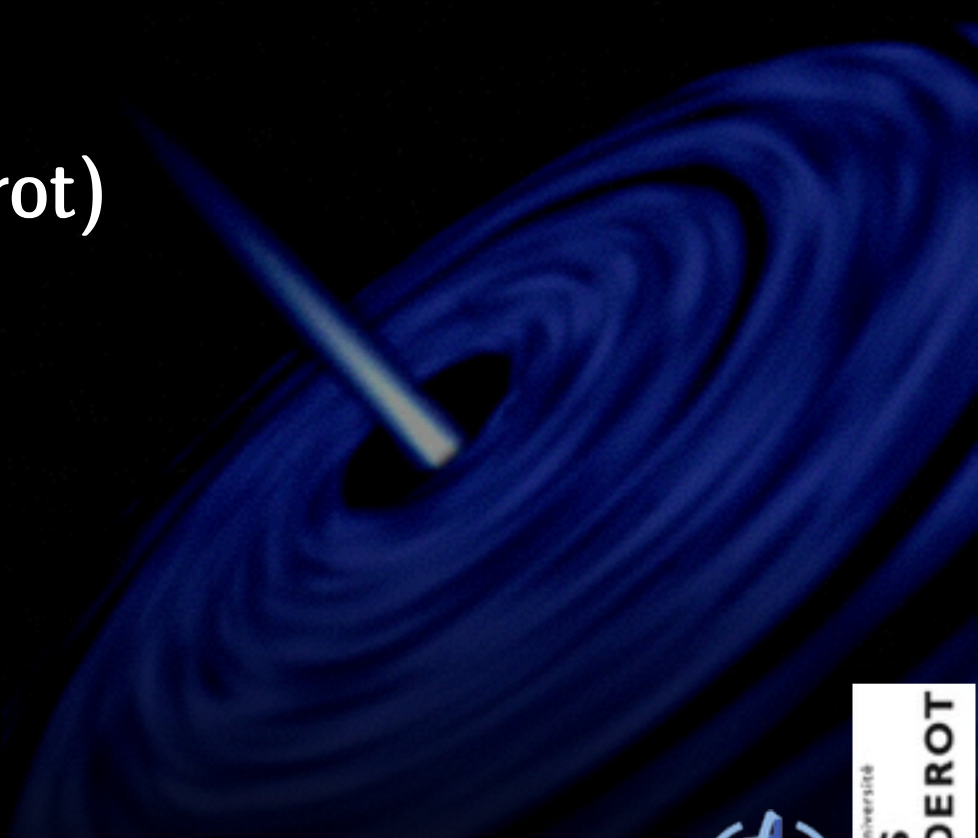
Scientific Challenges with LISA

Antoine Petiteau
(APC – Université Paris-Diderot)

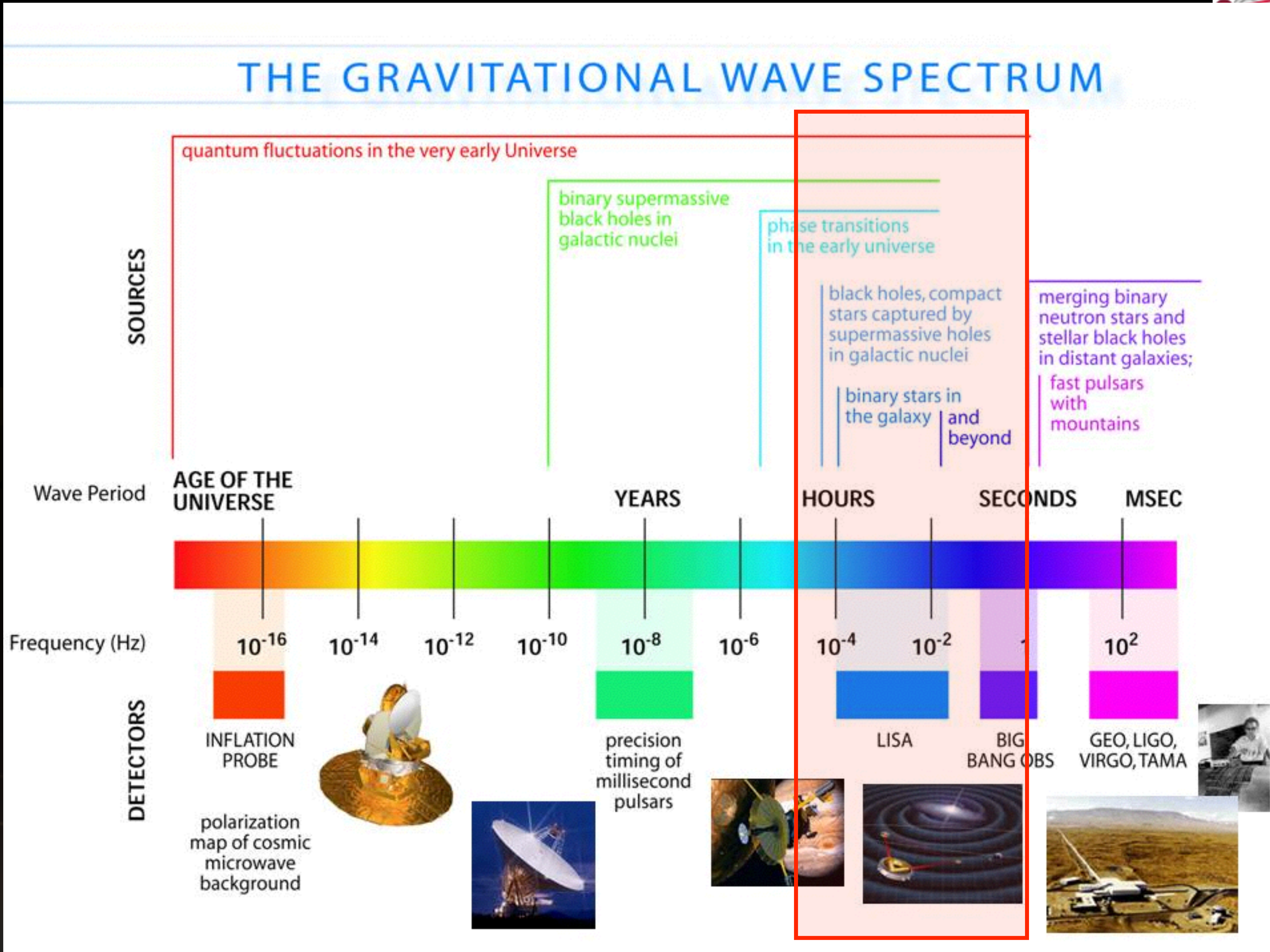
GRASS - Padova

27th Novem 2018



Outline

- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISA status and organisation
- LISA scientific performances
- Scientific Challenges
- Conclusion and perspectives

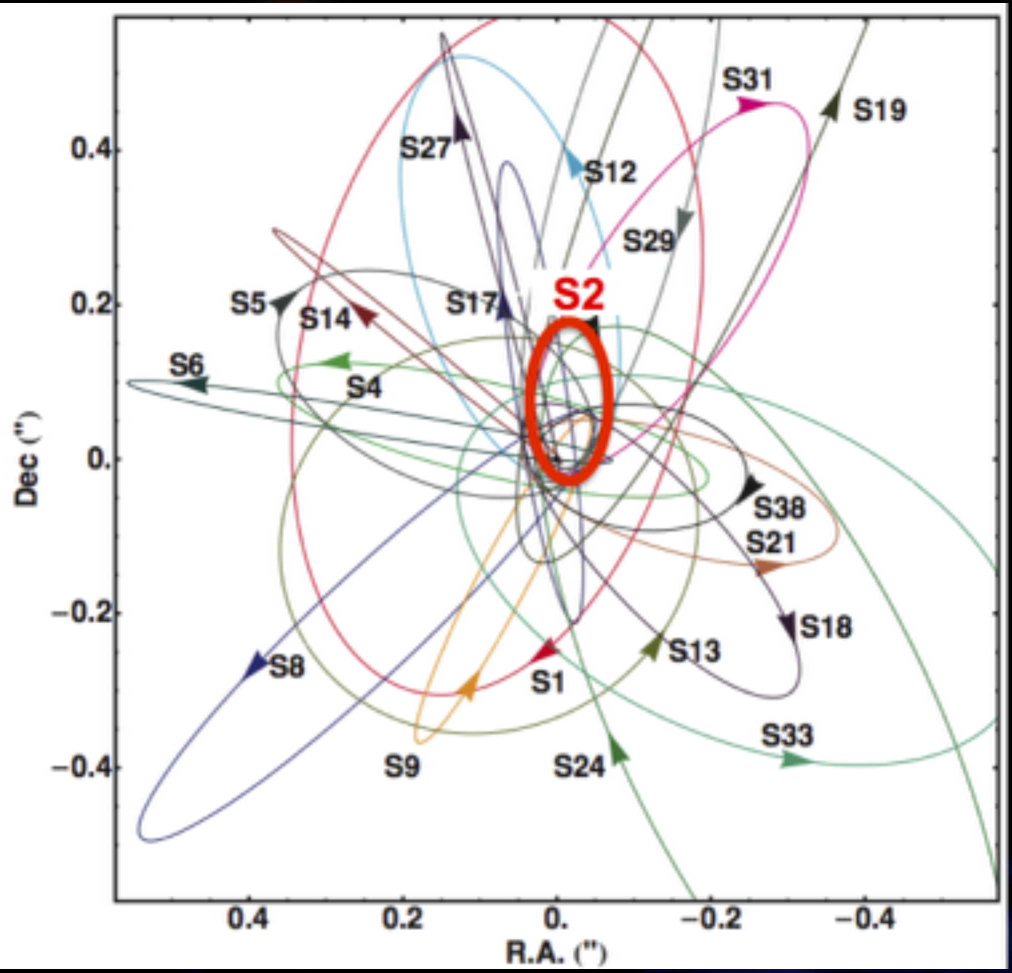


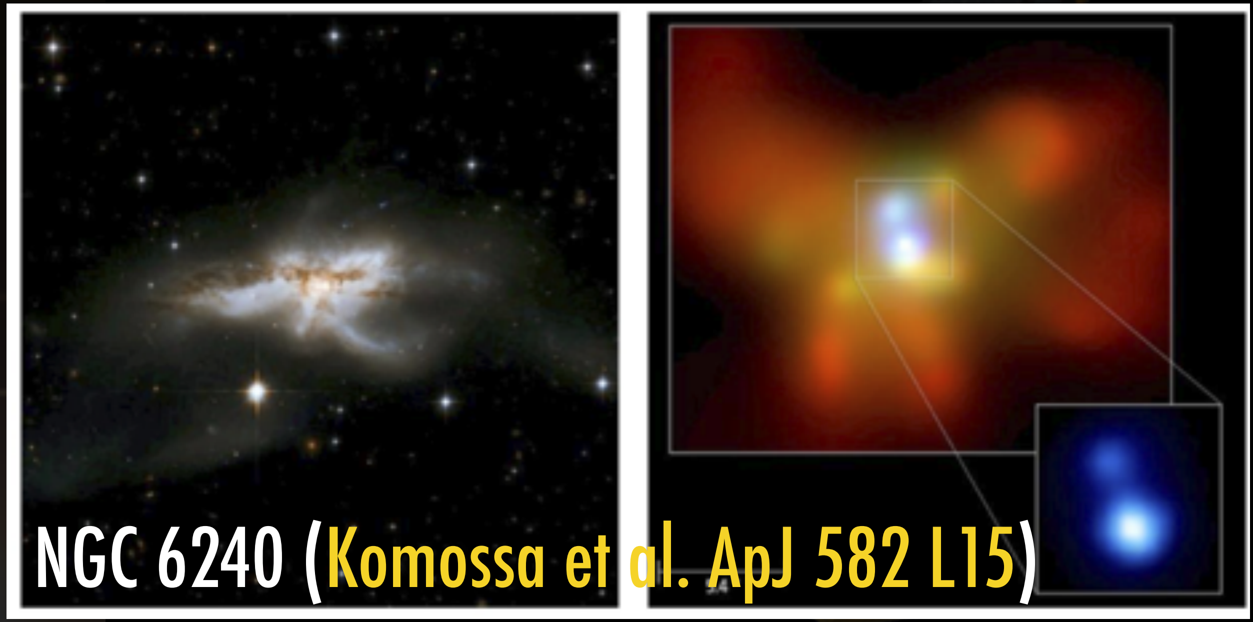
THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging 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

Supermassive black hole binaries

- Observations of Sgr A*, a dark massive object of $4.5 \times 10^6\ M_{Sun}$ at the centre of Milky Way.
- Supermassive Black Hole are indirectly observed in the centre of a large number of galaxies (Active Galactic Nuclei).
- Observations of galaxies mergers.

  → MBH binaries should exist.
- Observations of double AGN



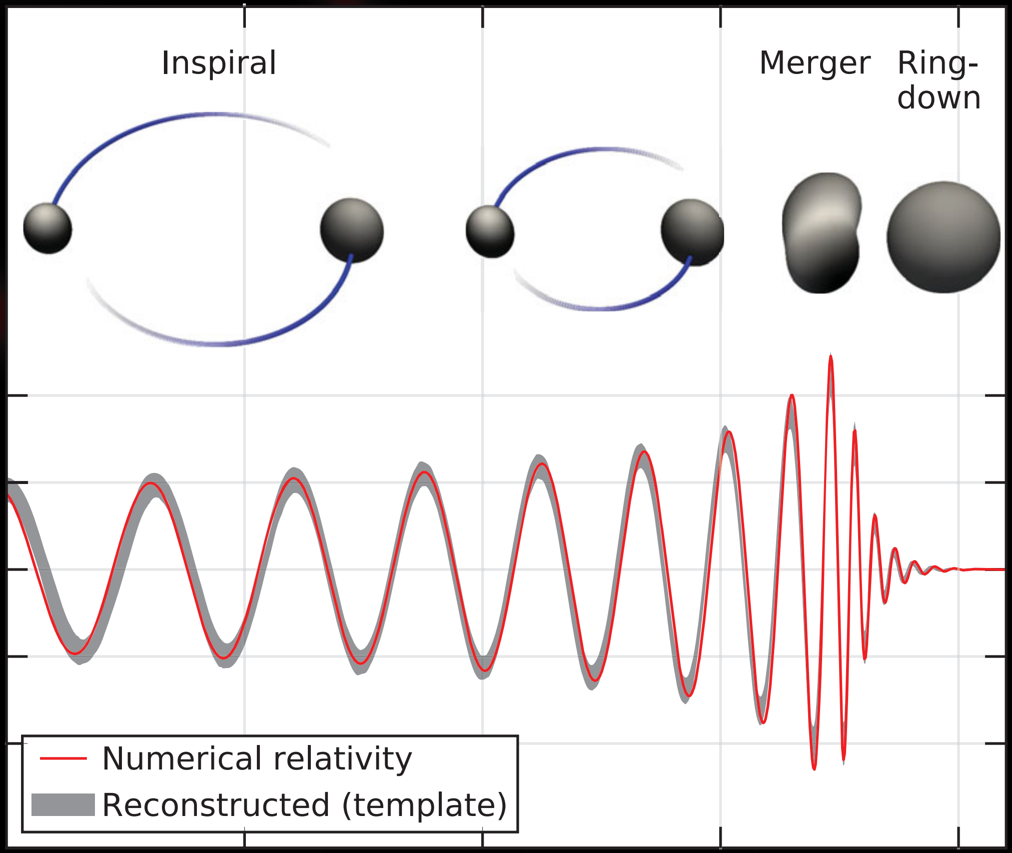


NGC 6240 (Komossa et al. ApJ 582 L15)

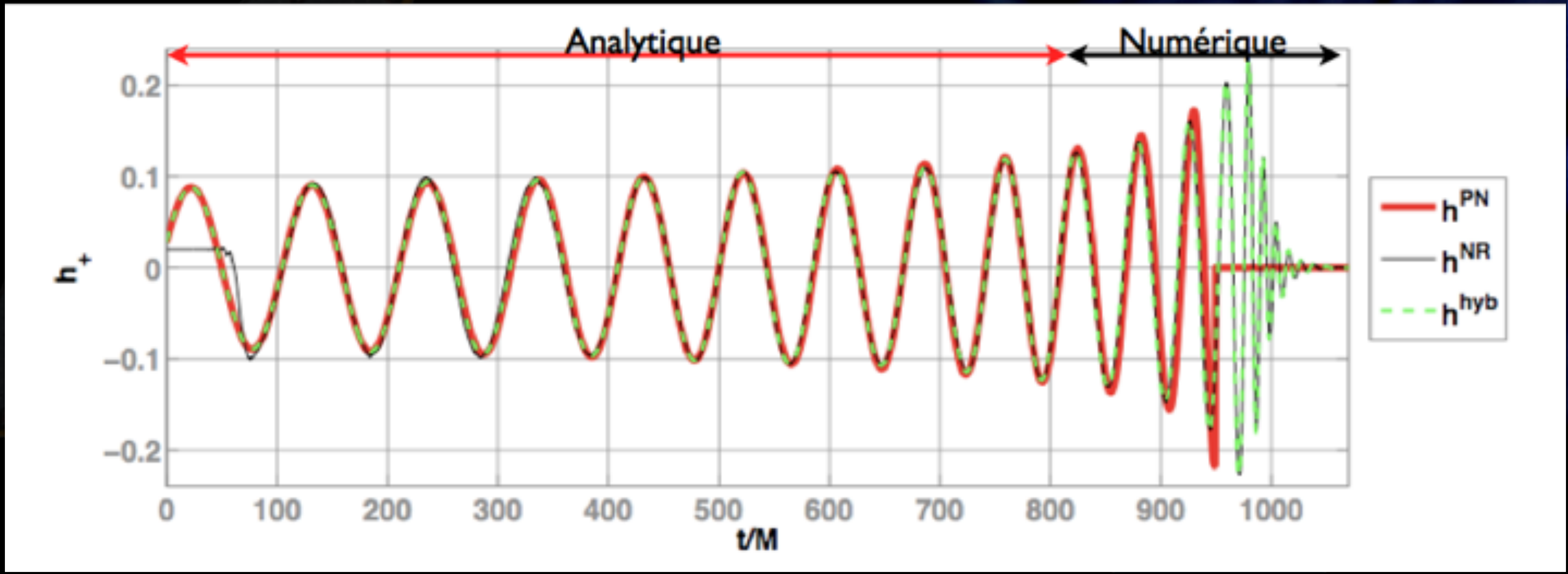
Antennae galaxies

Supermassive black hole binaries

- GW emission: 3 phases:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.

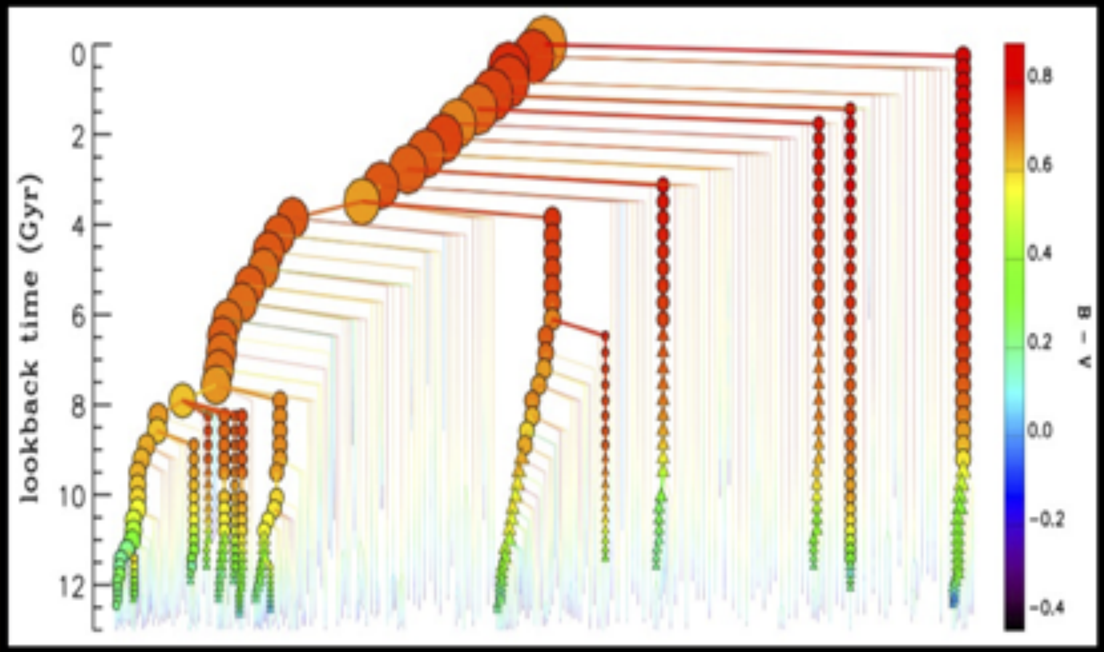


- No full waveform but several approximations exist :
  - Phenomenological waveform,
  - Effective One Body,
  - …



Supermassive black hole binaries

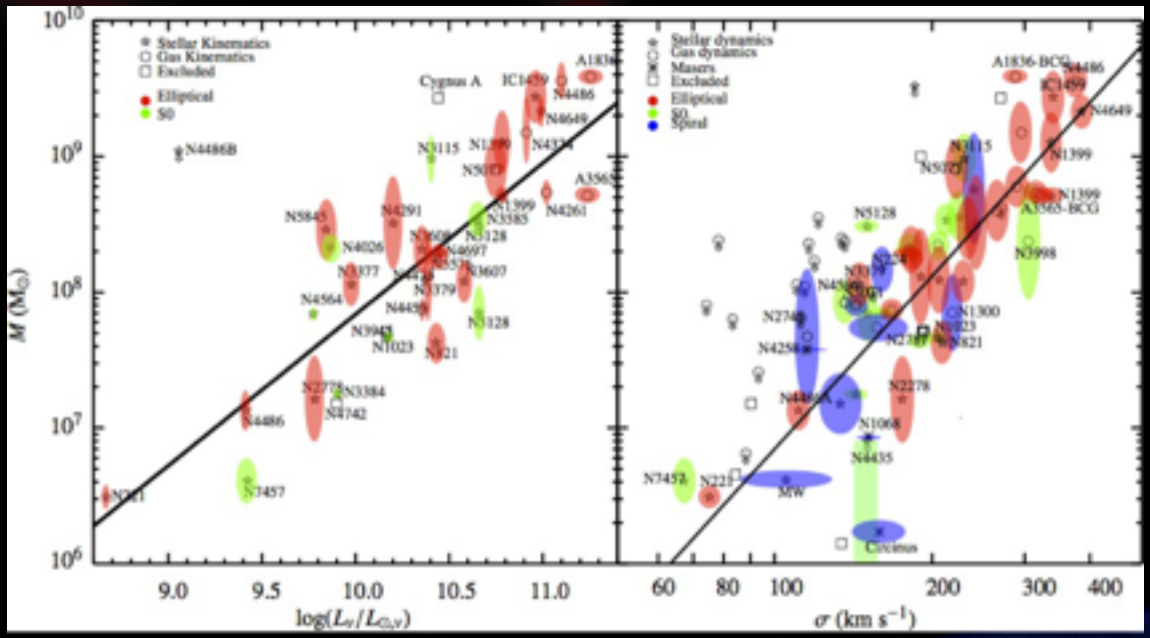
Galaxies merger tree (cosmological simulation)



From De Lucia et al 2006

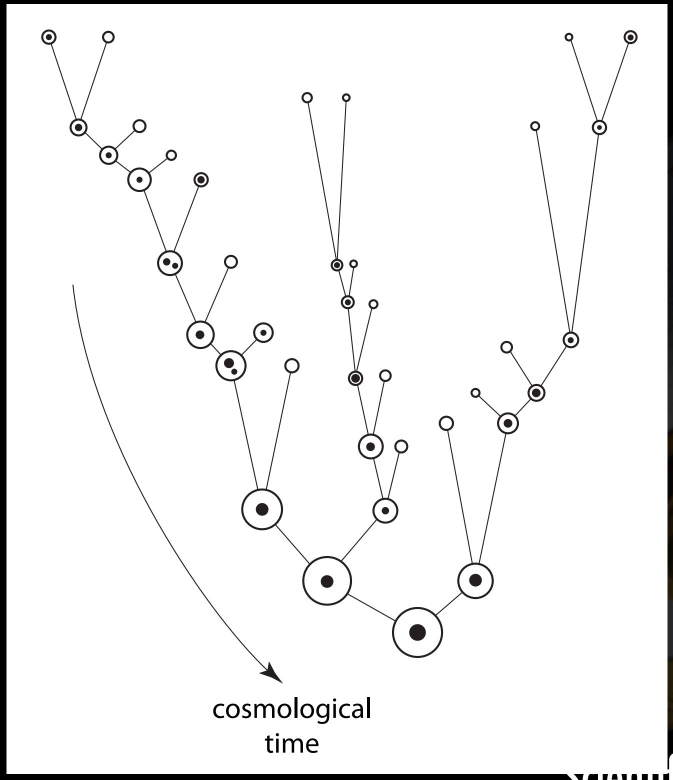
+

"M - σ relation": the speed of stars in bulge is linked to the central MBH mass



Gultekin 2009

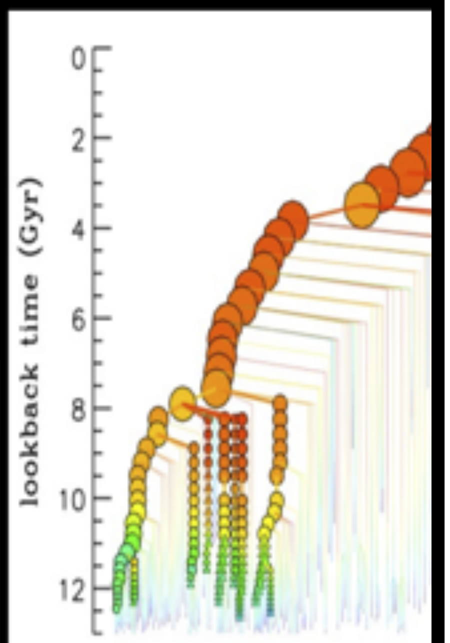
=



- Work from E. Barausse (IAP), A. Sesana (Univ. of Birmingham), M. Volonteri (IAP) et al.

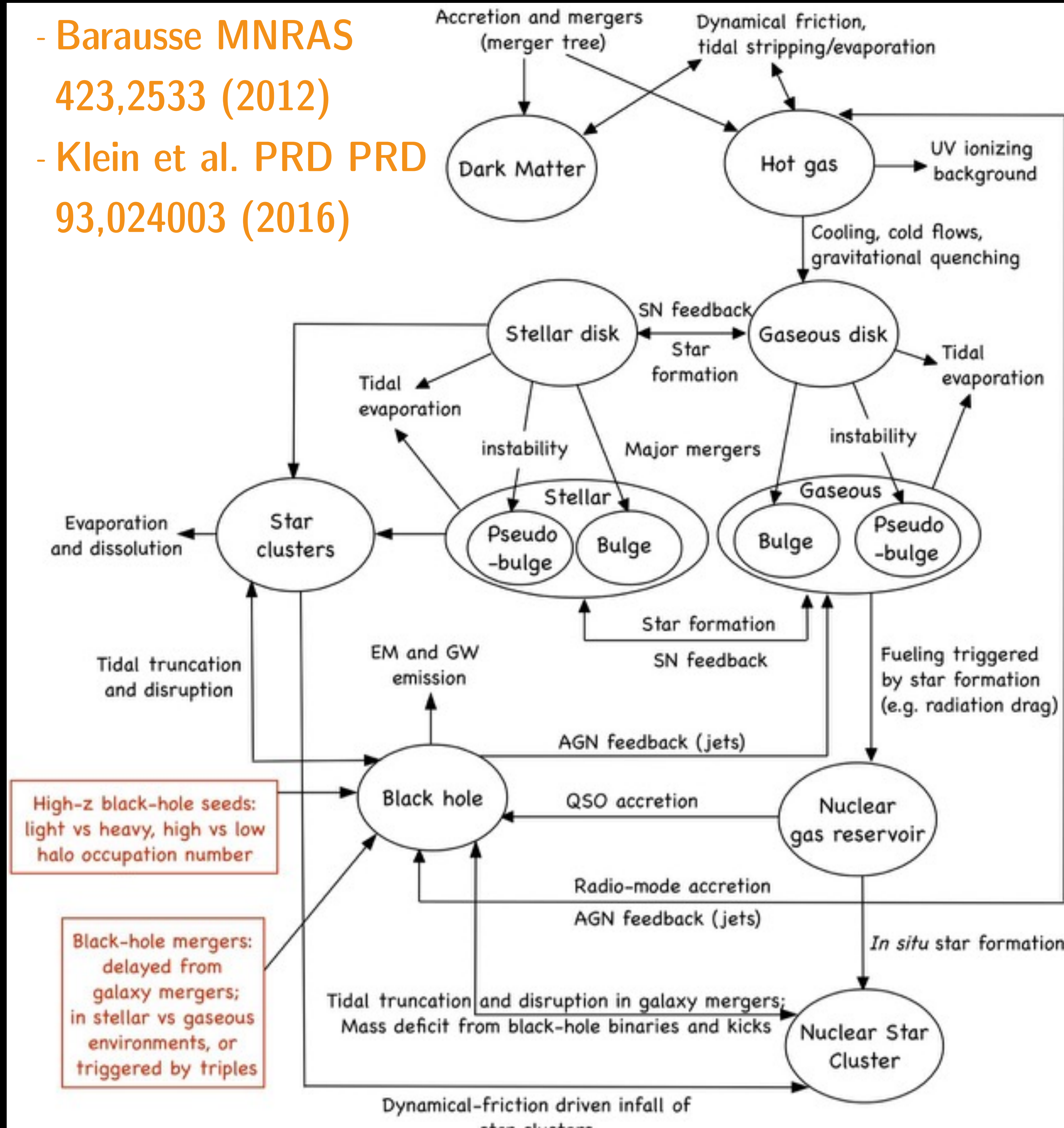
Supermassive black hole binaries

Galaxi
(cosmolo

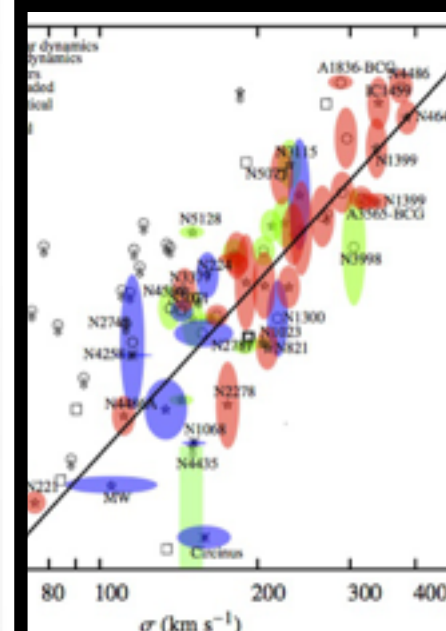


From De Lucia et

- Barausse MNRAS 423,2533 (2012)
- Klein et al. PRD PRD 93,024003 (2016)



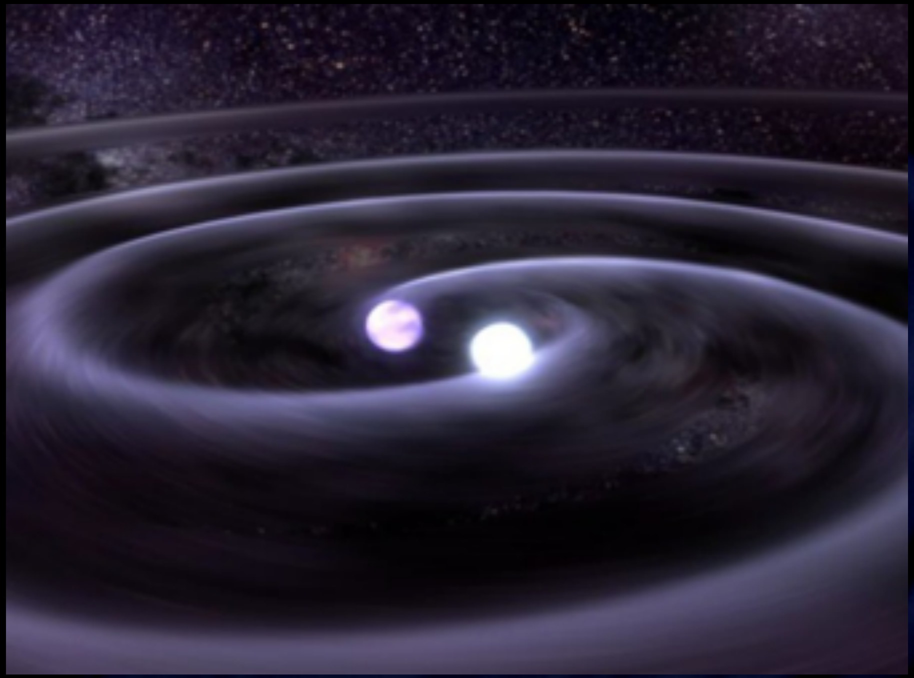
speed of stars in
entral MBH mass



(IAP), A.
gham), M.

Compact solar mass binaries

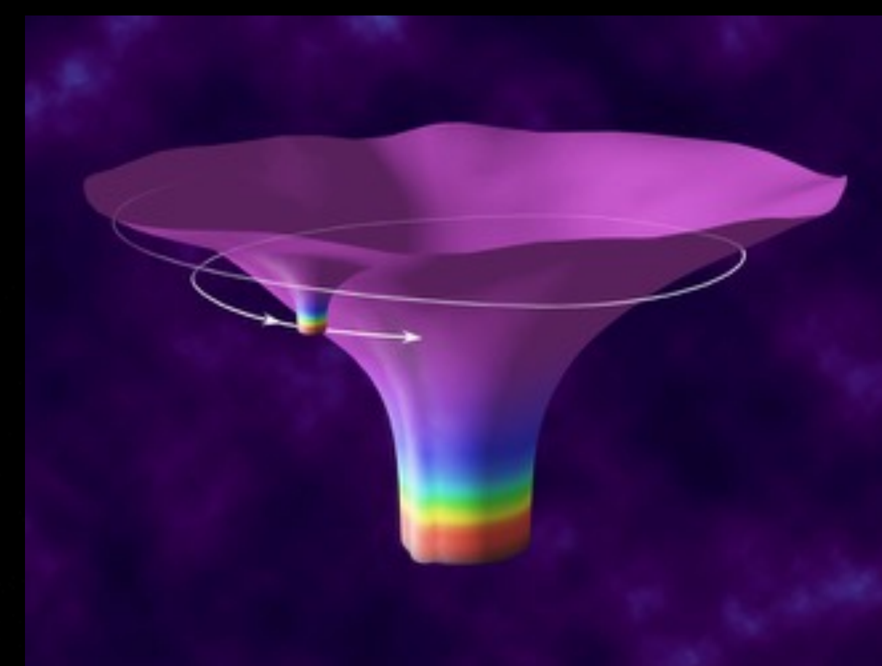
- Large number of stars are in binary system.
- Evolution in white dwarf (WD) and neutron stars (NS).
  => existence of WD-WD, NS-WD and NS-NS binaries
- Estimation for the Galaxy: 60 millions.
- Gravitational waves:
  - most part in the slow inspiral regime (quasi-monochromatic): GW at mHz
  - few are coalescing: GW event of few seconds at f > 10 Hz (LIGO/Virgo)



- Several known system emitting around the mHz

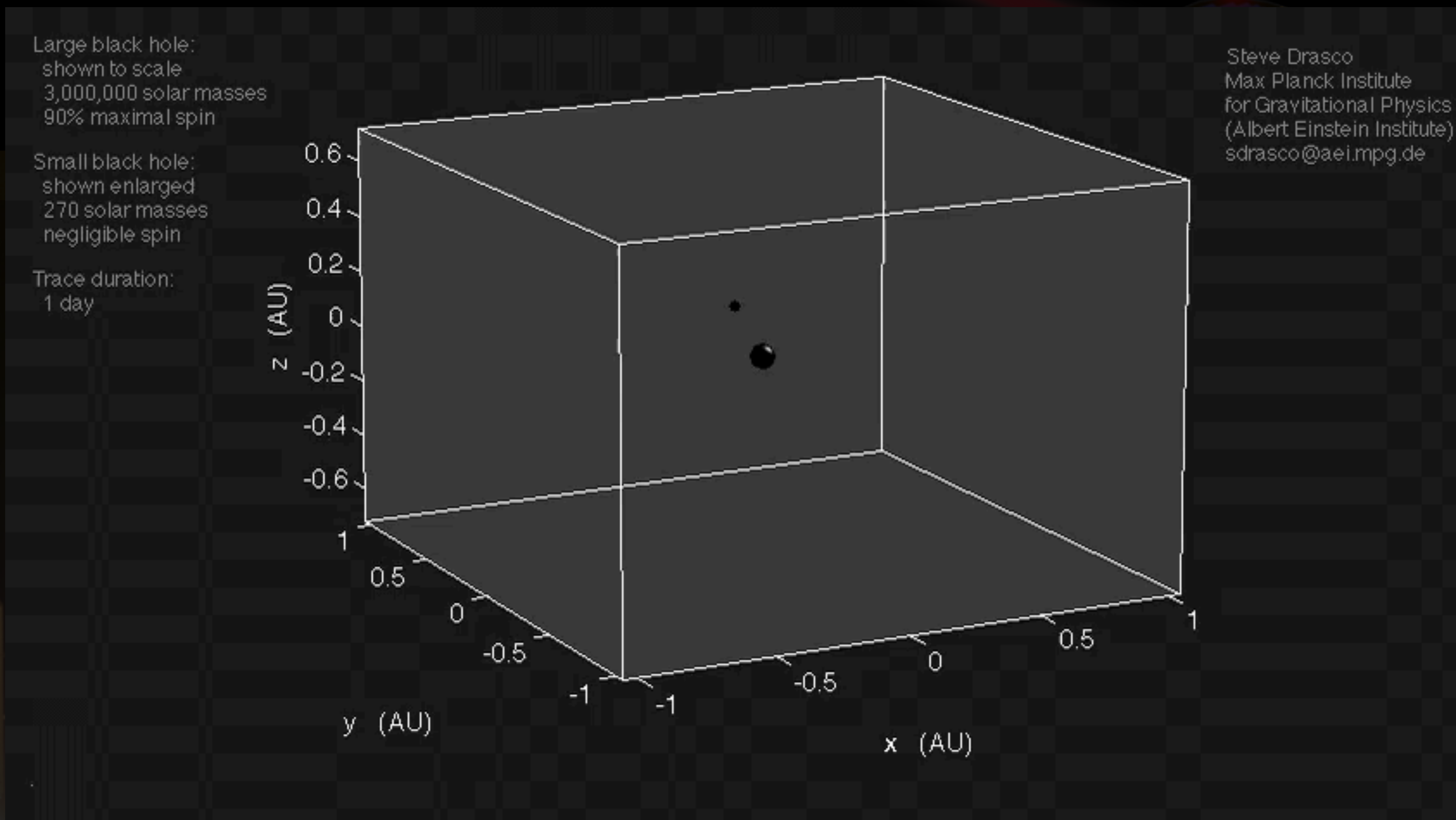
EMRIs

- Capture of a "small" object by massive black hole ($10 – 10^6\ M_{Sun}$)
  - Mass ratio > 200
  - GW gives information on the geometry around the black hole.
  - Test General Relativity in stong field
  - Frequency : 0.1 mHz to 0.1 Hz
  - Large number of source could be observed by space-based interferometer



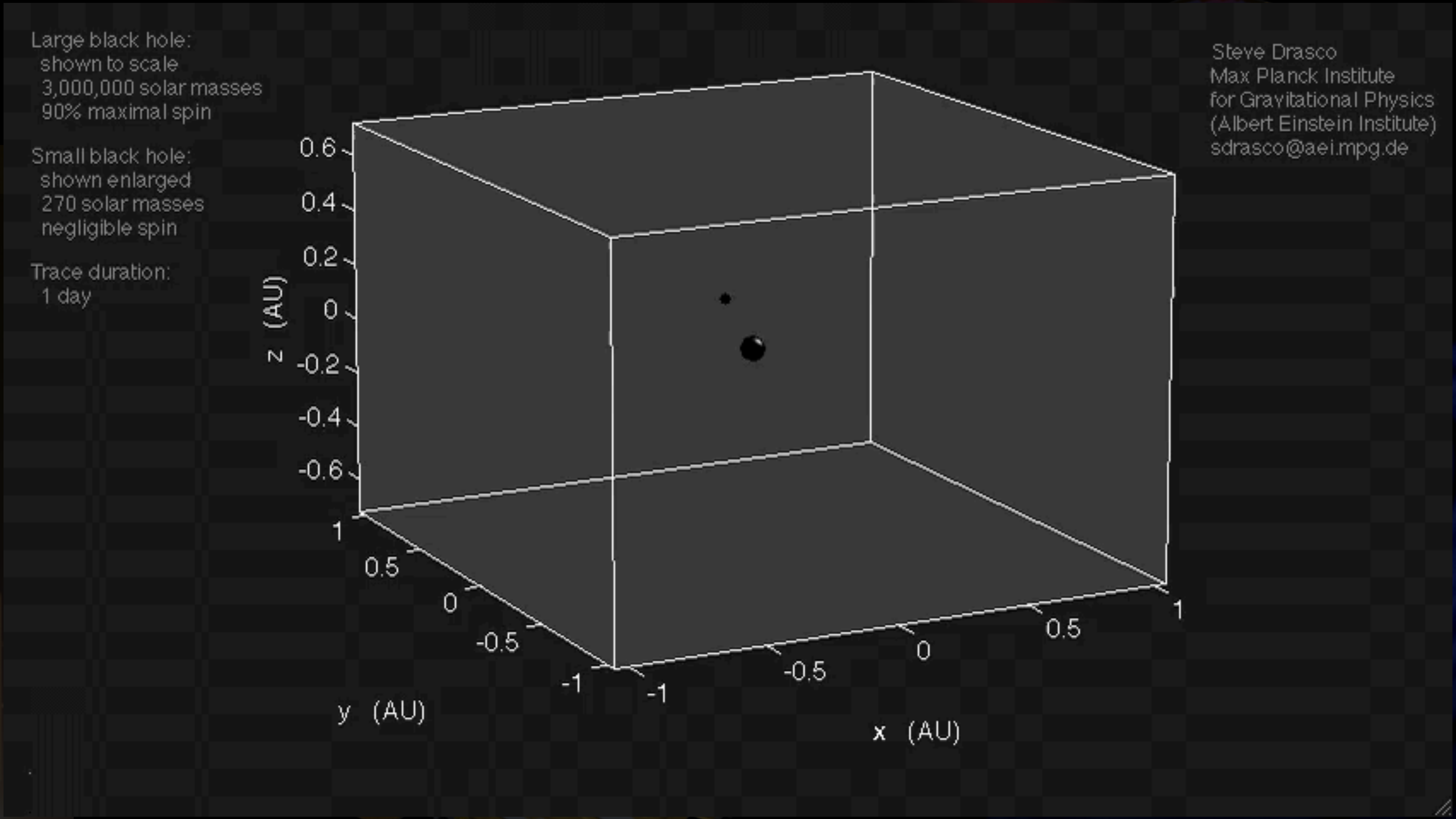
EMRIs

- Extreme Mass Ratio Inspiral: small compact objects (10 M_{Sun}) orbiting around a SuperMassive Black Hole



EMRIs

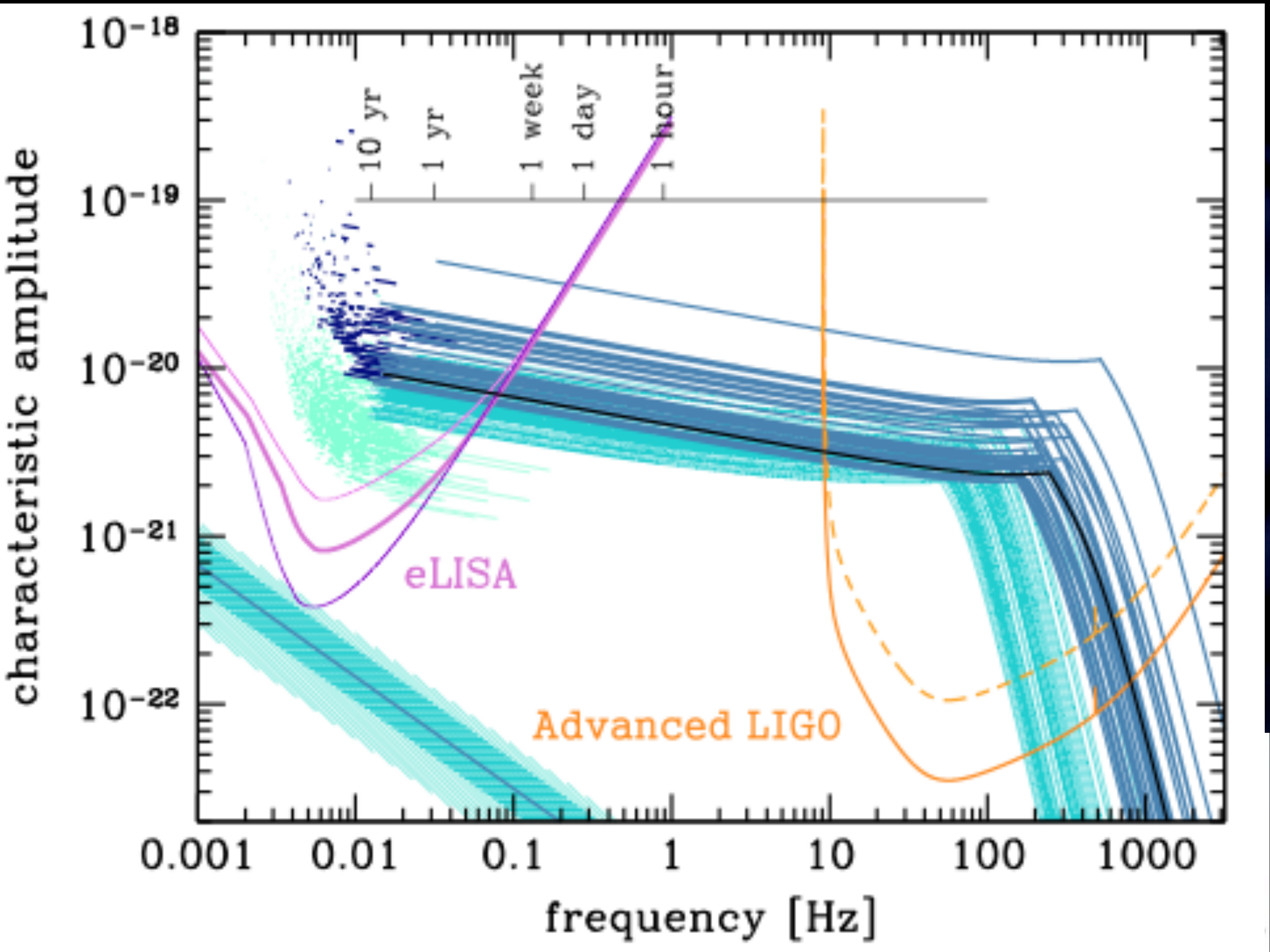
- Extreme Mass Ratio Inspiral: small compact objects (10 M_{Sun}) orbiting around a SuperMassive Black Hole



Black Hole Binaries

- LIGO/Virgo-type sources: binaries with 2 black holes of few tens solar masses.

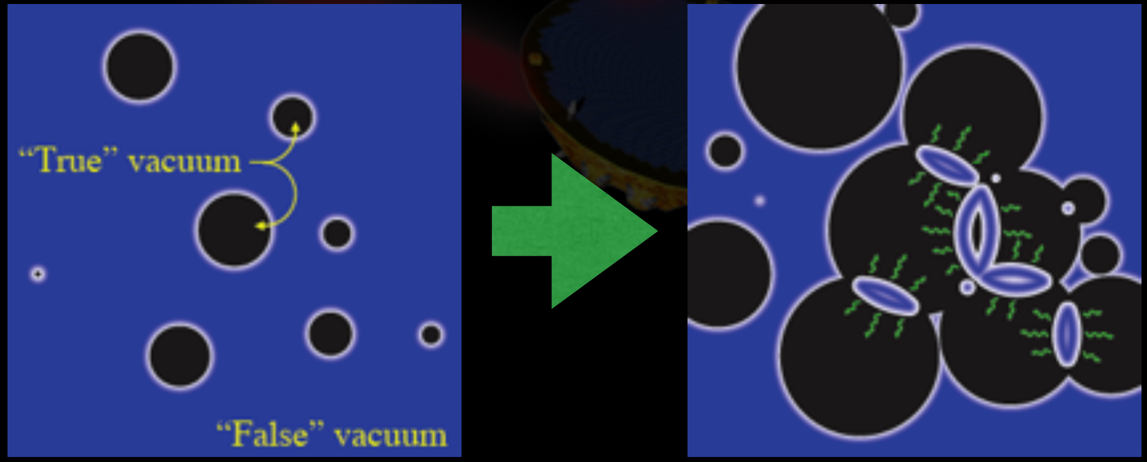
- During most part of the inspiral time, emission in the mHz band
  => multi-observatories GW astronomy

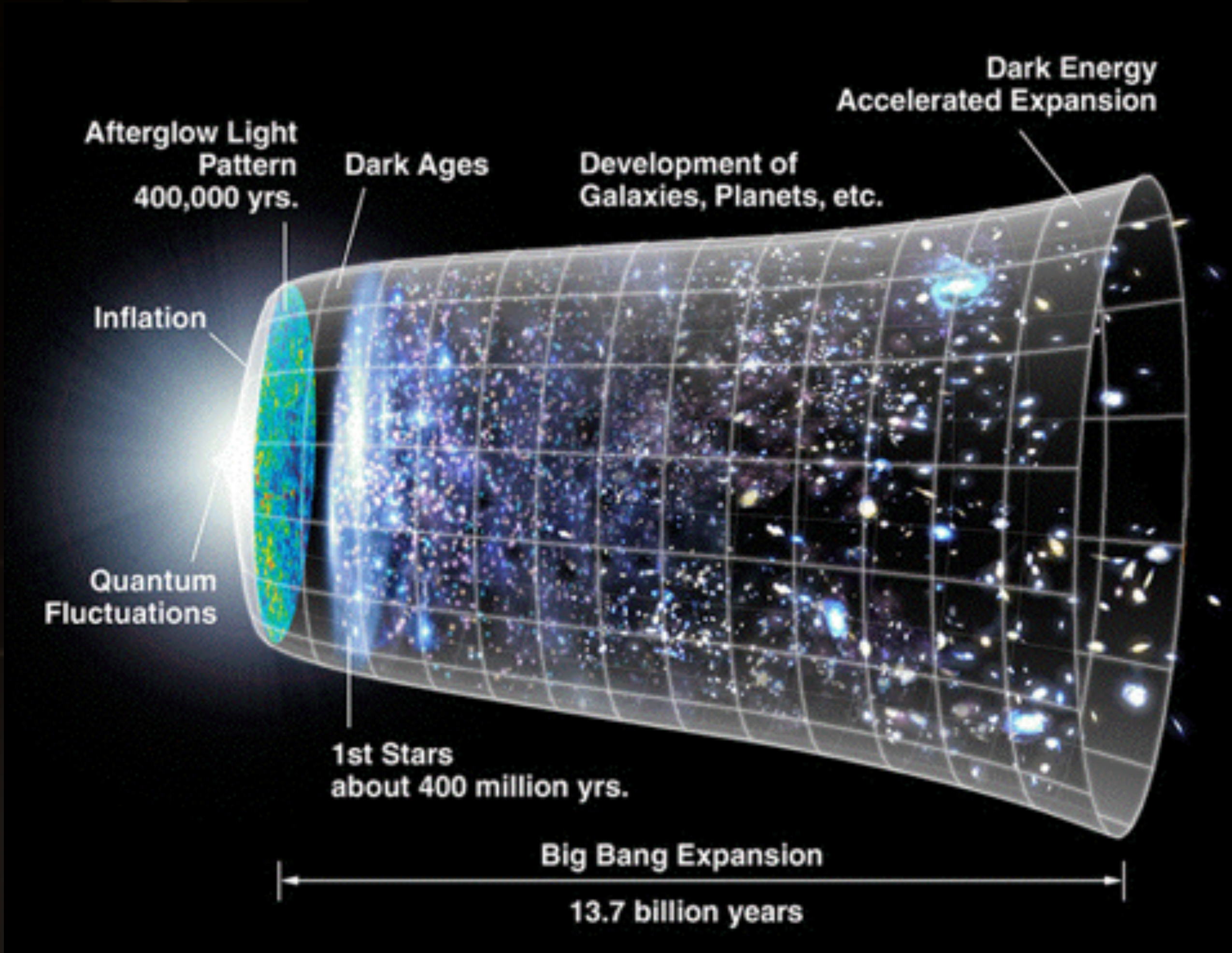


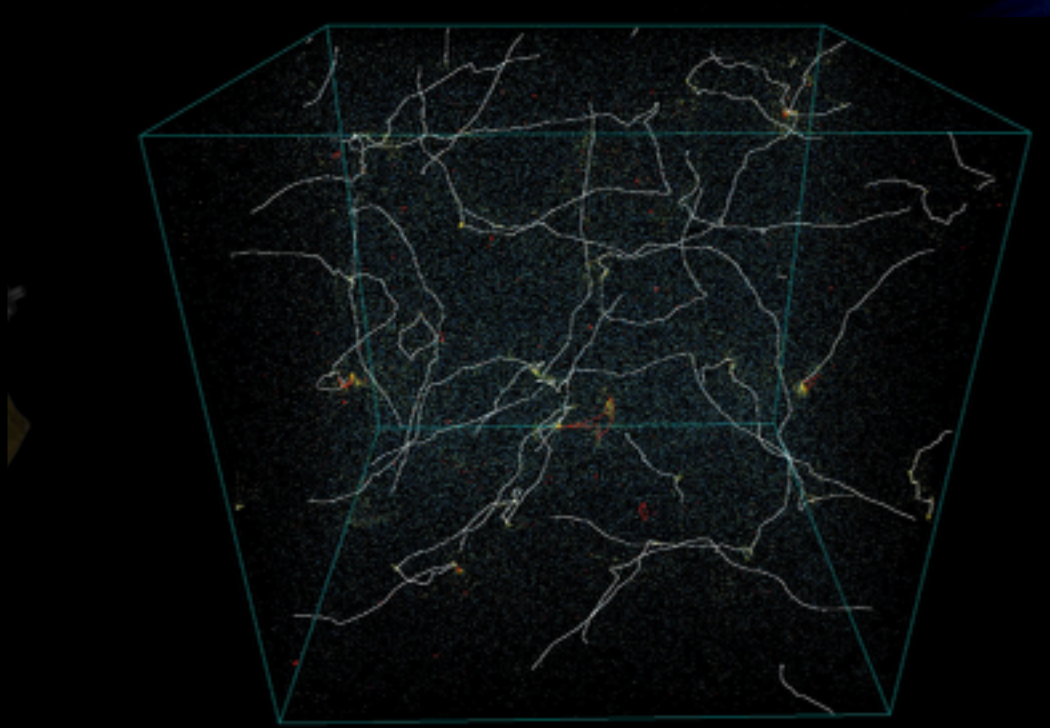
A. Sesana, PRL 116, 231102 (2016)

Cosmological backgrounds

- Variety of cosmological sources for stochastic background :
  - First order phase transition in the very early Universe
  - Cosmic strings network
  - …







Unknown sources

- High potential of discovery in the mHz GW band ?

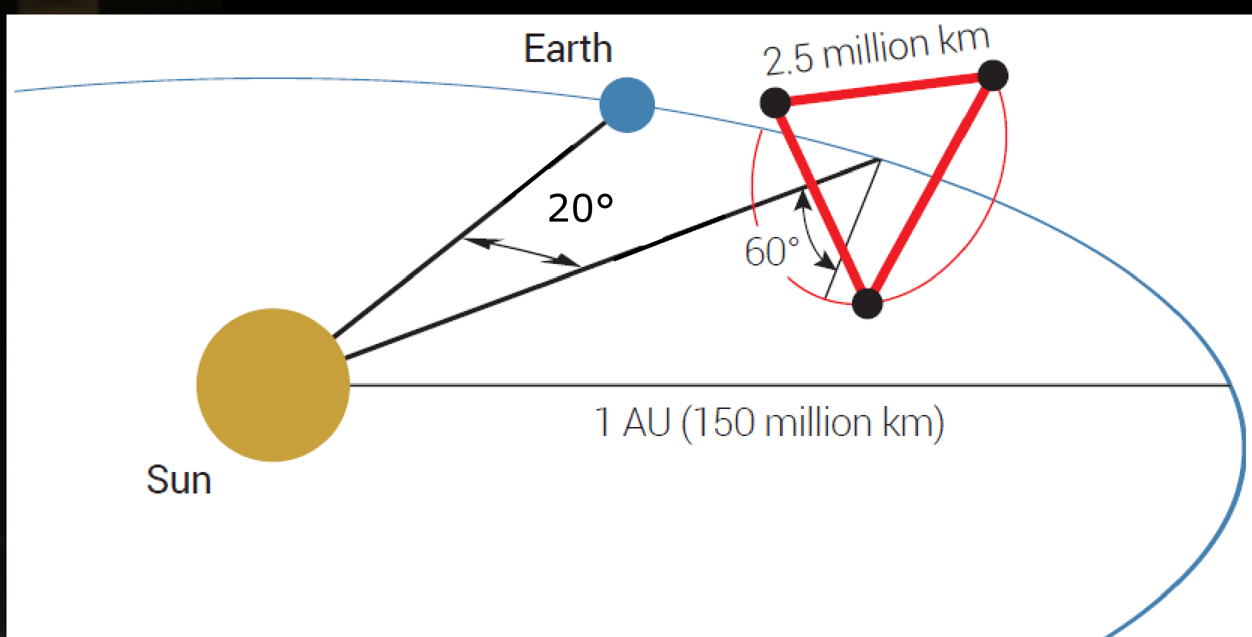
What can we learn ?

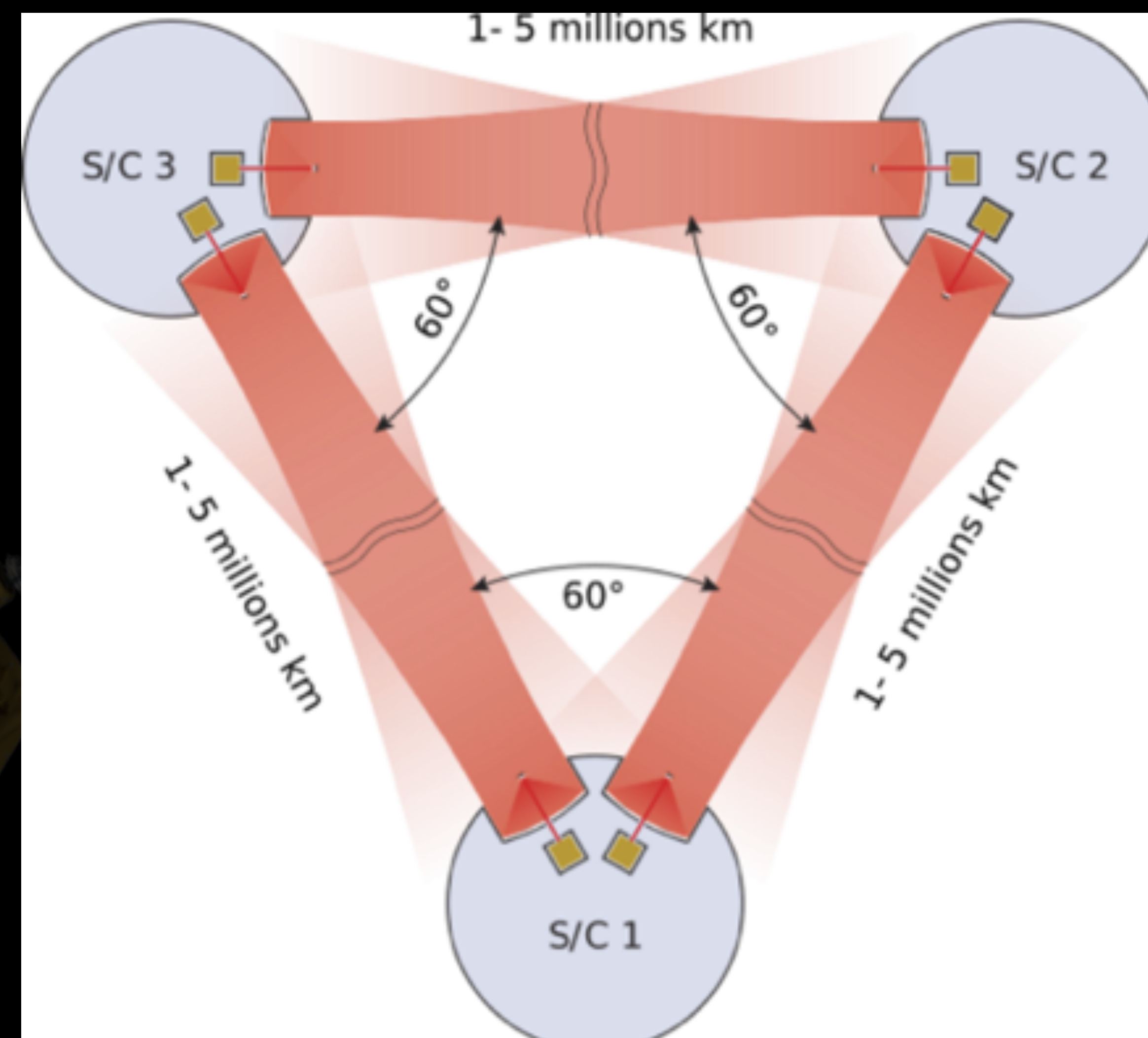
- The nature of gravity (testing the basis of general relativity)
- Fundamental nature of black hole: existence of horizon, ...
- Black holes as a source of energy,
- Nonlinear structure formation: seed, hierarchical assembly, accretion,
- Understanding the end of the life of massive stars,
- Dynamic of galactic nuclei,
- The very early Universe: Higgs TeV physics, topological defects, ...
- Constraining cosmological models,
- ...

=> Expand the new observational window on the Universe (with all the unexpected !): looking at dark side of the Universe !

LISA

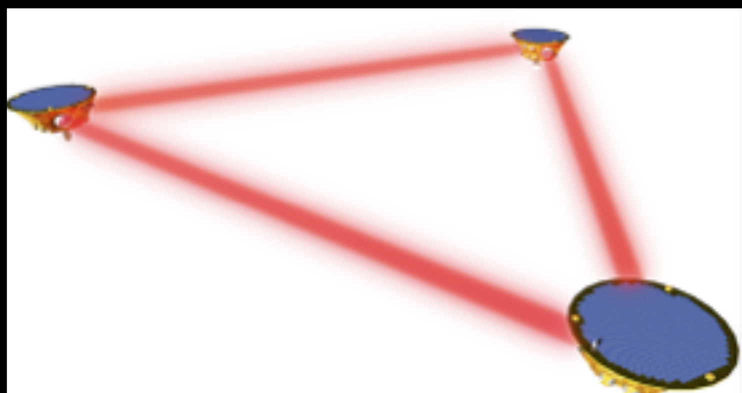
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of 10^{-21}: few picometers





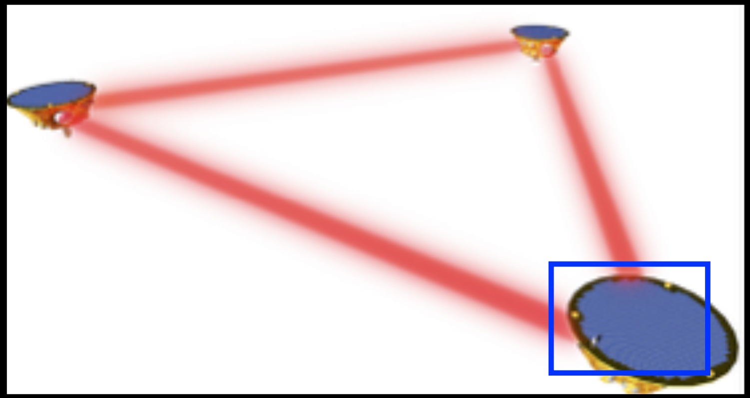
LISA

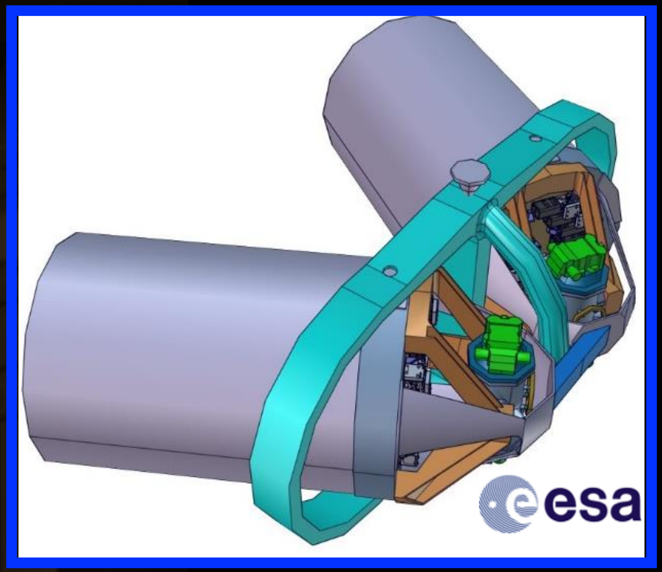
- Interferometric measurements in several steps:



LISA

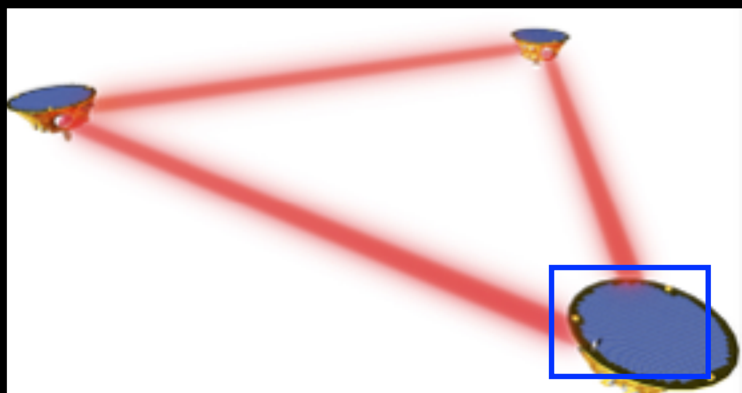
- Interferometric measurements in several steps:

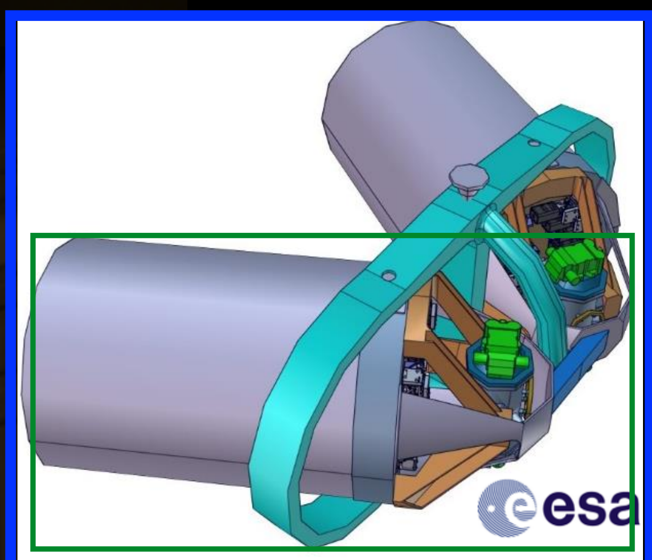


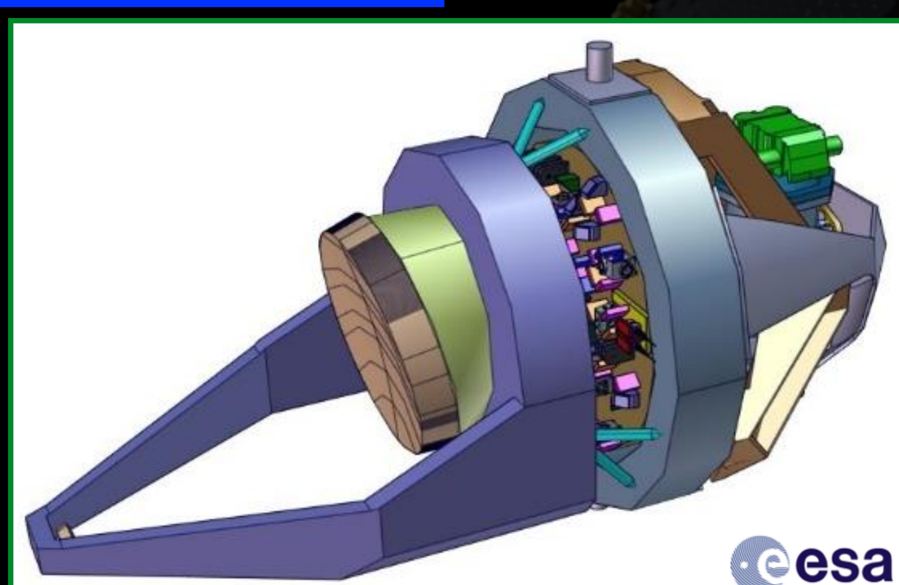


LISA

- Interferometric measurements in several steps:

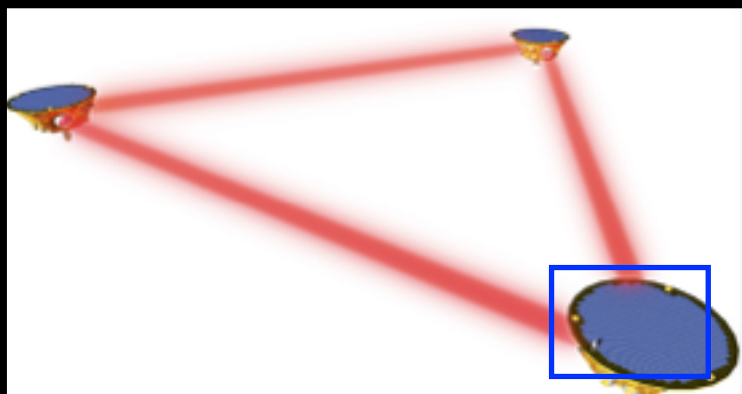


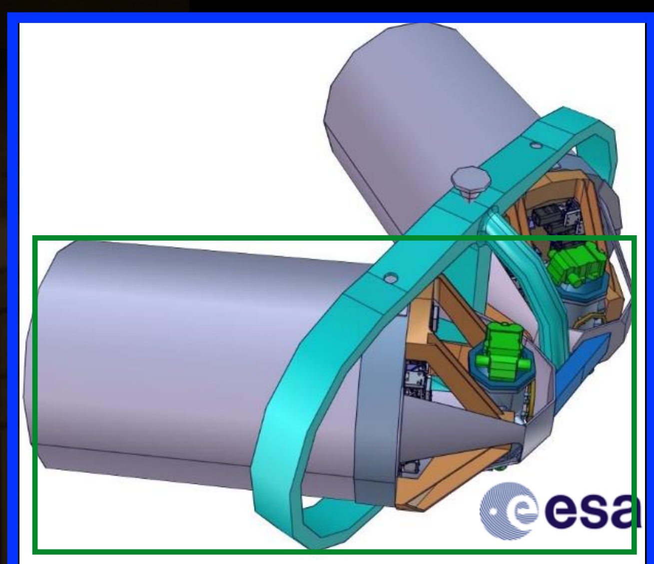


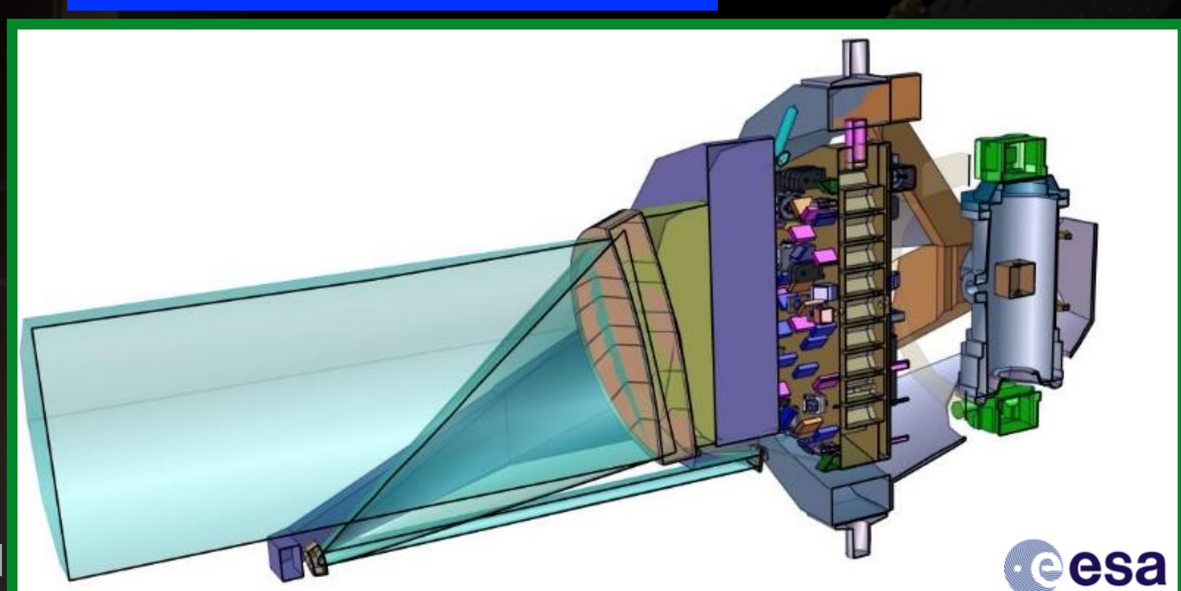


LISA

- Interferometric measurements in several steps:

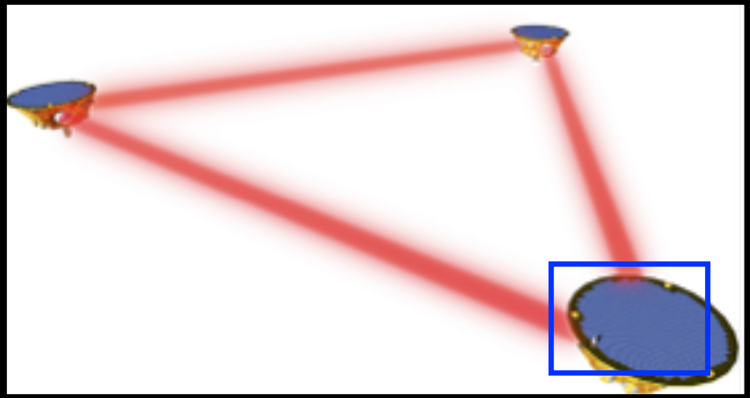


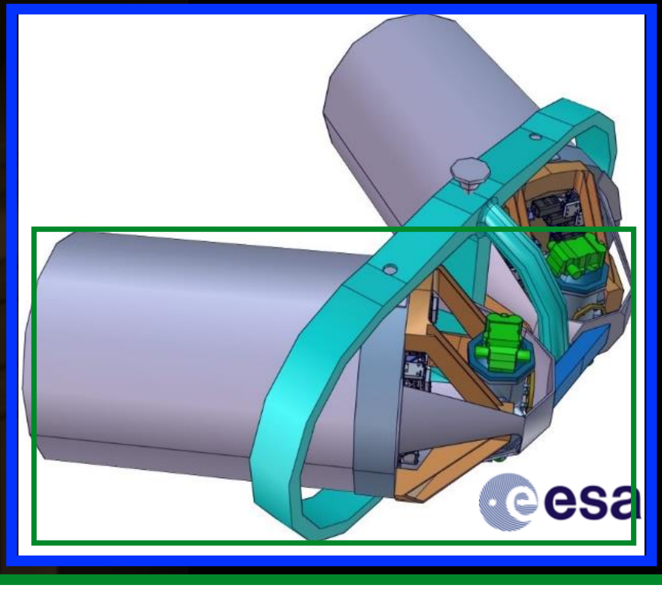


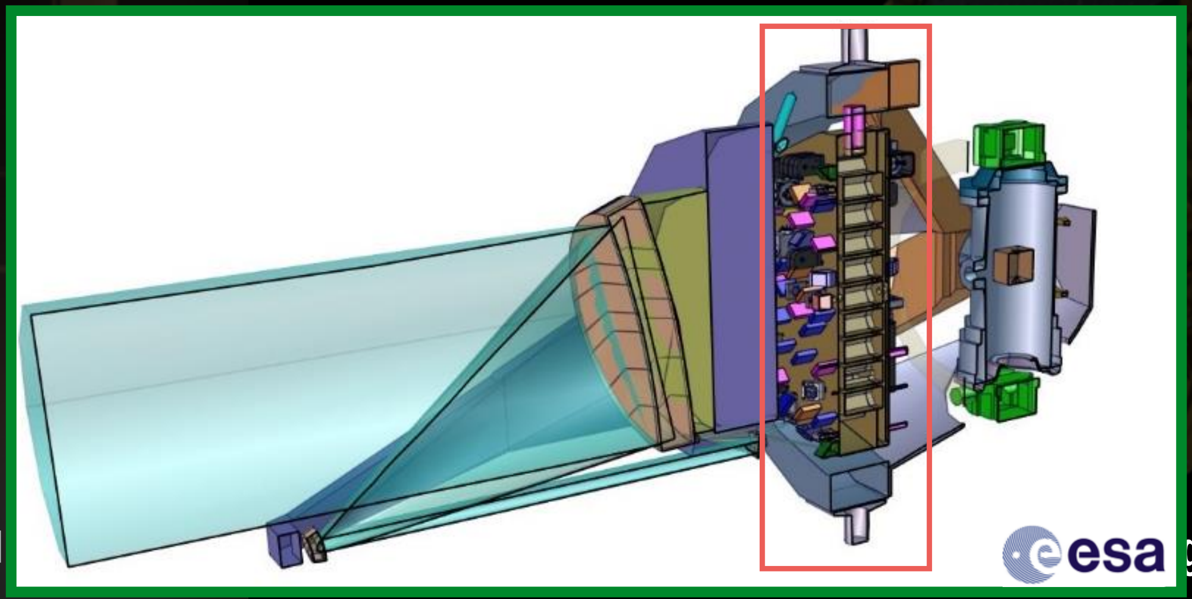


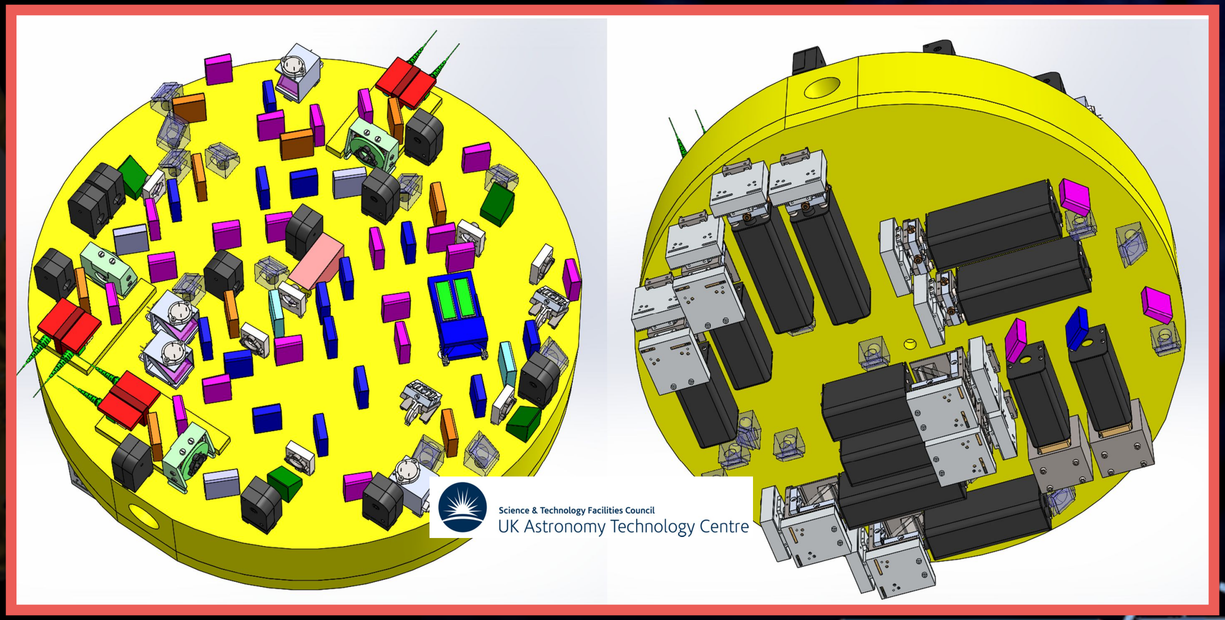
LISA

- Interferometric measurements in several steps:



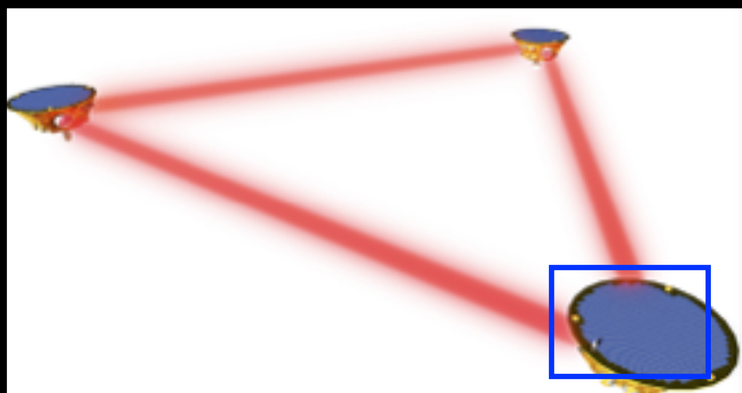




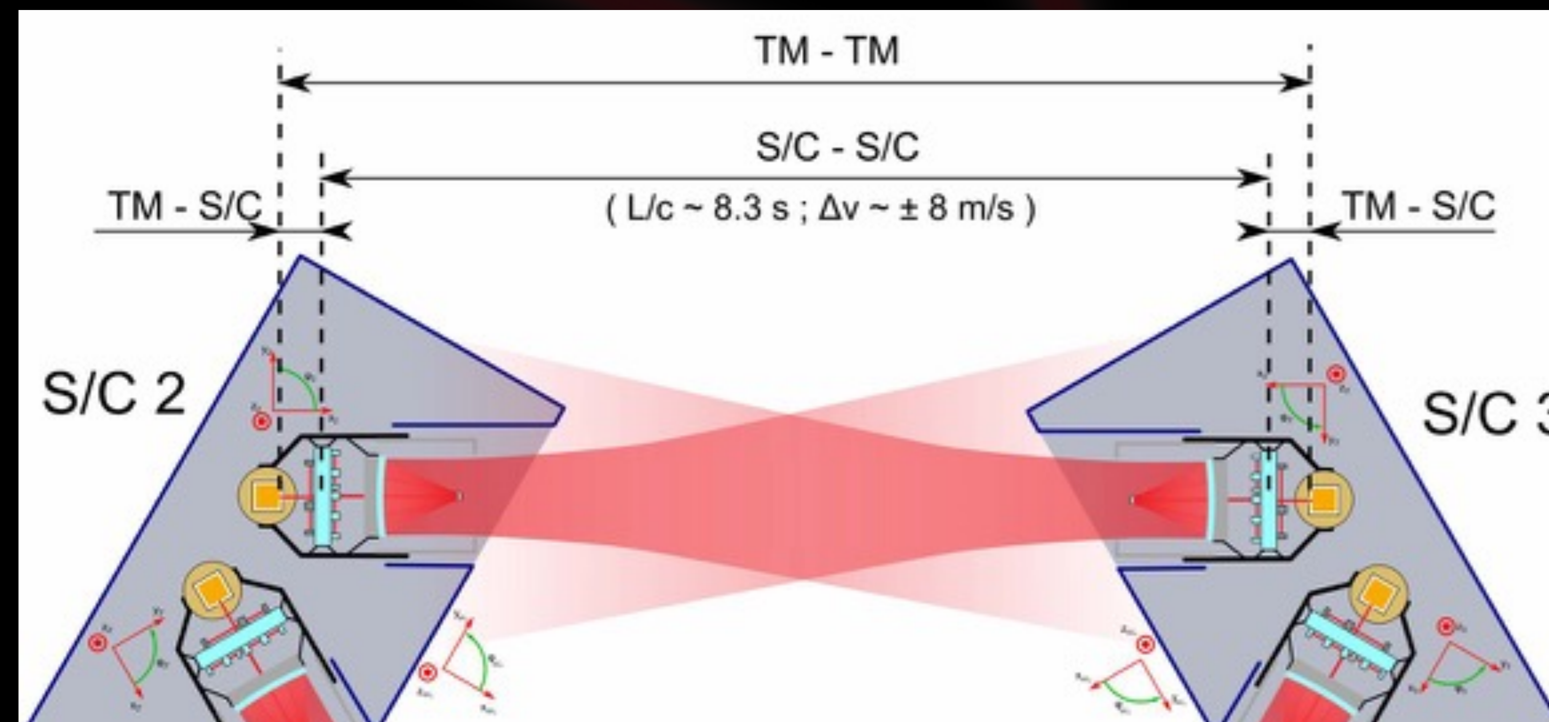


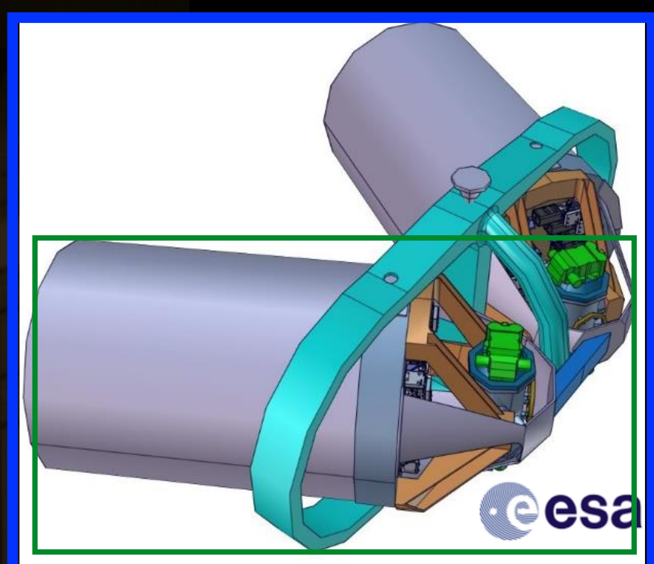
LISA

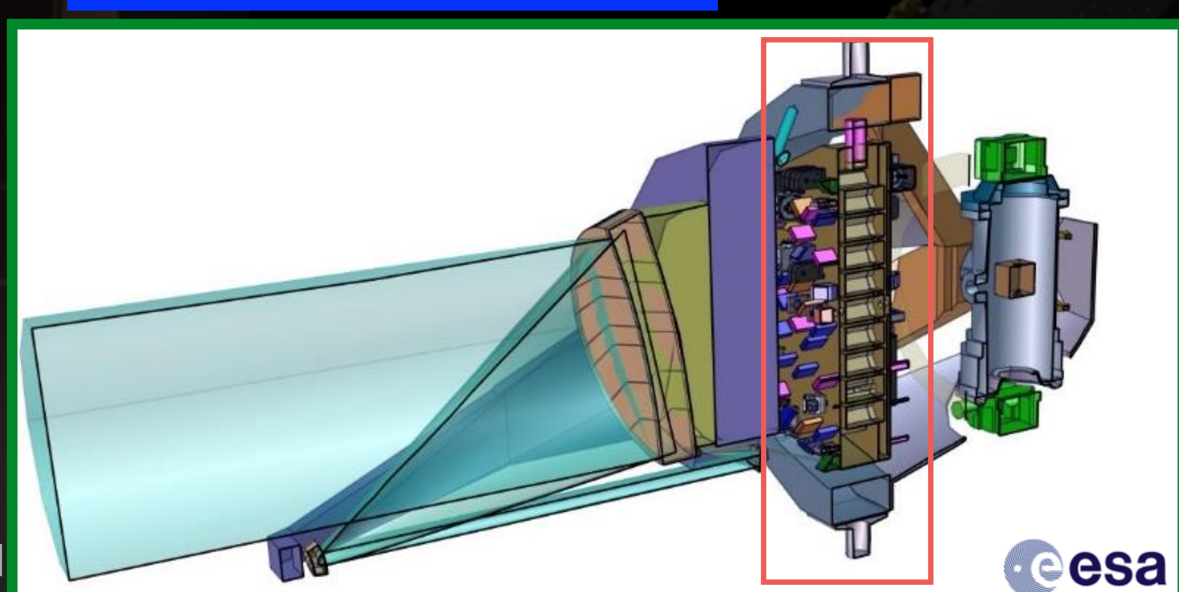
- Interferometric measurements in several steps:

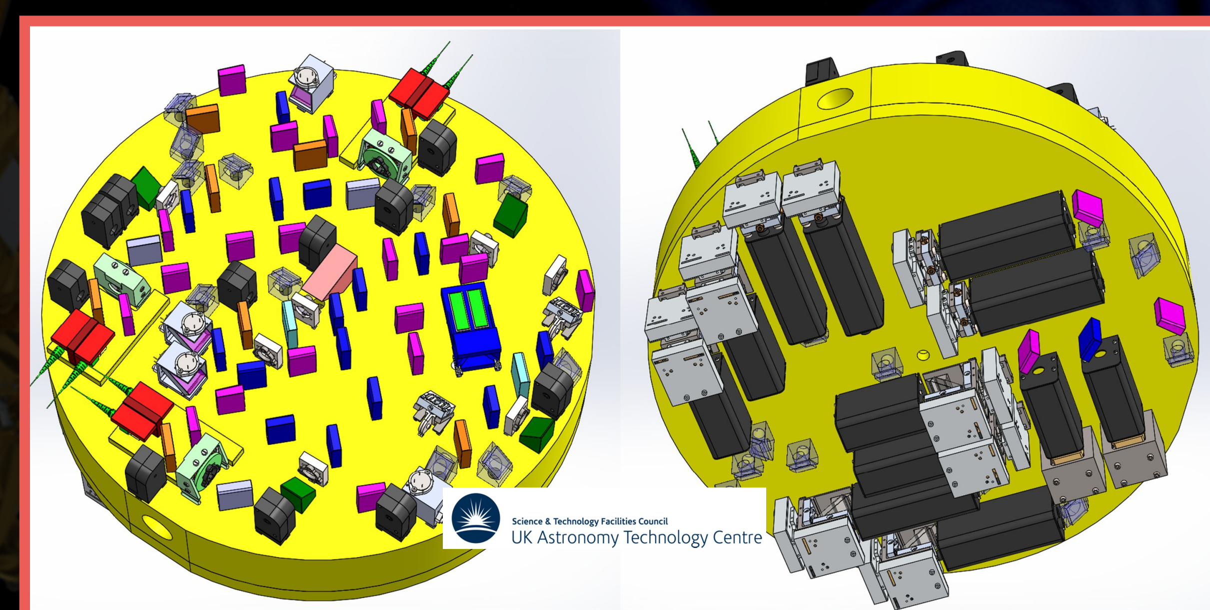


$$(\mathrm{TM2}\rightarrow\mathrm{SC2}) + (\mathrm{SC2}\rightarrow\mathrm{SC3}) + (\mathrm{SC3}\rightarrow\mathrm{TM3})$$



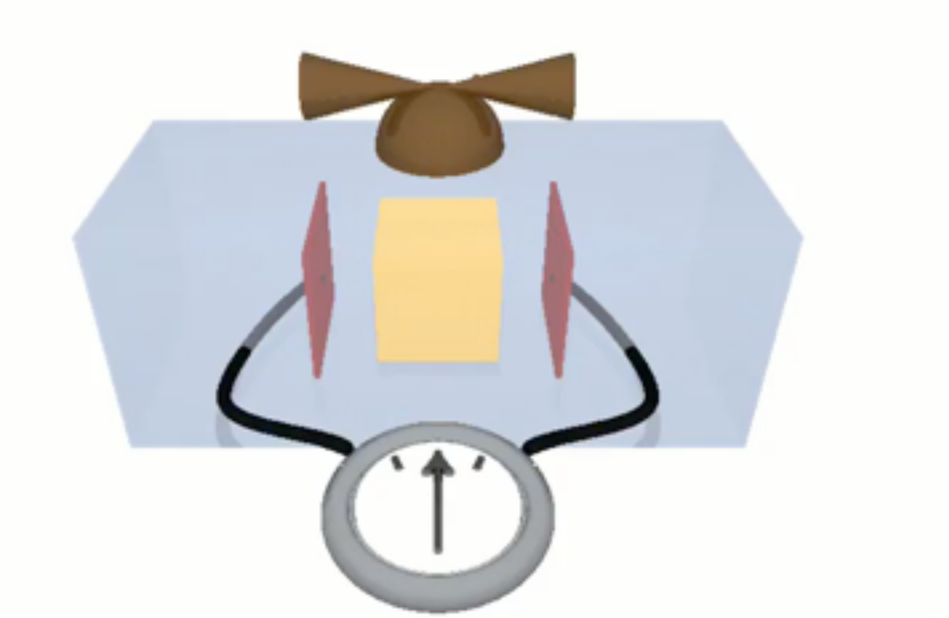


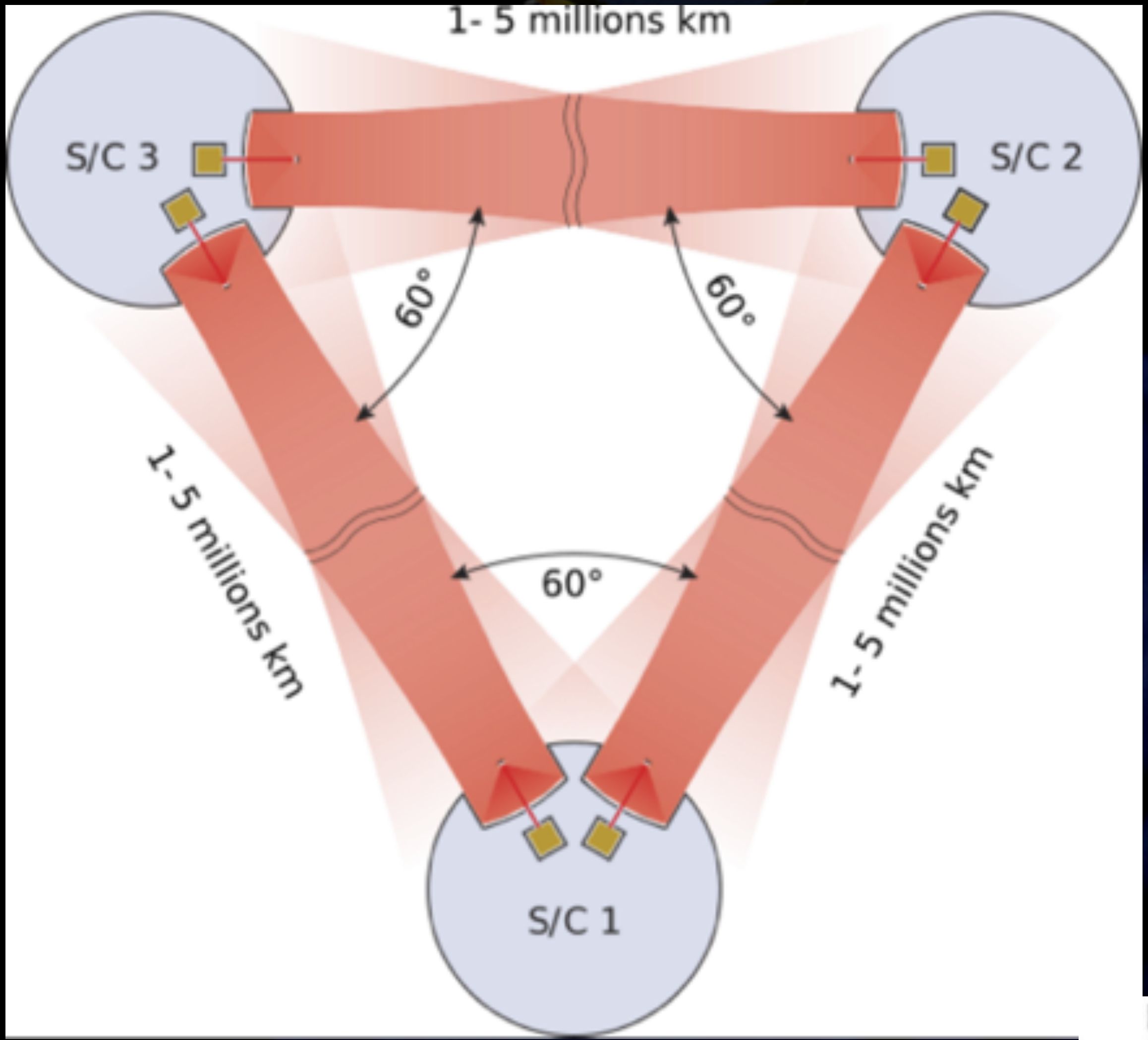




LISA

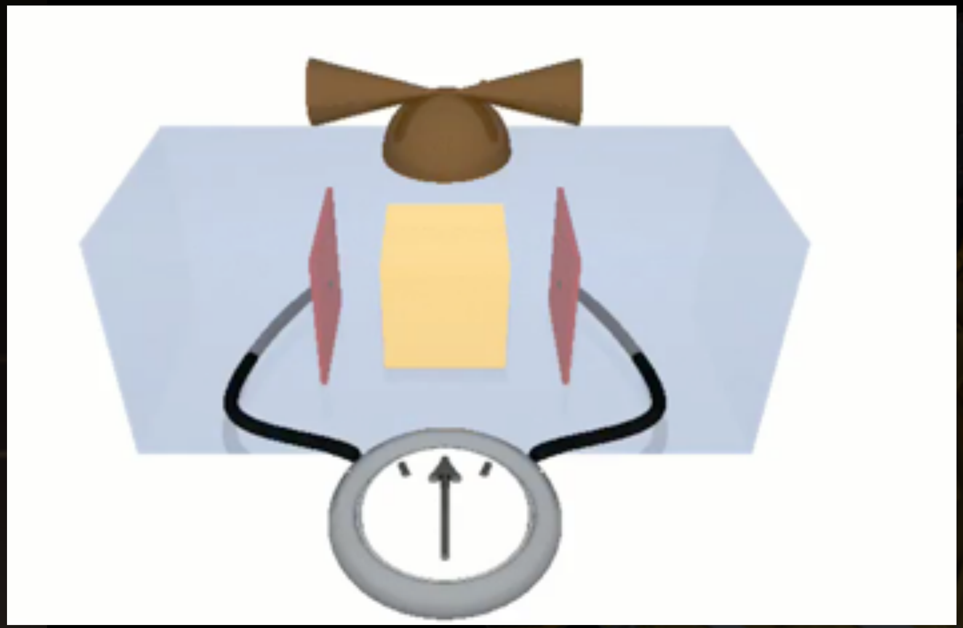
- Spacecraft (SC) should only be sensible to gravity:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing

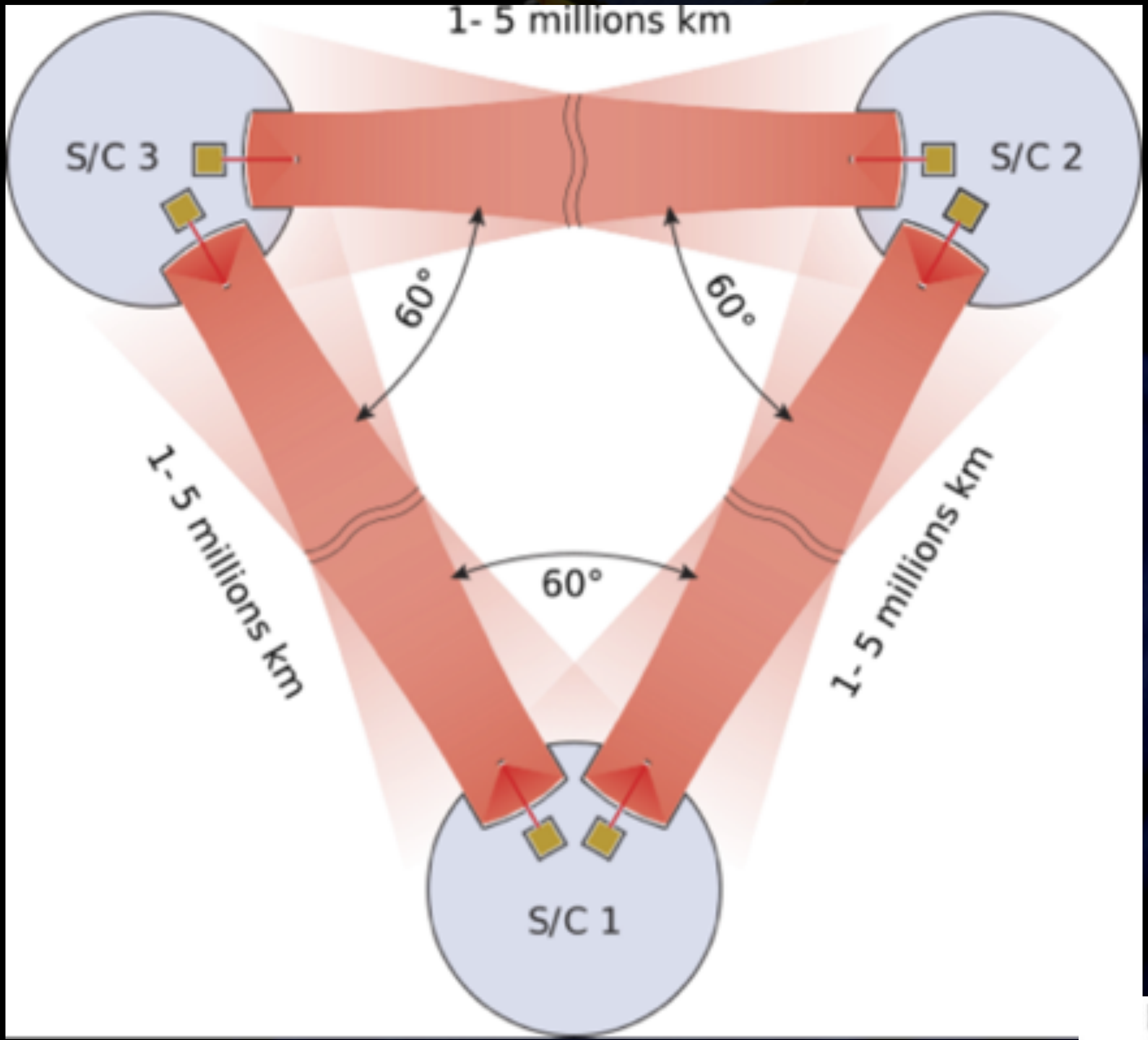




LISA

- 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

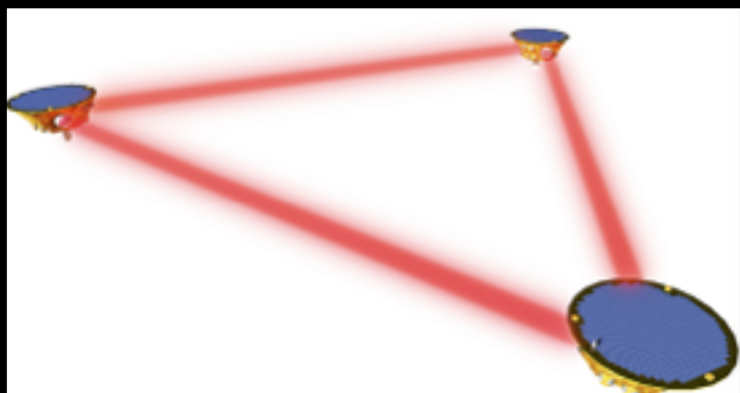


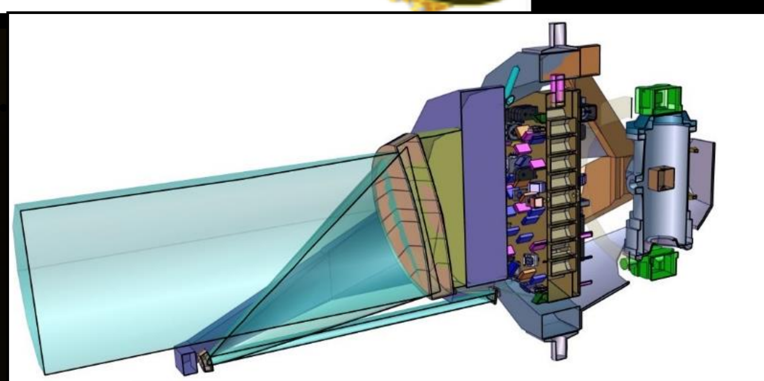


LISAPathfinder

See talk from Daniele Vetrugno

- Technological demonstrator for LISA

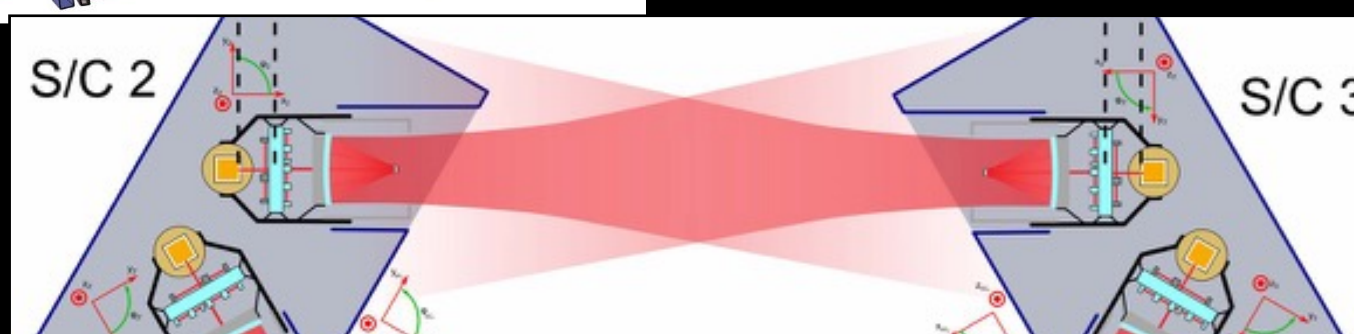


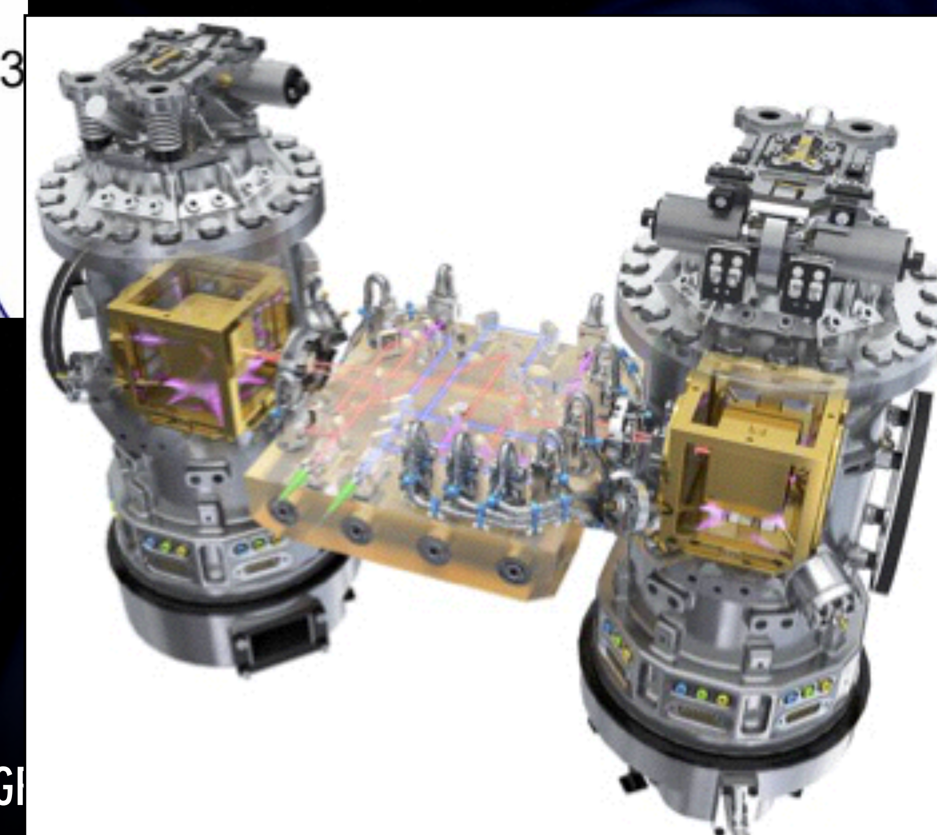


LISA :

- Interferometric measurement along arm 1:

(TM2→SC2) + (SC2→SC3) + (SC3→TM3)



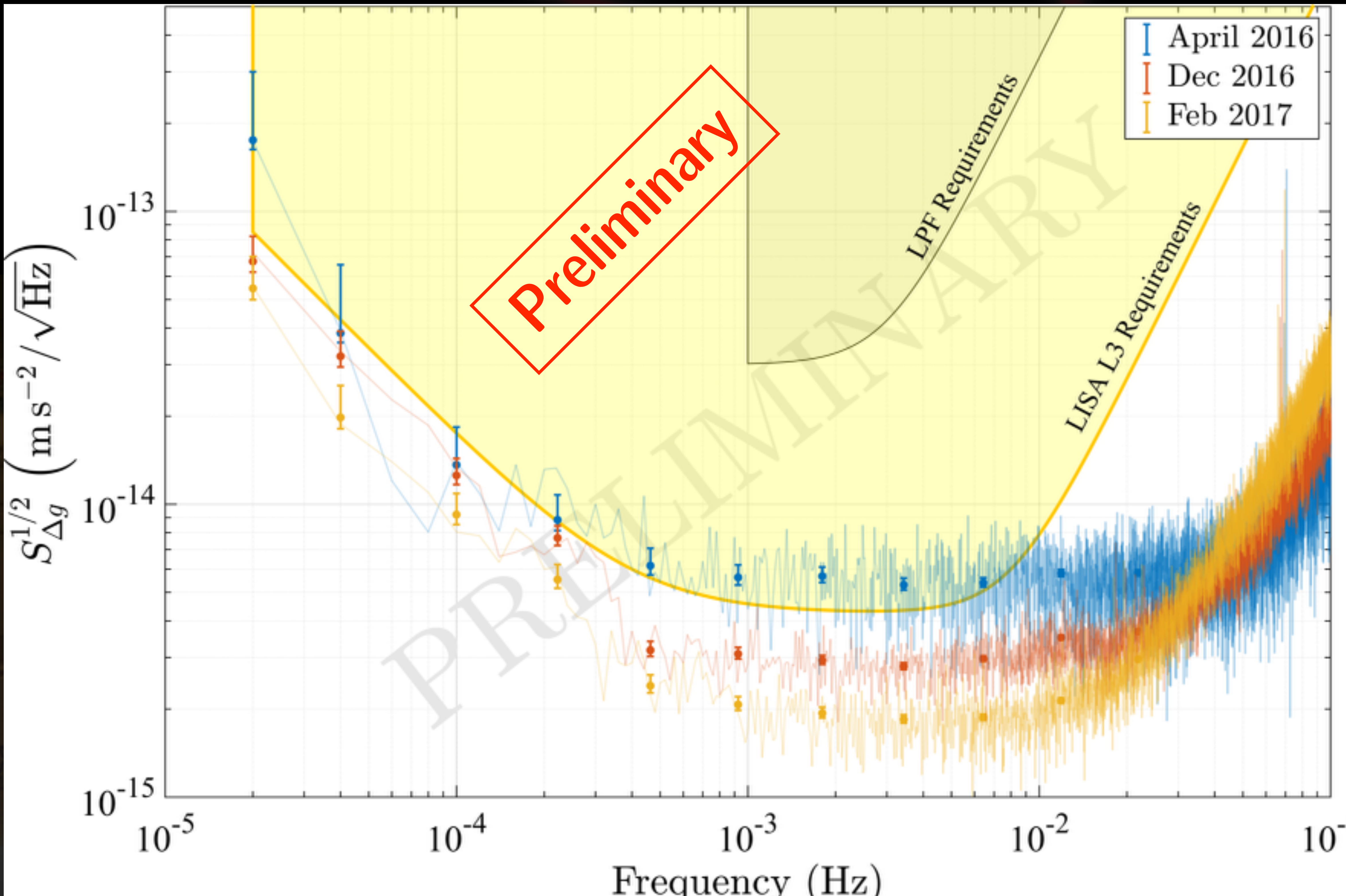


LISAPathfinder :

Reduce distance TM-TM at 37cm

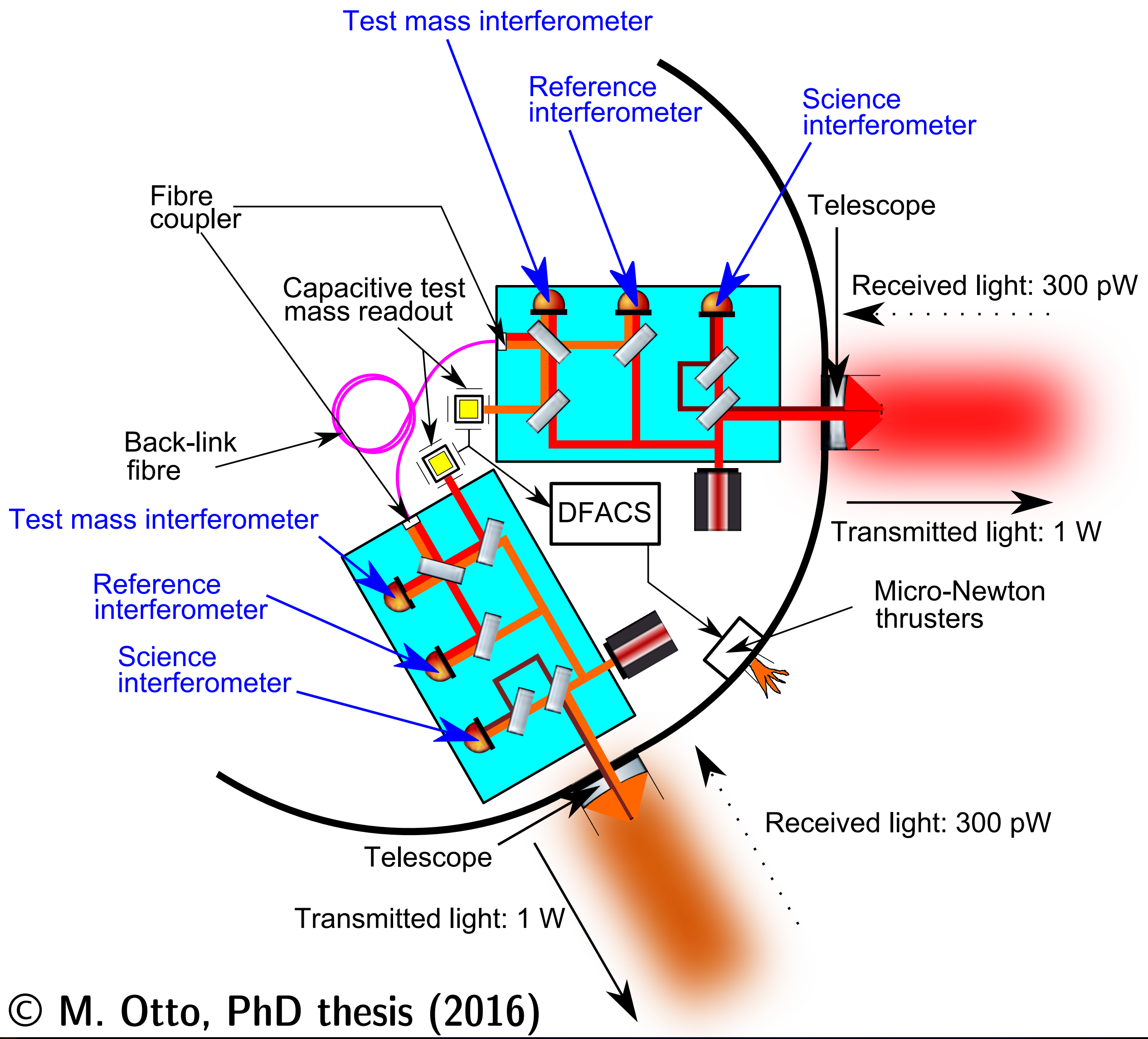
deltaG last measurement

See talk from Daniele Vetrugno



LISA

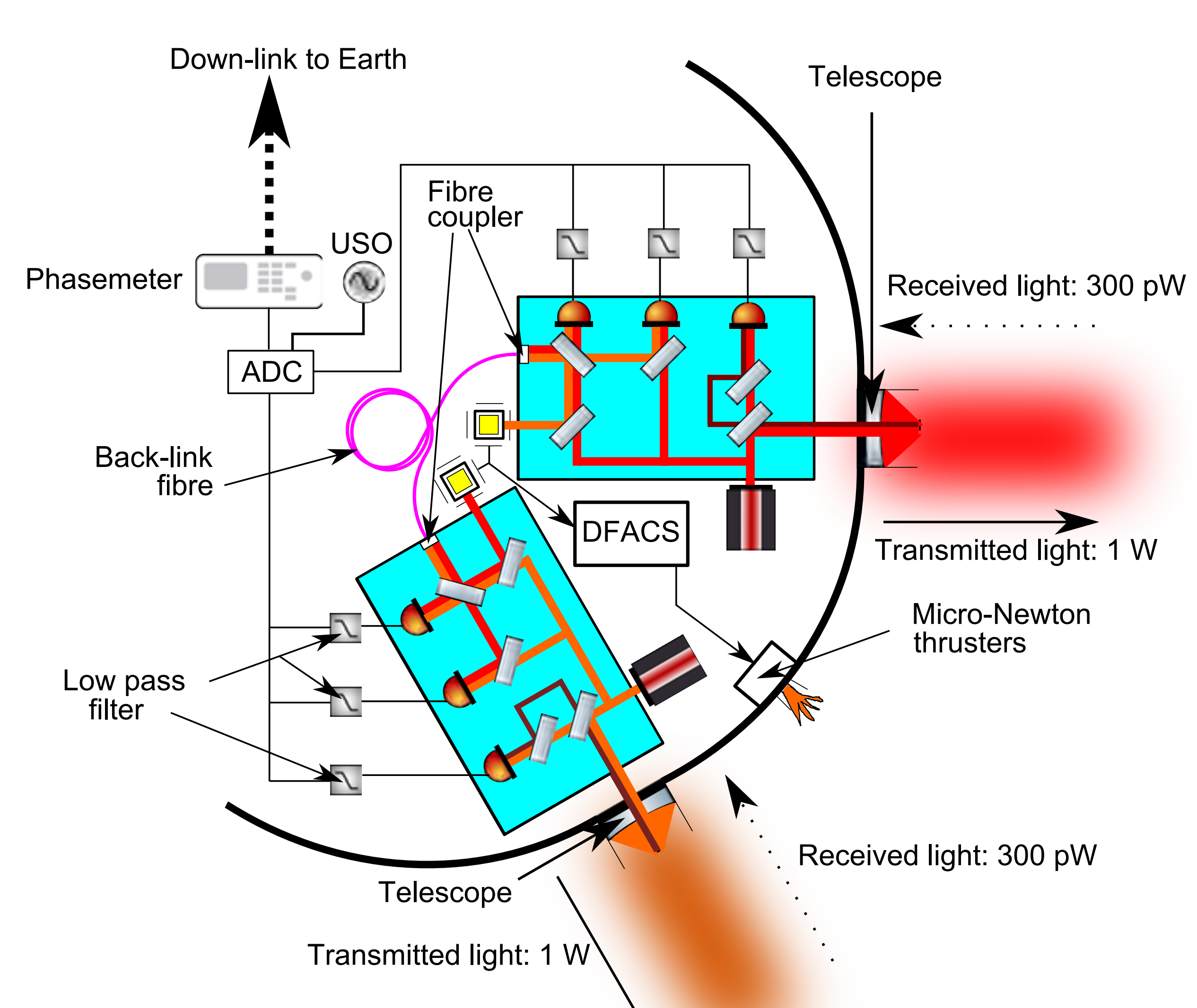
- Exchange of laser beam to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts
- Noises sources:
  - Laser noise : 10^{-13} (vs 10^{-21})
  - Clock noise (3 clocks)
  - Acceleration noise (see LPF)
  - Read-out noises
  - Optical path noises



© M. Otto, PhD thesis (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
  - Optical path noises

LISA technology requirements

- Free flying test mass subject to very low parasitic forces:
  - Drag free control of spacecraft (non-contacting spacecraft)
  - Low noise microthruster to implement drag-free
  - Large gaps, heavy masses with caging mechanism
  - High stability electrical actuation on cross degrees of freedom
  - Non contacting discharging of test-masses
  - High thermo-mechanical stability of spacecraft
  - Gravitational field cancellation
- Precision interferometric, local ranging of test-mass and spacecraft:
  - pm resolution ranging, sub-mrad alignments
  - High stability monolithic optical assemblies
- Precision million km spacecraft to spacecraft precision ranging:
  - High stability telescopes
  - High accuracy phase-meter
  - High accuracy frequency stabilization

LISA technology requirements

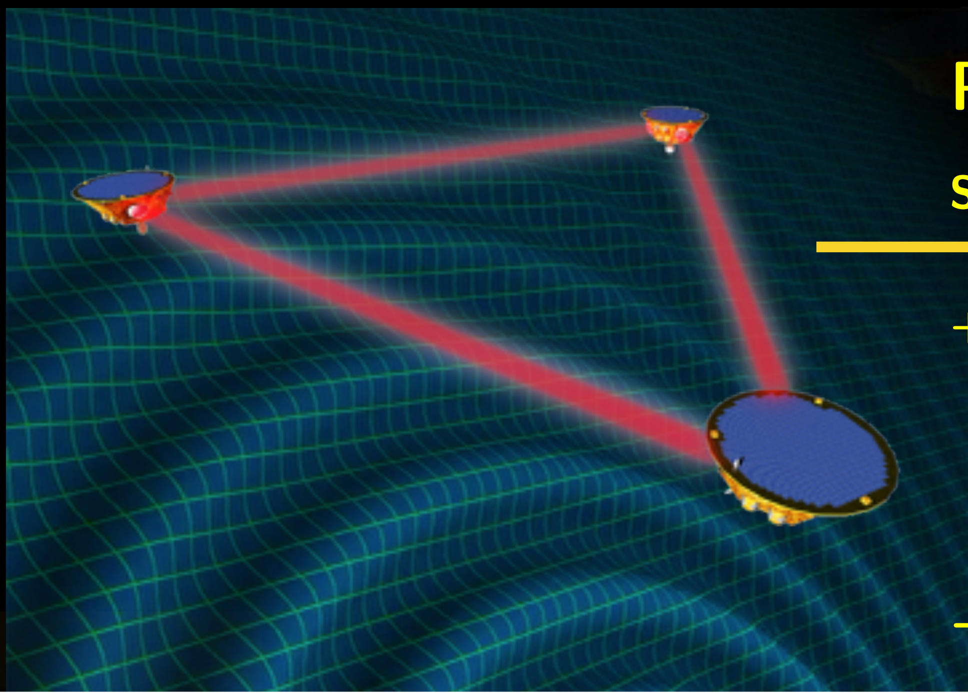
- Free flying test mass subject to very low parasitic forces:
  - ✓ Drag free control of spacecraft (non-contacting spacecraft)
  - ✓ Low noise microthruster to implement drag-free
  - ✓ Large gaps, heavy masses with caging mechanism
  - ✓ High stability electrical actuation on cross degrees of freedom
  - ✓ Non contacting discharging of test-masses
  - ✓ High thermo-mechanical stability of S/C
  - ✓ Gravitational field cancellation

Validated with LISAPathfinder

- Precision interferometric, local ranging of test-mass and spacecraft:
  - ✓ pm resolution ranging, sub-mrad alignments
  - ✓ High stability monolithic optical assemblies
- Precision million km spacecraft to spacecraft precision ranging:
  - ➡ High stability telescopes
  - ➡ High accuracy phase-meter and frequency distribution
  - ➡ High accuracy frequency stabilization (incl. TDI)

Ground-based demonstrators

LISA data



Phasemeters (carrier, sidebands, distance)

+ Gravitational Reference Sensor
+ Auxiliary channels

Corrections, calibrations

Resynchronisation (clocks)

Time-Delay Interferometry laser noise reduction

TDI data : 2 uncorrelated channels

GW data analysis

Catalog of GW sources with extracted waveforms

GW sources

- 10-100/yr SMBHBs
- 10-1000/yr EMRIs
- 60 millions Galactic binaries
- Large number of Black Hole binaries
- Cosmological backgrounds
- Unknown sources

History of LISA

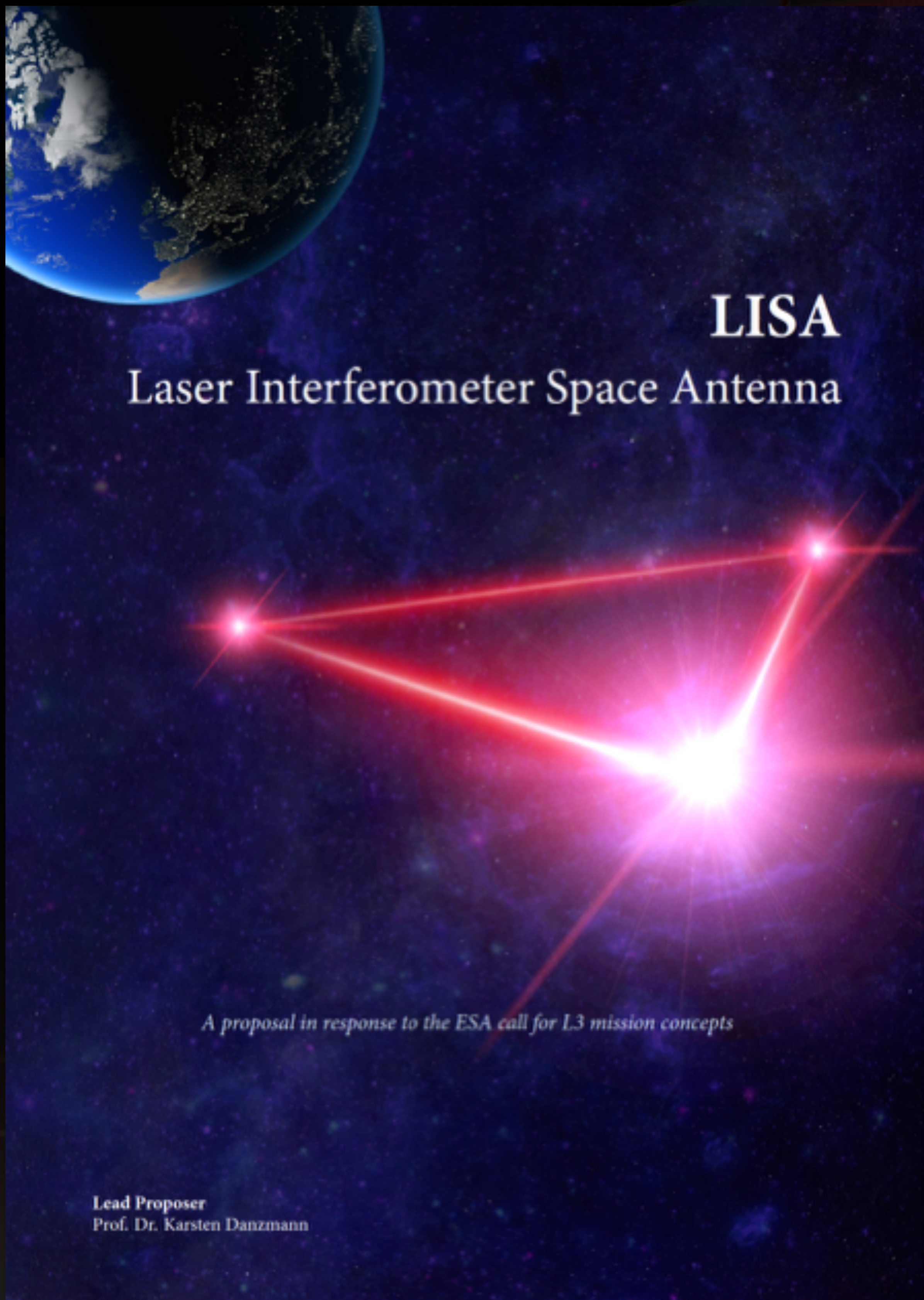
- 1978: first study based on a rigid structure (NASA)
- 1980s: studies with 3 free-falling spacecrafts (US)
- 1993: proposal ESA/NASA: 4 spacecrafts
- 1996-2000: pre-phase A report
- 2000-2010: LISA and LISAPathfinder: ESA/NASA mission
- 2011: NASA stops => ESA continue: reduce mission
- 2012: selection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

History of LISA

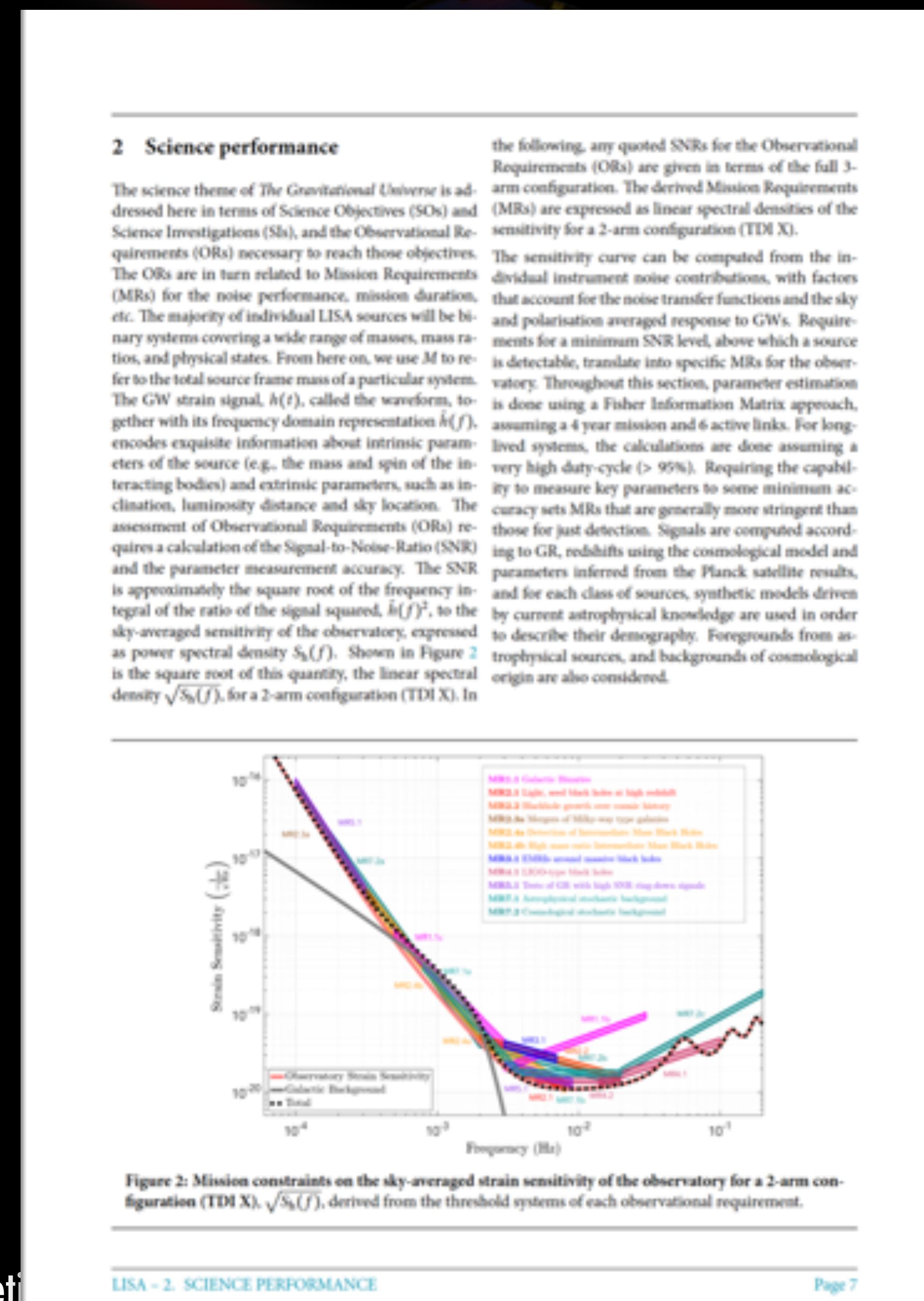
- 1978: first study based on a rigid structure (NASA)
- 1980s: studies with 3 free-falling spacecrafts (US)
- 1993: proposal ESA/NASA: 4 spacecrafts
- 1996-2000: pre-phase A report
- 2000-2010: LISA and LISAPathfinder: ESA/NASA mission
- 2011: NASA stops => ESA continue: reduce mission
- 2012: selection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

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

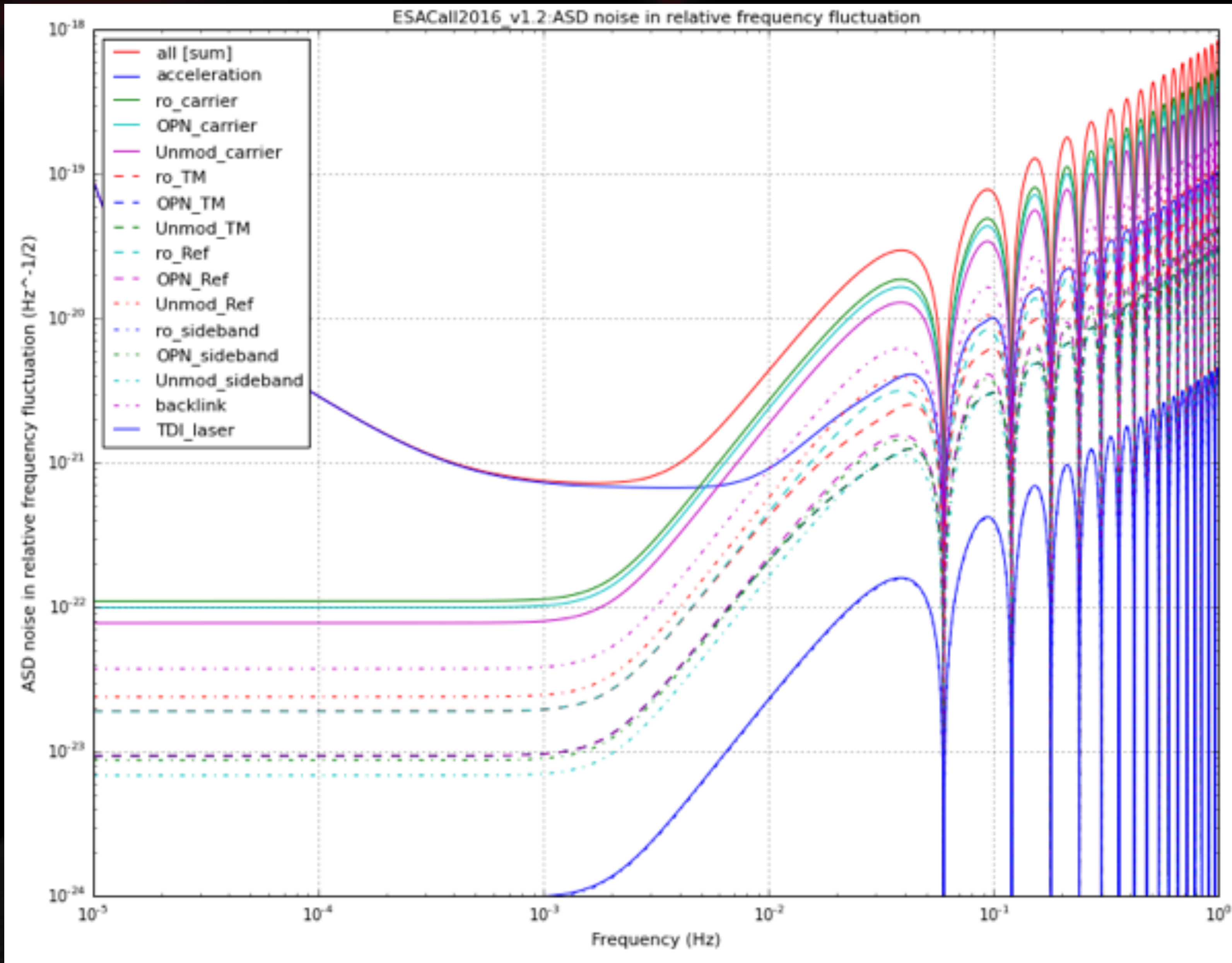
LISA science objectives

- 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 concept in the proposal

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

$$\begin{array}{ll} 100\,\mu\mathrm{Hz} \le f \le 0.1\,\mathrm{Hz} & \text{req.} \\ 20\,\mu\mathrm{Hz} \le f \le 1\,\mathrm{Hz} & \text{goal} \end{array}$$



- Noise budget:
  - Acceleration => LISAPathfinder

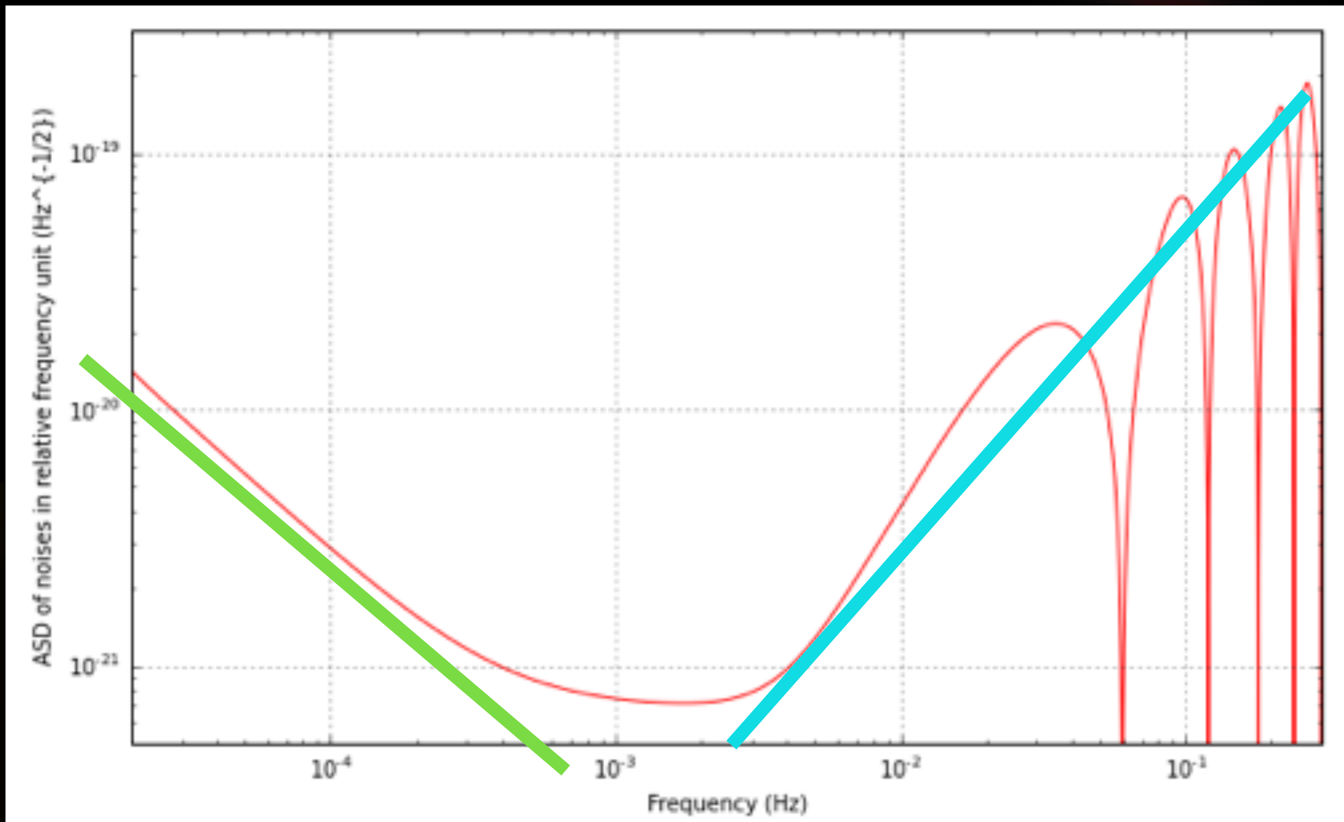
$$S_a^{1/2} \le 3 \cdot 10^{-15} \frac{\mathrm{m\,s^{-2}}}{\sqrt{\mathrm{Hz}}} \cdot \sqrt{1+\left(\frac{0.4\,\mathrm{mHz}}{f}\right)^2} \cdot \sqrt{1+\left(\frac{f}{8\,\mathrm{mHz}}\right)^4}$$

  - Interferometric Measurement System

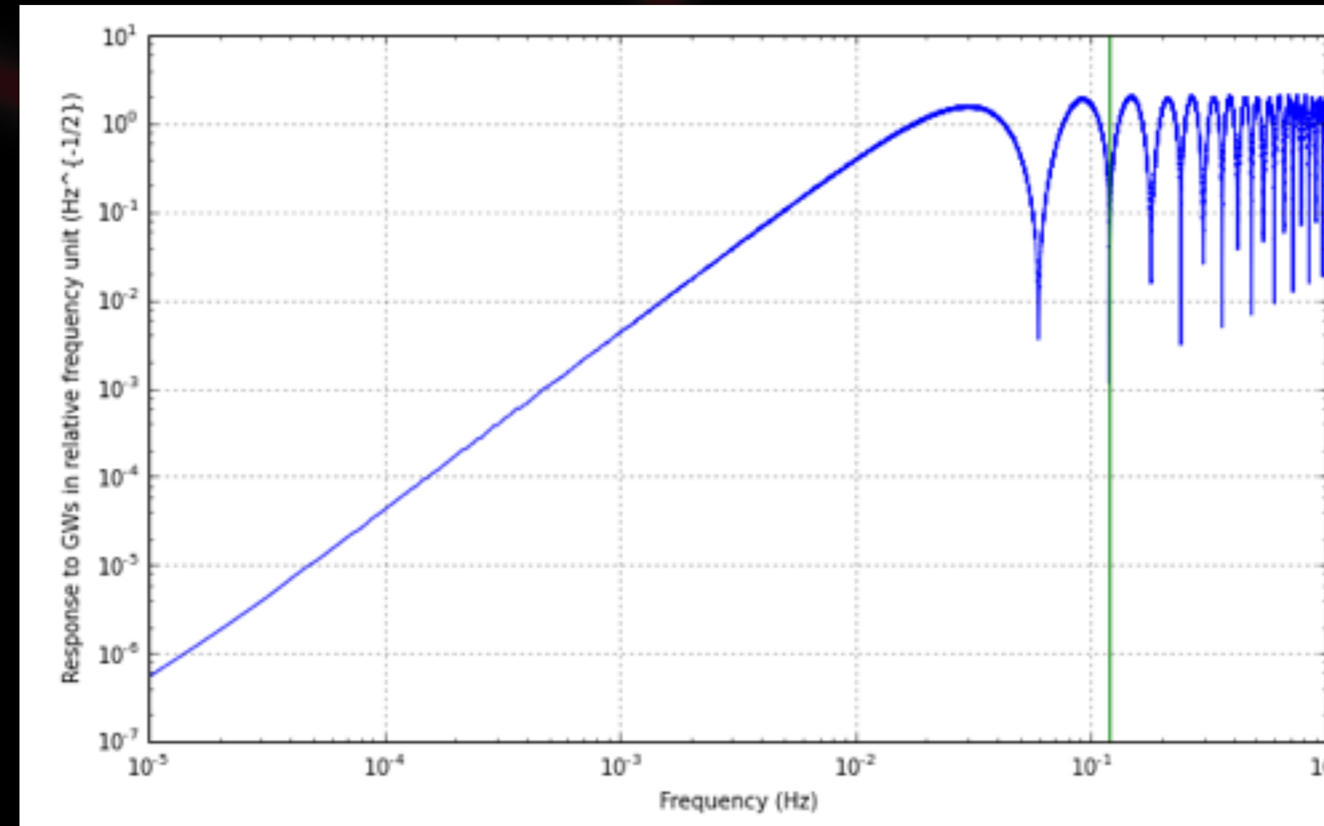
$$S_{\mathrm{IFO}}^{1/2} \le 10 \cdot 10^{-12} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \cdot \sqrt{1+\left(\frac{2\,\mathrm{mHz}}{f}\right)^4}$$

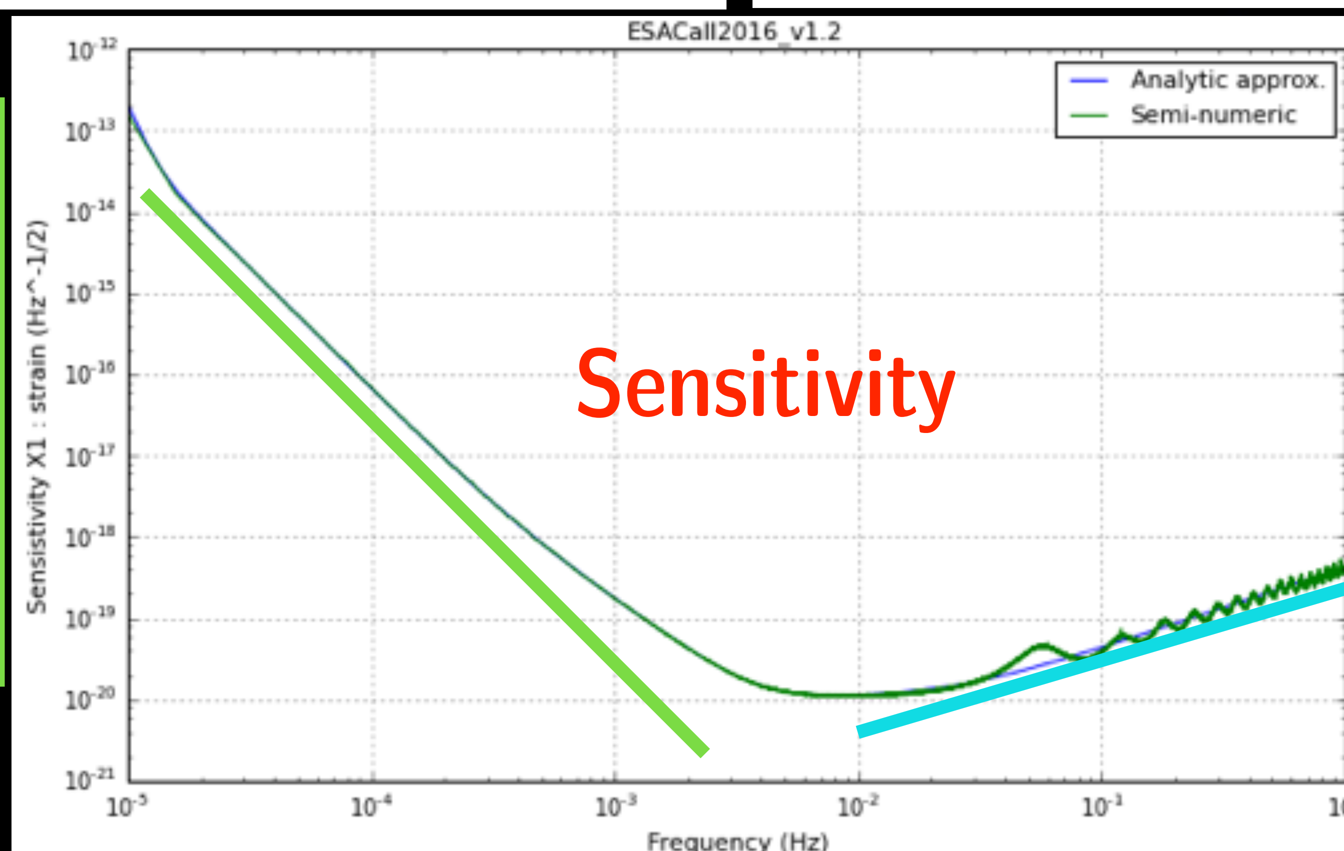
Sensitivity

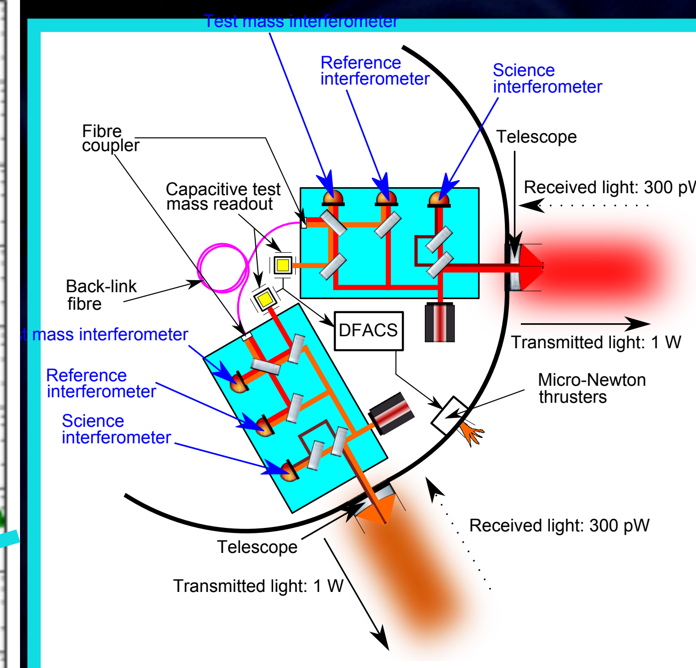
Noises



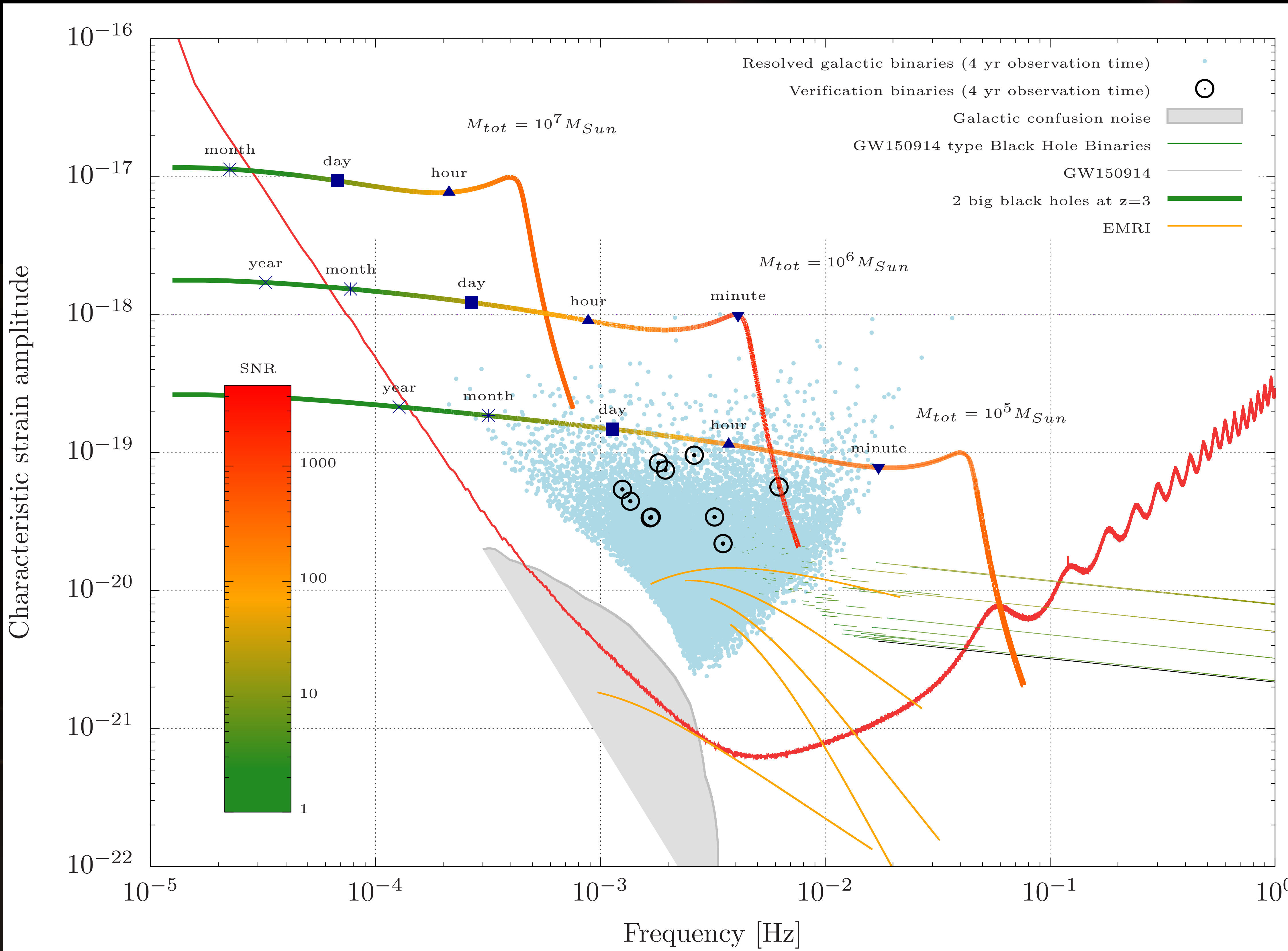
Response of the detector to GWs







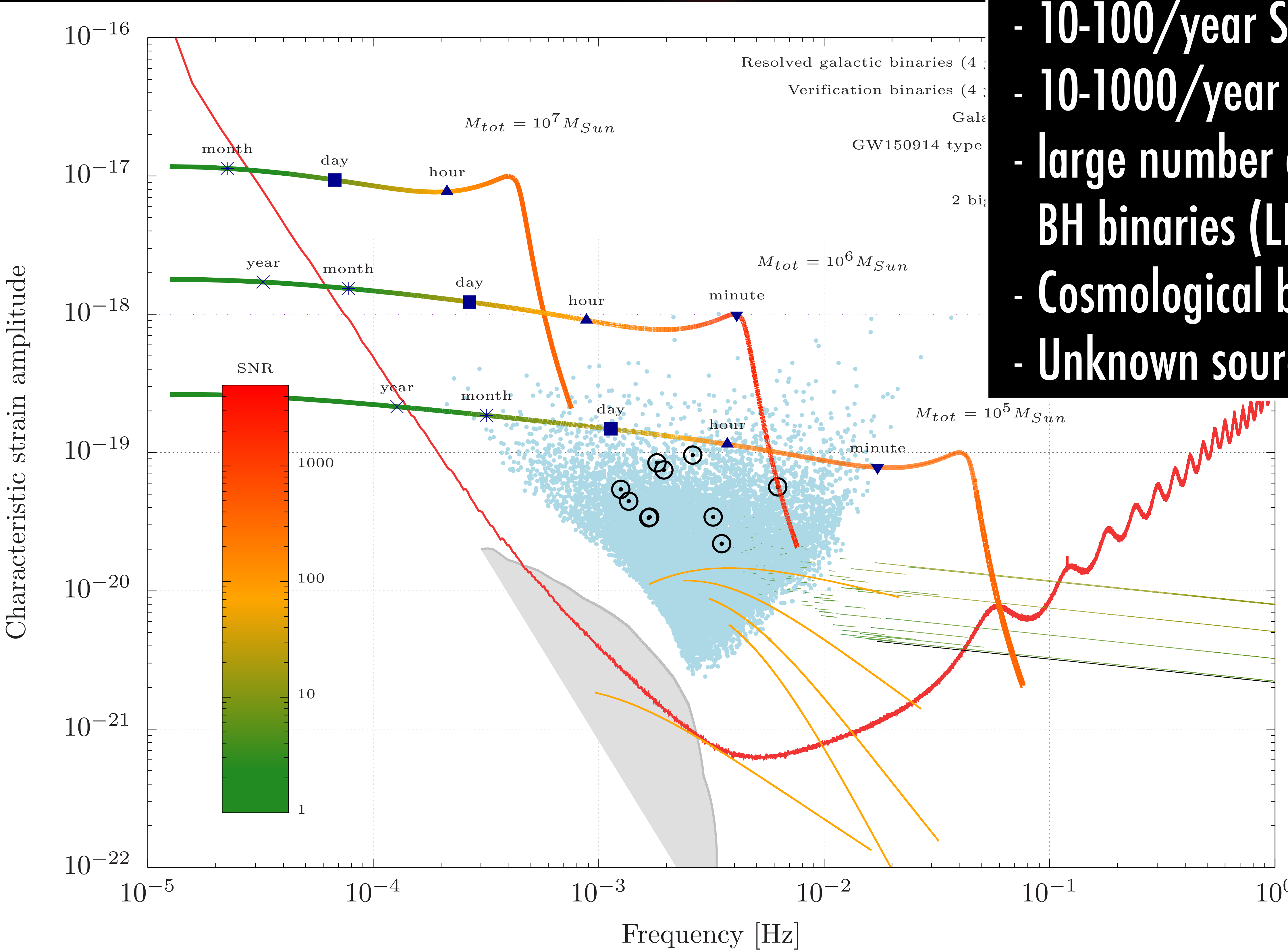
GW sources



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

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

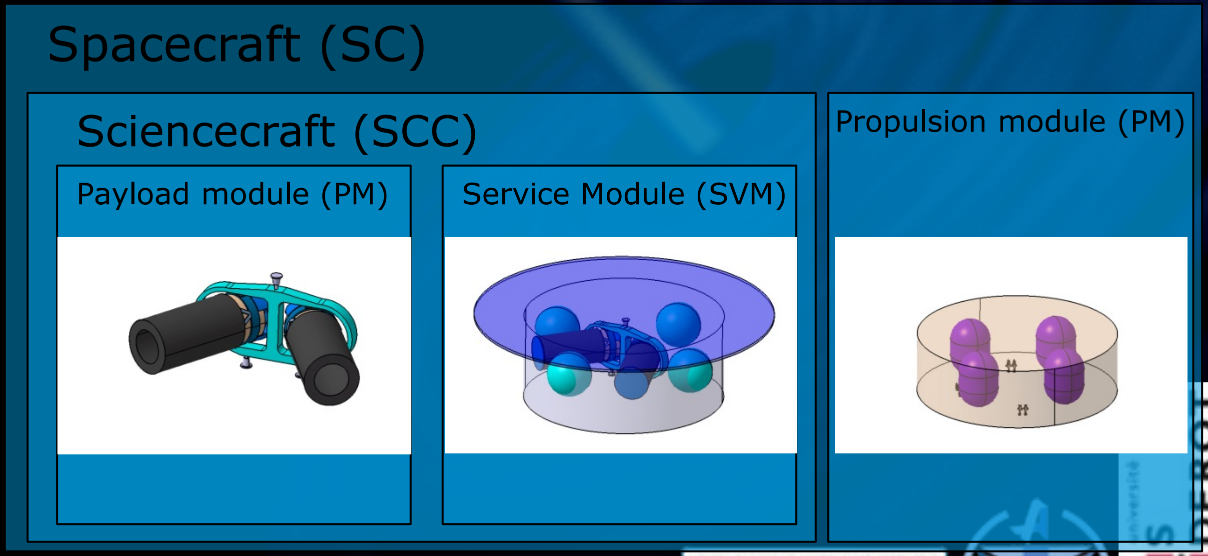


LISA at ESA

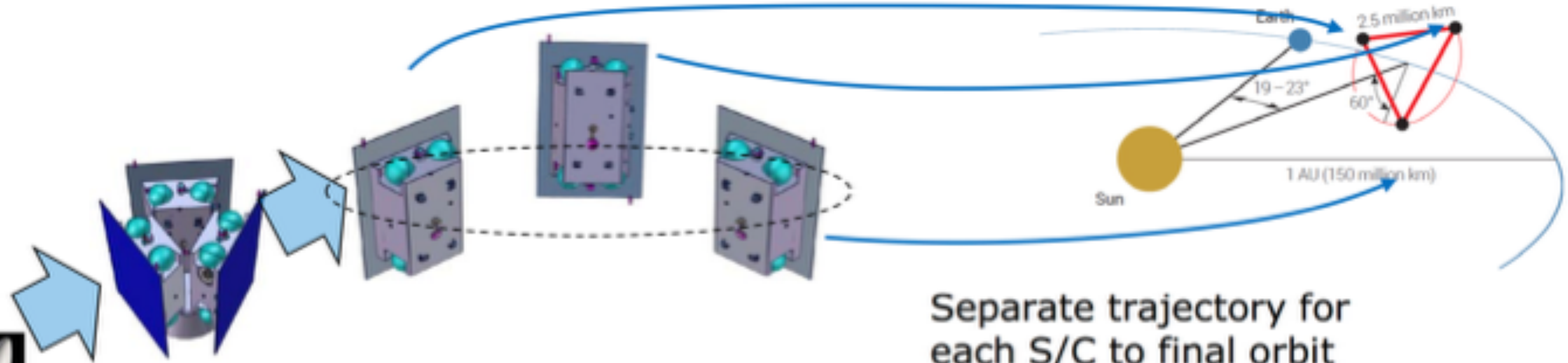
- 25/10/2016 : Call for mission
- 13/01/2017 : submission of «LISA proposal» (LISA consortium)
- 8/3/2017 : Phase 0 mission (CDF 8/3/17 → 5/5/17)
- 20/06/2017 : LISA mission approved by SPC
- 8/3/2017 : Phase 0 payload (CDF June → November 2017)
- 2018→2020 : competitive phase A : 2 companies compete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

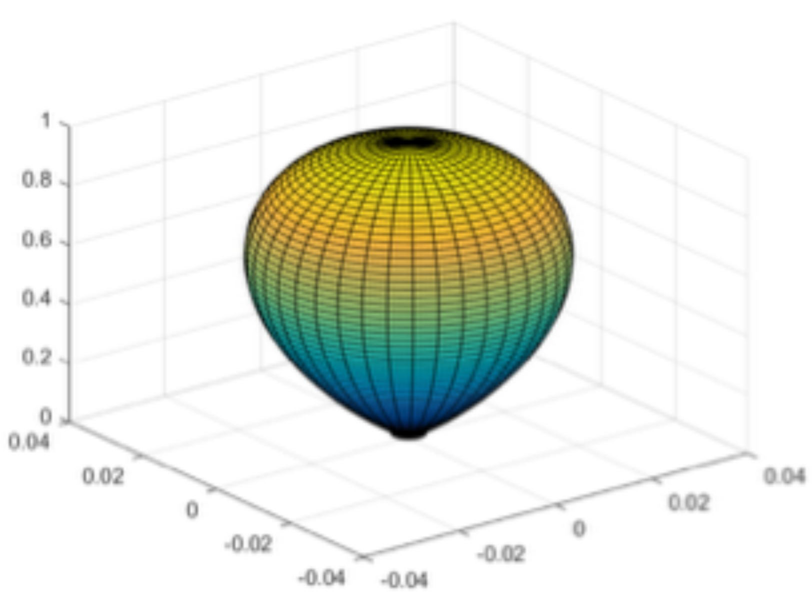


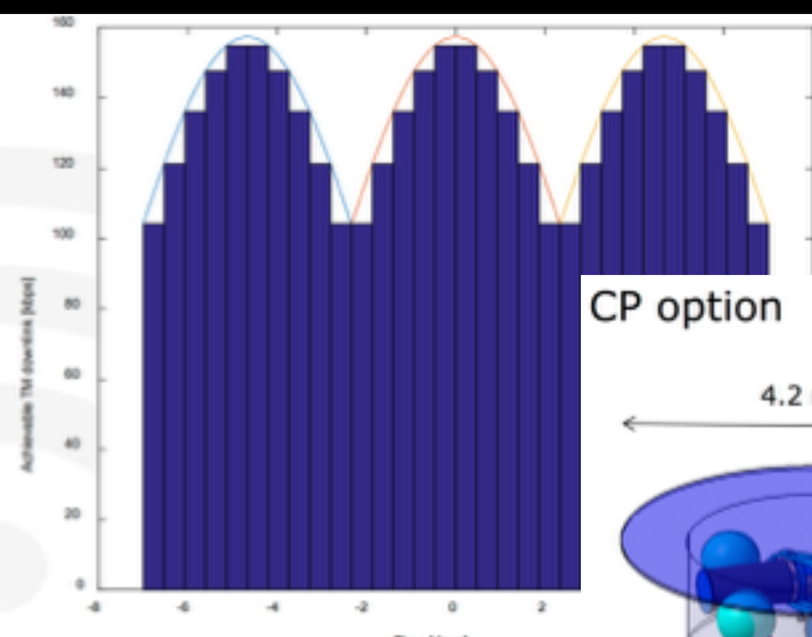
Separate trajectory for each S/C to final orbit

Separation of the stack right after launch

Launch in stacked configuration
Direct injection into escape trajectory

	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**



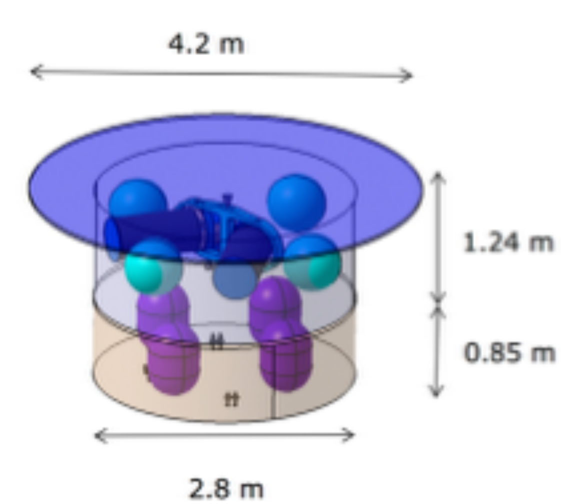


Dish
Average rate: 132.7 kbps
Max rate: 154.8 kbps
Min rate: 104.2 kbps
Margin: 4.1 dB (>3 dB)

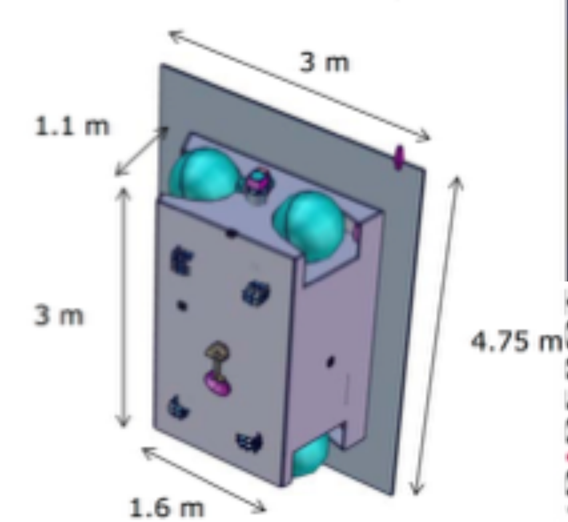
MGA (CP option)
Max rate: 13 kbps
Margin: 4.0 dB (>3 dB)

LGA
Max rate: 52 bps
Margin: 3.1 dB

CP option



EP and EP+ option



François Arago Centre

ESA Phase 0 Payload

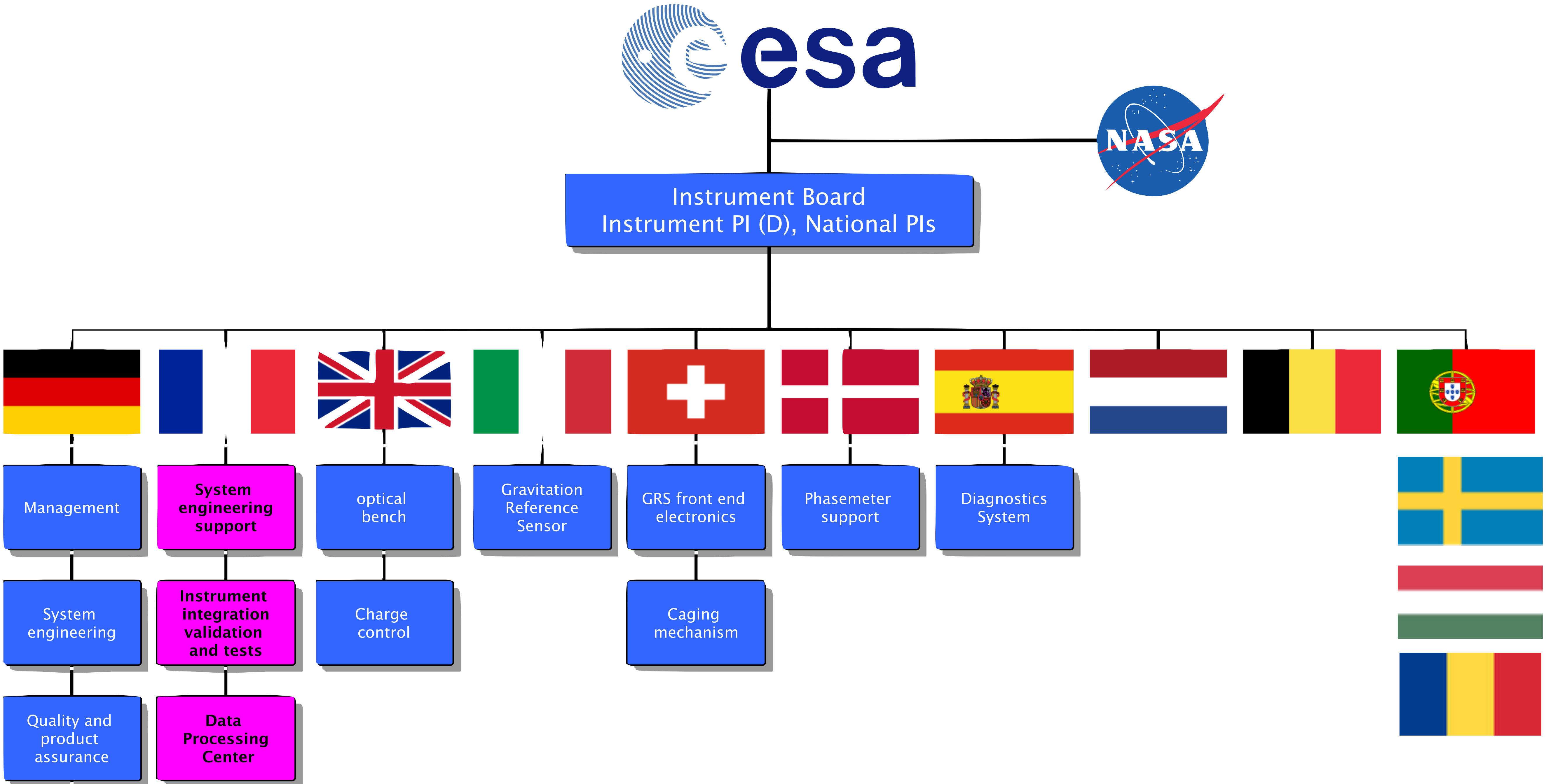
- From June to November
- Conducted by Payload Coordination Team with ESA
- Support of ESA CDF

=> Write the Payload Definition Document:

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

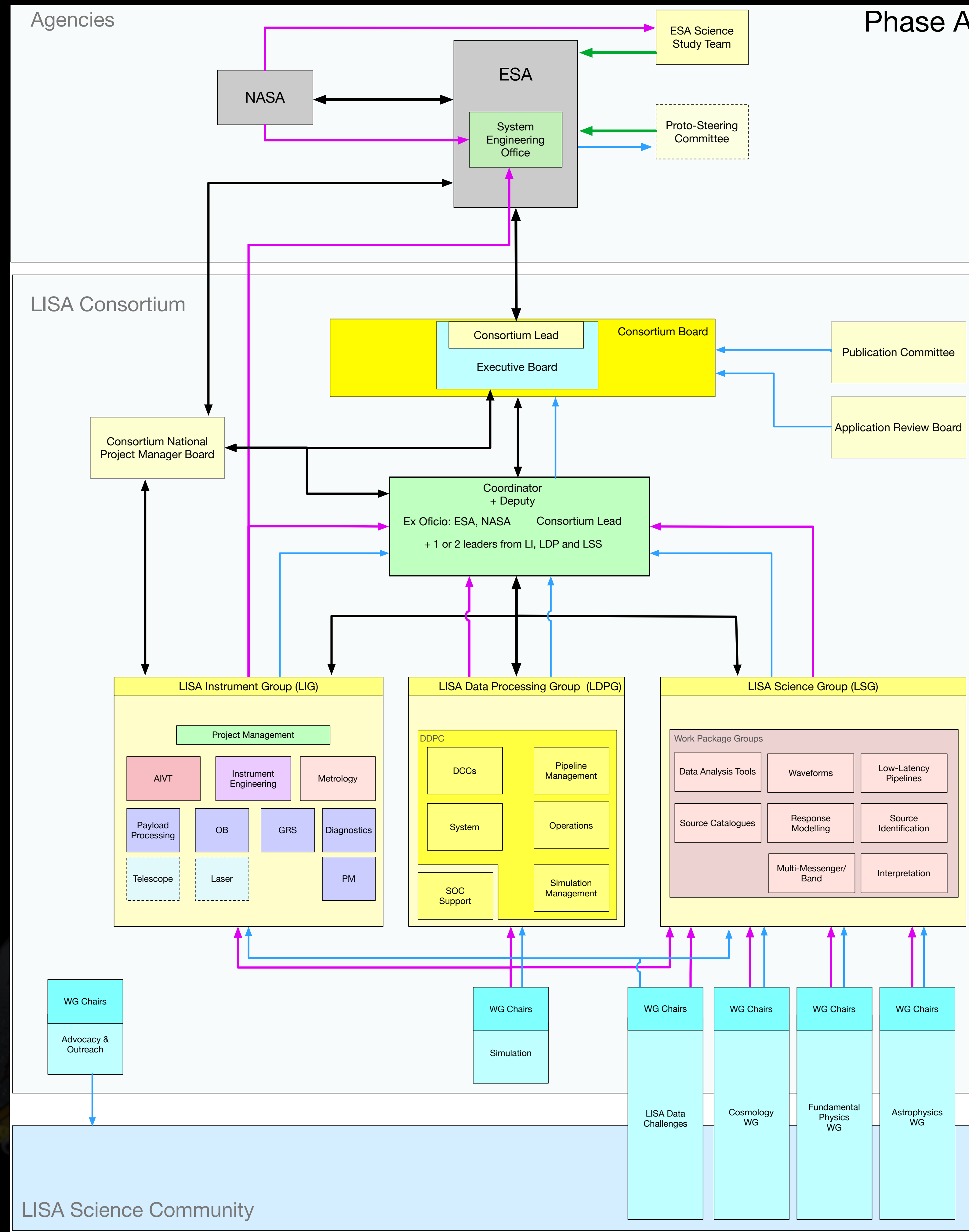
- Subsystems:
  - Laser
  - Diagnostics
  - Gravitational Reference Sensor
  - Mechanisms
  - Optical Bench
  - Telescope
  - Constellation Acquisition Sensor
  - PhaseMeter

LISA Consortium



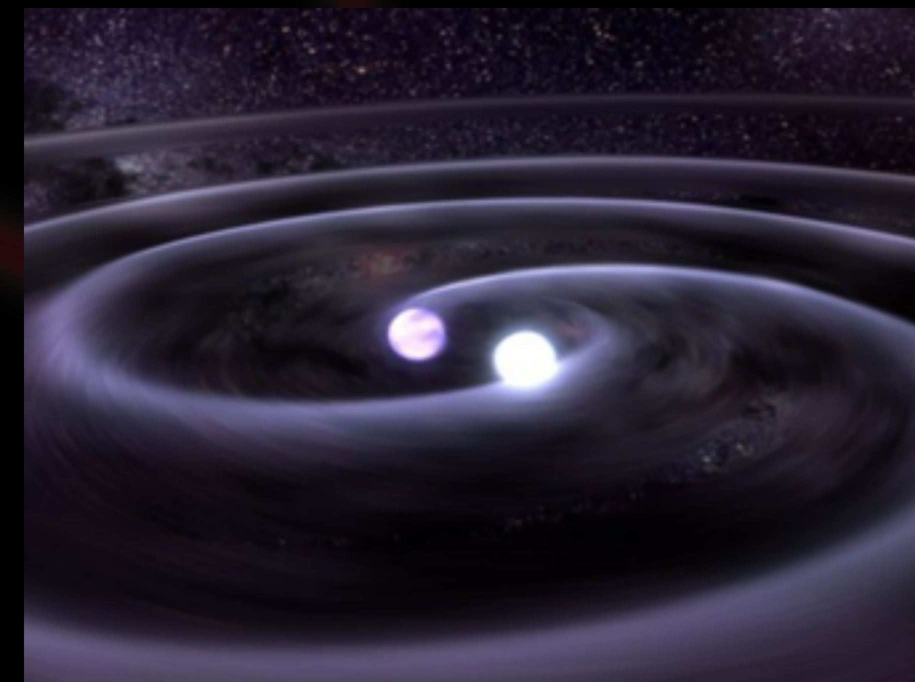
- Set for eLISA/NGO and enlarge later
- The LISA Consortium wrote the LISA proposal (core group) submitted it to ESA
- Letter of endorsement from National Agencies to ESA

Consortium organisation

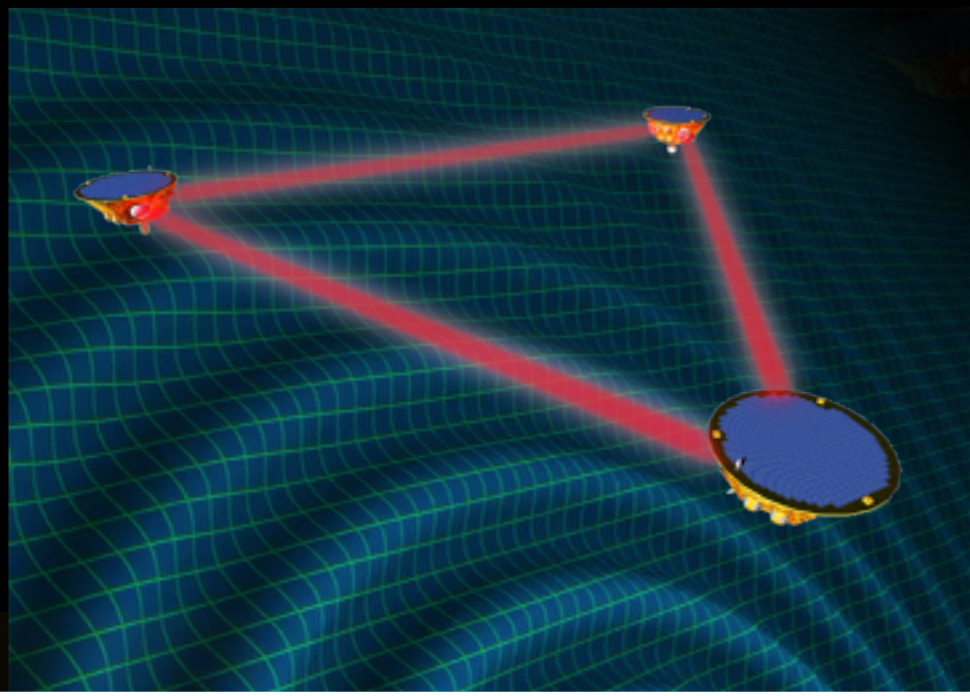


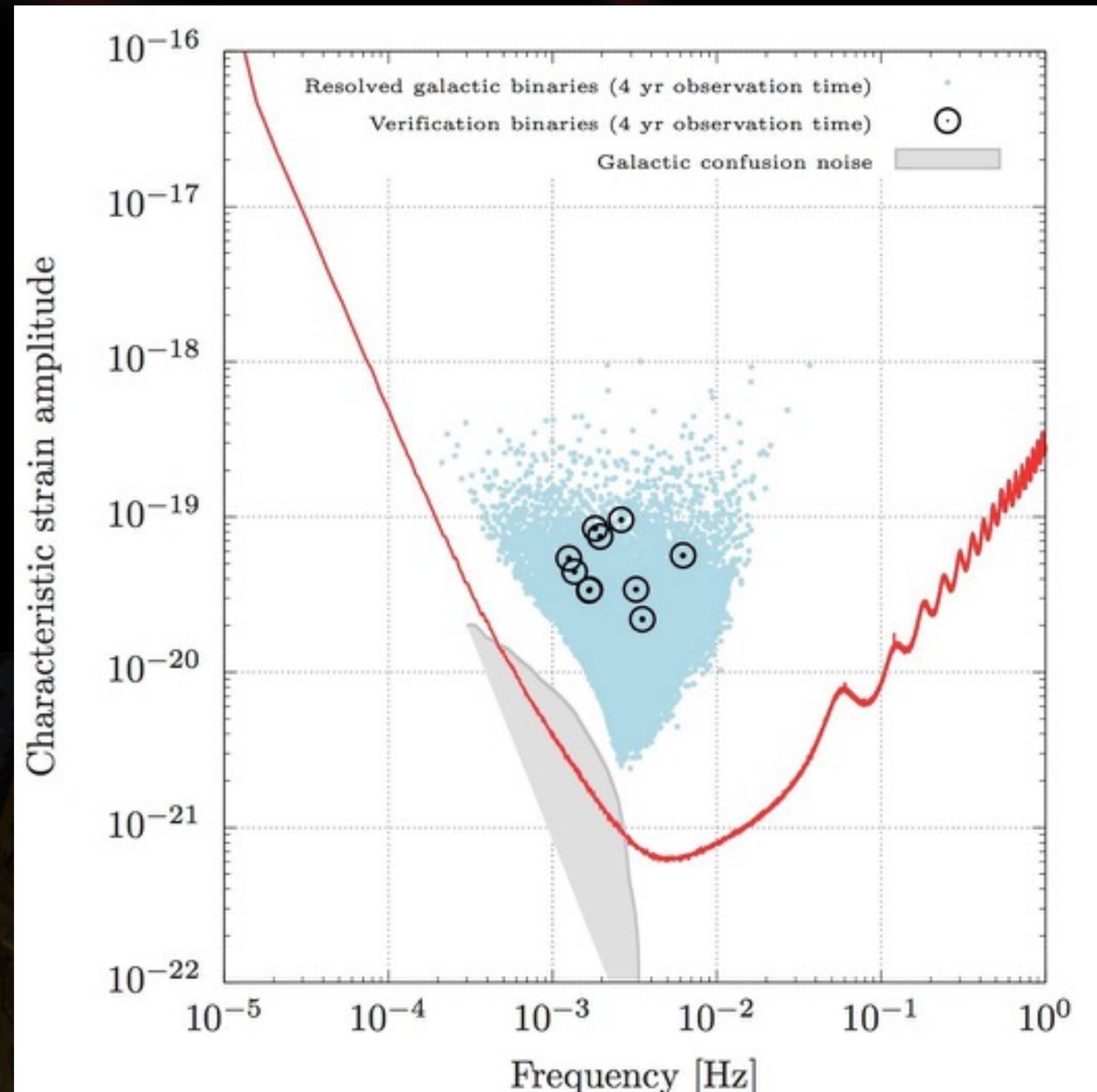
Galactic binaries

- 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)



Galactic binaries



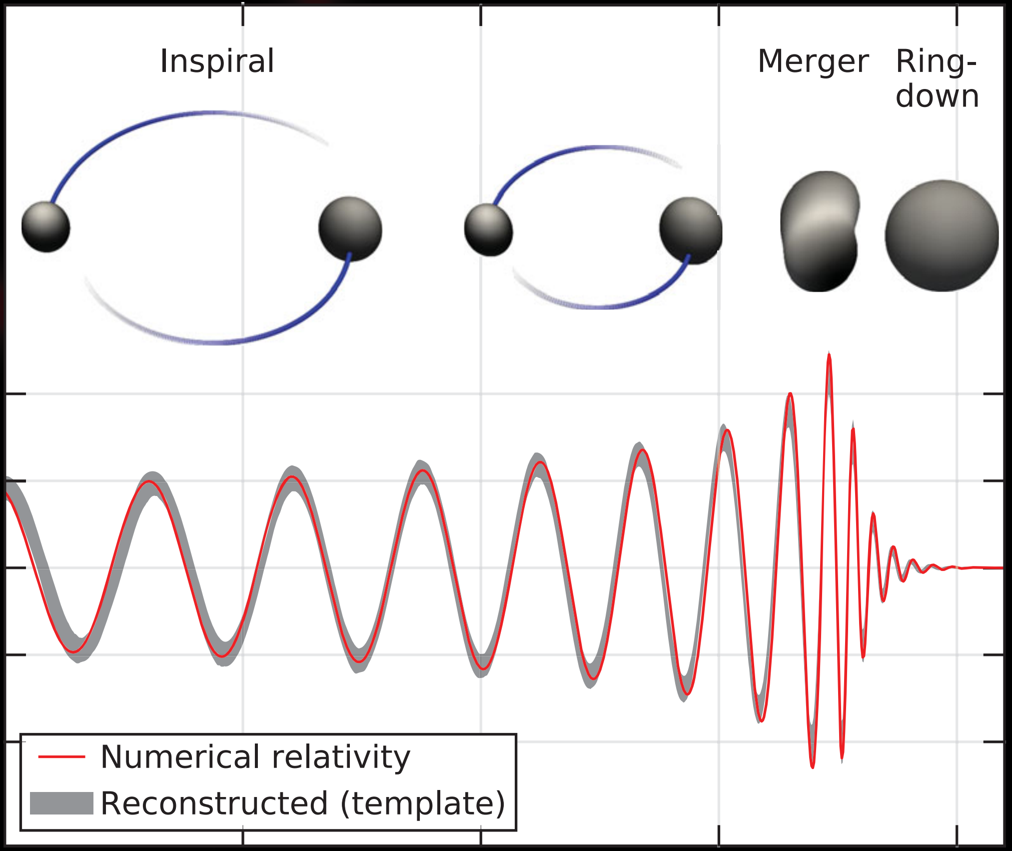


GW sources

- 6×10^7 galactic binaries

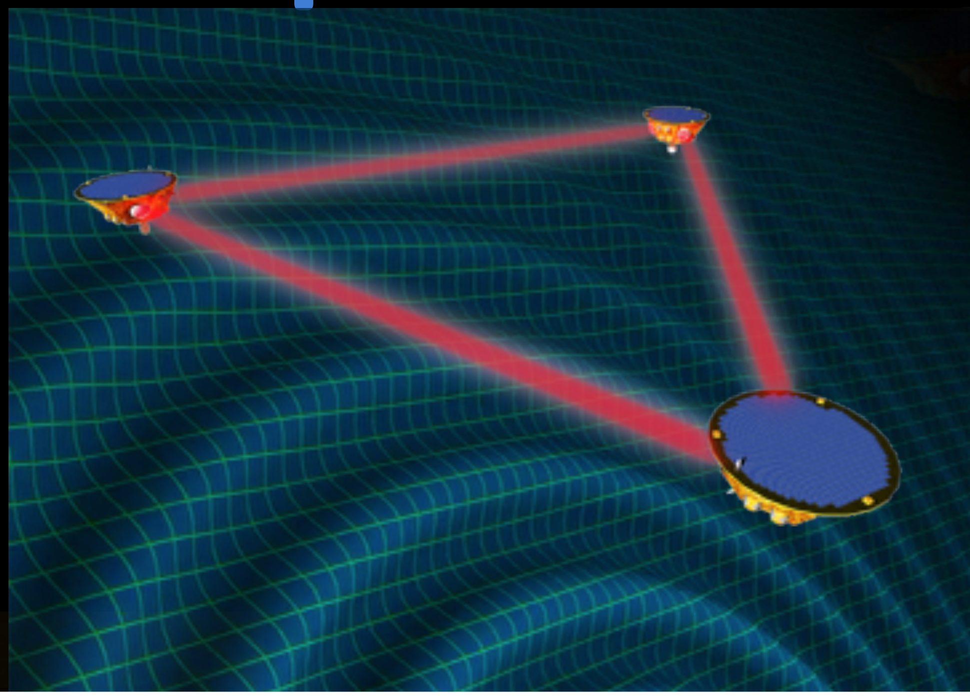
Super Massive Black Hole Binaries

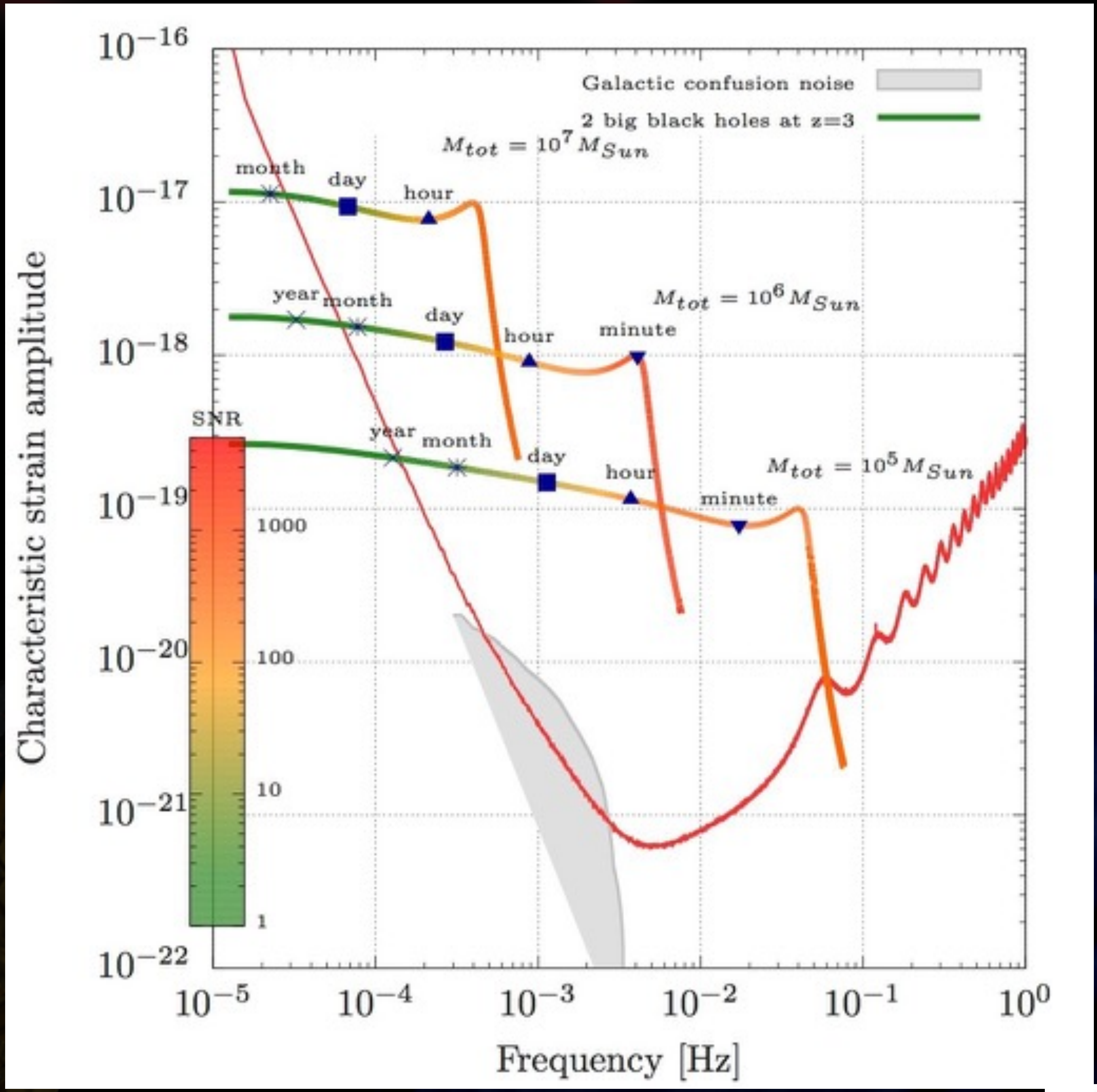
- Gravitational wave:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.



- Duration: between few hours and several months
- Signal to noise ratio: until few thousands
- Event rate: 10-100/year

Super Massive Black Hole Binaries





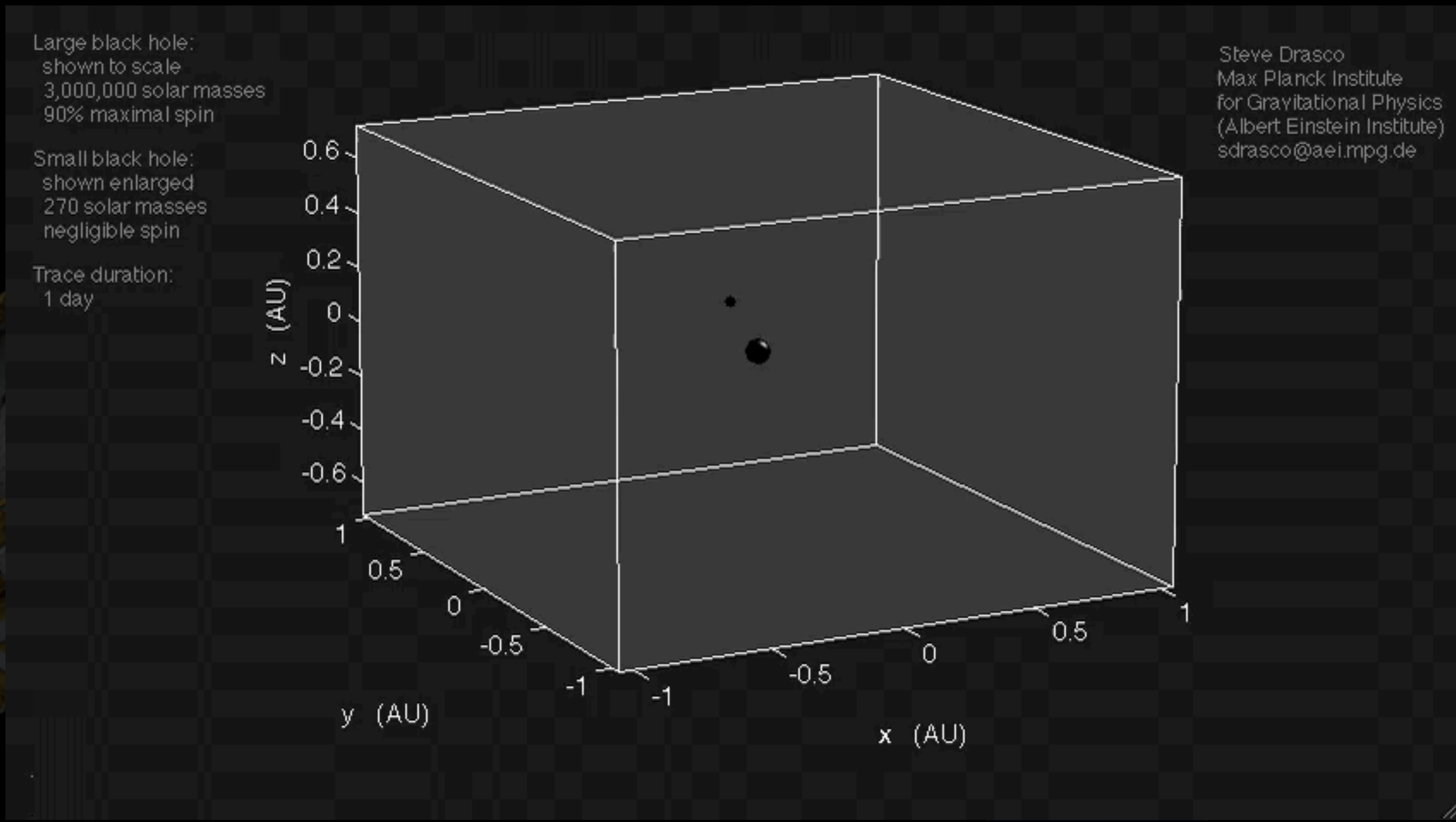
GW sources

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

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:

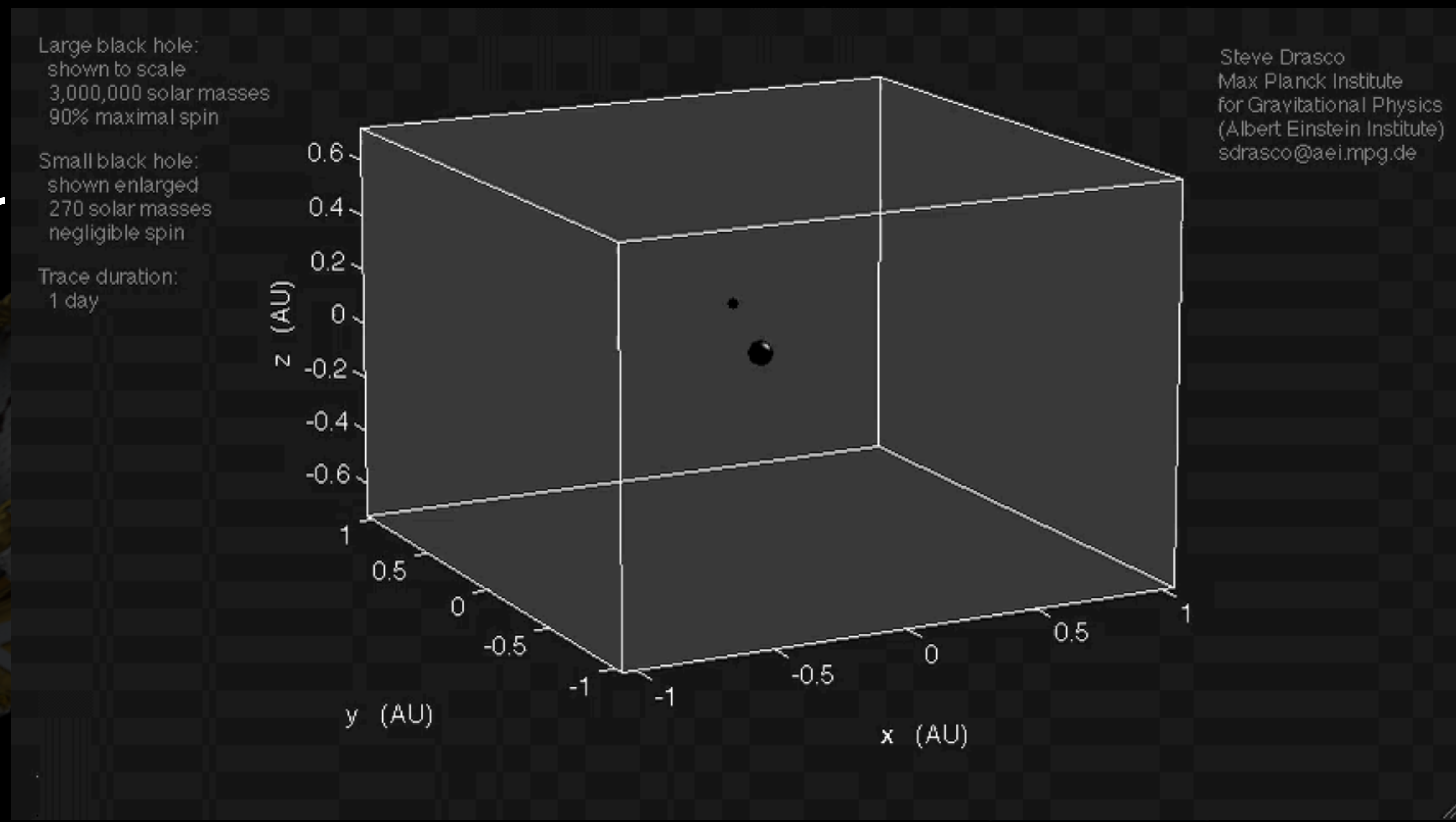
  from few events per year to few hundreds



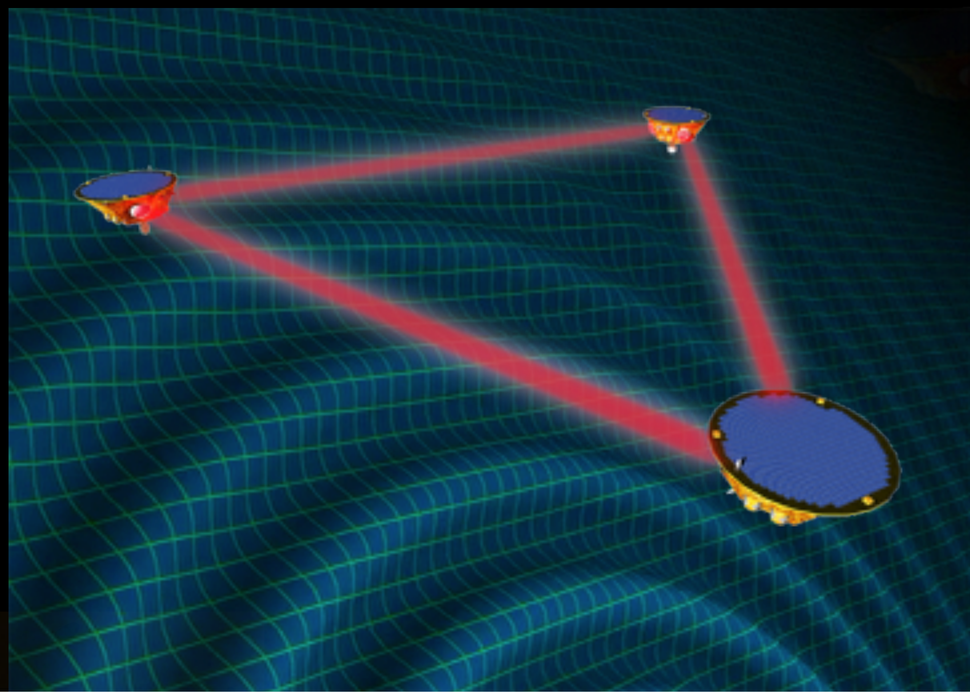
EMRIs

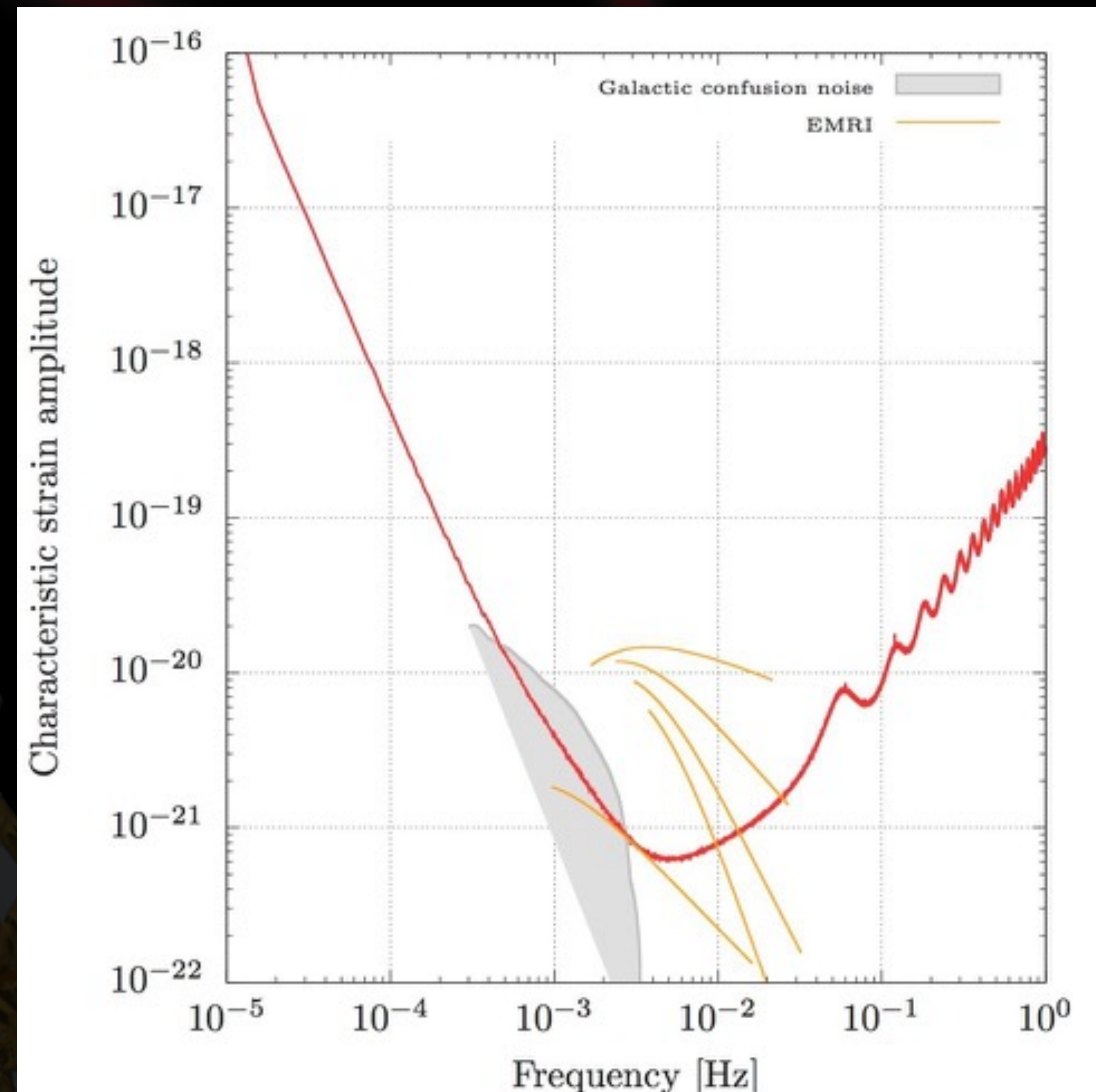
- Gravitational wave:
  - very complex waveform
  - No precise simulation at the moment
- Duration: about 1 year
- Signal to Noise Ratio: from tens to few hundreds
- Event rate:

  from few events per year to few hundreds



EMRIs





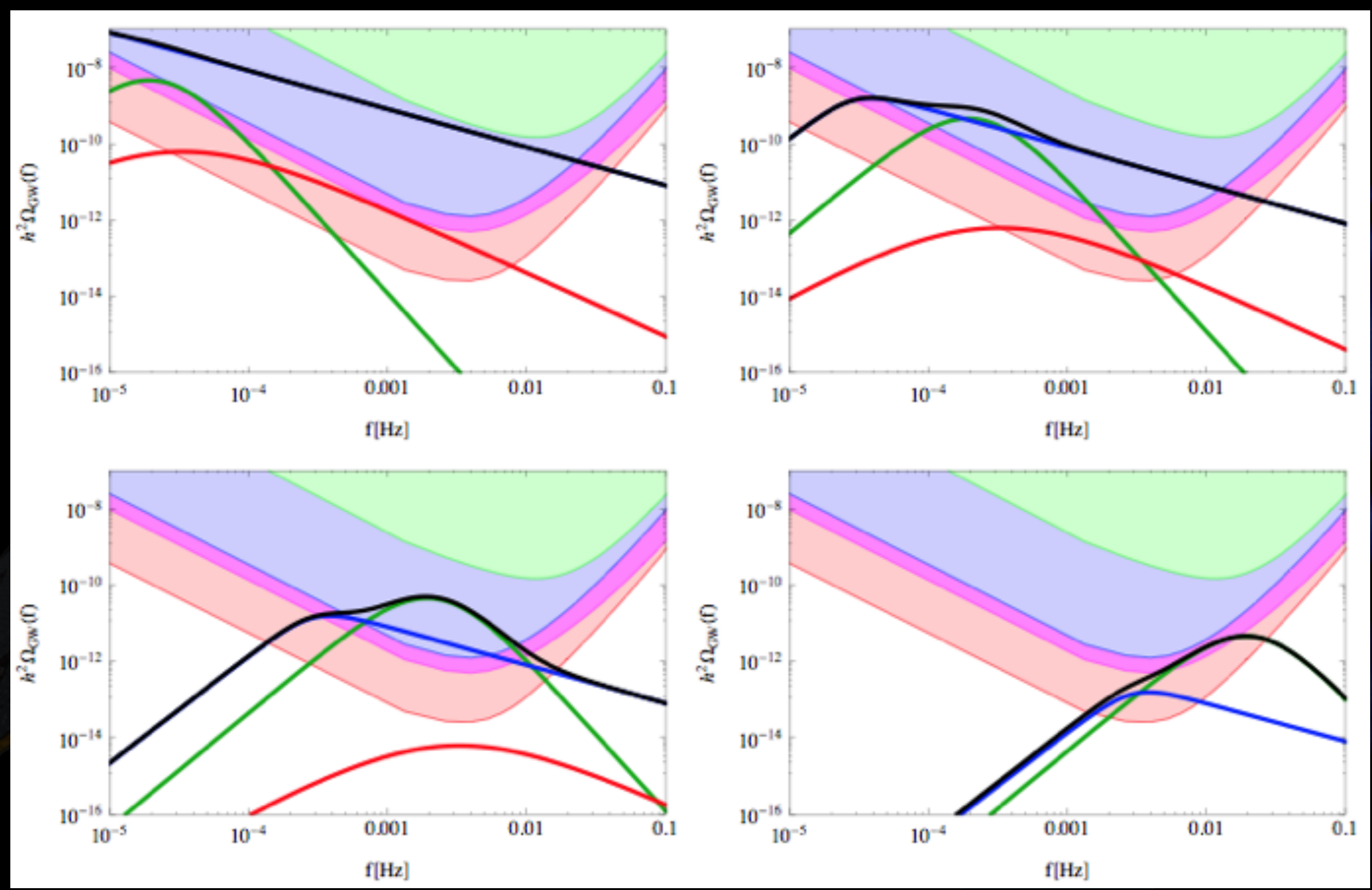
OG sources

- 6×10^7 galactic binariess
- 10-100/year SMBHBs
- 10-1000/years EMRIs

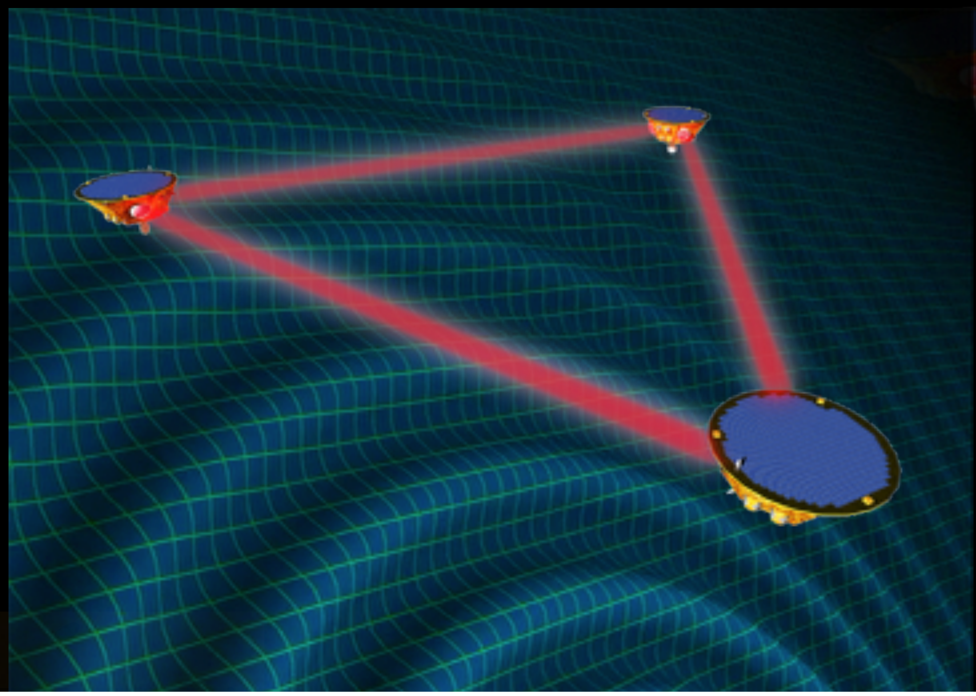
François Arago Centre

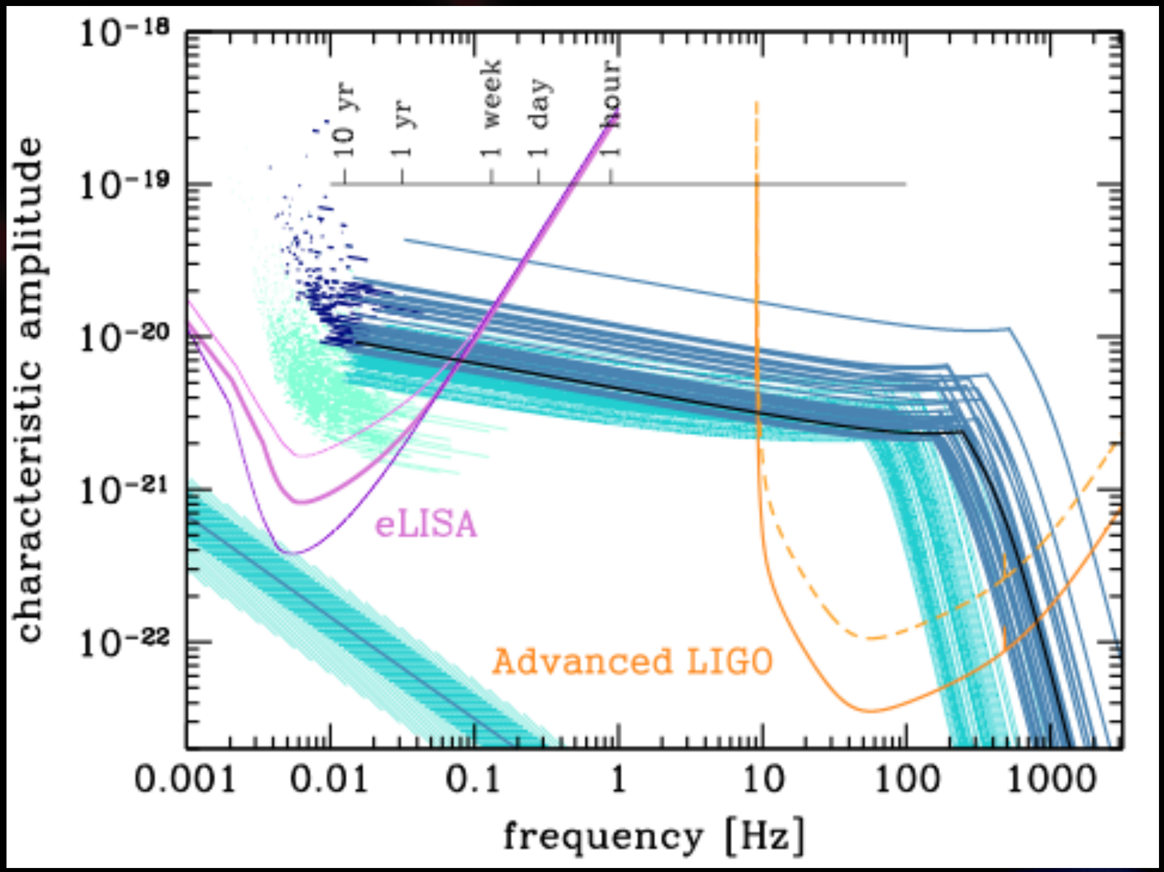
Cosmological backgrounds

- Work in progress for LPF-LISA …
- But studies done in the context of eLISA already showed:
  - Ex: first order phase transition in the very early Universe Caprini et al. JCAP 04, 001 (2016)
  - Cosmic strings network
  - …



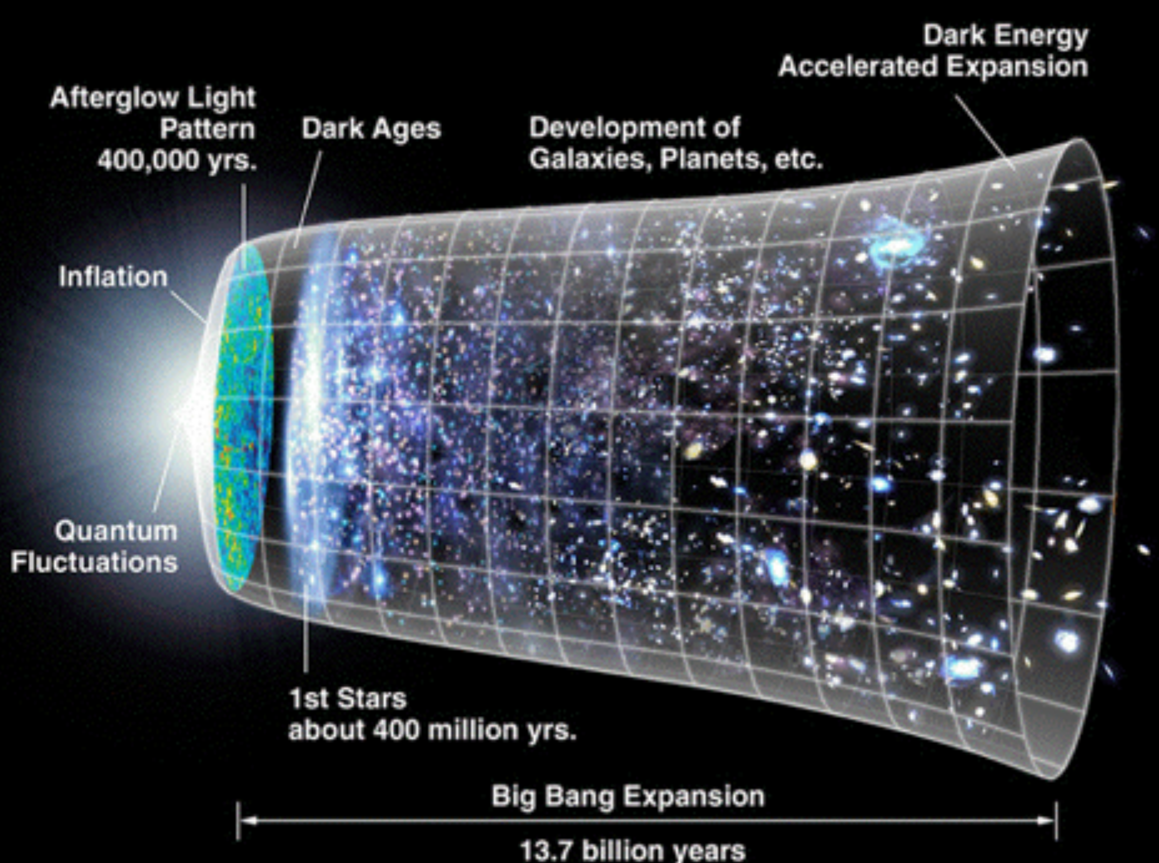
Others sources



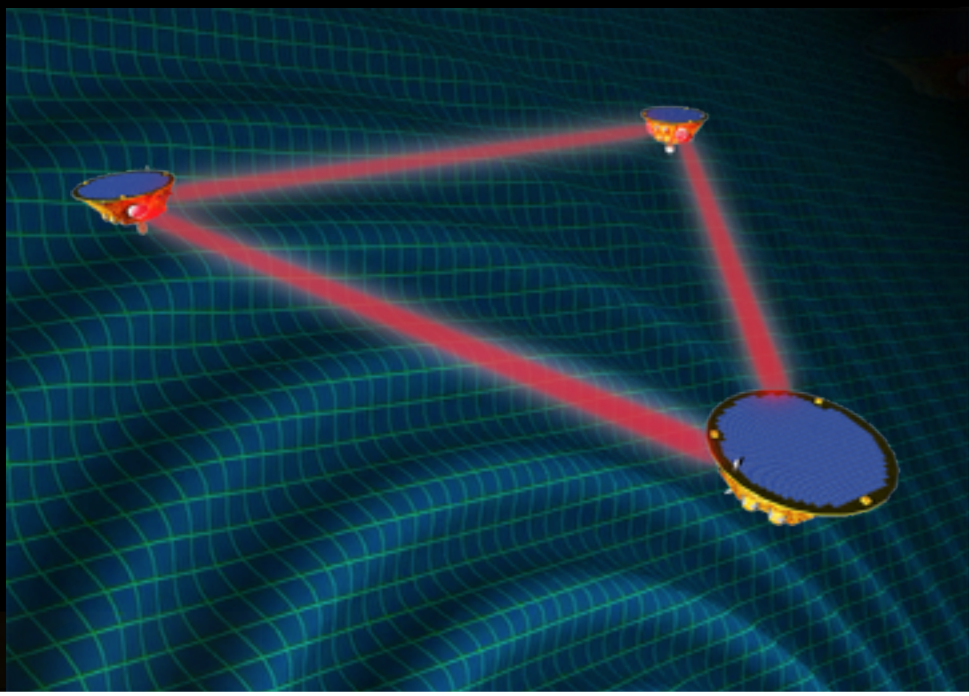


GW sources

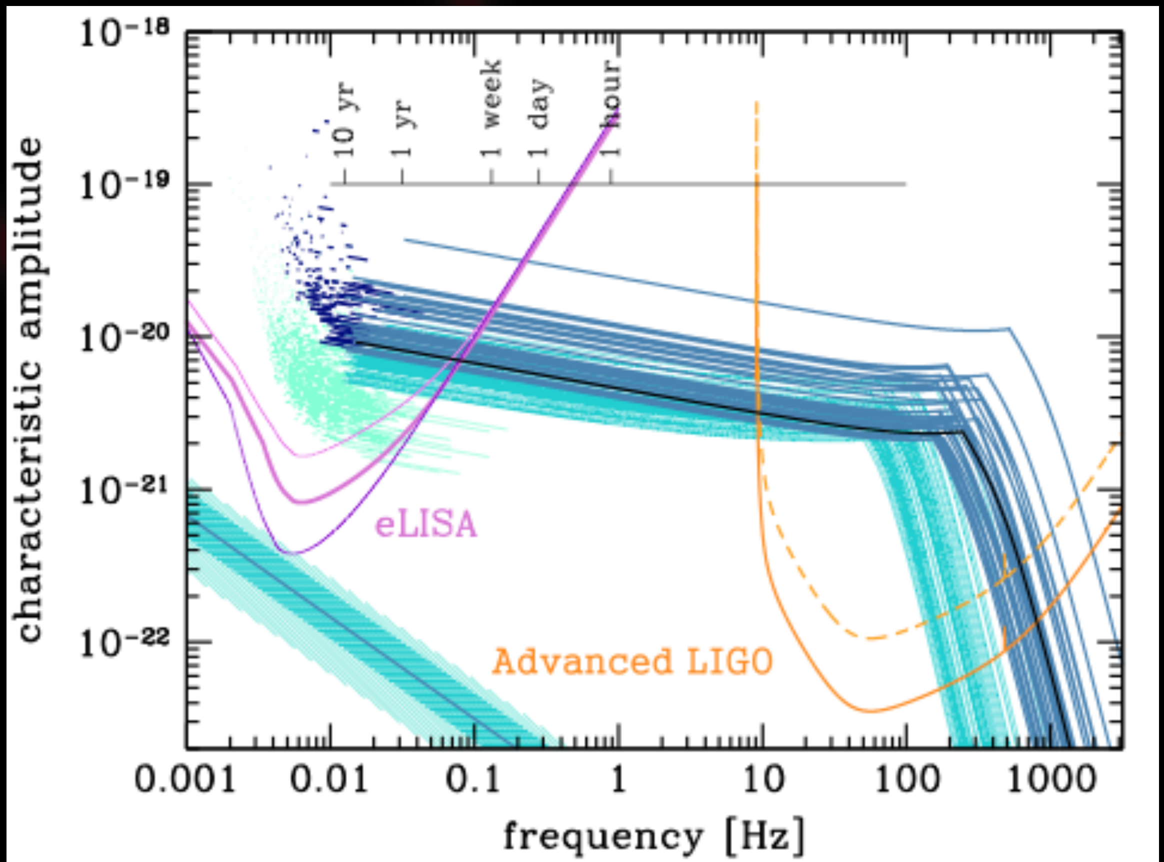
- 6×10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources



Others sources

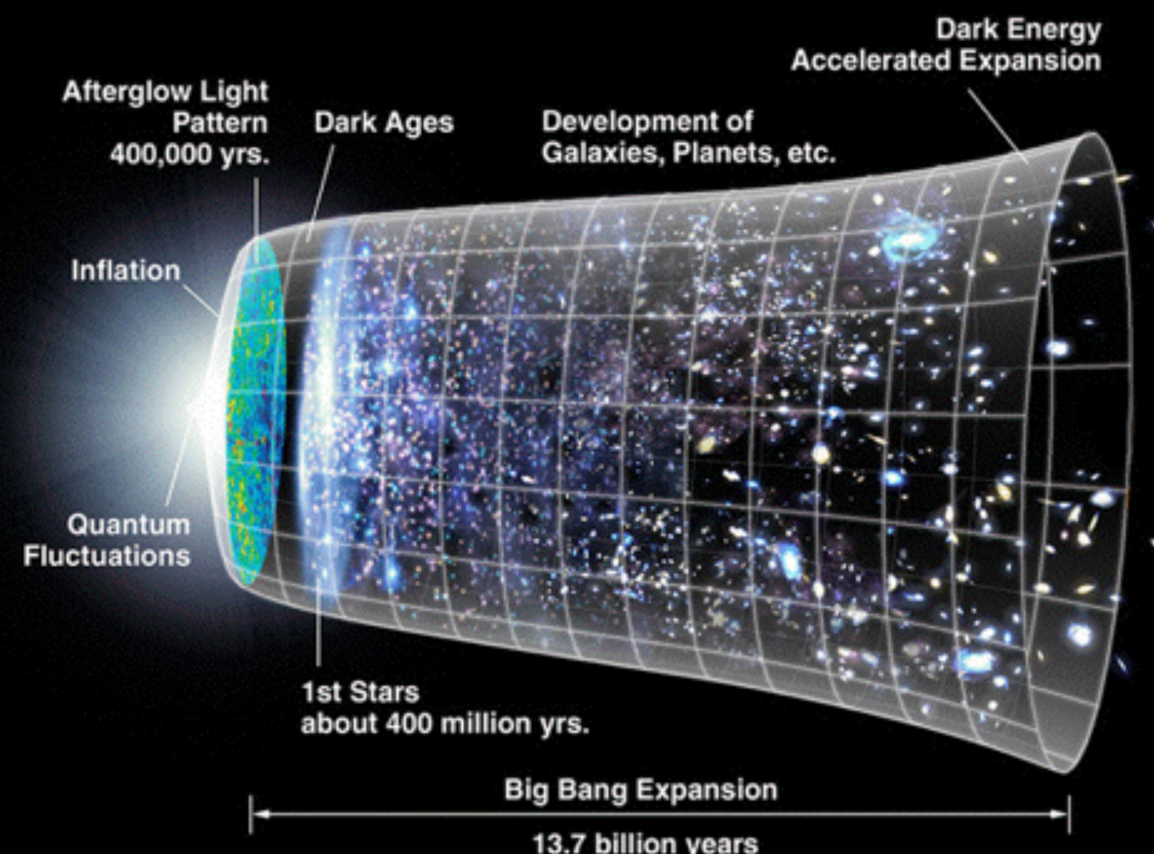


?



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



Scientific Challenges

- Gravitational Wave Science
  - Long waveforms
  - Waveforms for EMRIs
  - Waveforms for IMRIs
  - Multi-messenger => EM counterparts ?
  - Stochastic Background Modeling
  - Populations in particular SMBHs at very high redshift
  - Tests of GR
- Data processing
  - Algorithms for multiple source extraction
  - Distributed Data Processing Centre
  - Flexibility for pipelines development and for their transfer in production
  - Taking into account instrumental artefacts (gaps, glitches, non-stationarities, …)

Scientific Challenges

- Efficient System Engineering for an highly integrated mission
- Technologies:
  - Ultra-stable telescopes;
  - Complex phasemetre at high precision and frequency distribution;
  - Control and reduction of frequency noises;
  - Powerful and stable laser;
  - Fiber link (backlink);
  - Stray light;
  - Constellation acquisition;
  - Production of 6 Movable Optical Sub-Assembly;
  - ...

But no highly critical items!

Conclusion

- LISA will observe GWs between 10^{-5} and 1 Hz:
  - Large number of sources: compact objects binaries with large range of masses, stochastic backgrounds, …
  - Huge scientific potential: physic, astrophysics, cosmology, …
- LISAPathfinder + detections from ground-based observatories

  => Green light for LISA: large extension of the new window opened with LIGO/Virgo

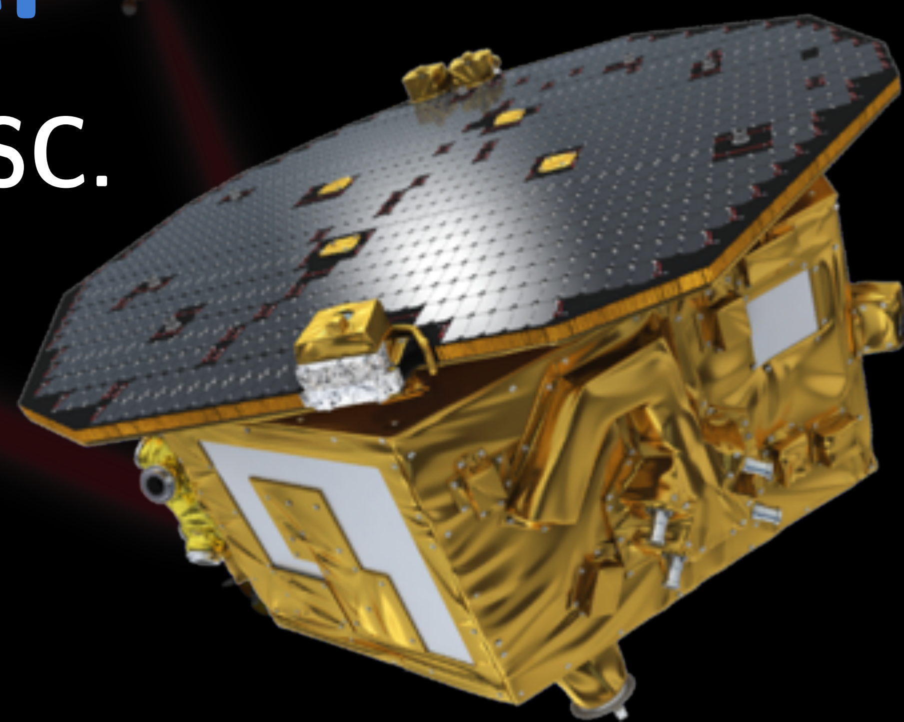
  => speed-up of the ESA planning:
  - Already done: call for mission, selection, phase 0
  - Next: phase A starting in April 2018…
- A number of very interesting scientific challenges but nothing individually very critical … but highly integrated mission.

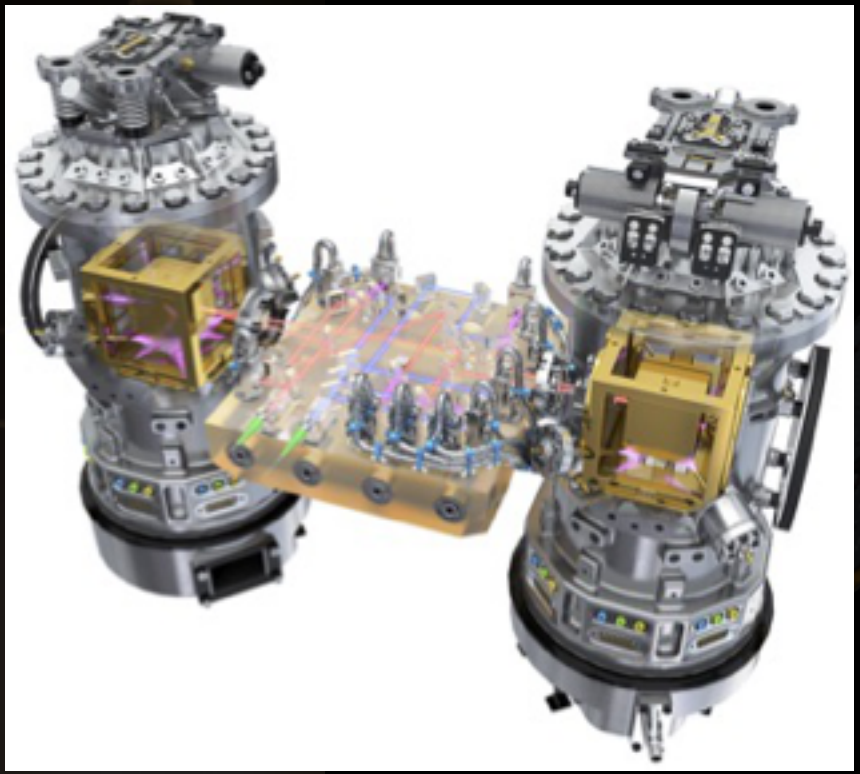
Thank you !

Thank you !

LISAPathfinder

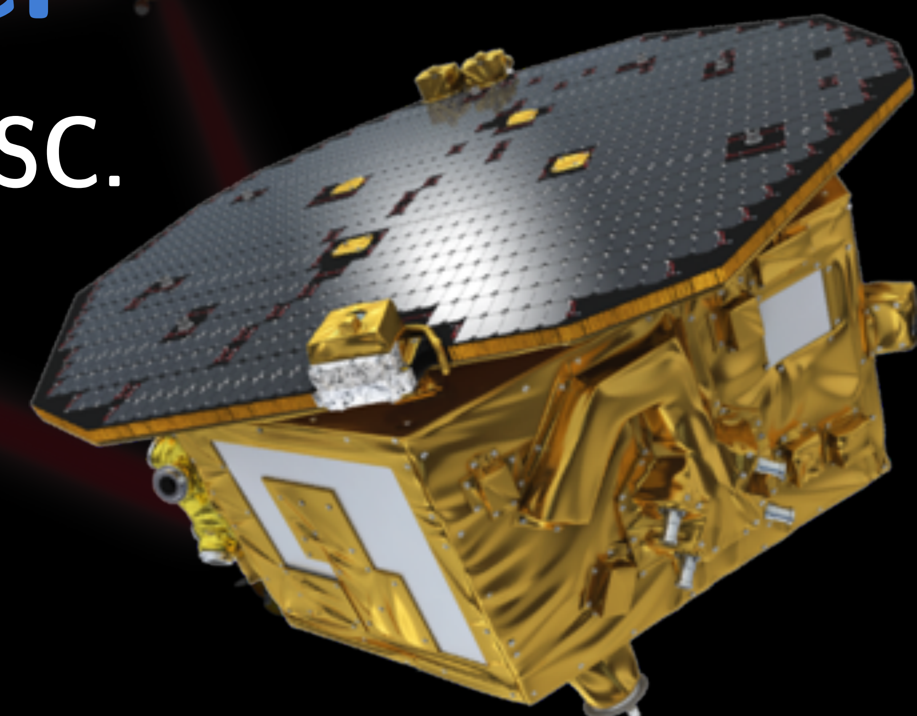
- Basic idea: Reduce one LISA arm in one SC.
- LISAPathfinder is testing :
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
  - Micro-thrusters



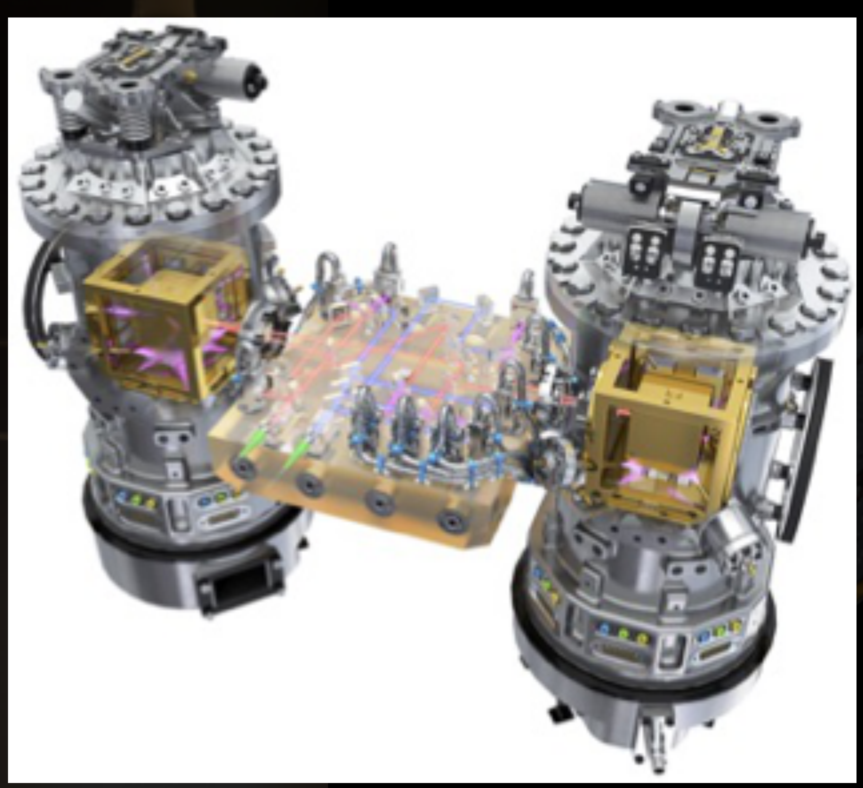


See talk from Daniele Vetrugno

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



See talk from Daniele Vetrugno