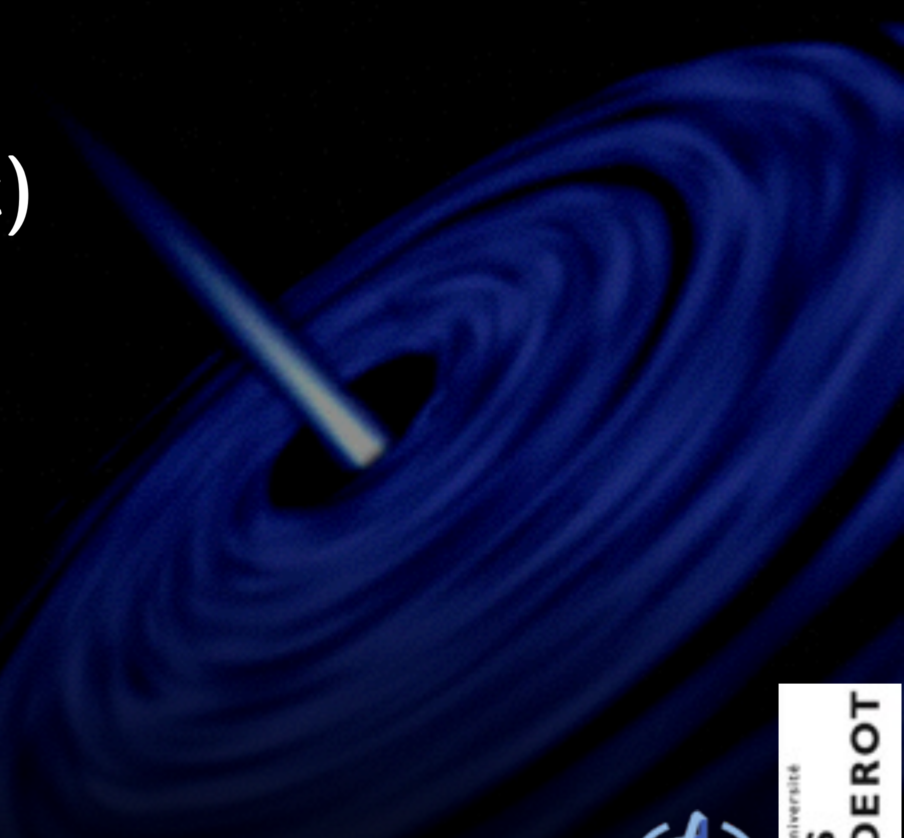
# LISA:

# observing gravitational waves from space

Antoine Petiteau

(APC – Université Paris-Diderot)



Séminaire CPPM - Marseille

27th November 2017

# Outline

- Introduction to gravitational waves
- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISAPathfinder
- LISA status and organisation
- LISA scientific performances
- The French contribution to LISA:
  - Data Processing Center
  - Integration / performance control
- Conclusion and perspectives

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# Some history ...

- Albert Einstein (1905/1916) :

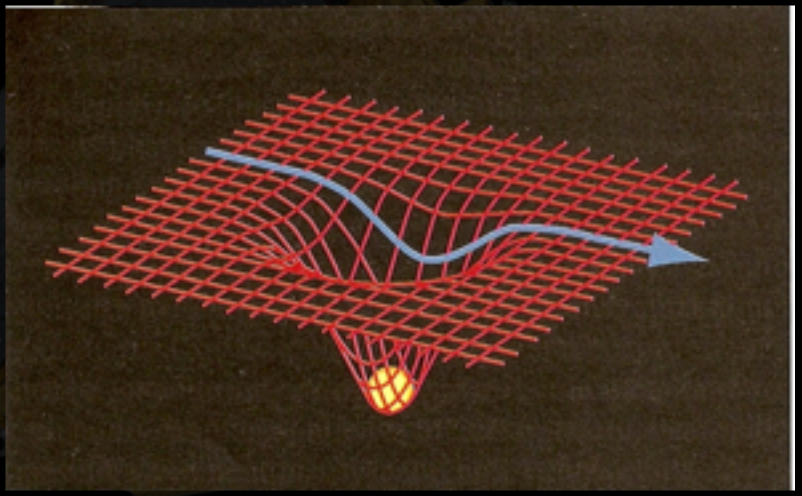
  there is no gravity force...

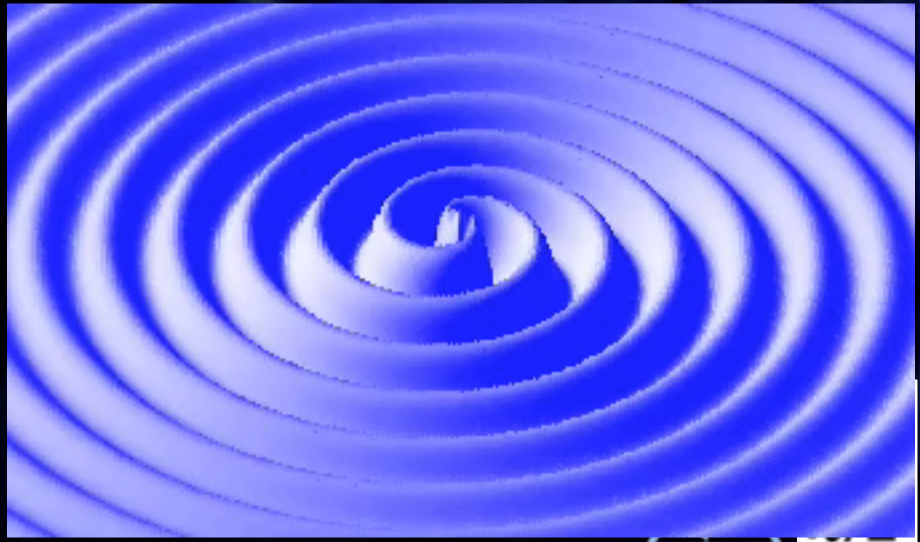
  - Mass deforms geometry of space-time.
  - Bodies are moving in a curve space.
  - Gravitational information propagates at the speed of light.
  - Dissipation of energy through deformation of space-time => gravitational waves

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

geometrical deformation

distribution of energy





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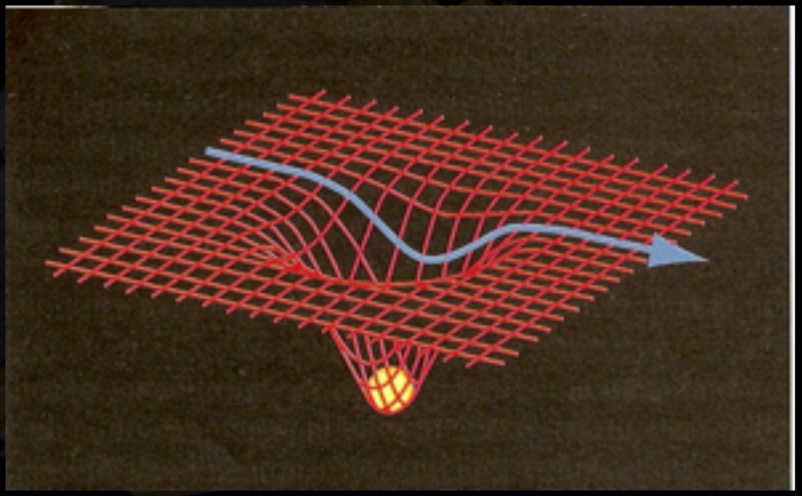
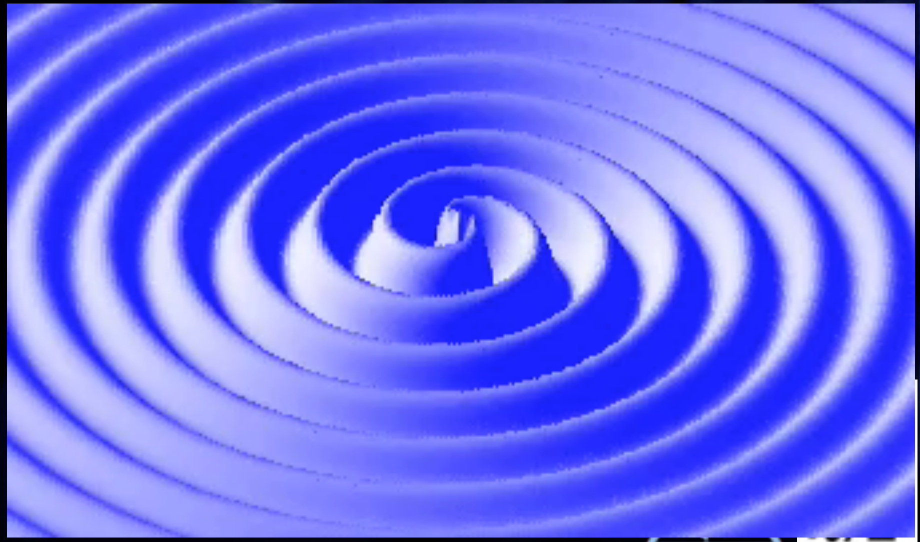
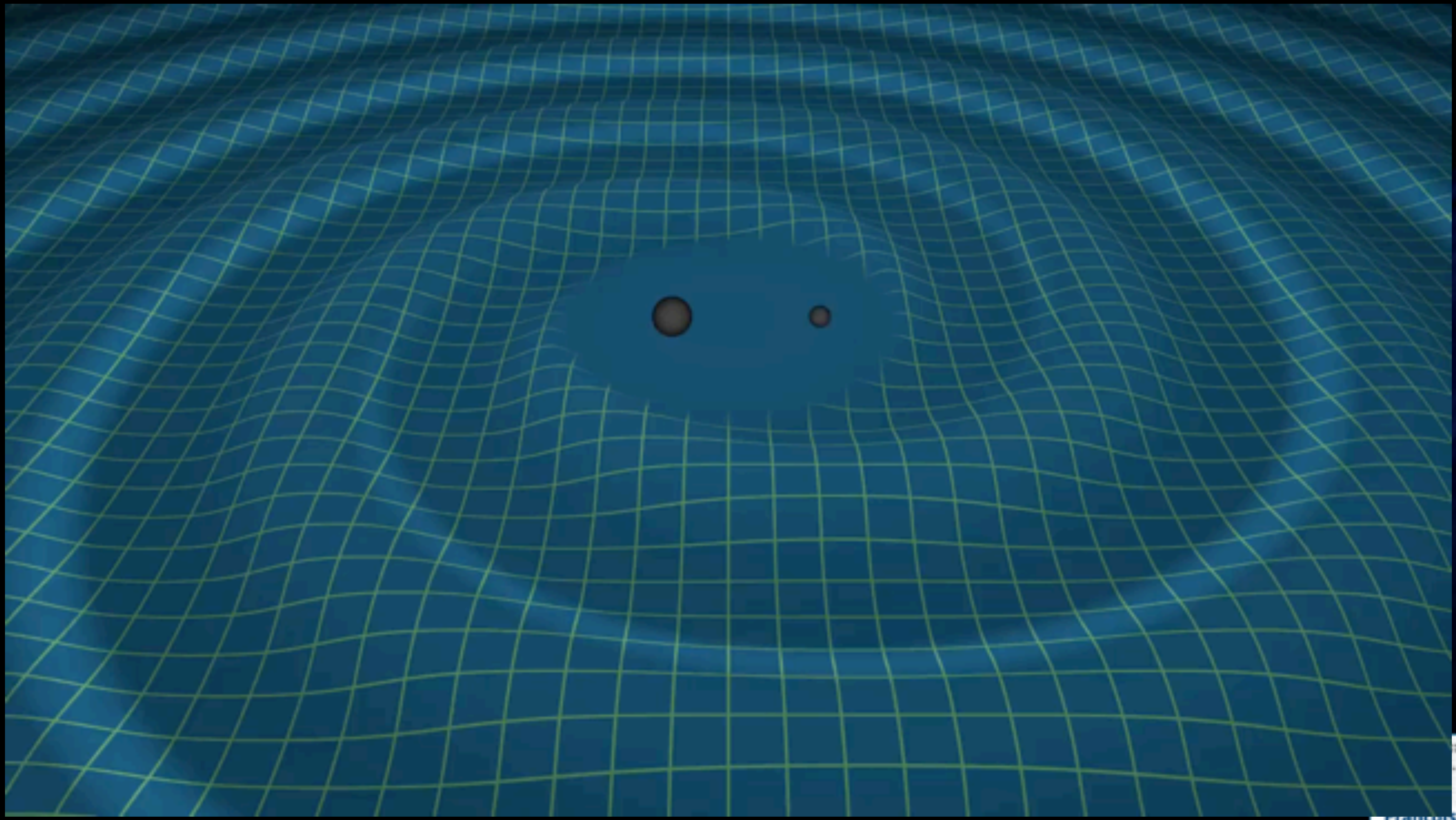




# Emission of GWs

- A gravitational wave is created during the non-spherical acceleration of one or several massive objects (variation of quadrupolar moment) :
  - emission: asymetric collapse, bodies in orbits or coalescing, ...
  - no emission: isolated, spherical body possibly in rotation



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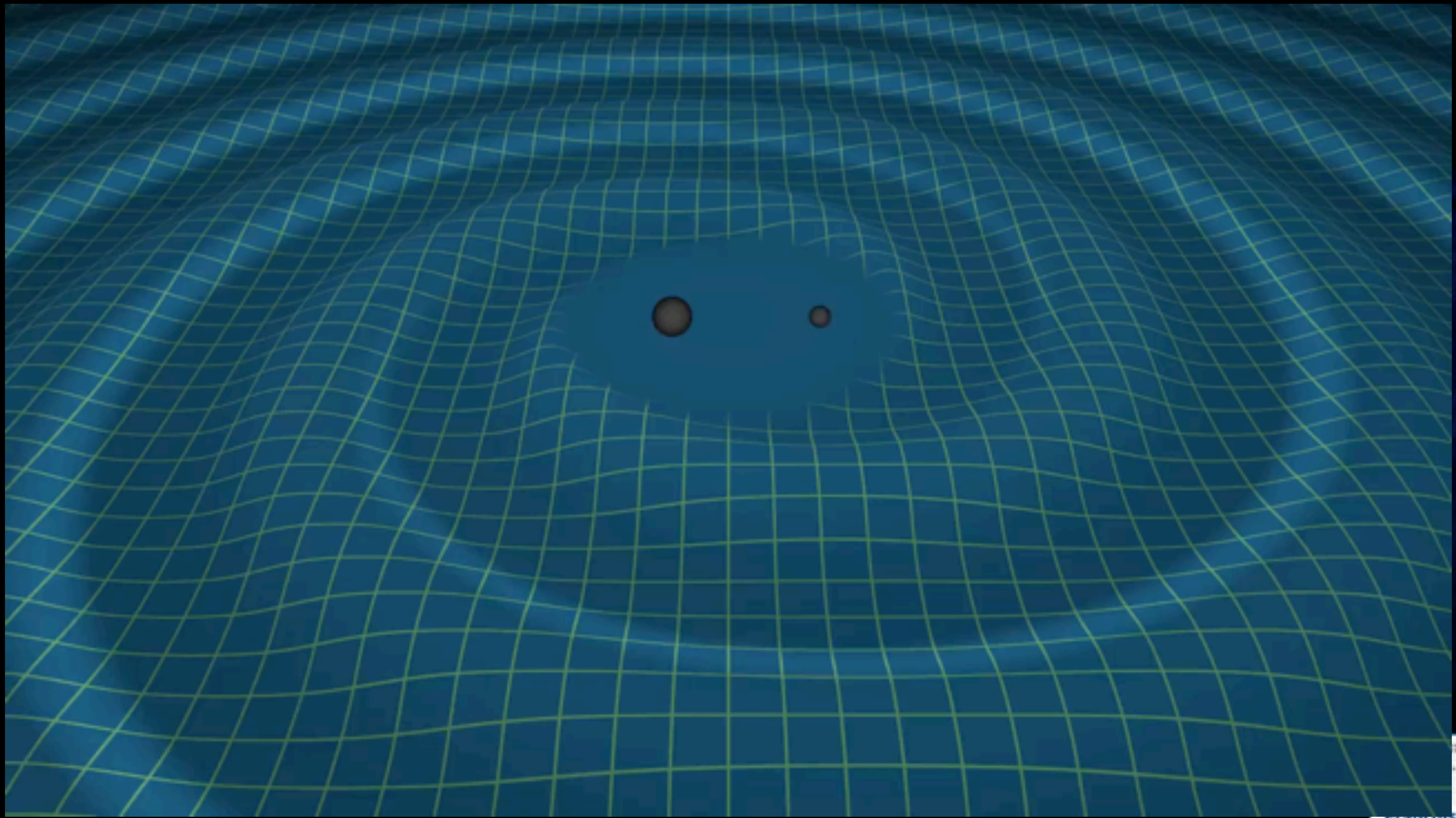
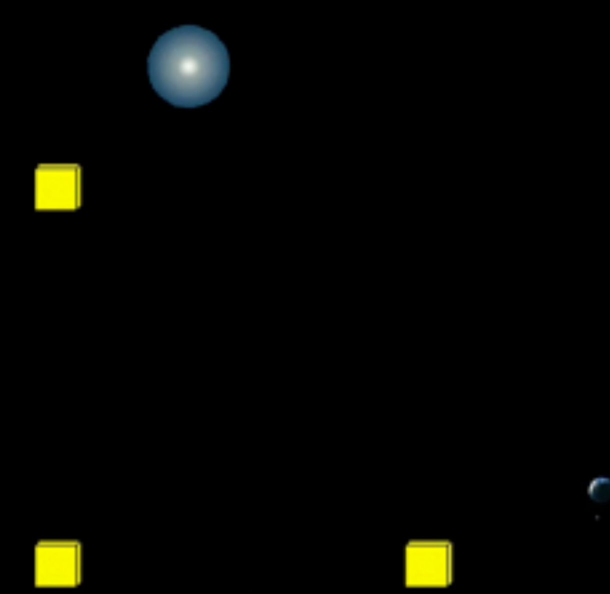


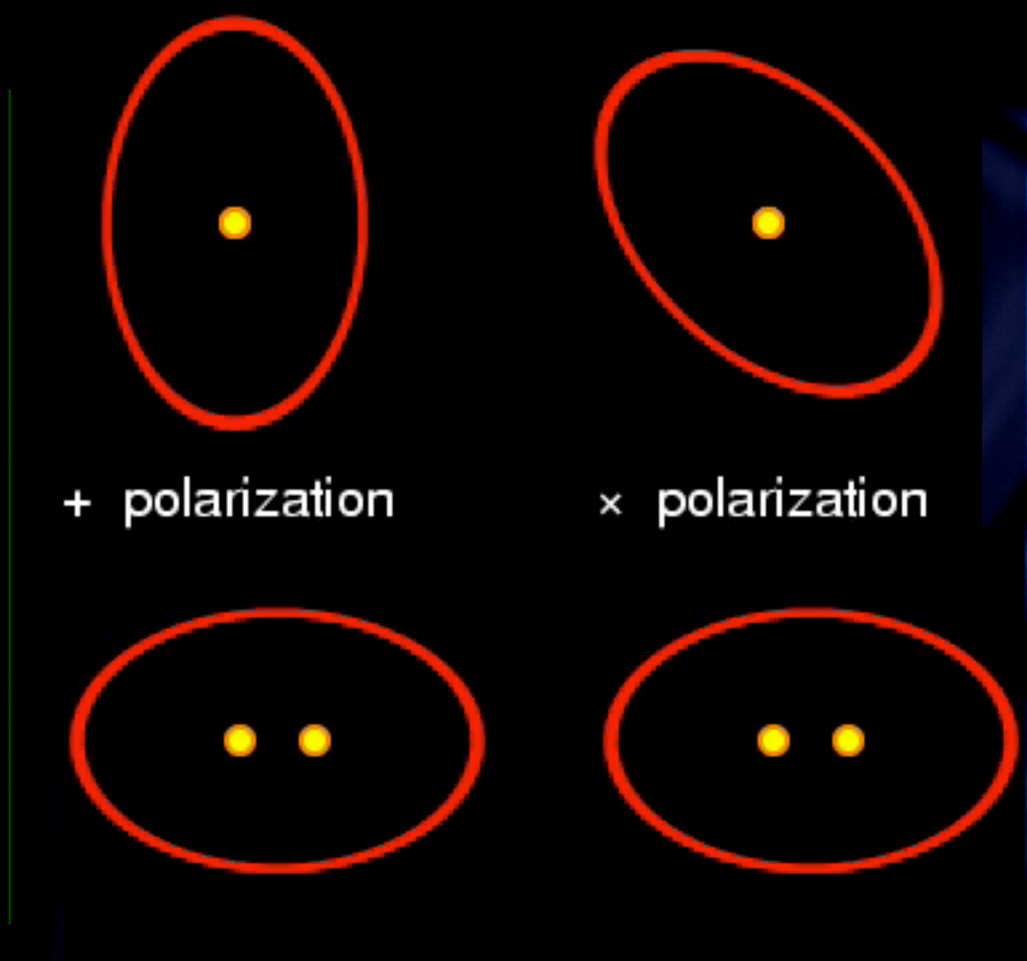
# Effects of GWs

- 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 $h_\times$

$$\frac{\delta L}{L} = \frac{h}{2}$$

deformation wave amplitude





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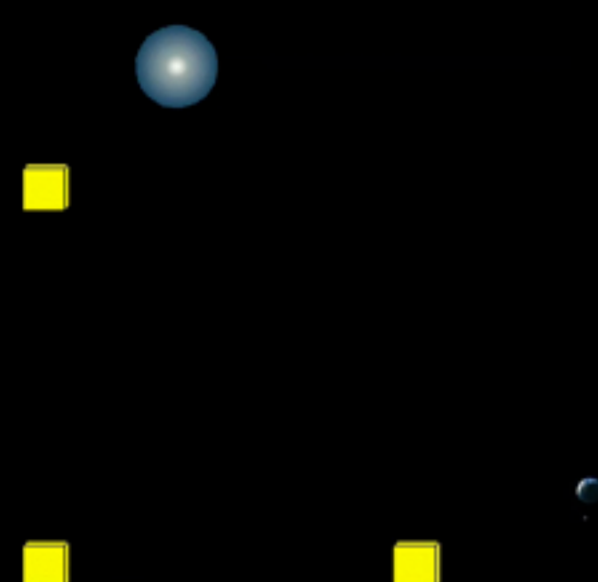

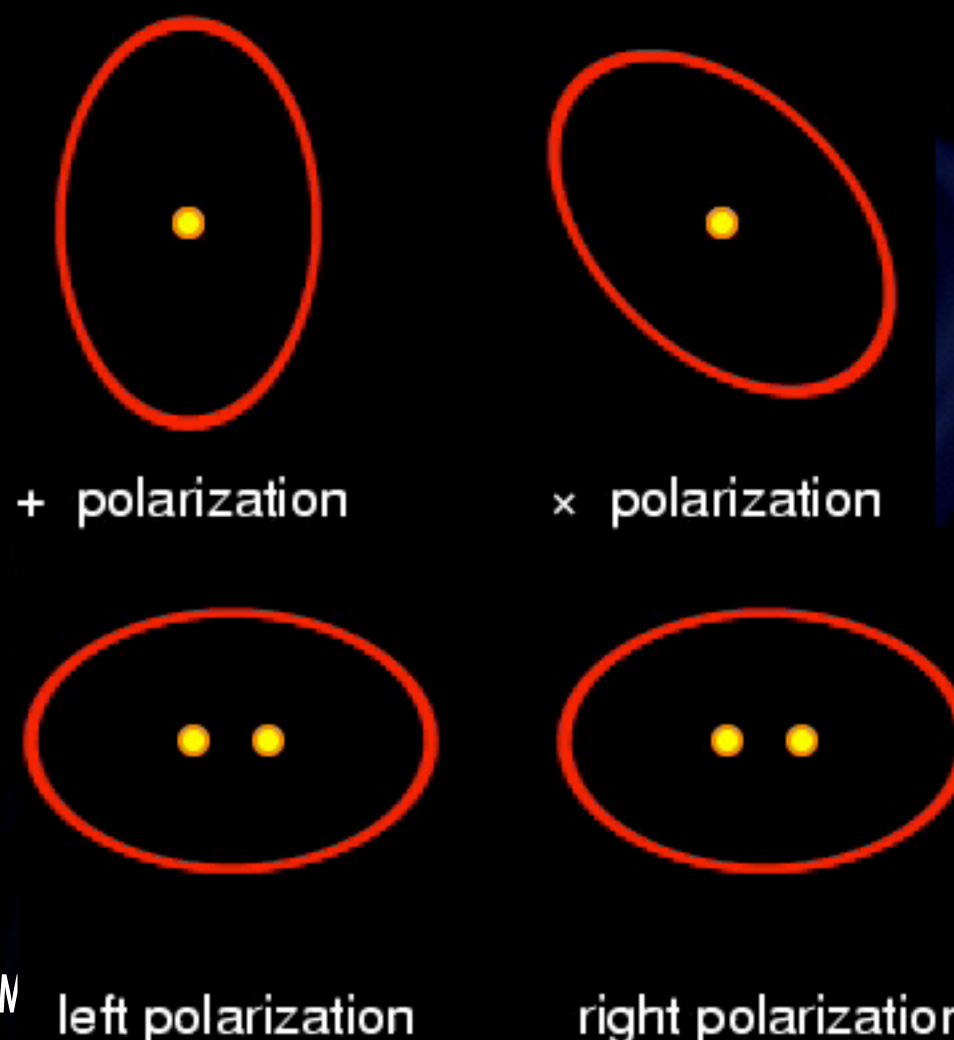

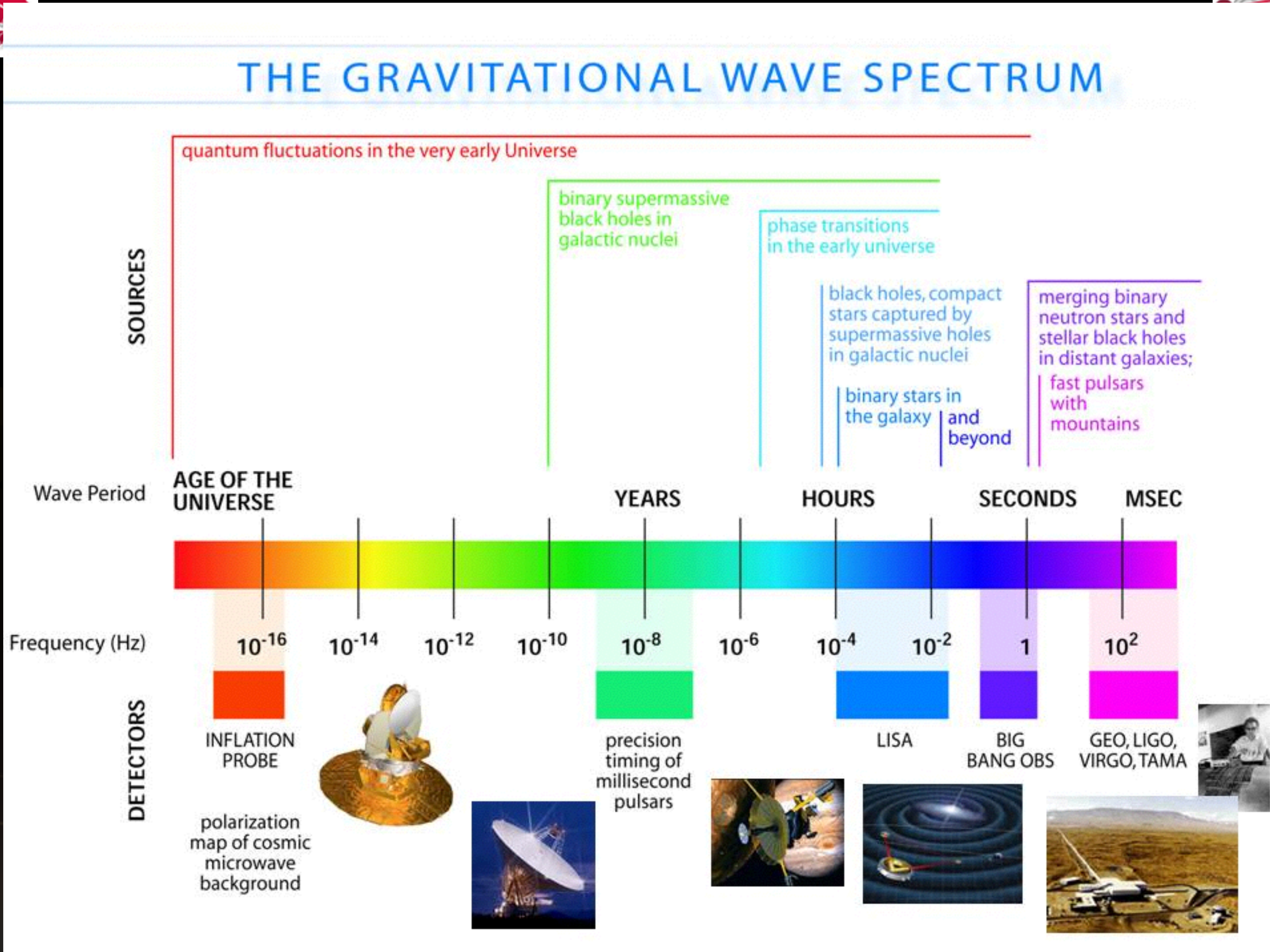
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quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
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AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
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102
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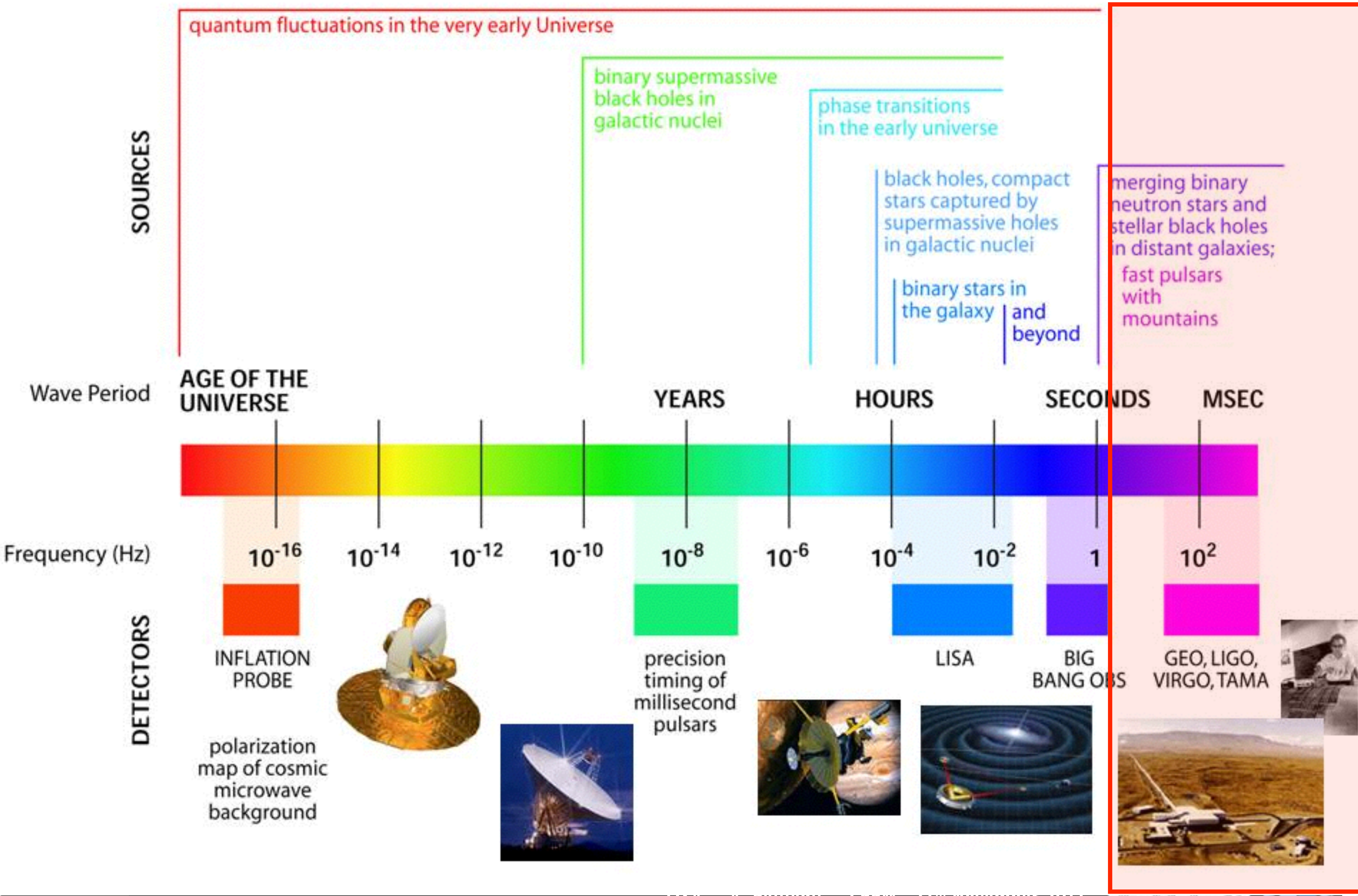
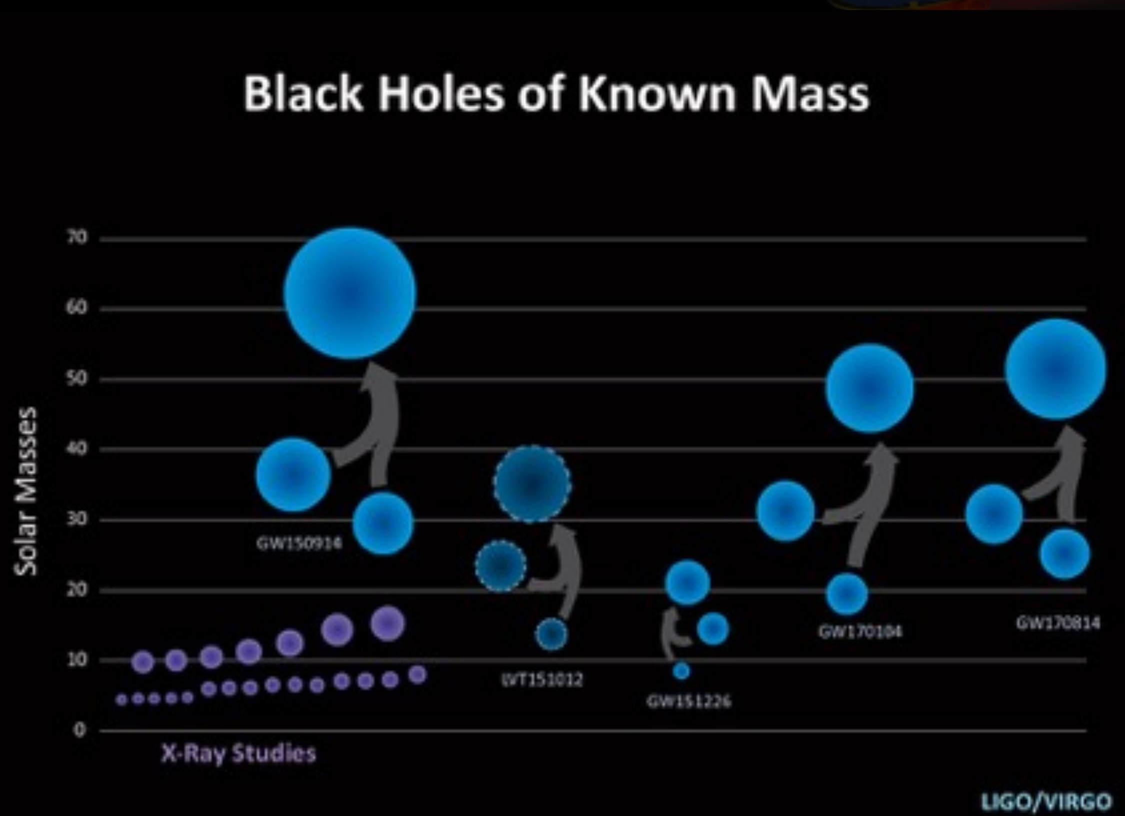
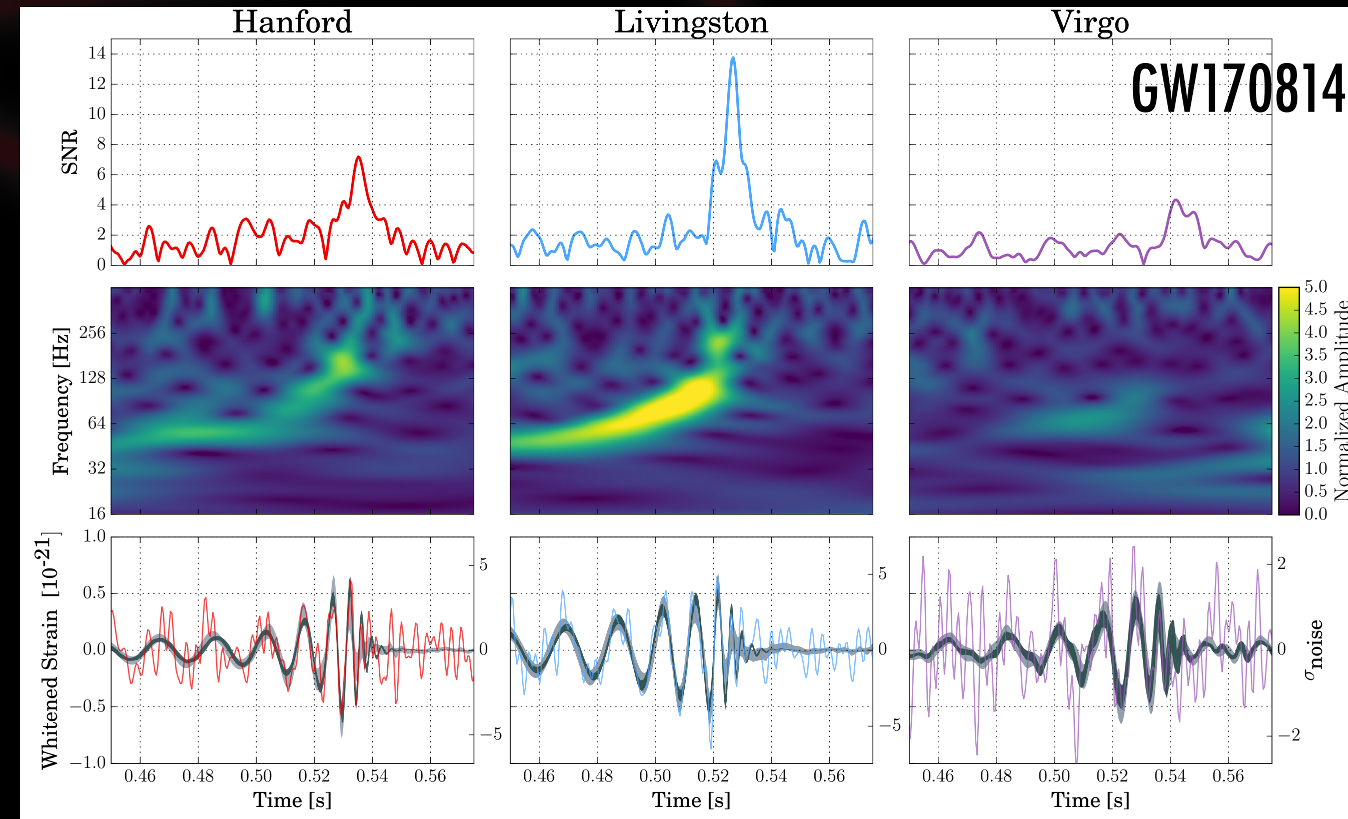
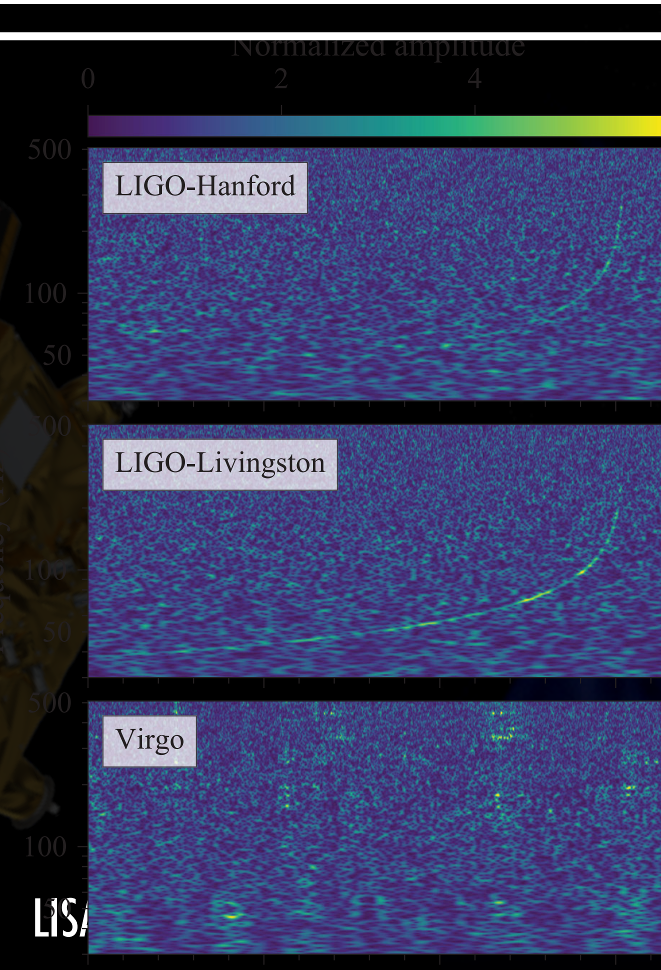


# Ground-based obs.: GWs detected




Binary Neutron Star - GW170817



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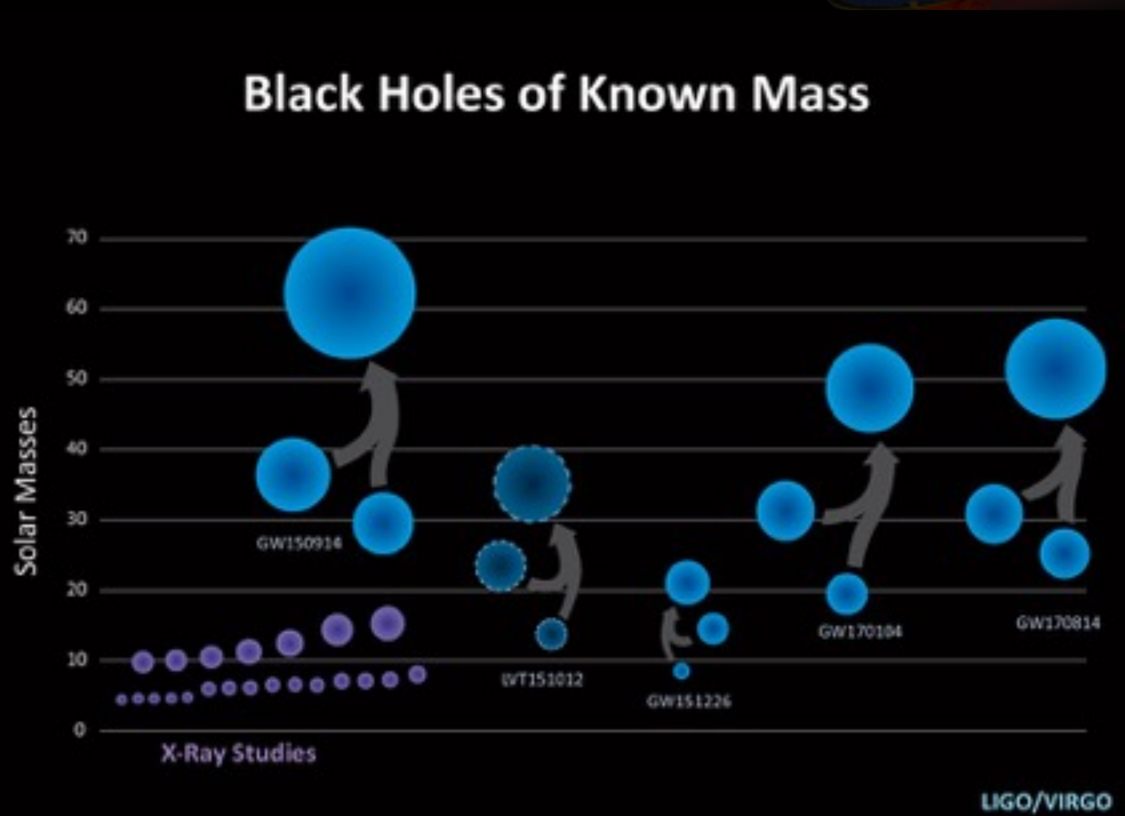


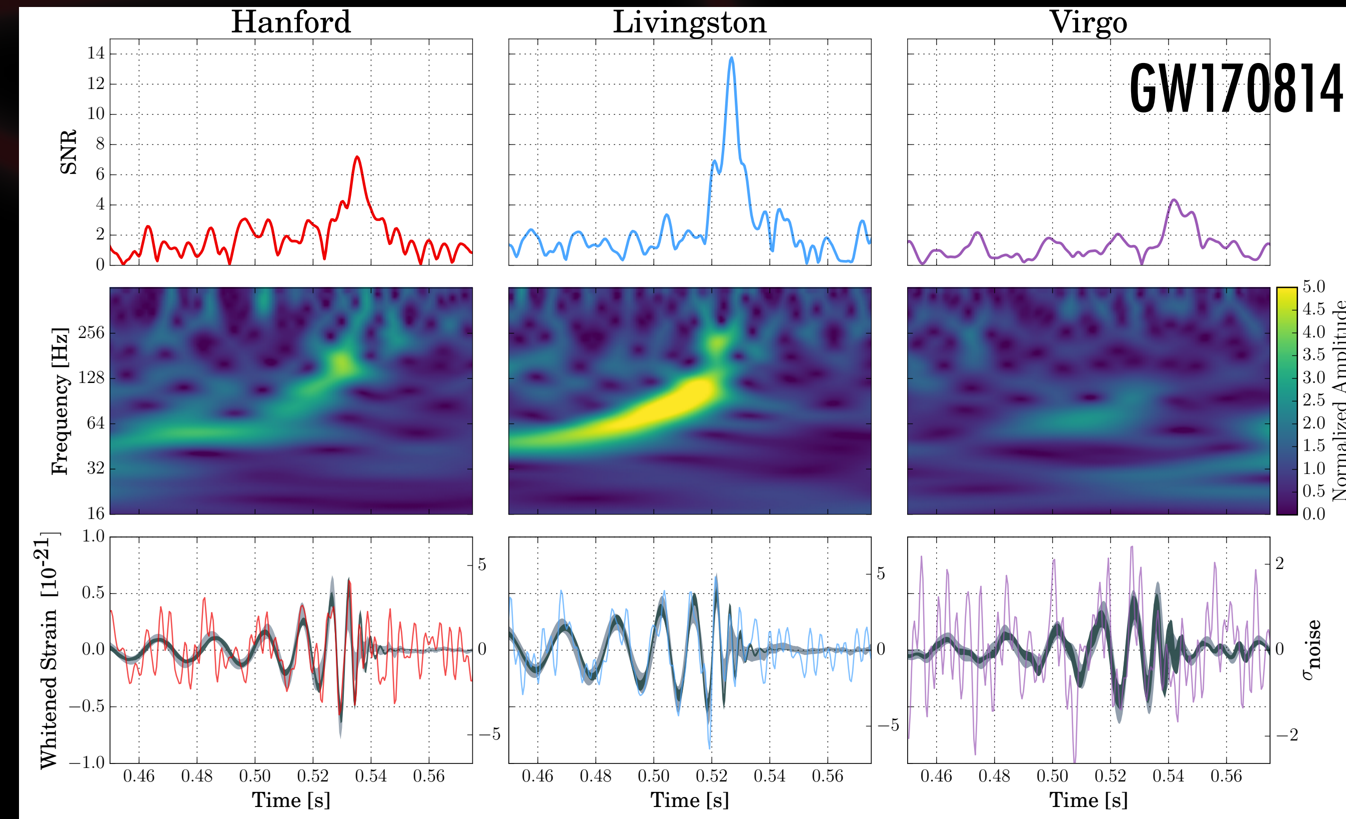


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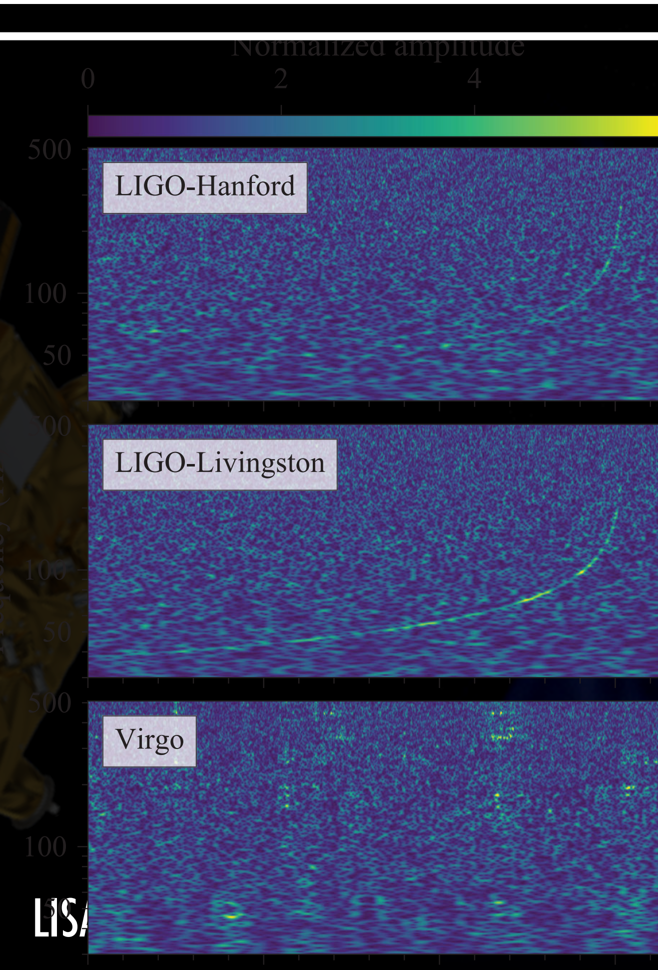

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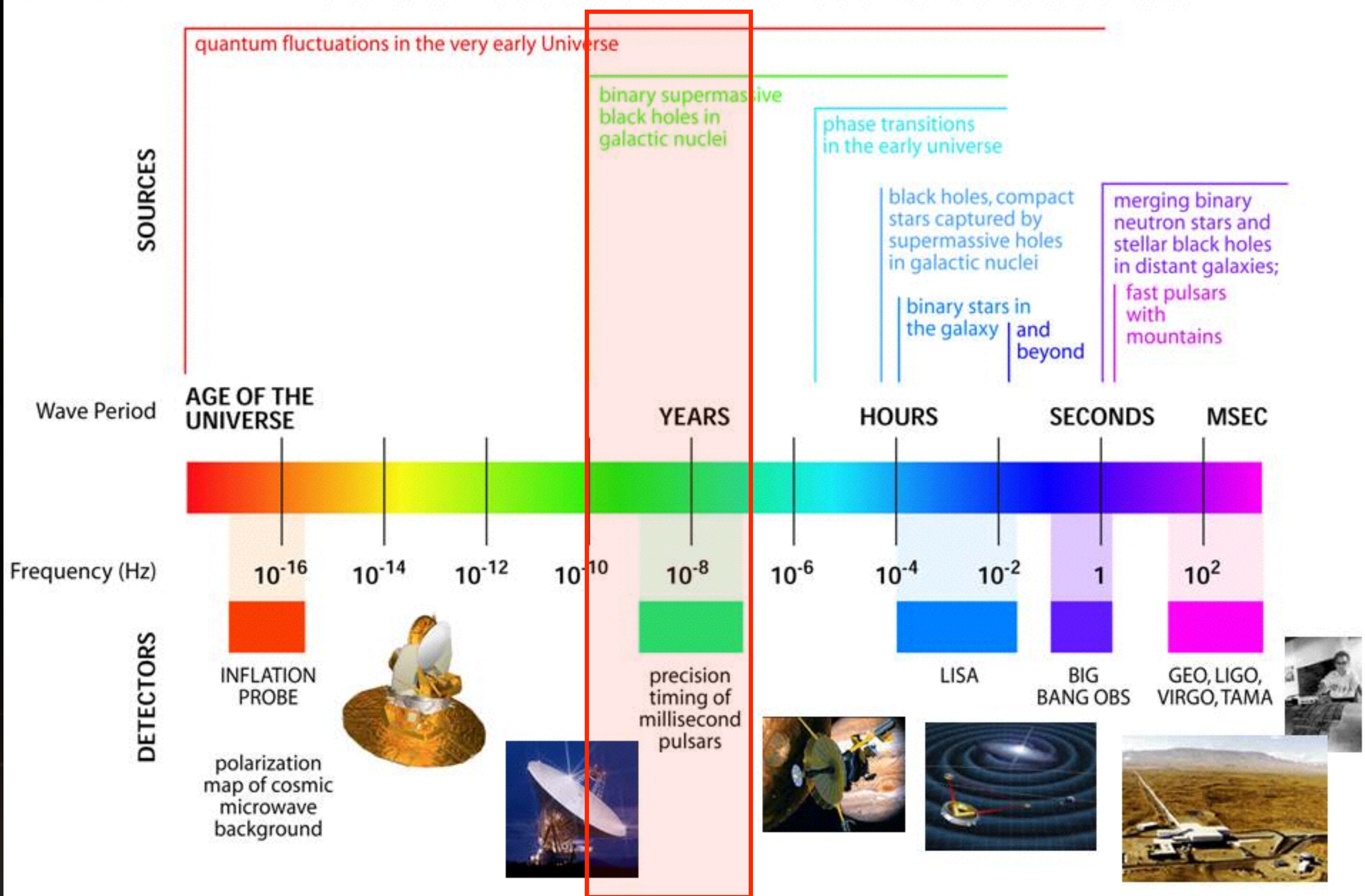
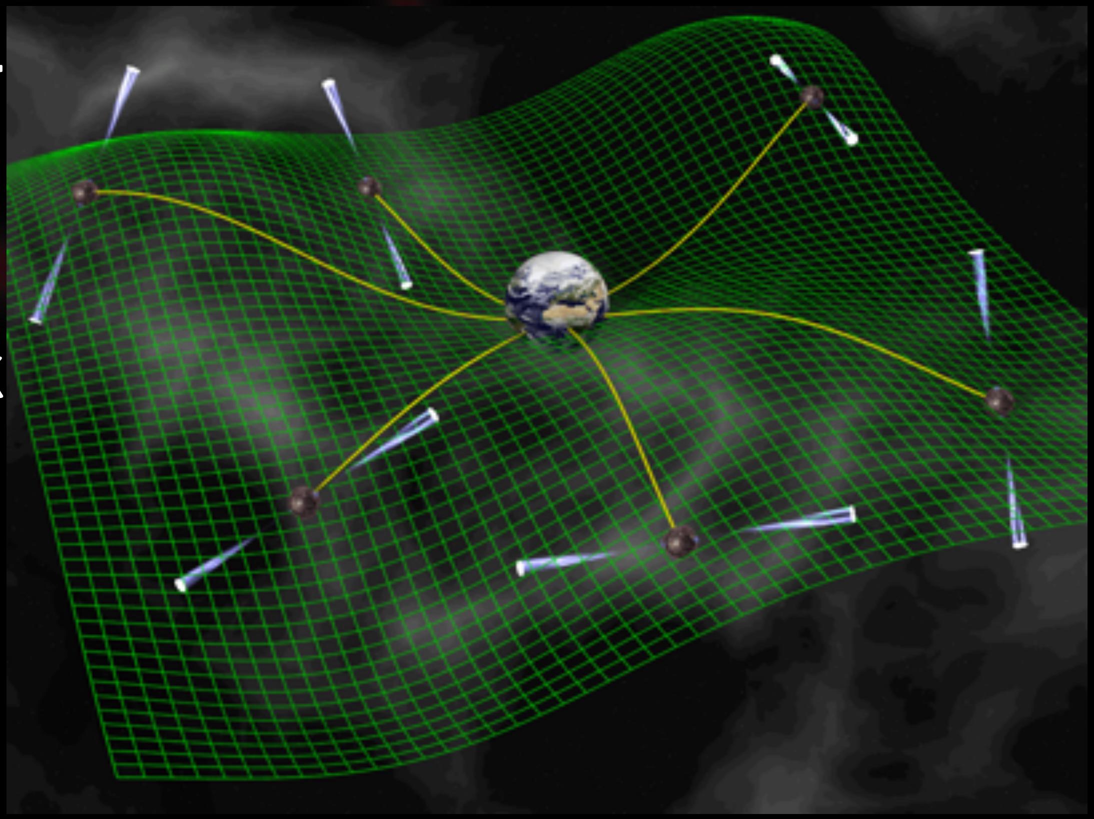
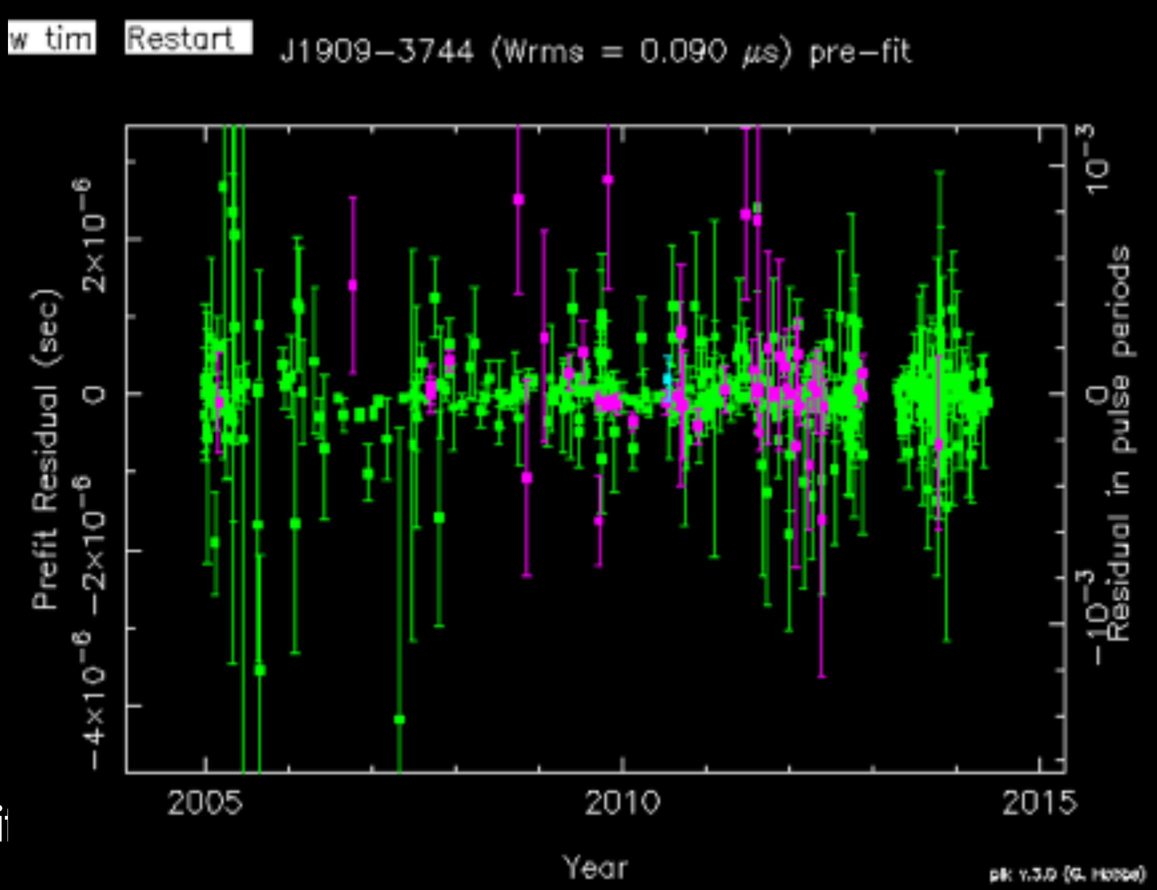
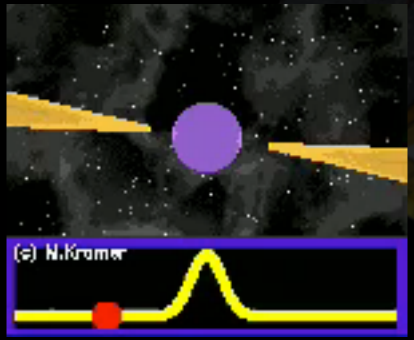


# Pulsar Timing Array

- Pulsar: magnetized rotating neutron star emitting pulse as a lighthouse
- Millisecond pulsar = high precision clock
- Series of extremely regular pulses are perturbed by GWs passing between pulsar and Earth
- By timing an array of milliseconds pulsars we can detect GWs at nHz
  - SuperMassive BH binaries
  - Cosmological backgrounds





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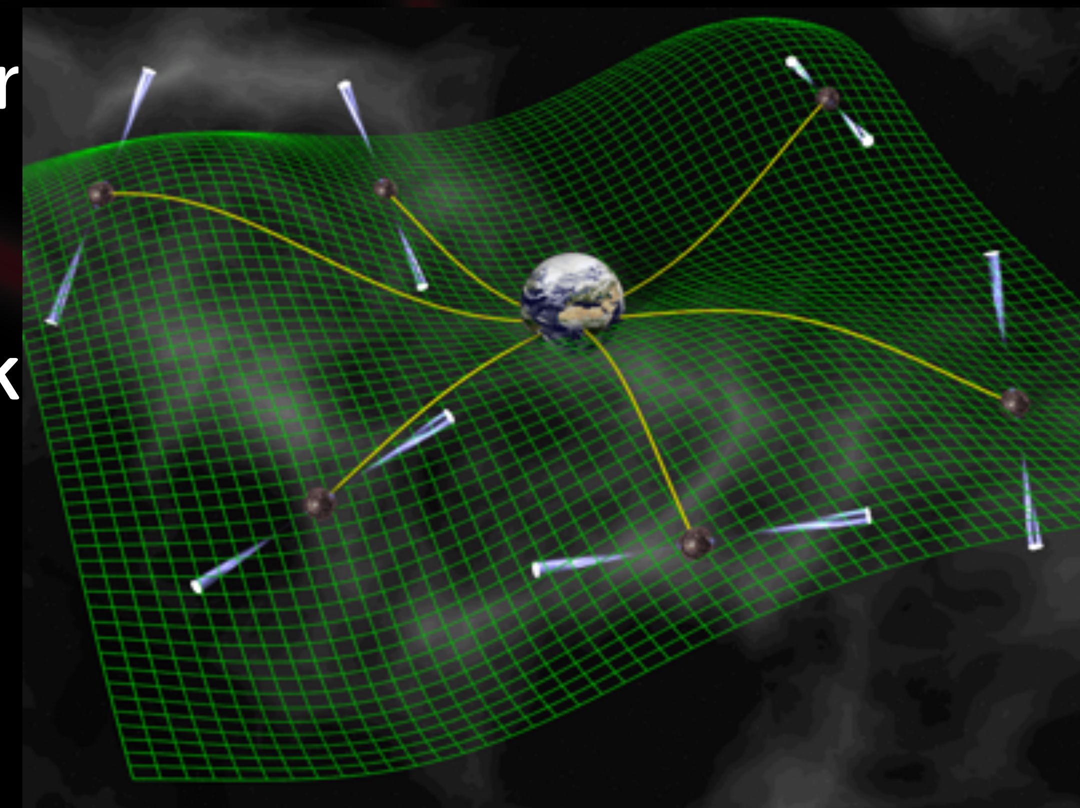

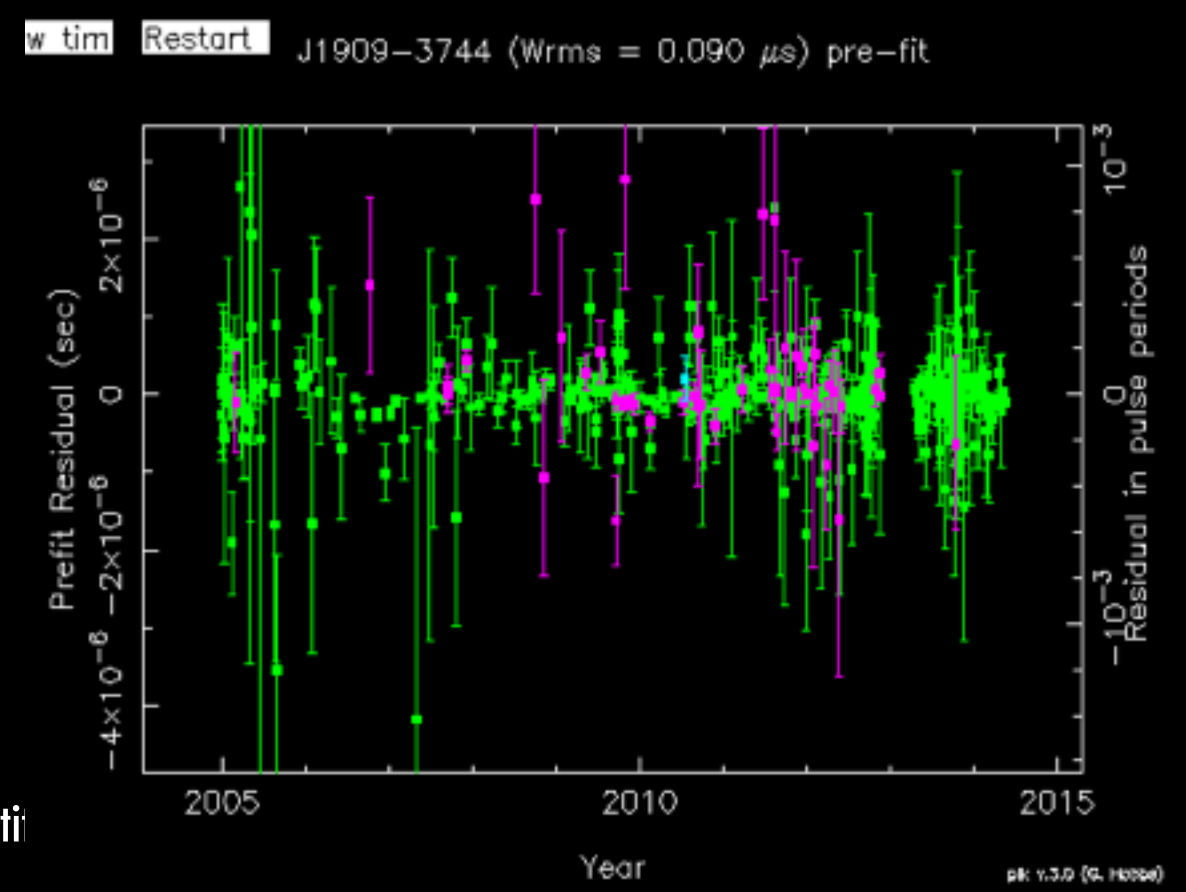


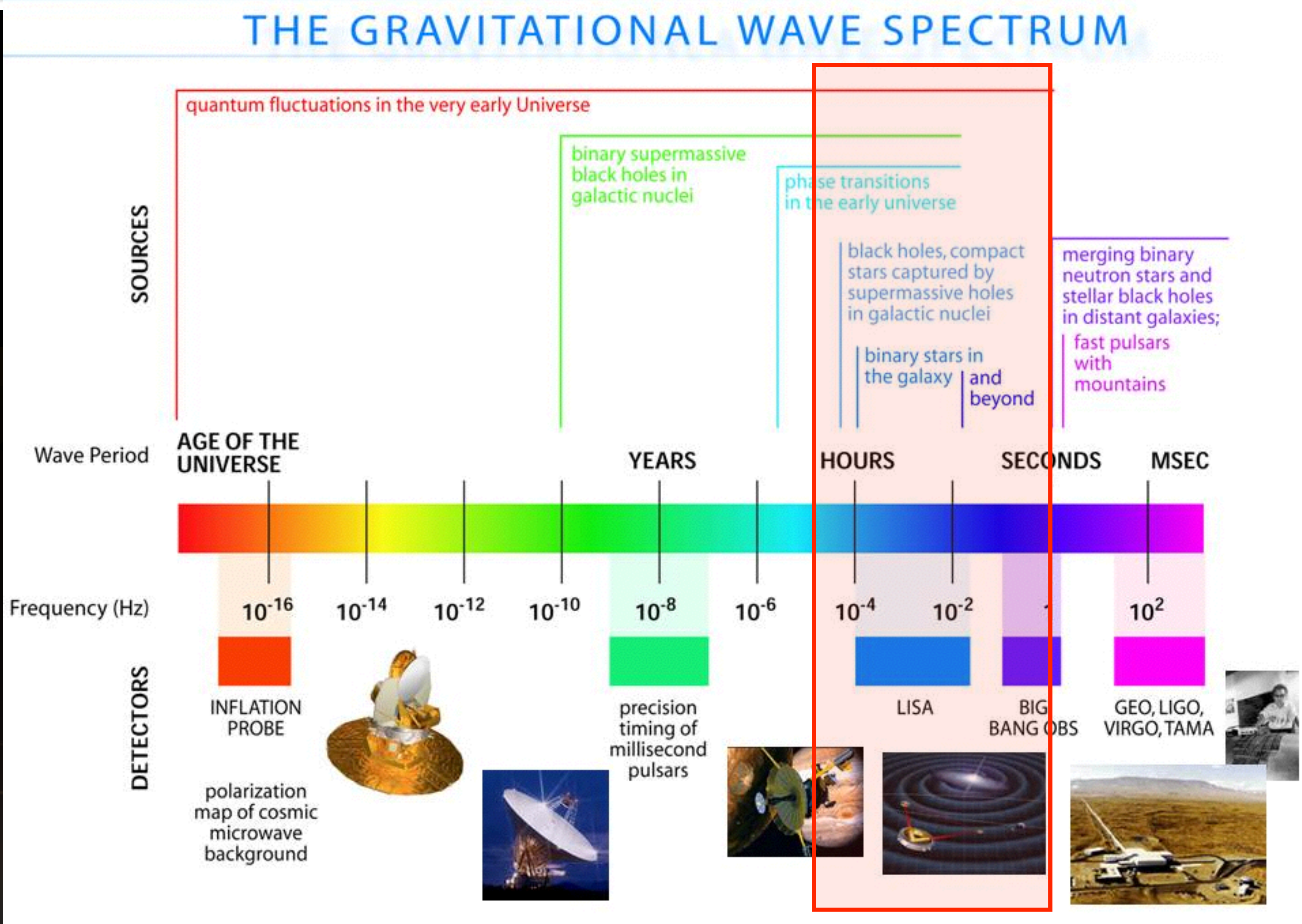

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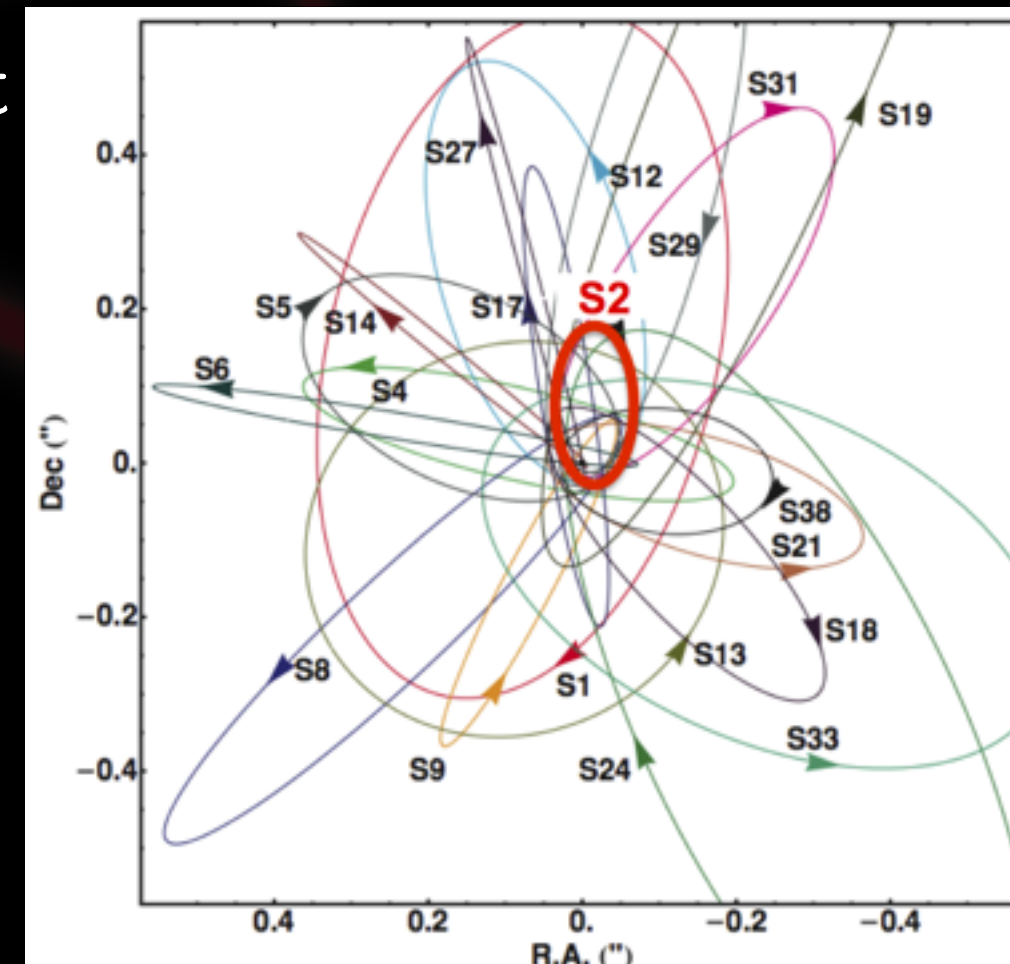
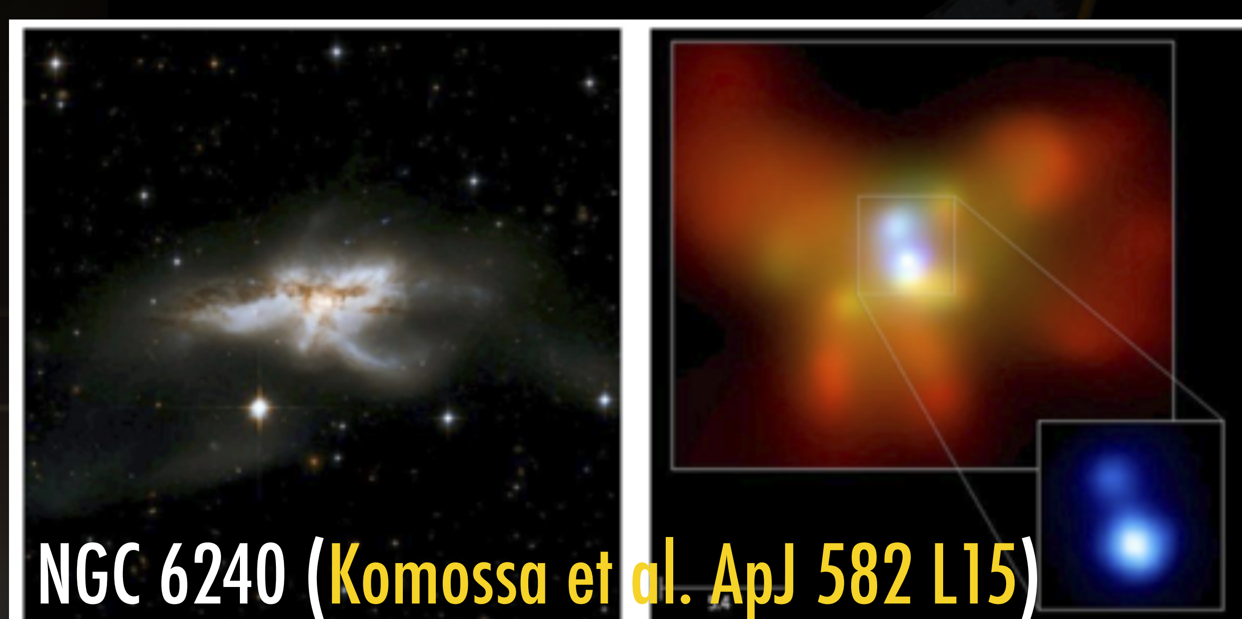
# Supermassive black hole binaries

- 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.
  $\rightarrow$ MBH binaries should exist.
- Observations of double AGN

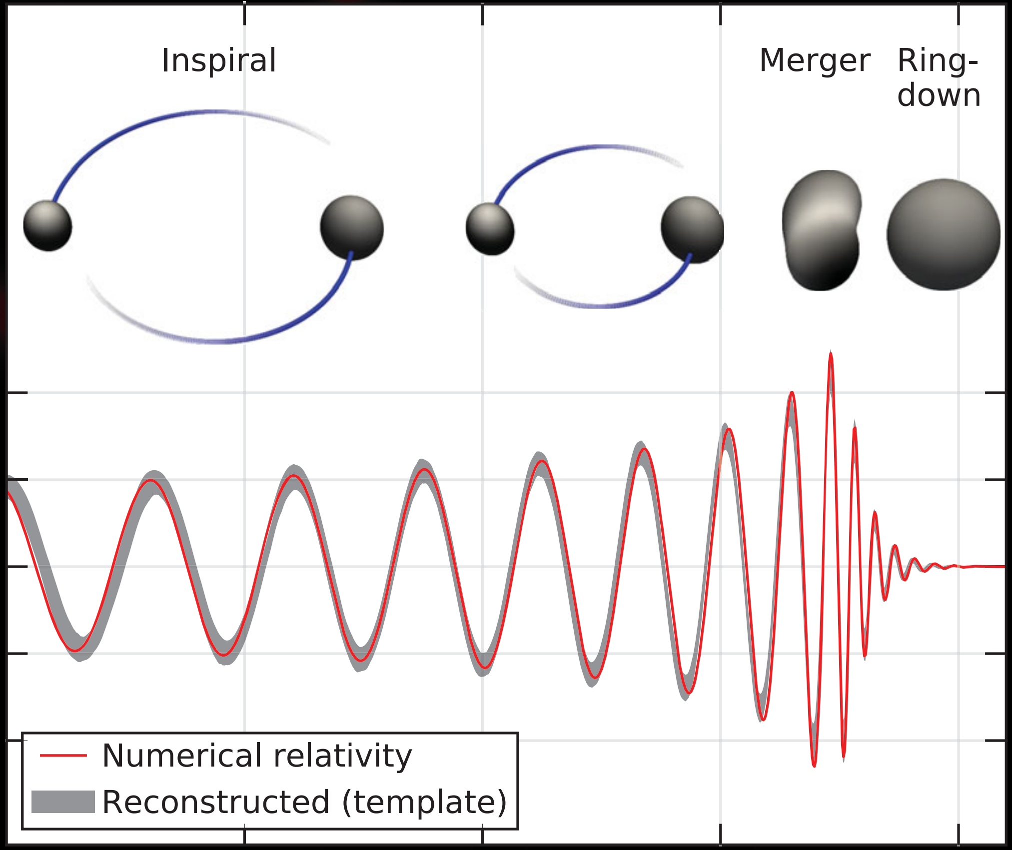




NGC 6240 (Komossa et al. ApJ 582 L15)

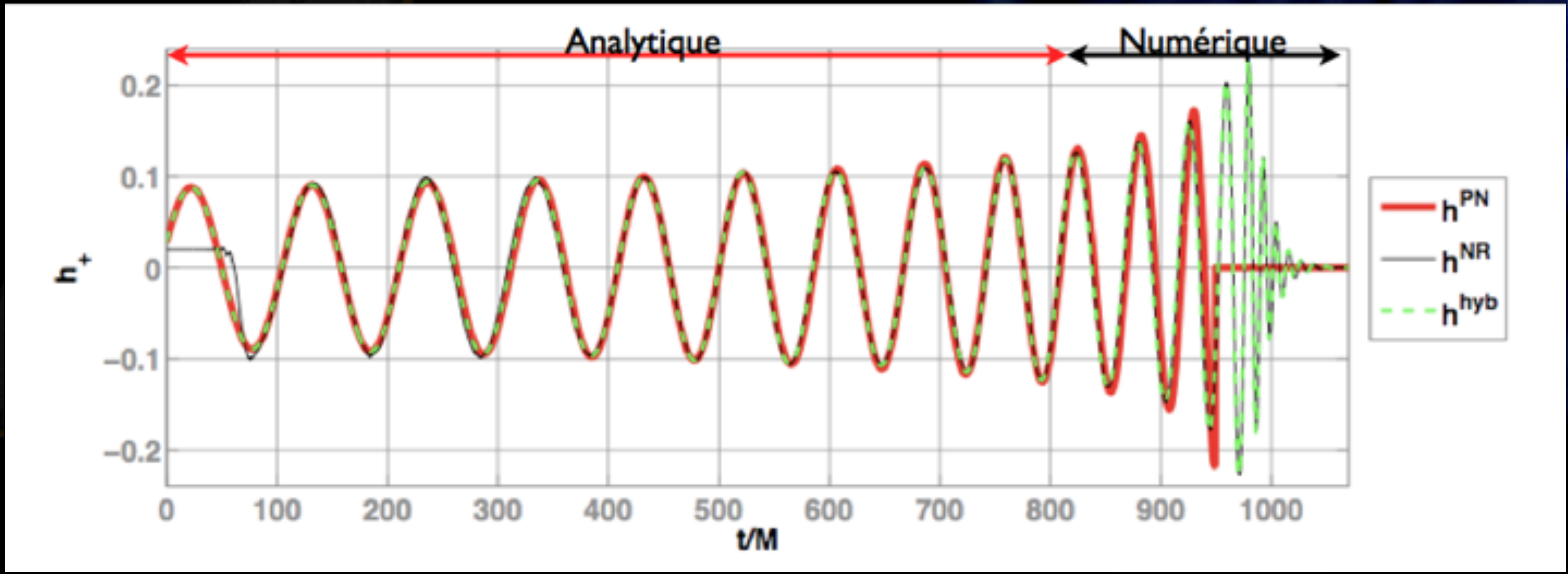

Antennae galaxies

# Supermassive black hole binaries

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

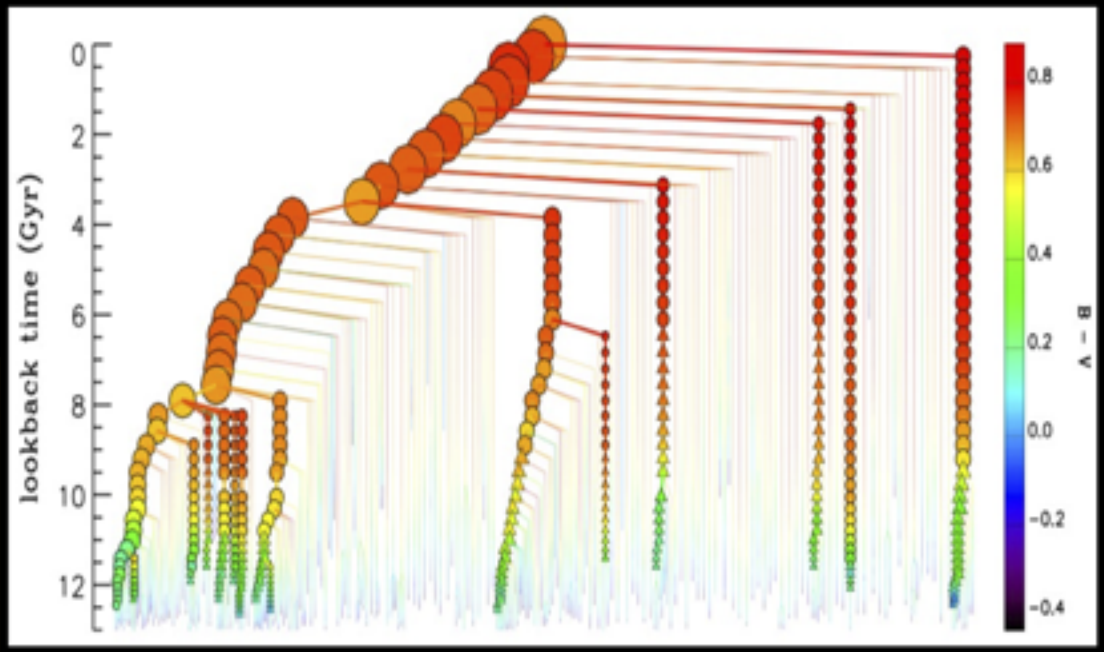



- No full waveform but several approximations exist :
  - Phenomenological waveform,
  - Effective One Body,
  - …



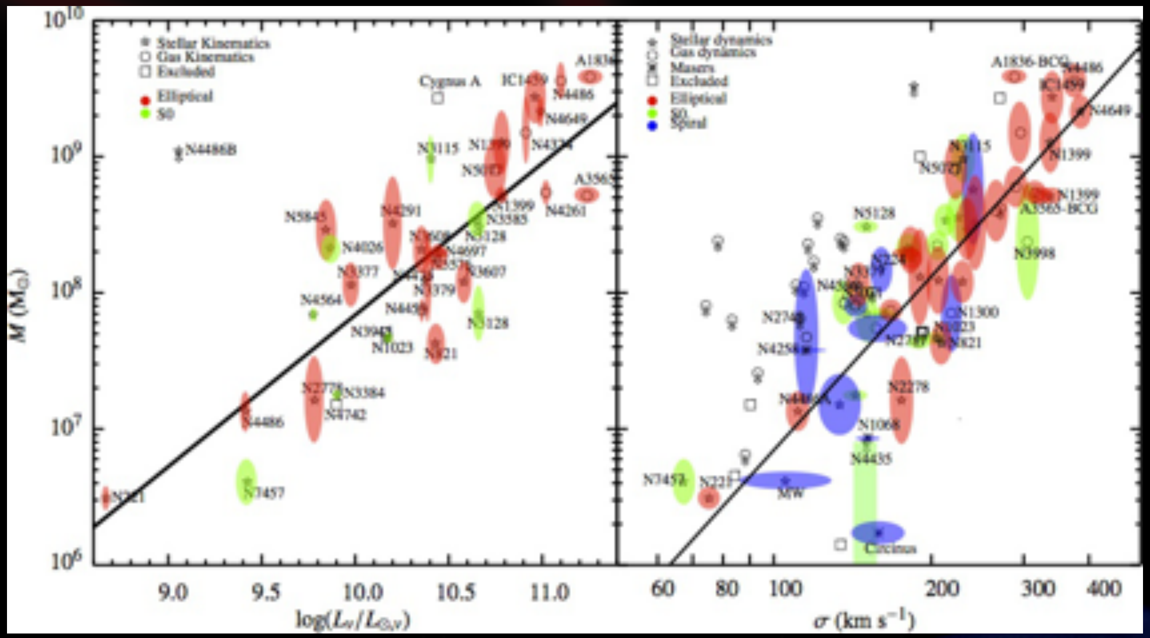
# Supermassive black hole binaries

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

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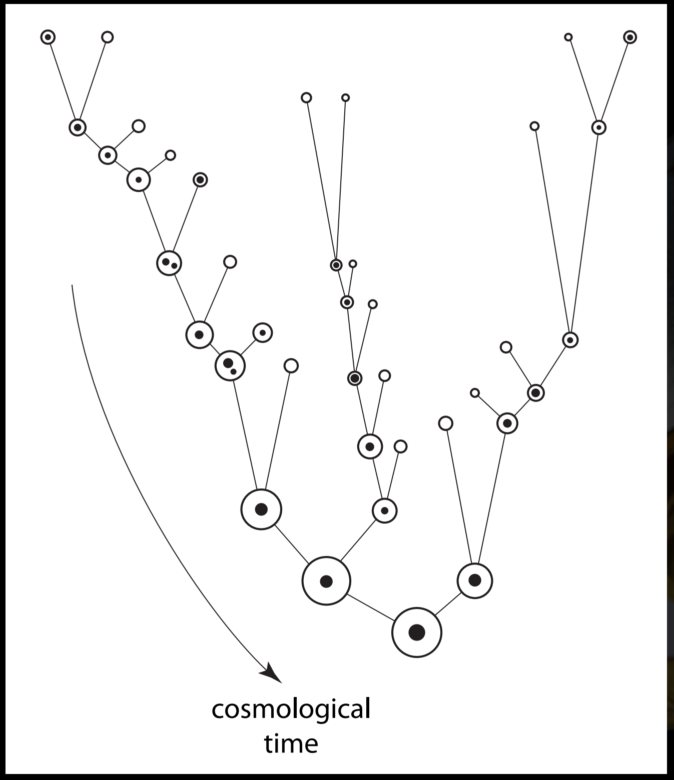
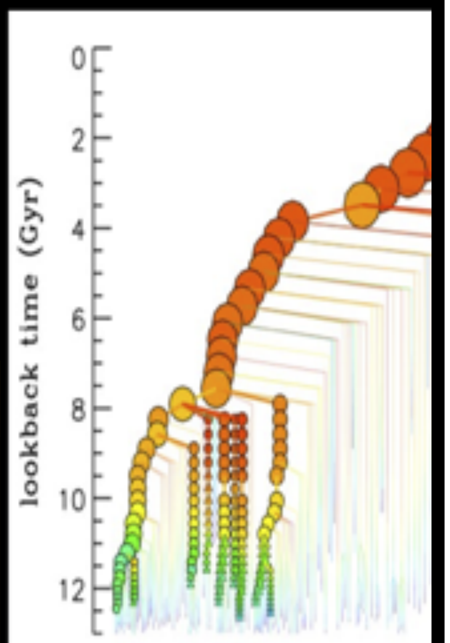



- Work from E. Barausse (IAP), A. Sesana (Univ. of Birmingham), M. Volonteri (IAP) et al.

# Supermassive black hole binaries

Galaxi
(cosmolo

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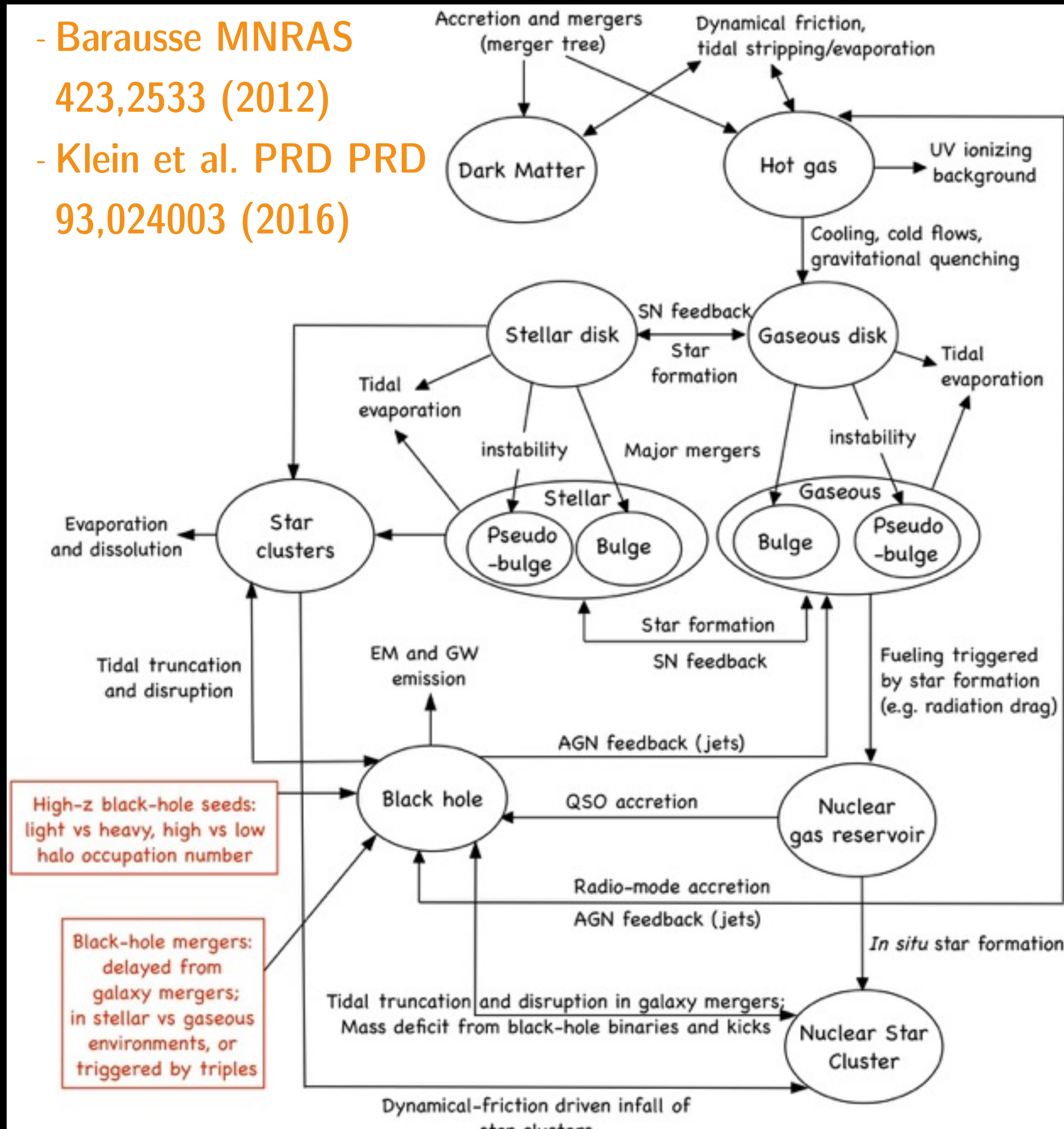


speed of stars in
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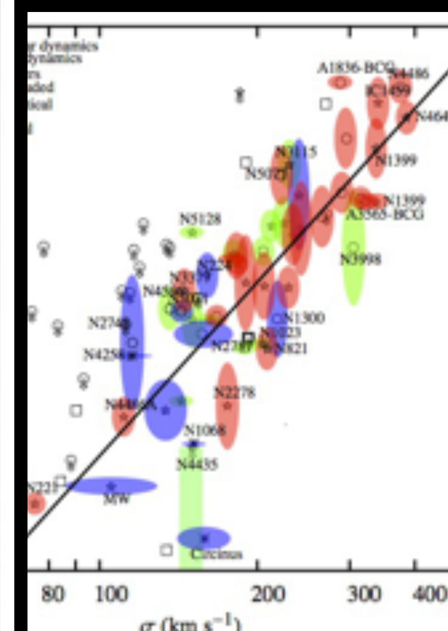
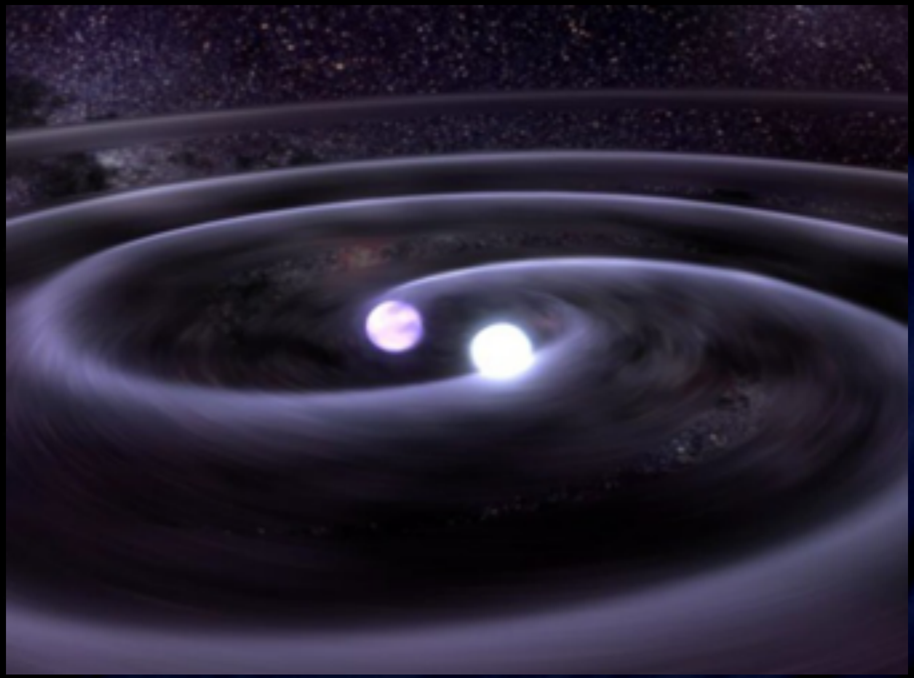



(IAP), A.
ngham), M.

# Compact solar mass binaries

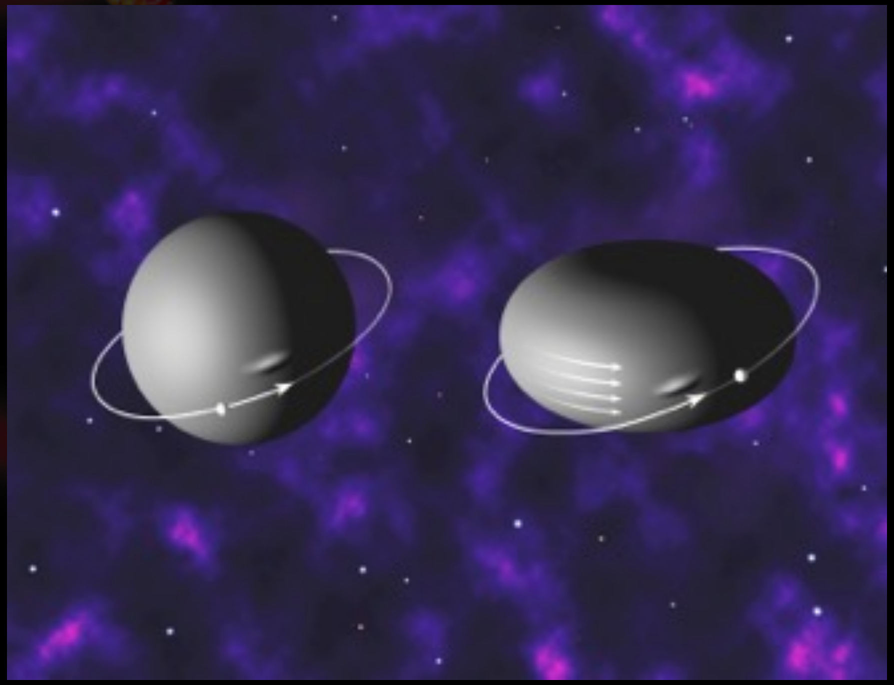
- Large number of stars are in binary system.
- Evolution in white dwarf (WD) and neutron stars (NS).
  => existence of WD-WD, NS-WD and NS-NS binaries
- Estimation for the Galaxy: 60 millions.
- Gravitational waves:
  - most part in the slow inspiral regime (quasi-monochromatic): GW at mHz
  - few are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

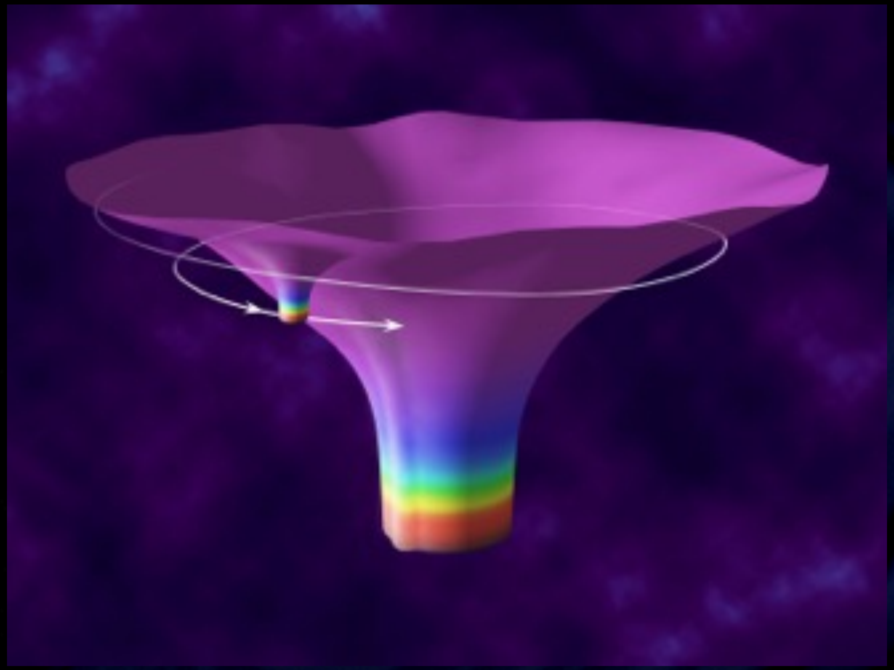


- Several known system emitting around the mHz

# EMRIs

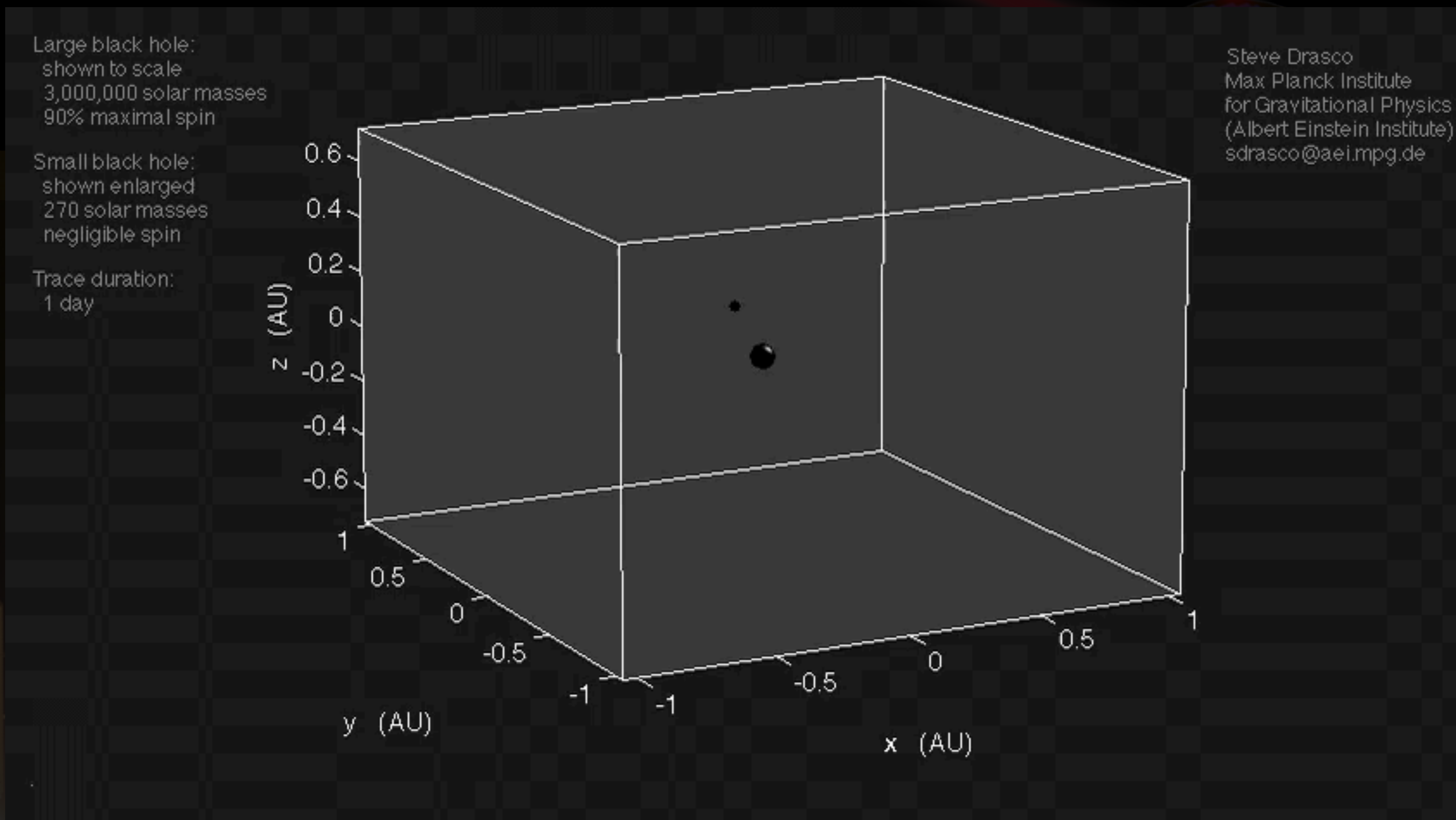
- Capture of a "small" object by massive black hole ($10 – 10^6\ M_{Sun}$)
  - Mass ratio > 200
  - GW gives information on the geometry around the black hole.
  - Test General Relativity in stong field
  - Frequency : 0.1 mHz to 0.1 Hz
  - Large number of source could be observed by space-based interferometer





# EMRIs

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



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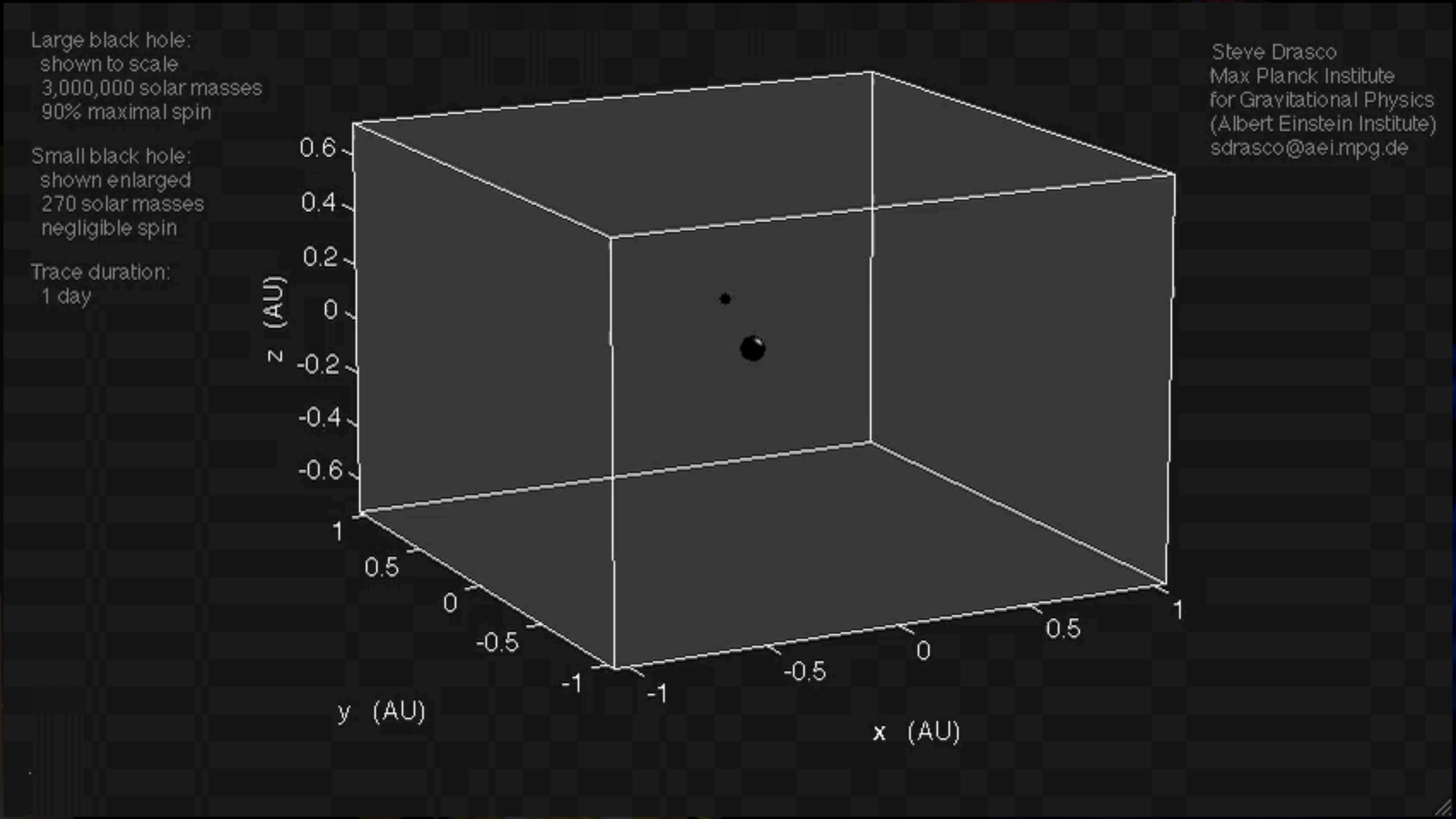
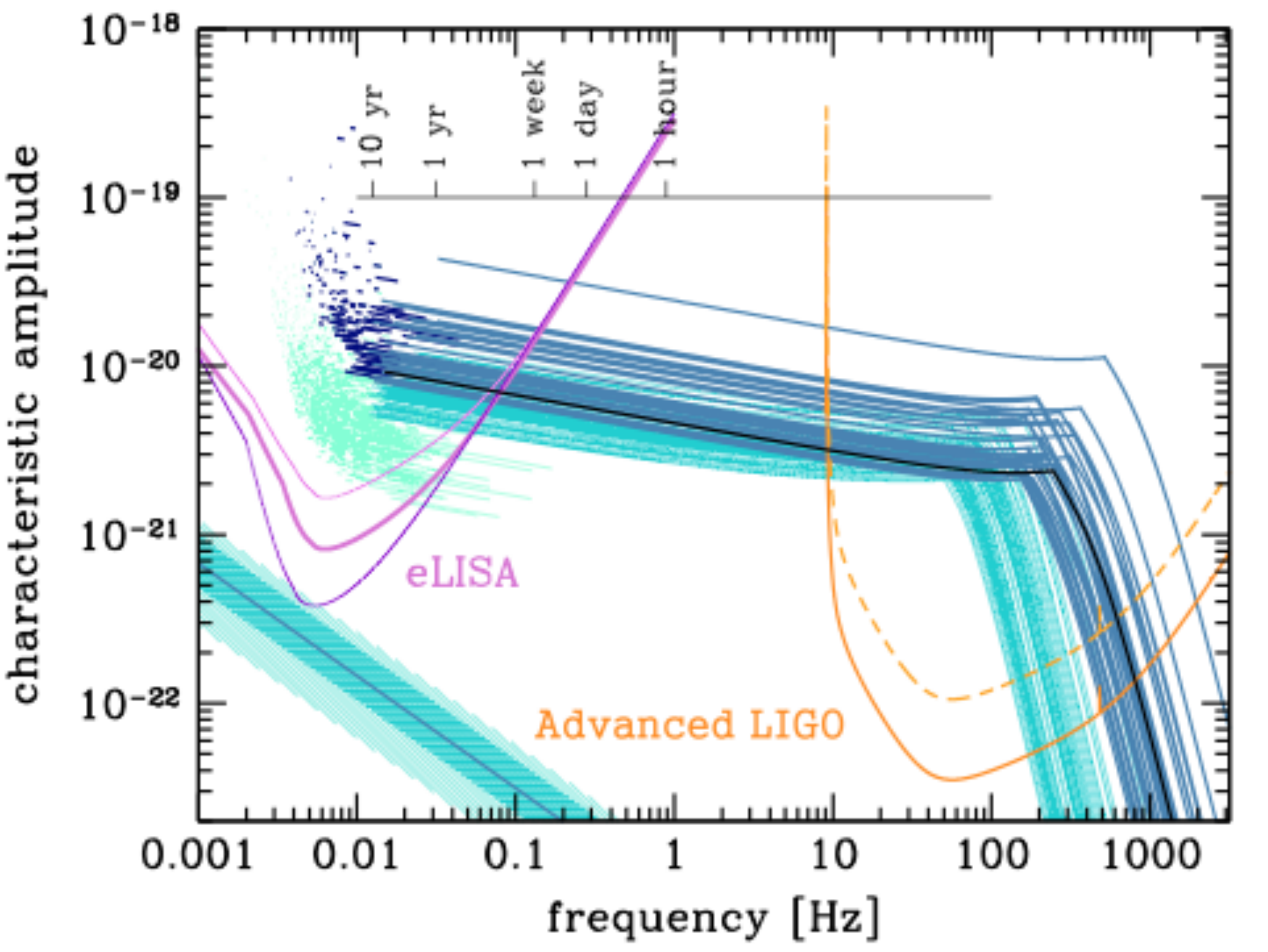


# Black Hole Binaries

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

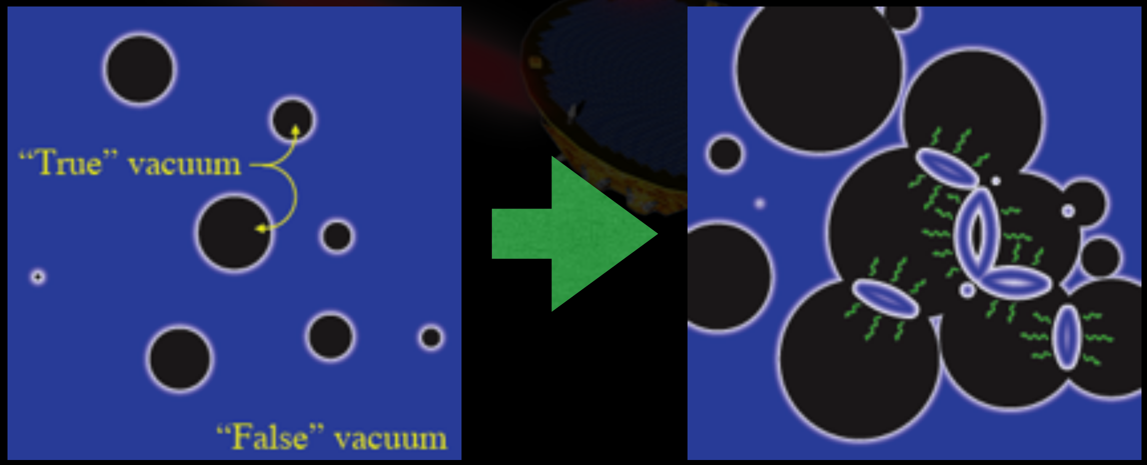
- During most part of the inspiral time, emission in the mHz band => multi-observatories GW astronomy

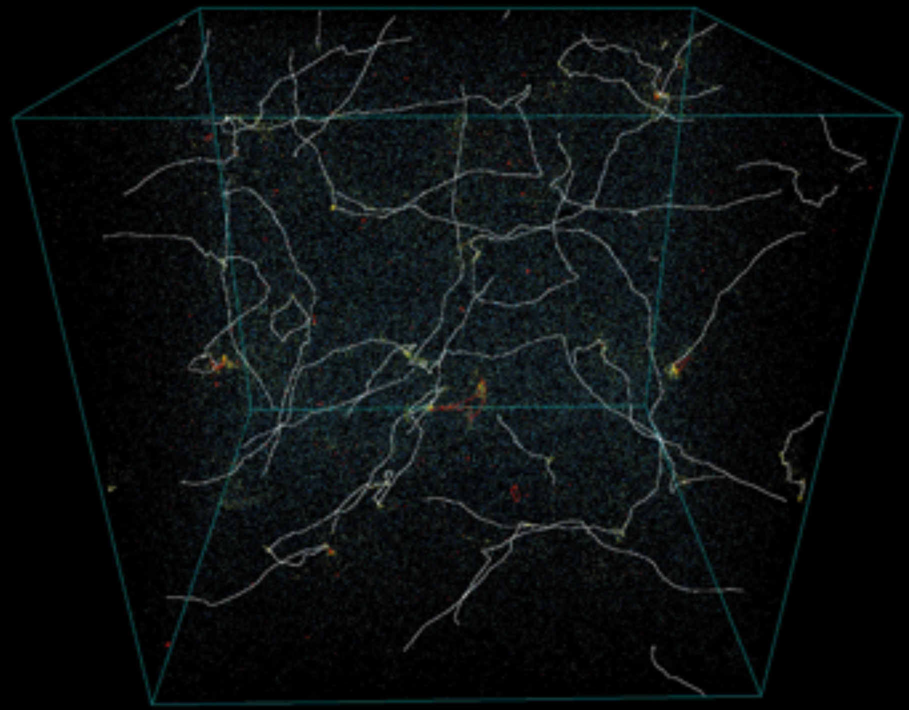


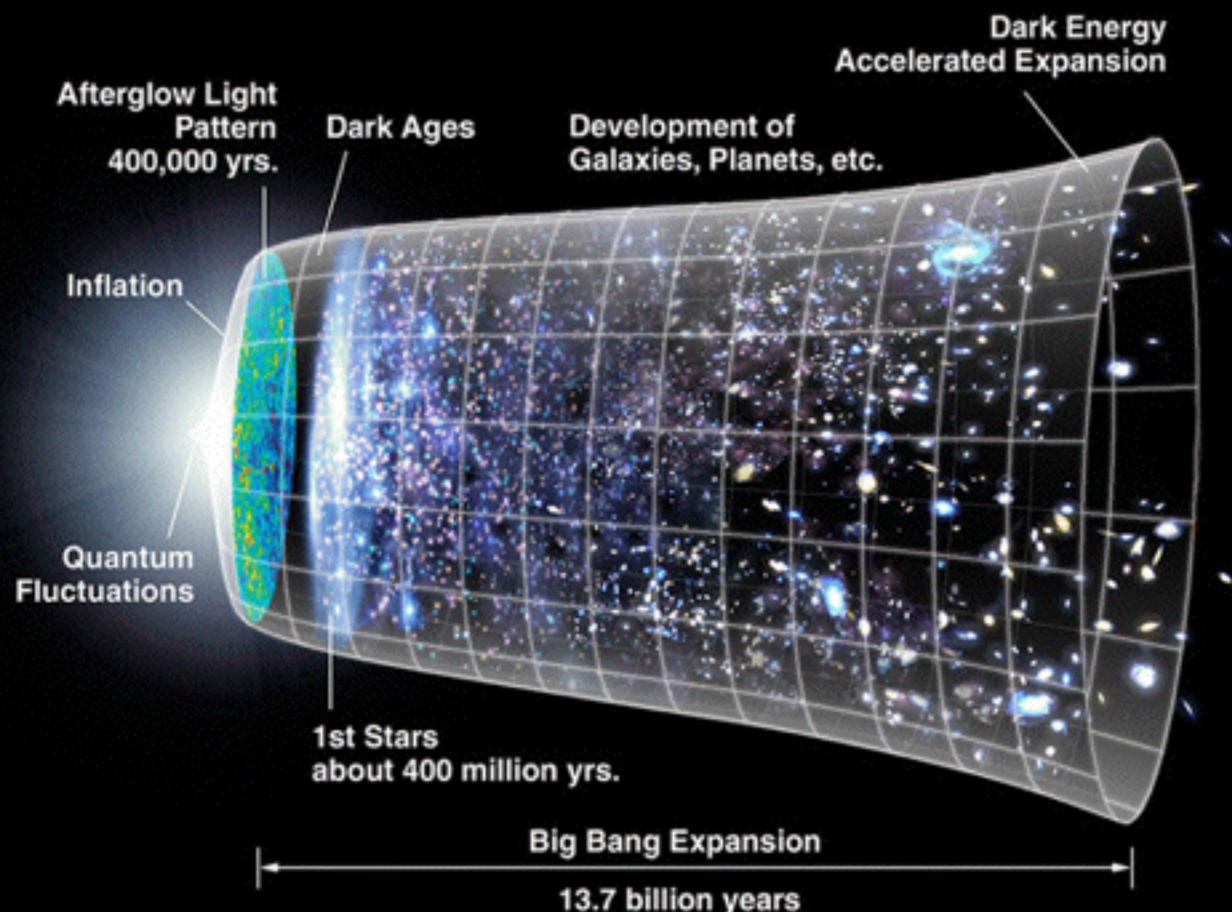

A. Sesana, PRL 116, 231102 (2016)

# Cosmological backgrounds

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



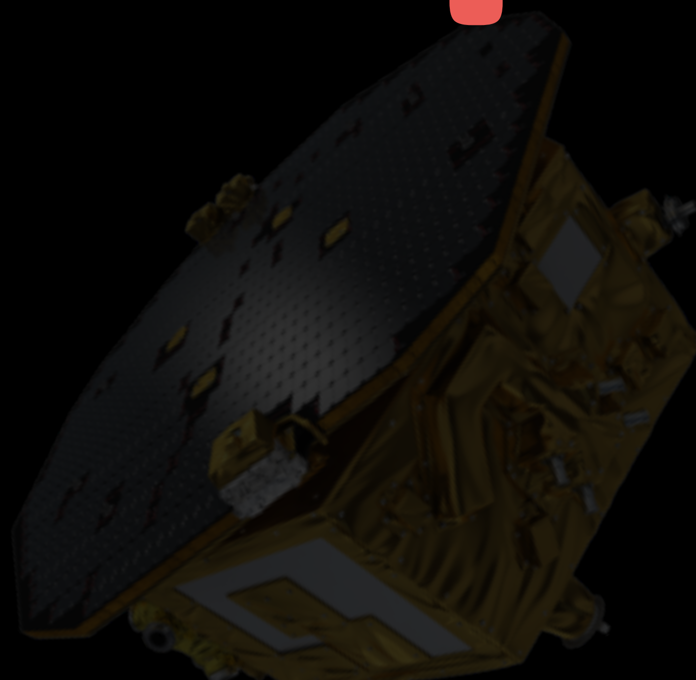





# Unknown sources

- 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 !

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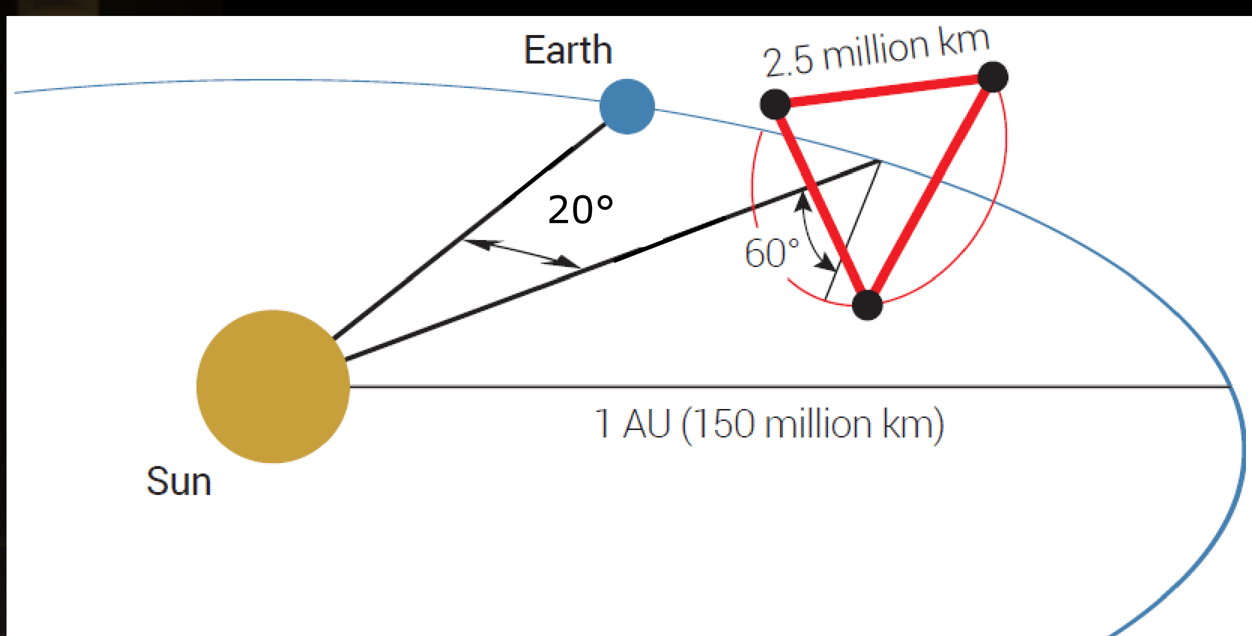
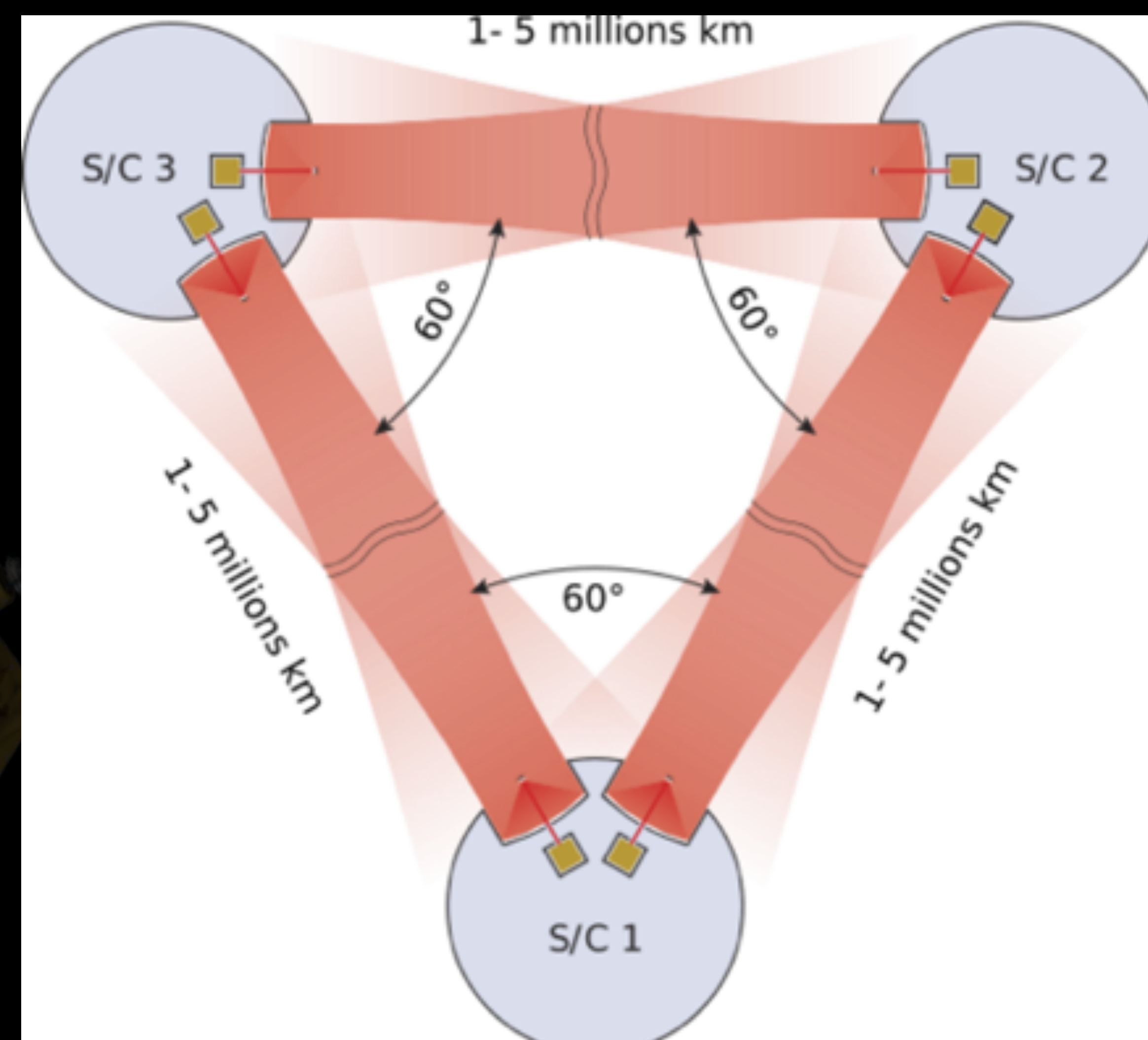
# LISA

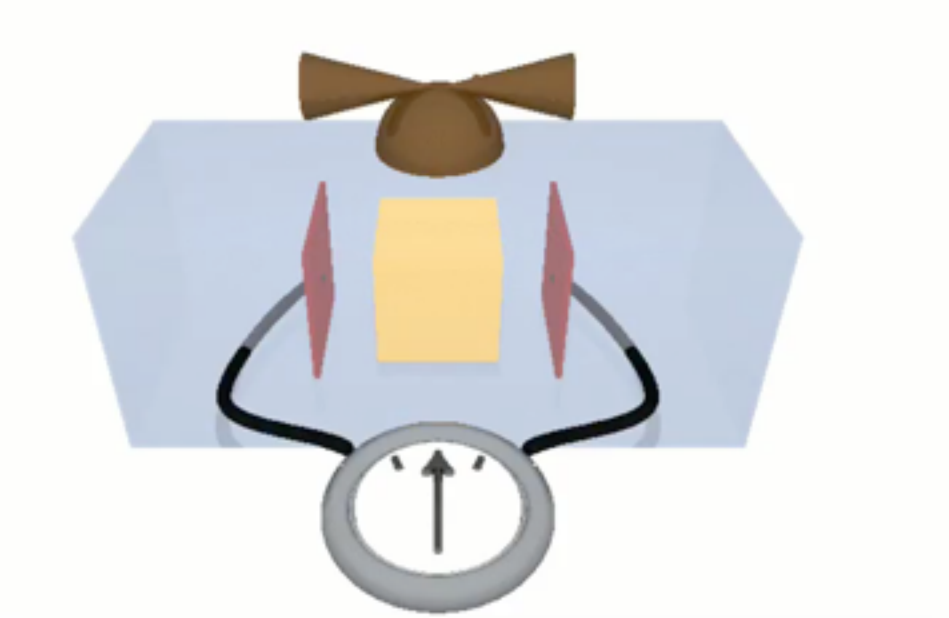
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of $10^{-21}$: few picometers

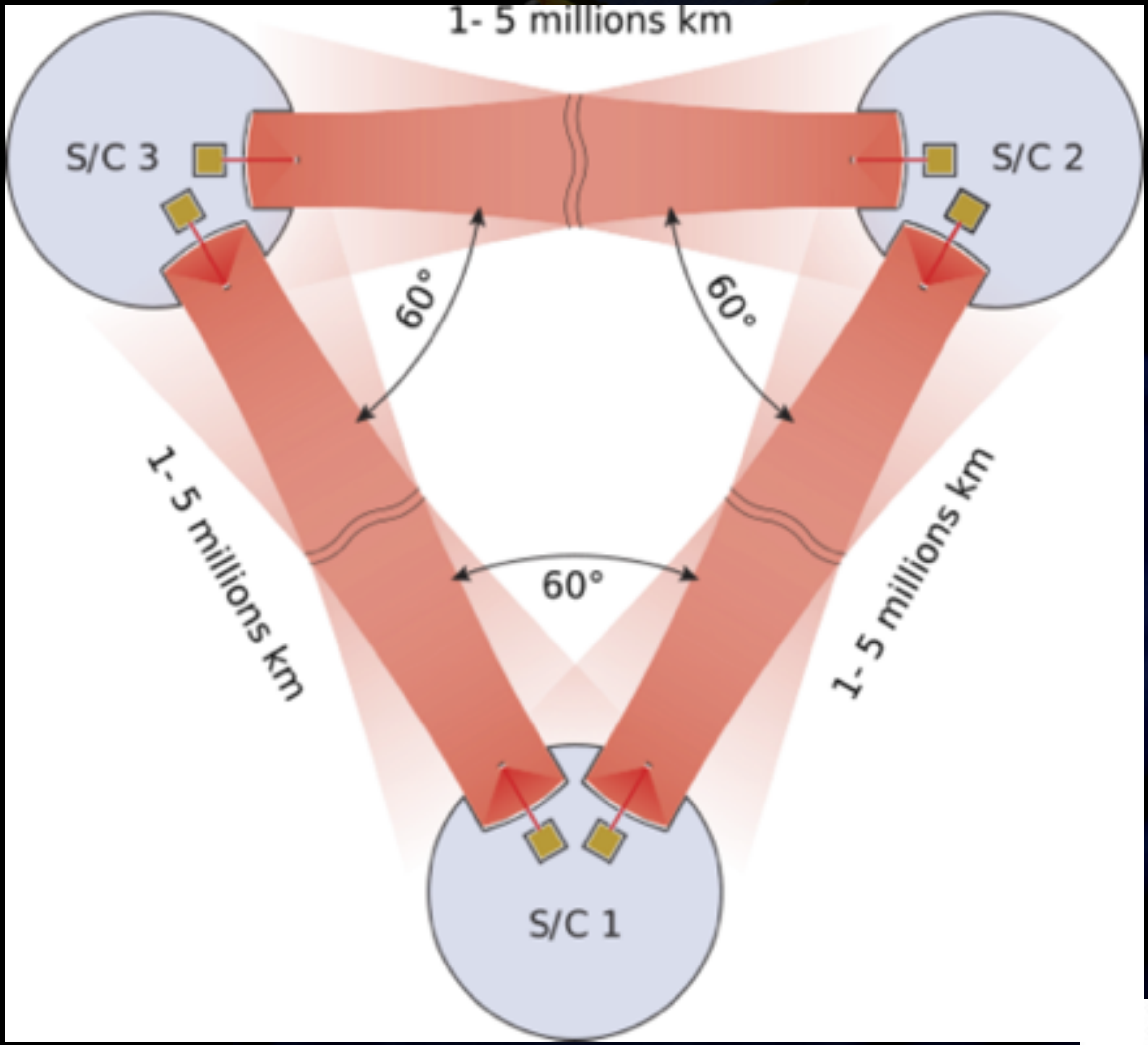


# LISA

- 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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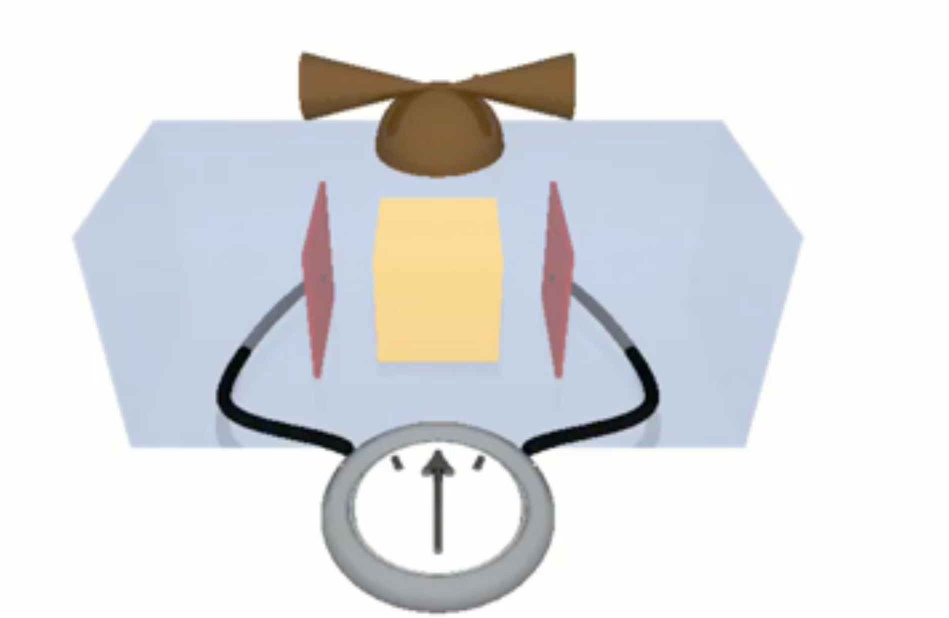
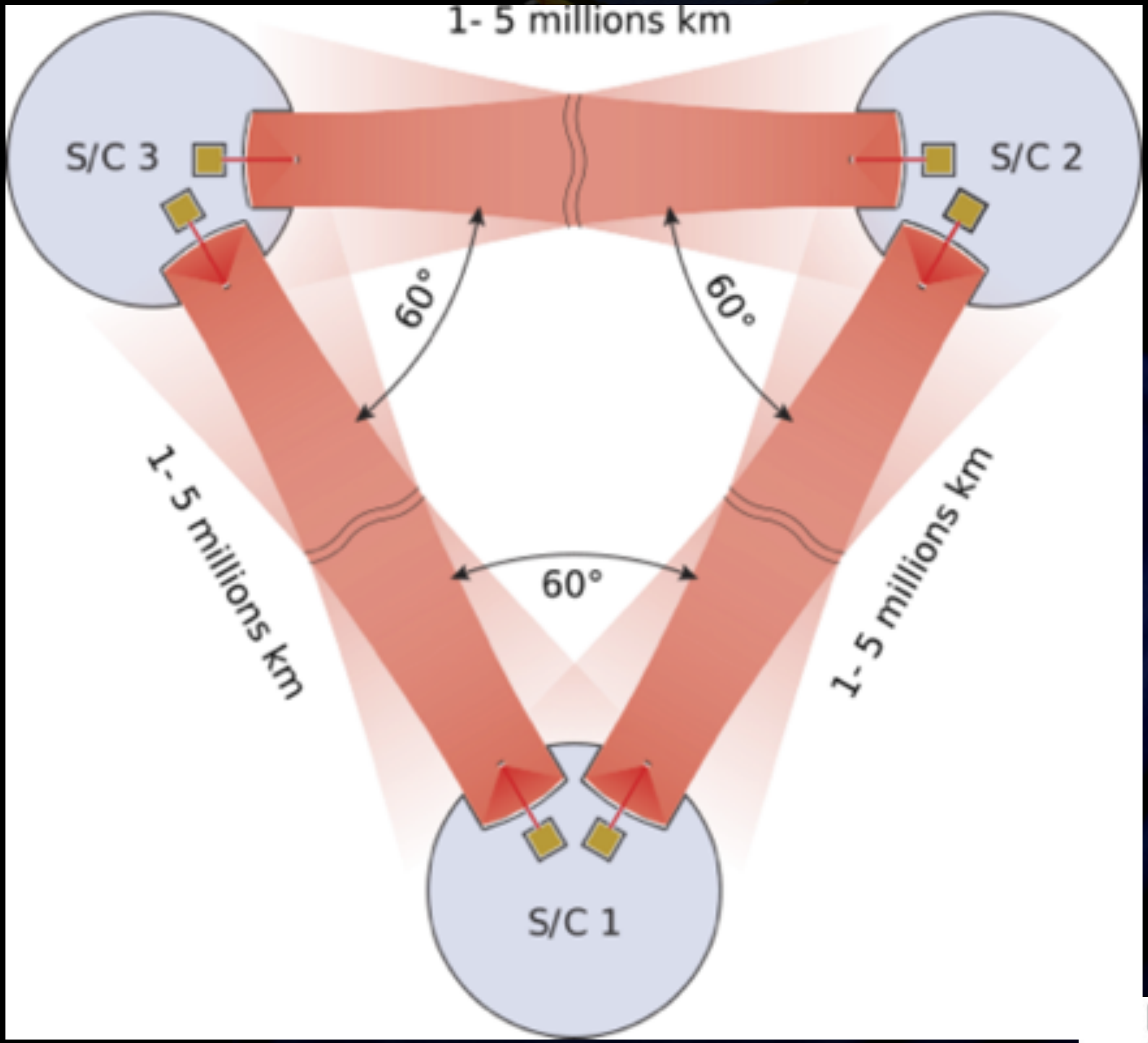
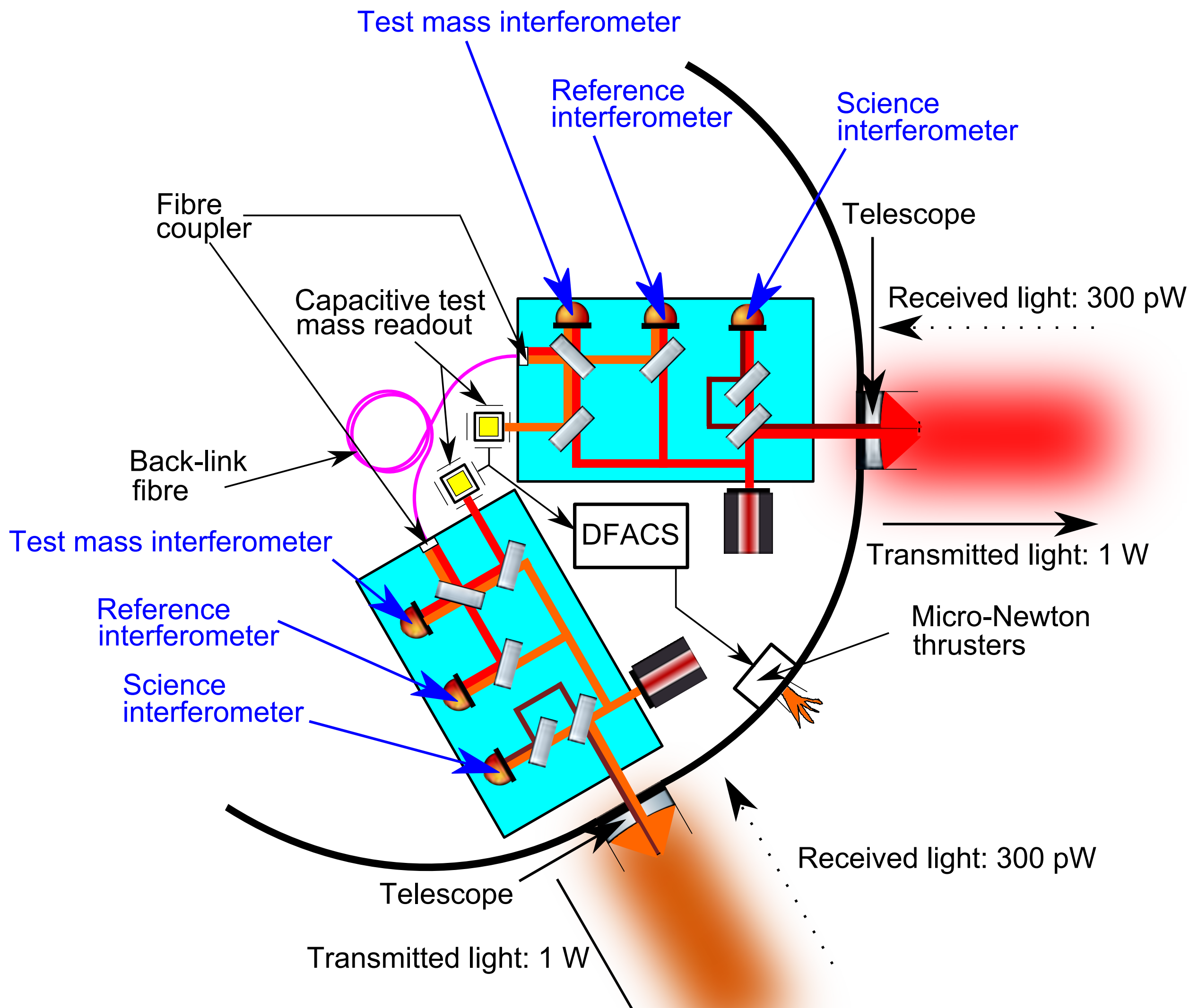




# LISA

- 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

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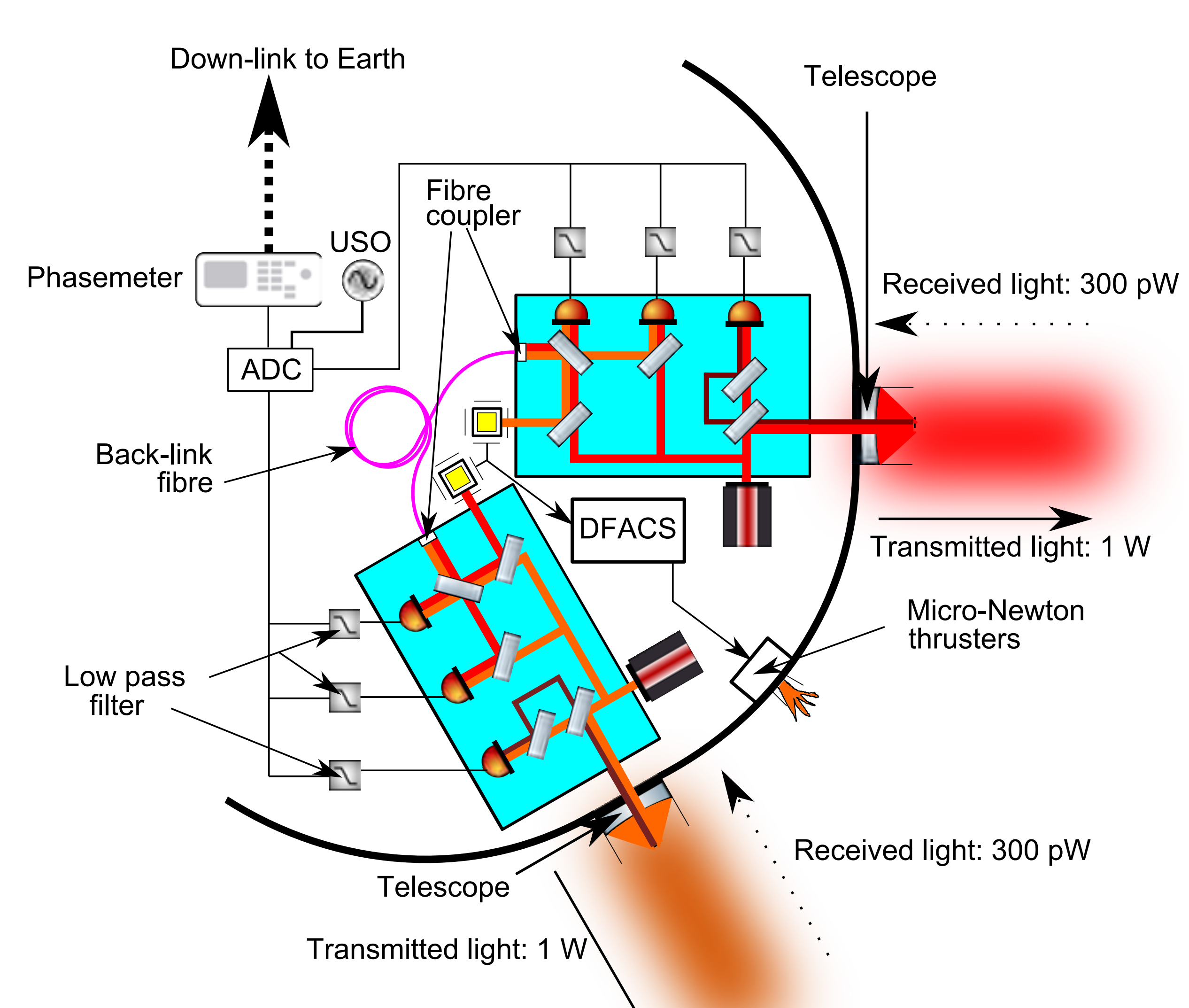


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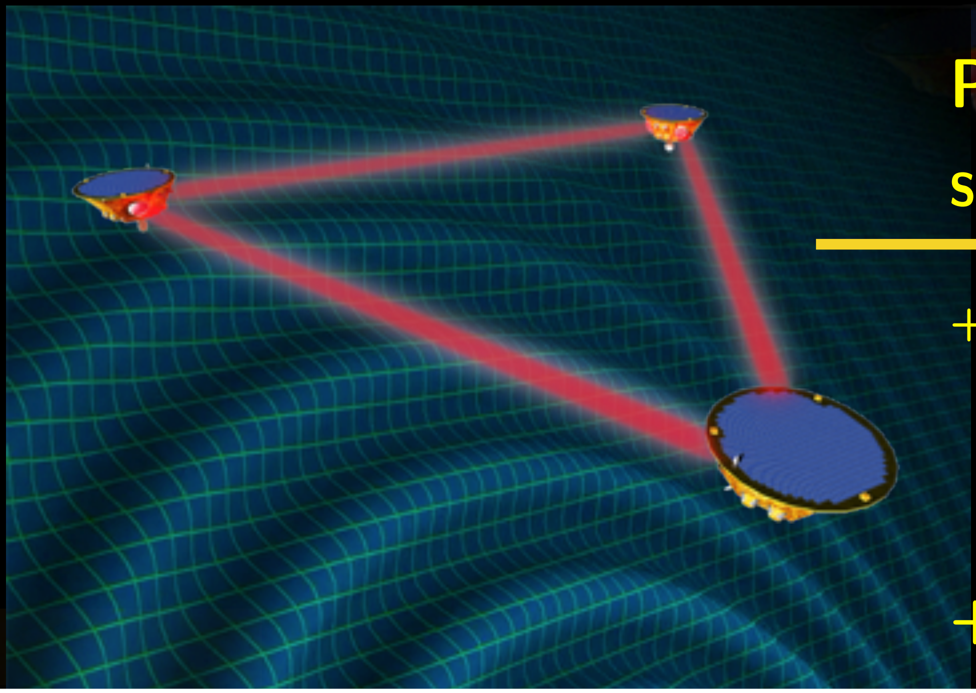
- Free flying test mass subject to very low parasitic forces:
  - Drag free control of spacecraft (non-contacting spacecraft)
  - Low noise microthruster to implement drag-free
  - Large gaps, heavy masses with caging mechanism
  - High stability electrical actuation on cross degrees of freedom
  - Non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

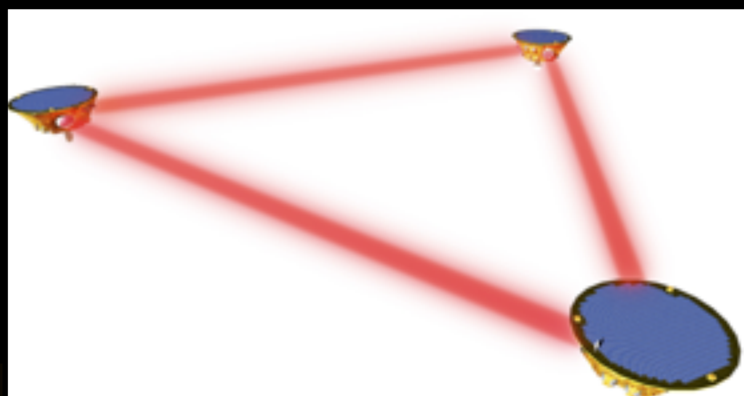
- 10-100/yr SMBHBs
- 10-1000/yr EMRIs
- 60 millions Galactic binaries
- Large number of Black Hole binaries
- Cosmological backgrounds
- Unknown sources

# Outline

- Introduction to gravitational waves
- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISAPathfinder
- LISA status and organisation
- LISA scientific performances
- The French contribution to LISA:
  - Data Processing Center
  - Integration / performance control
- Conclusion and perspectives

# LISAPathfinder

- Technological demonstrator for LISA

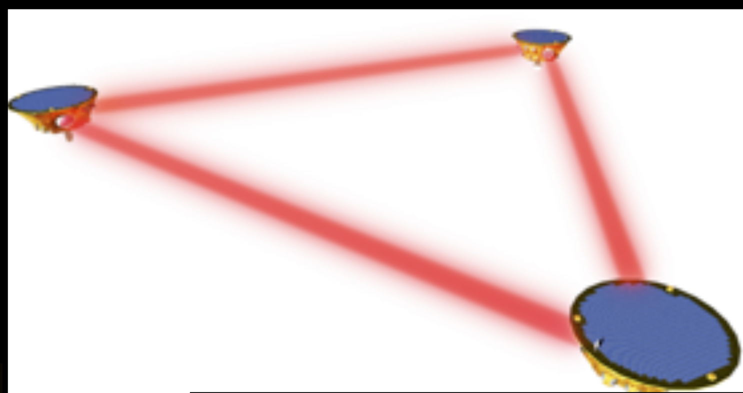


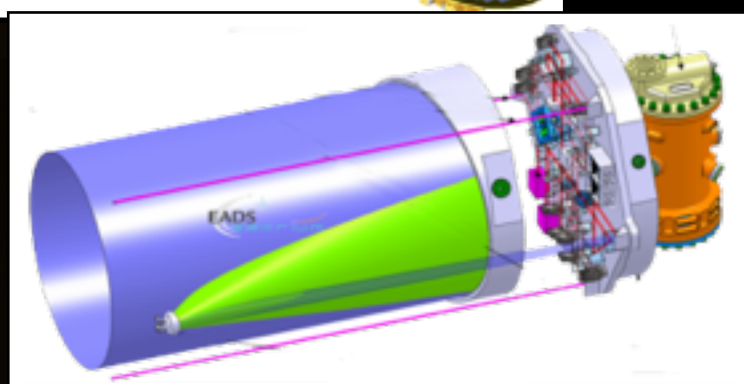
LISA :

- 3 spacecraft separated by millions of km
- Role of each spacecraft is to protect the fiducial test masses from external forces

# LISAPathfinder

- Technological demonstrator for LISA





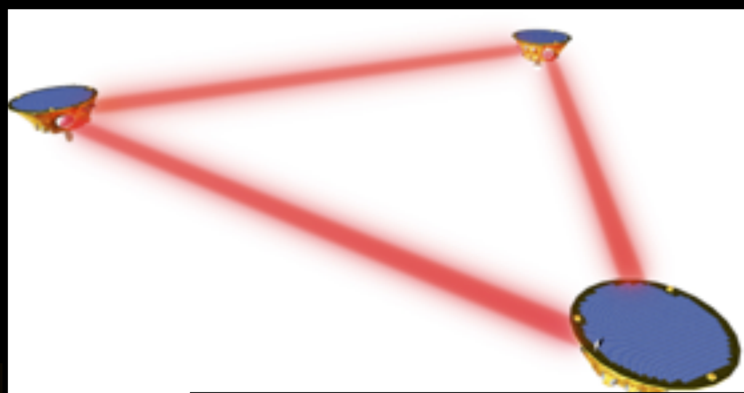
**LISA :**

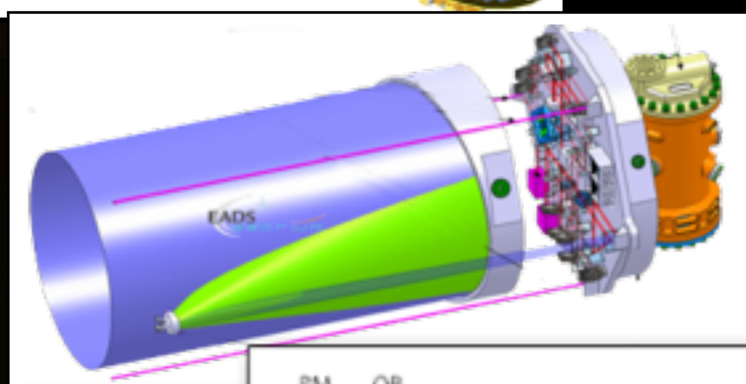
Locally measure distance from TM to SC using:

- Laser interferometry along sensitive axis (between SC)
- Capacitive sensing on orthogonal axes
- TM displacement measurements are used as input to DFACS which controls position and attitude of SC respect to the TM

# LISAPathfinder

- Technological demonstrator for LISA







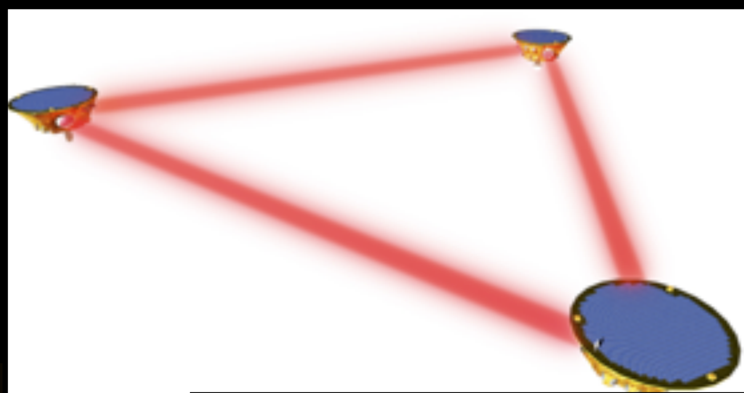
LISA :

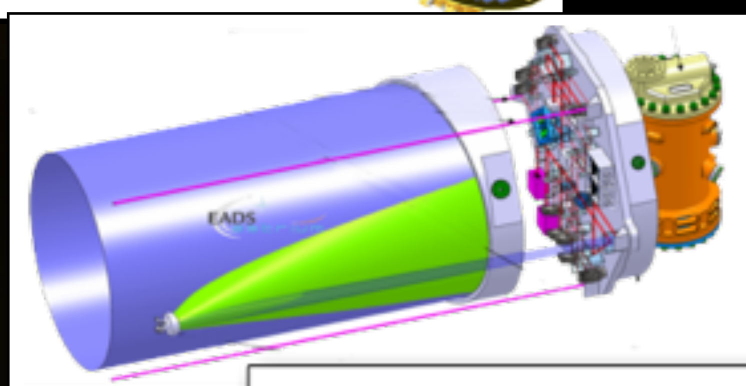
- Measure distance along using laser interferometry

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

# LISAPathfinder

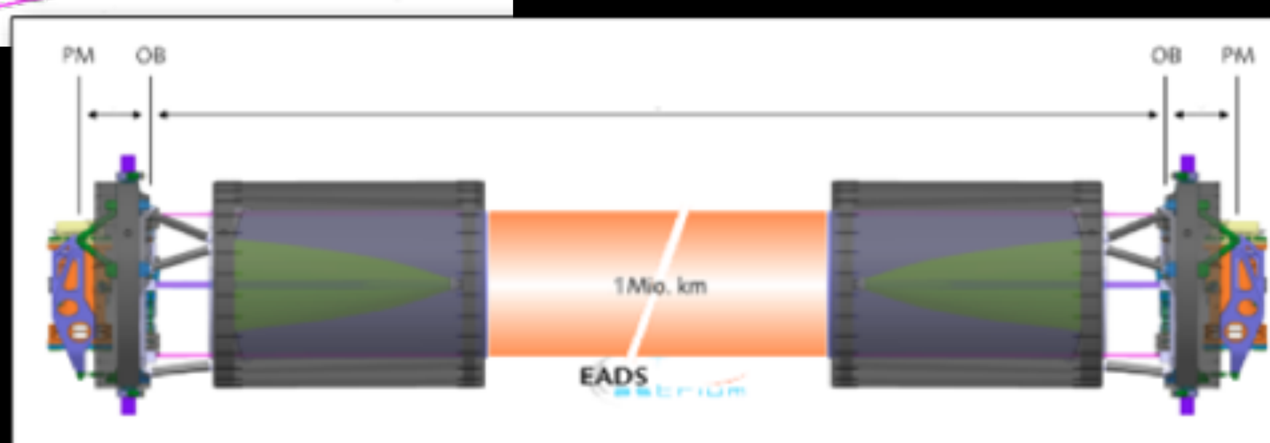
- Technological demonstrator for LISA

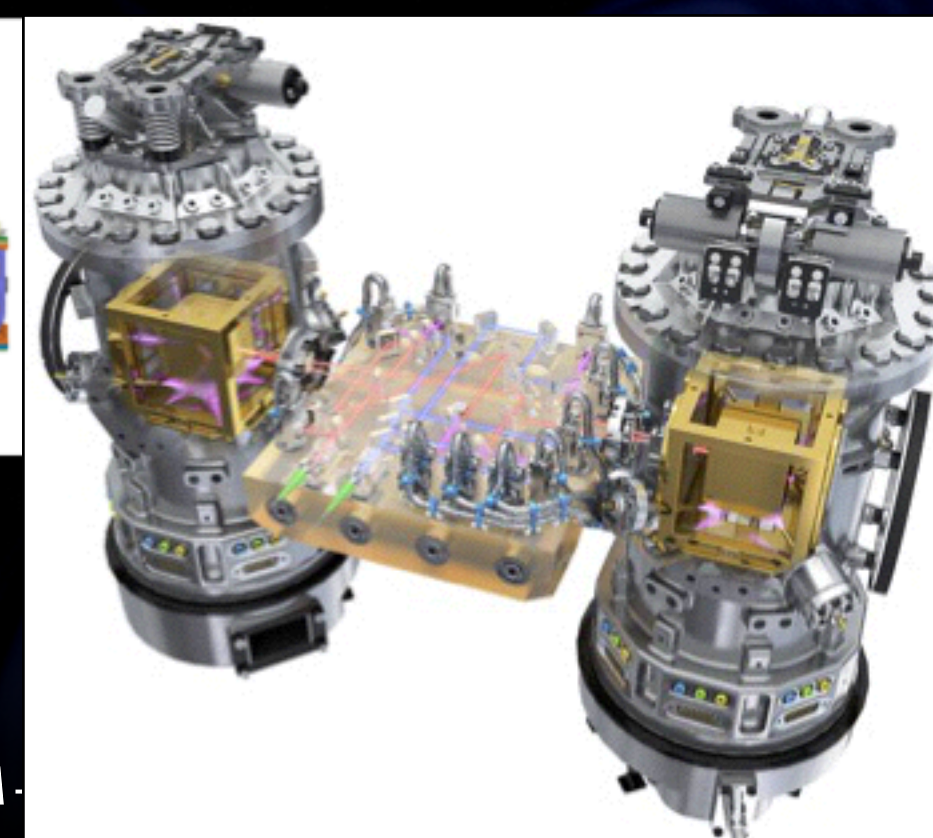




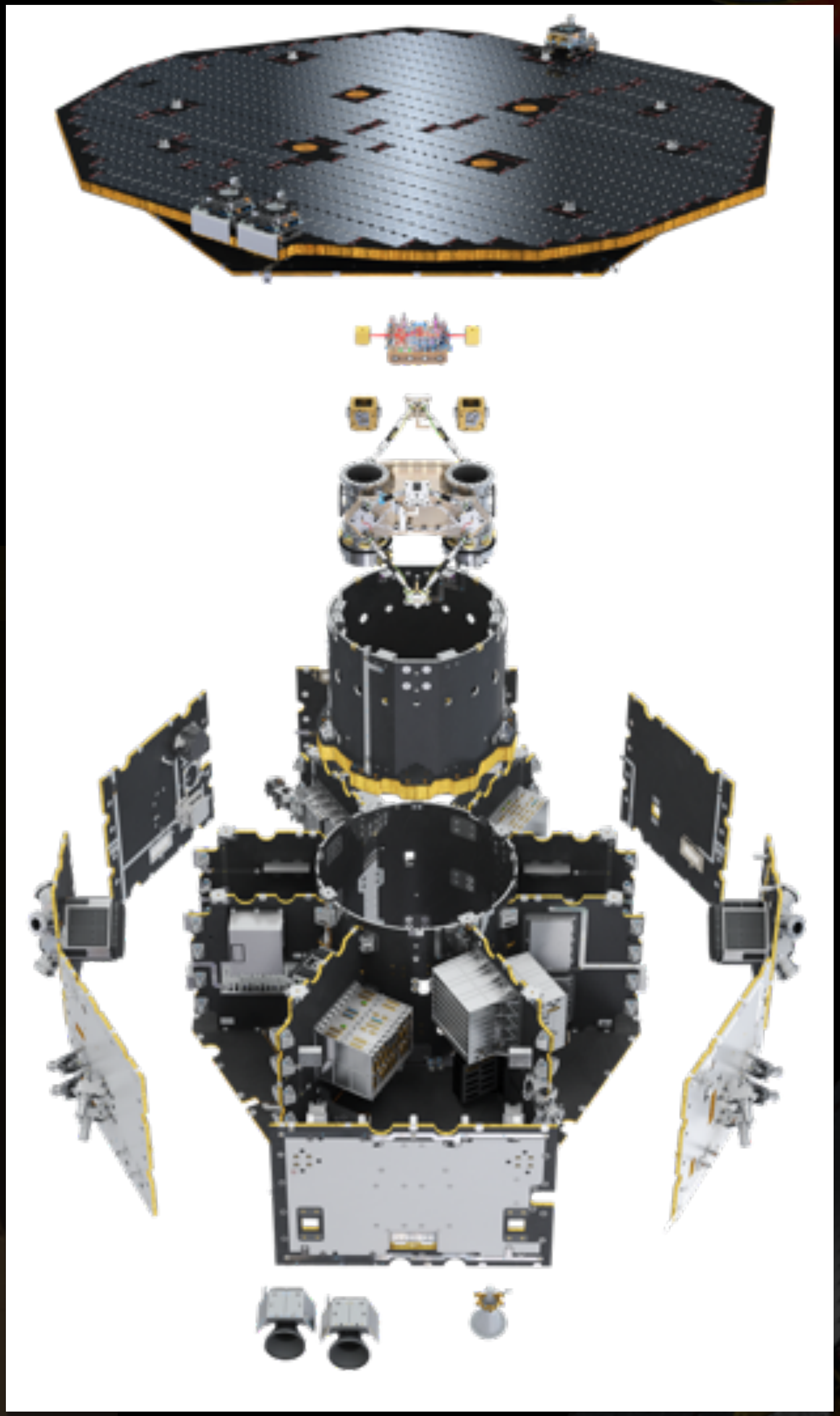

## LISAPathfinder:

- 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 timeline



# LISAPathfinder timeline

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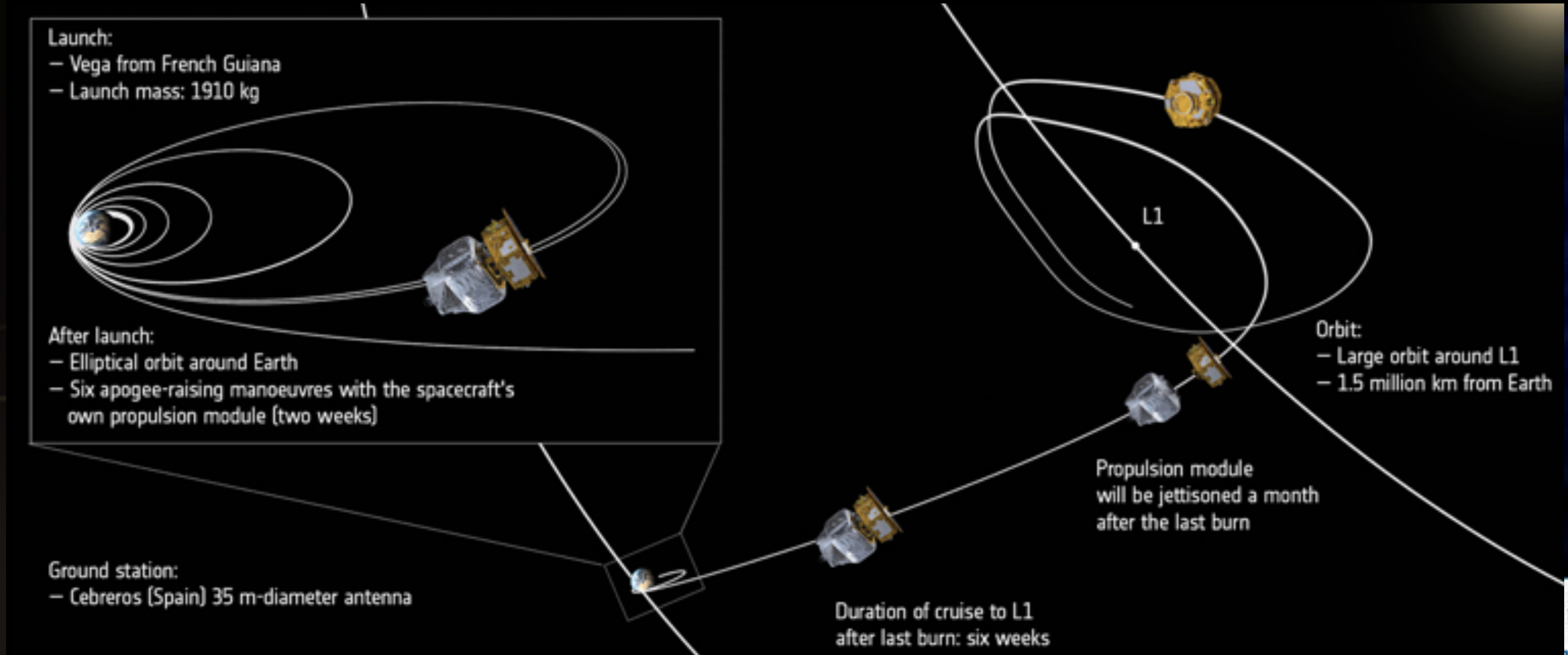
- 3/12/2015: Launch from Kourou
- 22/01/2016: arrived on final orbit & separation of propulsion module
- 17/12/2015 → 01/03/2016: commissioning
- 01/03/2016 → 27/06/2016: LTP operations (Europe)
- 27/06/2016 → 11/2016: DRS operations (US) + few LTP weeks
- 01/12/2016 → 31/06/2017: extension of LTP operations



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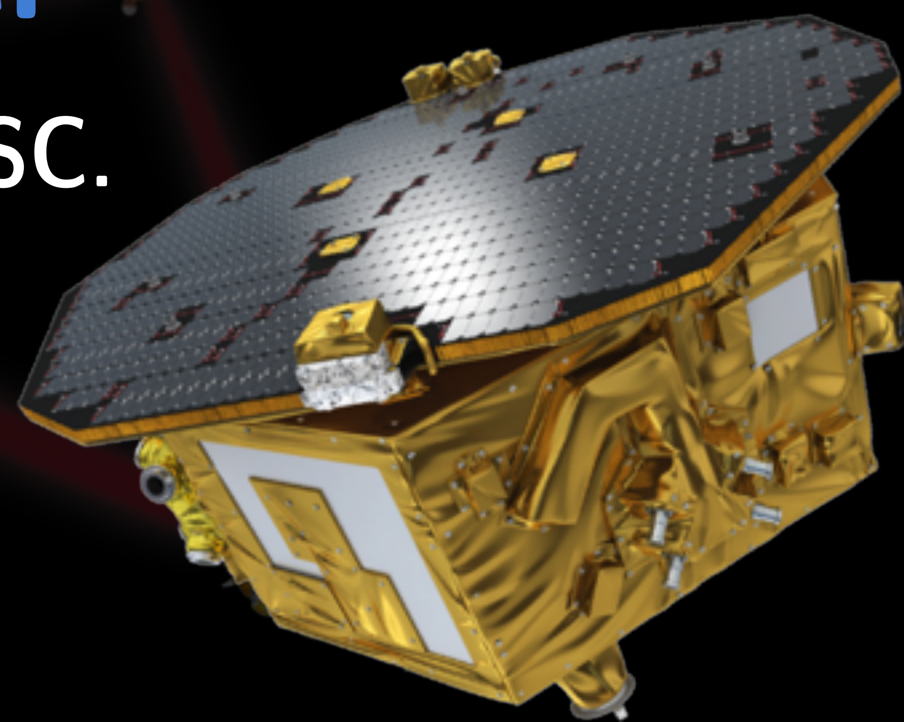
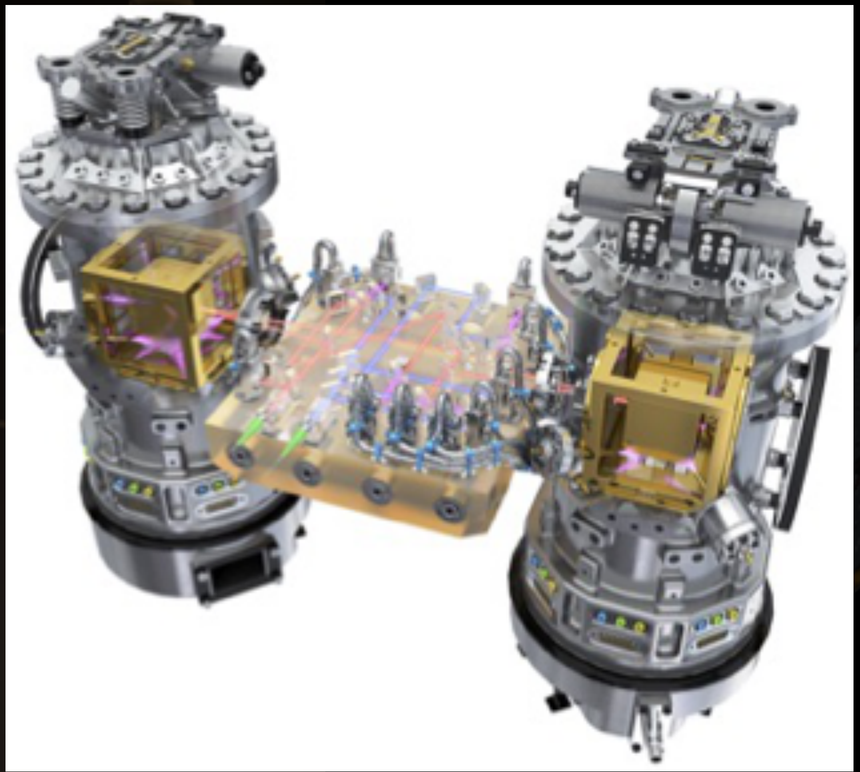
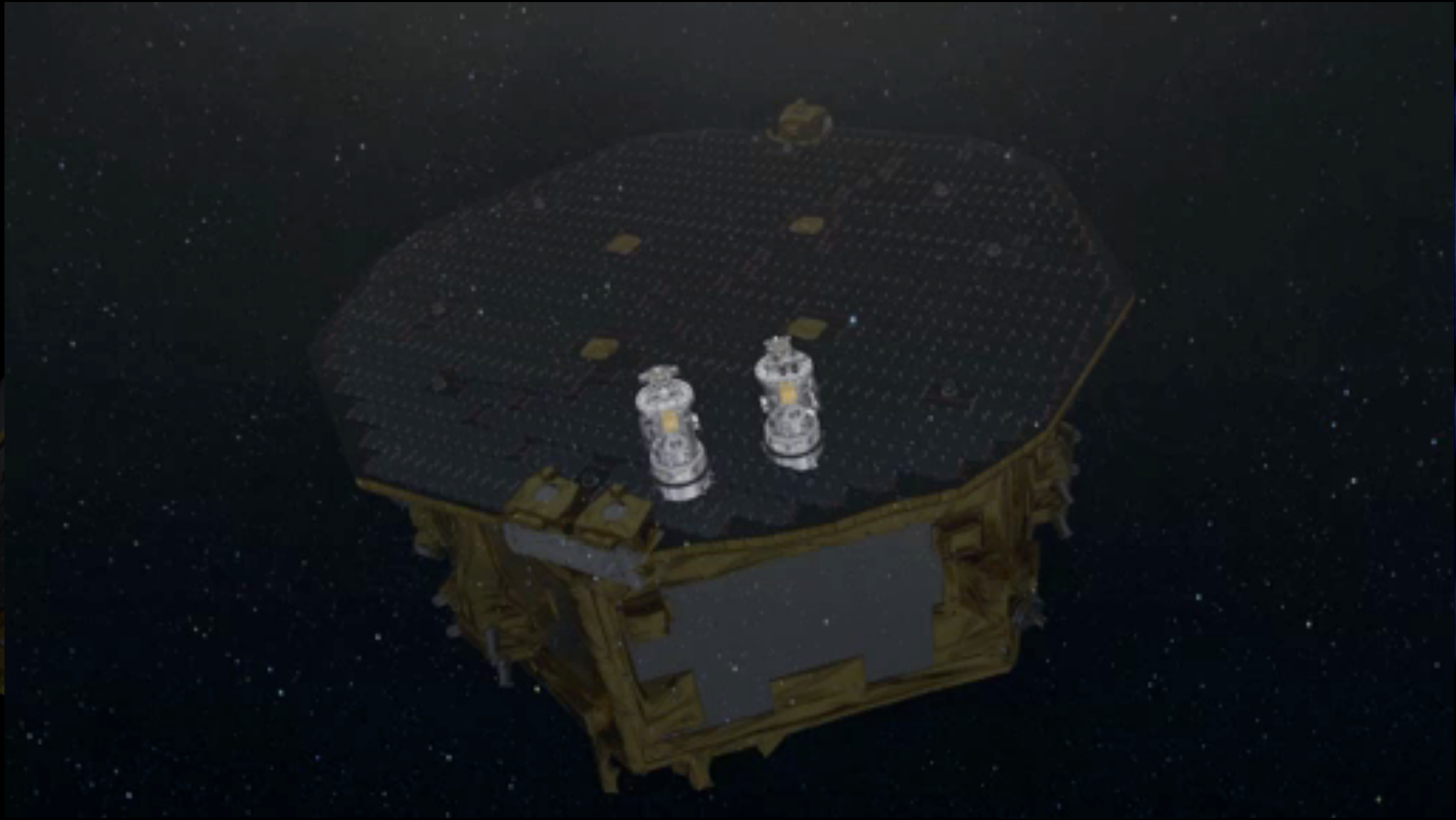
# LISAPathfinder



- 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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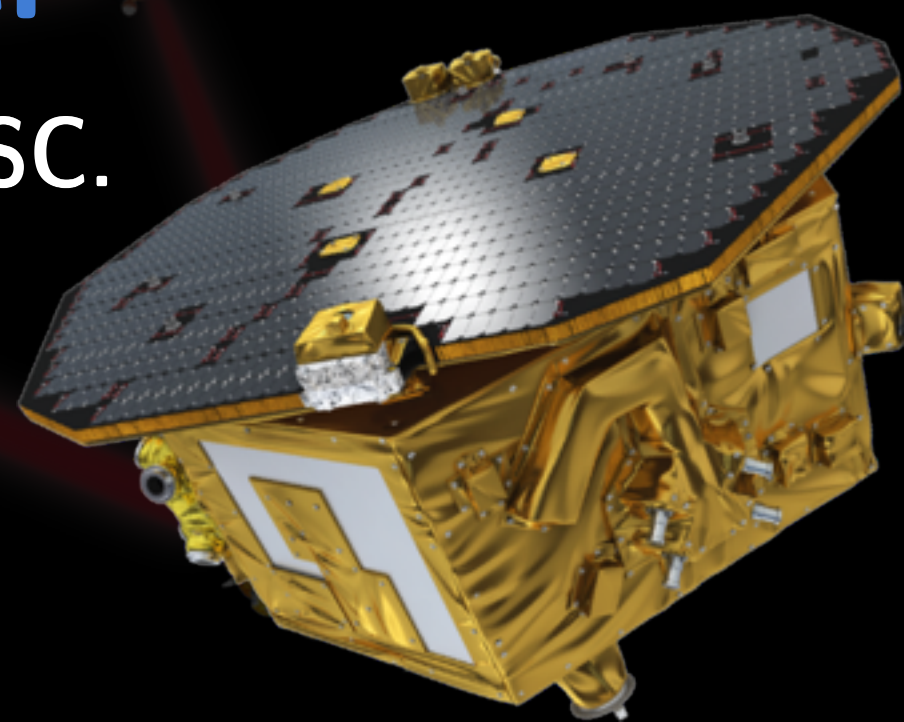
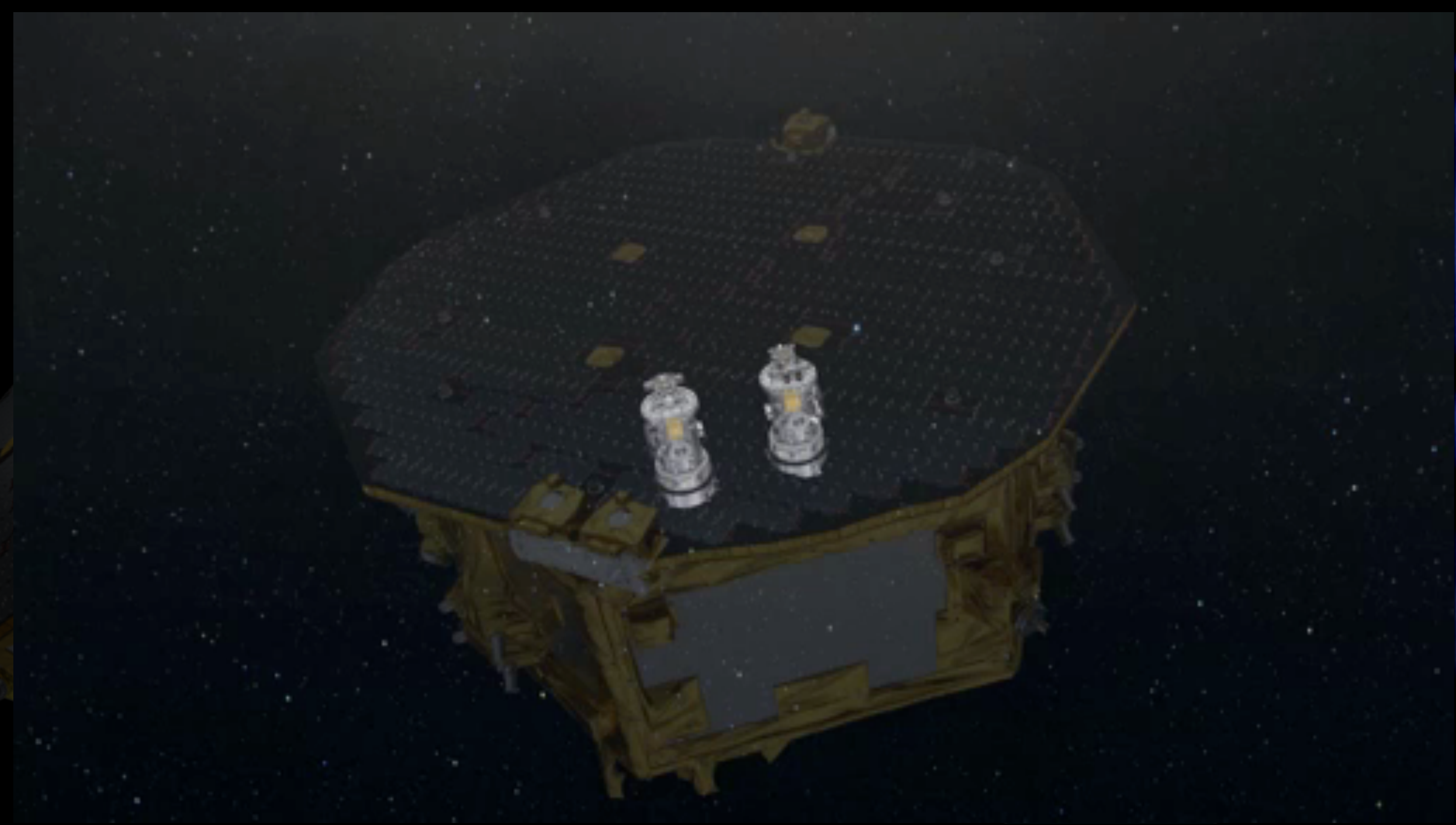
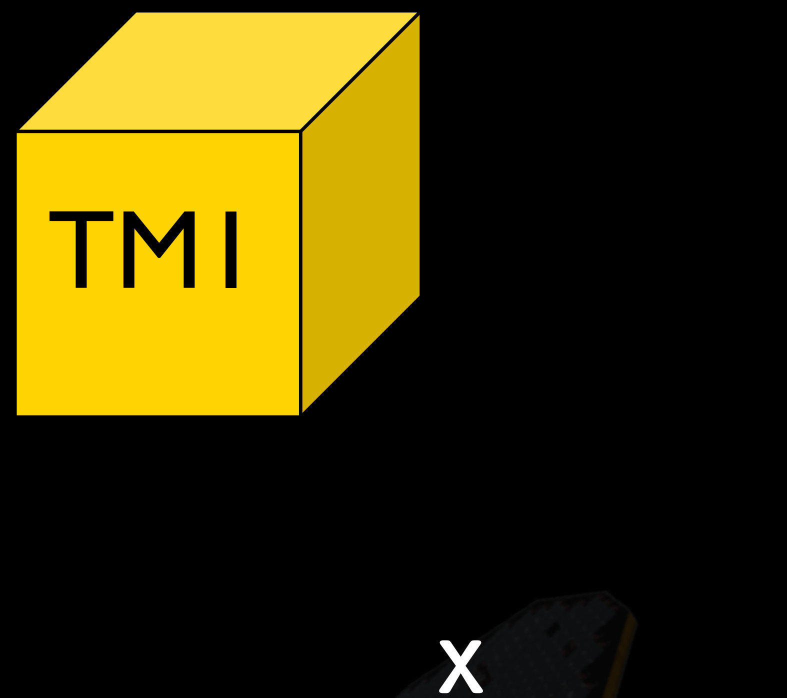


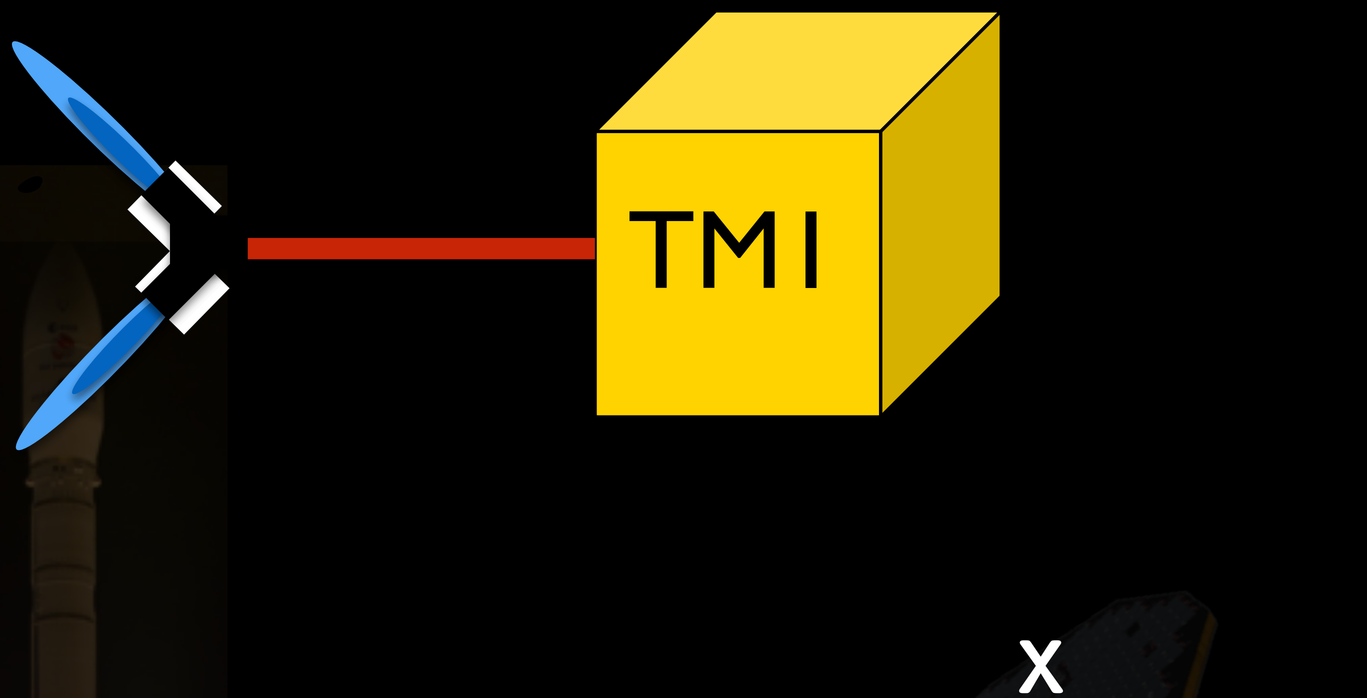


# The measurement - deltaG




by Joseph Martino

# The measurement - deltaG

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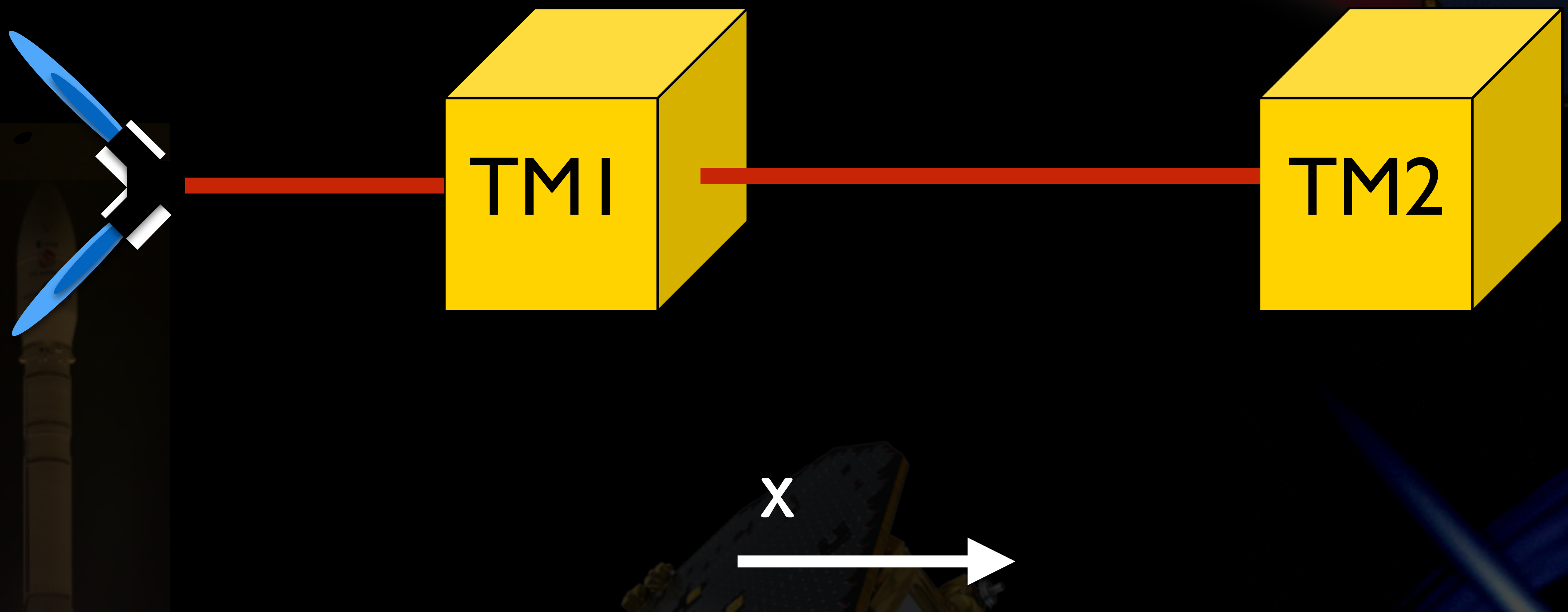


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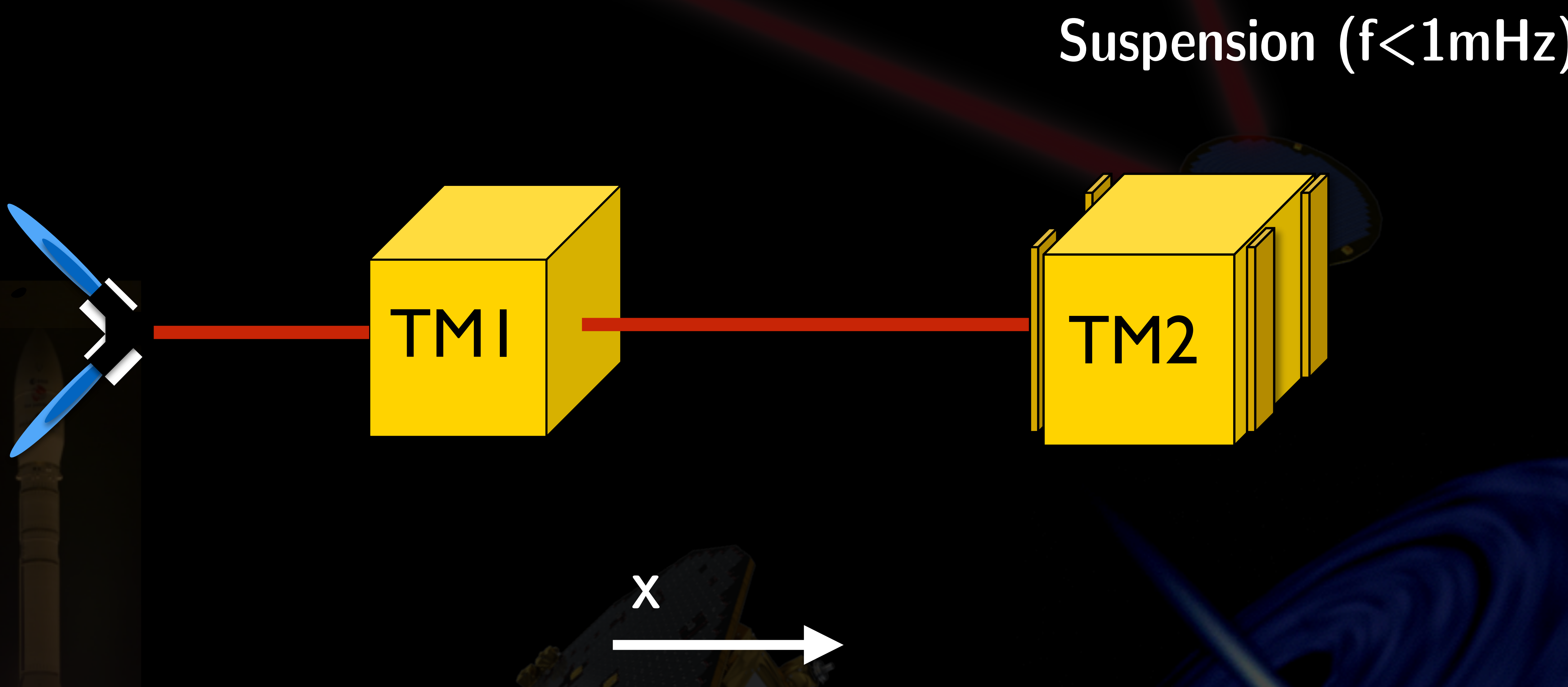
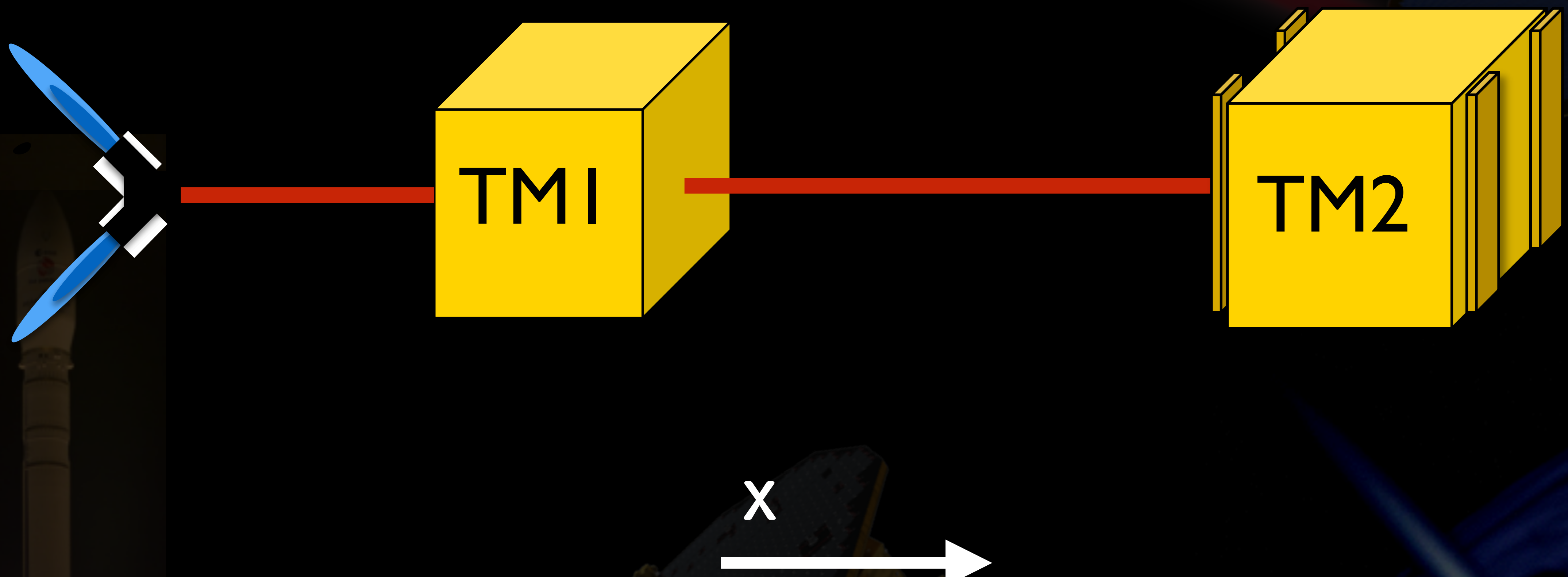



by Joseph Martino

# The measurement - deltaG

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

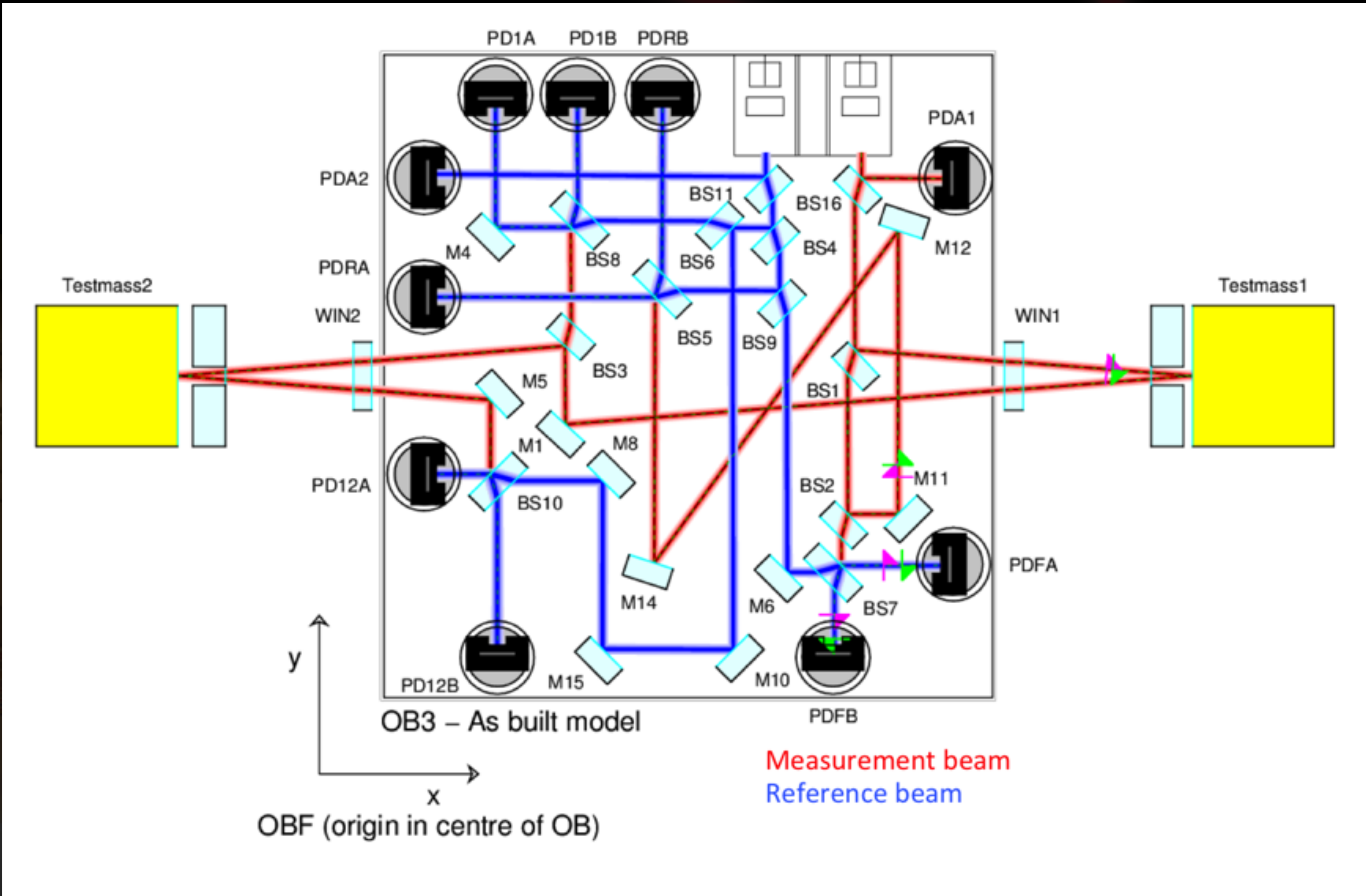
Suspension ($f<1$mHz)




by Joseph Martino

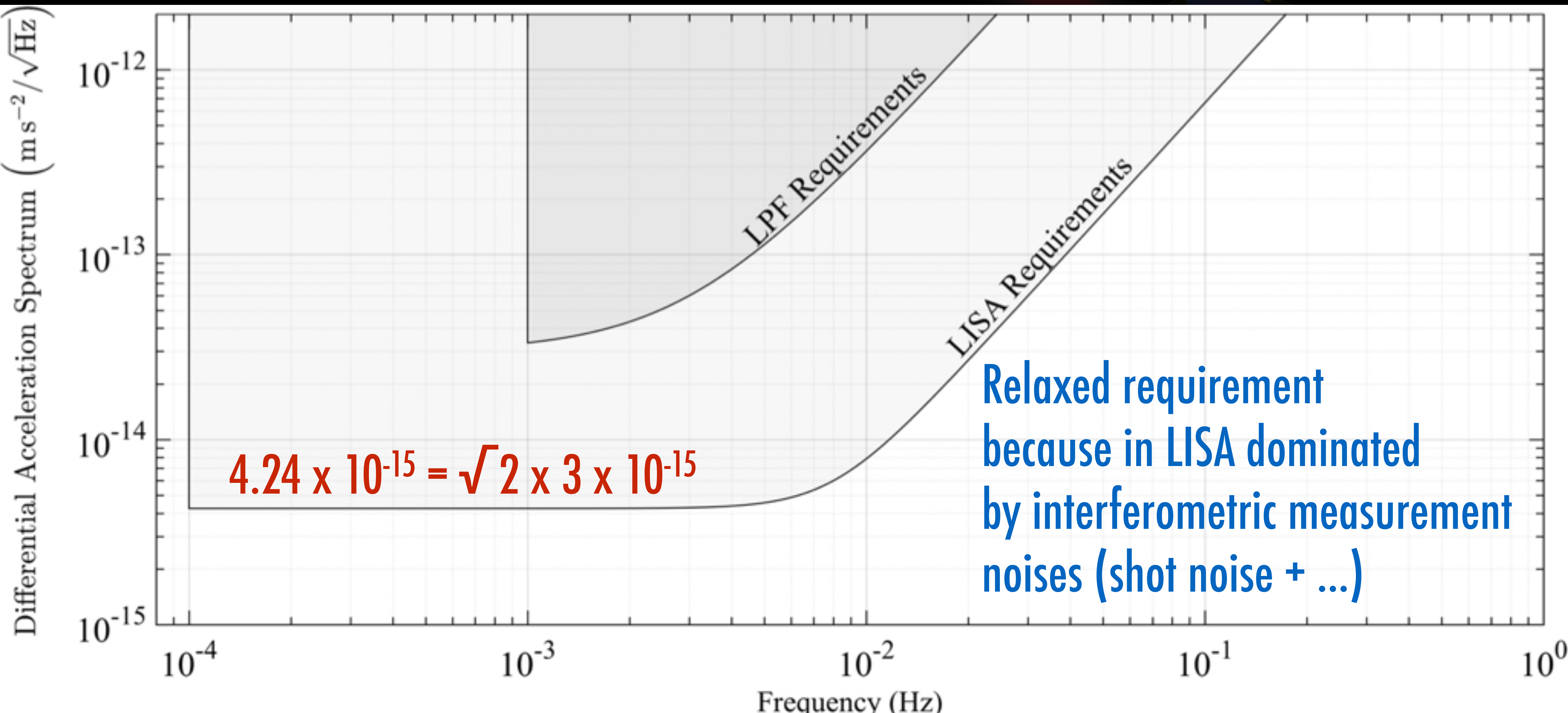
# Optical bench

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



# Requirements: LPF vs LISA

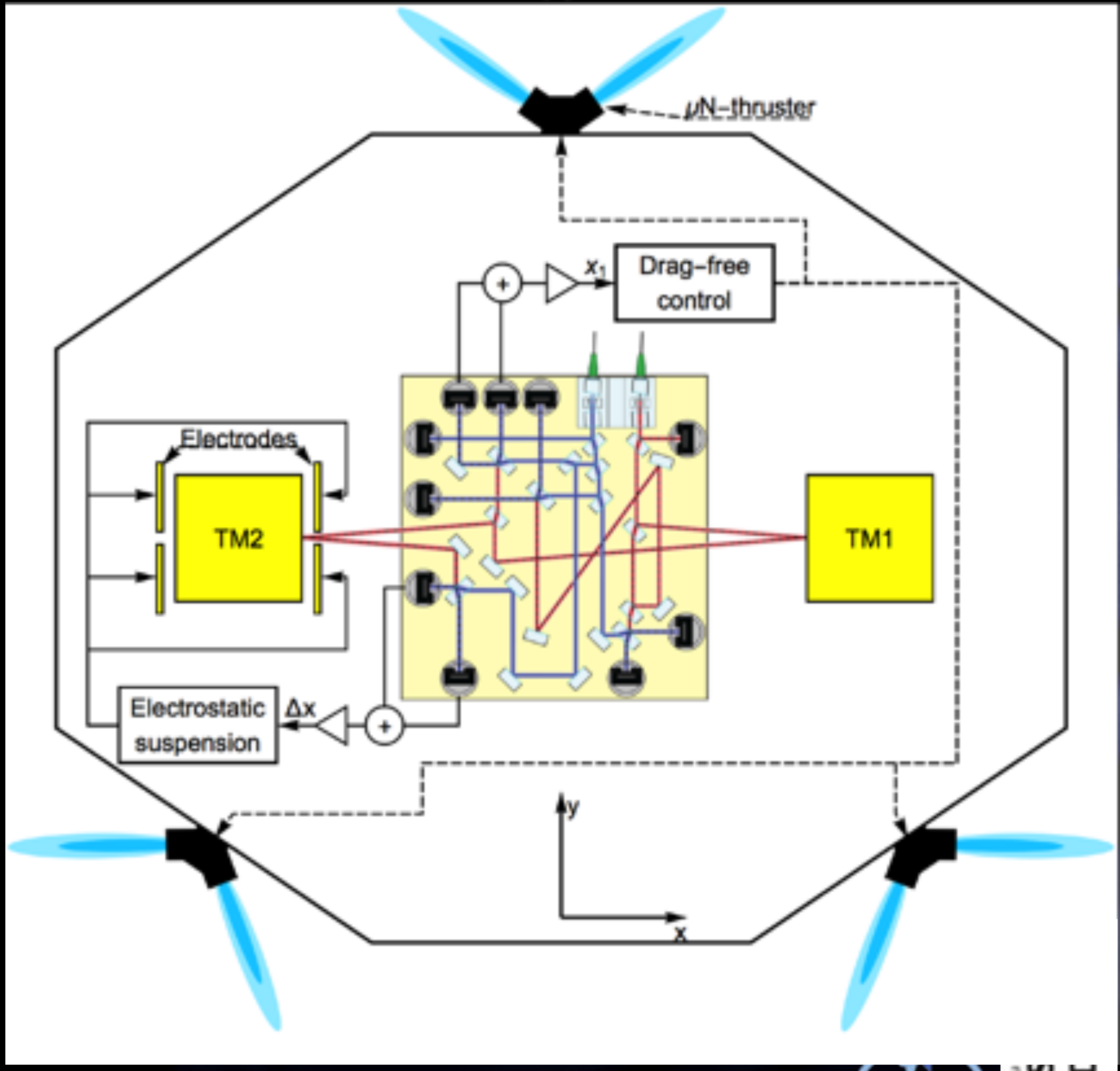
- Main LISAPathfinder (LPF) measurement : Δg : differential acceleration between the 2 test-masses



# Requirements: LPF vs LISA

Why the LISAPathfinder requirements are restricted compare to LISA ones ?

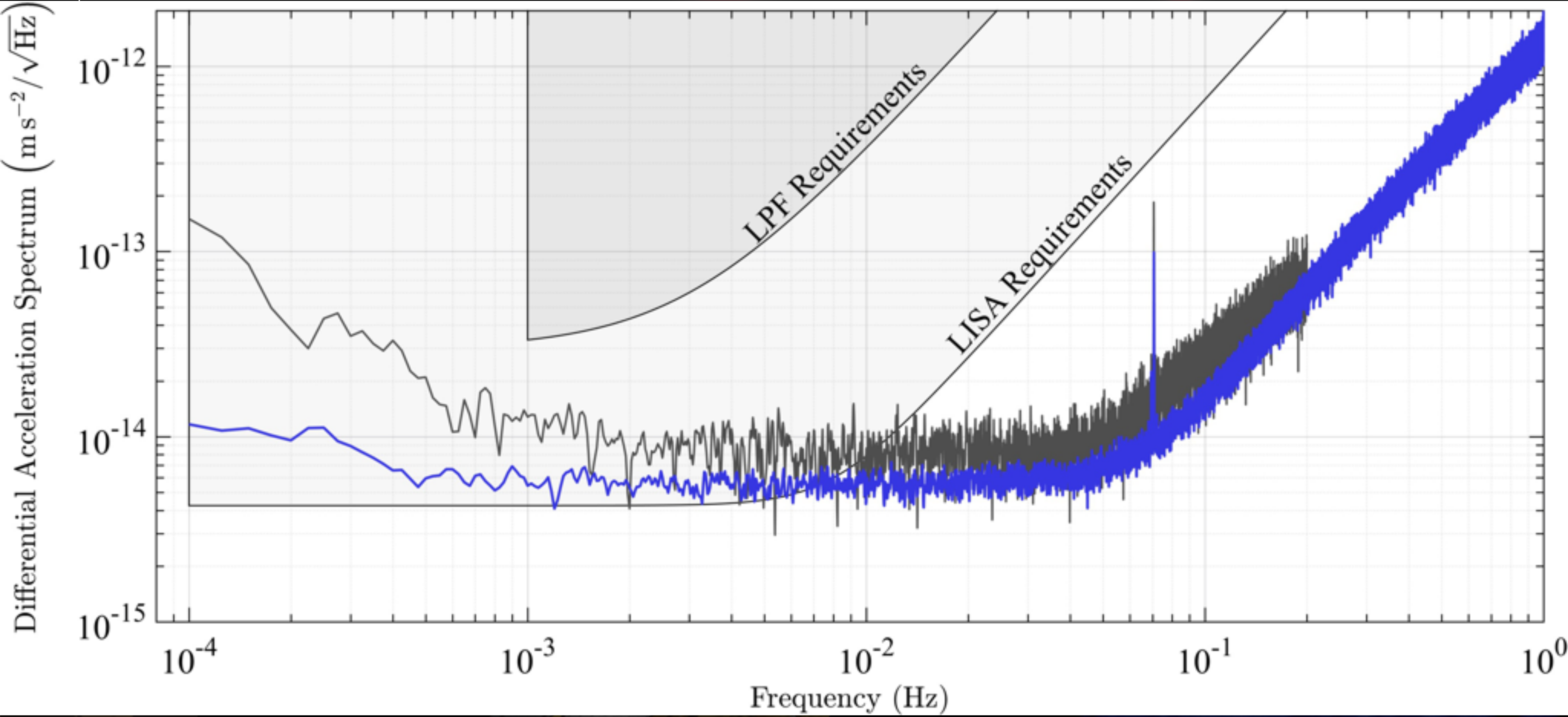
- We understand limitations with LISAPathfinder and correct for them in LISA
- Short arm limitation :
  - Gravitational field not perfectly flat => constant electrostatic actuation on test- mass 2
- f > 1 mHz : limit duration of industrial testing
- Industrial margin



# First results

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

- Results



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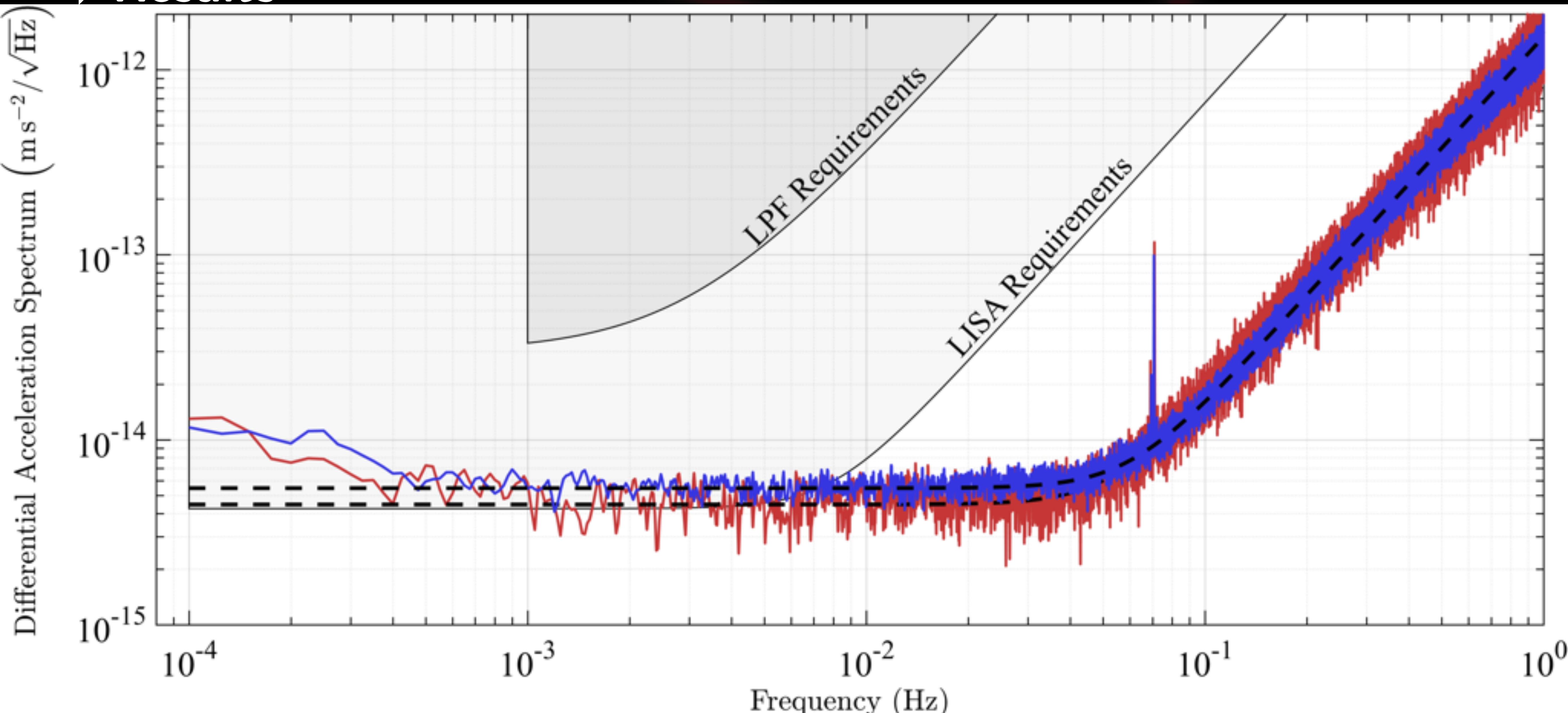

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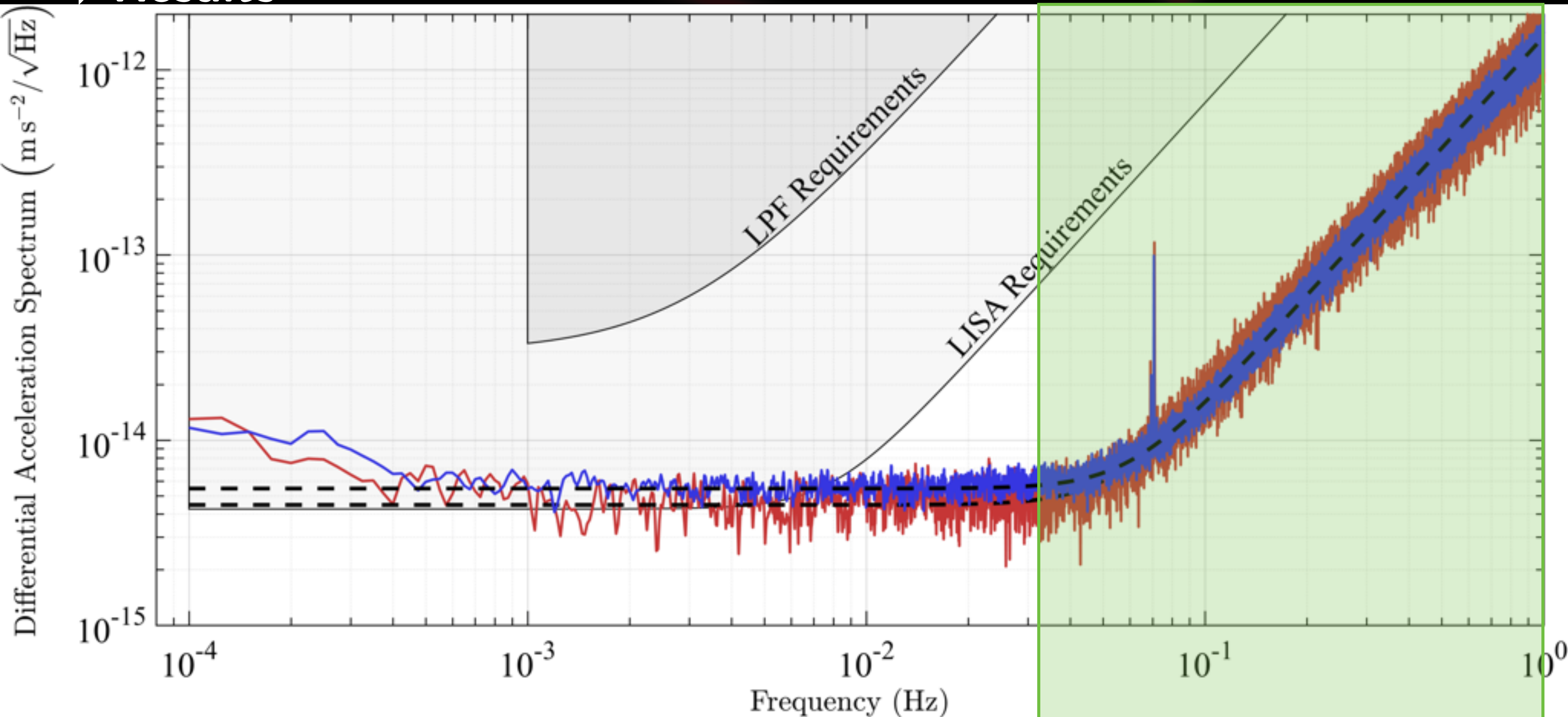
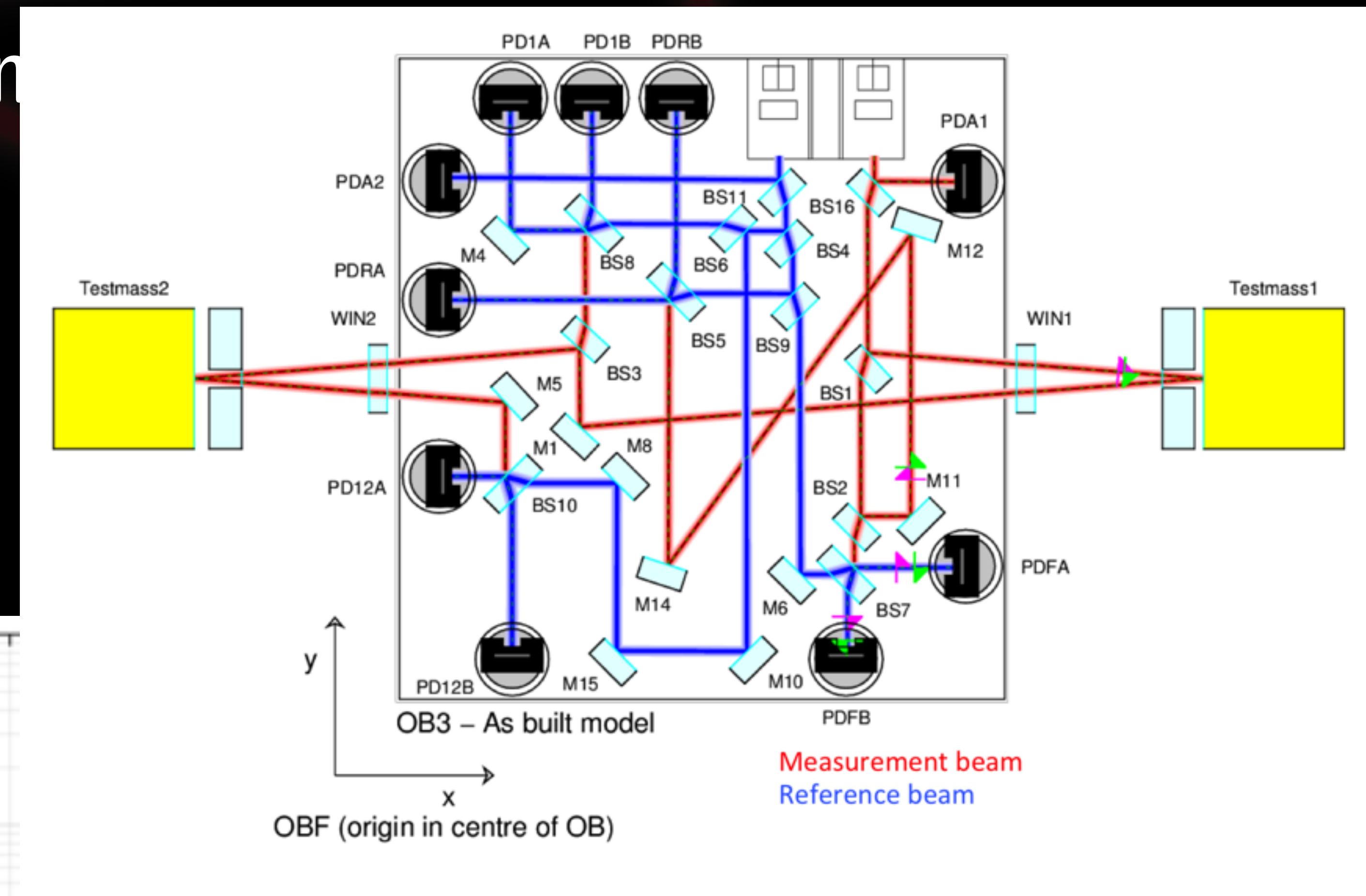
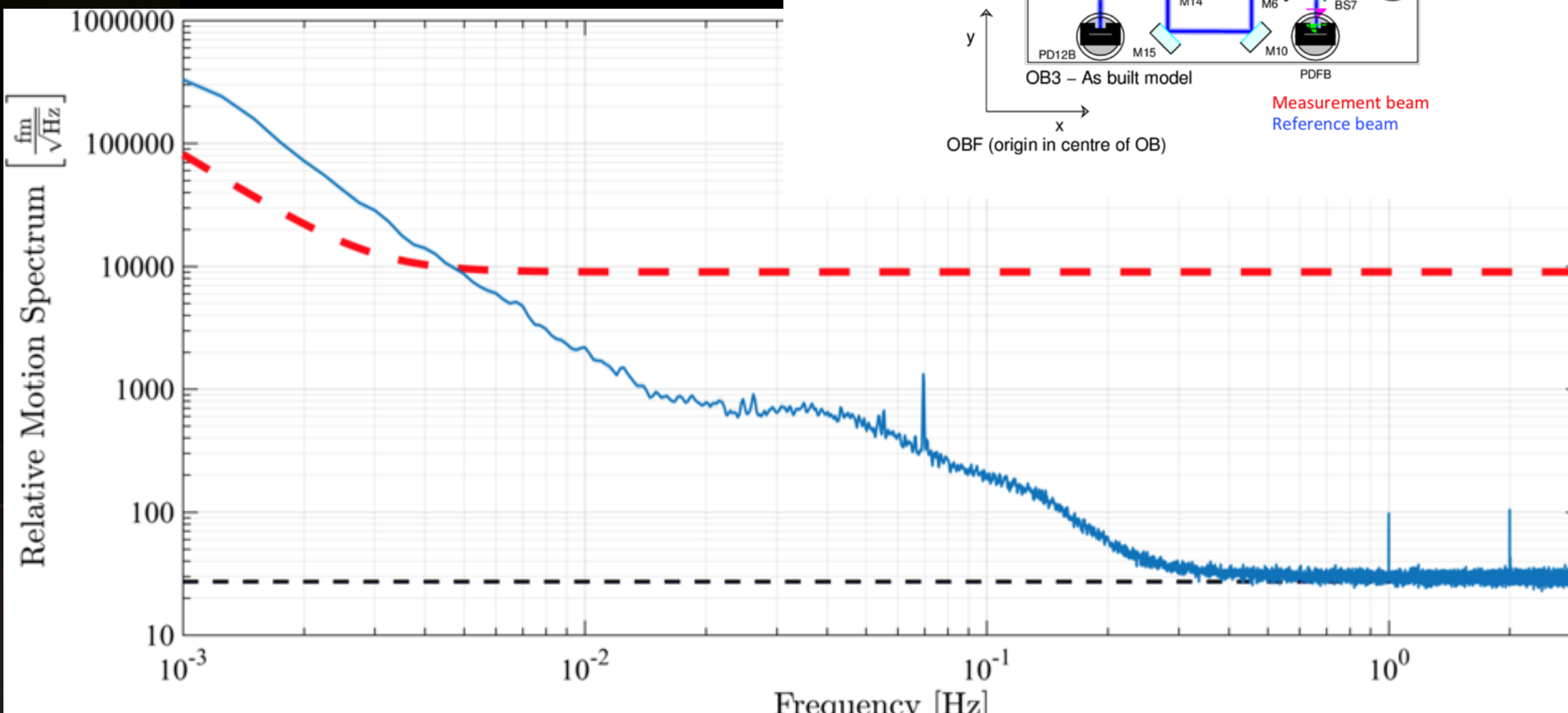



Interferometric noise
Not real test-mass motion

# High frequency limit

- Optical measurement syste
  - Interferometric precision:
    30 fm.Hz$^{-1/2}$
  - Orientation of test-masses



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

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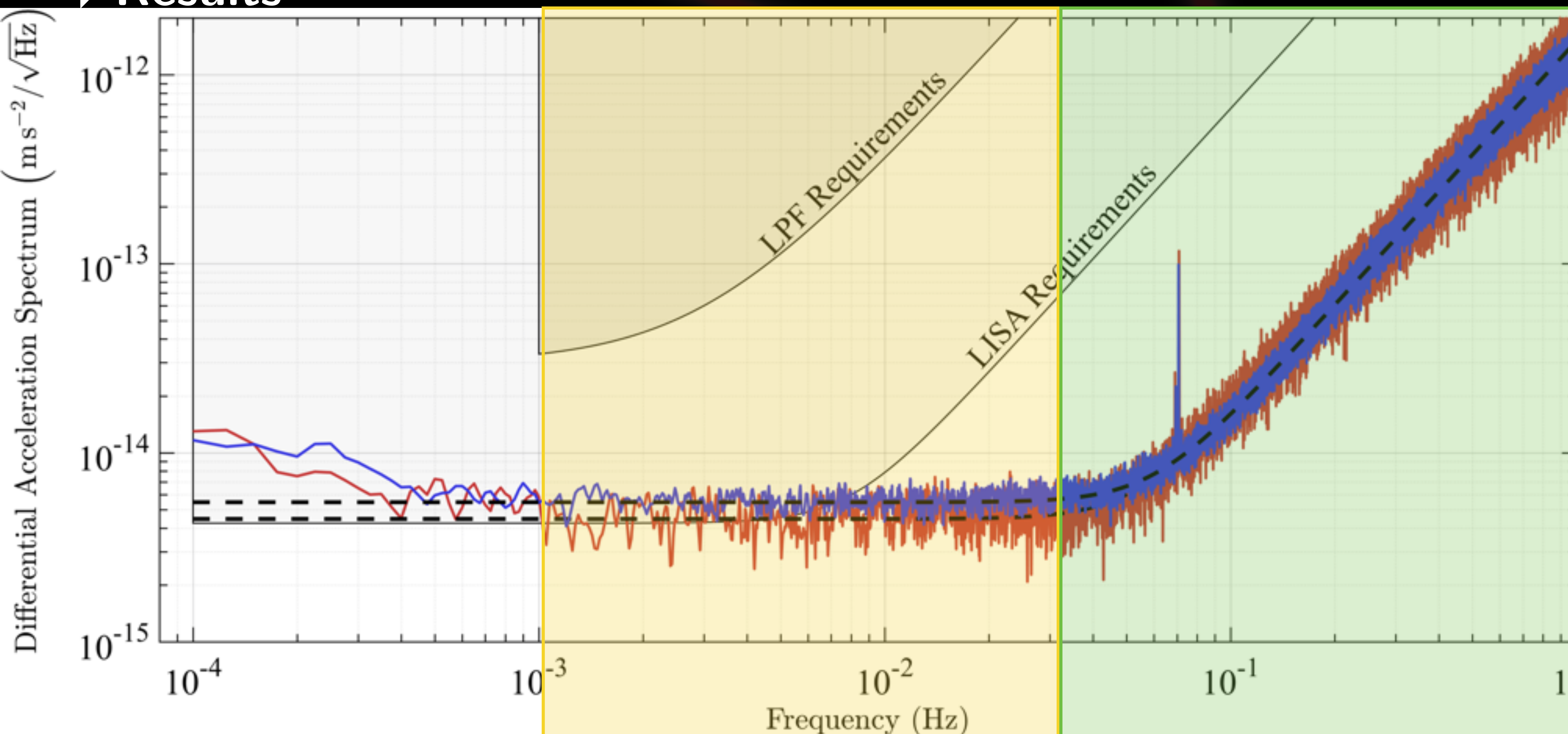
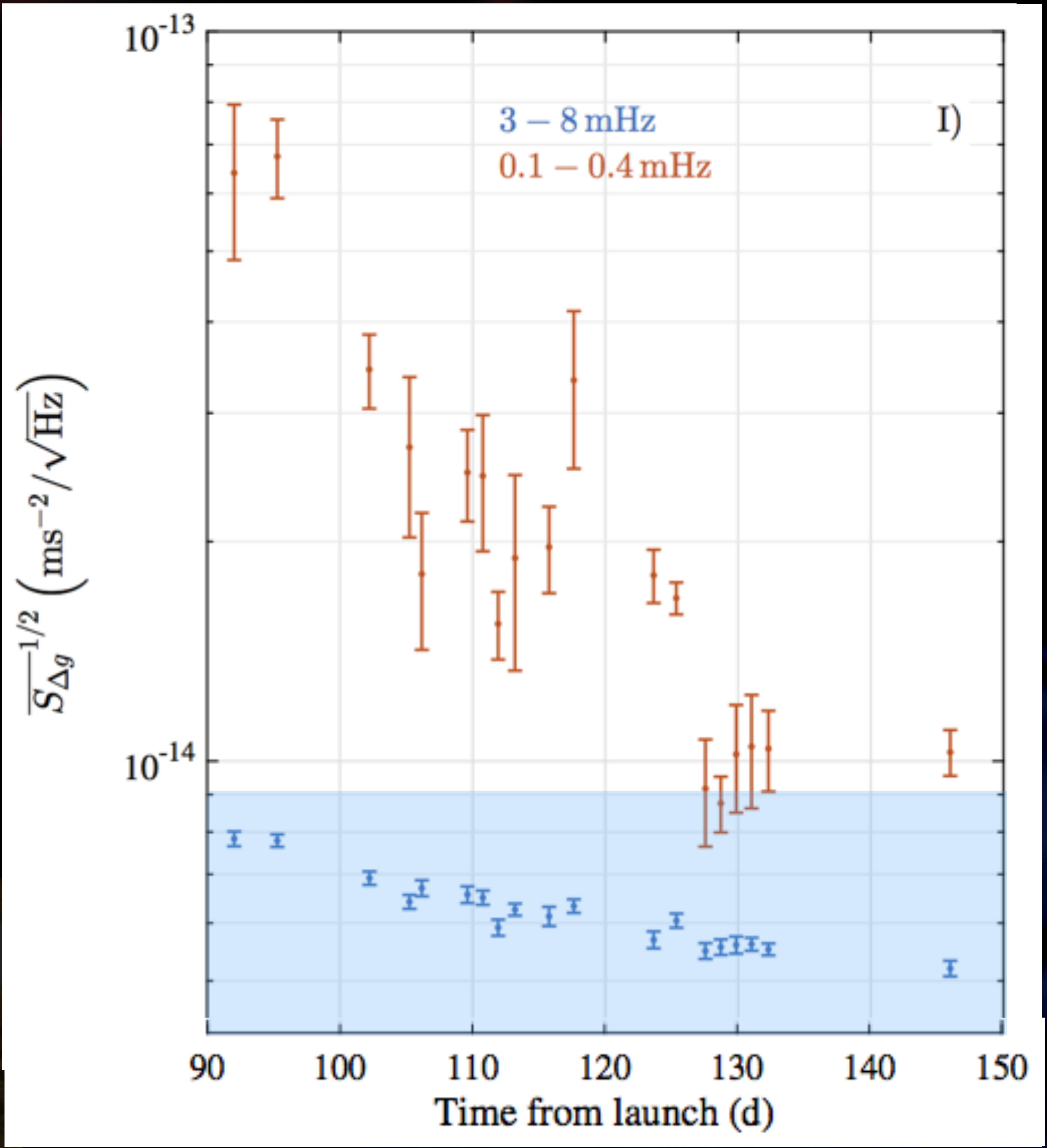



Brownian noise
Molecules within the noise hit test-masses

Interferometric noise
Not real test-mass motion

# Mid-frequency limit

- Noise in 1–10 mHz: brownian noise due to residual pressure:
  - Molecules within the housing hitting the test-masses
  - Possible residual outgassing
- Evolution:
  - Pressure decreases with time => constant improvement
- For LISA:
  - Better evacuation system … pump ?




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

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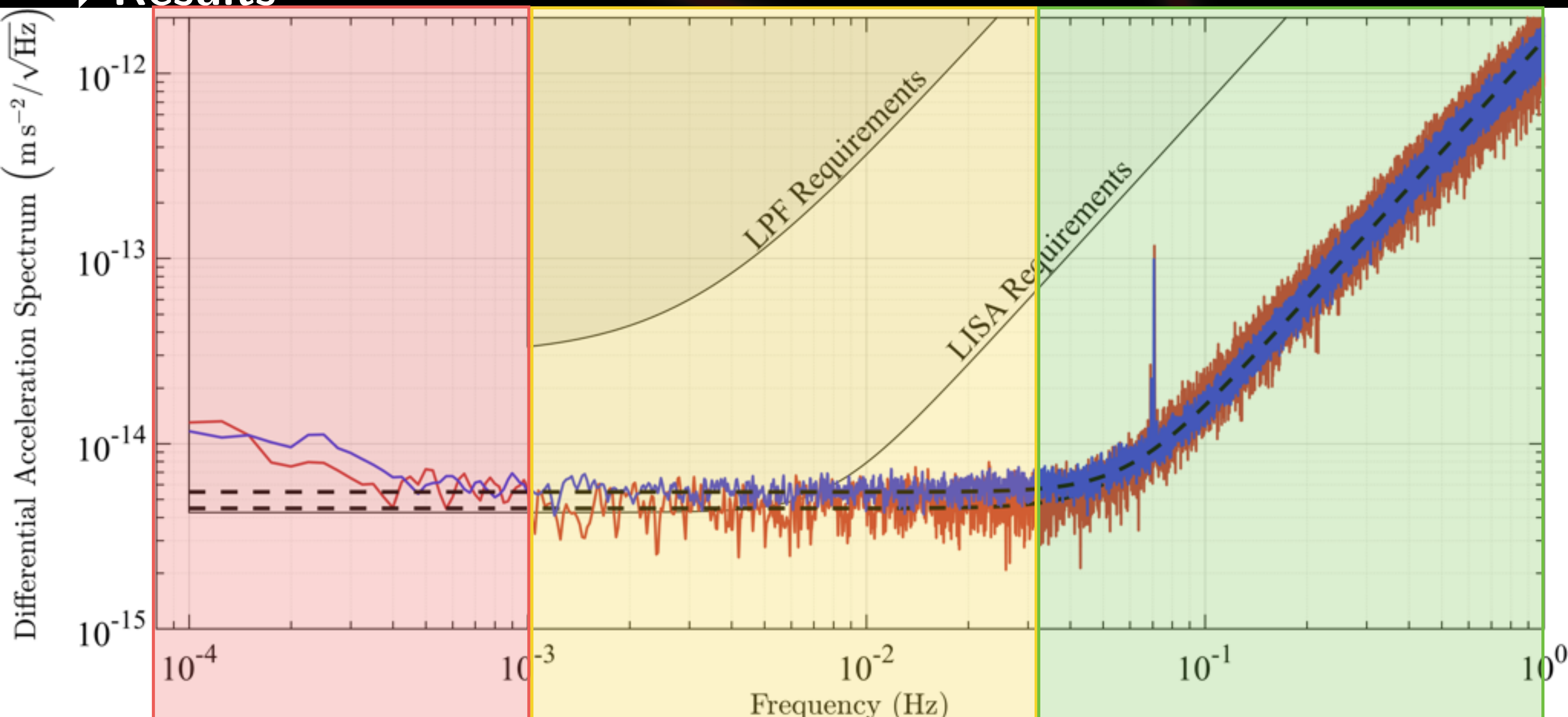


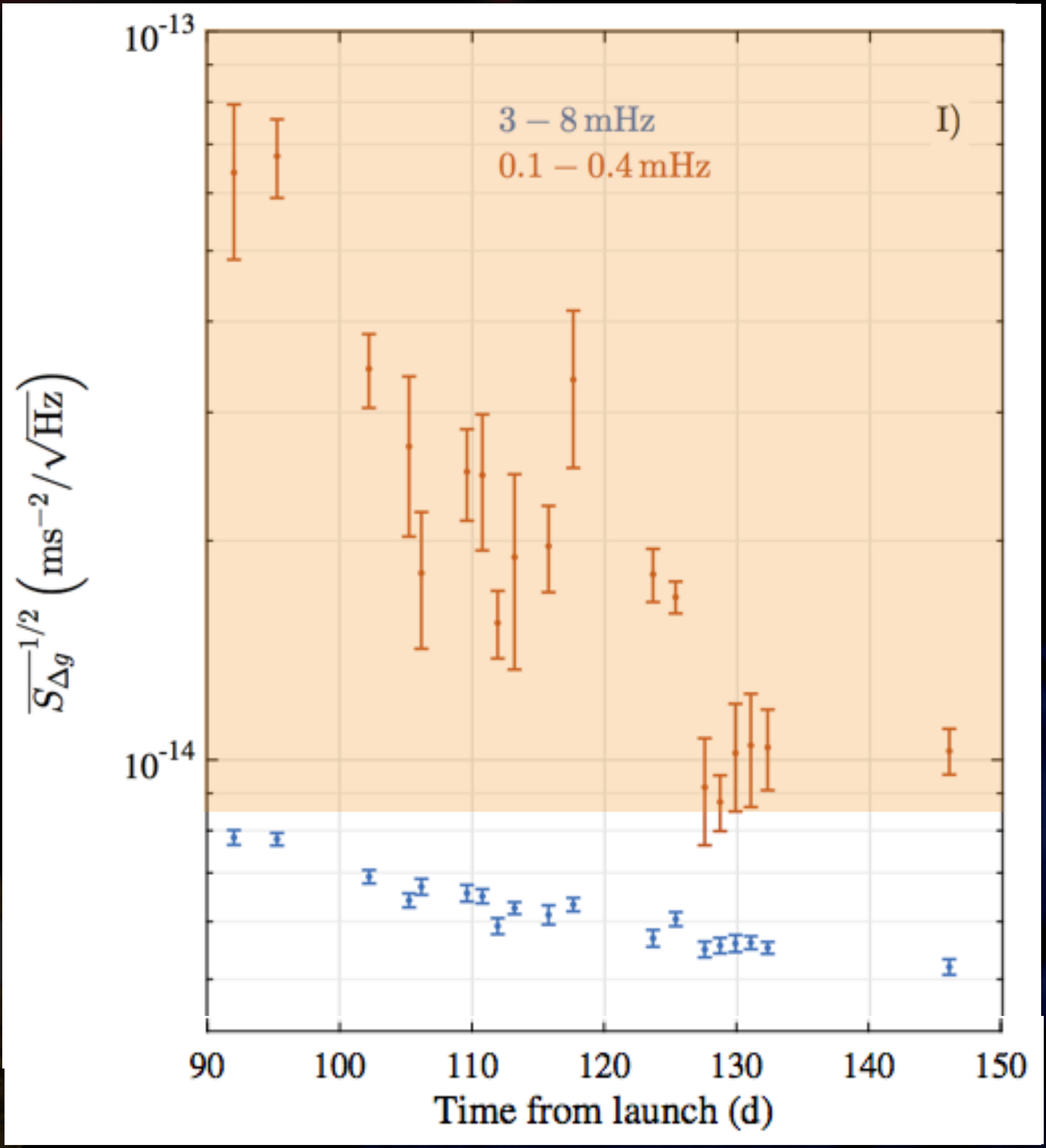

Low frequency noise
Investigation in progress
...

Brownian noise
Molecules within the noise
hit test-masses

Interferometric noise
Not real test-mass motion

# Low-frequency limit

- Noise in 0.1 – 1 mHz:
- 50% understood:
  actuation noises
- Still 50% not completely explained:
  - 1/f slope
  - Temperature ?
    Small glitches ?
- Work in progress …

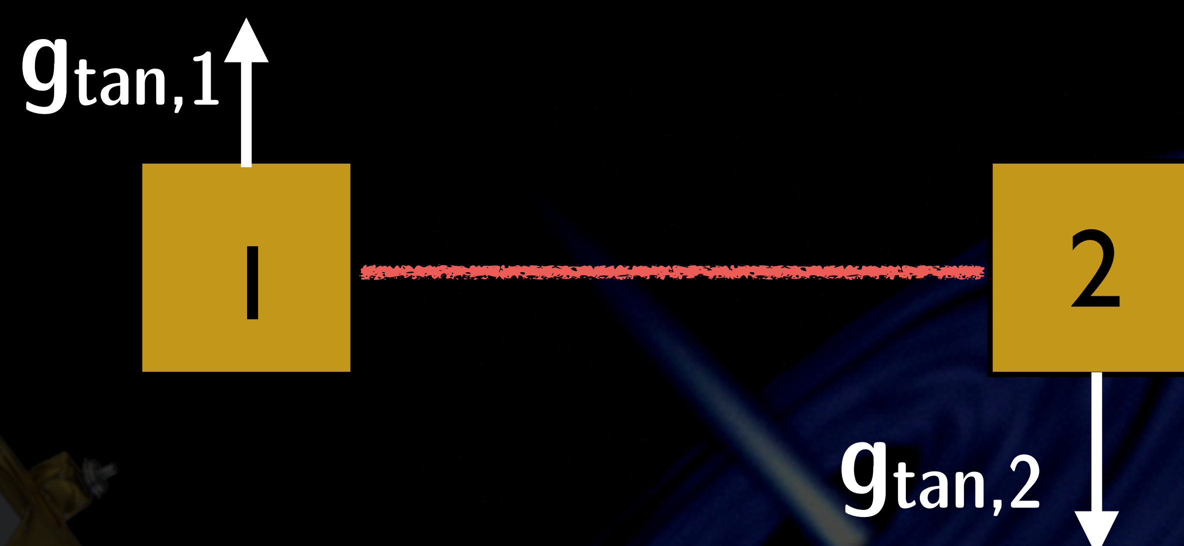



M. Armano et al. PRL 116, 231101 (2016)

# Angle Decorrelation - Euler Forces

by Joseph Martino

$$\Delta\vec{g}_{\mathrm{tang}} = \vec{g}_{\mathrm{tang},2} - \vec{g}_{\mathrm{tang},1}$$
$$= (\vec{r}_2 - \vec{r}_1) \times \dot{\vec{\Omega}}$$



# Outline

- Introduction to gravitational waves
- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISAPathfinder
- LISA status and organization
- LISA scientific performances
- The French contribution to LISA:
  - Data Processing Center
  - Integration / performance control
- Conclusion and perspectives

# 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
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- 2013: selection of ESA L3 : « The gravitational Universe »
- 2015-2016: success of LISAPathfinder + detection GWs

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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

François Arago Centre

université PARIS DIDEROT

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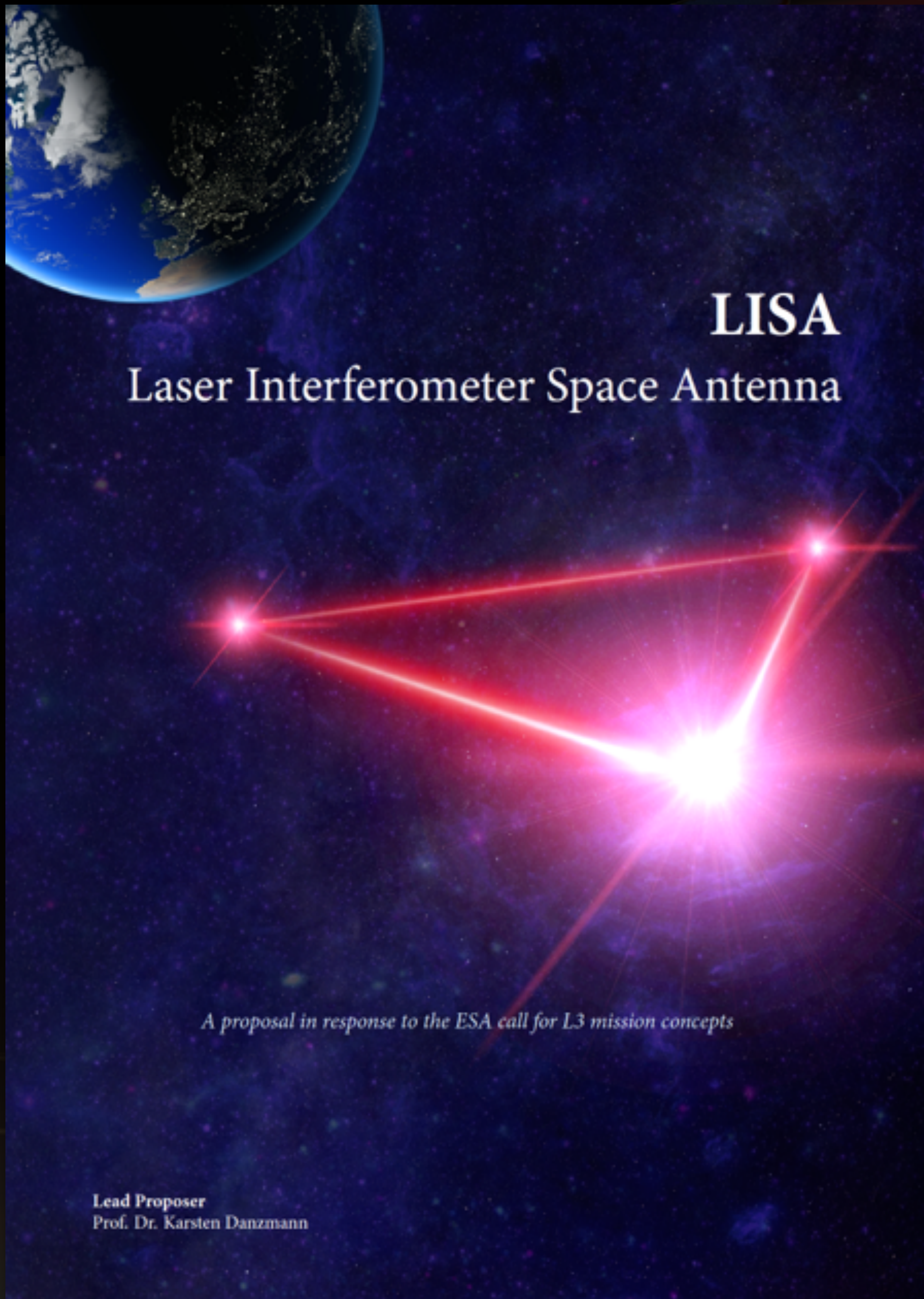
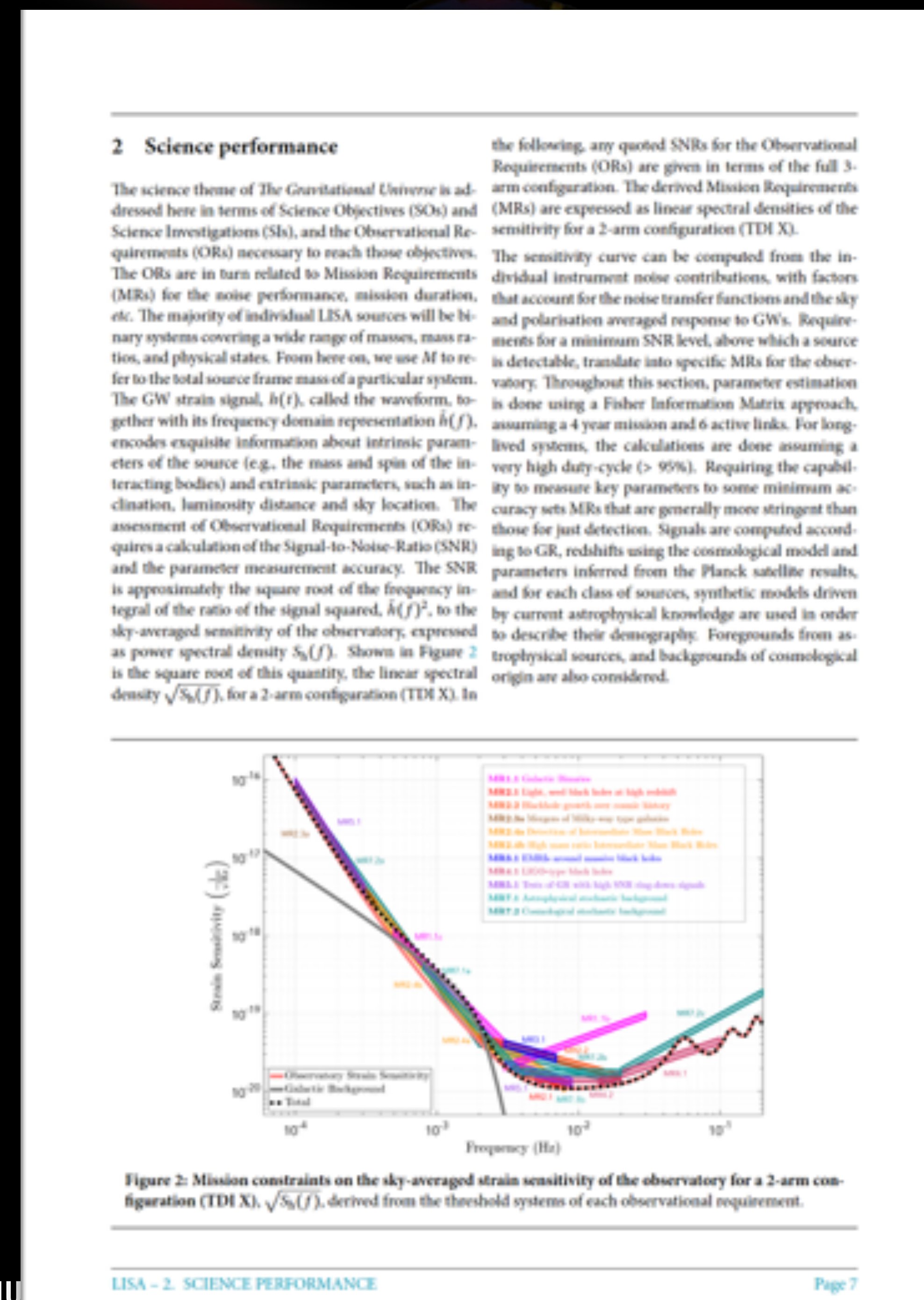
Call for mission at ESA

# 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 concept in the proposal

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

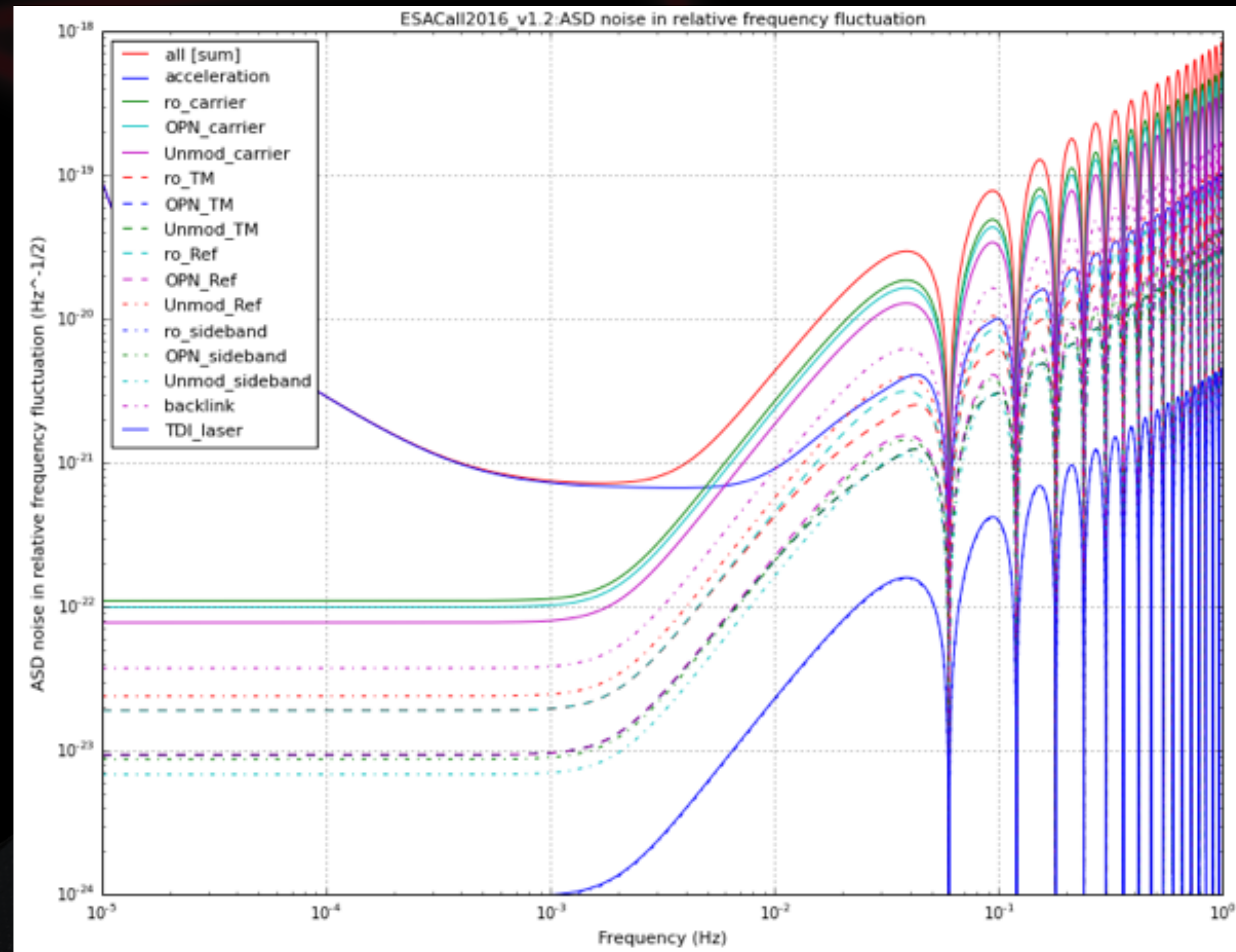
$$\begin{array}{ll} 100\,\mu\text{Hz} \le f \le 0.1\,\text{Hz} & \text{req.} \\ 20\,\mu\text{Hz} \le f \le 1\,\text{Hz} & \text{goal} \end{array}$$

- Noise budget:
  - Acceleration => LISAPathfinder

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

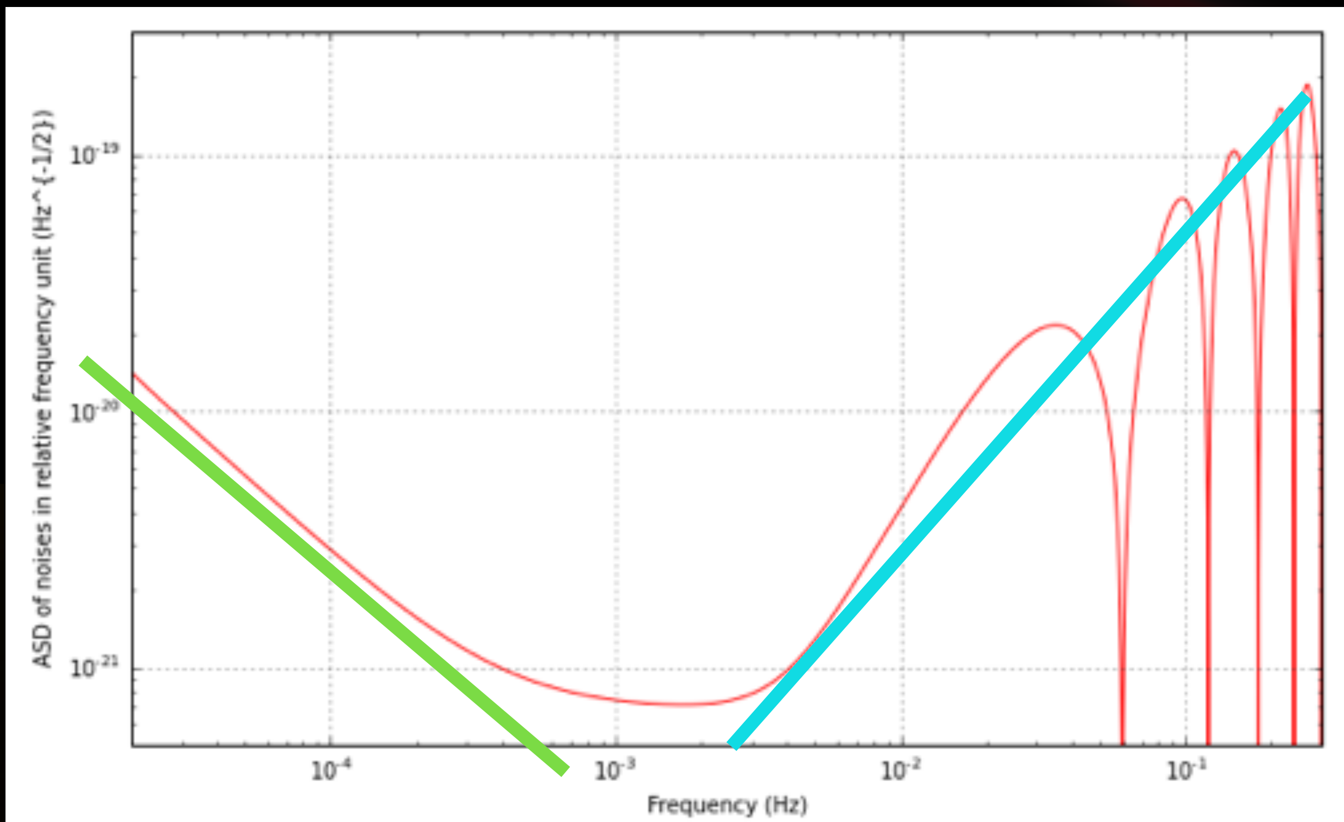
  - Interferometric Measurement System

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

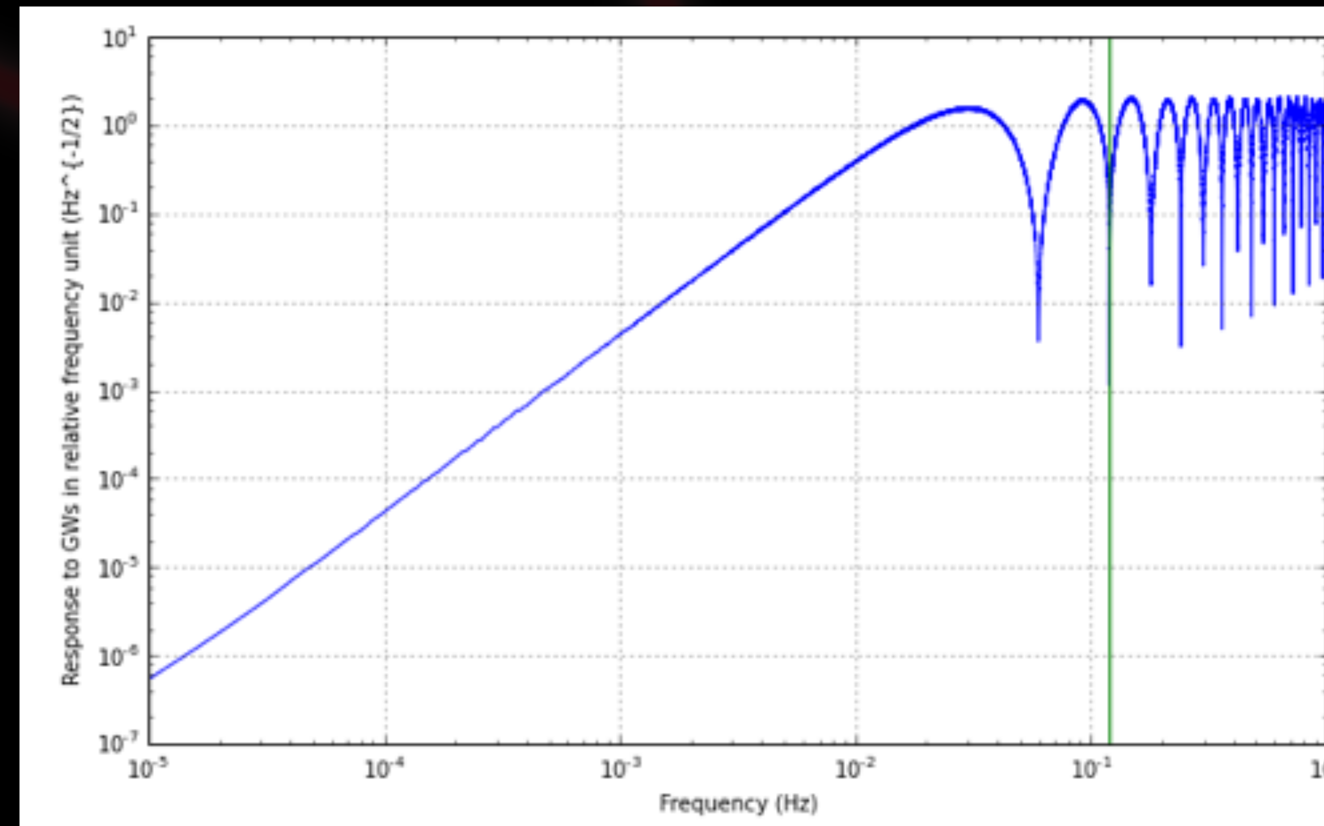


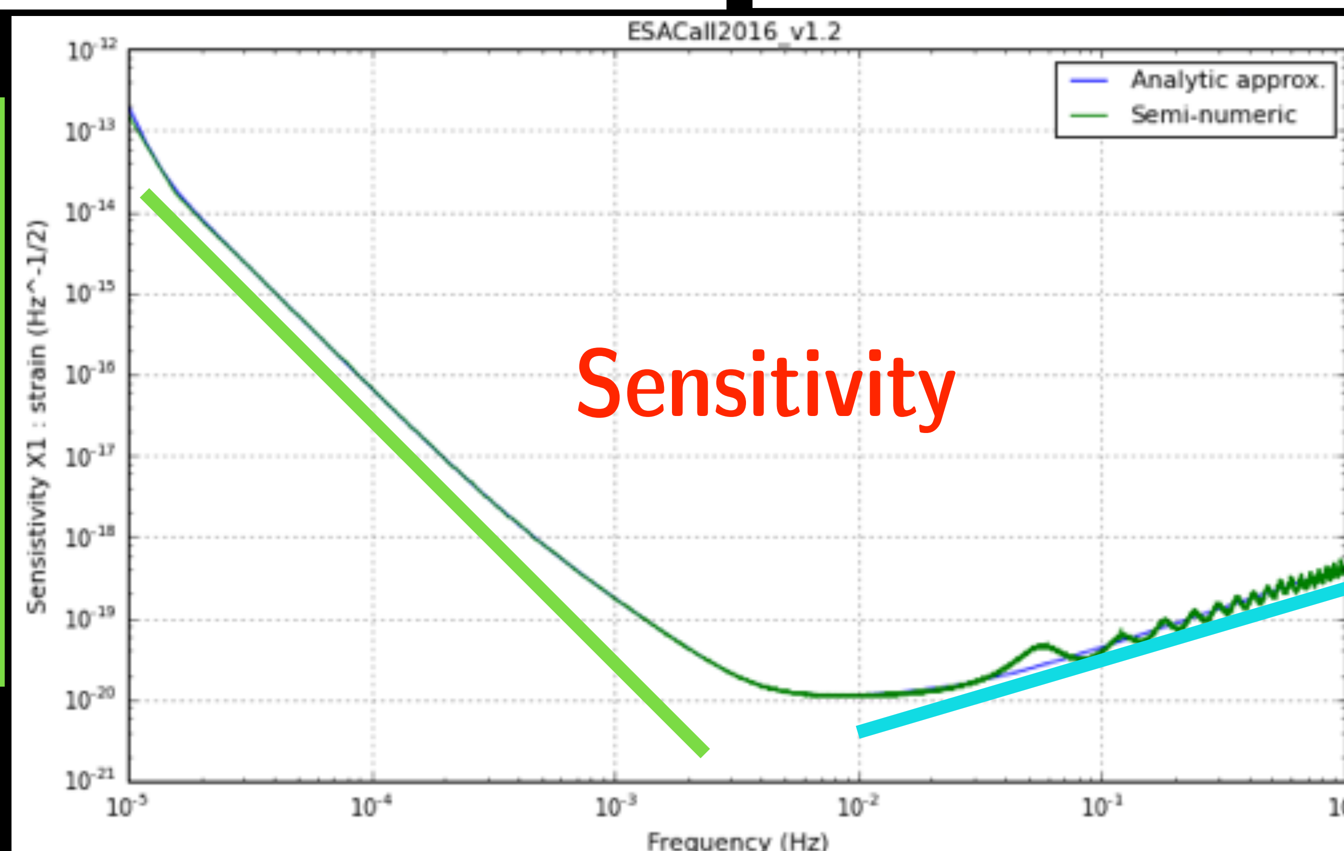
# Sensitivity

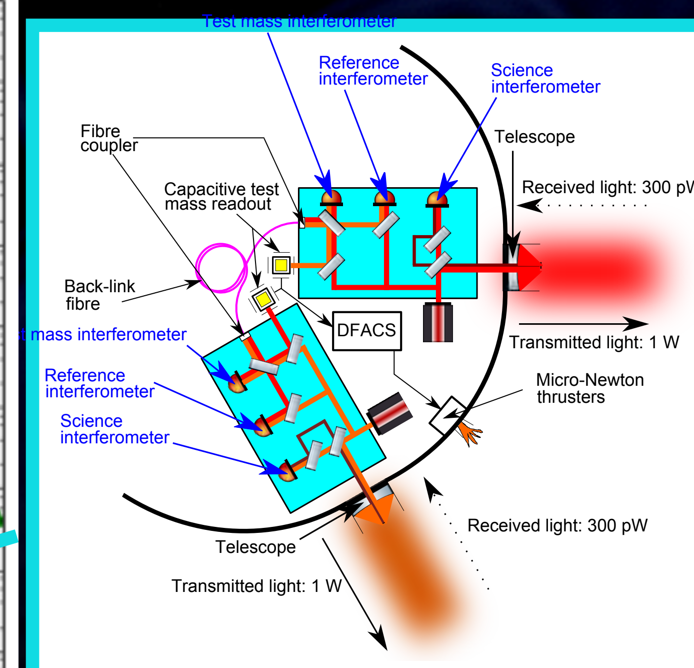
## Noises



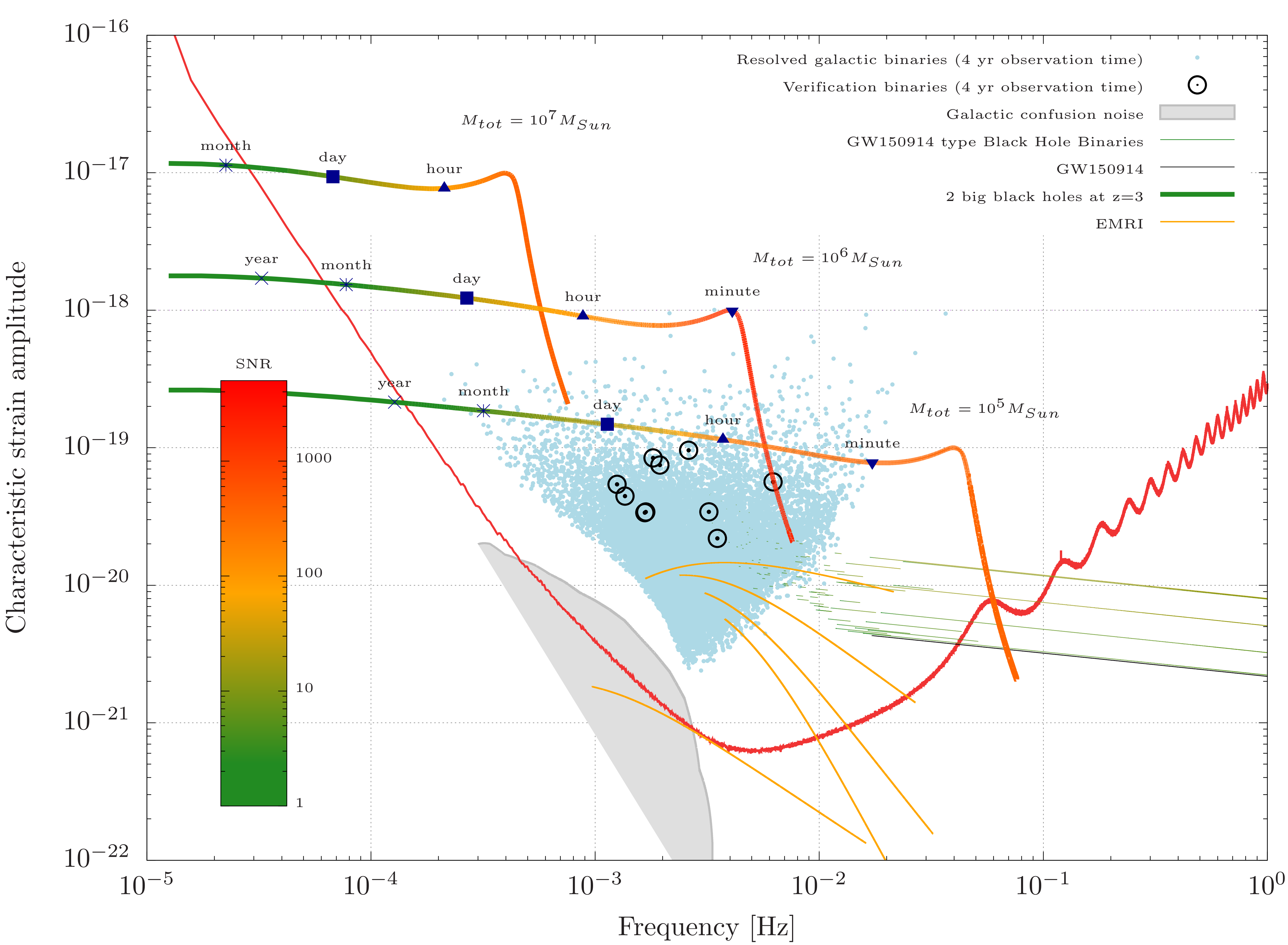

## Response of the detector to GWs



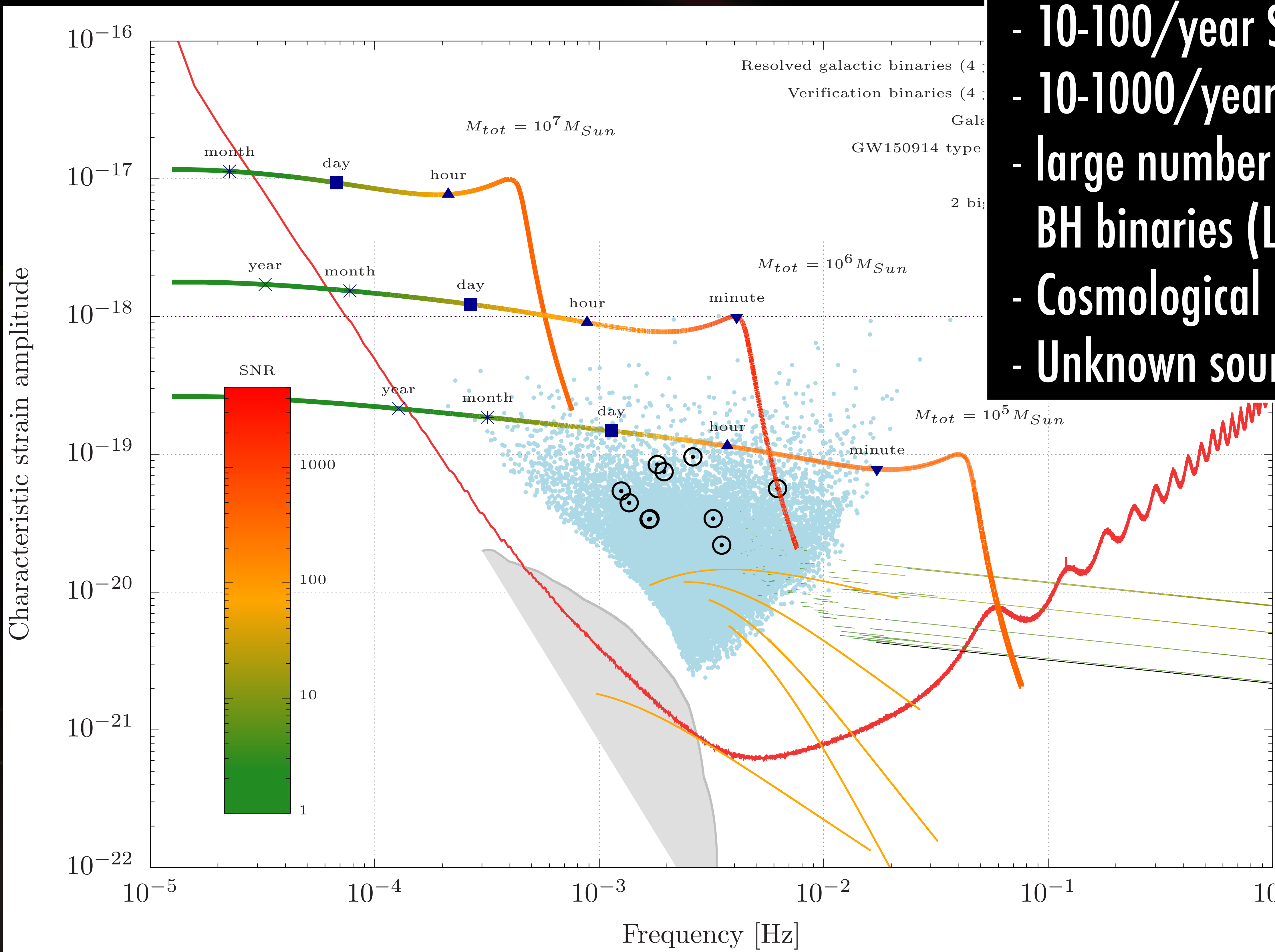



# GW sources



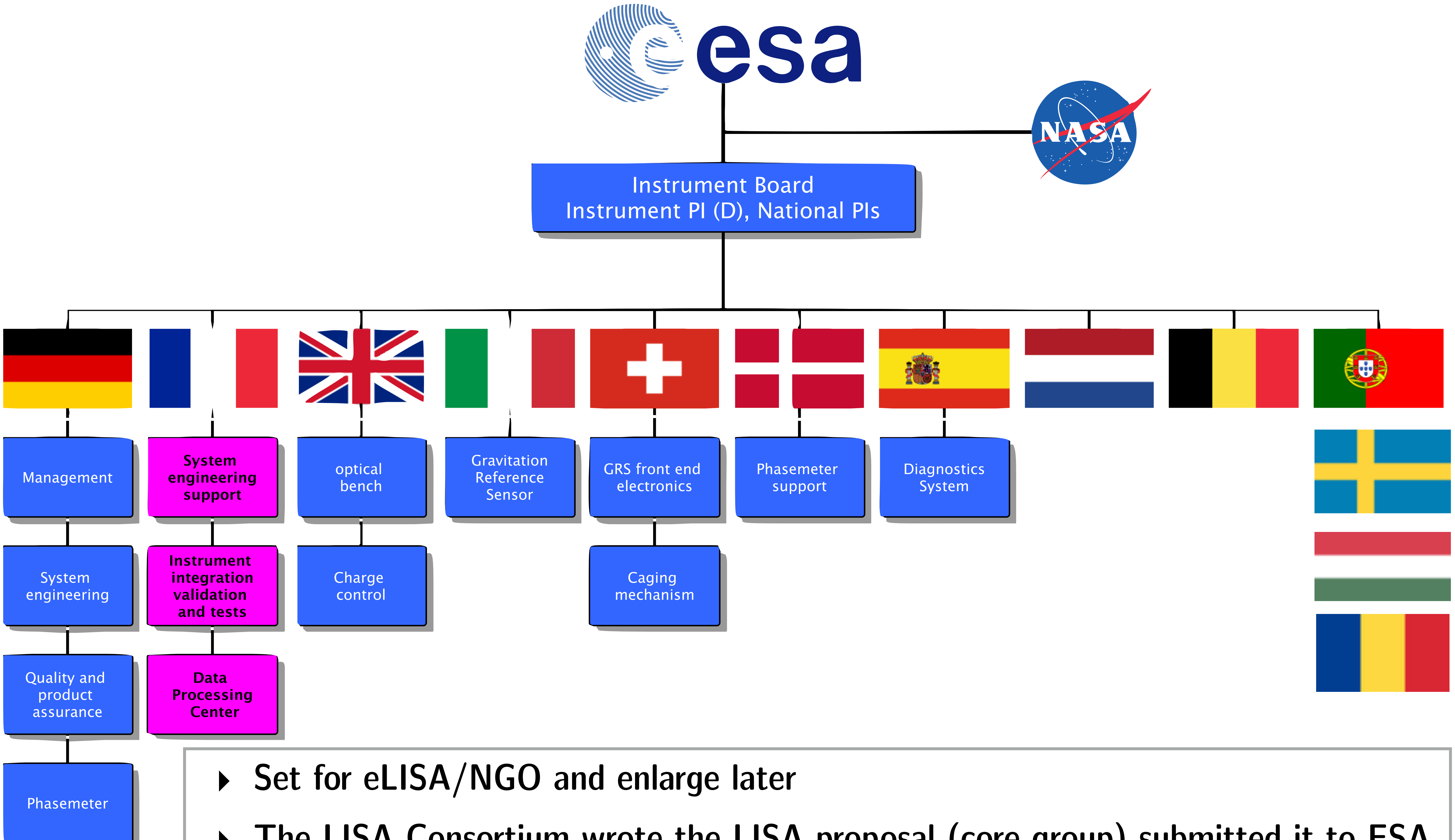
Characteristic strain amplitude
Frequency [Hz]
Resolved galactic binaries (4 yr observation time)
Verification binaries (4 yr observation time)
Galactic confusion noise
GW150914 type Black Hole Binaries
GW150914
2 big black holes at z=3
EMRI
$M_{tot} = 10^7 M_{Sun}$
$M_{tot} = 10^6 M_{Sun}$
$M_{tot}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

# GW sources




- 6 x$10^7$ 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

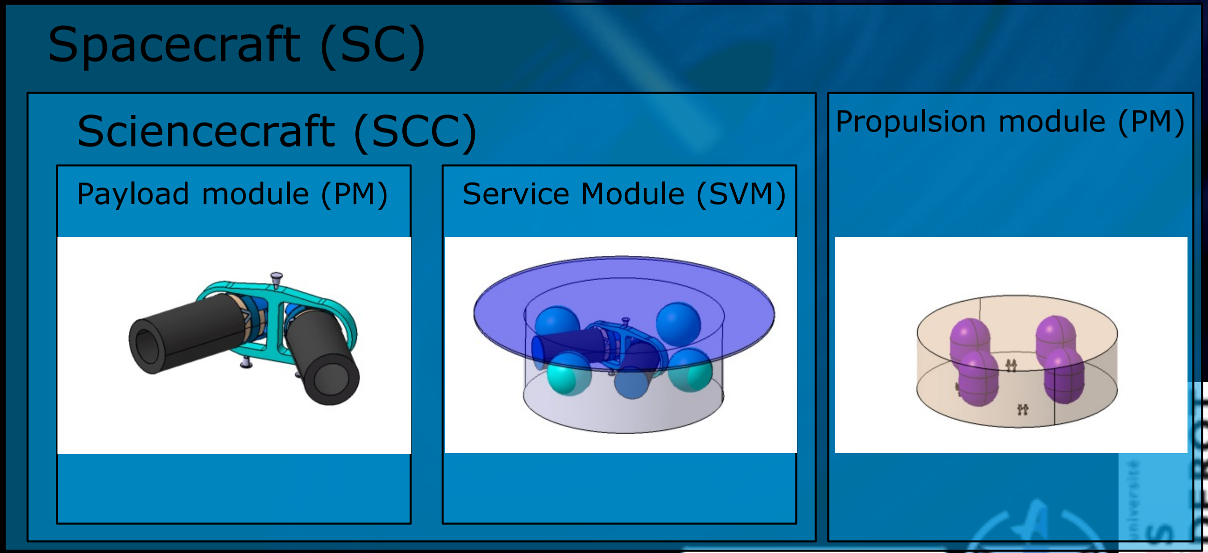
# LISA at ESA

- 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

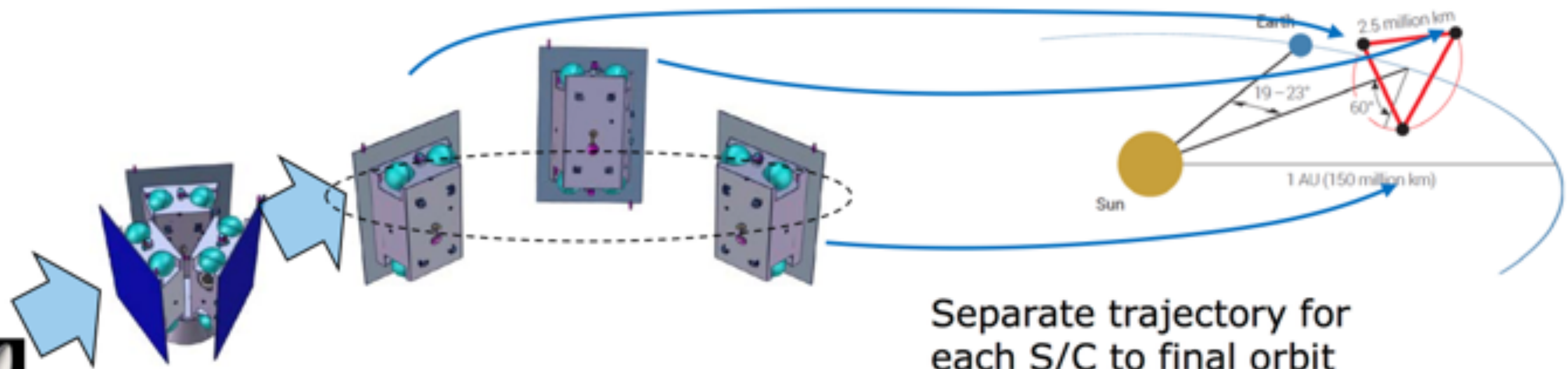
→ GW observations !

# 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

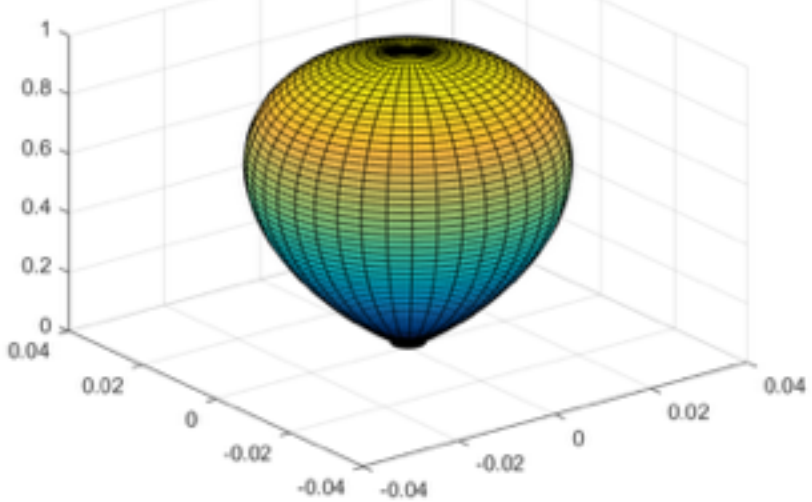


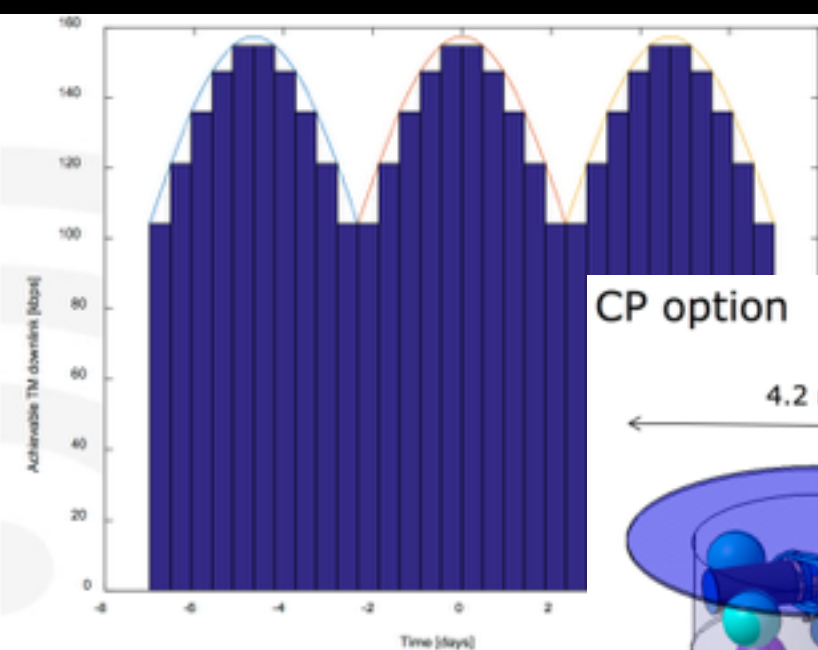

Separate trajectory for each S/C to final orbit

Separation of the stack right after launch

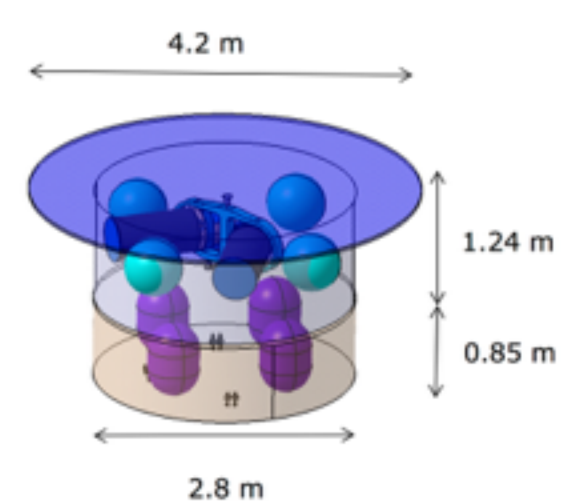
Launch in stacked configuration
Direct injection into escape trajectory

| | 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** |

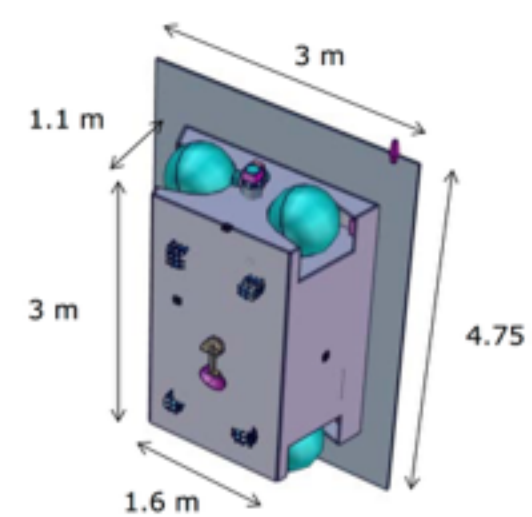




CP option




EP and EP+ option




**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**

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

# ESA next steps

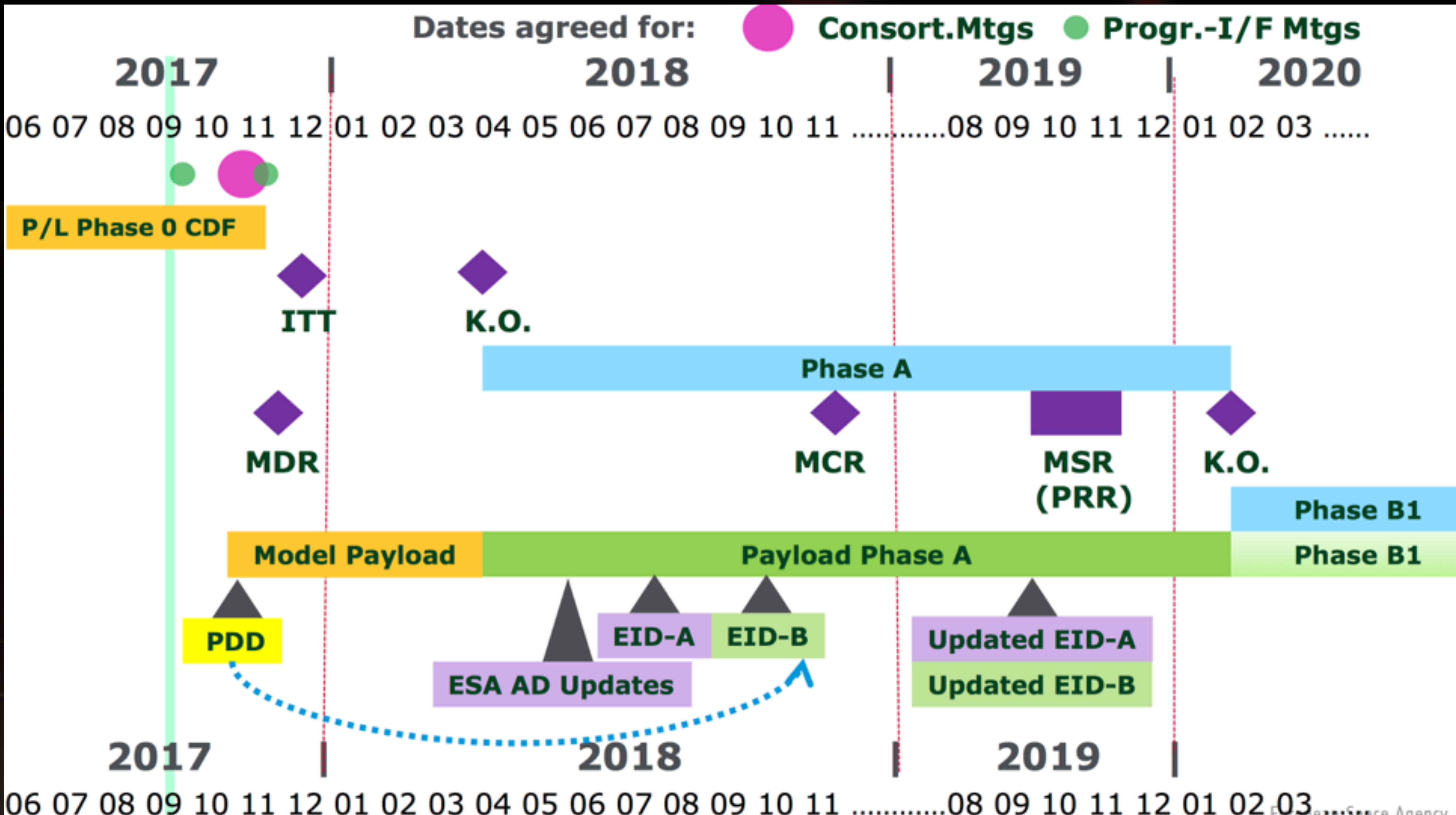
1. Payload Definition Document (PDD)
2. ESA appointed the Science Study Team: responsible for the Science Requirement Document (SRD):
3. SRD + PDD => input to the Mission Requirement Document (MRD)
4. MRD is used to defined the ITT: invitation to industries

   All these steps need to be done by december 2017

5. March 2018: start of phase A

# ESA Next steps

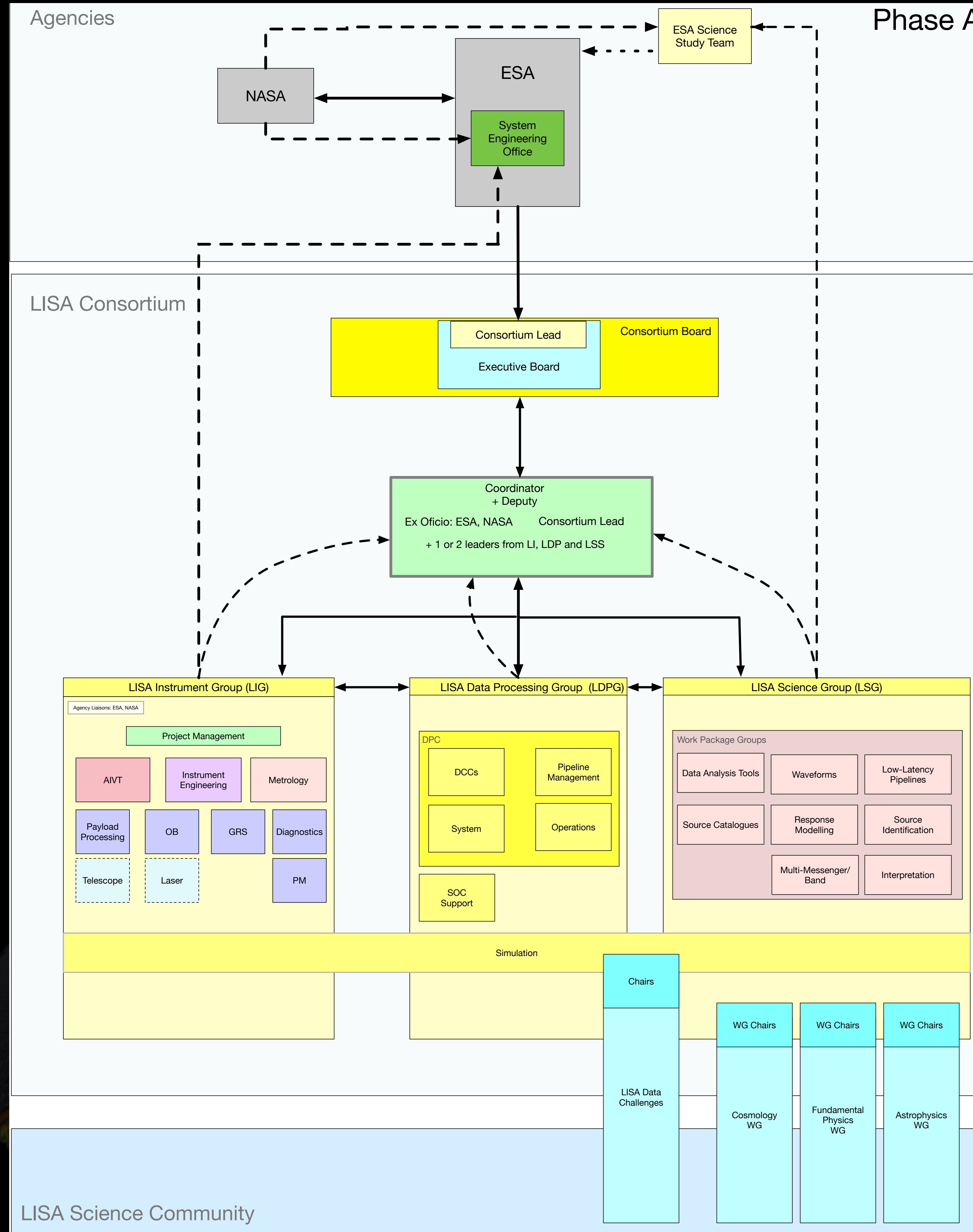
- Mission Definition/Consolidation/Selection/Adoption Review, Payload Definition Doc, Experiment Interface Doc.



# 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)
  - External:
    - N. Tanvir
    - J. Hjorth
  - LISA US:
    - K. Holley-Bockelmann
    - D. Shoemaker
  - Observers:
    - O. Jennrich (ESA)
    - I. Thorpe (NASA)
    - R. Sambruna (NASA)

# Consortium organisation

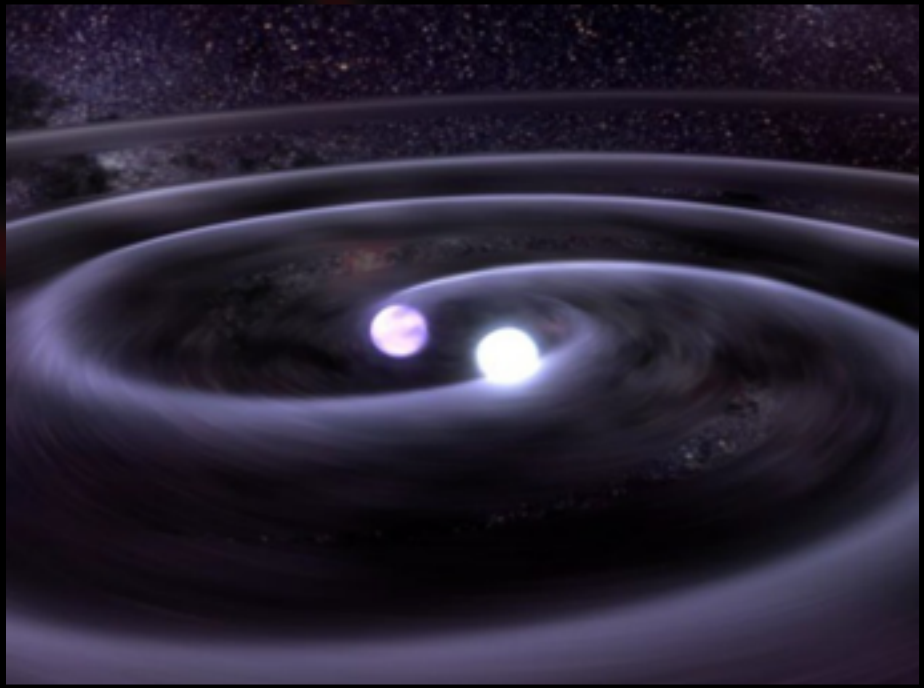


# Outline

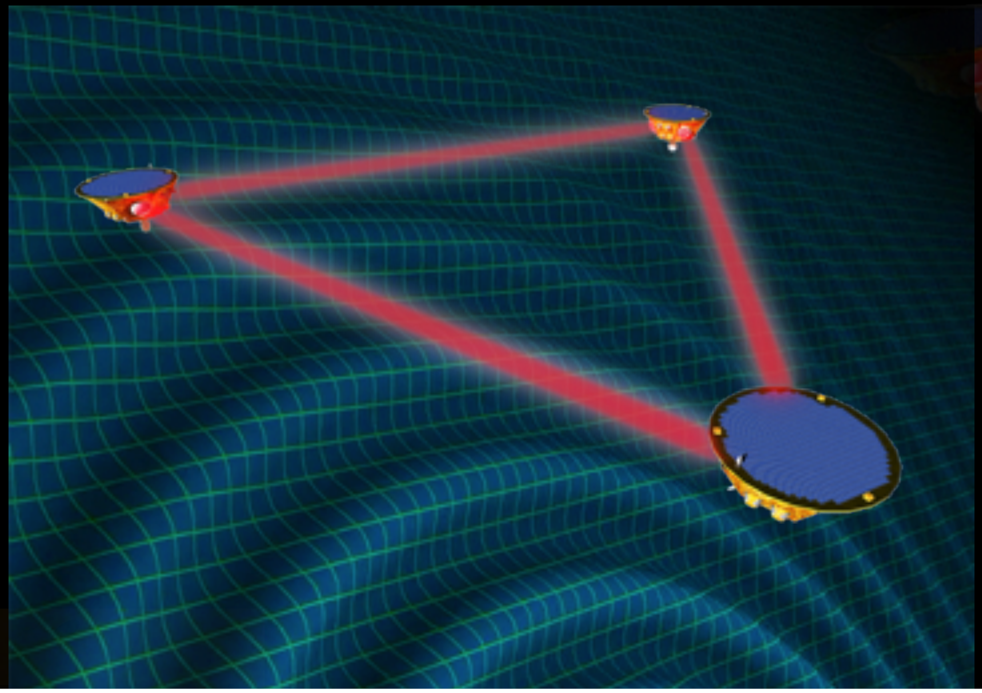
- Introduction to gravitational waves
- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISAPathfinder
- LISA status and organization
- LISA scientific performances
- The French contribution to LISA:
  - Data Processing Center
  - Integration / performance control
- Conclusion and perspectives

# 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)

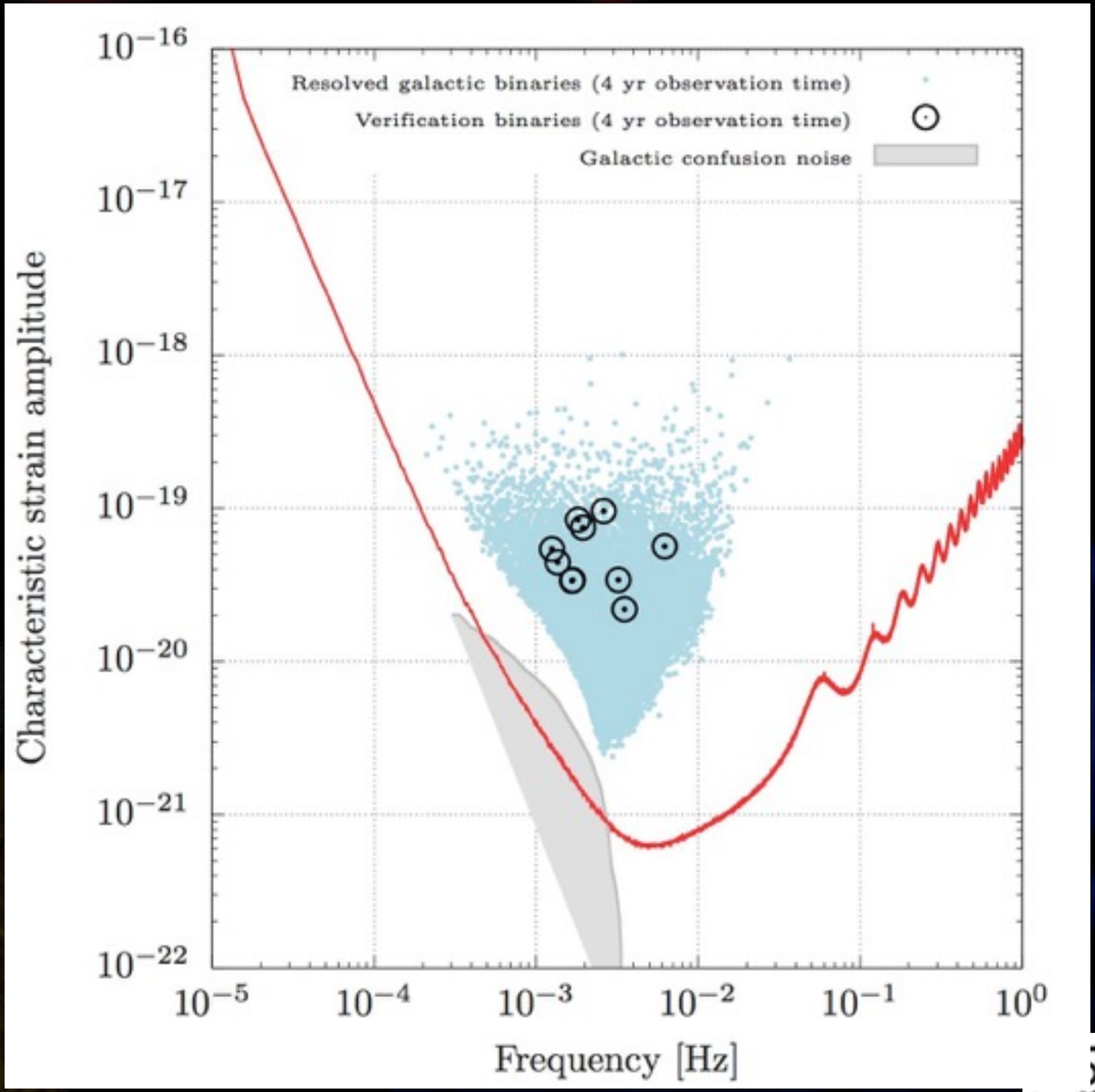


# Galactic binaries



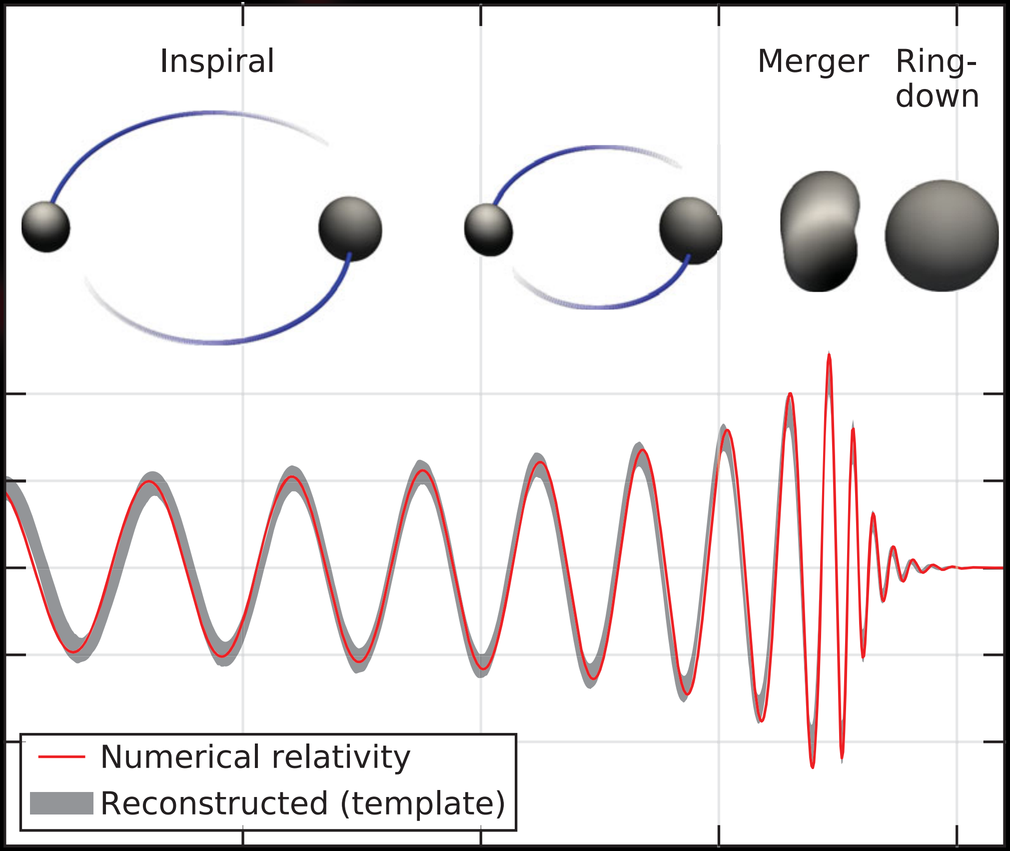
GW sources

- 6 x$10^7$ galactic binaries



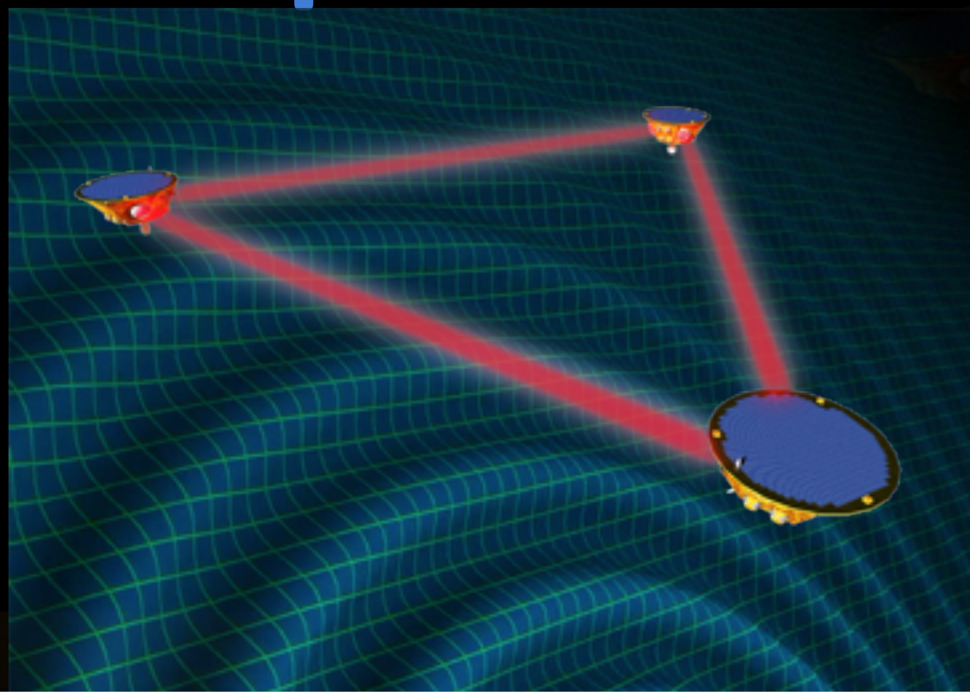
# Super Massive Black Hole Binaries

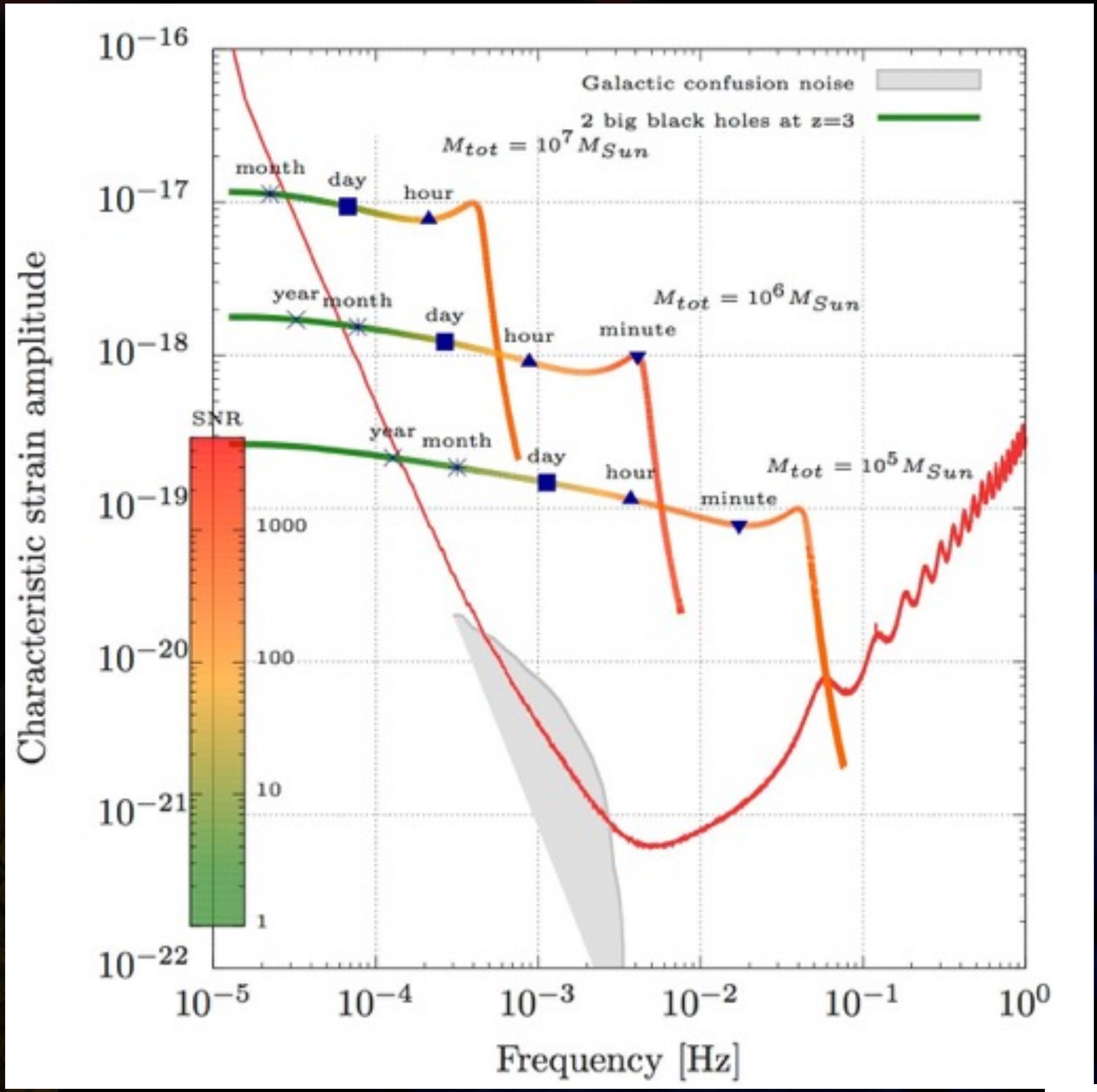
- Gravitational wave:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.




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

# Super Massive Black Hole Binaries





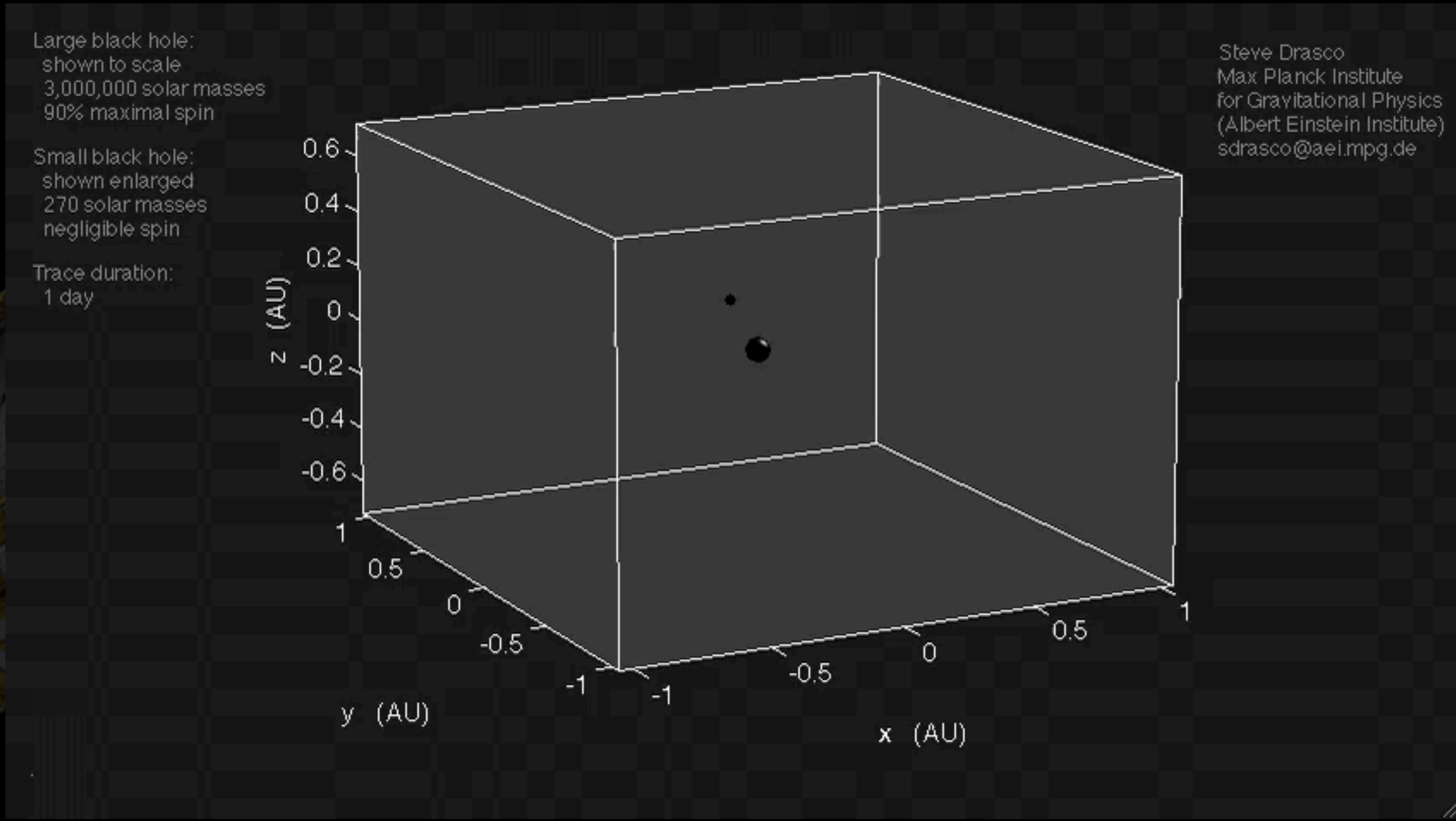

## OG sources

- $6 \times 10^7$ 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



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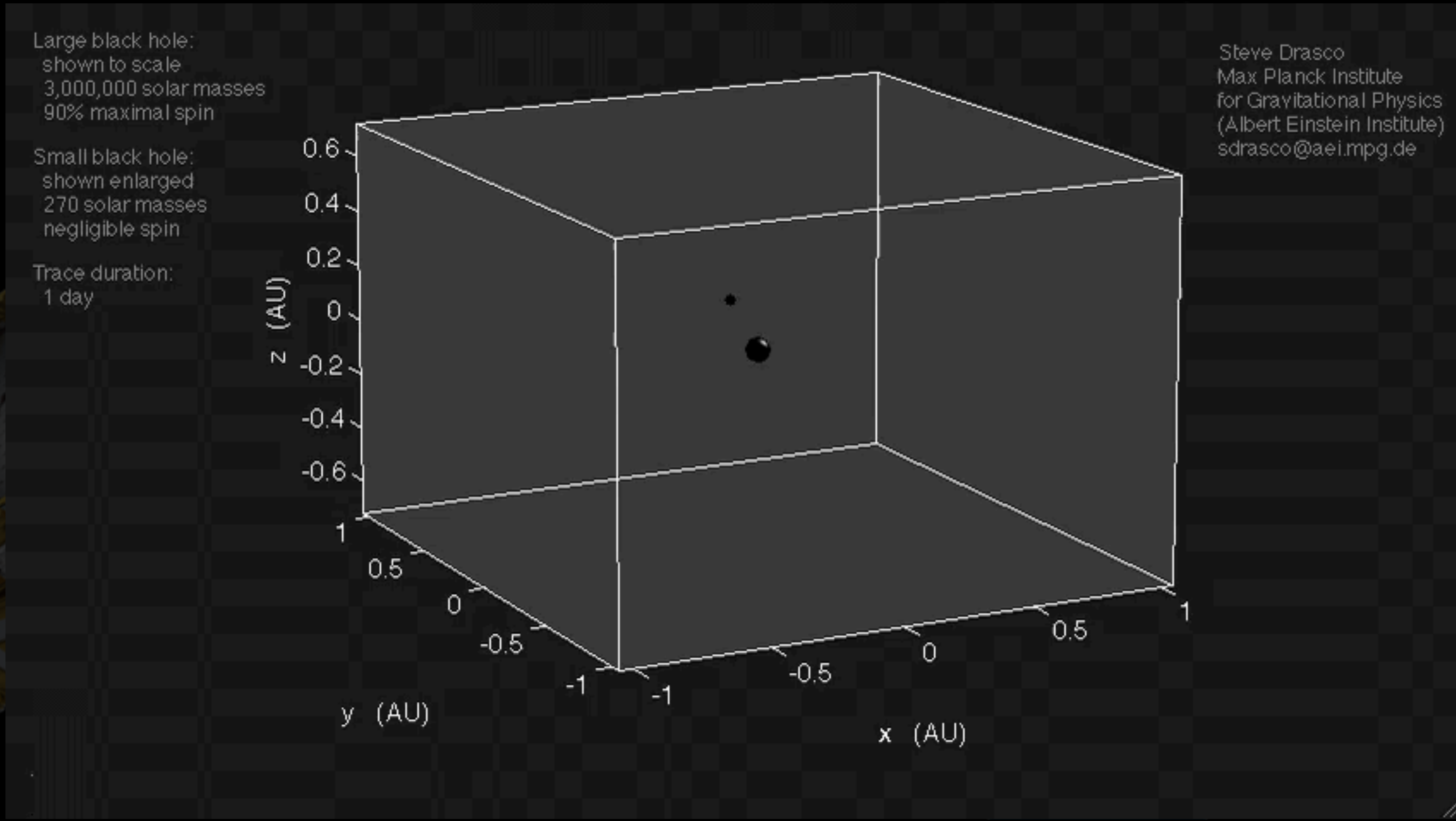
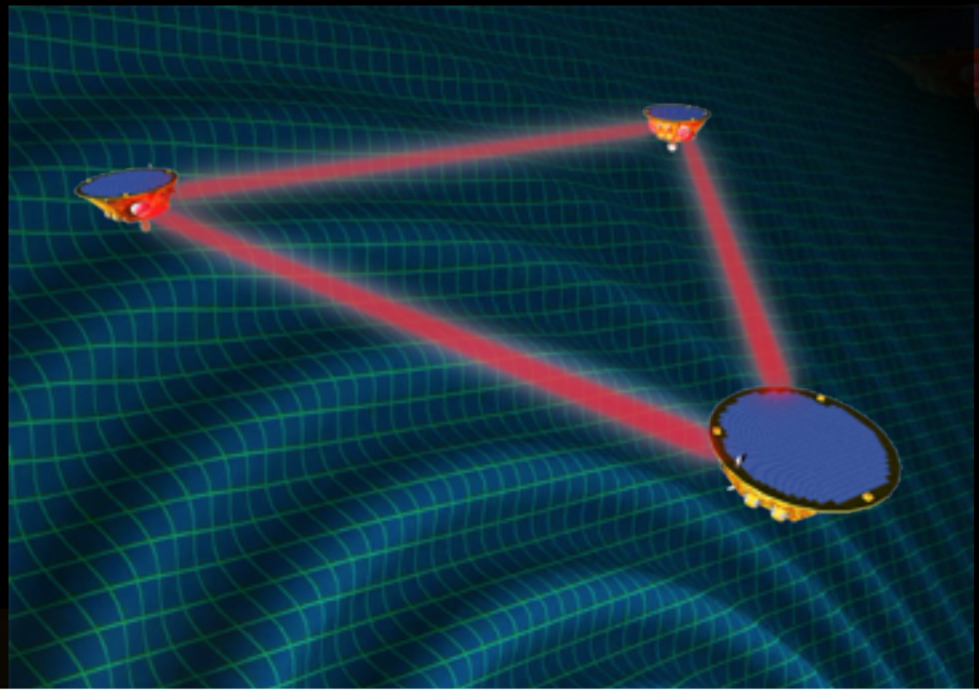


# EMRIs



## OG sources

- 6 x$10^7$ galactic binariess
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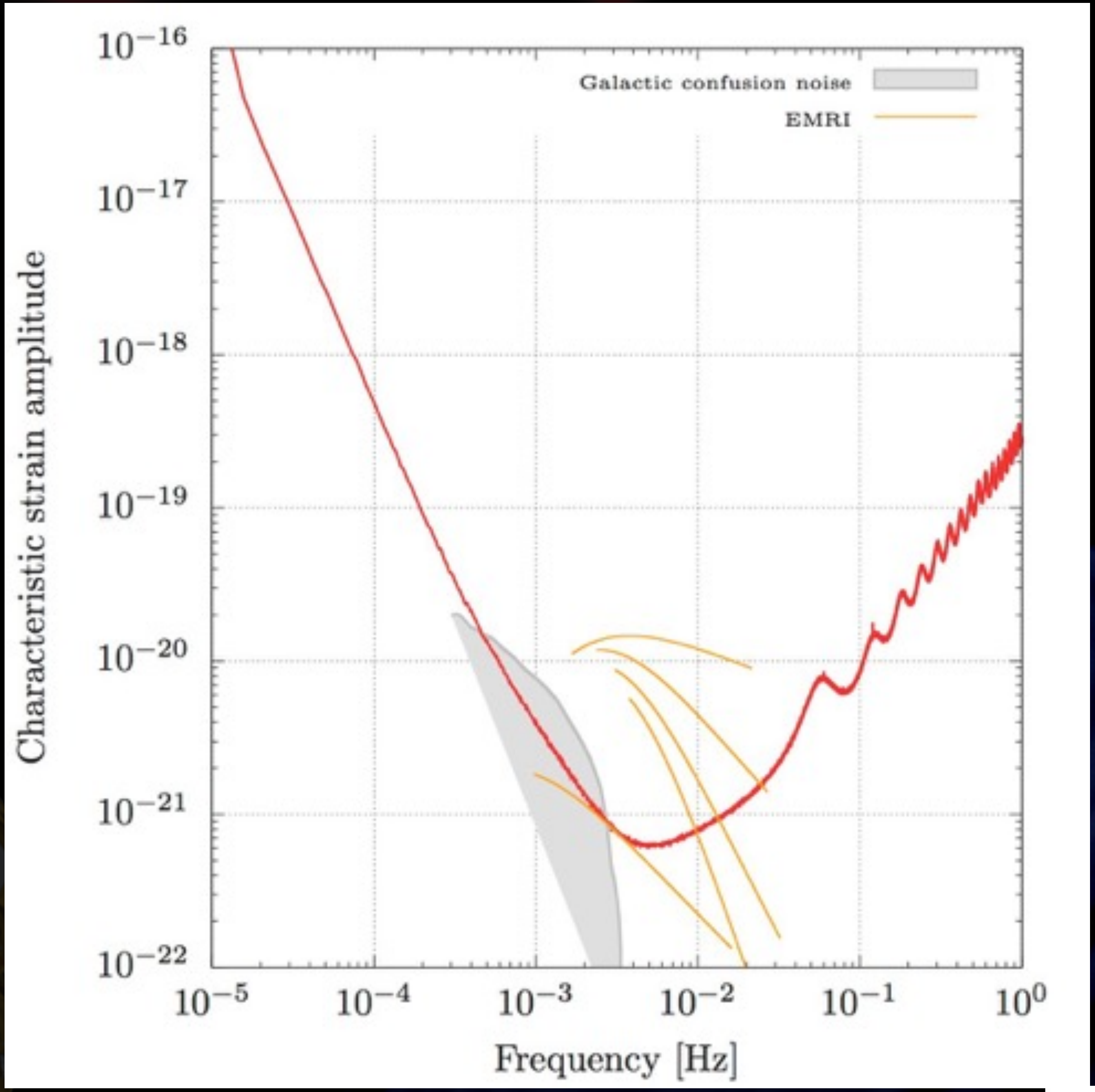
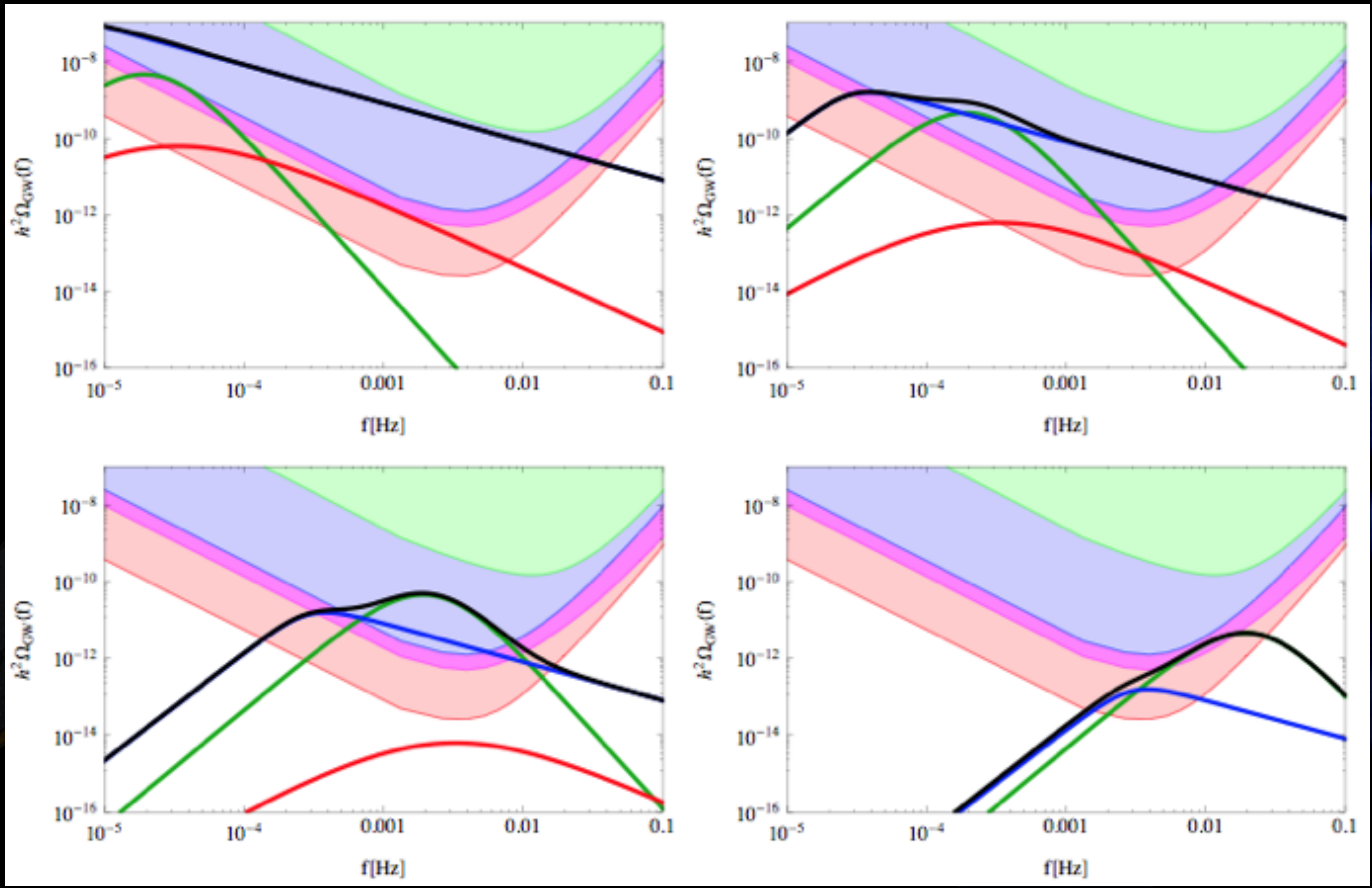
- 10-1000/years EMRIs

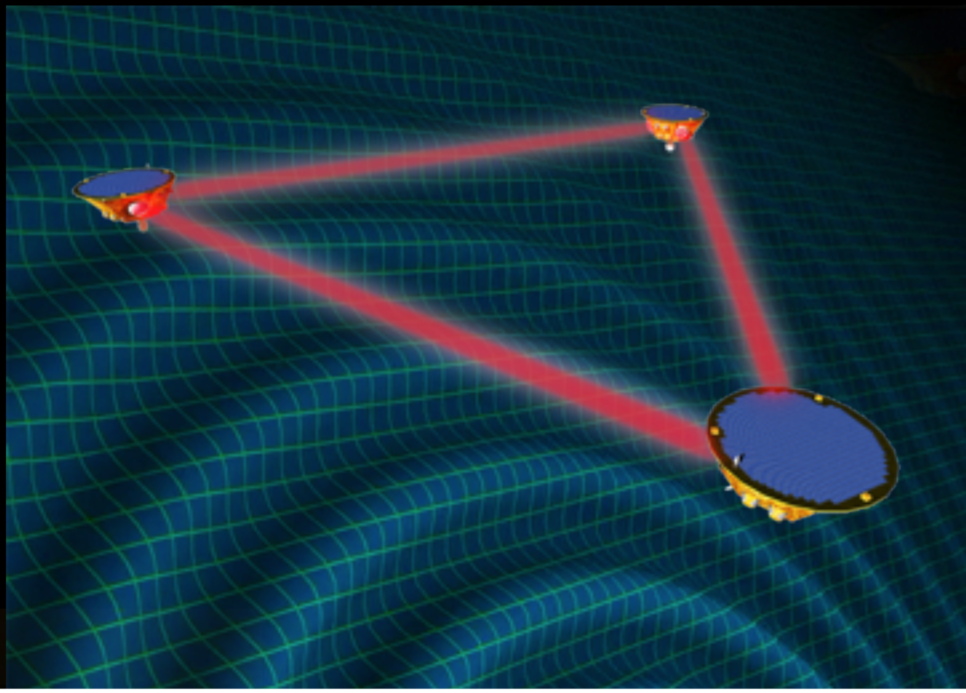


# Cosmological backgrounds

- 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



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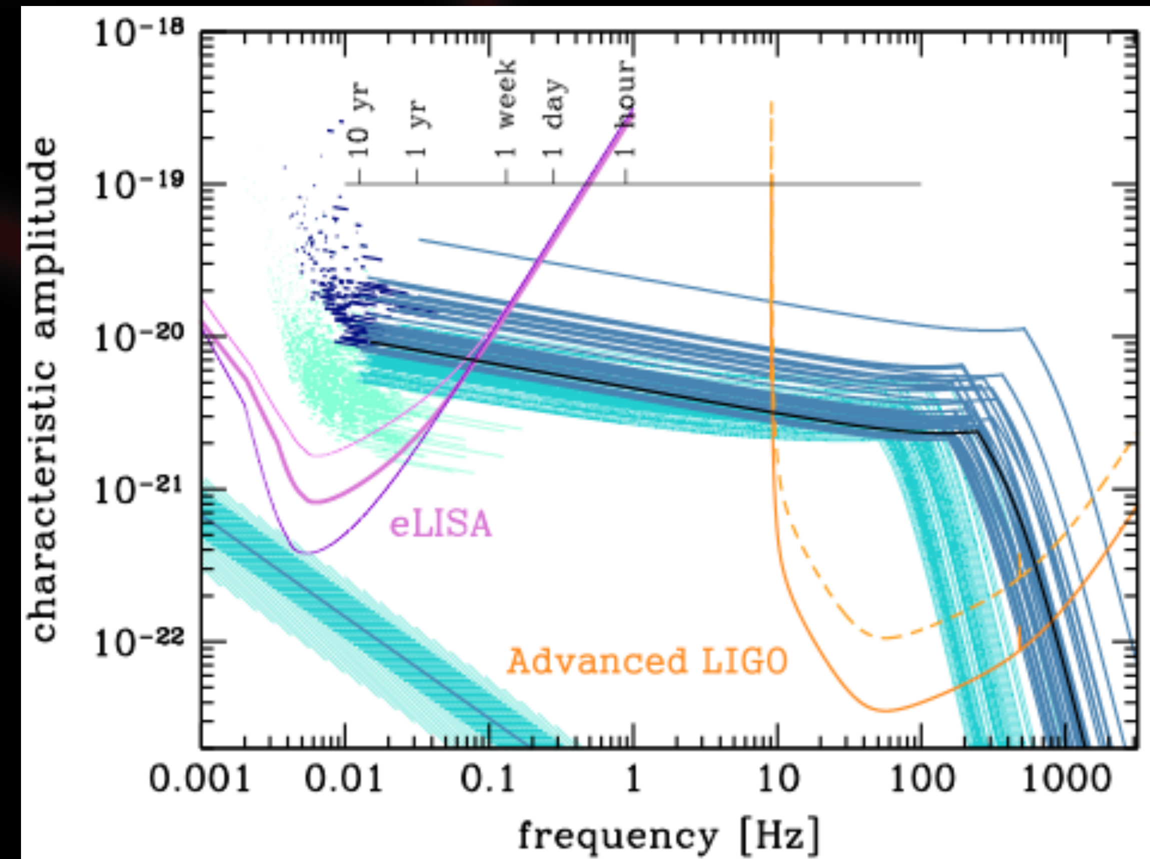


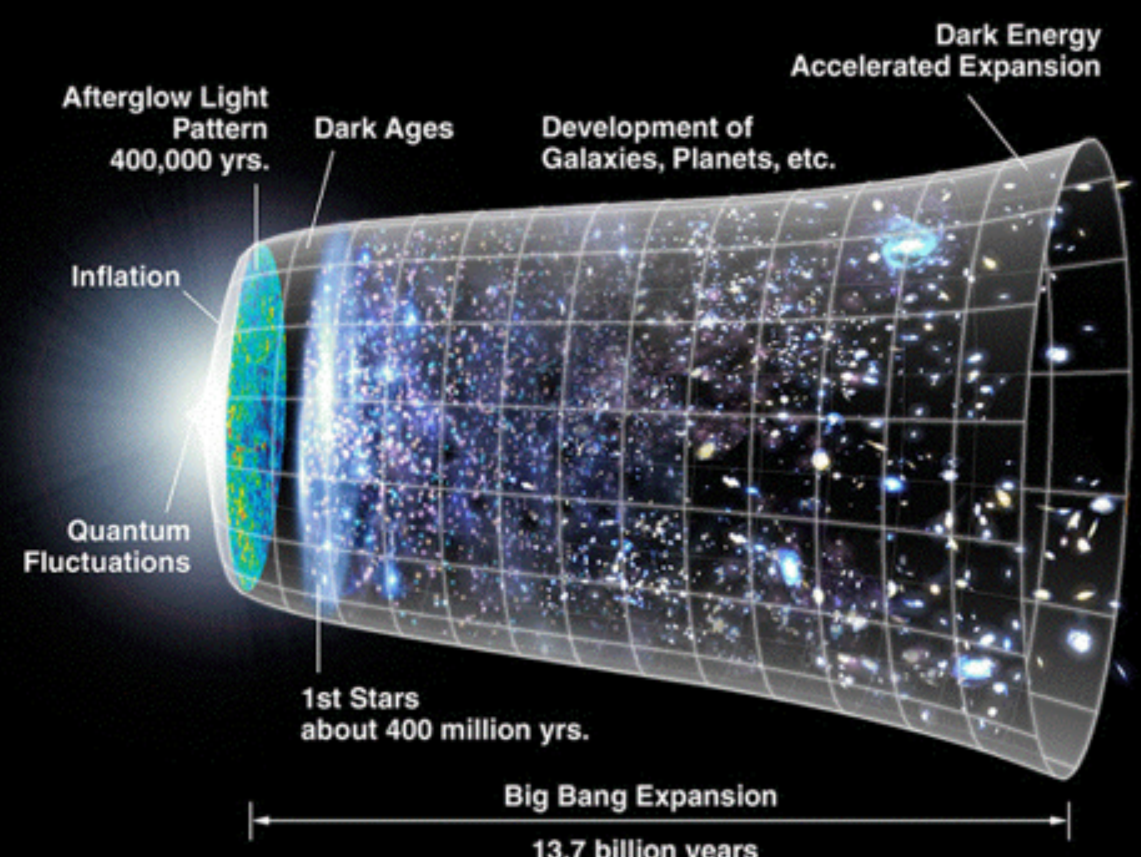

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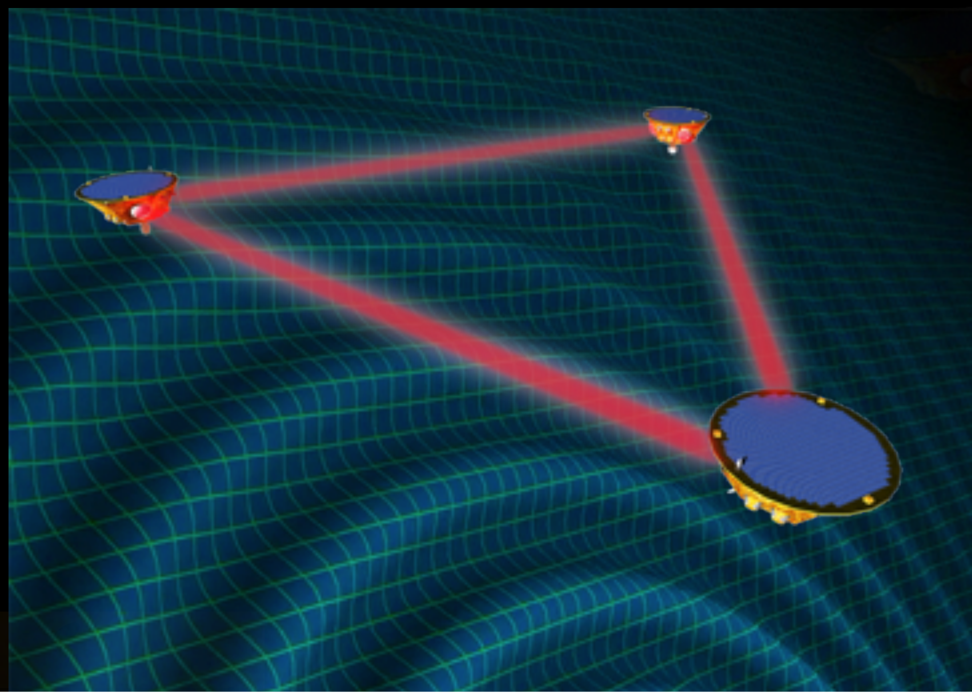
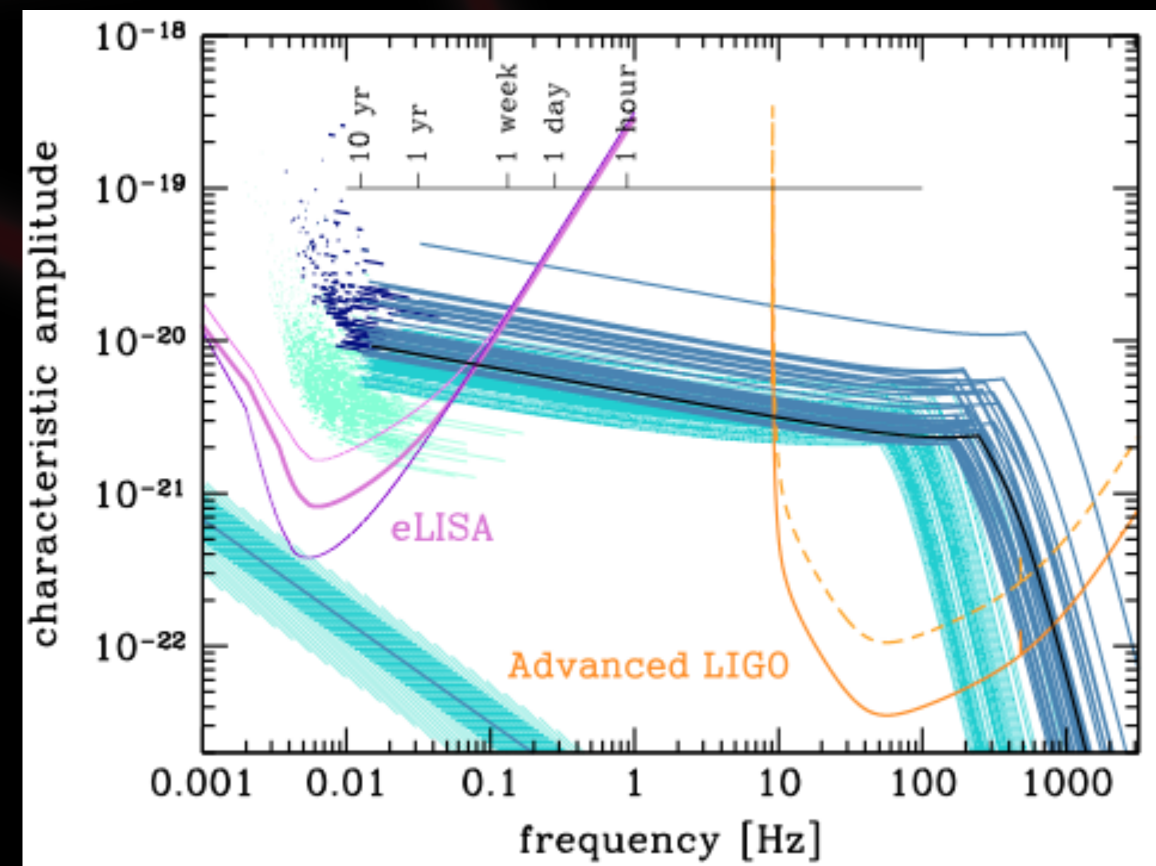


?

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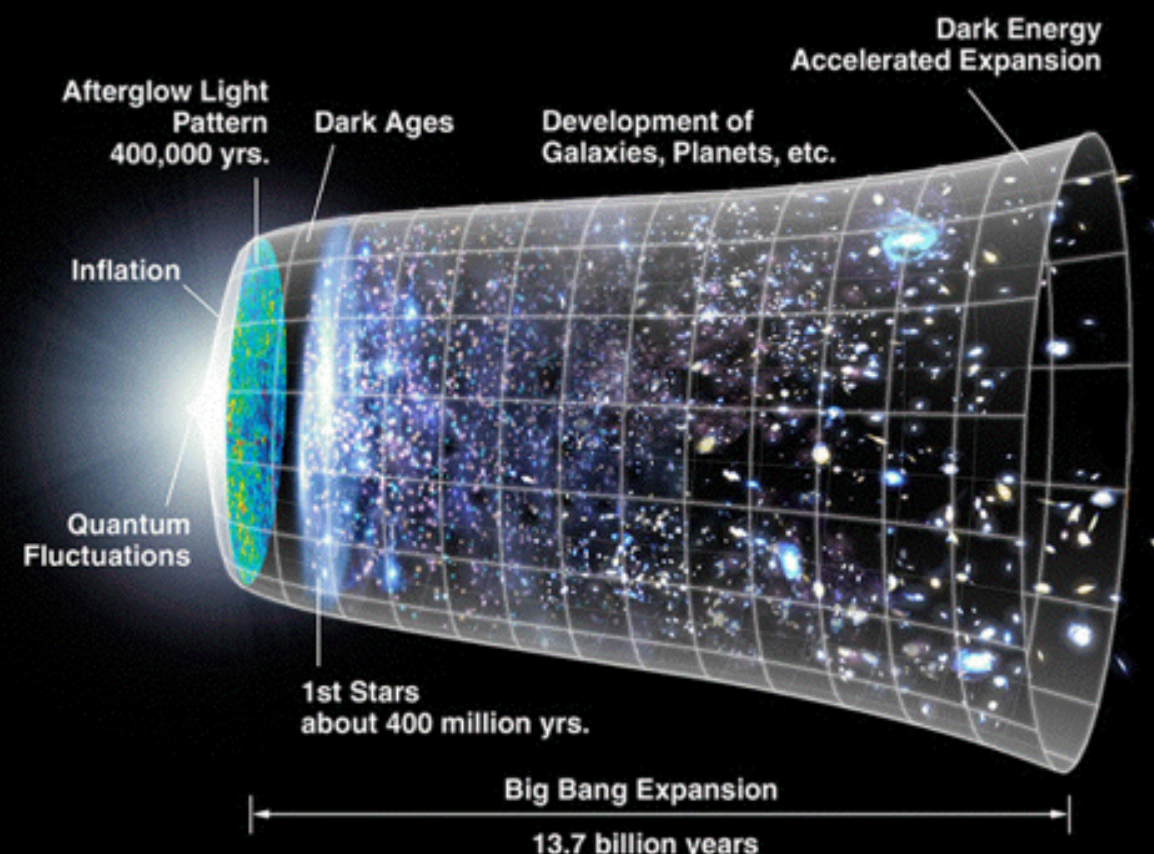

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- The French contribution to LISA:
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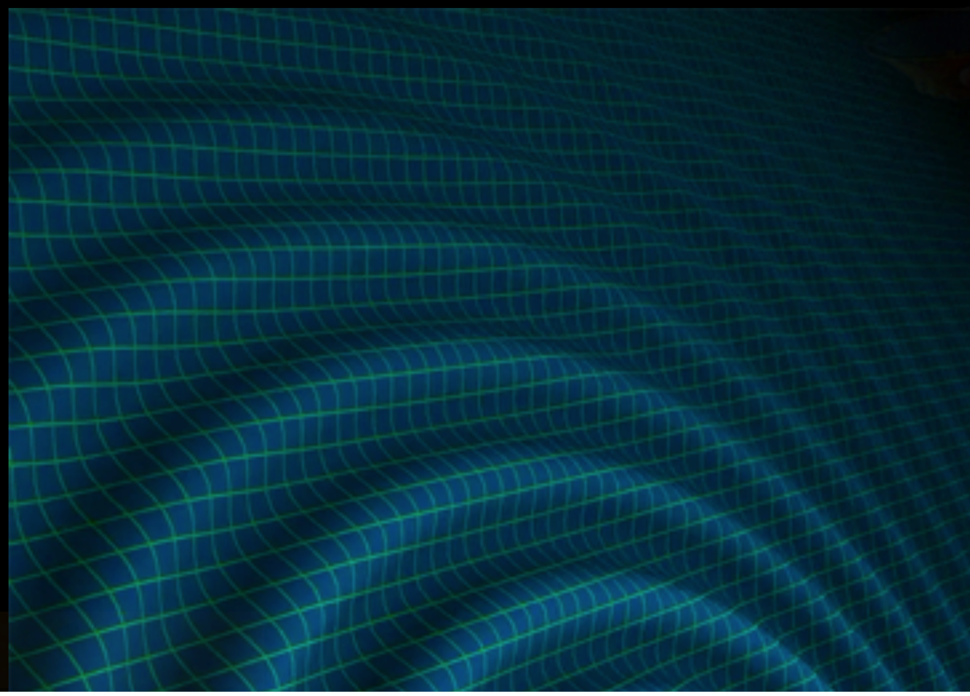
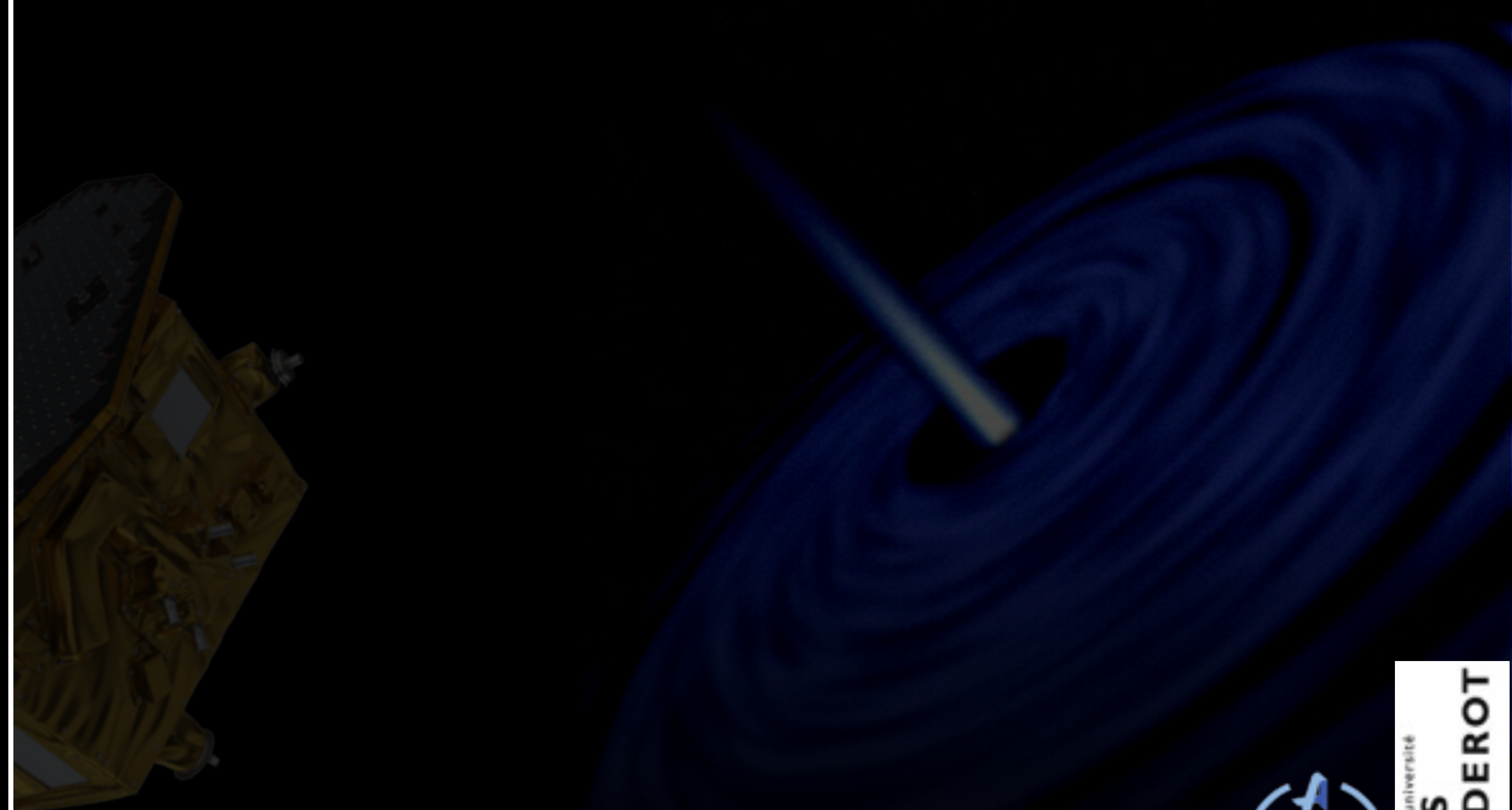
# LISA data

Gravitational wave sources emitting between 0.02mHz and 1 Hz

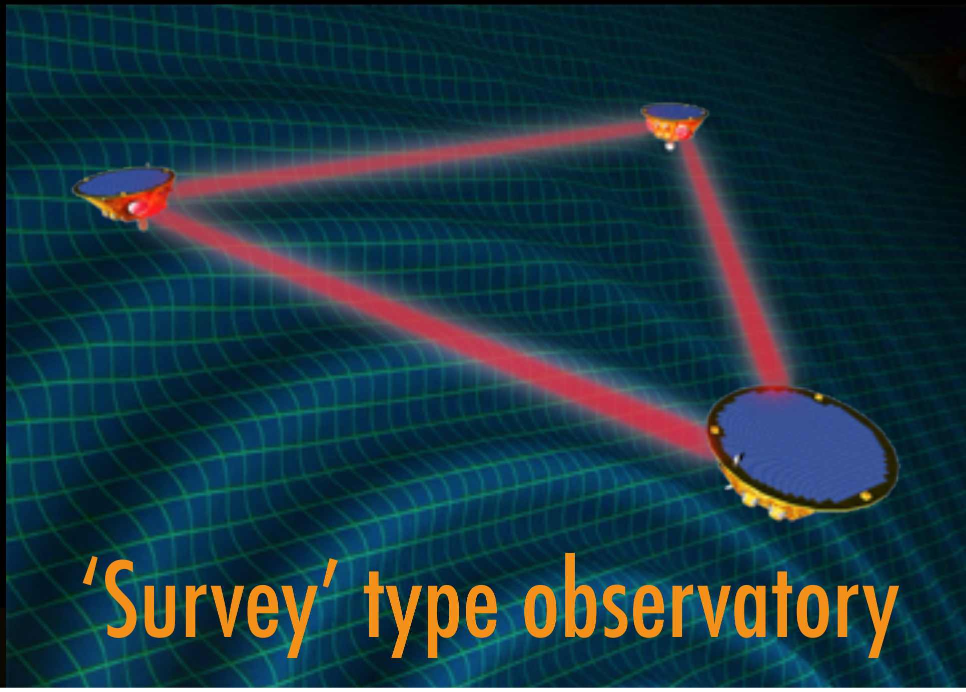
# LISA data



Gravitational wave sources emitting between 0.02mHz and 1 Hz



# LISA data




Gravitational wave sources emitting between 0.02mHz and 1 Hz

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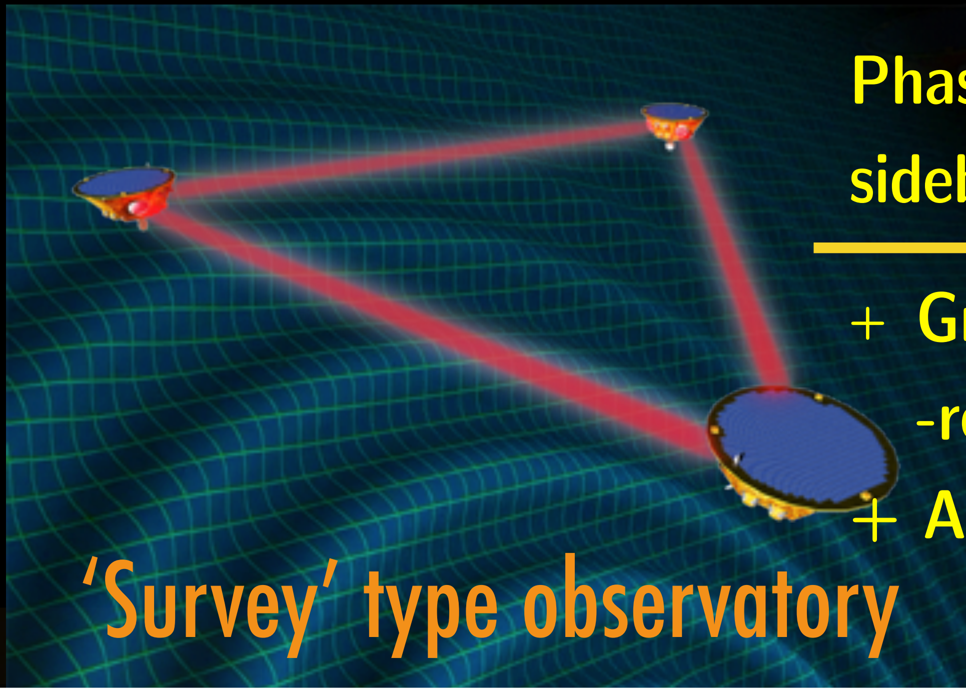
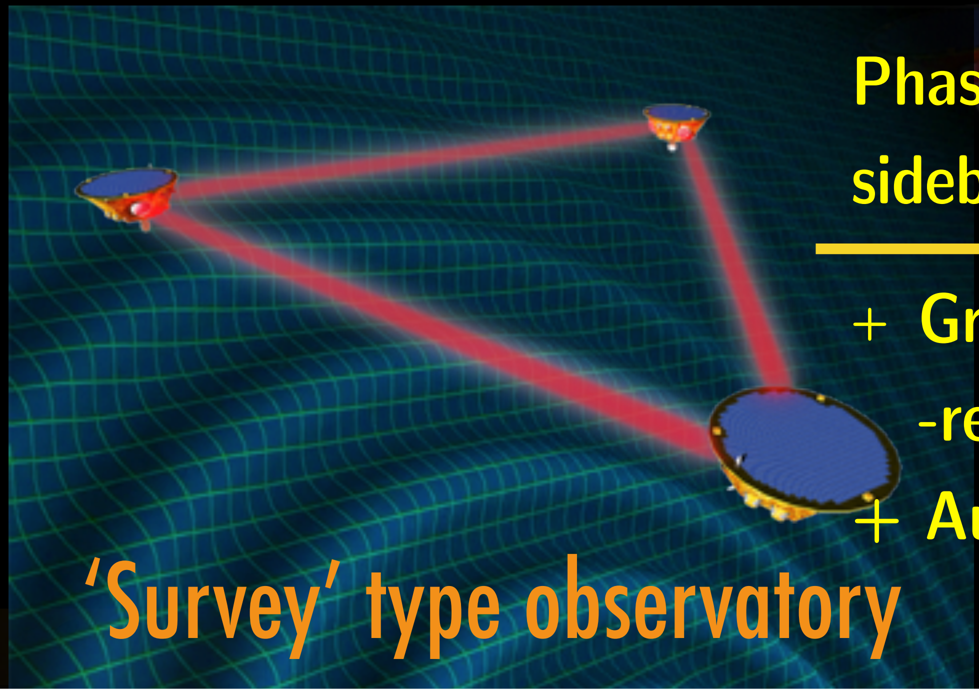



Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor
+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

# LISA data




Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor
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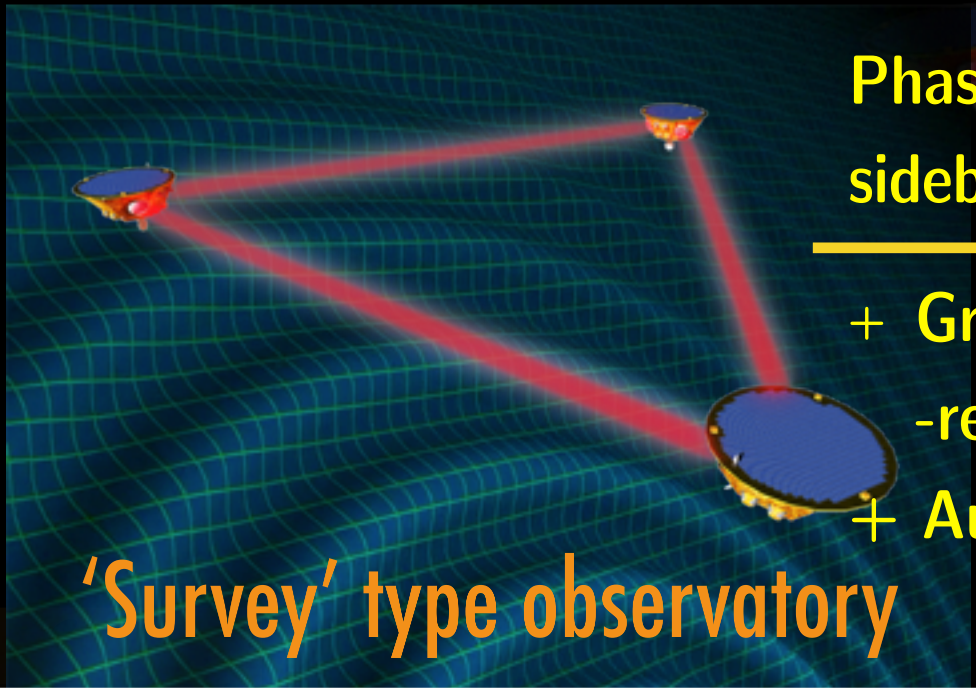
Gravitational wave sources emitting between 0.02mHz and 1 Hz

# LISA data

Phasemeter ...
sidebands, ...

+ Gravitati...
-rence Se...
+ Auxiliary ...

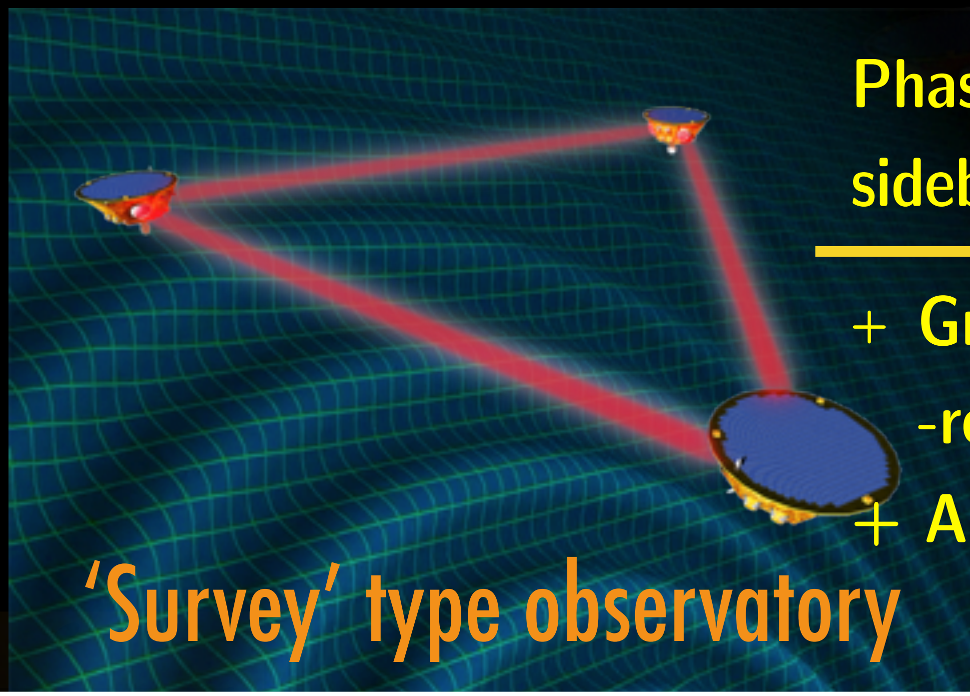


'Survey' type observatory

Gravitational wave sources emitting between 0.02mHz and 1 Hz

| 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** |

# LISA data

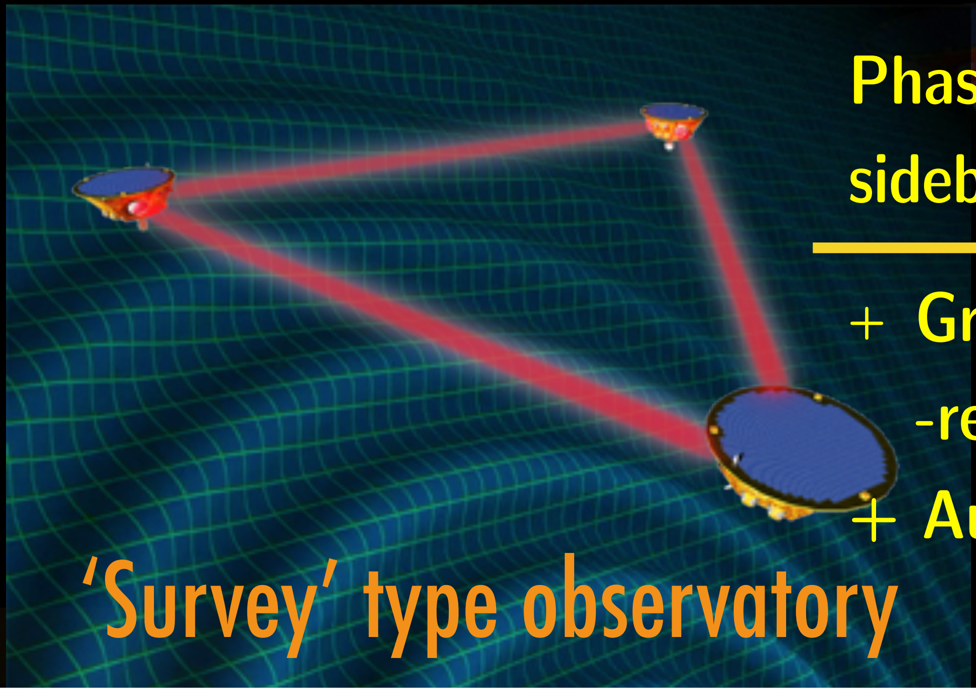



Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor
+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

# LISA data




Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor
+ Auxiliary channels

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

2 data channels TDI non-correlated

Gravitational wave sources emitting between 0.02mHz and 1 Hz

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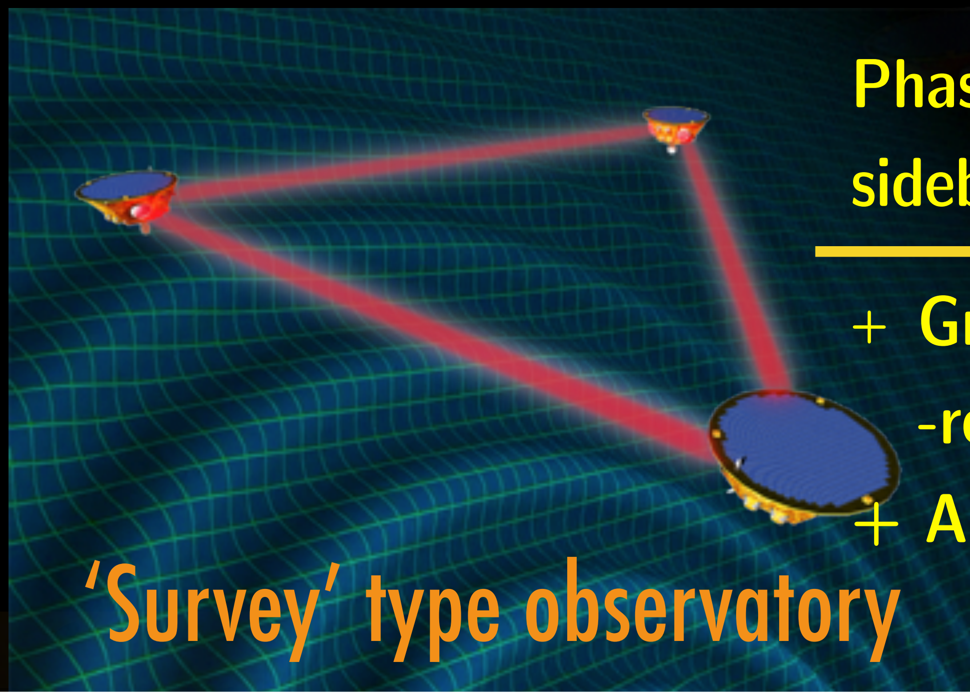

'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor

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Data Analysis of GWs

Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

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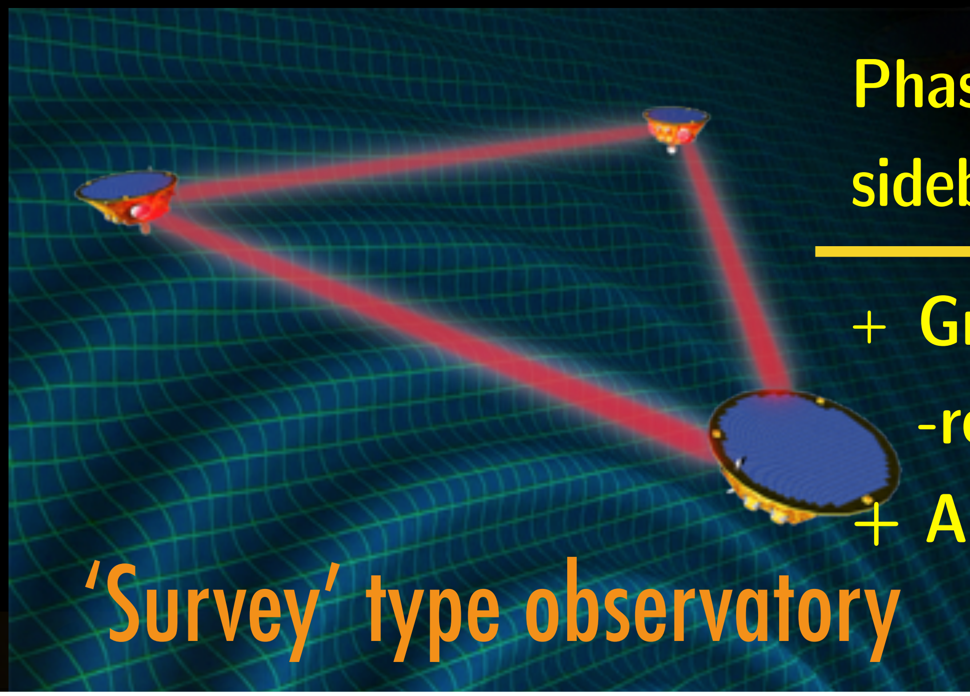



Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor

+ Auxiliary channels

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

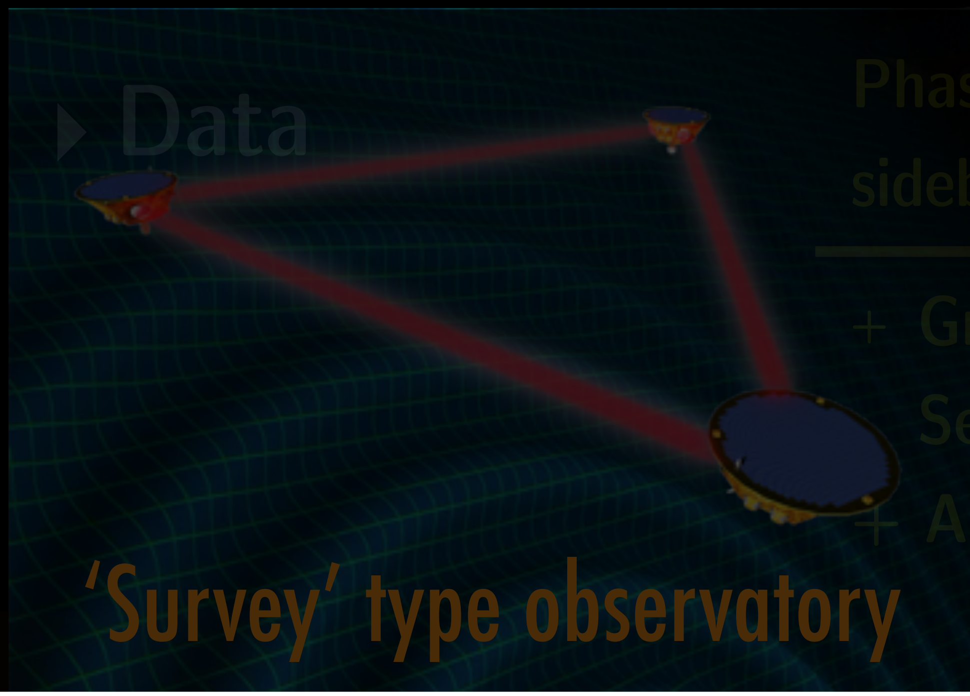
L1 — 2 data channels TDI non-correlated

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

# LISA DPC




Phasemeters (carrier, sidebands, distance)

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L1 — 2 data channels TDI non-correlated

L2 — Data Analysis of GWs

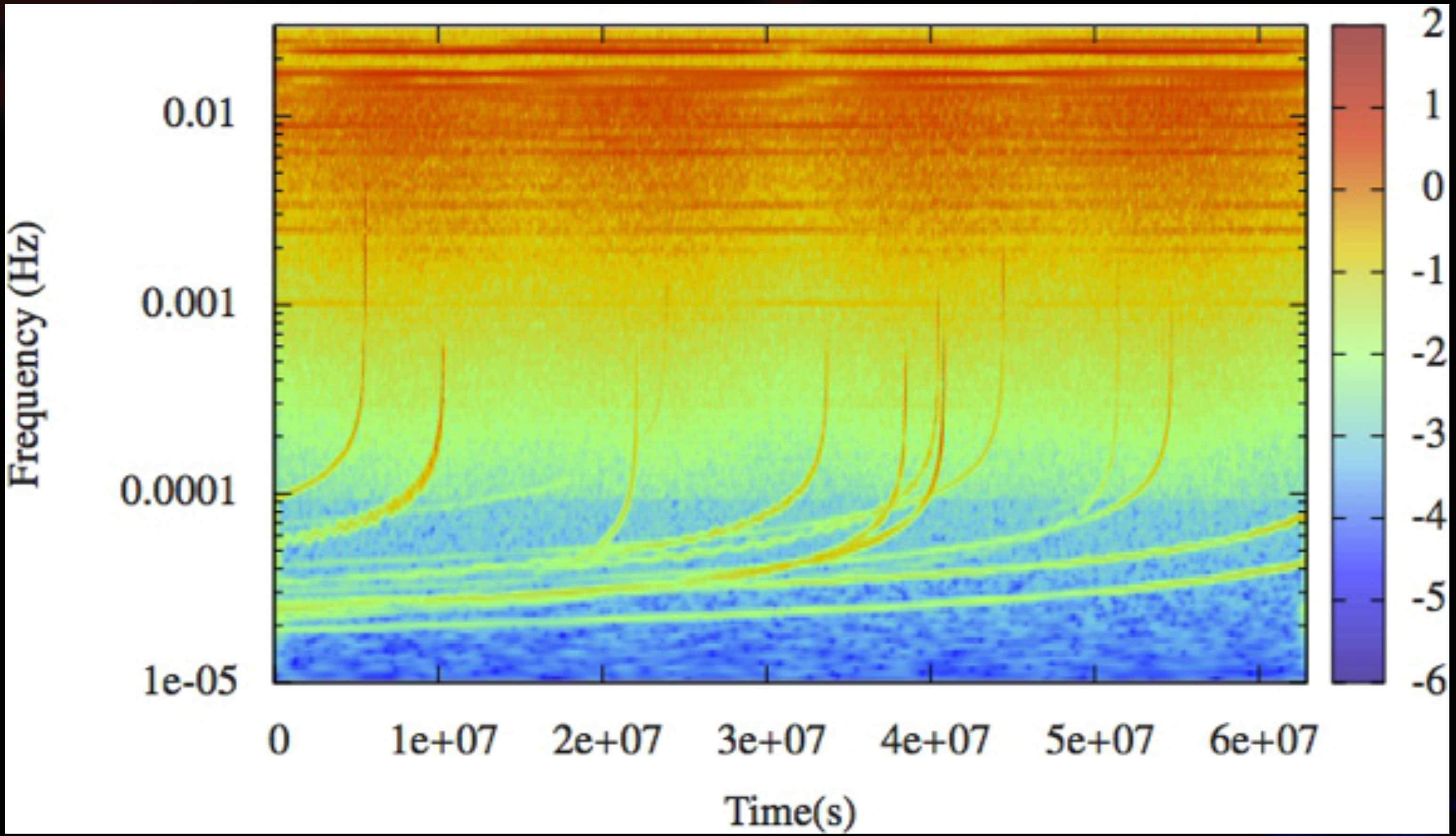
L3 — Catalogs of GWs sources with their waveform

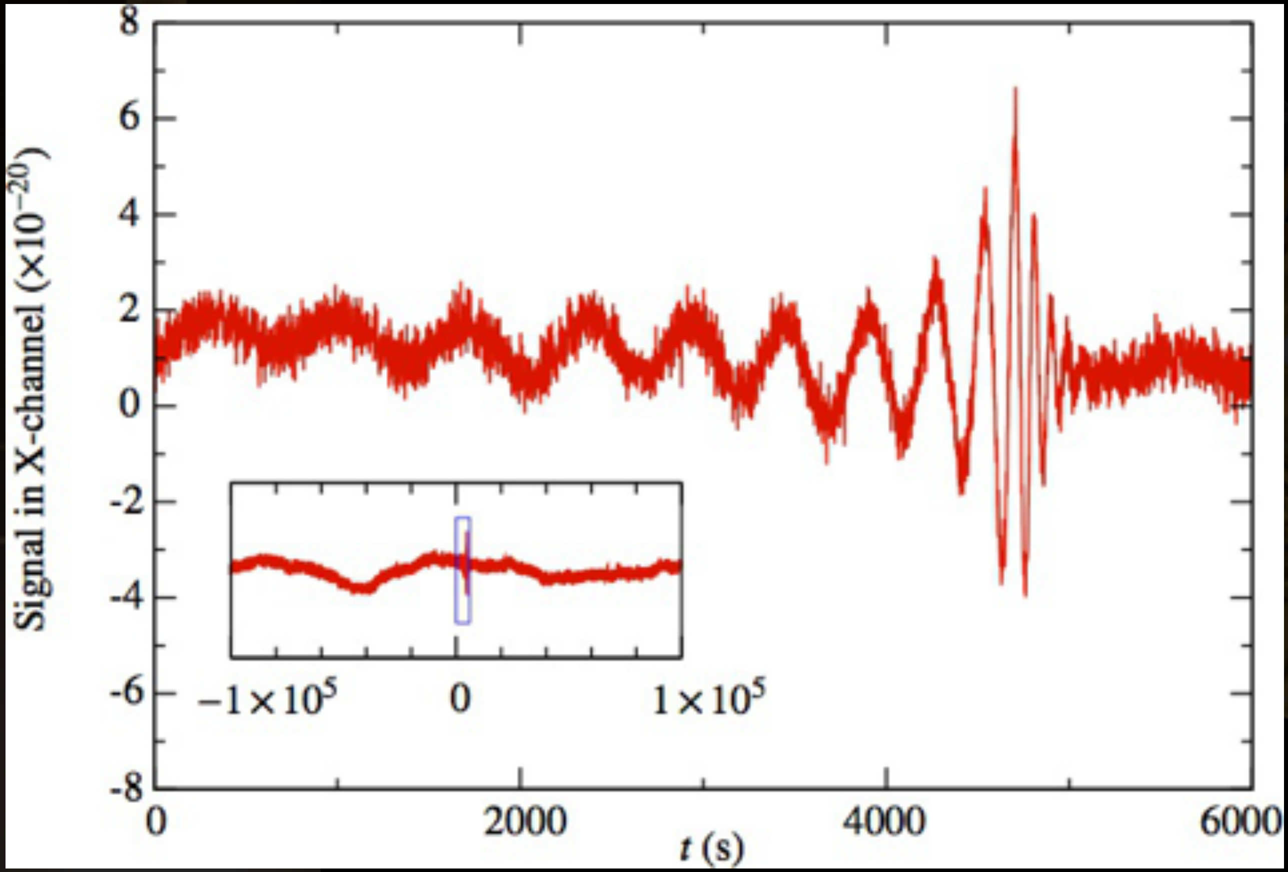
## GW sources

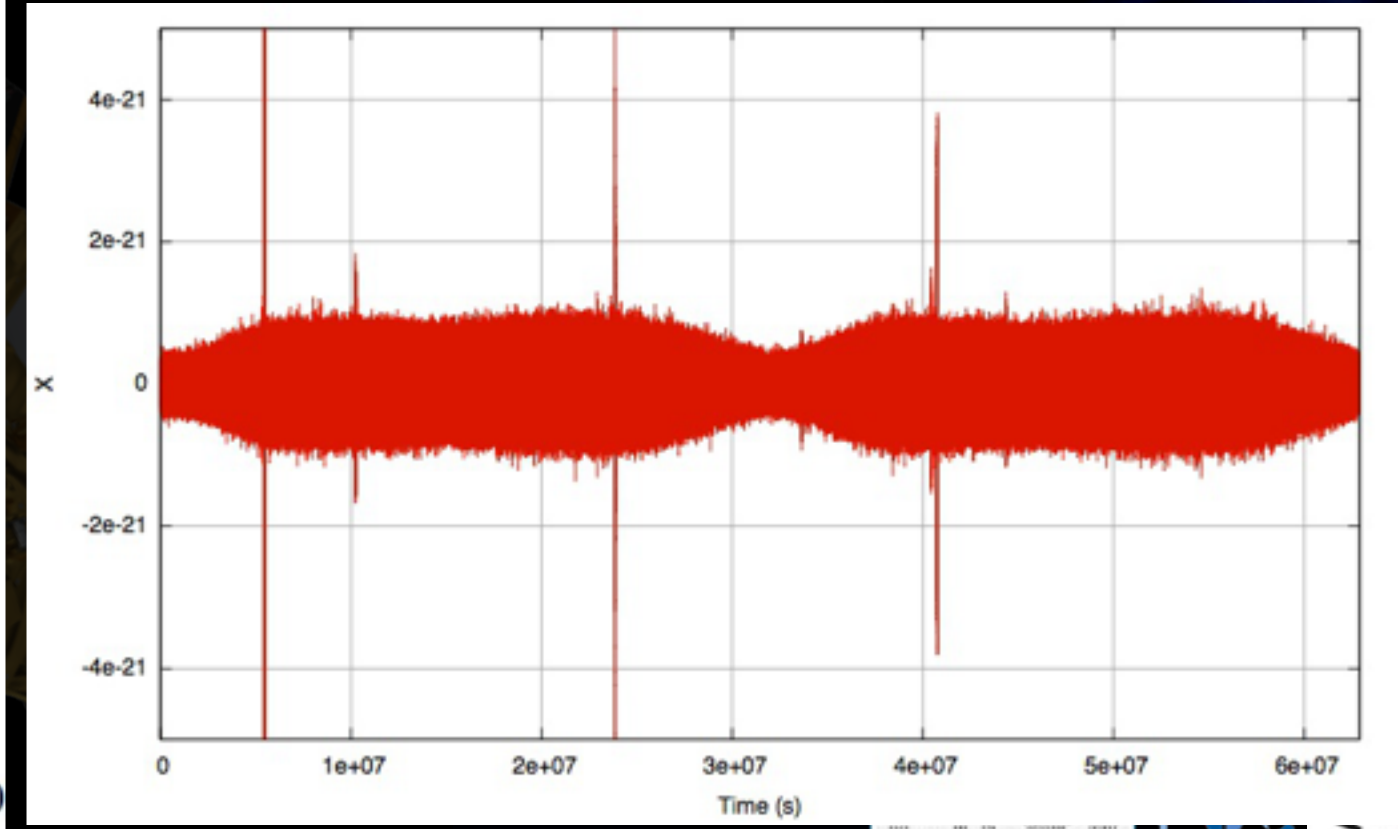
- $6 \times 10^7$ galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources

# GWs in LISA data

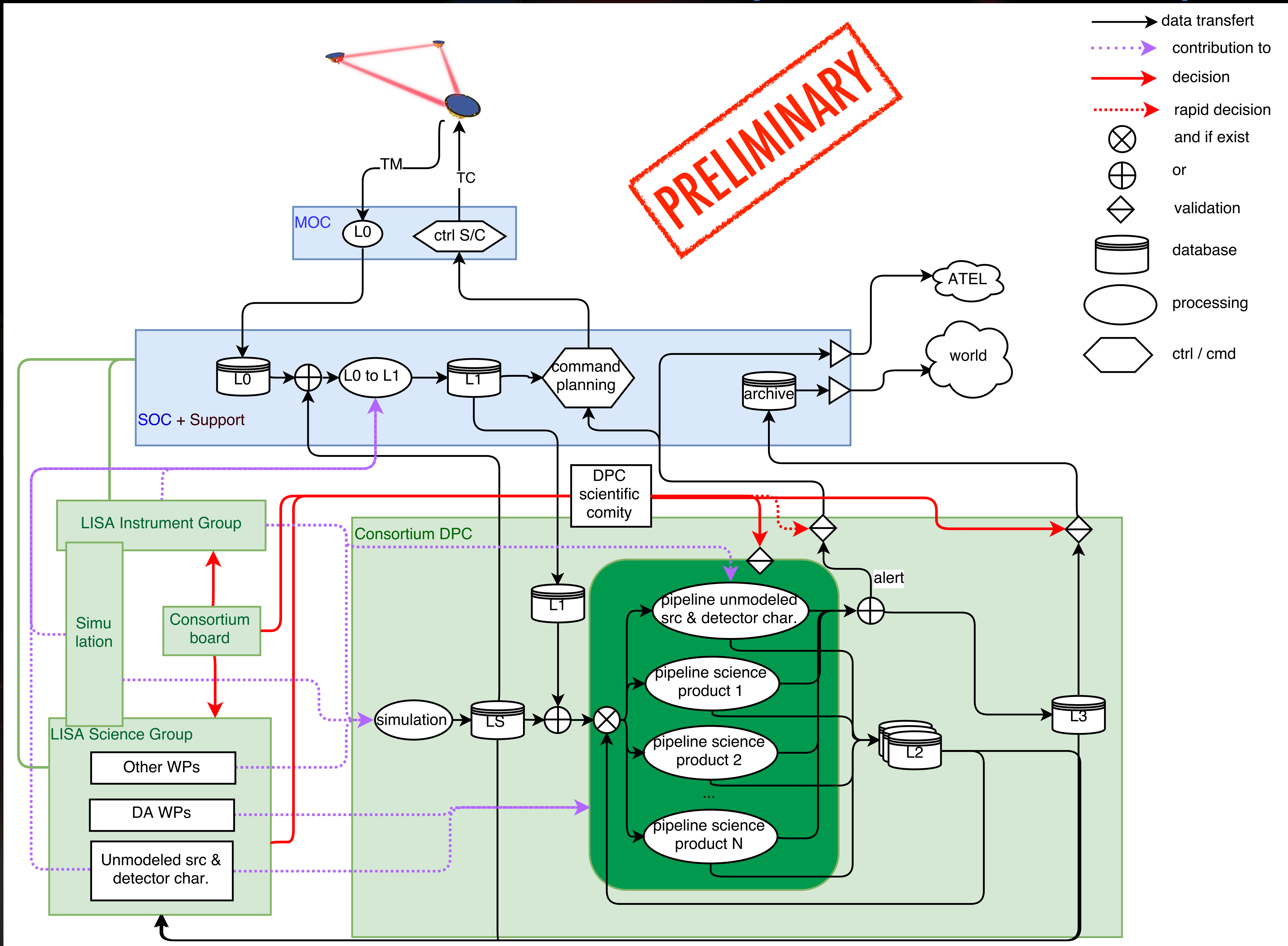
- Example of simulated data (LISACode):
  - about 100 SMBHs,
  - Galactic binaries



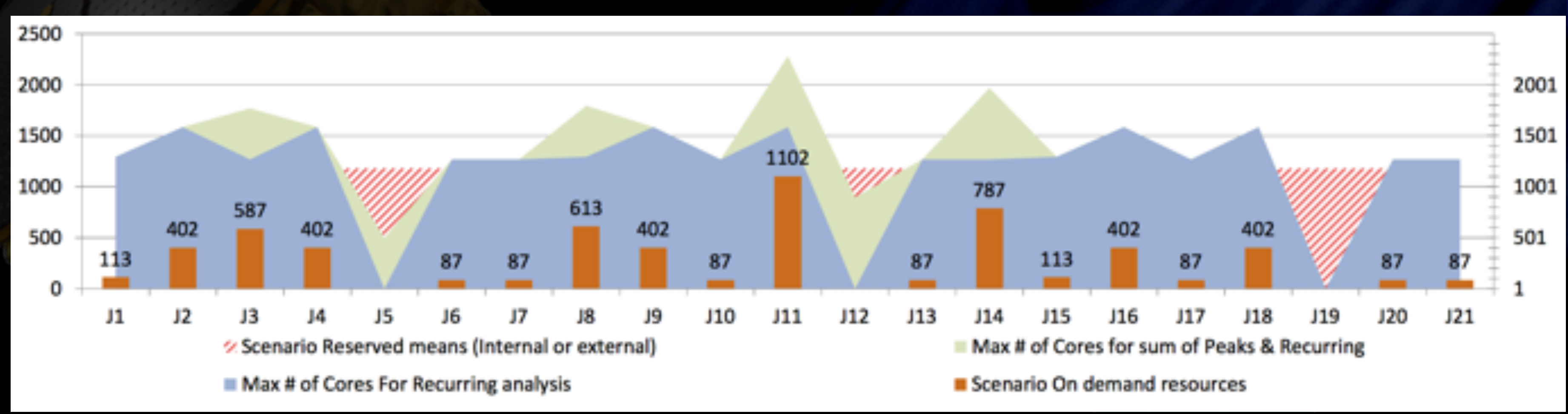
# Ground Segment (Consortium)



# DPC CNES Phase 0

- In 2013-2014, CNES did a phase-0 with APC & CapGemini
- Results of this Phase-0 :
  - Doable within a reasonable budget (~ 22 millions euros)
  - Developments & pipelines: First analysis of this kind + potential unknown sources ➡ Keep flexibility + continuous evolution
  - Infrastructure : fluctuations of the computational charge : permanent sources + transient sources + continuous evolution of codes (full reprocessing phase)

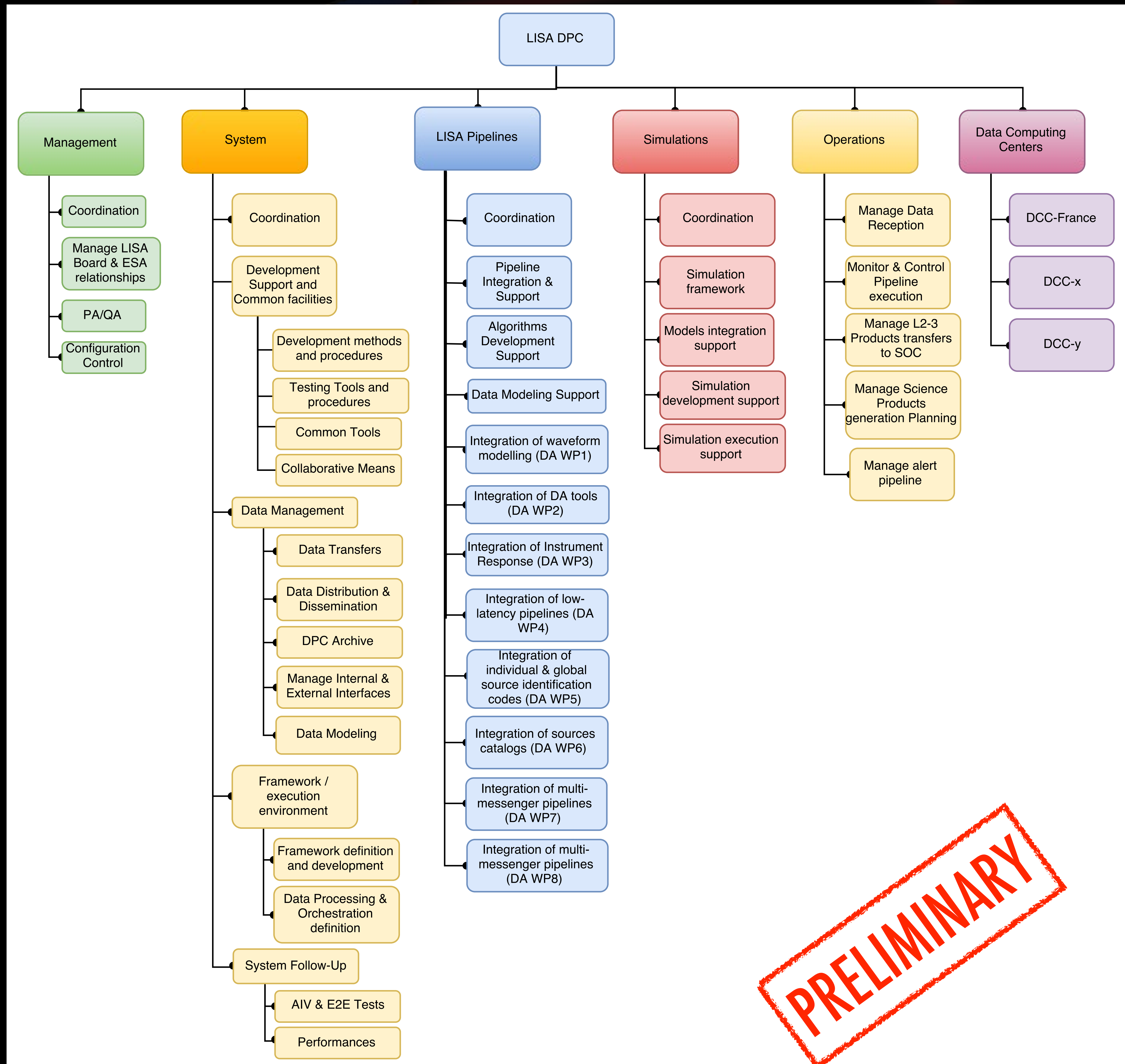
➡ mixed infrastructure based on regular cluster + cloud to absorb variation of needs with time



# Current vision of the DPC

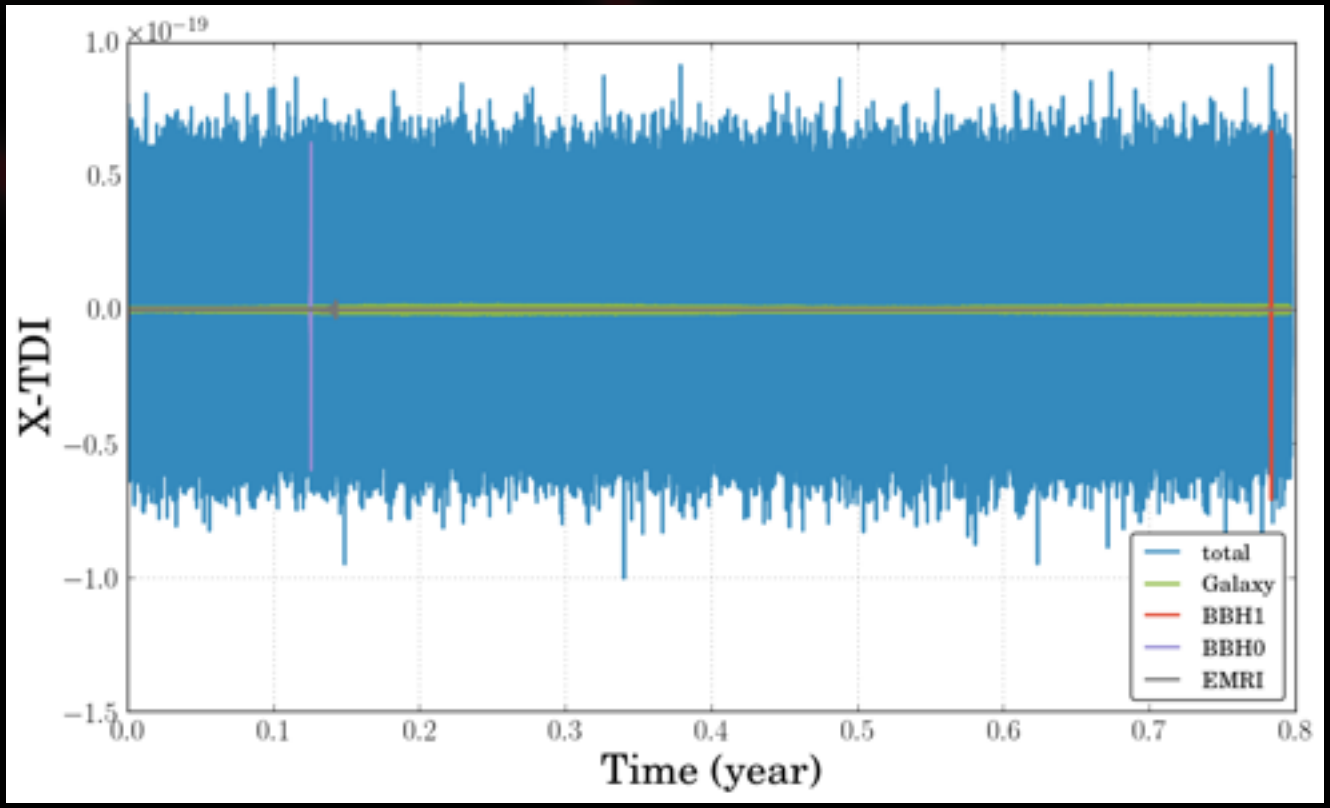
- DPC: unique entity responsable for the data processing (driving, integration of software block, ...)
- DPC in charge of delivering L2 & L3 products + what's necessary to reproduce/refine the analysis (i.e. input data + software + its running environment + some CPU to run it).
- Data Computing Centres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

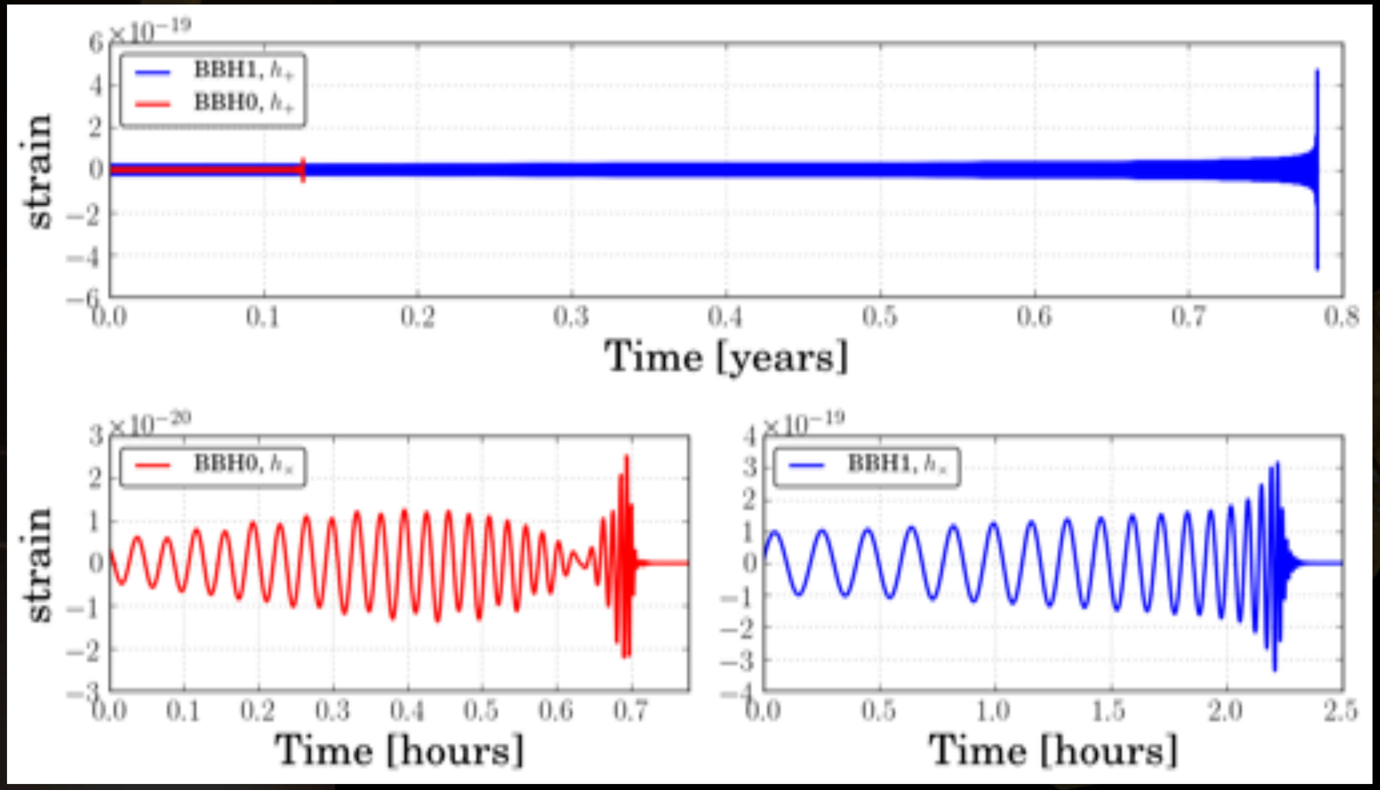
# DPC Organisation

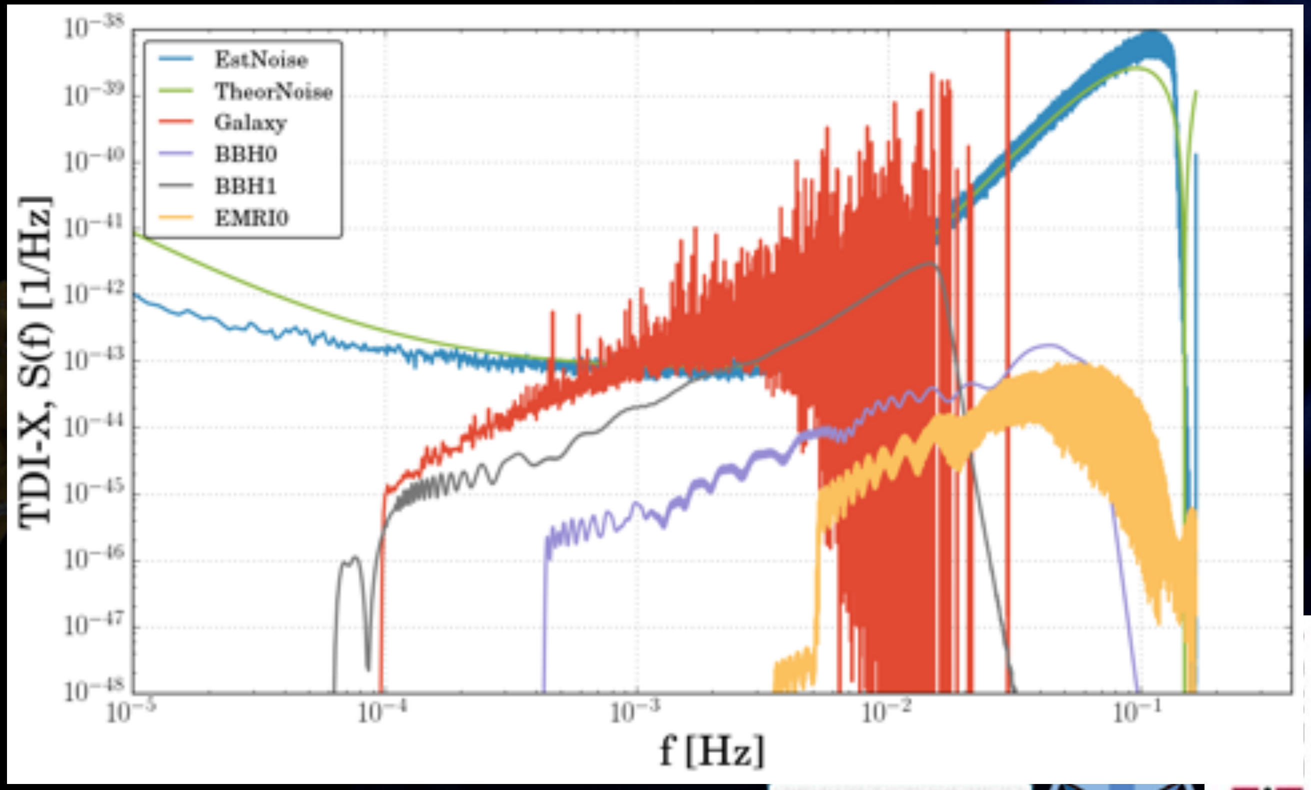


# LISA Data Challenges

- 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



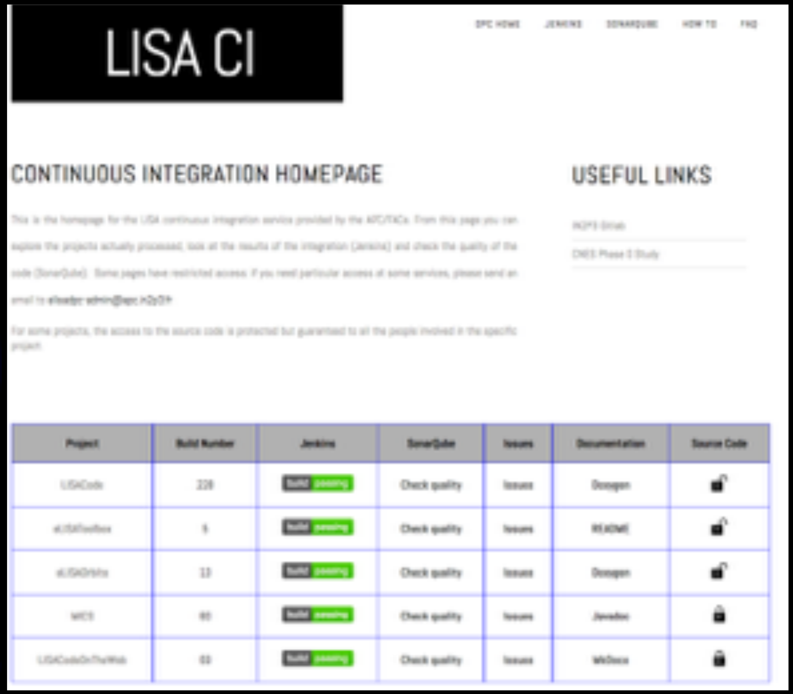





François Arago Centre

# Proto-DPC: basics

- Development environment: in prod. https://elisadpc.in2p3.fr/home
  - Goals
    - Ease the collaborative work: reason why it's already started
    - Guarantee reproducibility of a rapidly evolving & composite DA pipeline
    - Keep control of performance, precision, readability, etc
  - Use existing standard tool
    - Control version system
    - Continuous integration (like in Euclid, LSST)
    - Docker image




  - Done:
    - Simple install of open & standard tools (Jenkins, SonarQube, gitlab CI)
    - Worked on moving from 'simple' to 'automatic' using Docker
    - More projects, more users to come.

# Proto-DPC: basics

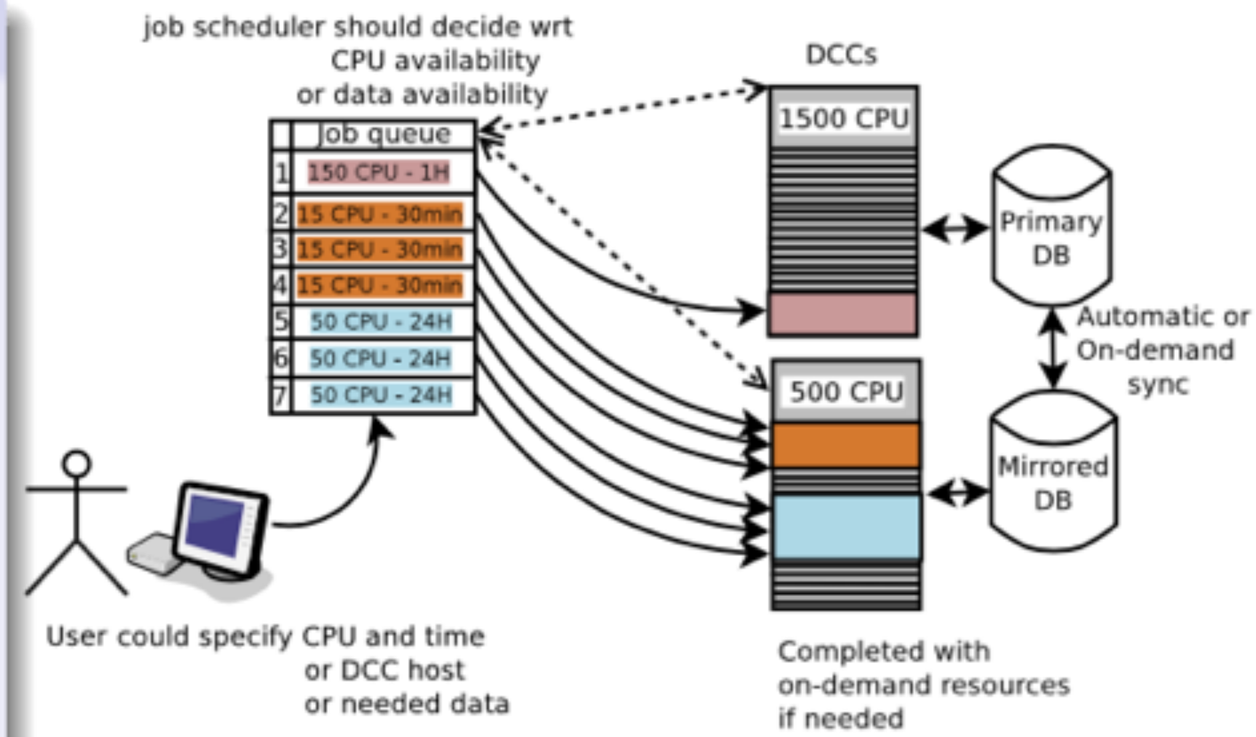
- Data basis & data model: in R&D
  - Motivations
    - Data sharing among people and computing centers
    - Mainly processed, temporary or intermediate data: need meta data management to use them
    - A lot of information: a web 2.0 (intuitive) interface is mandatory (search engine, DB request, tree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

# Proto-DPC: basics

- 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).

# Outline

- Introduction to gravitational waves
- Gravitational wave sources in the millihertz regime
- LISA : a space-based gravitational wave observatory
- LISAPathfinder
- LISA scientific performances
- The French contribution to LISA:
  - Data Processing Center
  - Integration / performance control
- Conclusion and perspectives

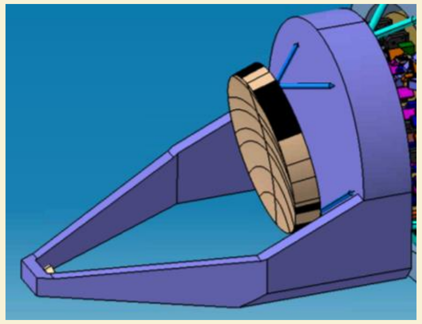
# Integration & performance model

- In LISA, the "instrument" is the satellites' constellation !
  - Highly integrated spacecraft
  - Strong interactions between subsystems (payload & platform)
- A (very) precise knowledge of the noise sources and detector response is required.
- The Consortium must have the hands on a complete and precise performance model:
  - End-to-end simulator (development just started ...)
  - Validation and performance tests designs
  - Tests and checkout benches development
  - Integration and qualification activities

# AIV/T

- Consortium is responsible for delivering integrated/tested/validated MOSA

Telescope (T) + Optical Bench (OB) + GSR Head (GRSH) = Moving Optical SubAssembly (MOSA)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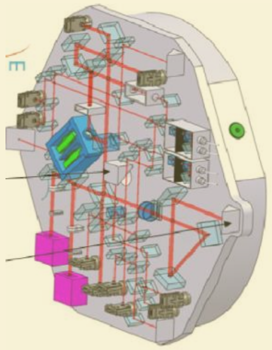
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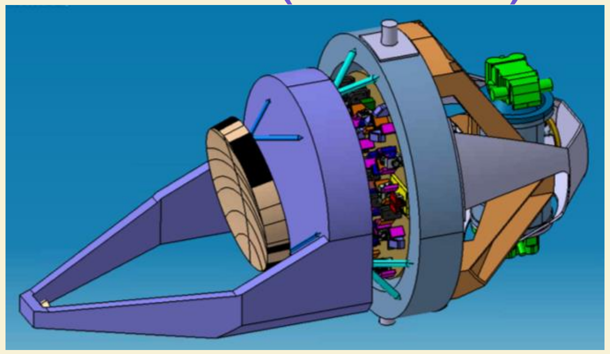

- Additional elements:
  - MOSA support structure,
  - Phase Measurement Subsystem (PMS),
  - Laser Assembly (LA),
  - Diagnostic subsystem (temperature sensors & heaters)

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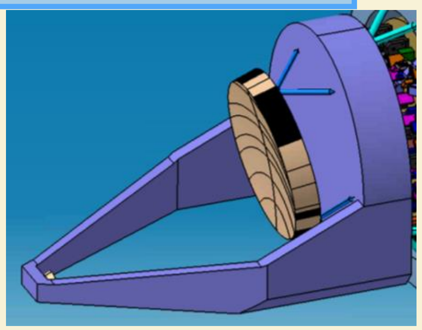
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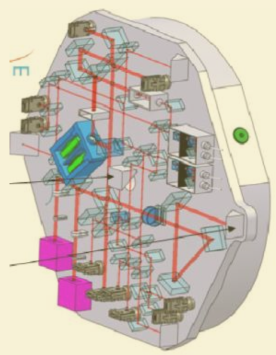
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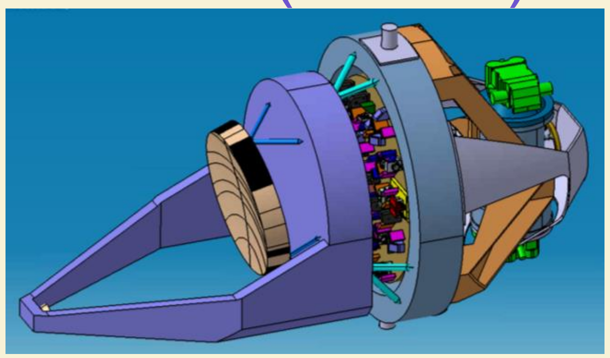

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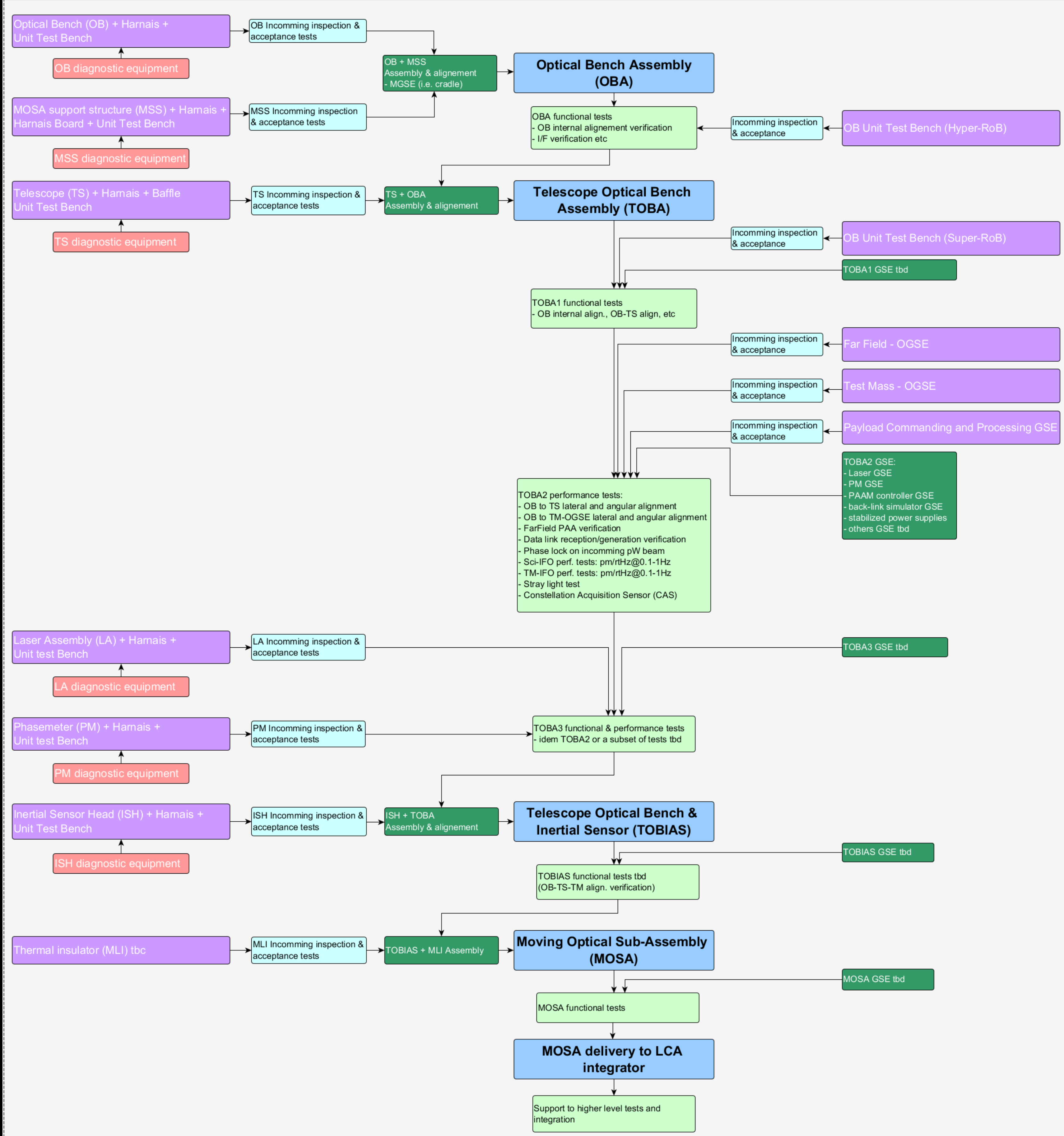
  - MOSA support structure,
  - Phase Measurement Subsystem (PMS),
  - Laser Assembly (LA),
  - Diagnostic subsystem (temperature sensors & heaters)

ESA/NASA

# Models philosophy

- MOSA Elegant BreadBoard (EBB) [TBC]
  - Demonstrates development criticality
- MOSA Structural and Thermal Model (STM)
  - Validate thermal and mechanical models;
  - AIVT flows with dummy for telescope, GRS, OB
- MOSA (Engineering) Qualification Model (E)QM
  - Representative for MOSA design concept & AIVT process
- 6 Flight Models (FM)
- Spare

# Top Level MOSA AIV/T flow




Legend of colours:
- Magenta: units + additional elements to be delivered by various providers
- Light blue: acceptance tests, to be defined by various units providers, carried out by units providers with MOSA integrator
- Light green: functional/performance tests to be carried out by MOSA integrator (+help of various providers)
- Dark green: GSE to be developed by MOSA integrator (+ other contributors)
- Dark blue: integrated sub-assemblies

MOSA Top Level AIV/T Flow

# GSE/SCOEs & infrastructure

- Far-Field OGSE => simulate laser beam from distant S/C
- Test Mass OGSE => mimic the movements of the TM
- Super/Hyper RoB => readout of heterodyne photodetectors
- Phase Reference Distribution System OGSE
- Payload Commanding and Processing GSE
- Dedicated GSE: stable laser, phasemeter, test bench for stray light characterization, real time command/control, ...
- MOSA MGSE => mechanical load of MOSA + FF-OGSE
- Climatic chamber, cleanliness (class 100)

# Summary 1

- 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: success
  - Performances > 7 times better than the requirements
- LISAPathfinder + detections of 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

# Summary 2

- LISA Consortium re-organised in a stronger and suitable structure for phase A

https://elisadpc.in2p3.fr/lisafrance

- French contributions organized via LISAFrance
  - Data Processing Center: flexible and distributed, proto-DPC in dev.

    => LISA Data Challenge; contact proto-DPC team; contribute to one of the activities organize by the LISA Data Processing Group
  - AIV/T of MOSA and performance control: number of GSE, models, etc to develop => join the phase A activities leaded by CNES
  - Science => join a working group; contribute to work packages (more than > 60 WPs for Science/DA in definition)
- LISA project started: a lot to do, a lot of possible contribution!

# Thank you !

# Thank you !

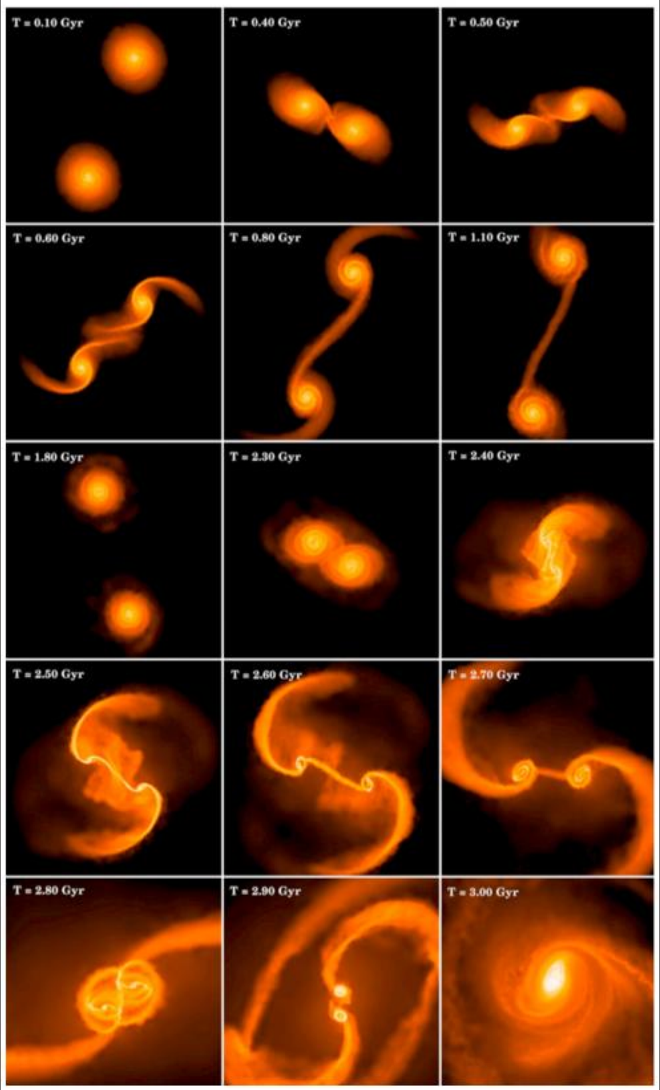

# LISA Data Processing Group

- Responsibilities (for phase A ...):
  - Develop and coordinate the unique DPC for LISA;
  - Prepare and execute the pipelines to produce L2 and L3 products as well as other defined scientific products and deliver them to the SOC;
  - Manage the interfaces between pipeline design and pipeline implementation;
  - Aid in the management and execution of large-scale simulations and provide structures for data management;
  - Coordinate the definition and development of LISA DCC;
  - Aid in the definition of Consortium support to ESA's ground-segment;
  - Coordinate the definition and implementation of the data analysis frameworks and operations environment;
  - Coordinate the development and management of data analysis pipelines;

# LISA Data Processing Group

- The development of the DPC includes:
  - definition and maintenance of the pipeline and data analysis development environment;
  - design and implementation of the pipeline and analysis operations environment;
  - design and implementation of data storage facilities and databases;
  - implementation and operation of consortium IT services;
  - management and implementation of pipelines for simulation and data analysis.

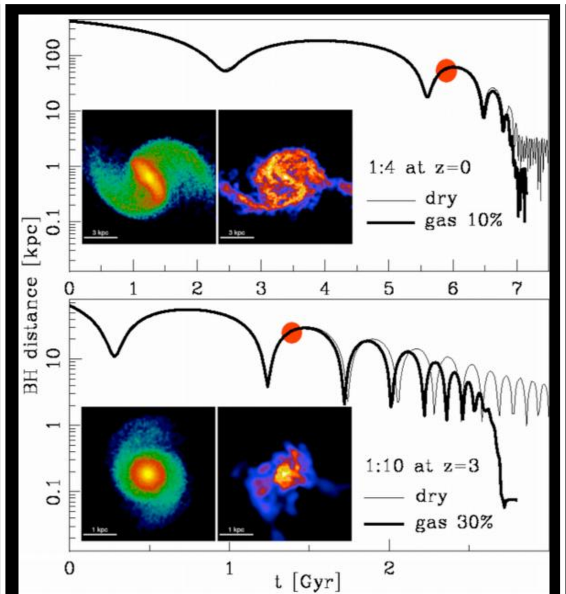
# MBH binaries: Formation &

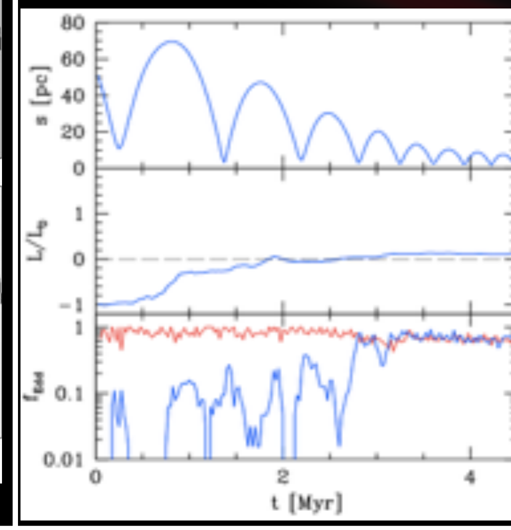


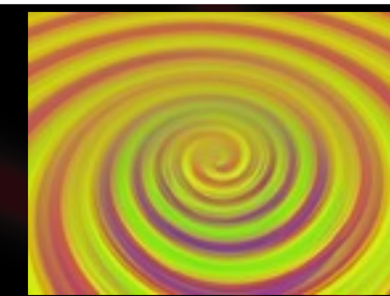

✤ Colpi & Dotti (2009) Review, astro-ph 0906.4339

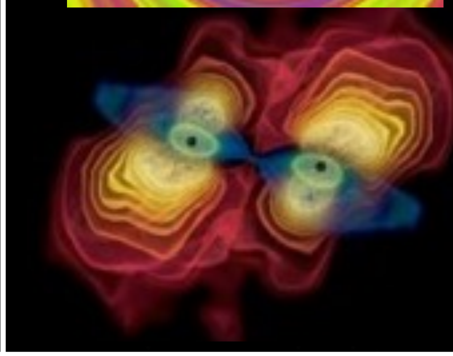
✤ Talk F. Combes

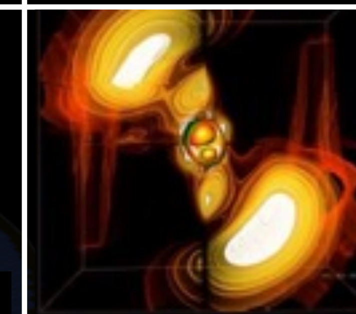
✤ Talk J. de Freitas-Pacheco







| Galaxies mergers | Binary formation | Close binary | Merger |
|---|---|---|---|
| 100 kpc → 100 pc | 100 pc → sub-parsec | sub-pc→few M (au) | |
| ~ few Gyr | ~ few Myr | | ~ few hours |
| ★ Dynamical friction<br>★ Stellar formation<br>★ Tidal shocks<br>★ Gas dynamics<br>✤ Callegari & al. (2009) ApJ 696 L89 | ★ Gas-dynamical friction<br>★ Circularization<br>★ Orbital angular momentum can flip<br>★ 3 bodies interaction<br>✤ Dotti & al. (2009) MNRAS 396-1640 | Inspiral of the 2 BHs due to gravitational wave emission | ★ GW "burst",<br>★ Recoil velocities of remnant BH. |

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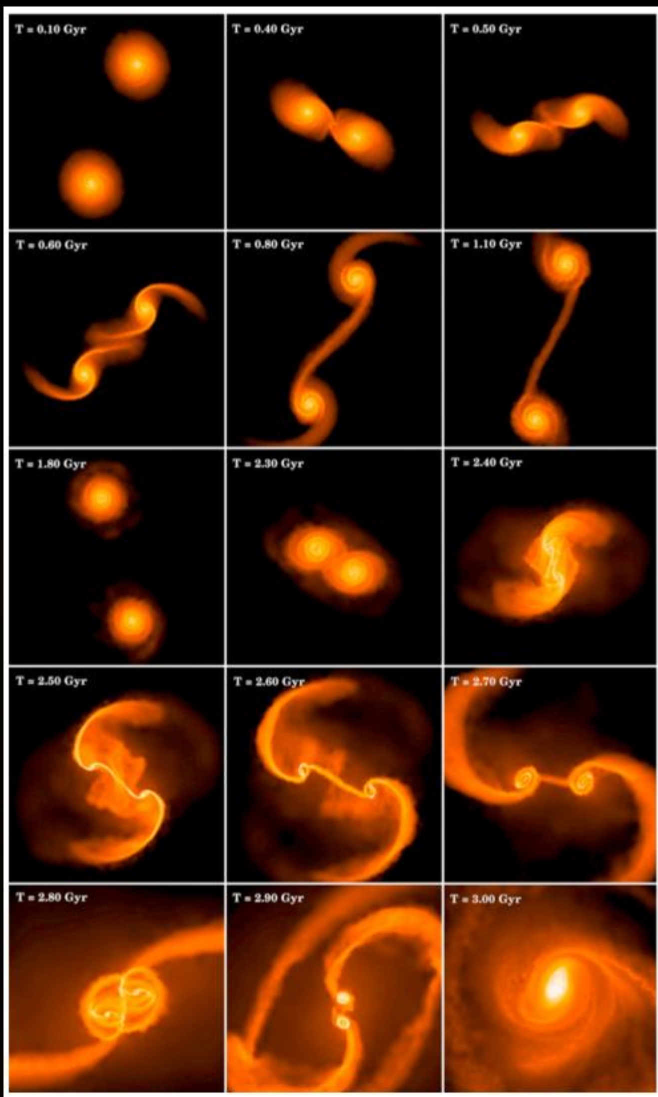

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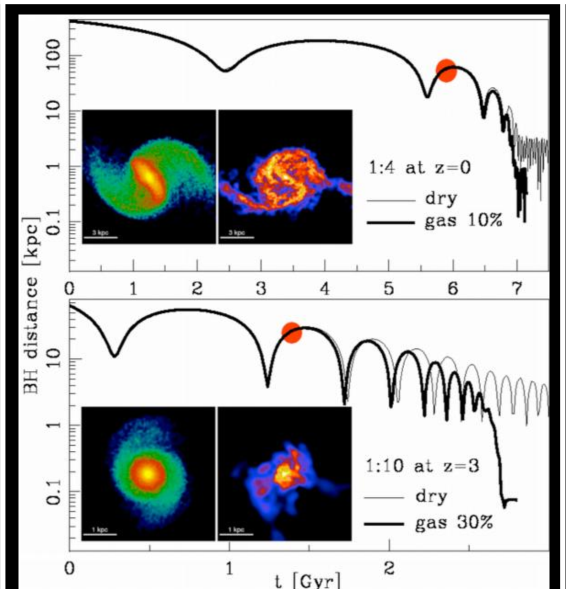
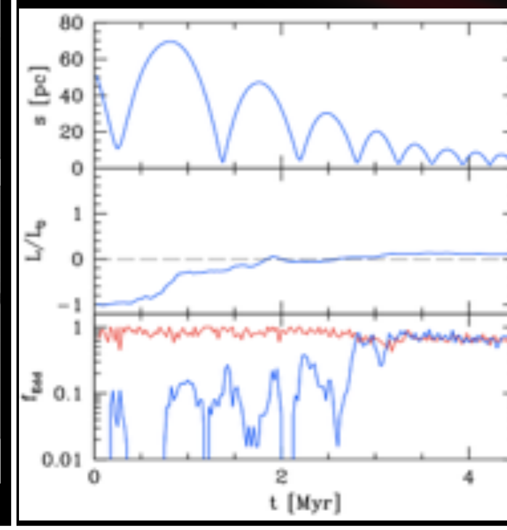
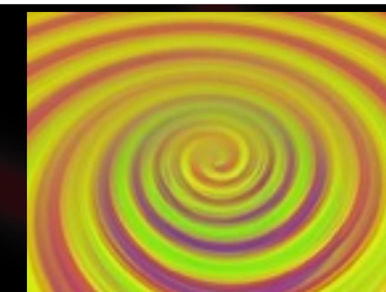
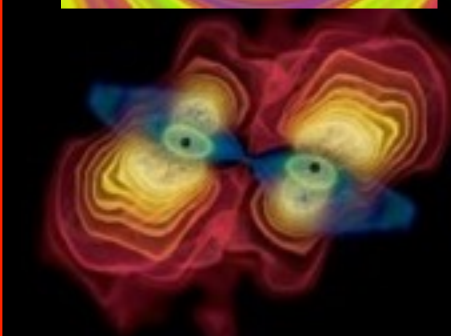
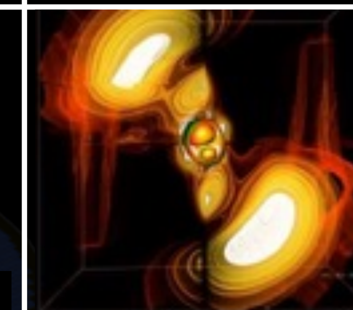
|   |   |   |  |
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# LISA:
# observing gravitational waves from space

Antoine Petiteau
(APC – Université Paris-Diderot)
Co-PI LISA, PI of LISAPathfinder for France,
Member of LISA Board, Executive Board and Science Study Team

Séminaire CPPM - Marseille
27th November 2017