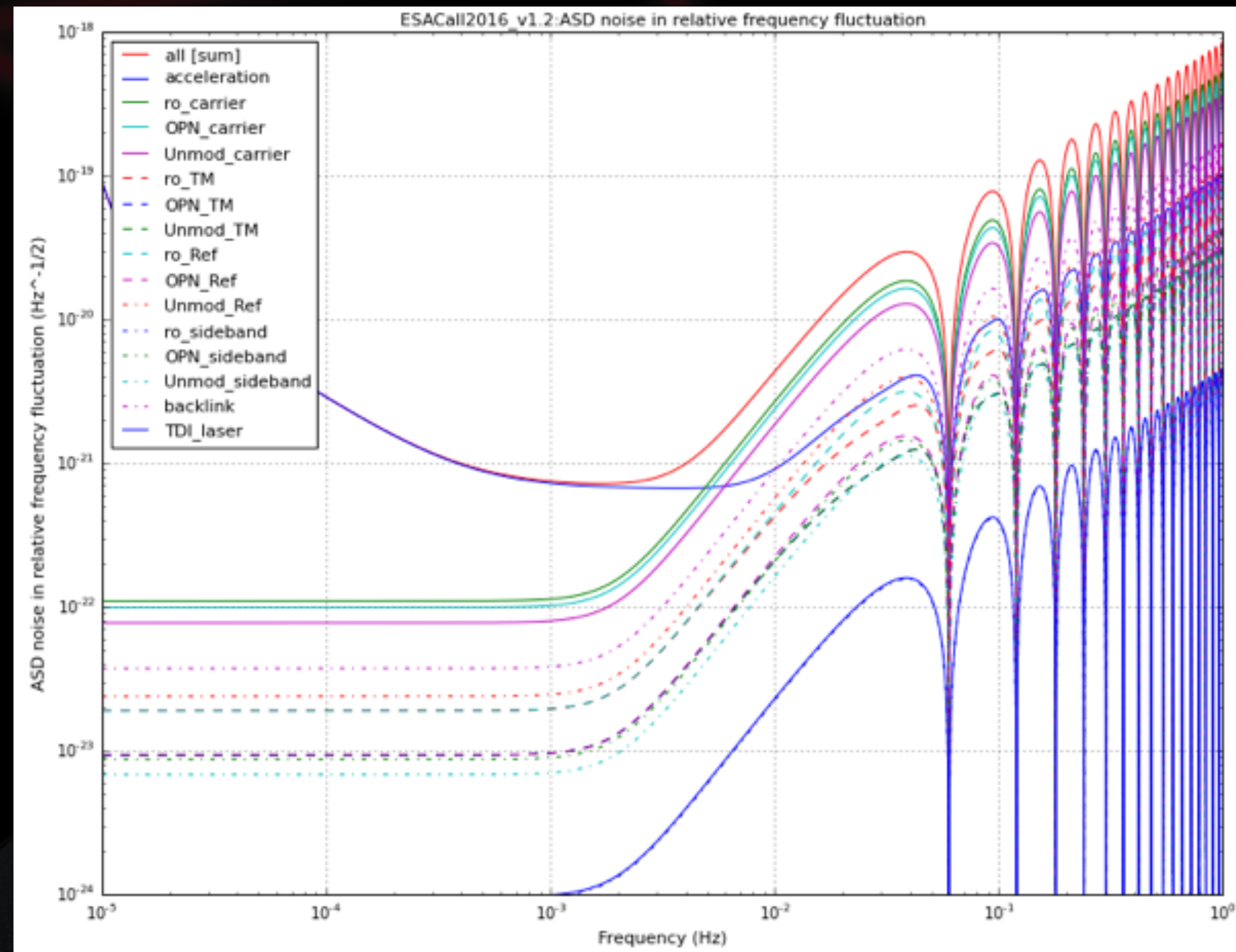
Figure 2: Mission constraints on the sky-averaged strain sensitivity of the observatory for a 2-arm configuration (TDI X), $\sqrt{S_h(f)}$, derived from the threshold systems of each observational requirement.

LISA – 2. SCIENCE PERFORMANCE Page 7

LISA concept in the proposal

- 3 arms, 2.5 km
- Launch Ariane 6.4
- Propulsion:
  - micro-prop: cold gaz
  - prop. module
- Frequency band:

$$100\,\mu\mathrm{Hz} \le f \le 0.1\,\mathrm{Hz} \quad \text{req.}$$
$$20\,\mu\mathrm{Hz} \le f \le 1\,\mathrm{Hz} \quad \text{goal}$$



- Noise budget:
  - Acceleration => LISAPathfinder

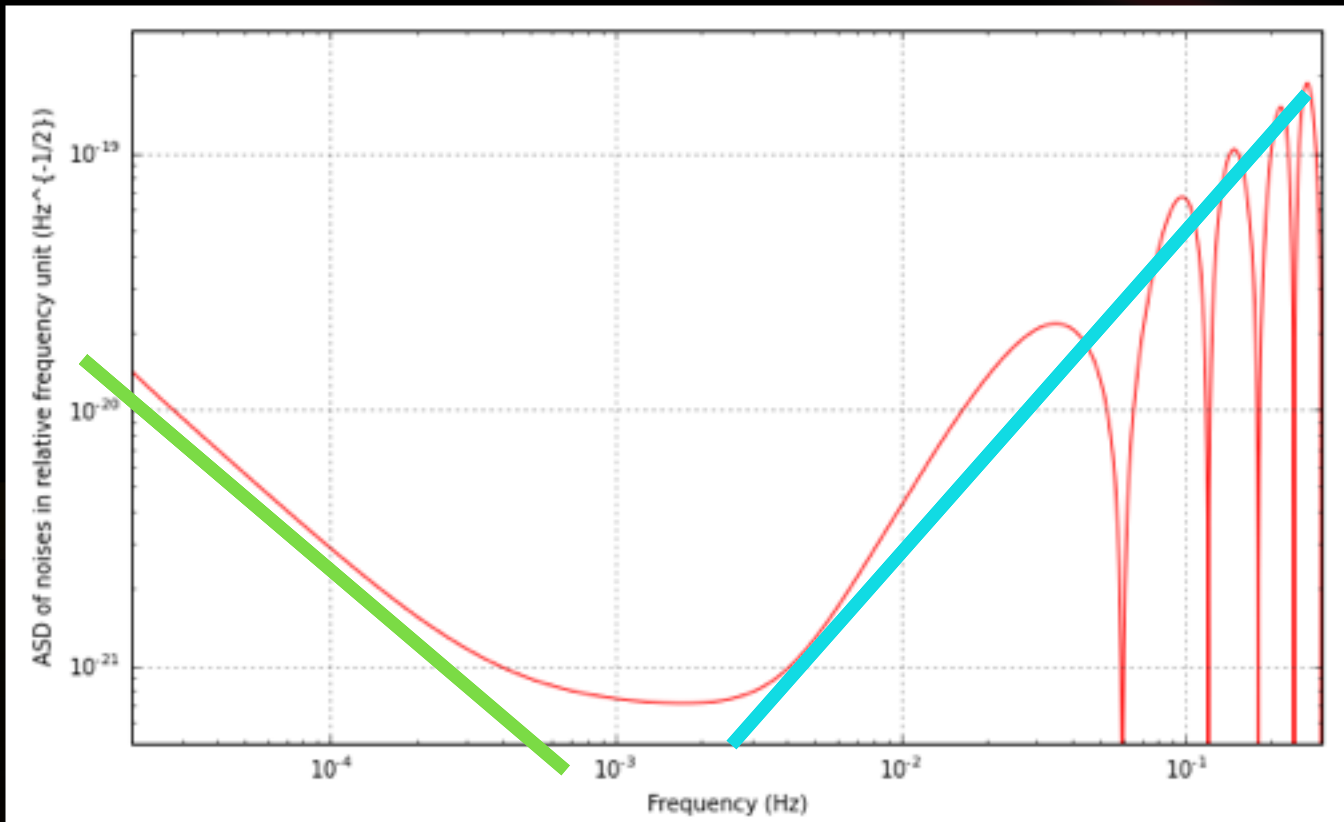
$$S_a^{1/2} \le 3\cdot10^{-15}\,\frac{\mathrm{m\,s^{-2}}}{\sqrt{\mathrm{Hz}}}\cdot\sqrt{1+\left(\frac{0.4\,\mathrm{mHz}}{f}\right)^2}\cdot\sqrt{1+\left(\frac{f}{8\,\mathrm{mHz}}\right)^4}$$

  - Interferometric Measurement System

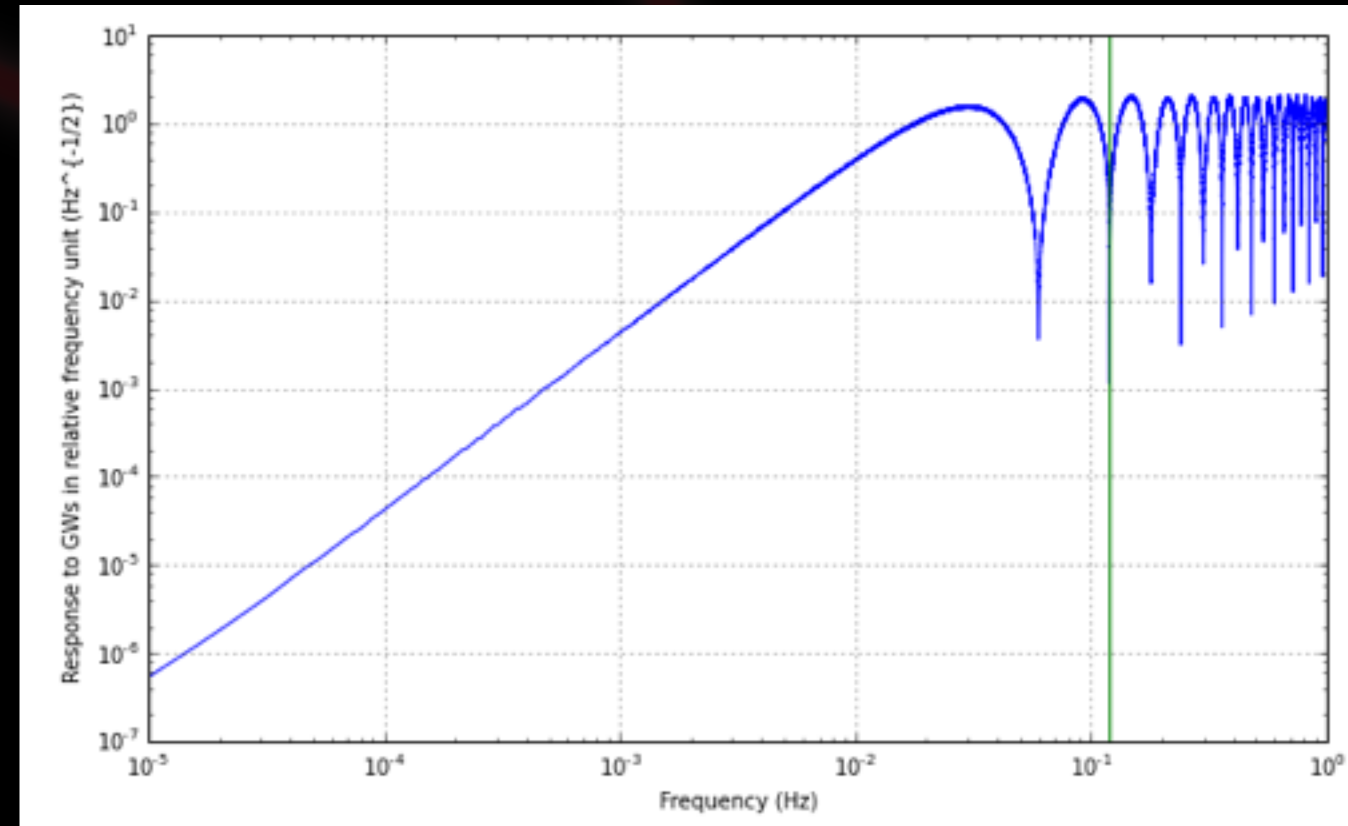
$$S_{\mathrm{IFO}}^{1/2} \le 10\cdot10^{-12}\,\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\cdot\sqrt{1+\left(\frac{2\,\mathrm{mHz}}{f}\right)^4}$$

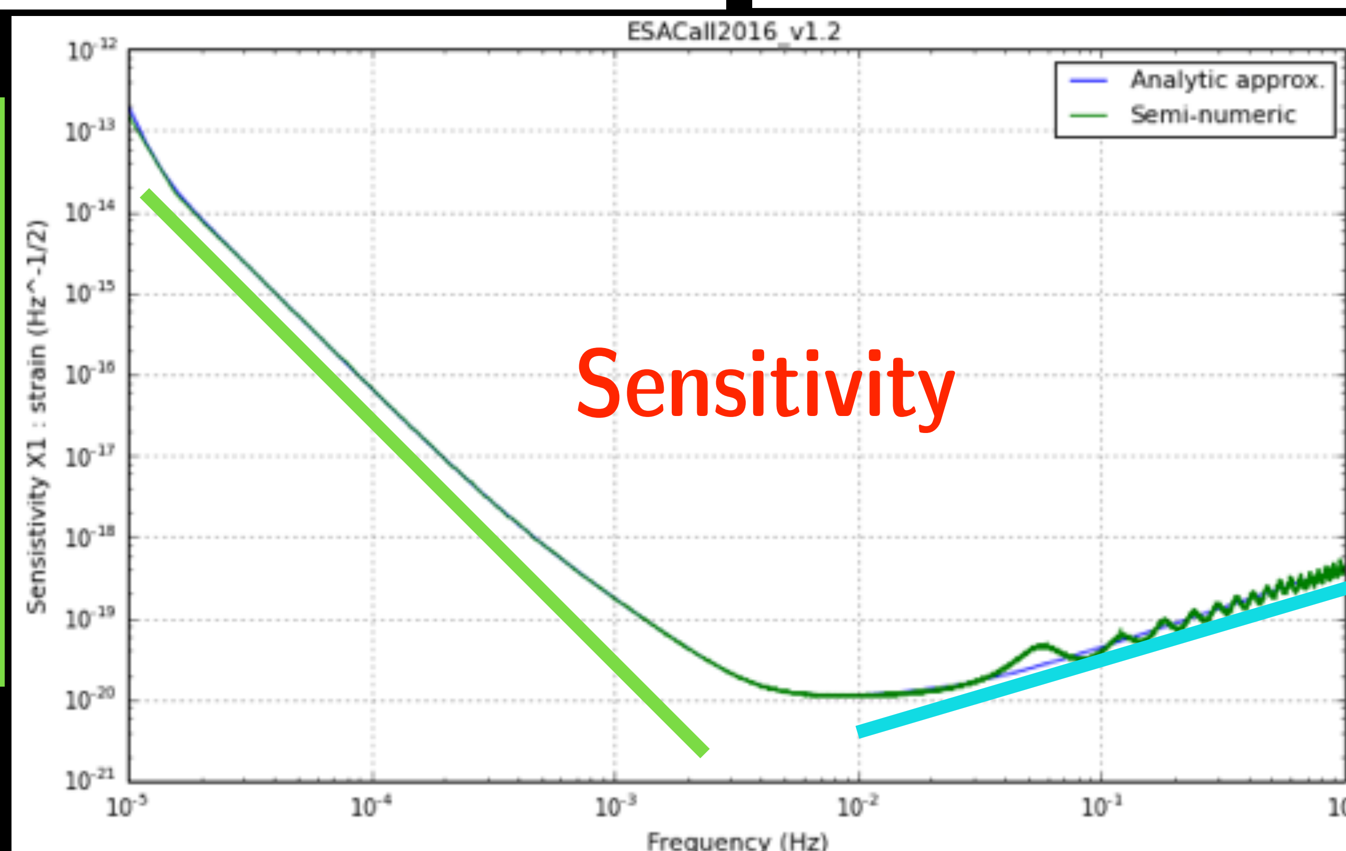
Sensitivity

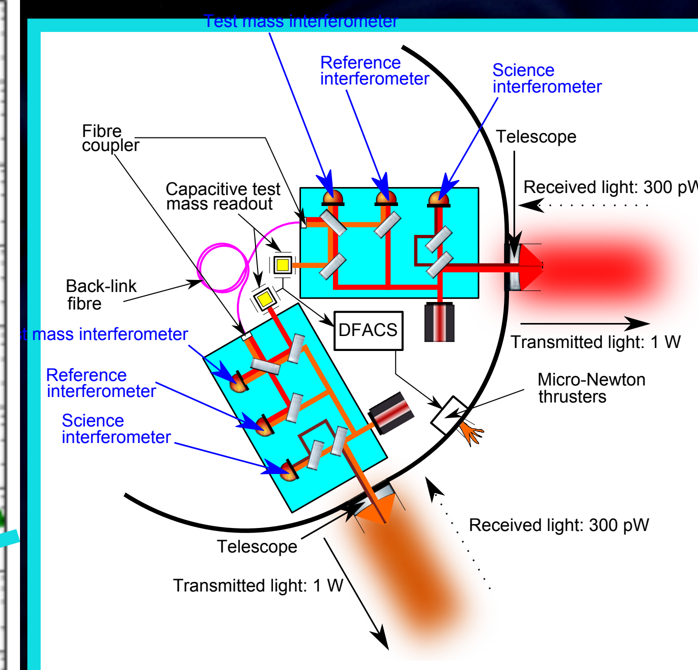
Noises



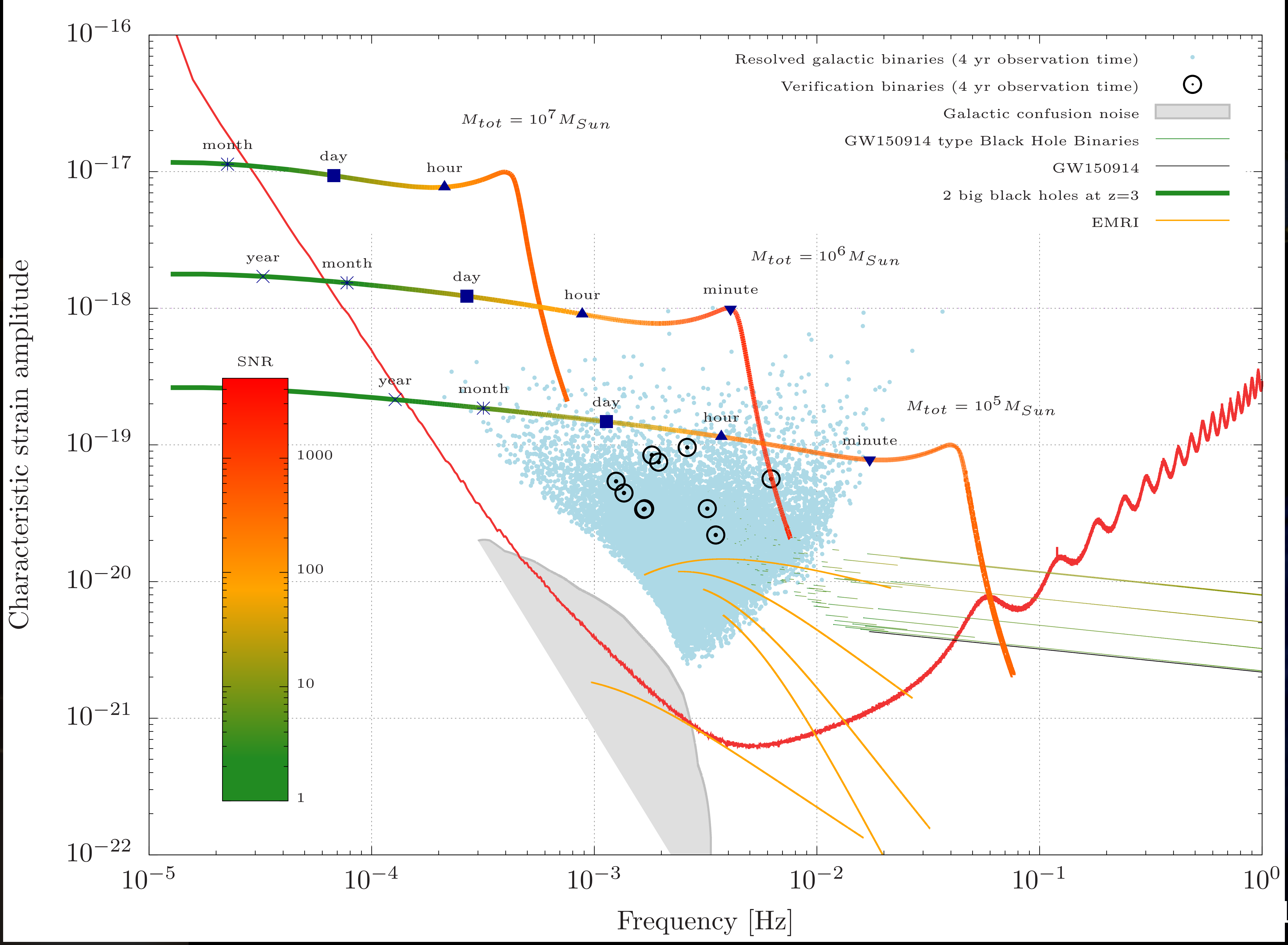
Response of the detector to GWs







GW sources

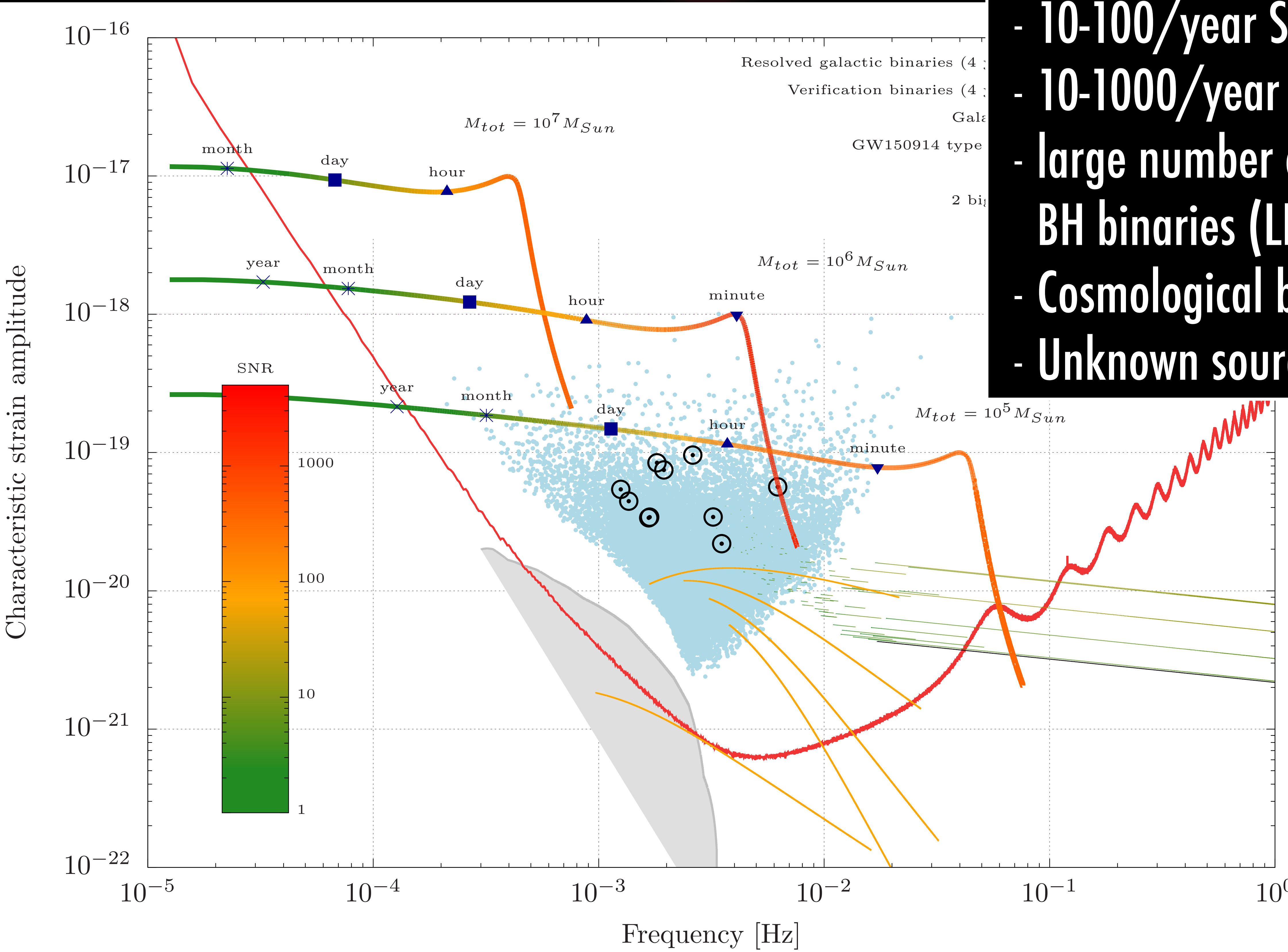


Resolved galactic binaries (4 yr observation time)
Verification binaries (4 yr observation time)
Galactic confusion noise
GW150914 type Black Hole Binaries
GW150914
2 big black holes at z=3
EMRI
$M_{tot} = 10^7 M_{Sun}$
$M_{tot} = 10^6 M_{Sun}$
$M_{tot} = 10^5 M_{Sun}$
month
day
hour
year
minute
SNR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

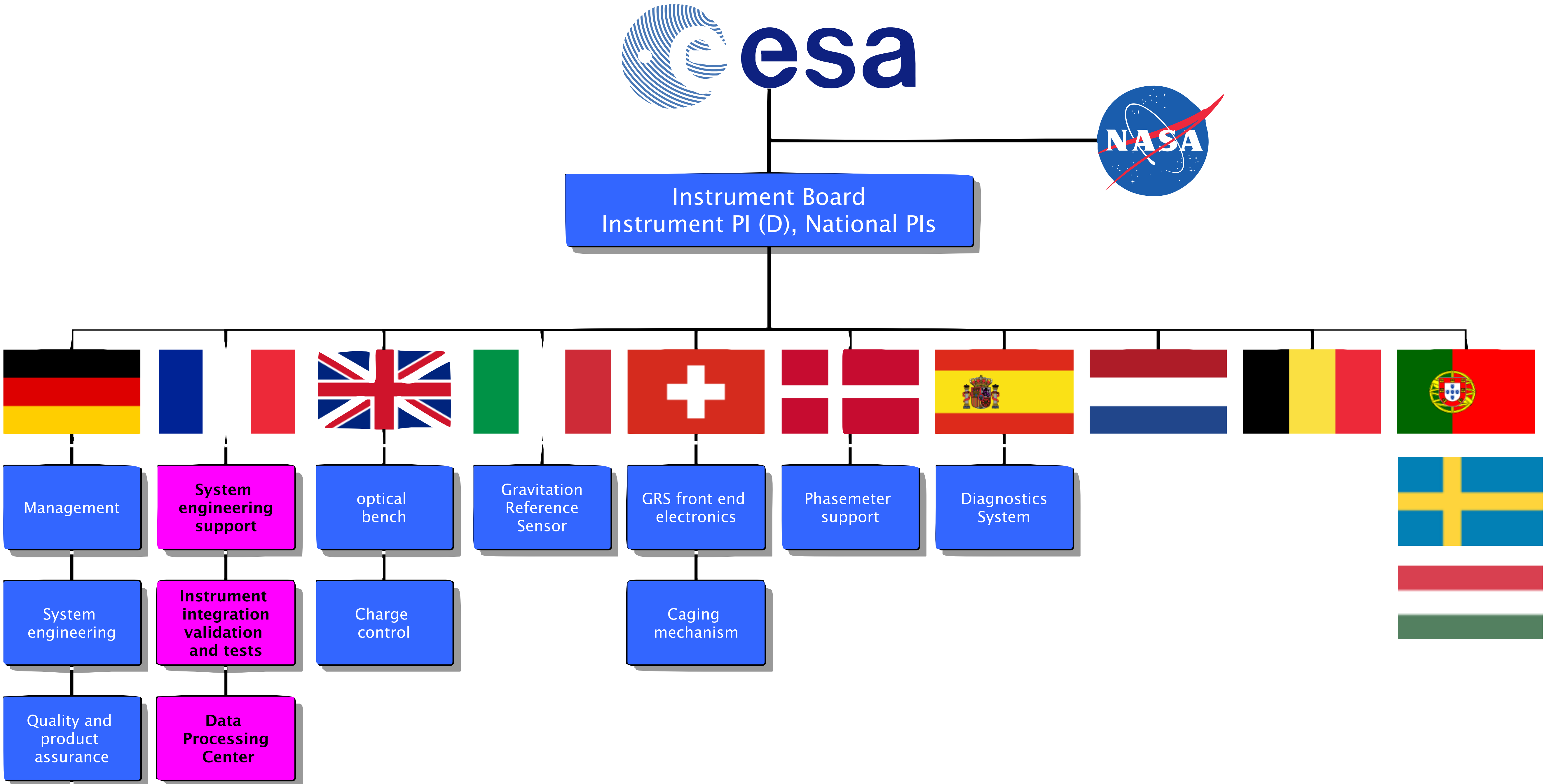
GW sources

See talk from Chiara Caprini

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



LISA Consortium



- Set for eLISA/NGO and enlarge later
- The LISA Consortium wrote the LISA proposal (core group) submitted it to ESA
- Letter of endorsement from National Agencies to ESA

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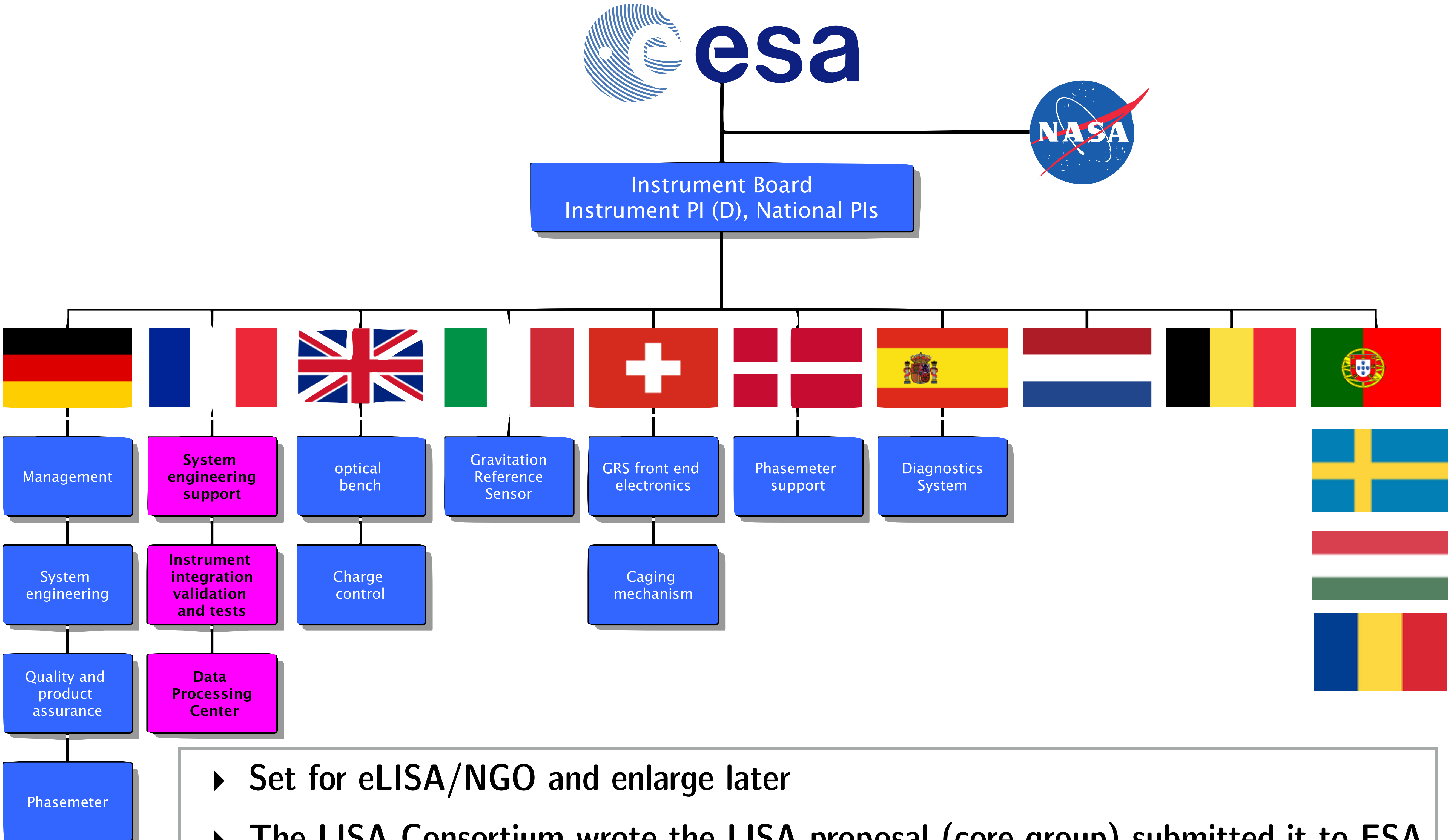

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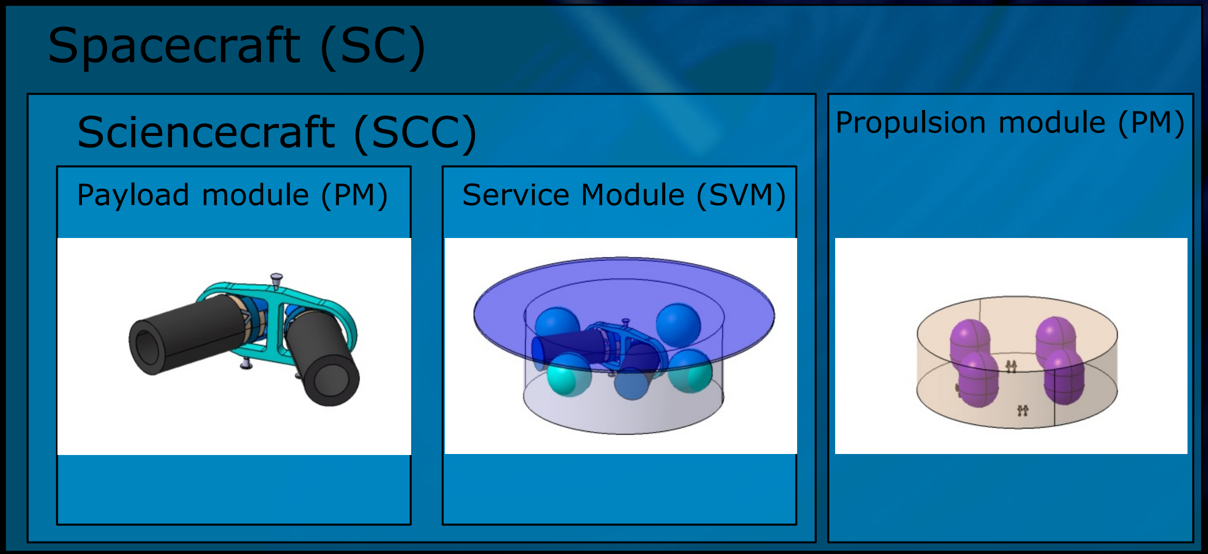
LISA at ESA

- 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

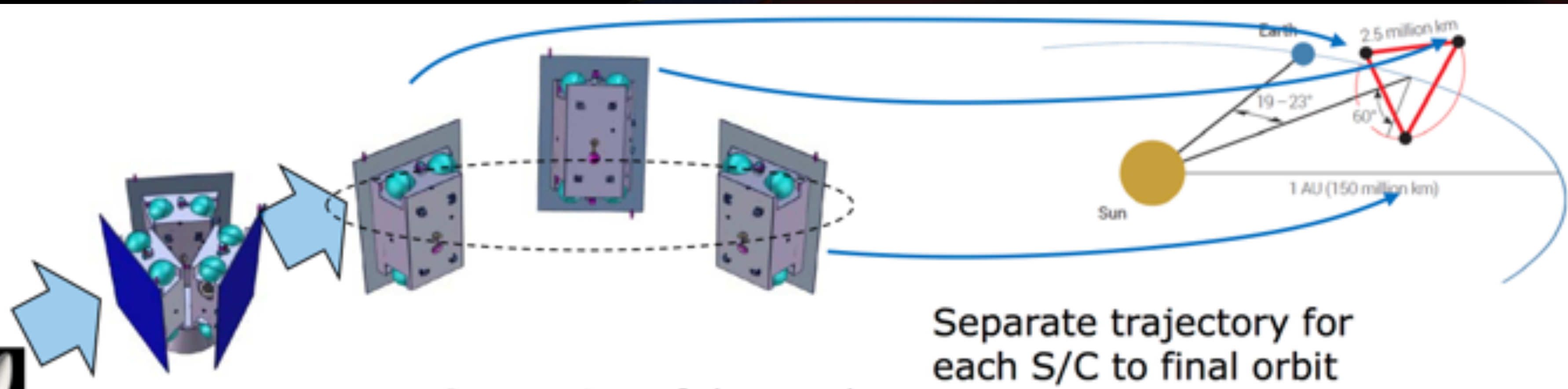
GW observations !

ESA Phase 0 mission

- 13 Concurrent Design Facility from March to May 2017
- Conducted by ESA with few members of the consortium
- Drivers: thermal stability/range, mechanical stability, mass, power, data rate, volume, integration, ...
- Several studied options:
  - Propulsion: chemical (CP) / electrical (EP & EP+)
  - Micro-propulsion: cold-gas (CP & EP)/ electrical (EP+)
  - Communication,
  - Shape,
  - Launch strategies, orbits,
  - ...



ESA Phase 0 mission

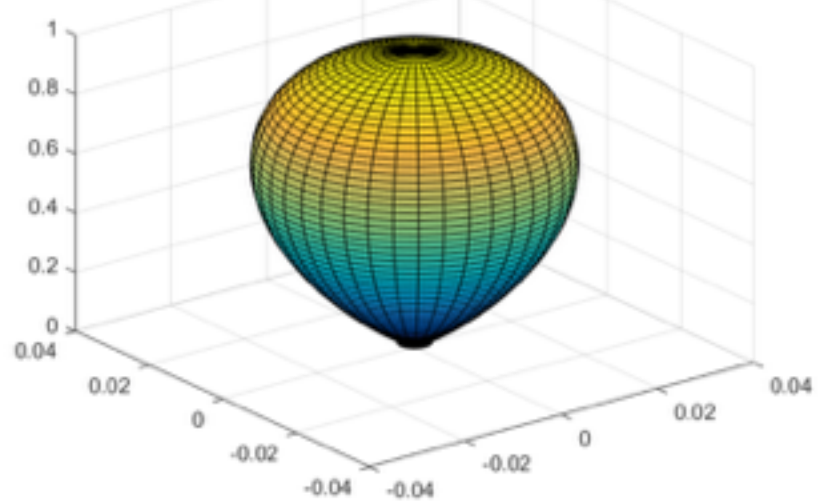


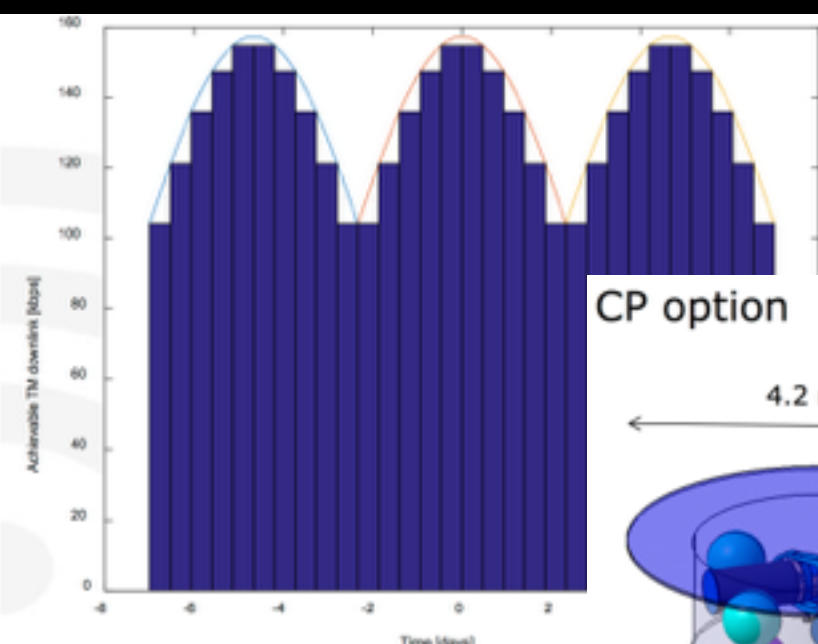
Launch in stacked configuration
Direct injection into escape trajectory

Separation of the stack right after launch

Separate trajectory for each S/C to final orbit

	CP	EP	EP+
Chemical Propulsion	314.8	190.2	4.4
Electric Propulsion	0.0	80.7	170.6
Propulsion dry	**315**	**271**	**175**
Cprop mass	1115	0	0
Eprop mass	0	148	117
Microprop mass	200	240	20
Total	**3244**	**1881**	**1522**

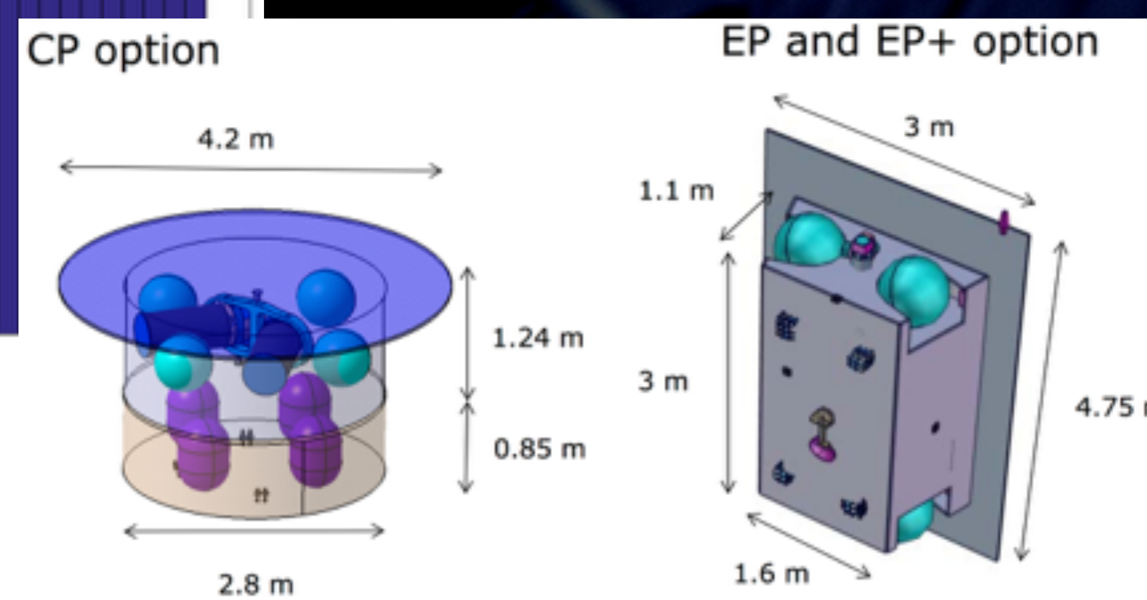




Dish
Average rate: 132.7 kbps
Max rate: 154.8 kbps
Min rate: 104.2 kbps
Margin: 4.1 dB (>3 dB)

MGA (CP option)
Max rate: 13 kbps
Margin: 4.0 dB (>3 dB)

LGA
Max rate: 52 bps
Margin: 3.1 dB



ESA Phase 0 Payload

- From June to November
- Conducted by Payload Coordination Team with ESA
- Support of ESA CDF

=> Write the Payload Definition Document:

- System requirements
- Architecture
- Budgets
- Commissioning
- Communications
- Control
- Critical items
- Data
- Electrical
- Environment
- Failure modes

- Subsystems:
  - Laser
  - Diagnostics
  - Gravitational Reference Sensor
  - Mechanisms
  - Optical Bench
  - Telescope
  - Constellation Acquisition Sensor
  - PhaseMeter

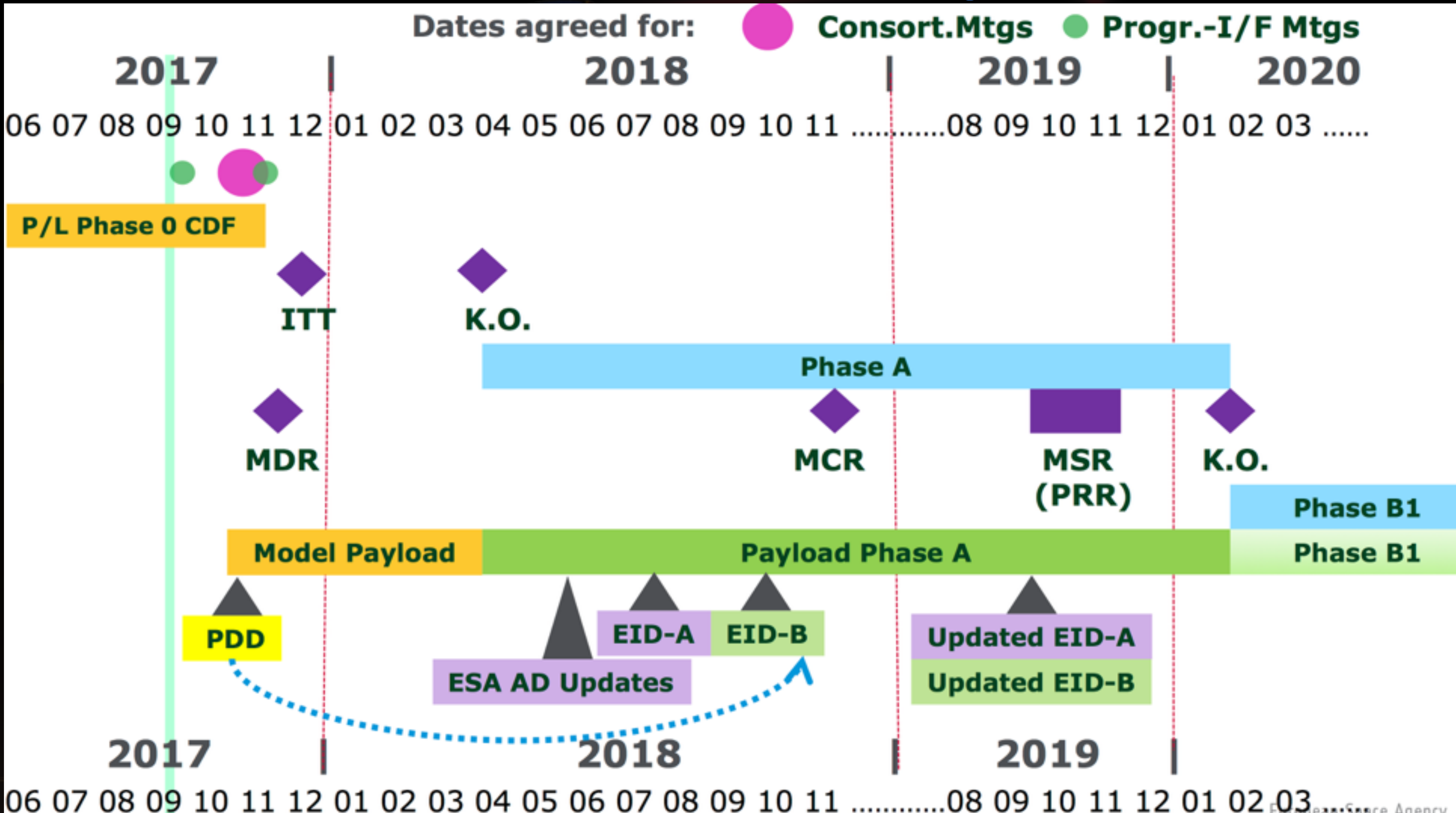
ESA next steps

1. Payload Definition Document (PDD)
2. ESA appointed the Science Study Team: responsible for the Science Requirement Document (SRD):
3. SRD + PDD => input to the Mission Requirement Document (MRD)
4. MRD is used to defined the ITT: invitation to industries

   All these steps need to be done by december 2017

5. March 2018: start of phase A

ESA Next steps

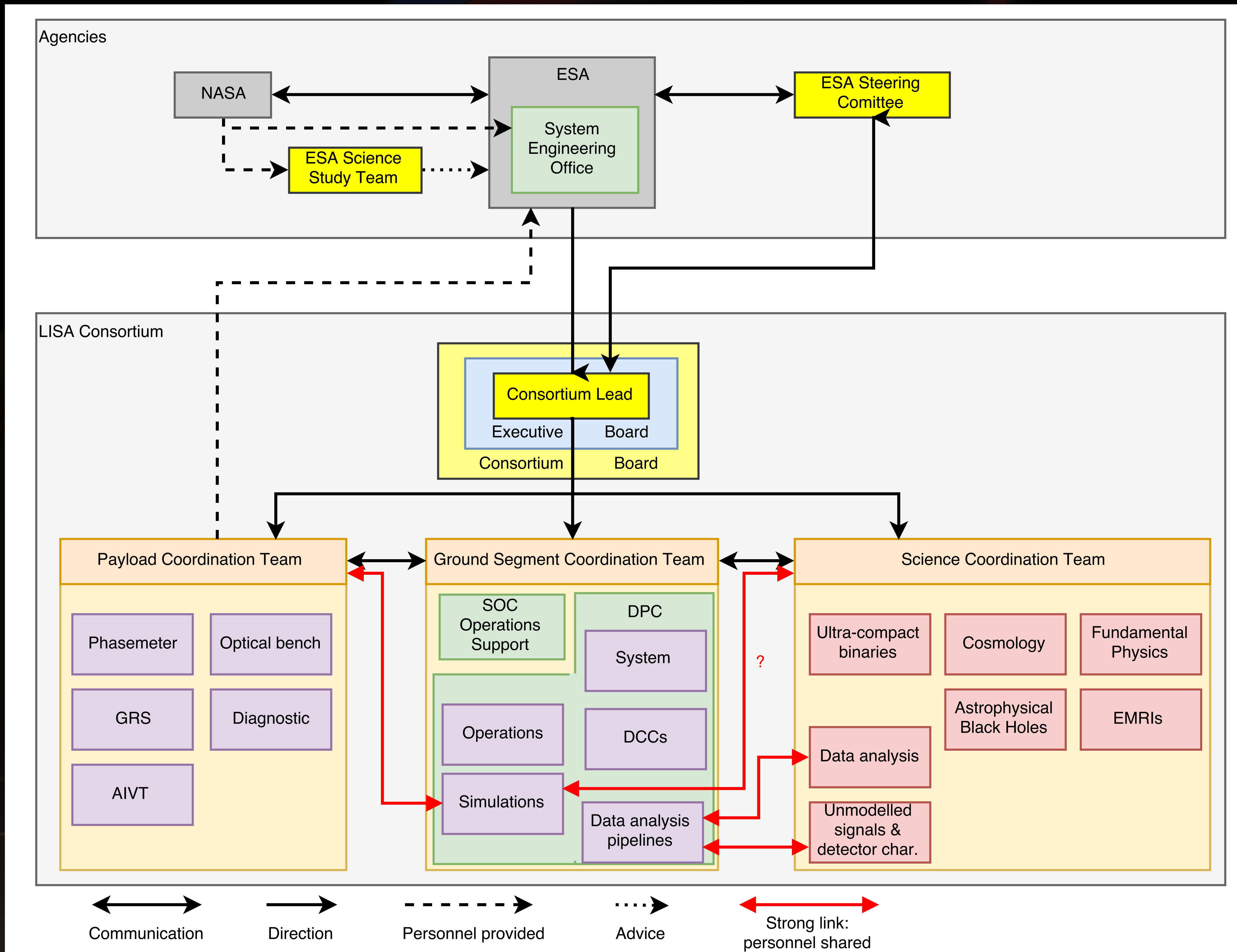


- Mission Definition/Consolidation/Selection/Adoption Review, Payload Definition Doc, Experiment Interface Doc.

ESA Team(s)

- Project Study Scientist: Paul McNamara
- Project Study Manager: Martin Gelher
- CDF: Diego Escorial Olmos + ESA experts
- Science Study Team:
  - LISA Europe:
    - K. Danzmann (Germany)
    - M. Colpi (Italy)
    - P. Jetzer (Switzerland)
    - M. Hewitson (Germany)
    - G. Nelemans (Neederland)
    - A. Petiteau (France)
    - C. Sopuerta (Spain)
    - H. Ward (UK)
    - Bill Weber (Italy)
  - External:
    - N. Tanvir
    - J. Hjorth
  - LISA US:
    - K. Holley-Bockelmann
    - D. Shoemaker
  - Observers:
    - O. Jennrich (ESA)
    - I. Thorpe (NASA)
    - R. Sambruna (NASA)

LISA Consortium



LISA Consortium

- Board (executive board):
  - K. Danzmann (DE),
  - B. Schutz (DE),
  - A. Petiteau (FR),
  - C. N. Man(FR),
  - W. J. Weber (IT),
  - M. Colpi (IT),
  - G. Domenico (CH),
  - P. Jetzer (CH),
  - A. Vecchio (UK),
  - H. Ward (UK),
  - D. Shoemaker(US),
  - N. Cornish (US),
  - G. Mueller (US),
  - S. L. Larson (US),
  - G. Nelemans(NL),
  - C. F. Sopuerta (E),
  - A. Hornstrup (DK),
  - T. Hertog (BE),
  - Z. Frei (HU),
  - V. Cardoso (PT),
  - R. Church (SE),
  - L. Caramete (RO)
- Payload Coordination Team => in place
  - M. Hewitson (AEI), B. Weber (UTN), E. Fitzimons (Glasgow), G. Heinzel (AEI), H. Halloin (APC), N. Dinu-Jaegger (ARTEMIS), G. Mueller(Florida), L. Ferraioli (ETH), J. Livas (NASA), ...
- Ground Segment Coordination Team => in progress
- Science Coordination Team => to be done but already strong Cosmology Working Group (C. Caprini et al.)

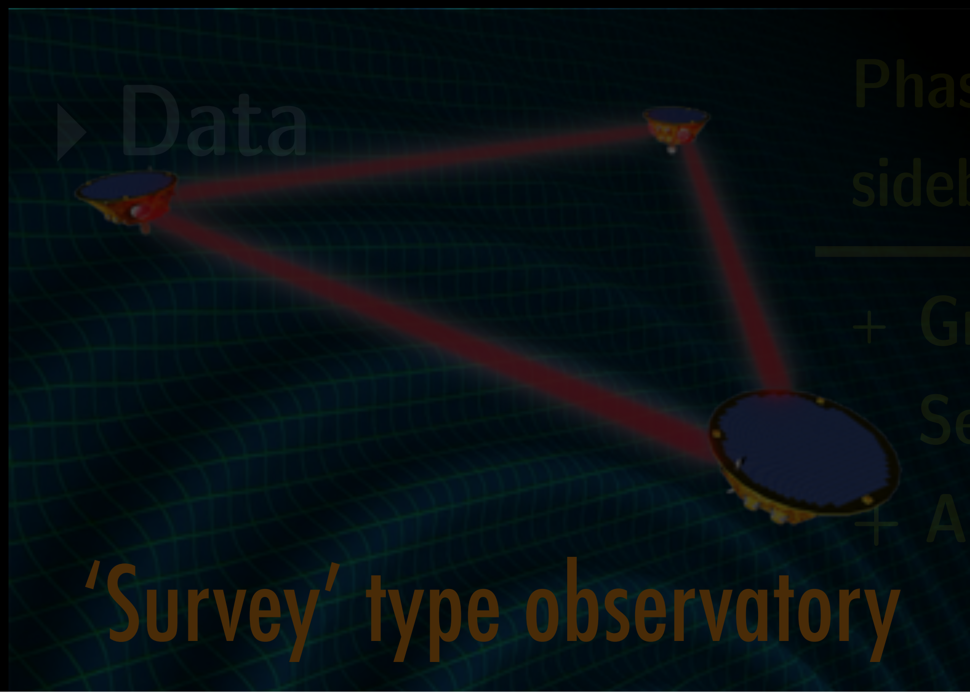
NASA ?

- "Confortable" as be junior partner, ESA leading the mission
- Contribution to the ESA mission: payload and non-payload
- 2 roles: member of the consortium (funding & hardware) and direct partner to ESA
- NASA LISA Study Team:
  - science case (decadal 2019), science advisor, communication (NASA science community <=> consortium)
- 5 technologies (telescope, laser, phase meter, CMS, micro-thrusters) + mission contribution => decision on final contribution 2024 or before

French contributions

- Main contributions (deliverable):
  - Assembly Integration Verification and Test of part of the payload [talk from Nicoleta Dinu-Jaeger]
  - Performance Control [talk from Nicoleta Dinu-Jaeger]
  - Data Processing Center [talk from Maude Le Jeune]
- Others:
  - LISA Pathfinder [talk from Joseph Martino]
  - LISA Data Challenge [talk from Stas Babak]
  - Simulations [talk from Jean-Baptiste Bayle]
  - Science: cosmology, astrophysics, fundamental physics [talks this afternoon]
  - …

LISA DPC



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

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

Conclusion

- After the success of LISAPathfinder and GW detection, LISA consortium submitted a proposal approved by ESA SPC
- LISA official started at ESA: phase 0 until dec. 2017 then phase A:
  - Good technological readiness due to decades of development
    => accelerated process (at the moment)
  - Payload definition in progress & discussion on the ground segment
- LISA Consortium is evolving to a more "solid" structure:
  - Definition of coordination teams
  - LISA community is growing very quickly
- French (potential) contributions identified: detailed def. in phase A
  => Need for a French organisation/consortium: LISAFrance
    => this meeting!

Thank you