LISA:

exploring the Universe using low frequency gravitational waves

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(APC – Université Paris-Diderot)

Journée de prospectives pour le futur des OGs

21th June 2018

Outline

- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISAPathfinder
- LISA status and organisation
- LISA scientific performances
- LISAFrance
  - Distributed Data Processing Center
  - AIV(T)
- Conclusion and perspectives

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THE GRAVITATIONAL WAVE SPECTRUM

SOURCES

quantum fluctuations in the very early Universe

binary supermassive black holes in galactic nuclei

phase transitions in the early universe

black holes, compact stars captured by supermassive holes in galactic nuclei

binary stars in the galaxy | and beyond

merging binary neutron stars and stellar black holes in distant galaxies;

fast pulsars with mountains

Wave Period

AGE OF THE UNIVERSE | YEARS | HOURS | SECONDS | MSEC

Frequency (Hz)

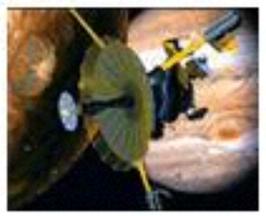
10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

DETECTORS

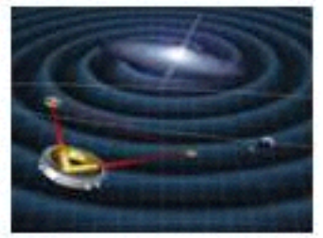
INFLATION PROBE

polarization map of cosmic microwave background

precision timing of millisecond pulsars



LISA



BIG BANG OBS

GEO, LIGO, VIRGO, TAMA

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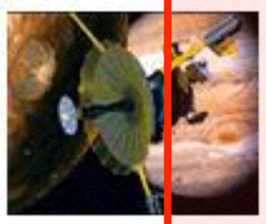

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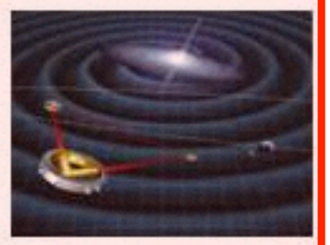


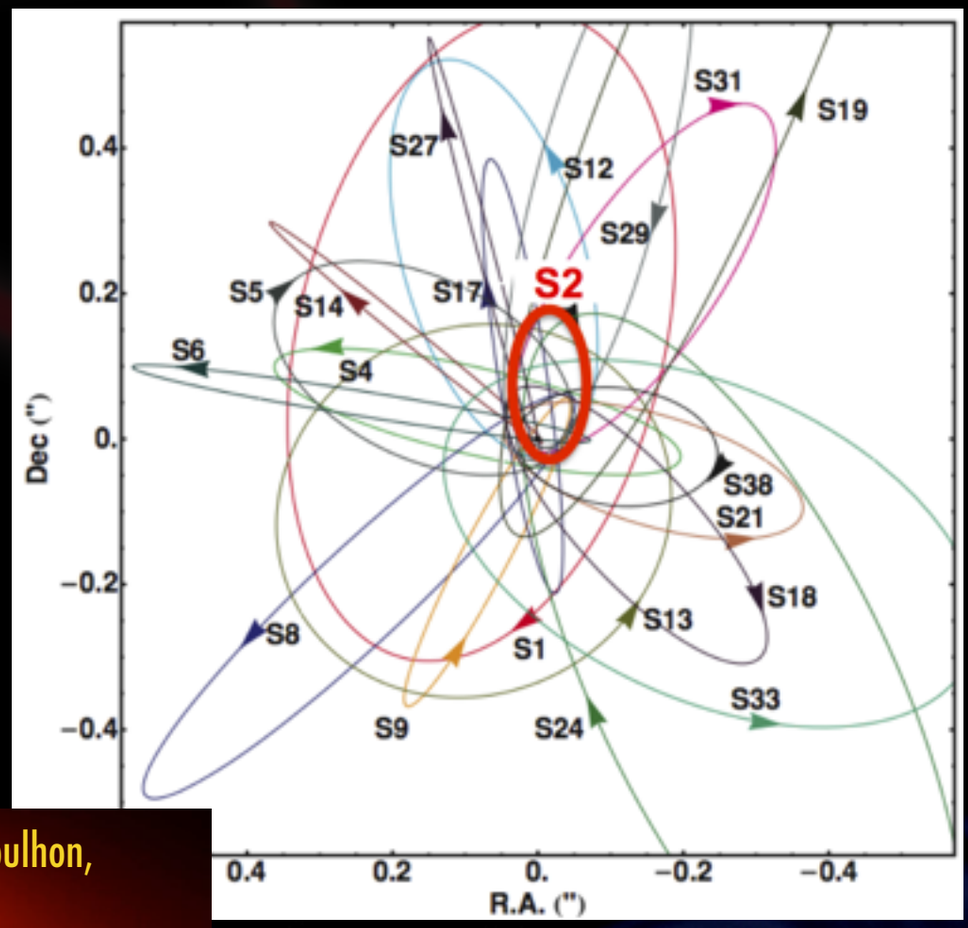
BIG BANG OBS

GEO, LIGO, VIRGO, TAMA

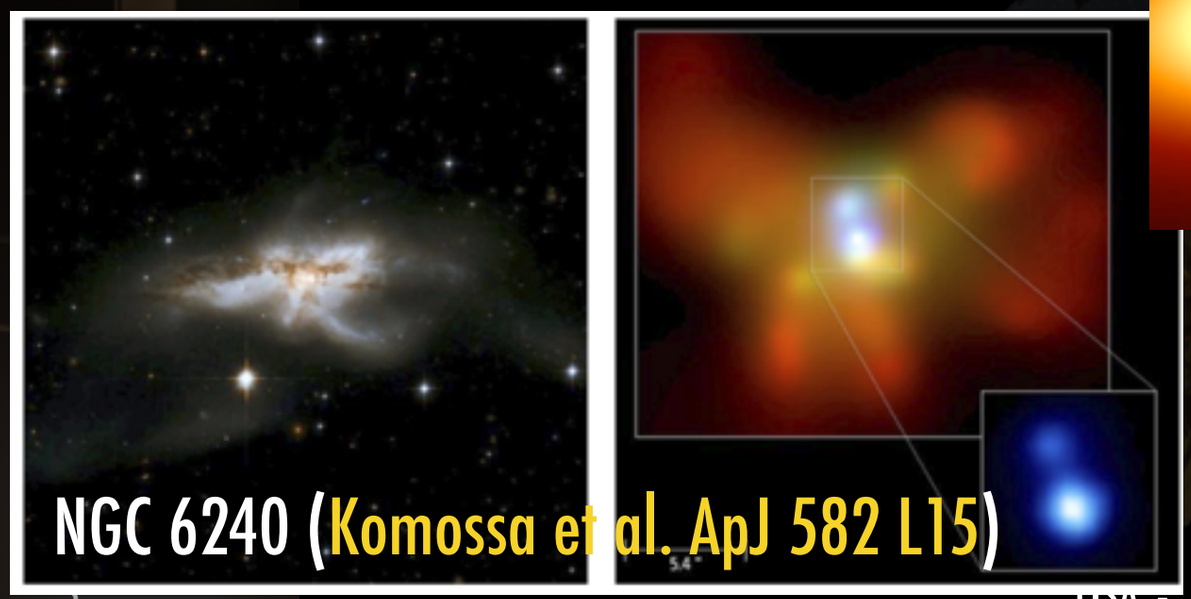
Supermassive black hole binaries

- Observations of Sgr A*, a dark massive object of 4.5×10^6 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



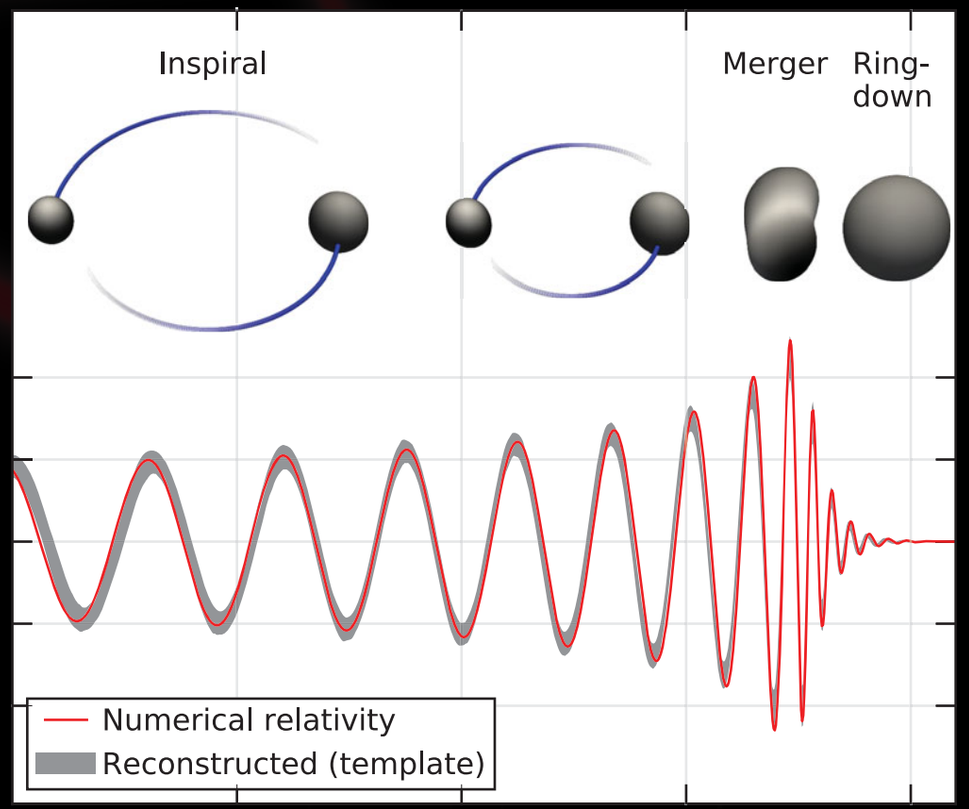

© Vincent, Paumard, Gourgoulhon, Perrin (2011)


NGC 6240 (Komossa et al. ApJ 582 L15)

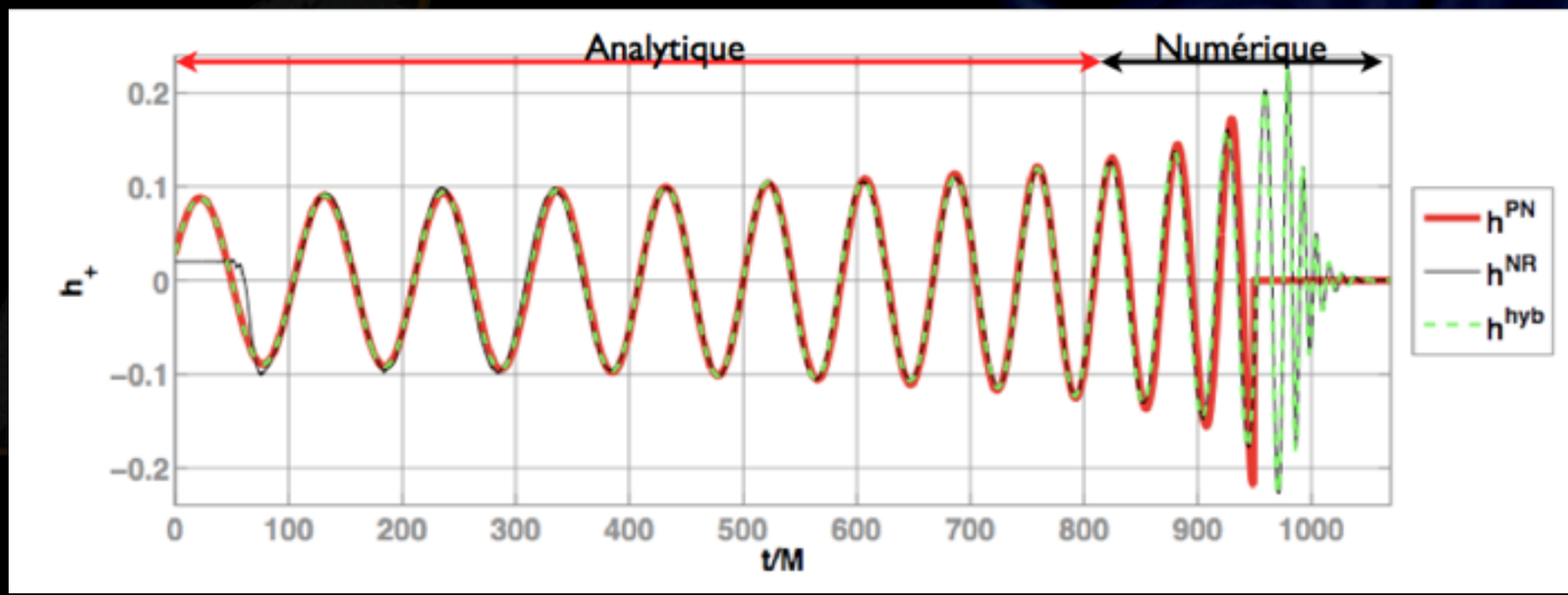

Antennae galaxies

Supermassive black hole binaries

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

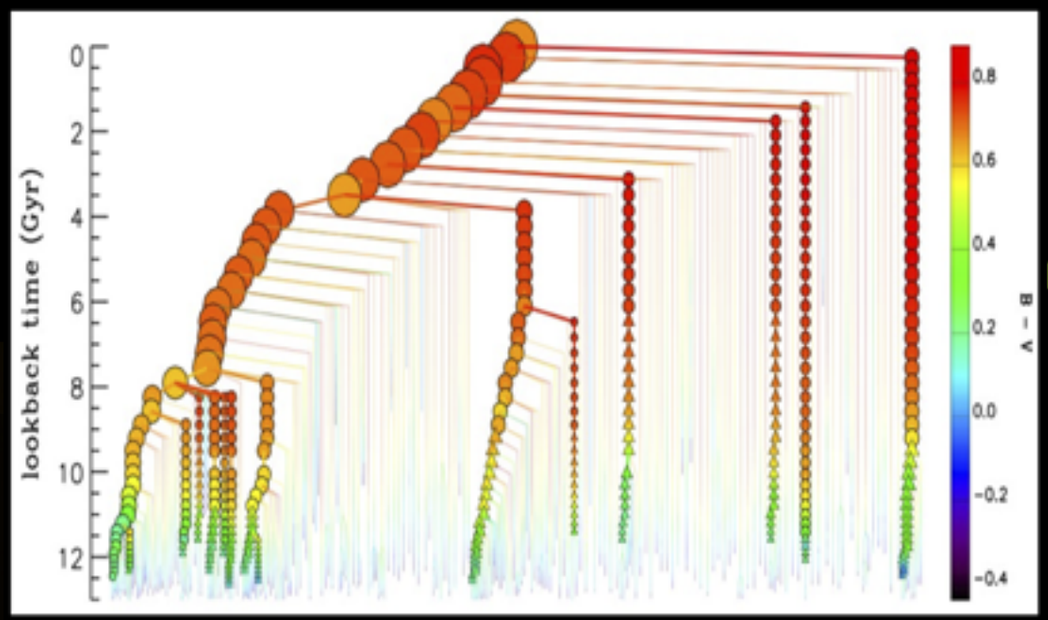


- No full waveform but several approximations exist :
  - Phenomenological waveform,
  - Effective One Body,
  - ...



Supermassive black hole binaries

Galaxies merger tree
(cosmological simulation)



From De Lucia et al 2006

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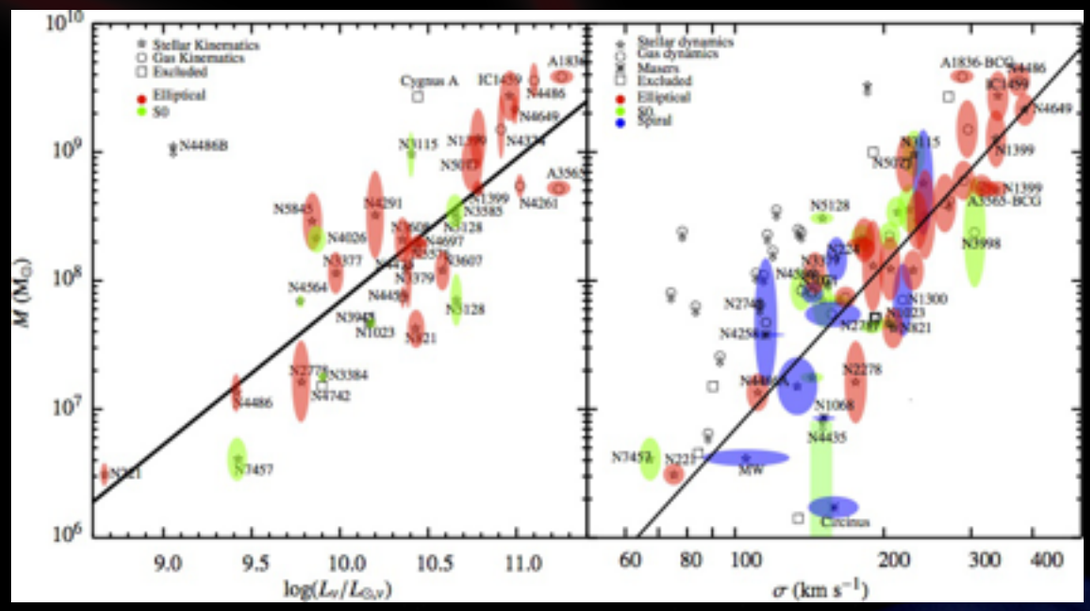
"M - σ relation": the speed of stars in bulge is linked to the central MBH mass



Gultekin 2009

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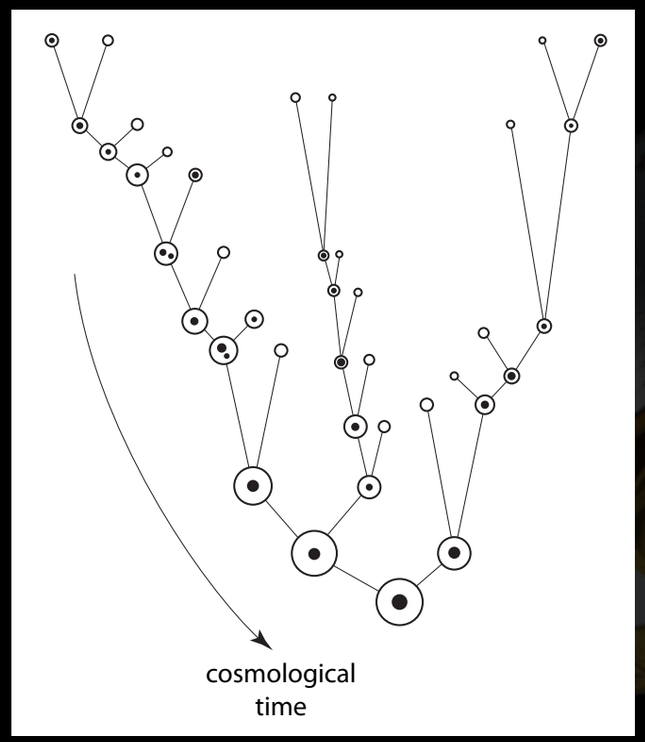
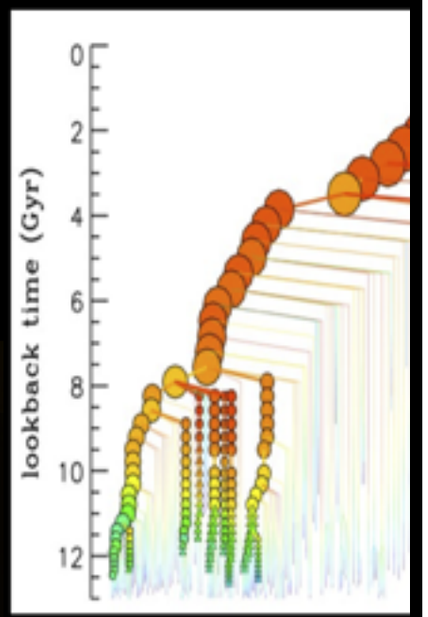


- Work from E. Barausse (IAP), A. Sesana (Univ. of Birmingham), M. Volonteri (IAP) et al.

Supermassive black hole binaries

Galaxi
(cosmolo

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



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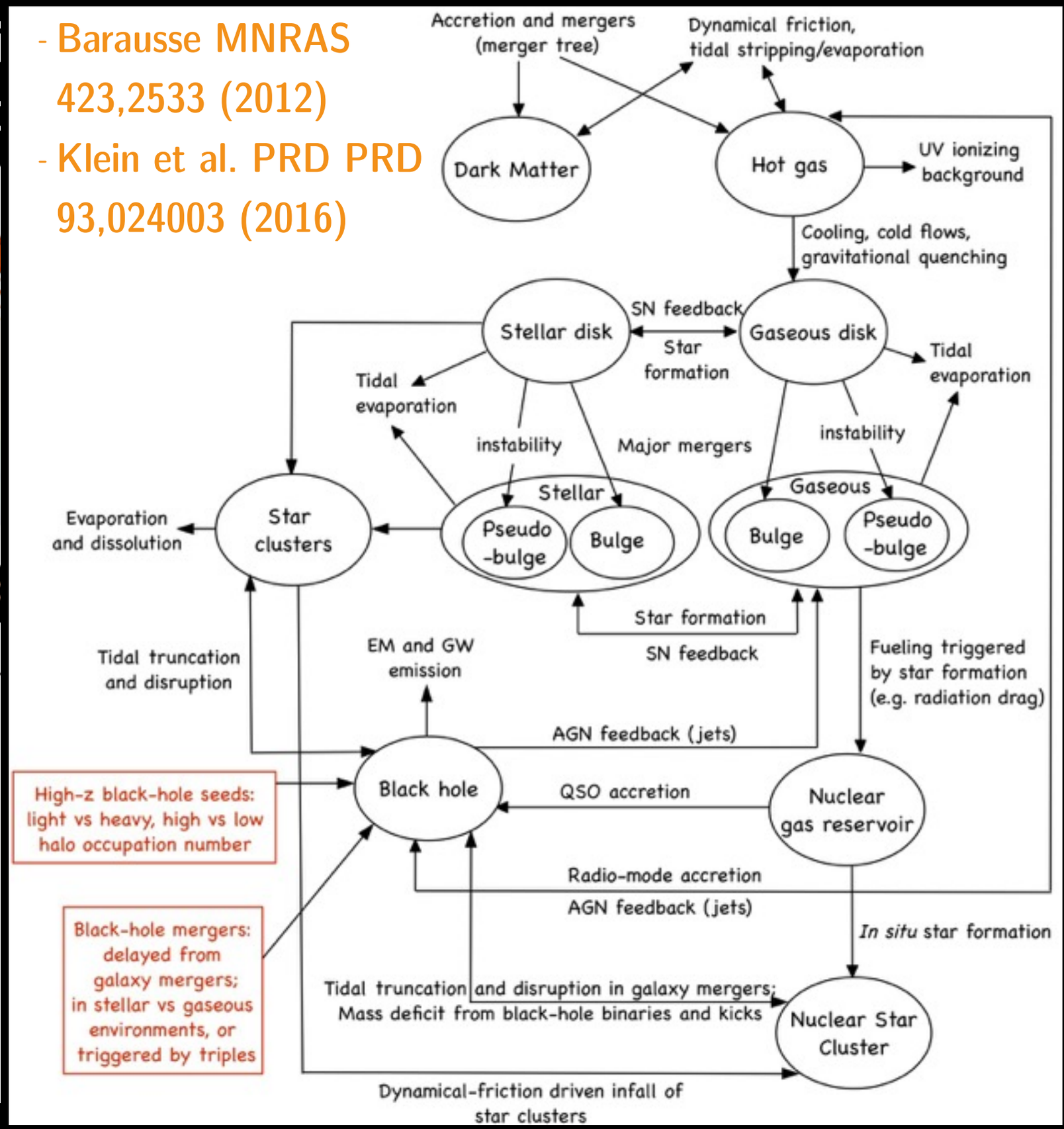
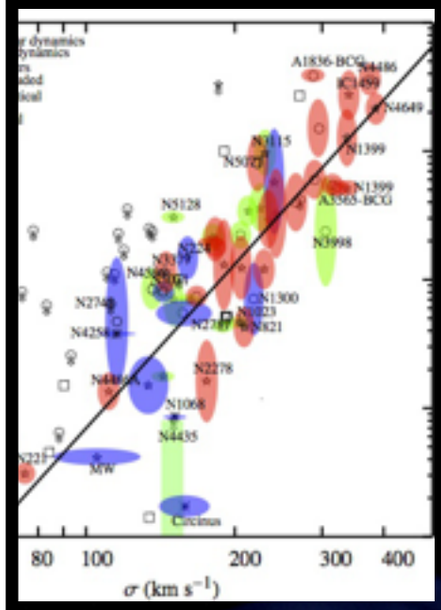


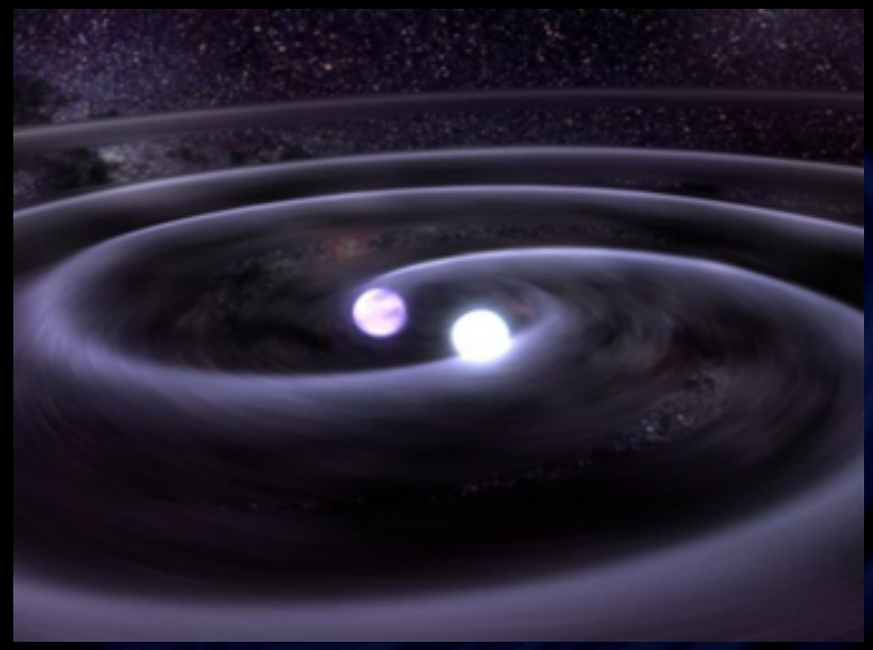
speed of stars in
entral MBH mass



(IAP), A.
ıgham), M.

Compact solar mass binaries

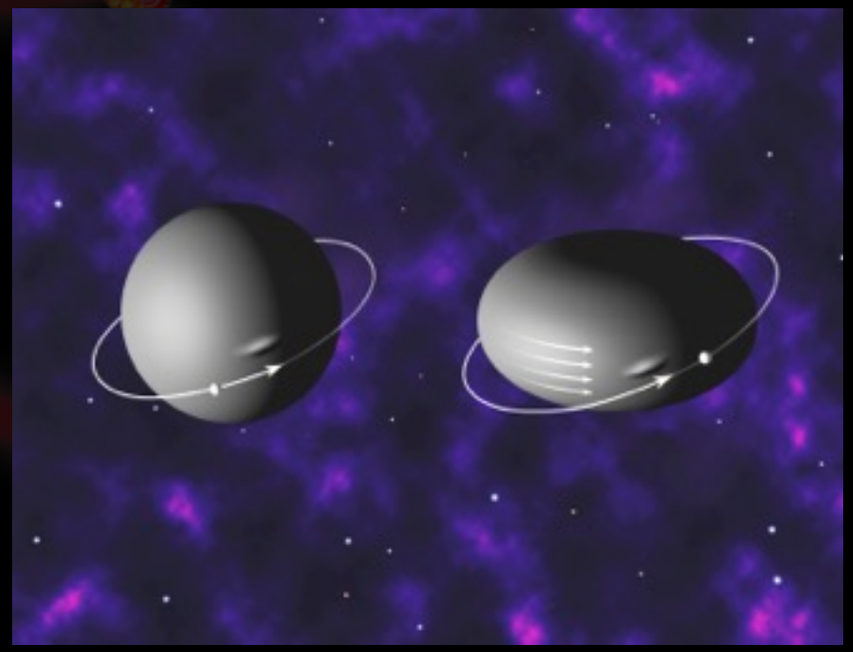
- Large number of stars are in binary system.
- Evolution in white dwarf (WD) and neutron stars (NS).
  $\Rightarrow$ existence of WD-WD, NS-WD and NS-NS binaries
- Estimation for the Galaxy: 60 millions.
- Gravitational waves:
  - most part in the slow inspiral regime (quasi-monochromatic): GW at mHz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

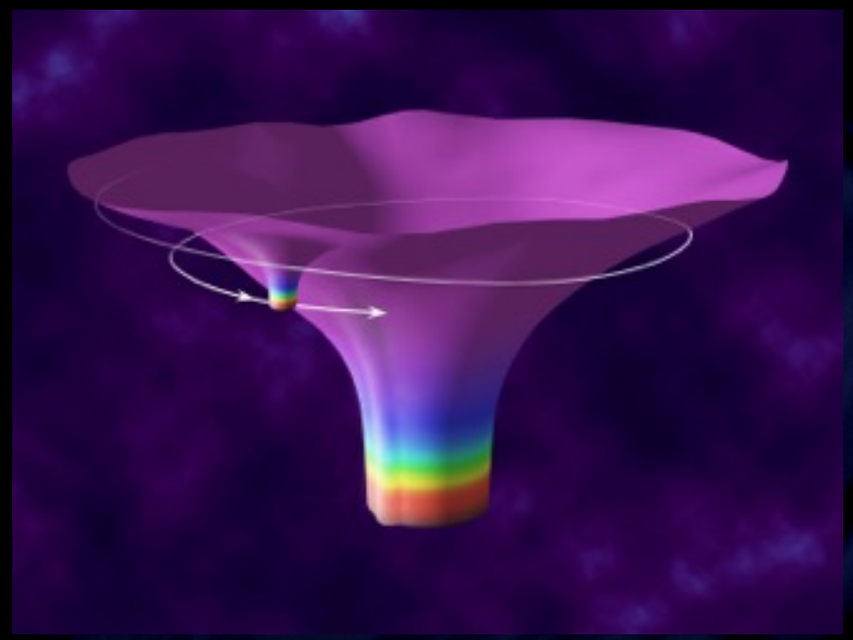


- Several known system emitting around the mHz
  $\Rightarrow$ guaranteed sources

EMRIs

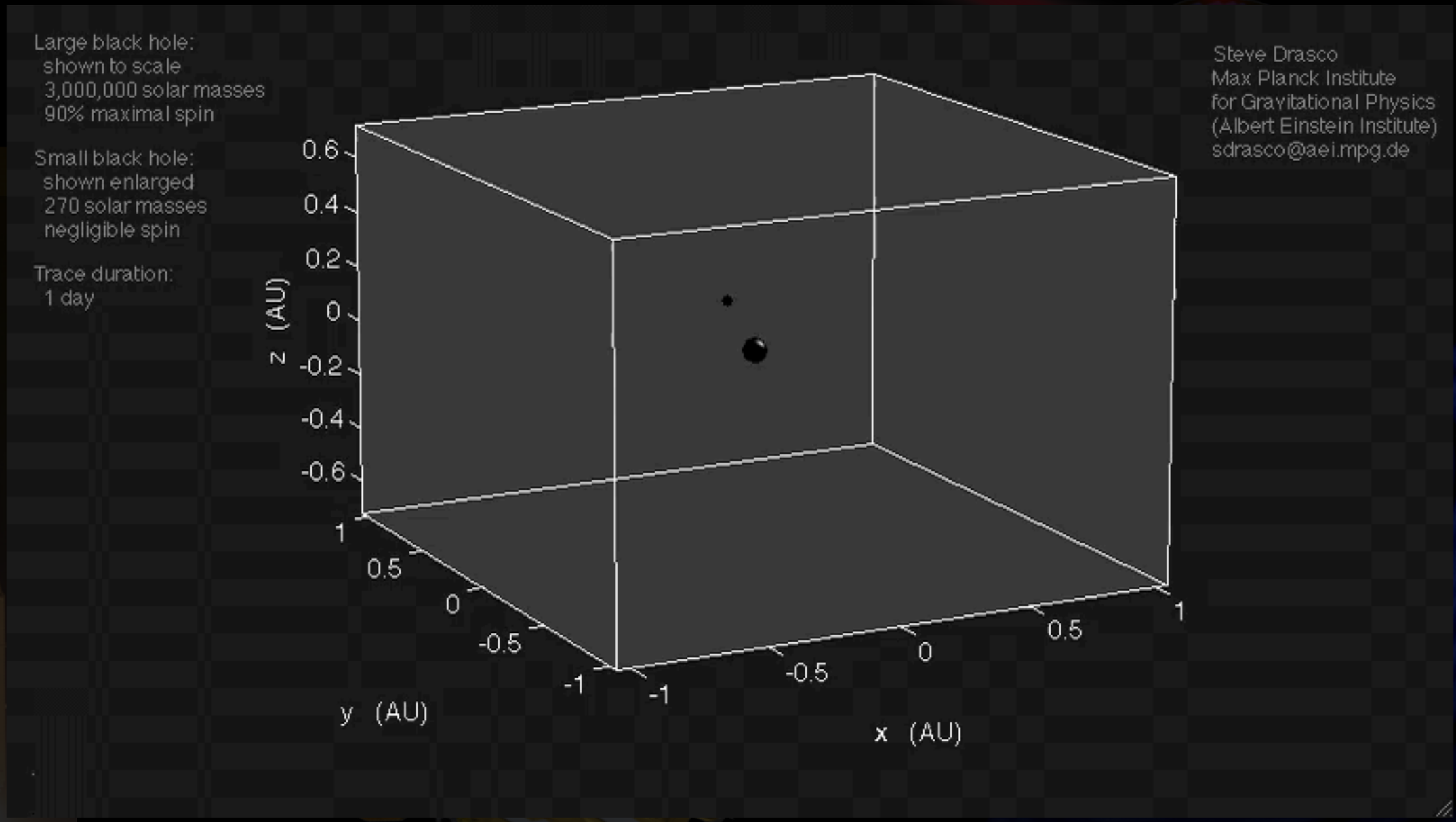
- Capture of a “small” object by massive black hole (10 – 10^6 M_{Sun})
  - Mass ratio > 200
  - GW gives information on the geometry around the black hole.
  - Test General Relativity in stong field
  - Frequency : 0.1 mHz to 0.1 Hz
  - Large number of source could be observed by space-based interferometer





EMRIs

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



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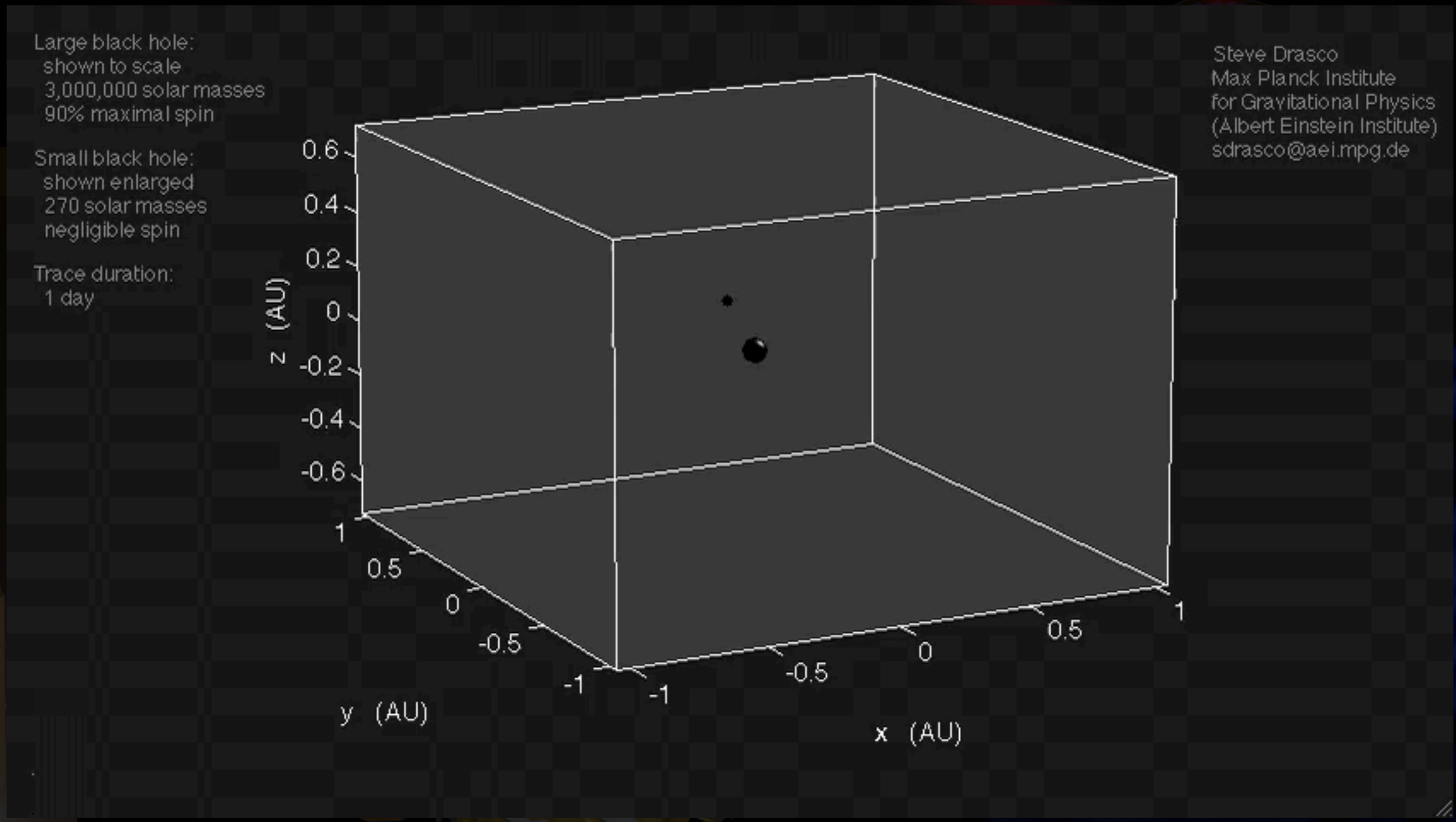
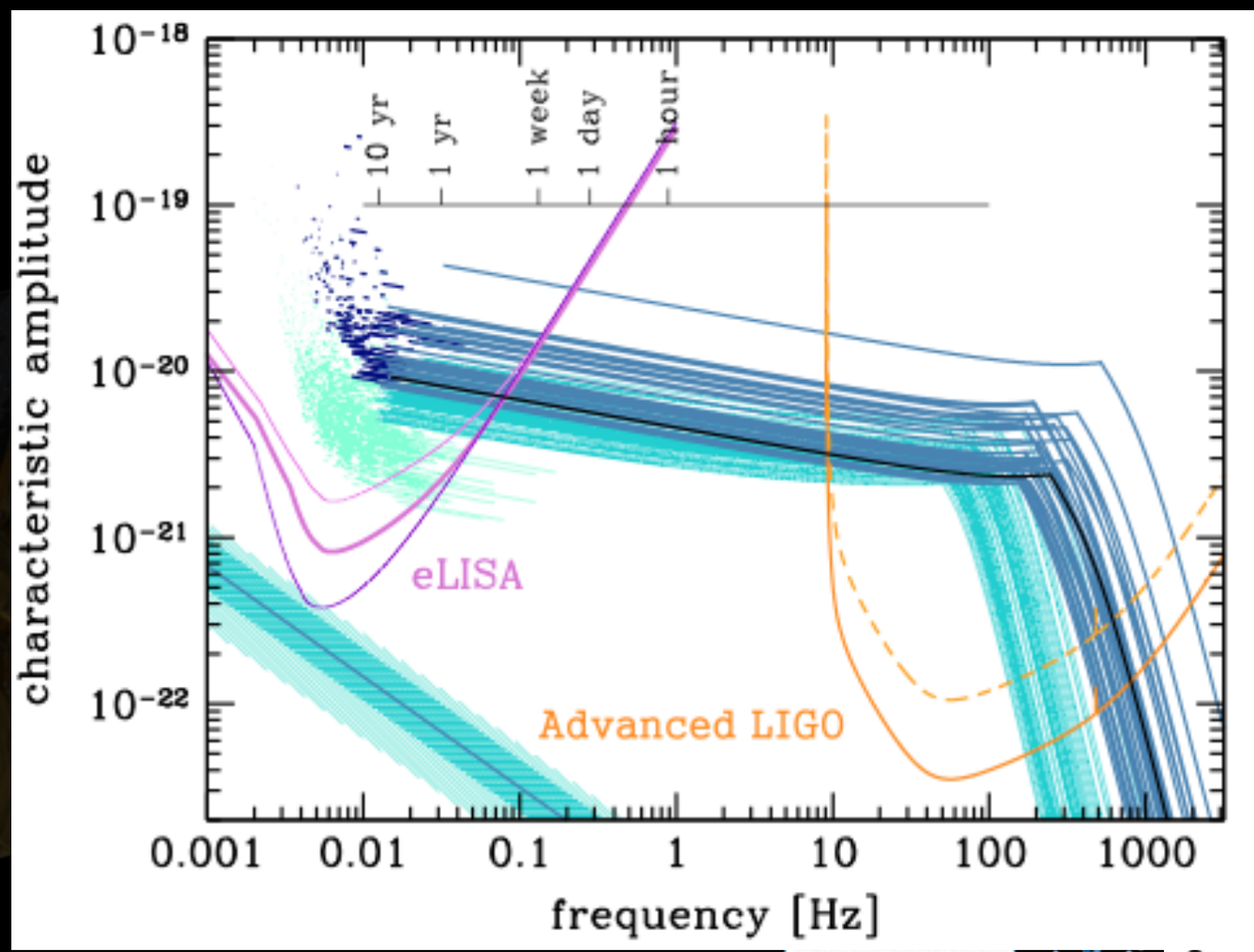


Stellar Mass Black Hole Binaries

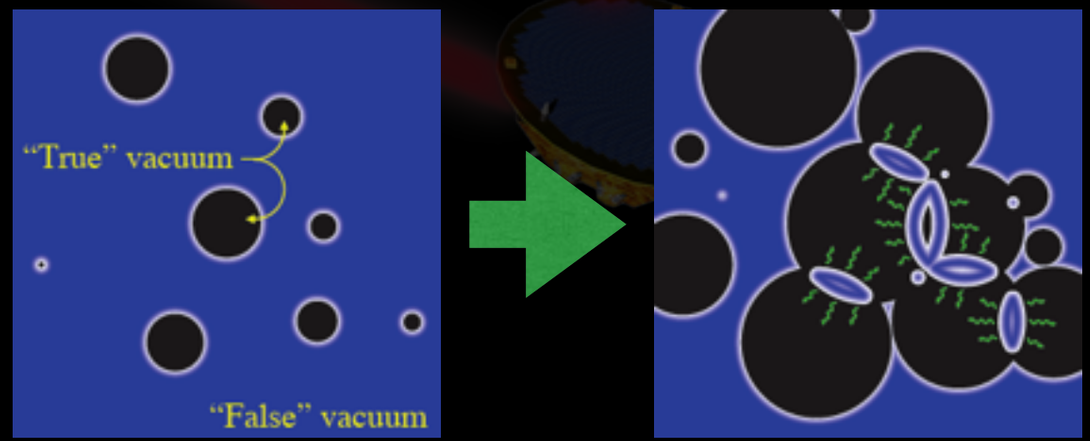
- LIGO/Virgo-type sources: binaries with 2 black holes of few tens solar masses.
- During most part of the inspiral time, emission in the mHz band
  => multi-observatories GW astronomy

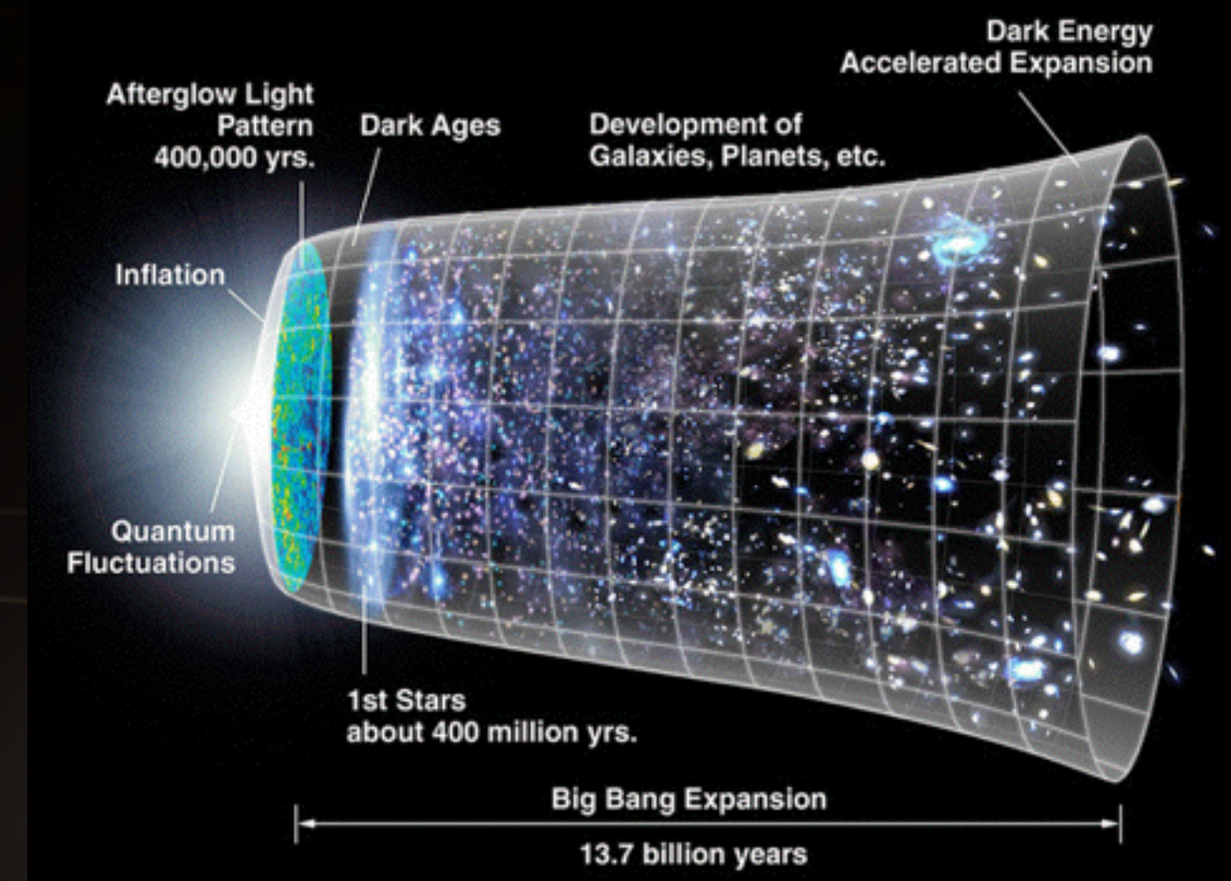
A. Sesana, PRL 116, 231102 (2016)

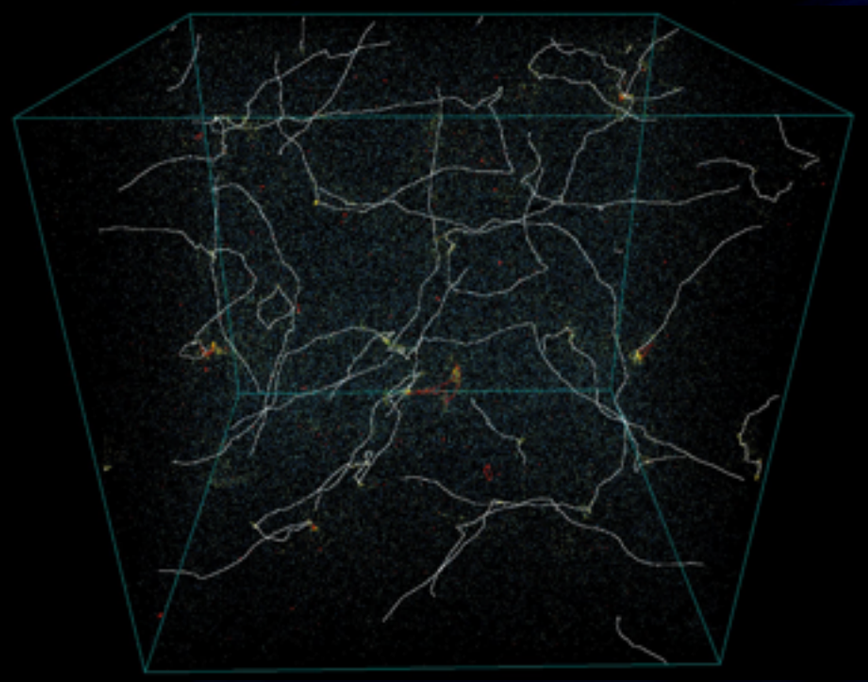


Cosmological backgrounds

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



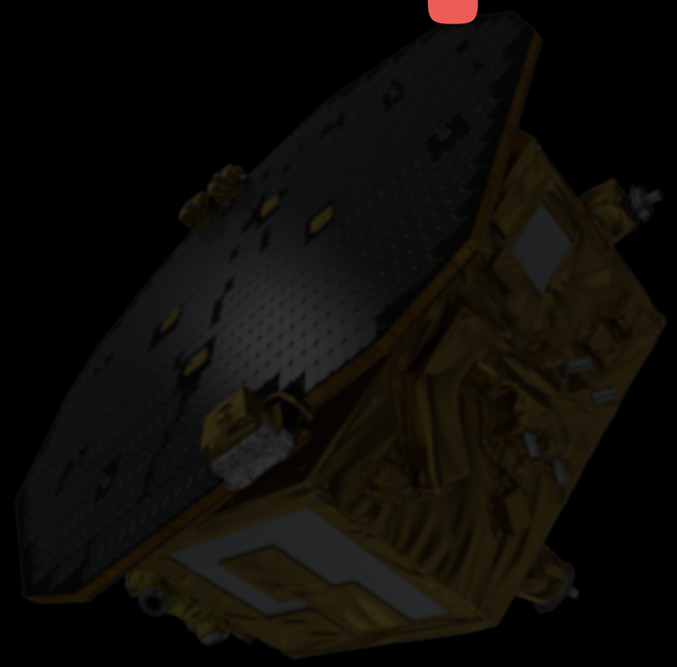




Unknown sources

- 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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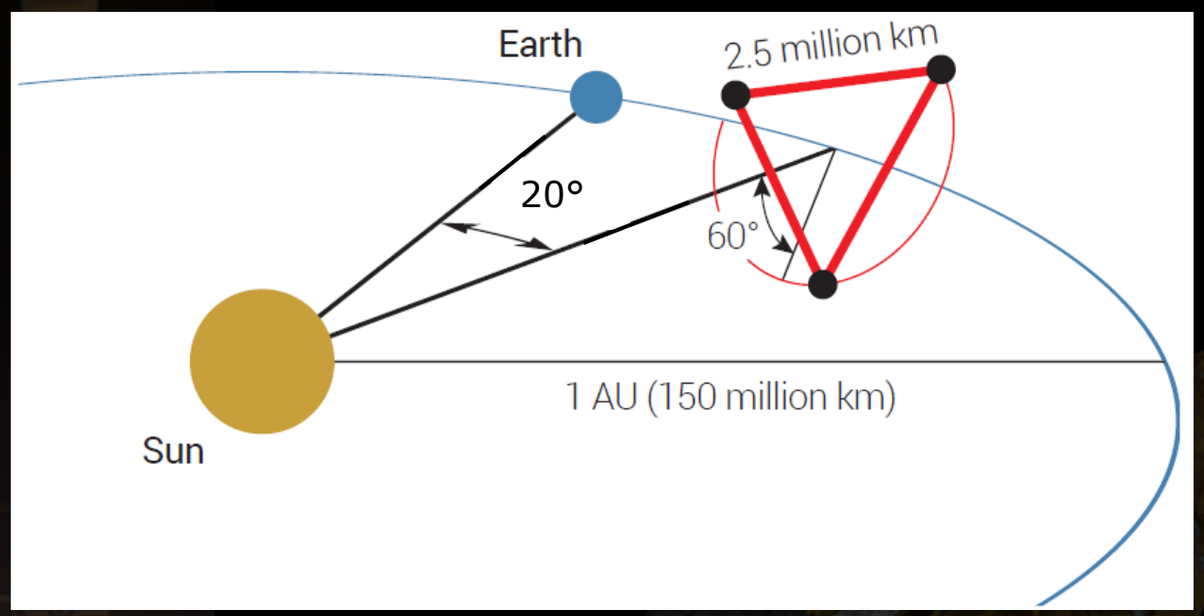
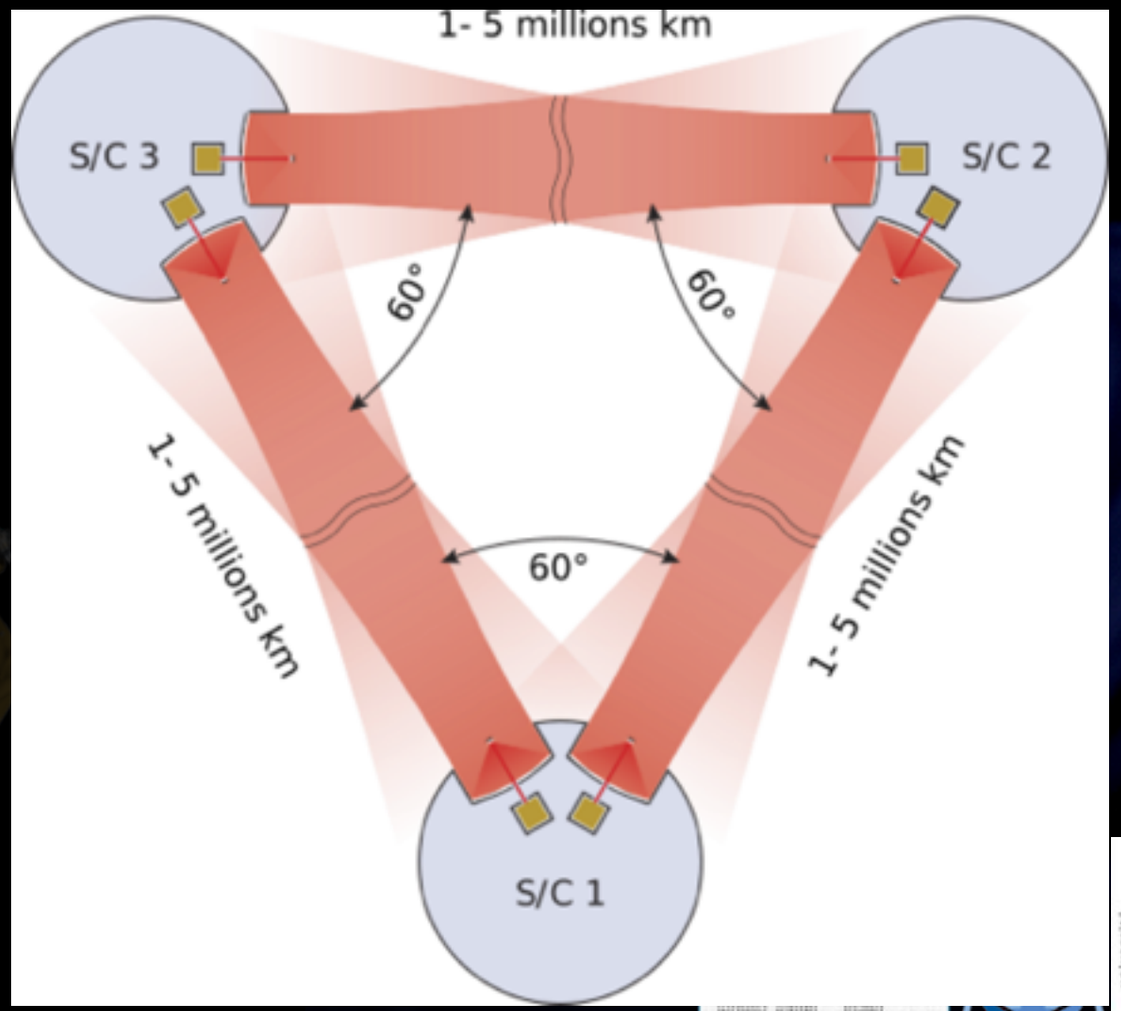
LISA

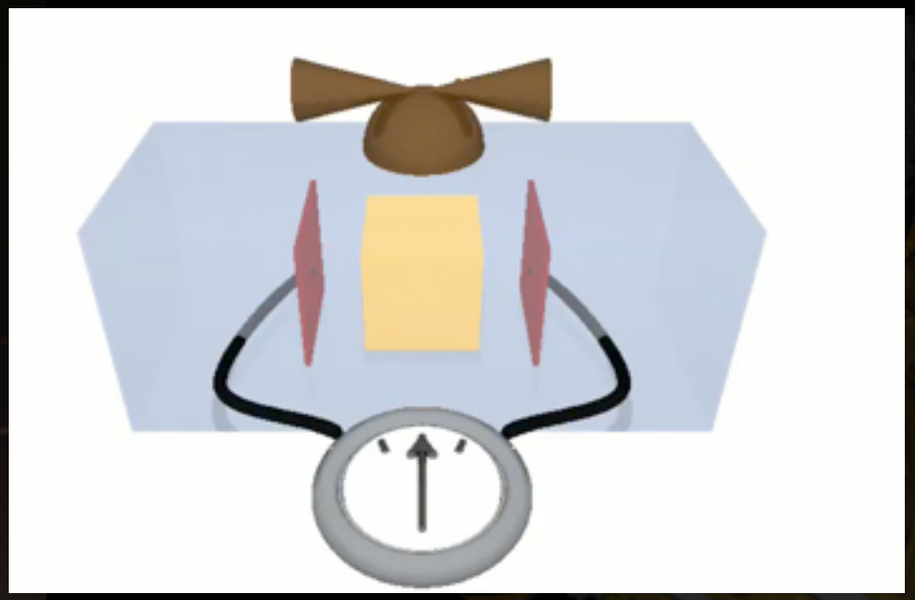
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of 10^{-21}: few picometers

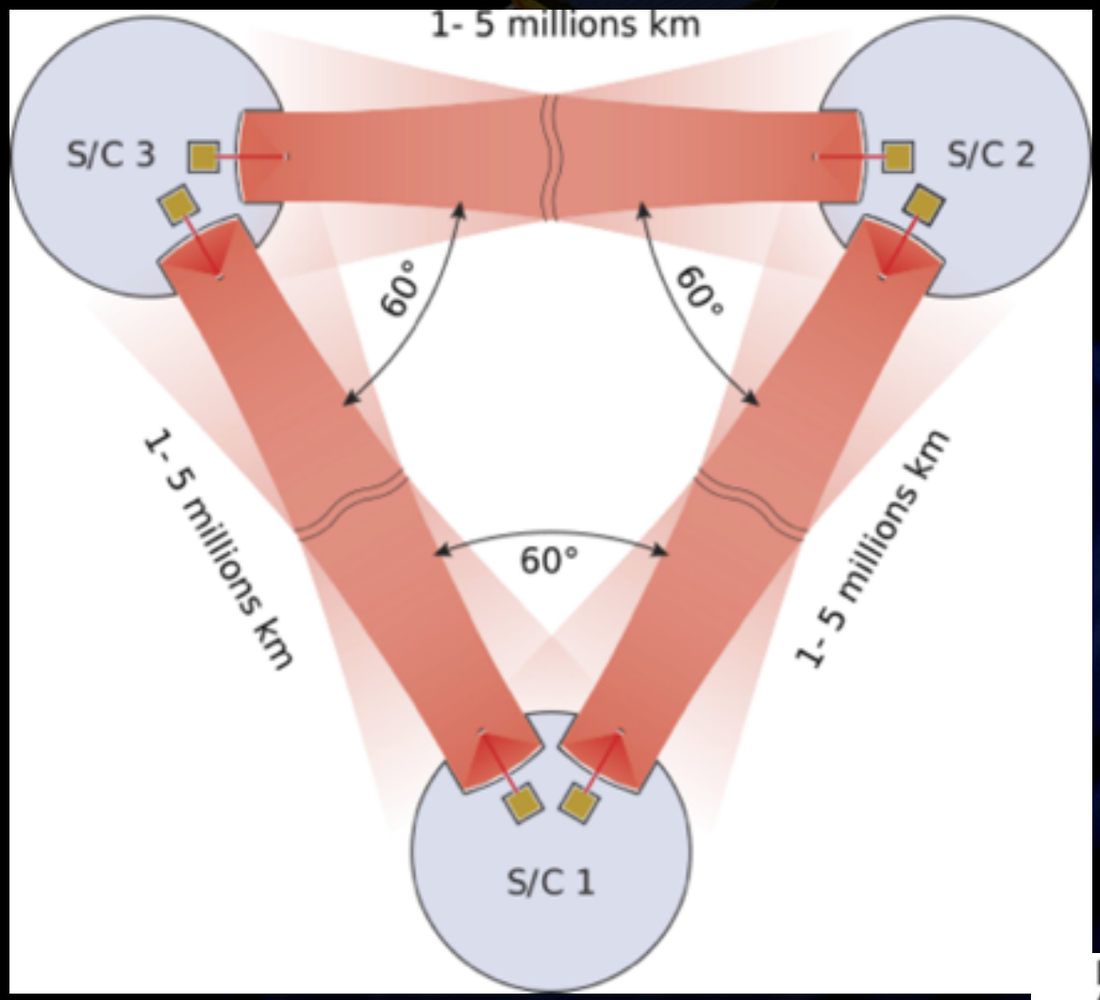




LISA

- 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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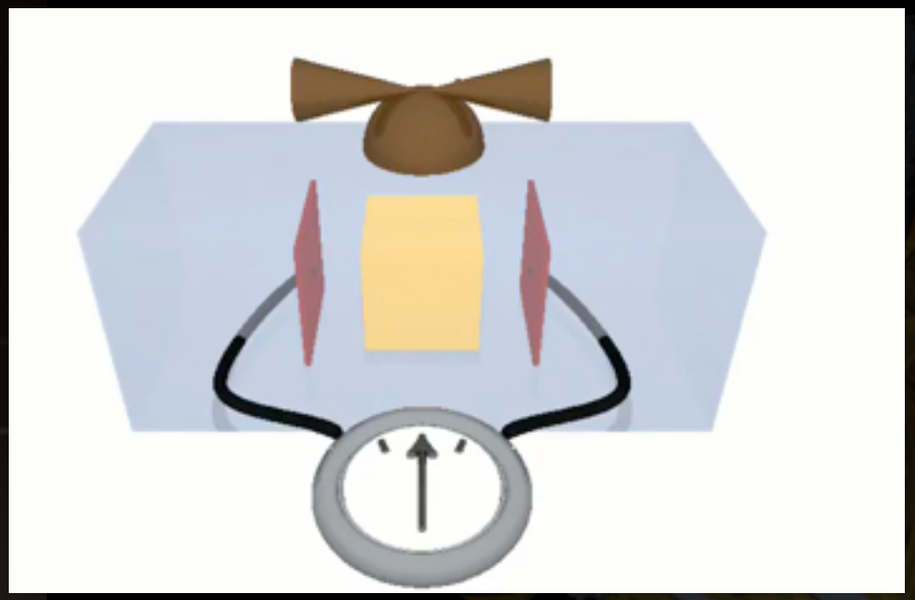
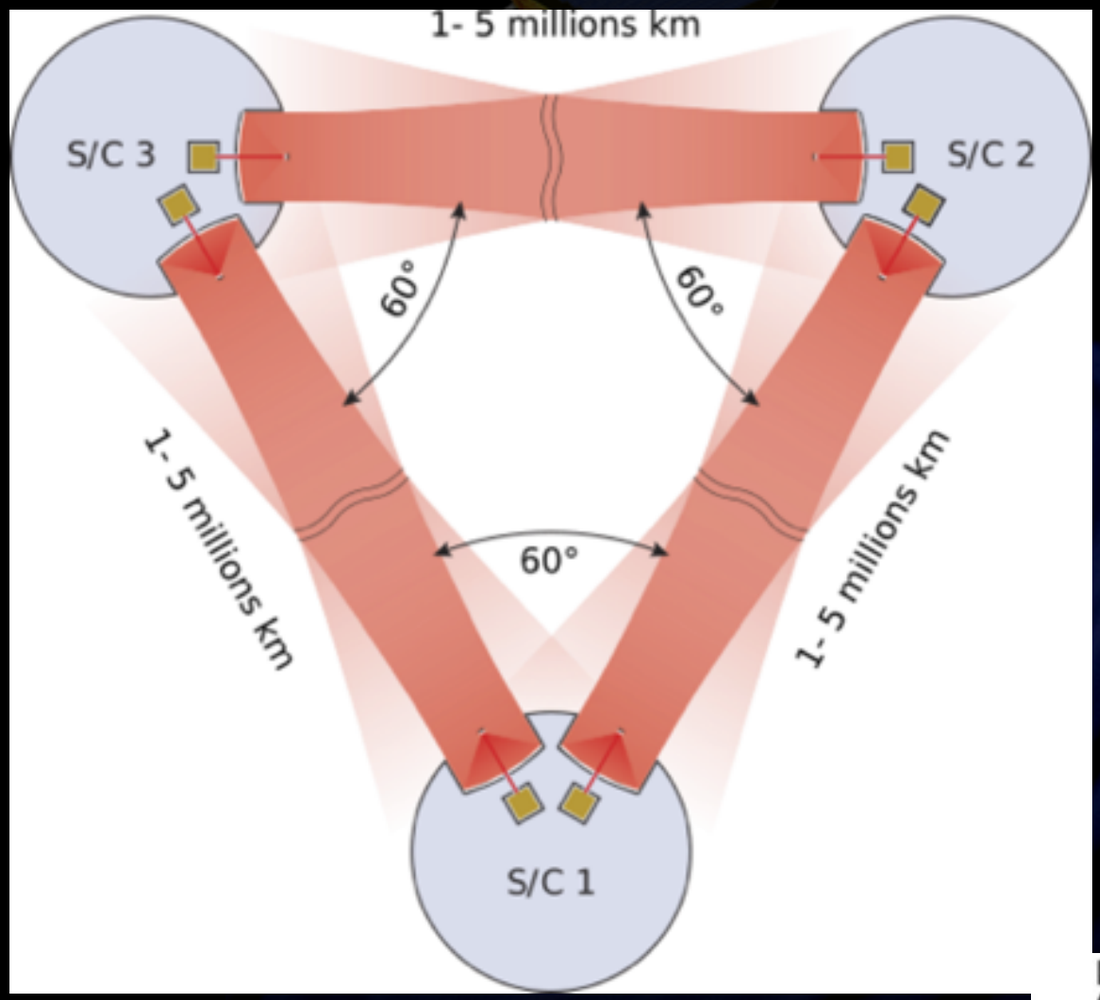
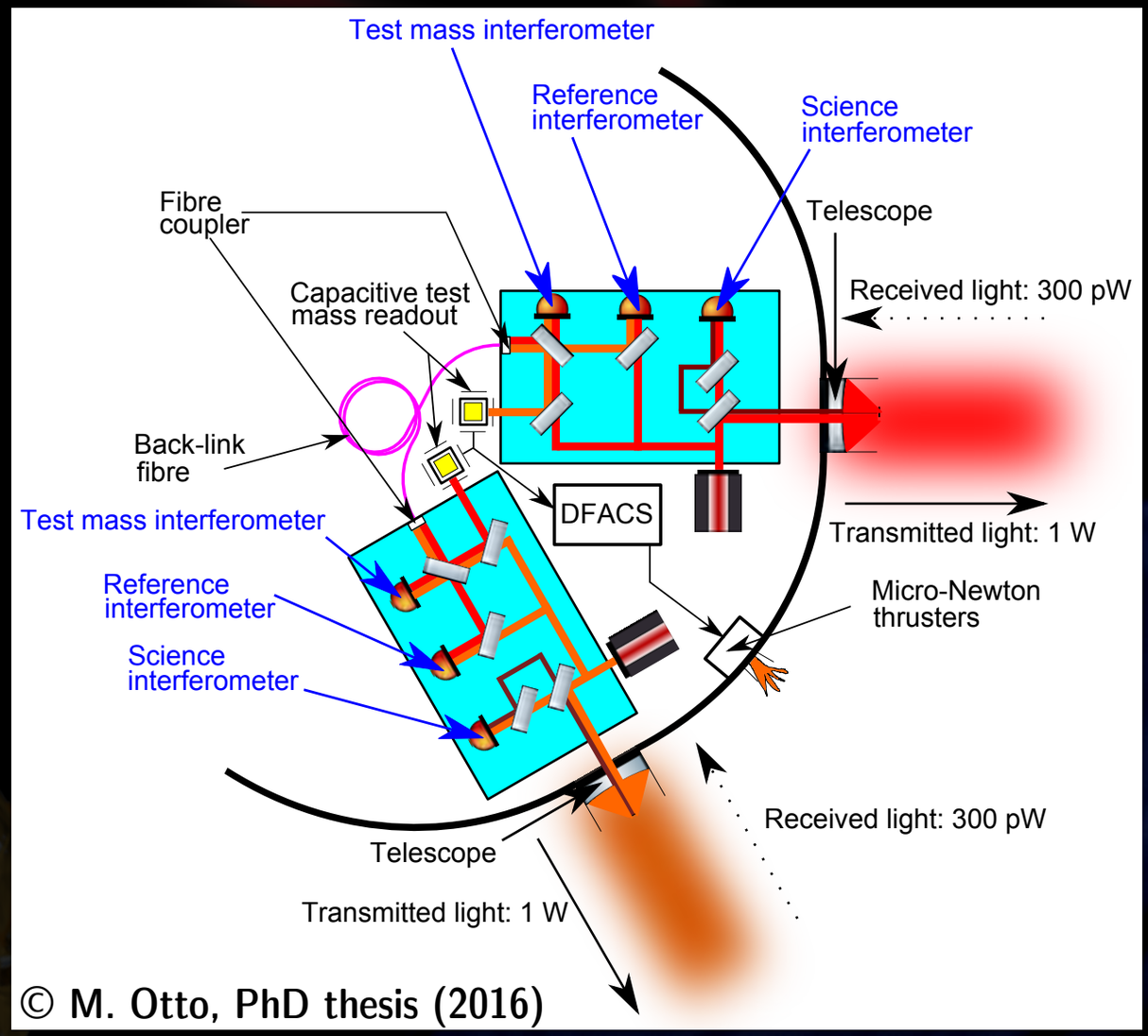




LISA

- 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
- 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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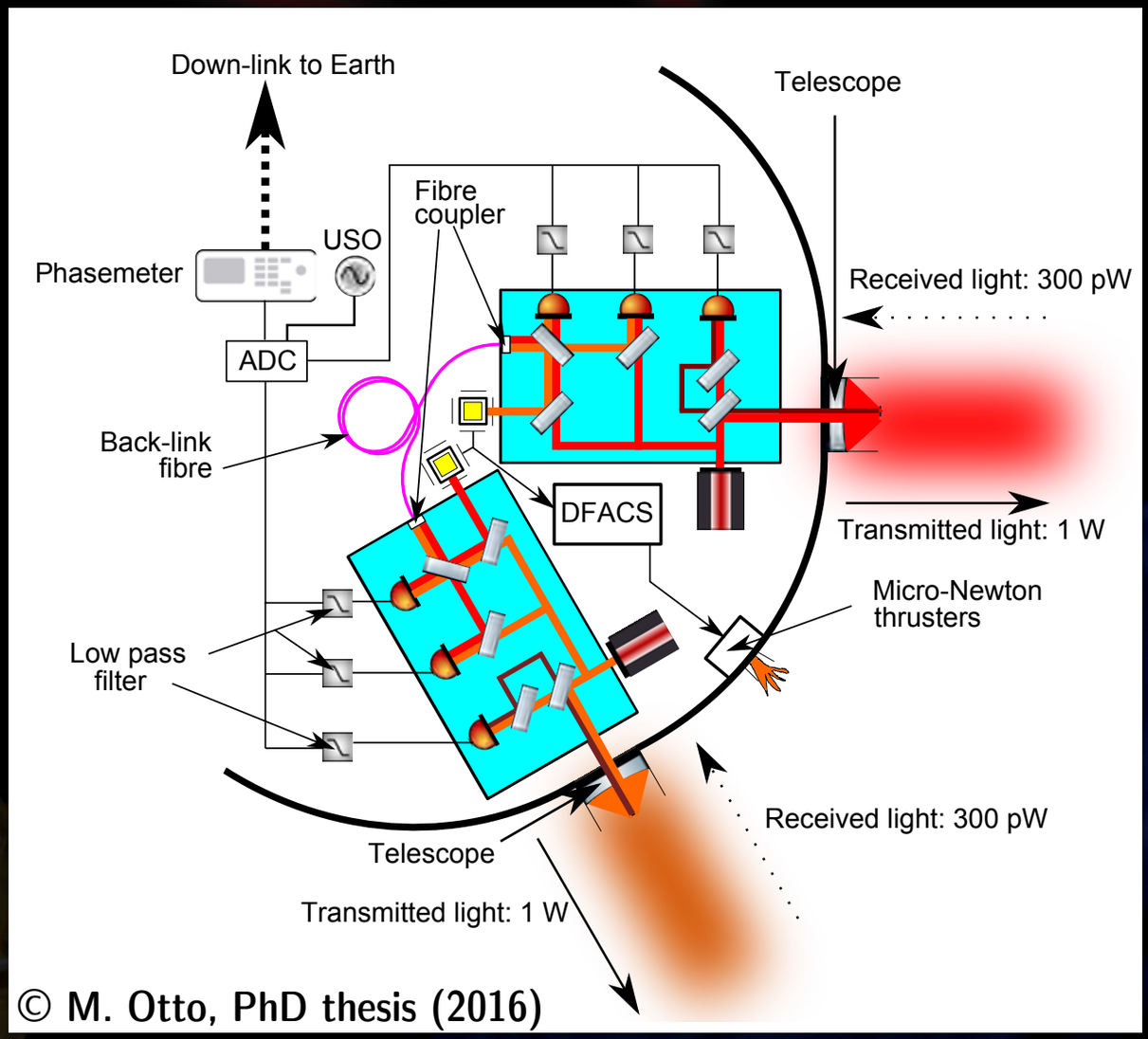

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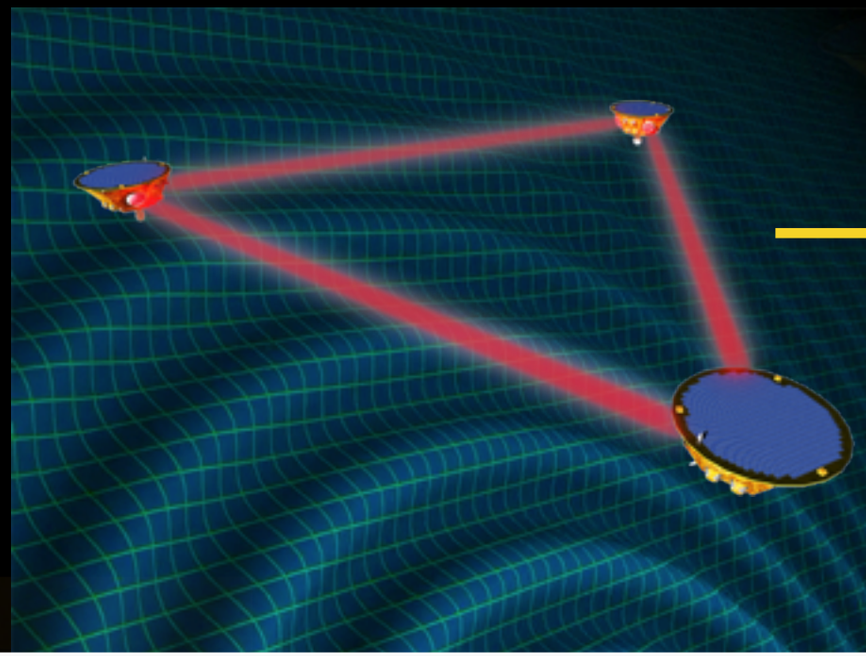
LISA technology requirements

- 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 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

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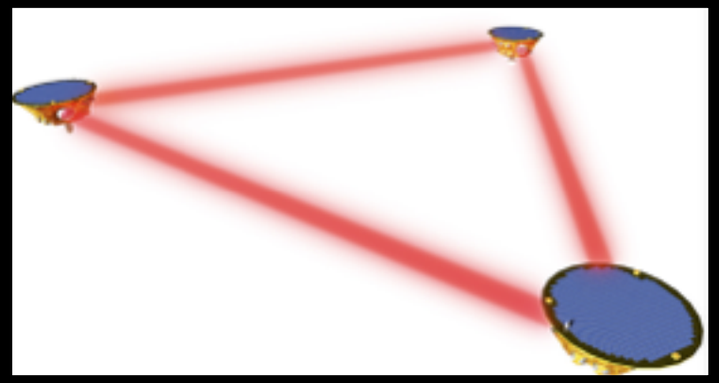
- A measurements in several steps



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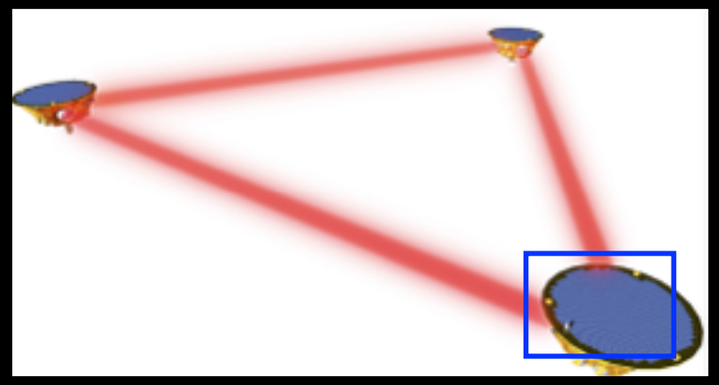

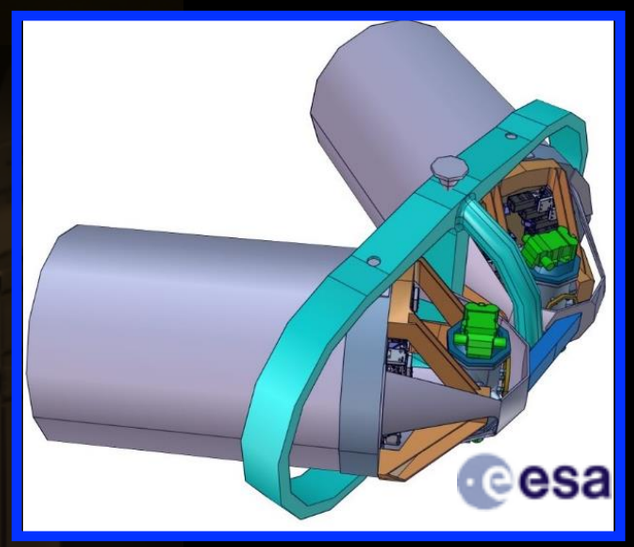

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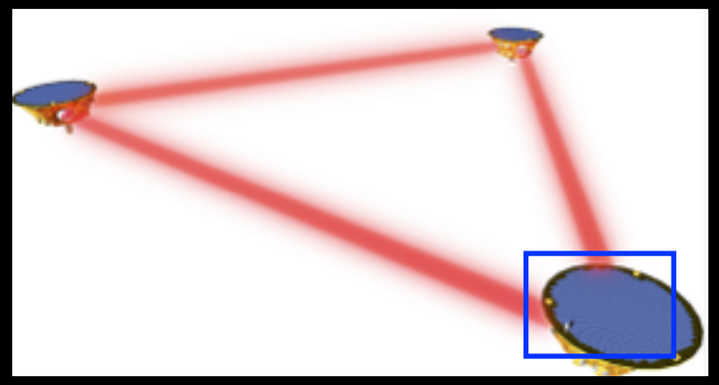

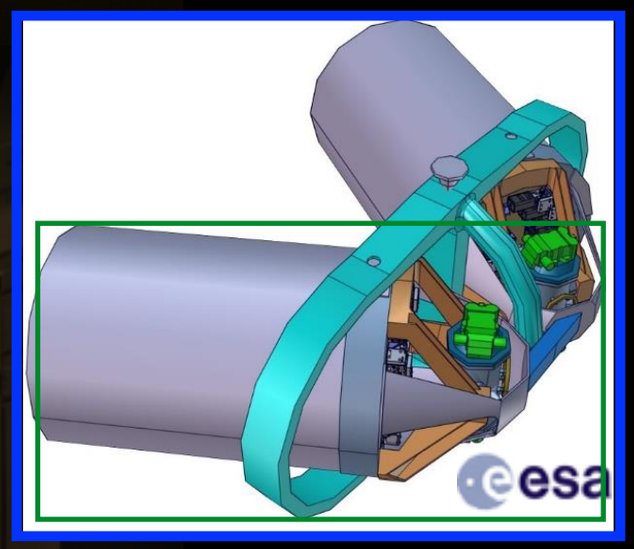

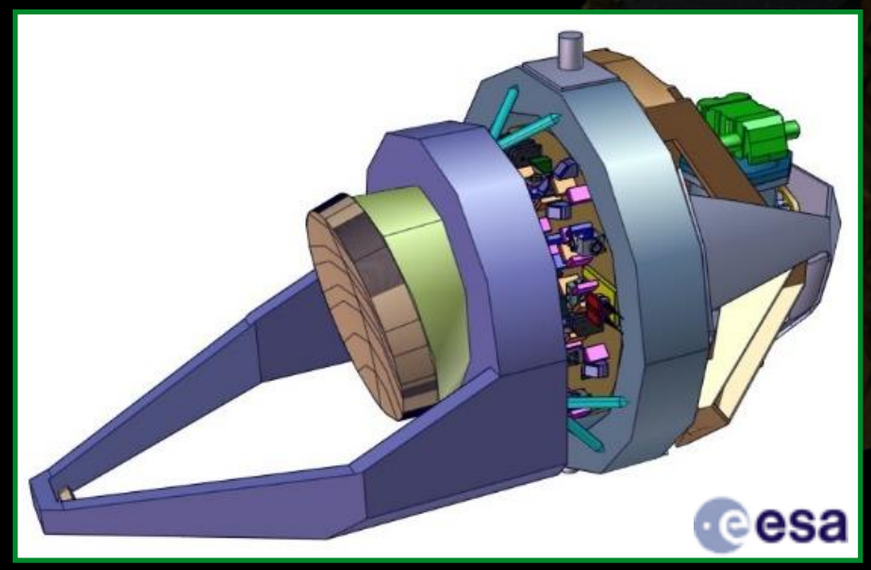

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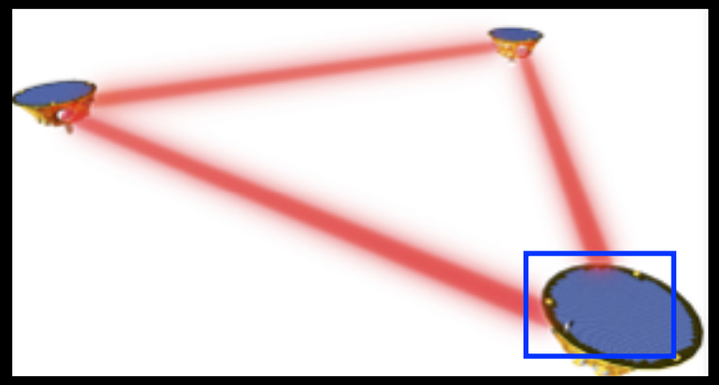
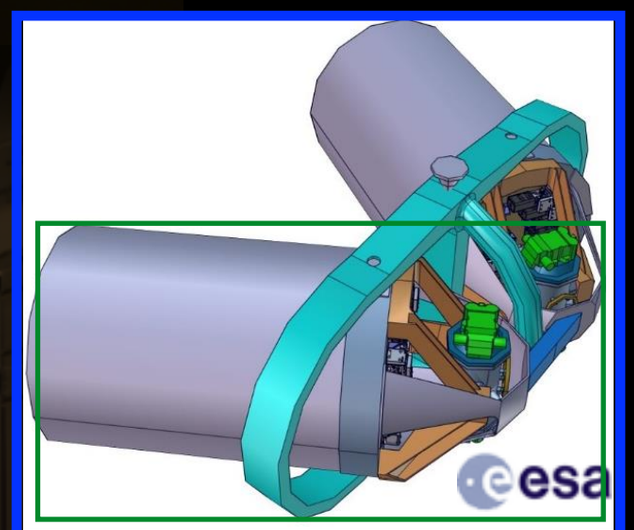
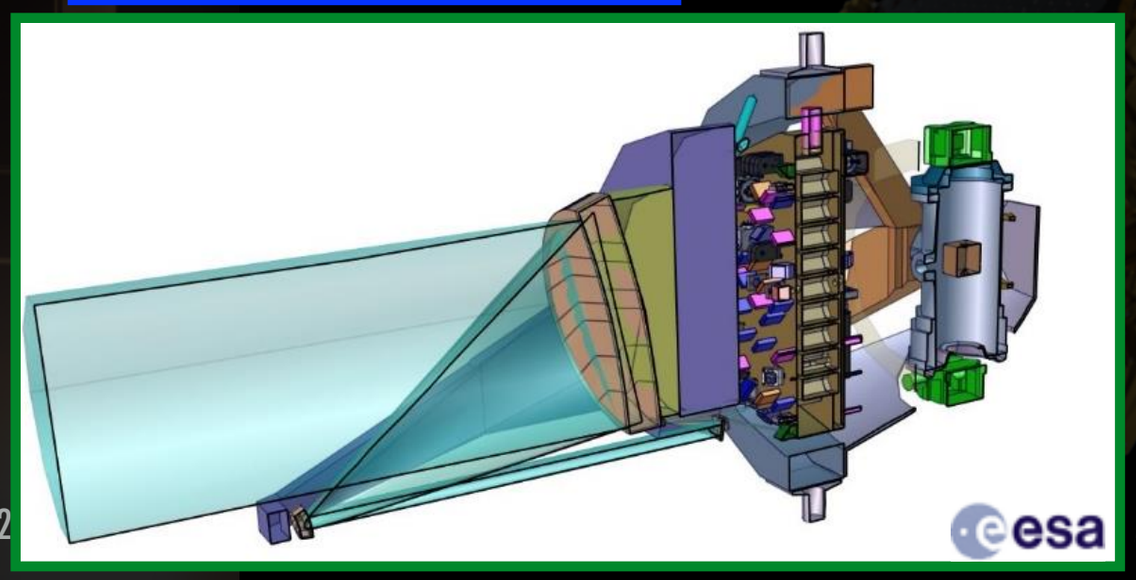
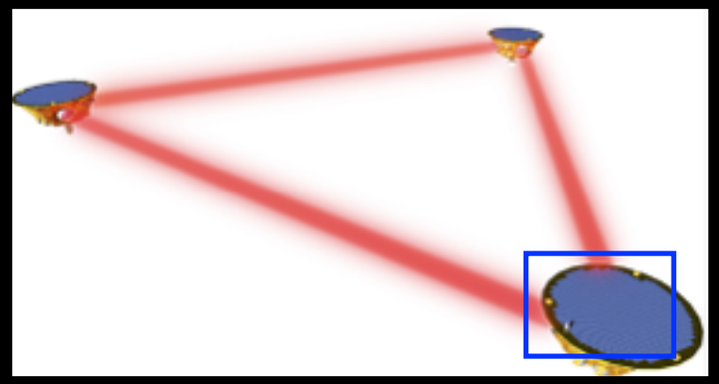


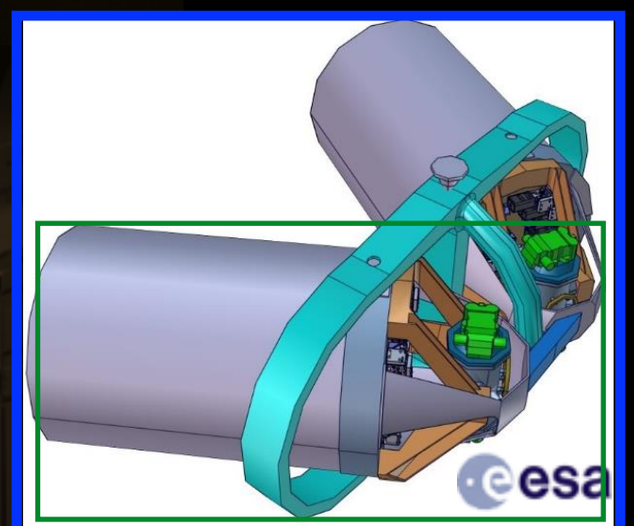


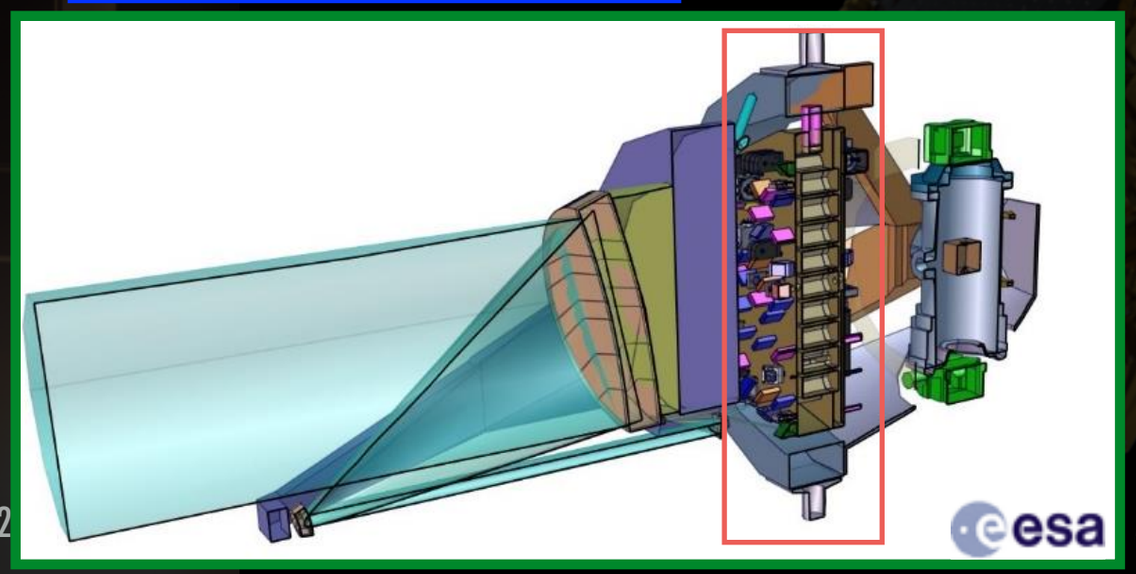


LISA

- A measurements in several steps



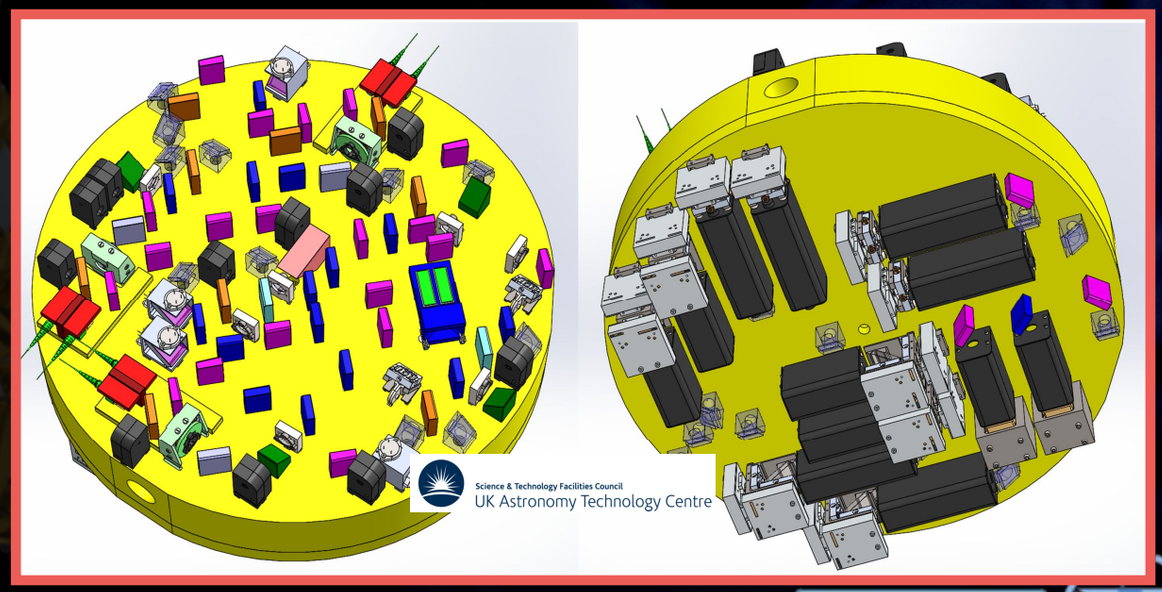




LISA:

Local measurement of distance from TM to SC using:

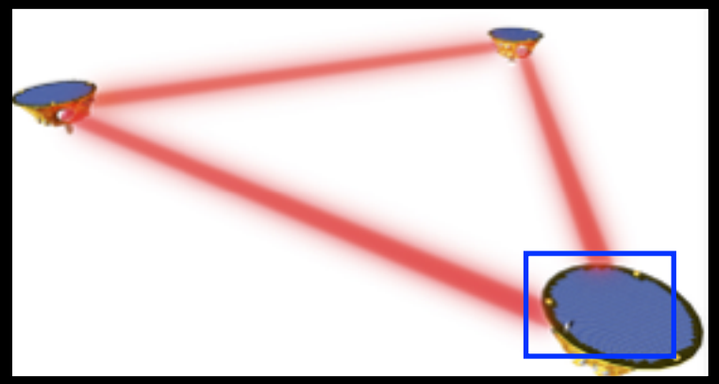
- Laser interferometry along sensitive axis (between SC)
- Capacitive sensing on orthogonal axes
- TM displacement measurements are used as input to DFACS which controls position and attitude of SC respect to the TM

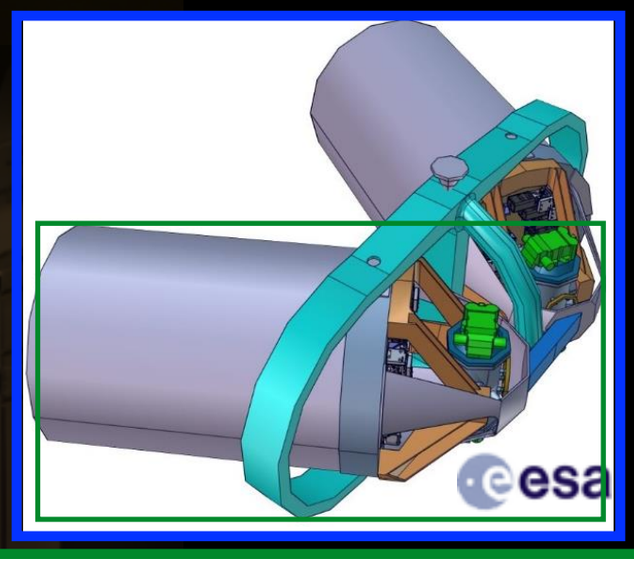


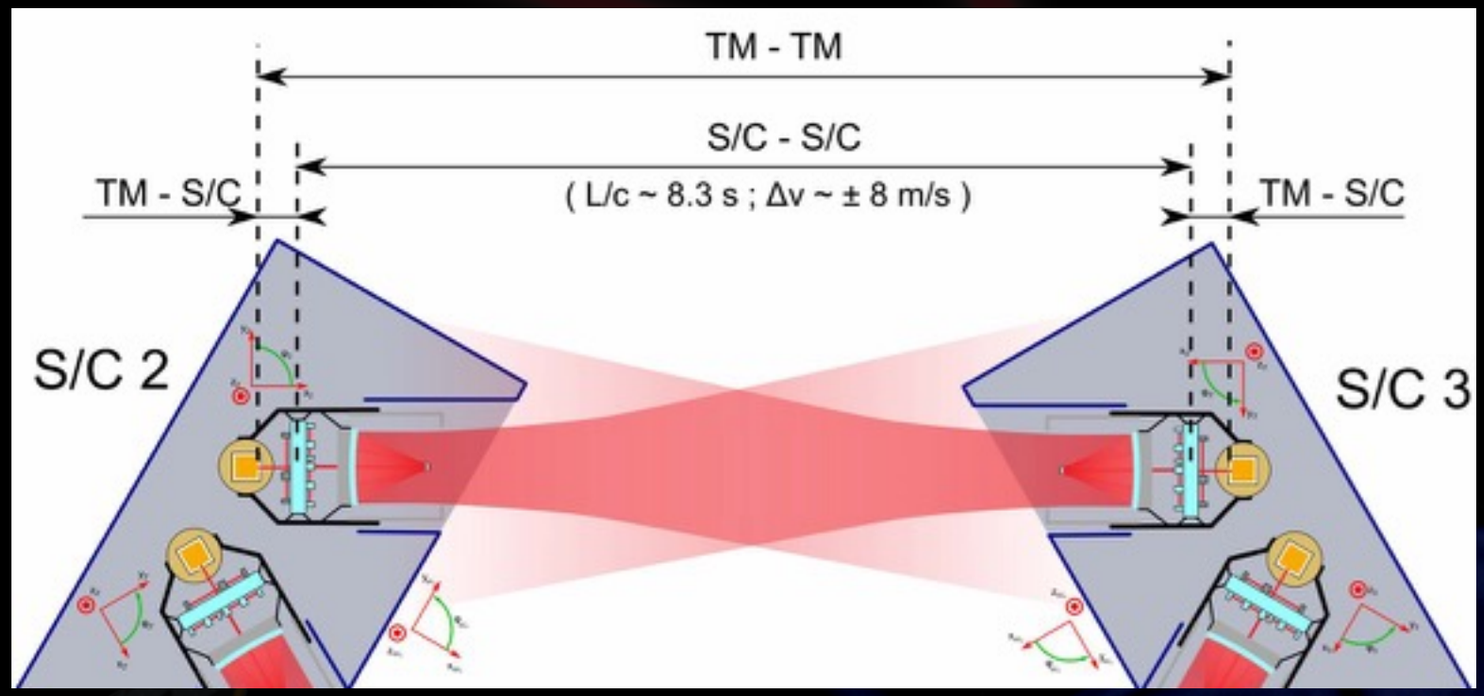
LISA

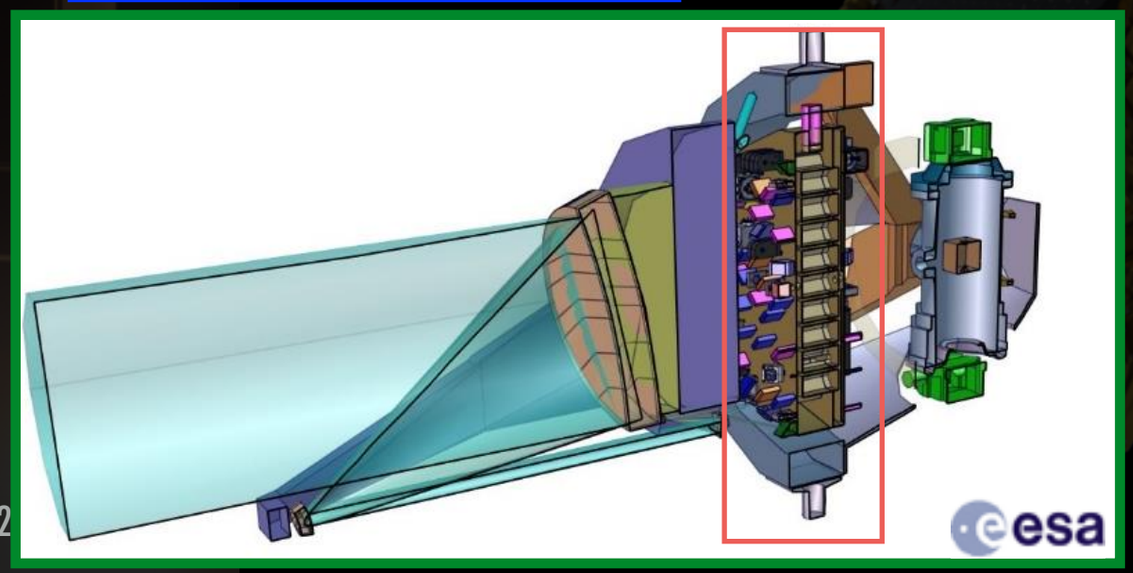
- A measurements in several steps

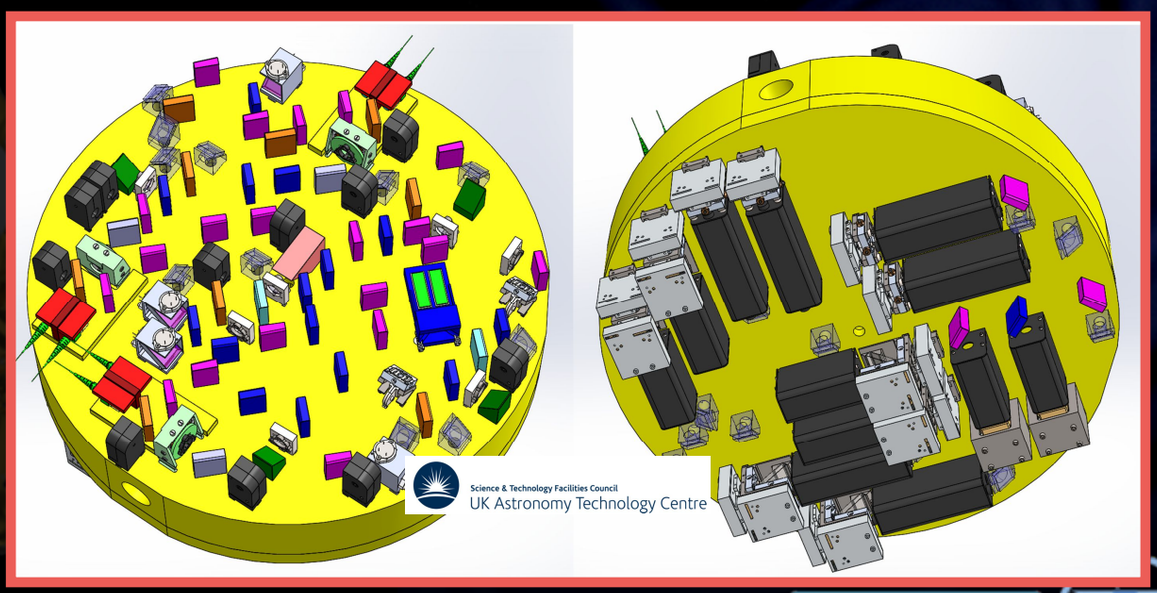
(TM2→SC2) + (SC2→SC3) + (SC3→TM3)





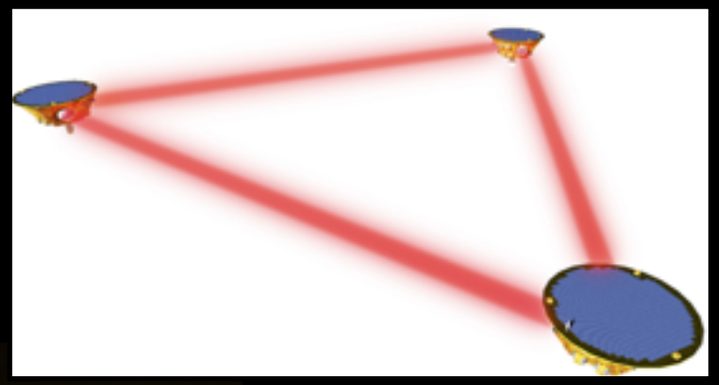


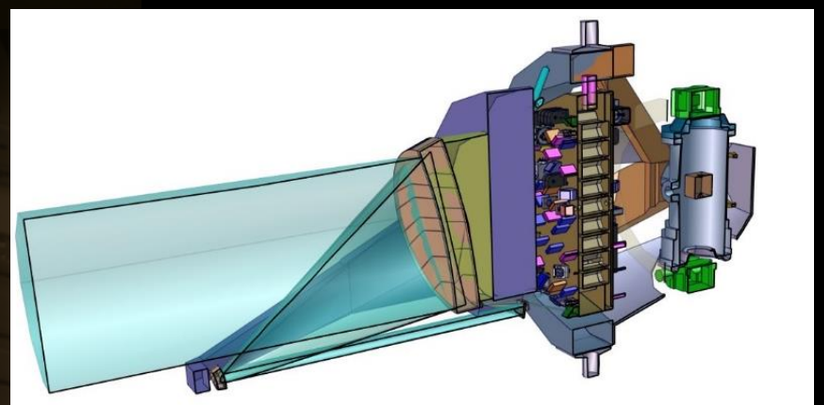




LISAPathfinder

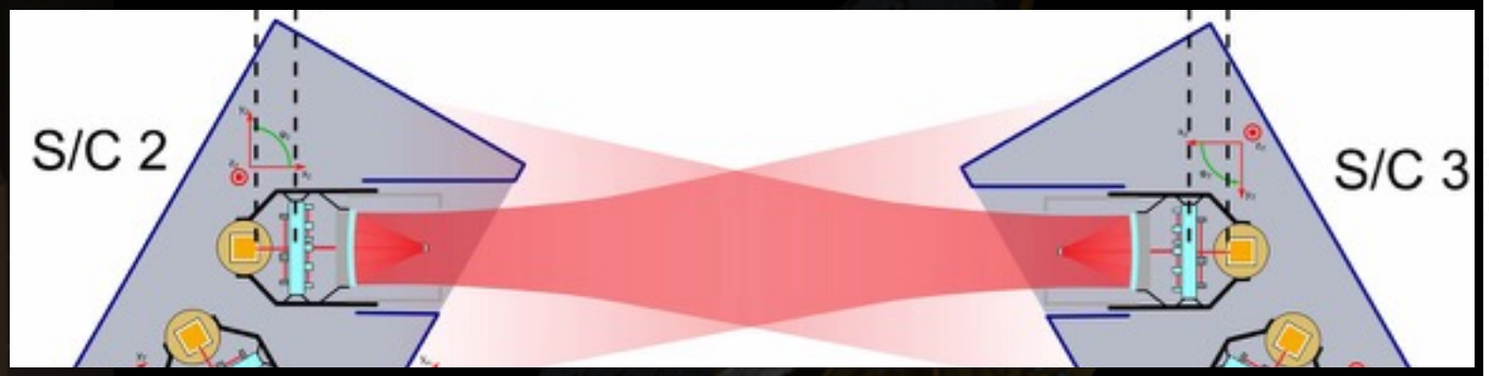
- Technological demonstrator for LISA

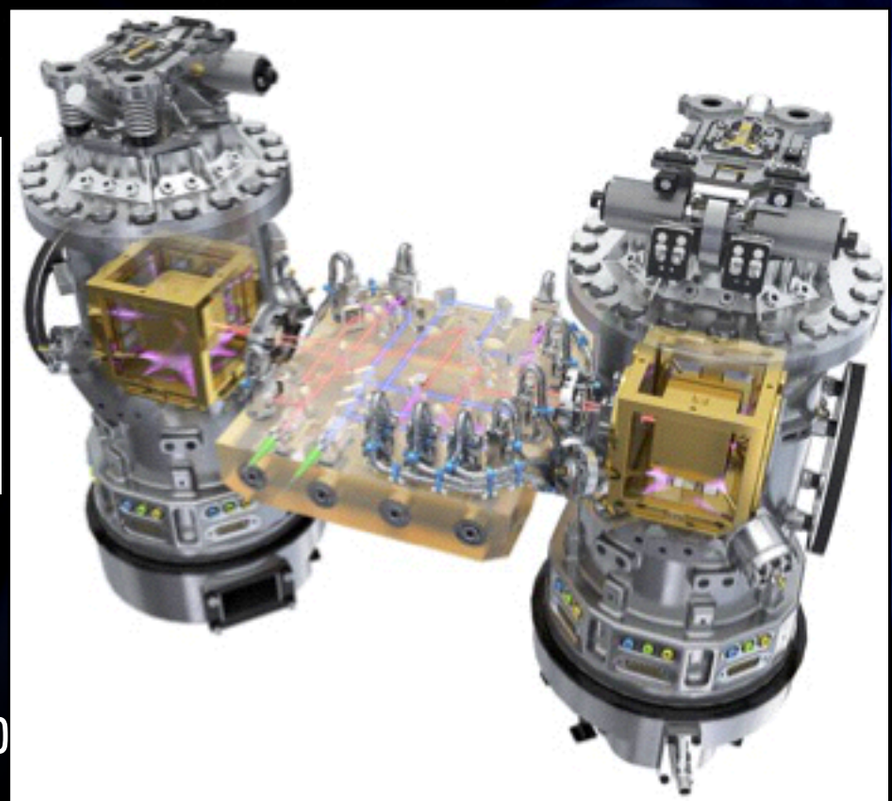




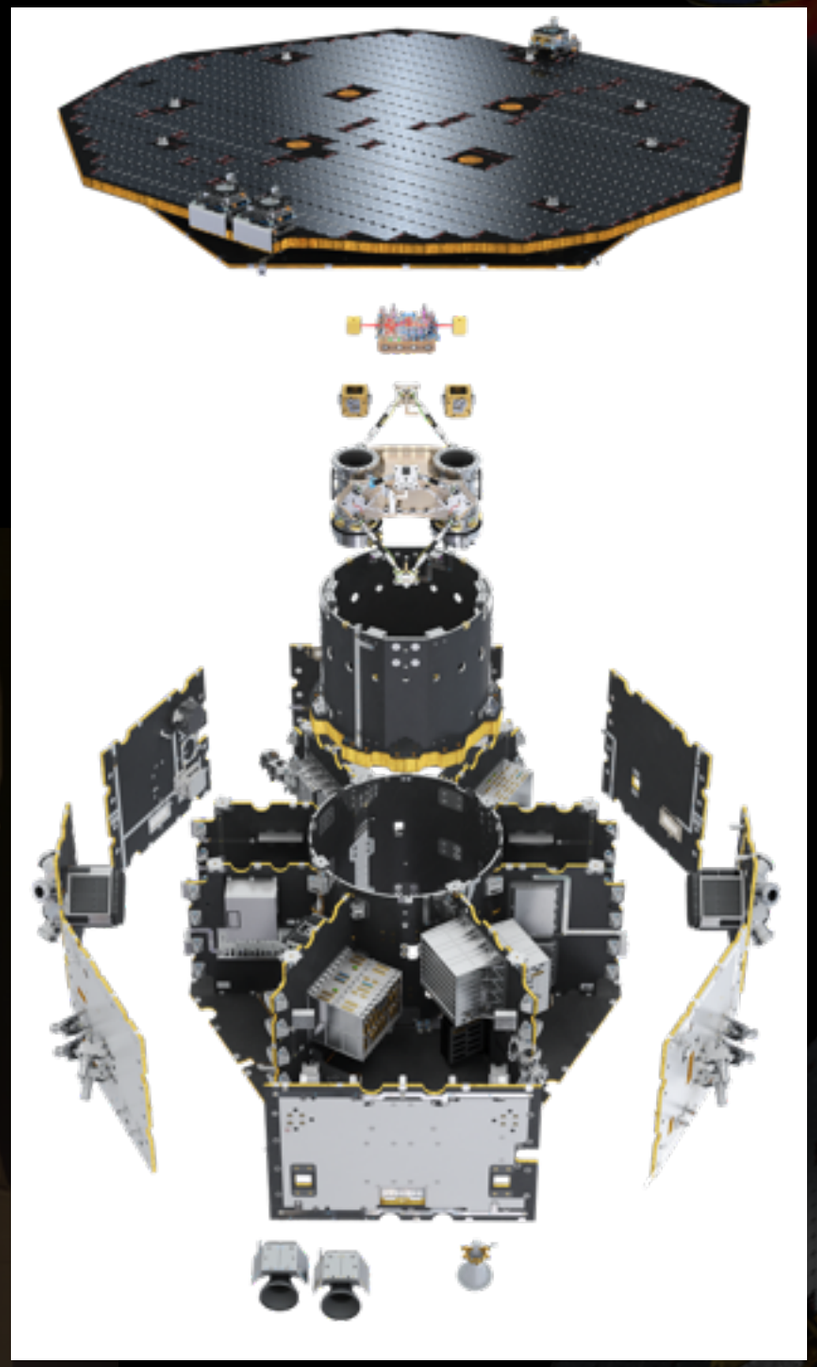
LISAPathfinder:

- 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





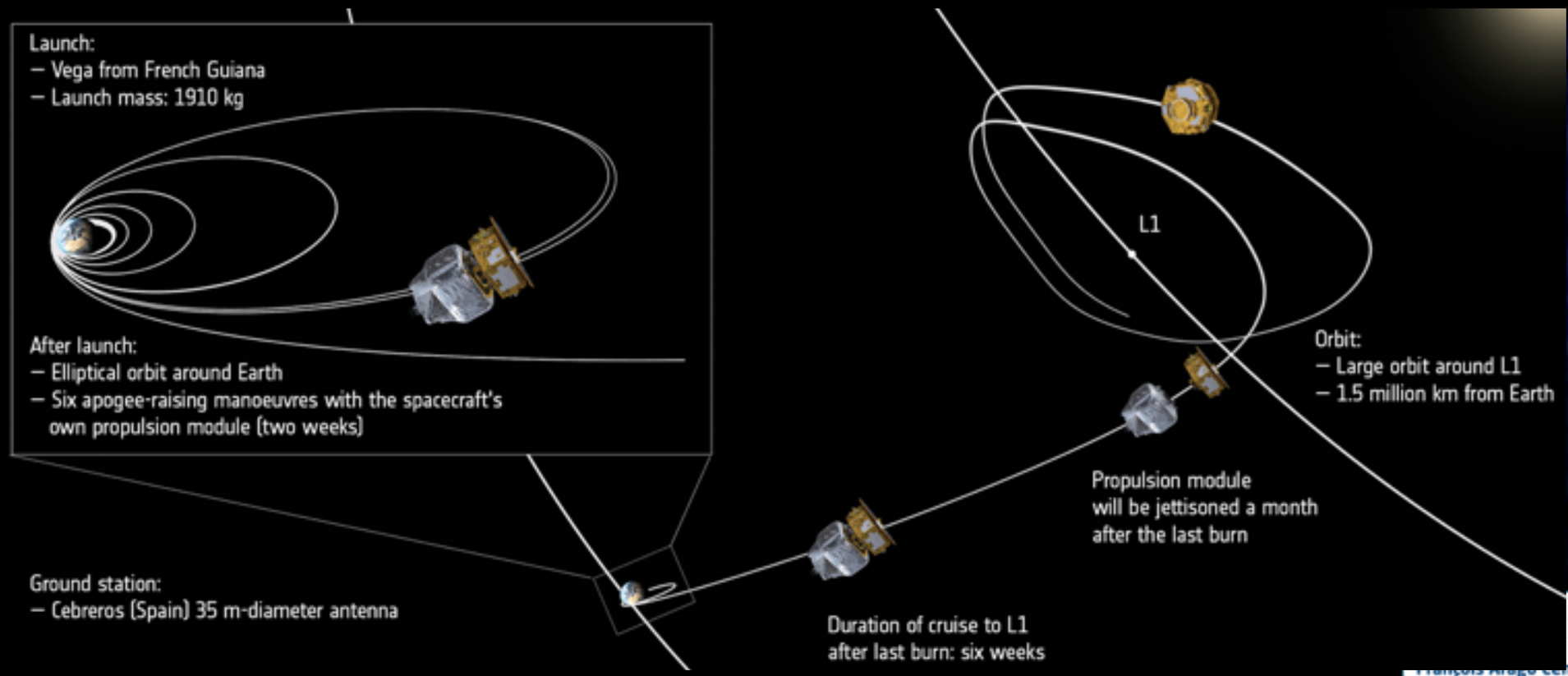
LISAPathfinder timeline



LISAPathfinder timeline

LISAPathfinder timeline

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



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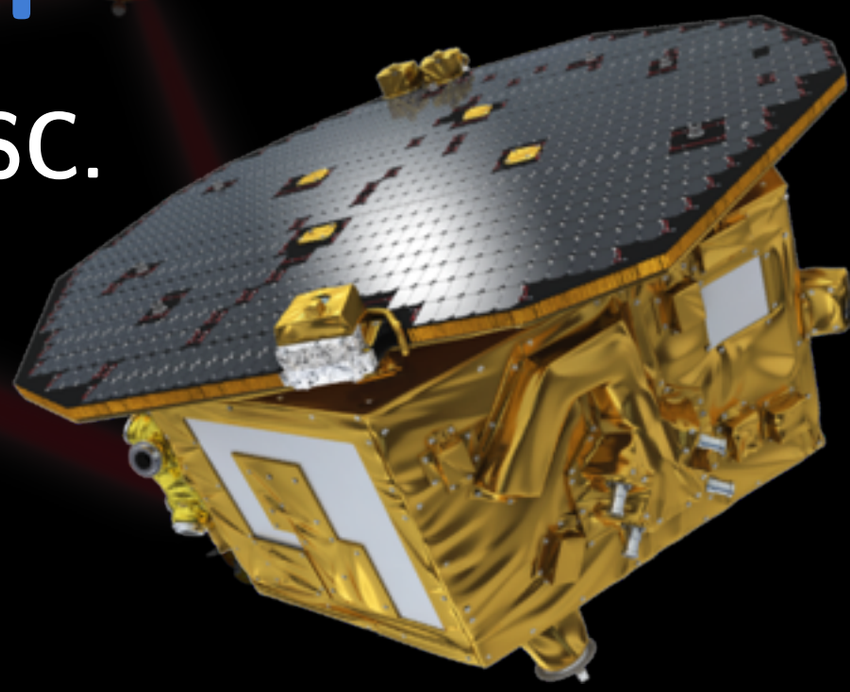
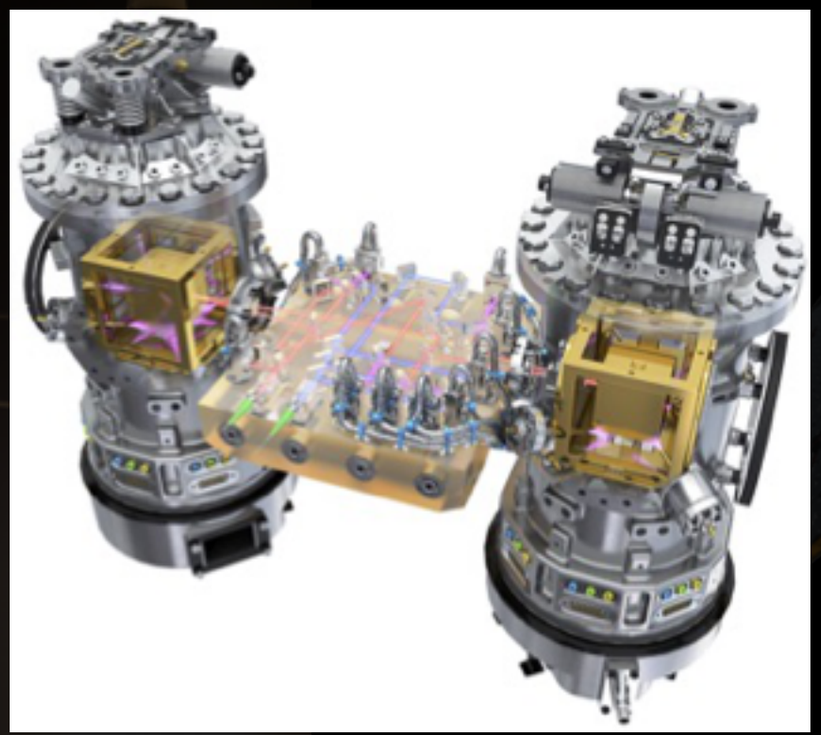
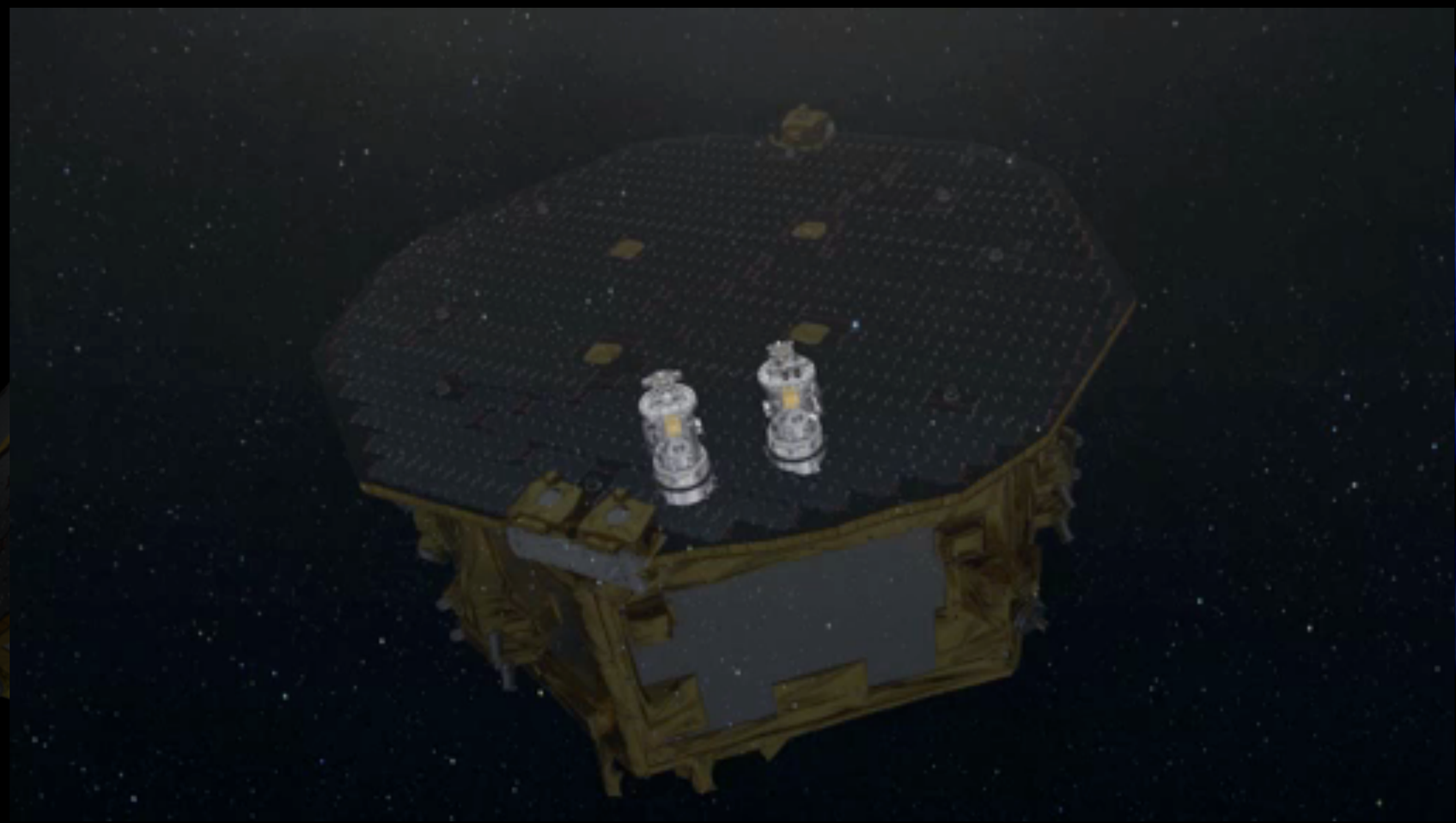
LISAPathfinder

- 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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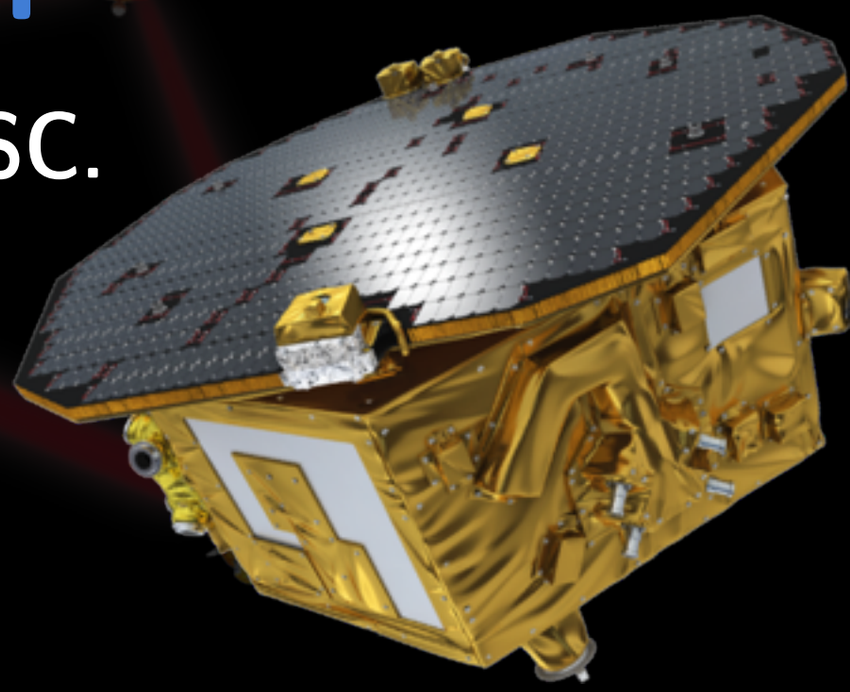
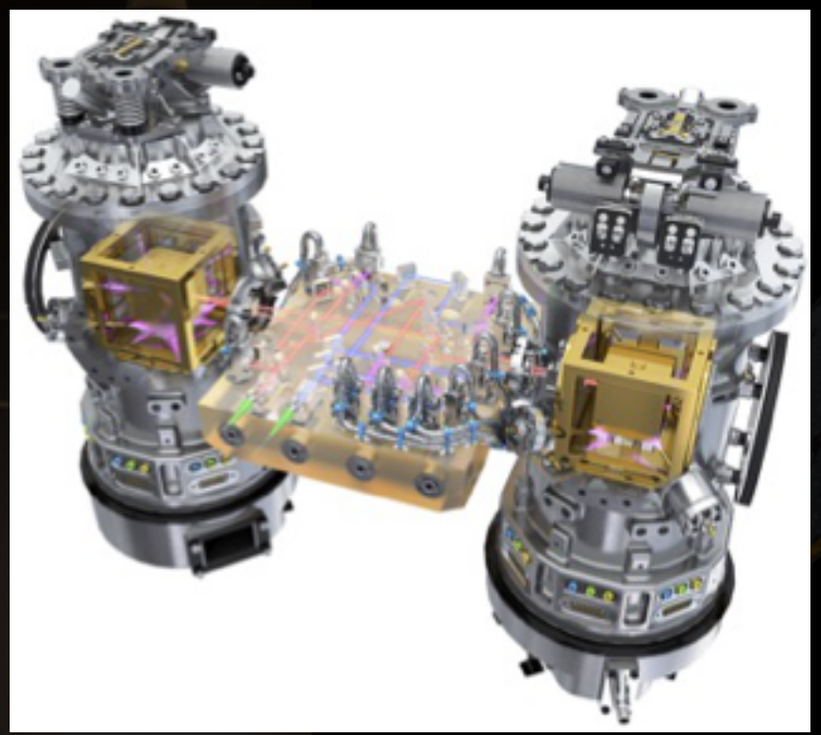
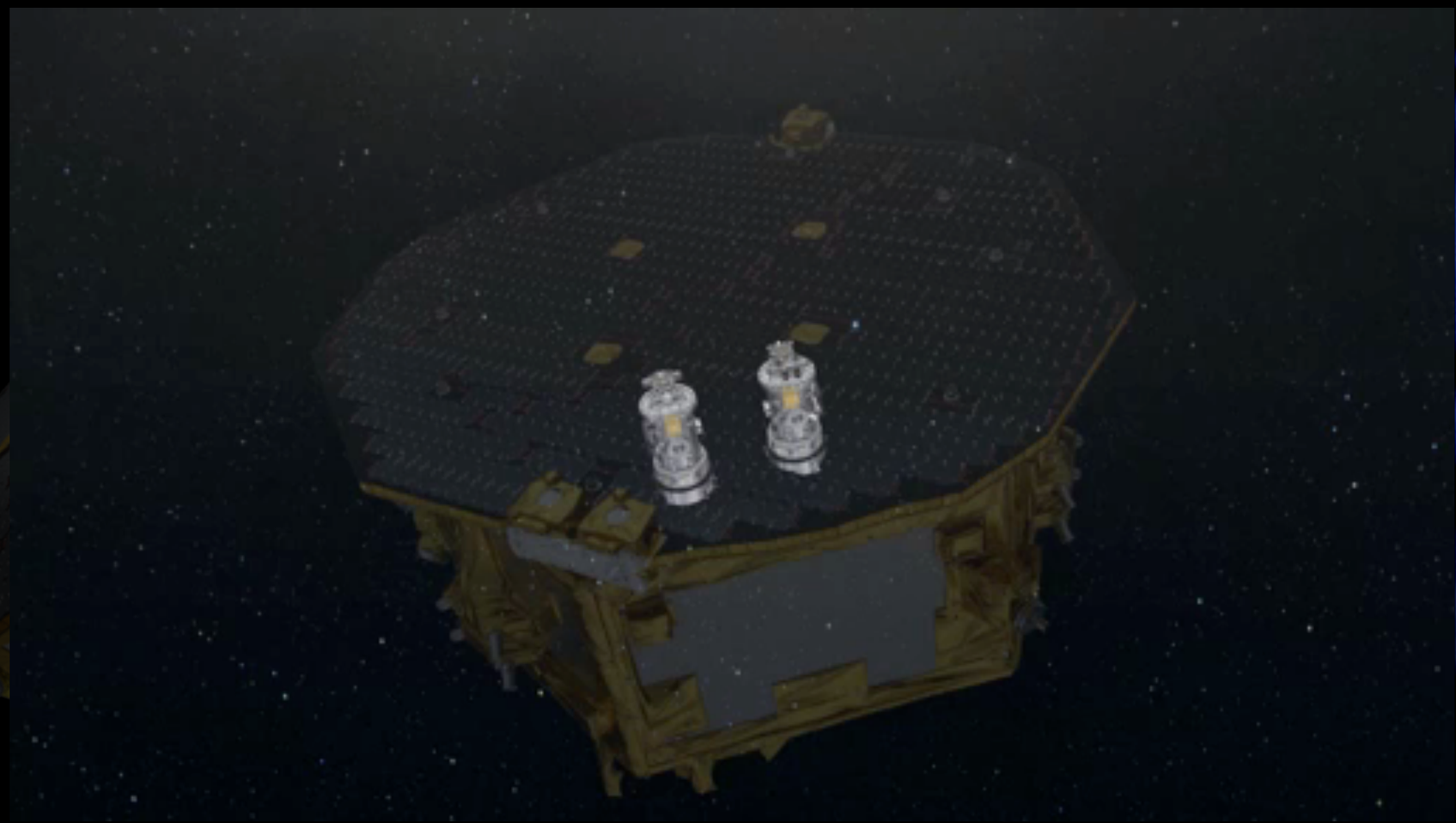
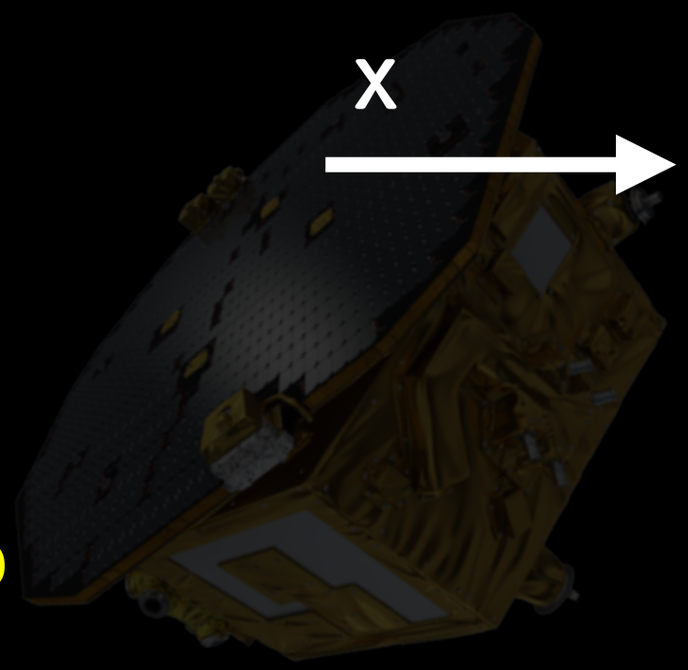


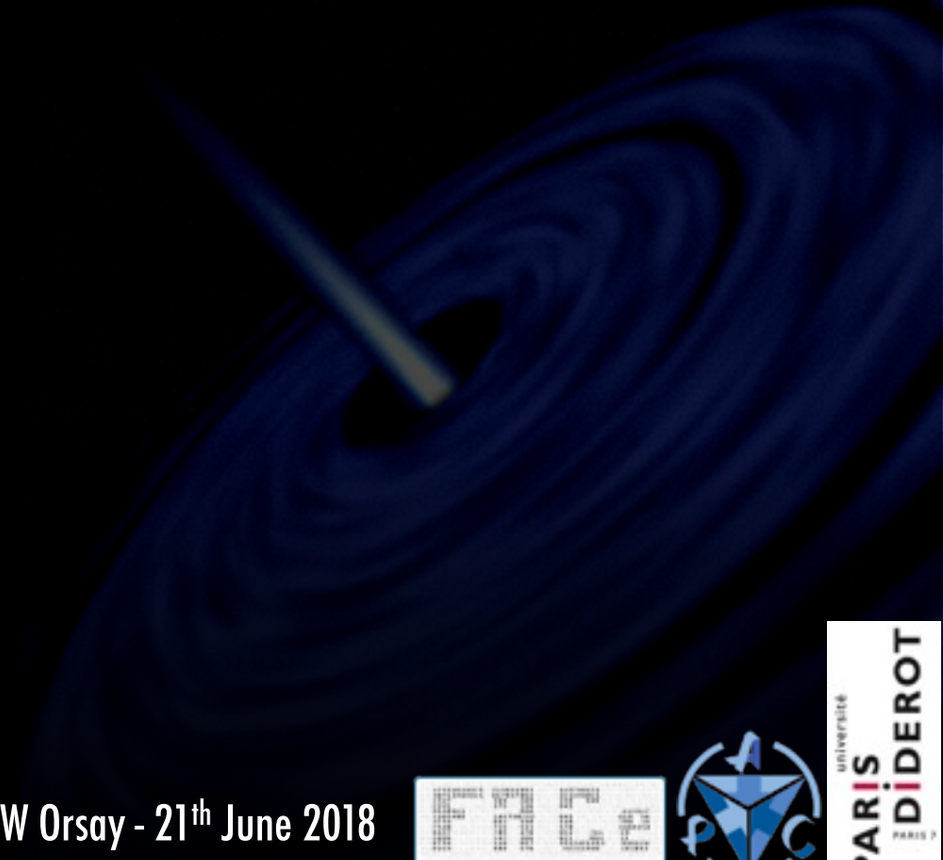




The measurement - deltaG

TMI





by Joseph Martino

The measurement - deltaG

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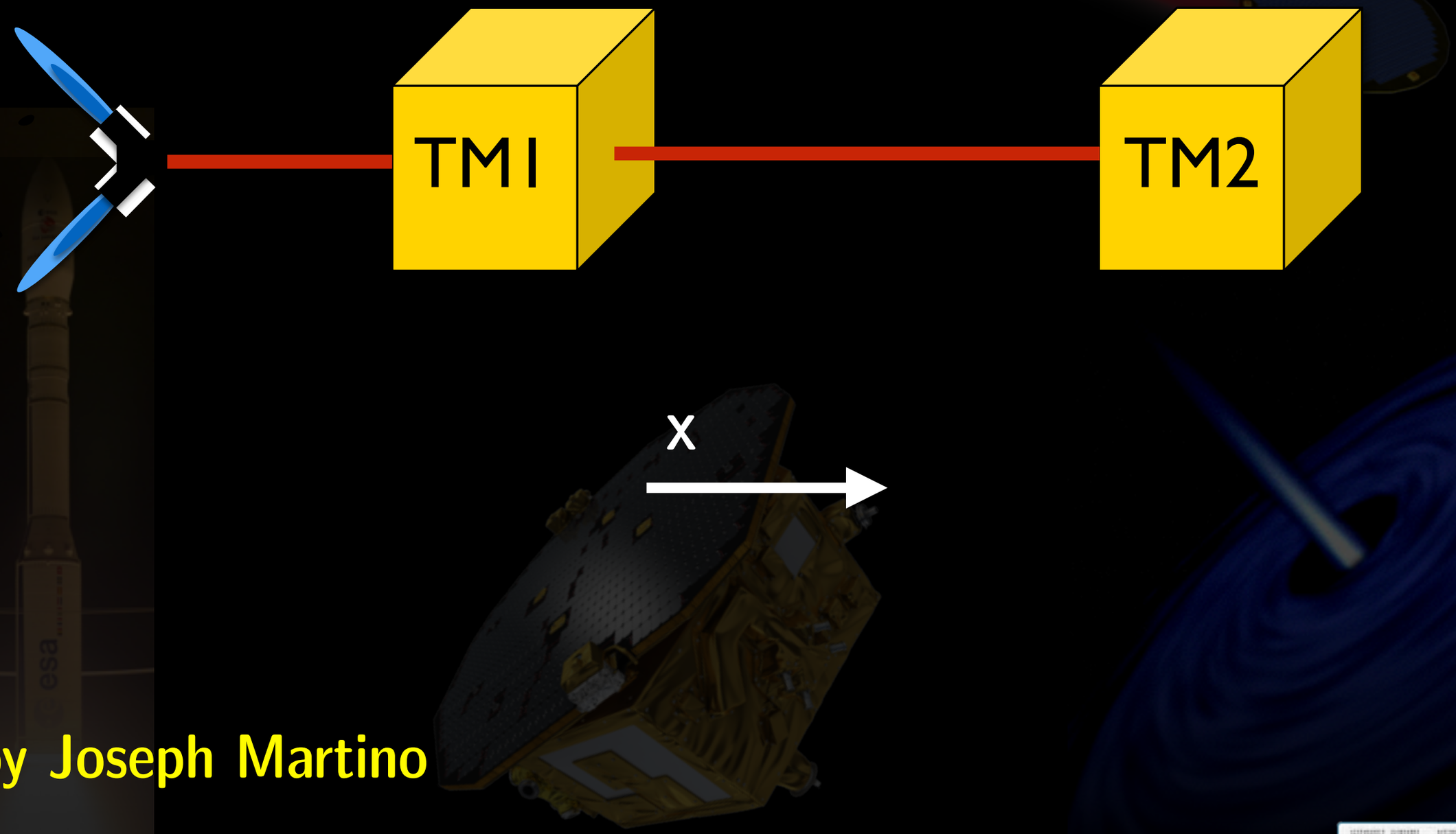
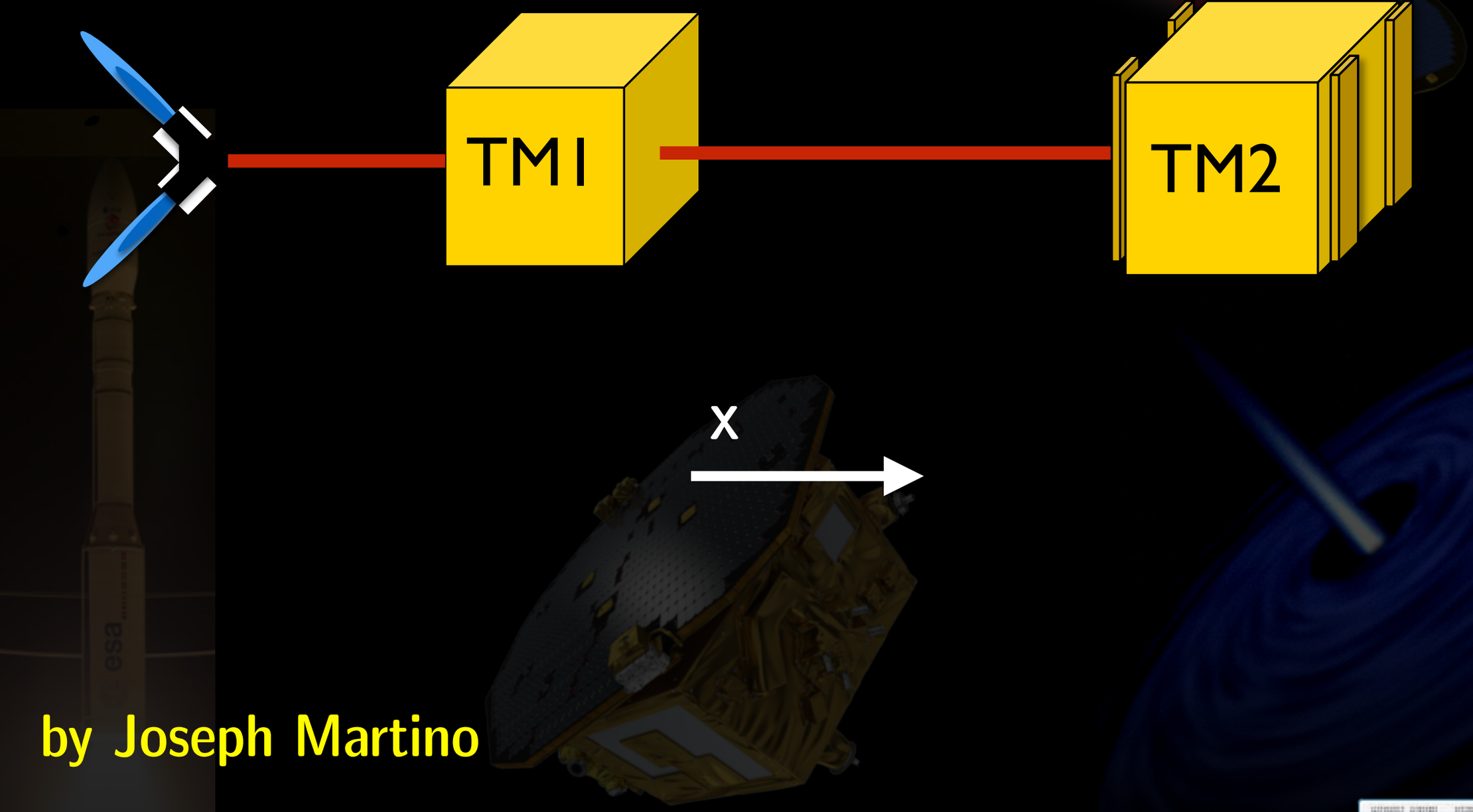


by Joseph Martino

The measurement - deltaG

Suspension (f<1mHz)

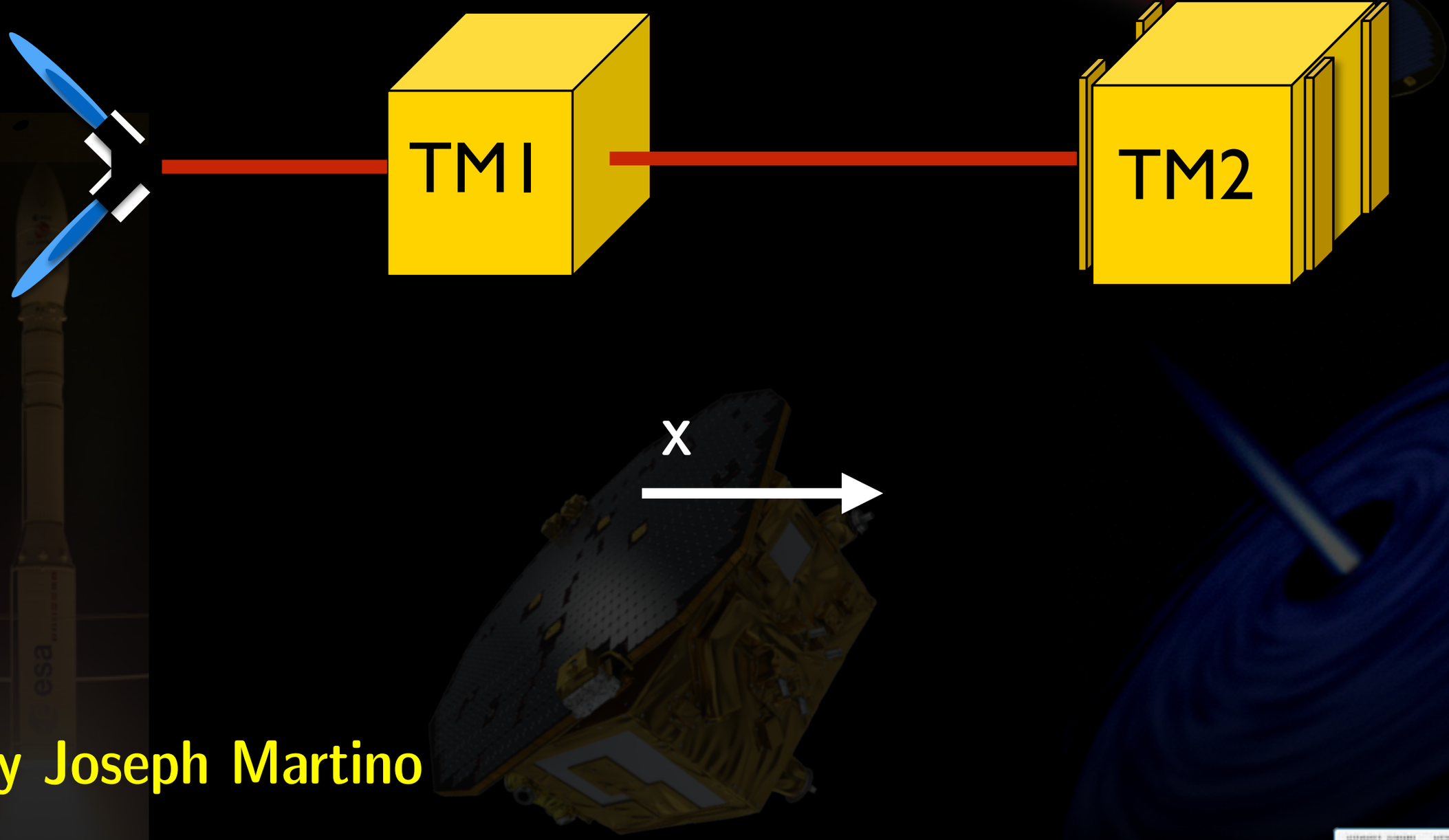


by Joseph Martino

The measurement - deltaG

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

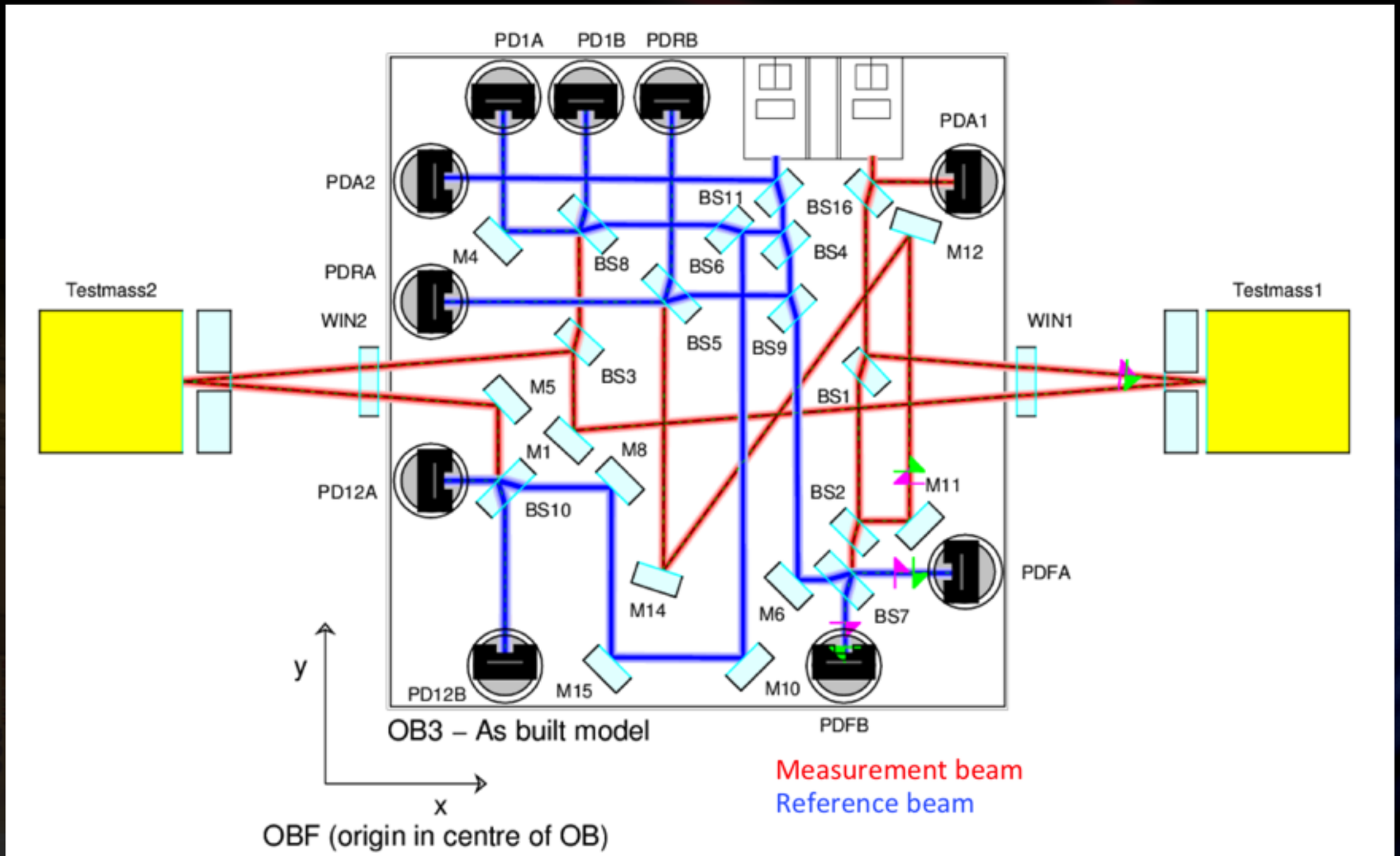
Suspension (f<1mHz)



by Joseph Martino

Optical bench

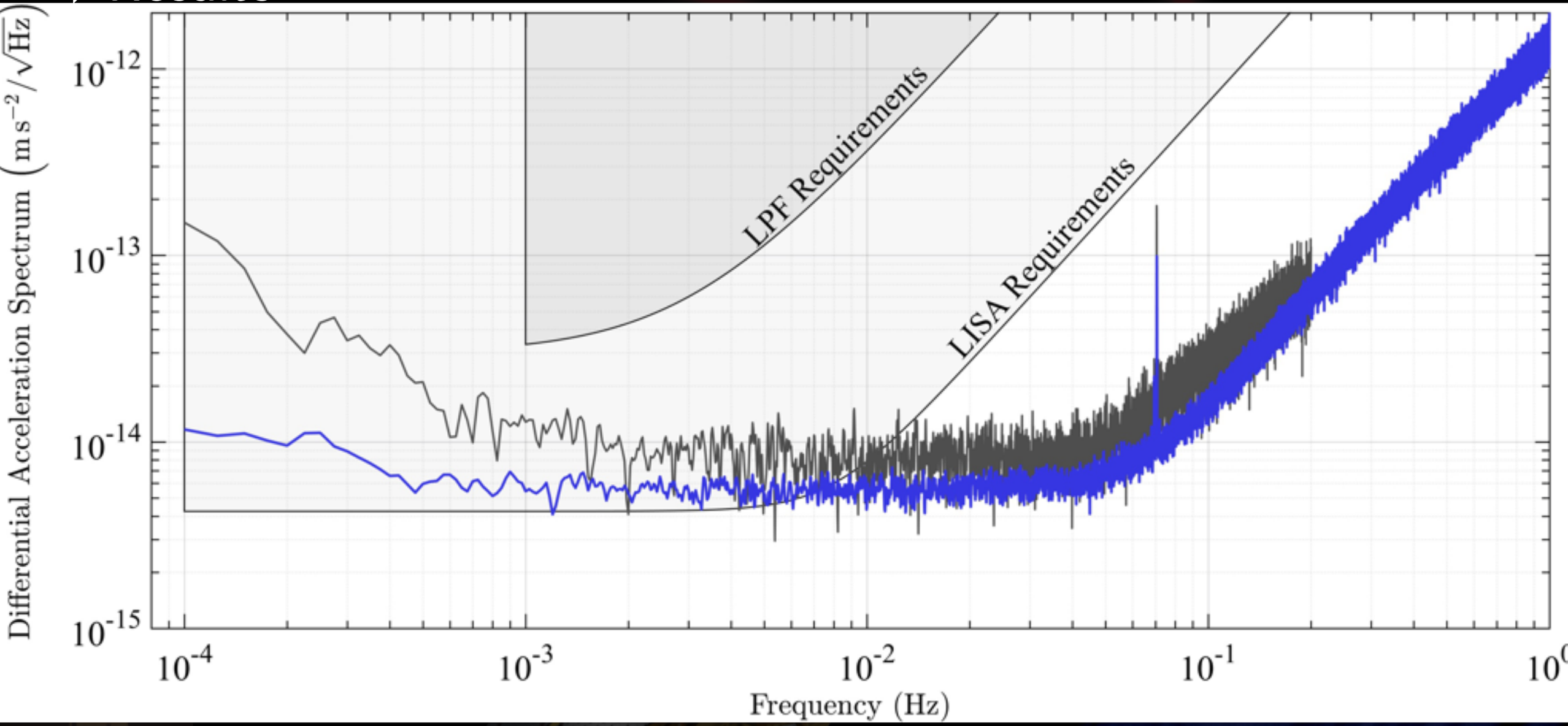
deltaG = d^2(o12)/dt^2 - Stiff * o12 - Gain * Fx2



First results

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

- Results



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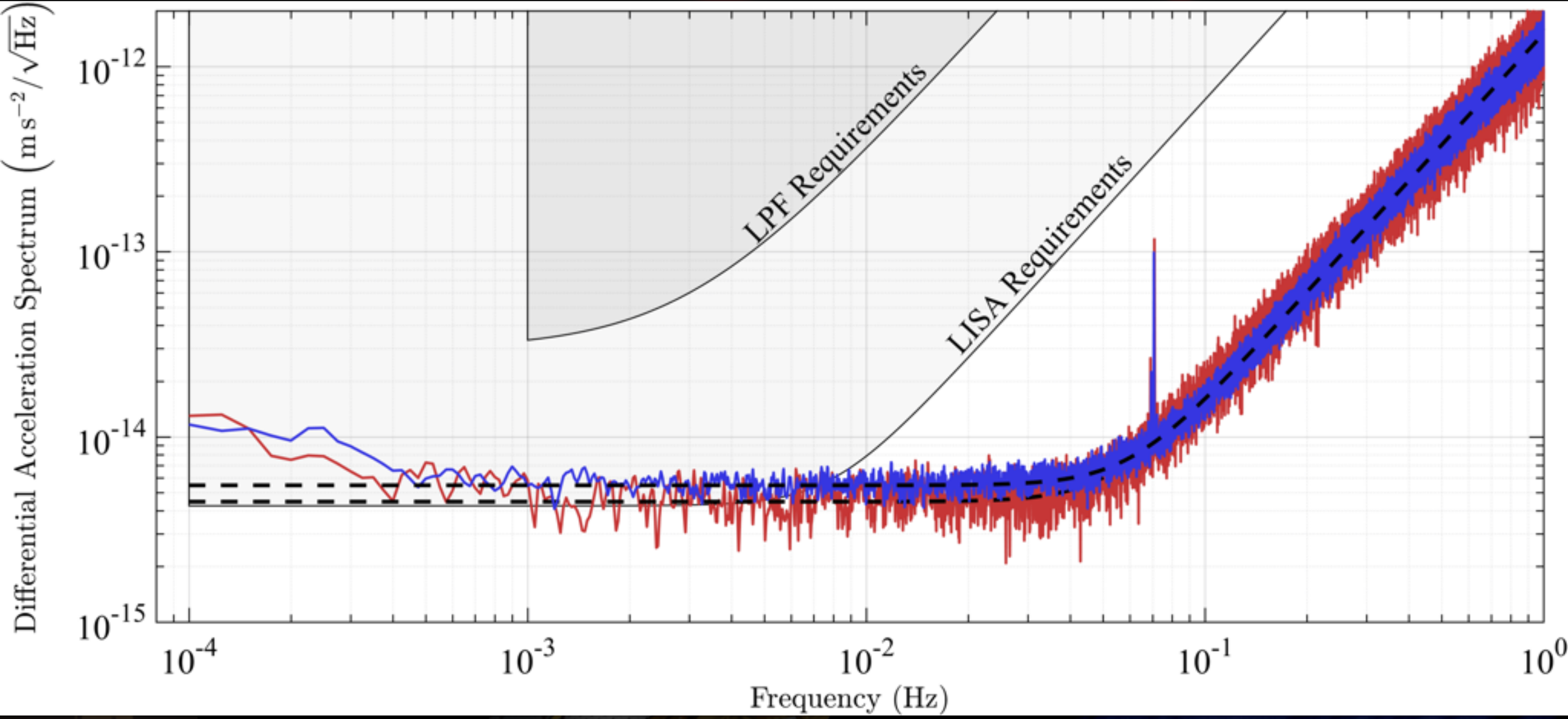
M. Armano et al. PRL 116, 231101 (2016)



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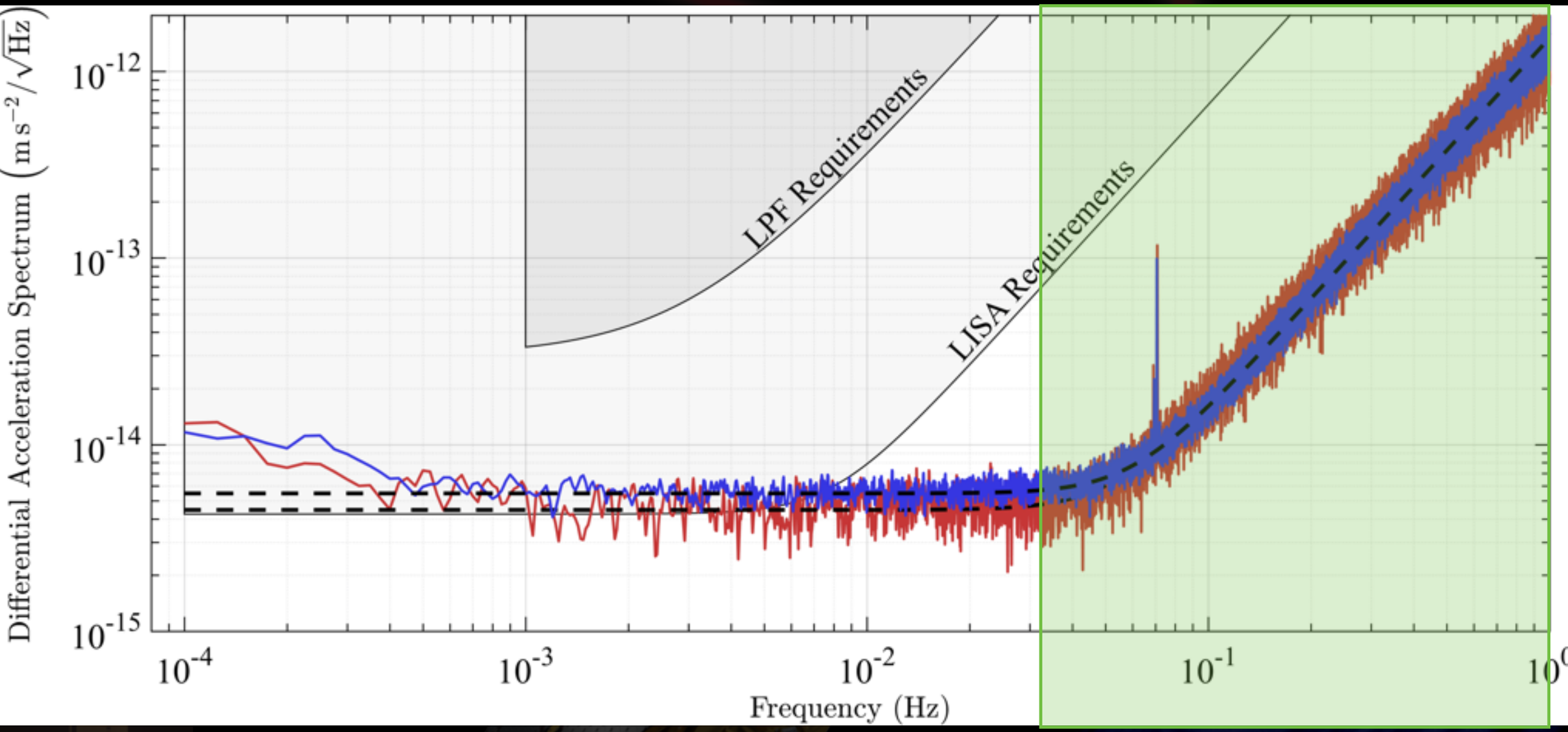
M. Armano et al. PRL 116, 231101 (2016)

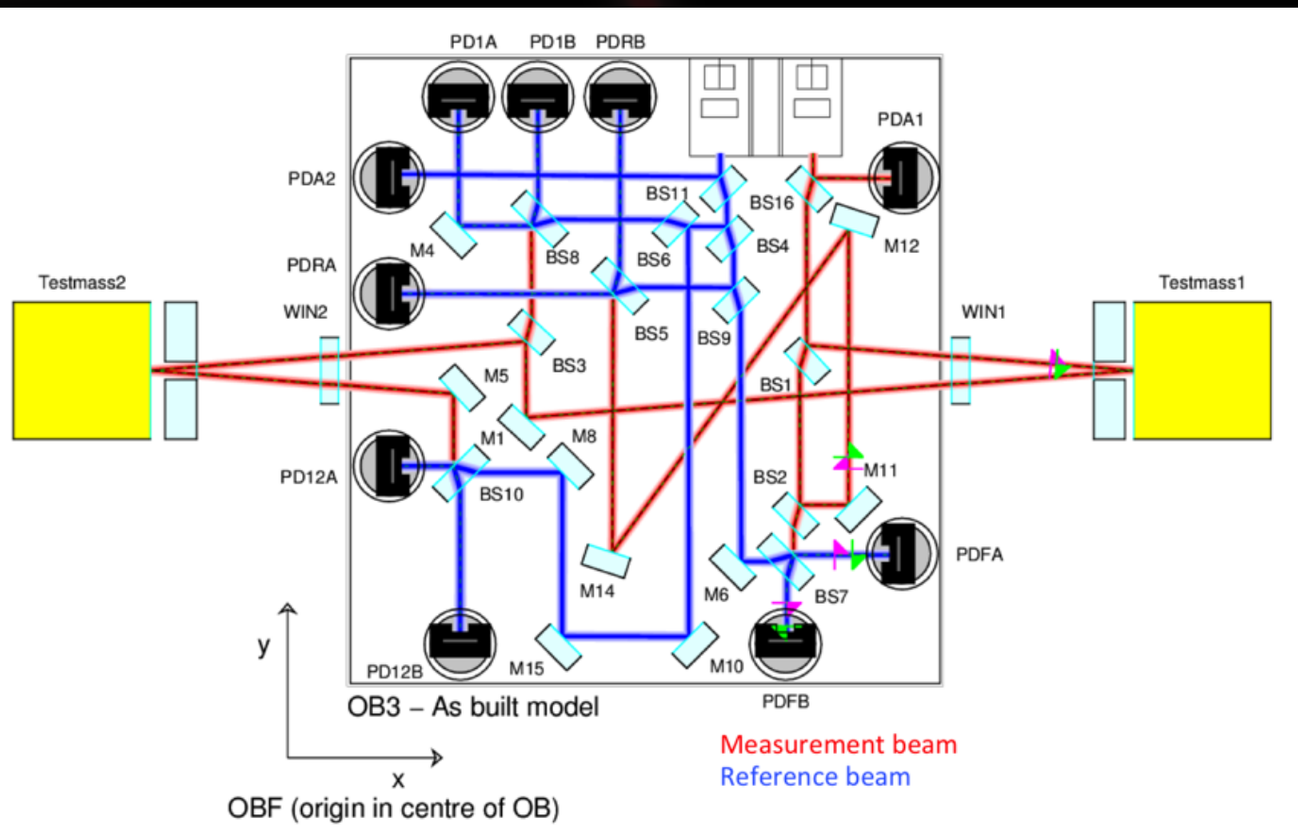


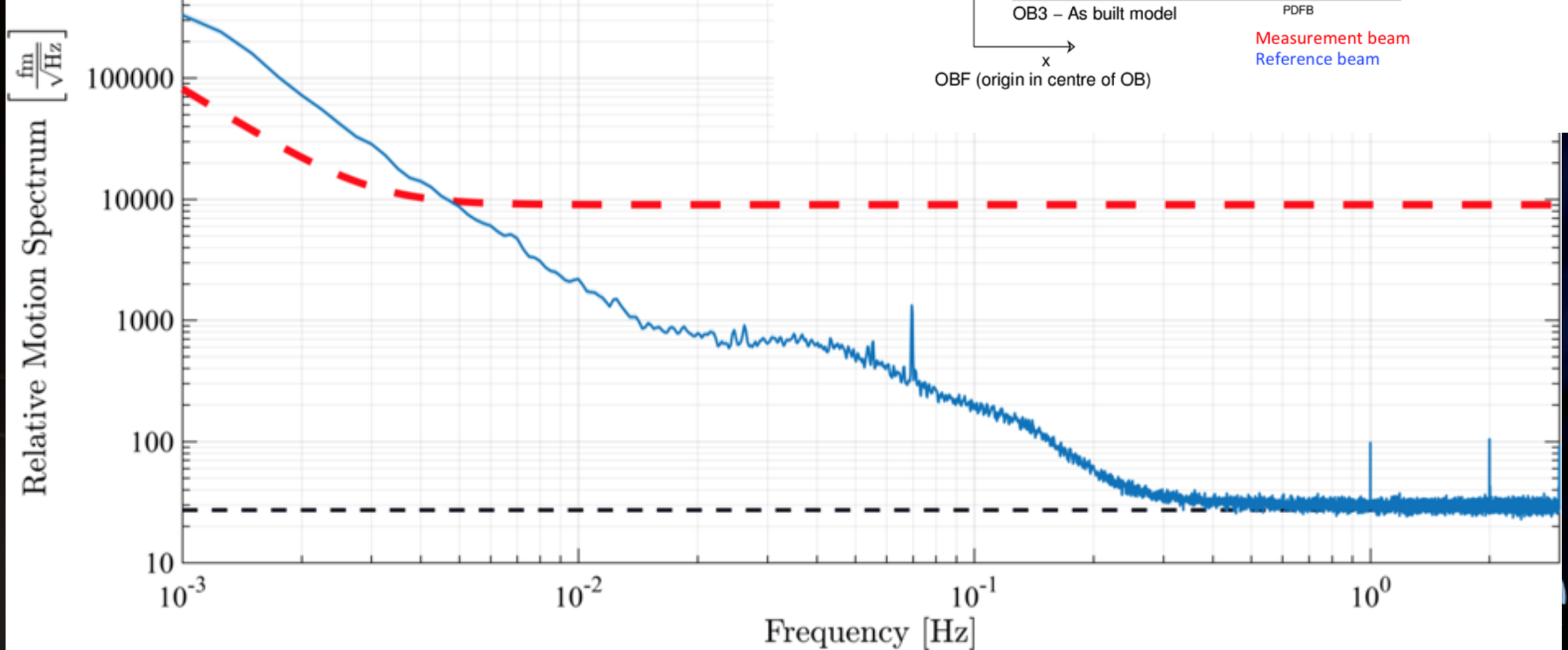
Interferometric noise
Not real test-mass motion

High frequency limit

- Optical measurement system:
  - Interferometric precision:

    30 fm.Hz$^{-1/2}$
  - Orientation of test-masses





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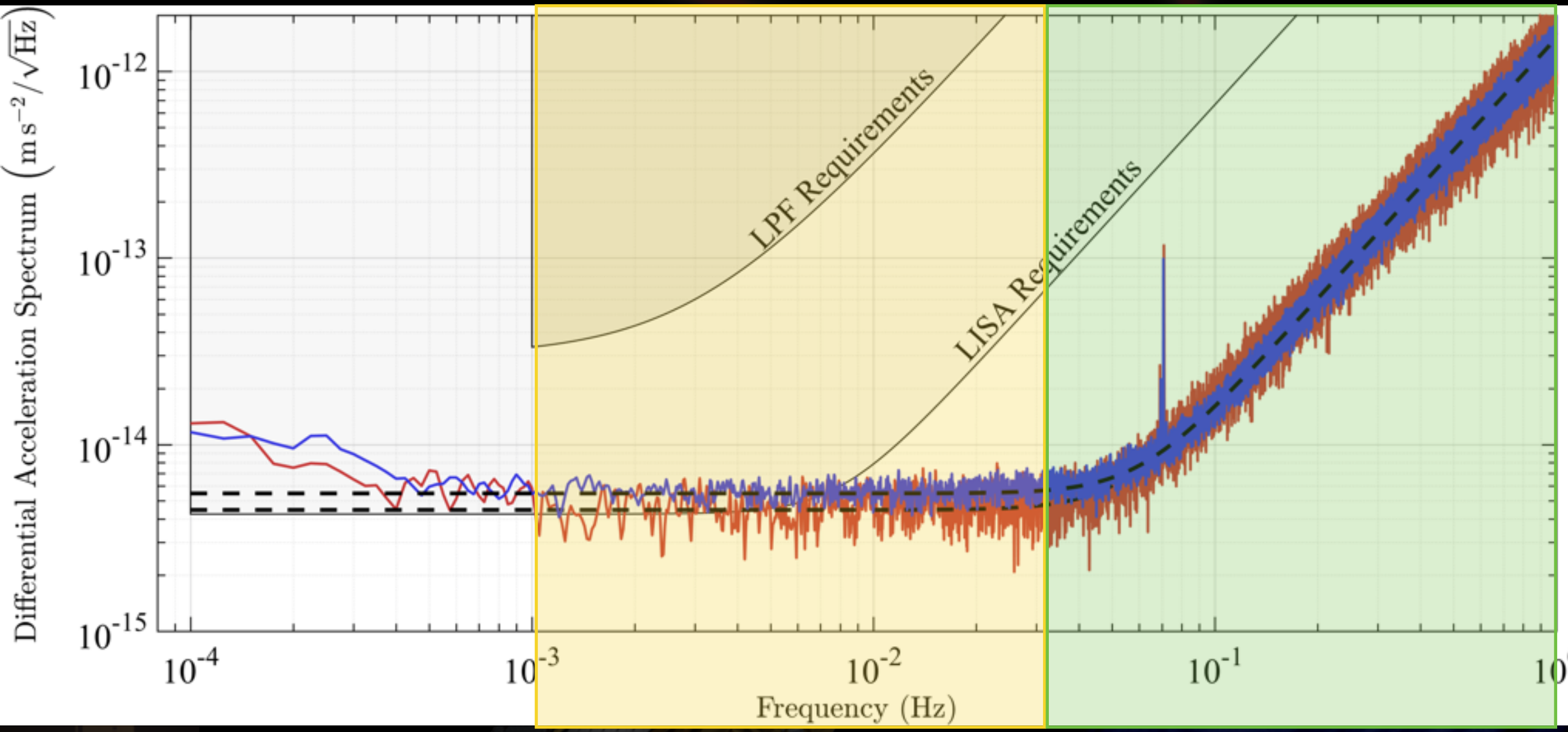
M. Armano et al. PRL 116, 231101 (2016)

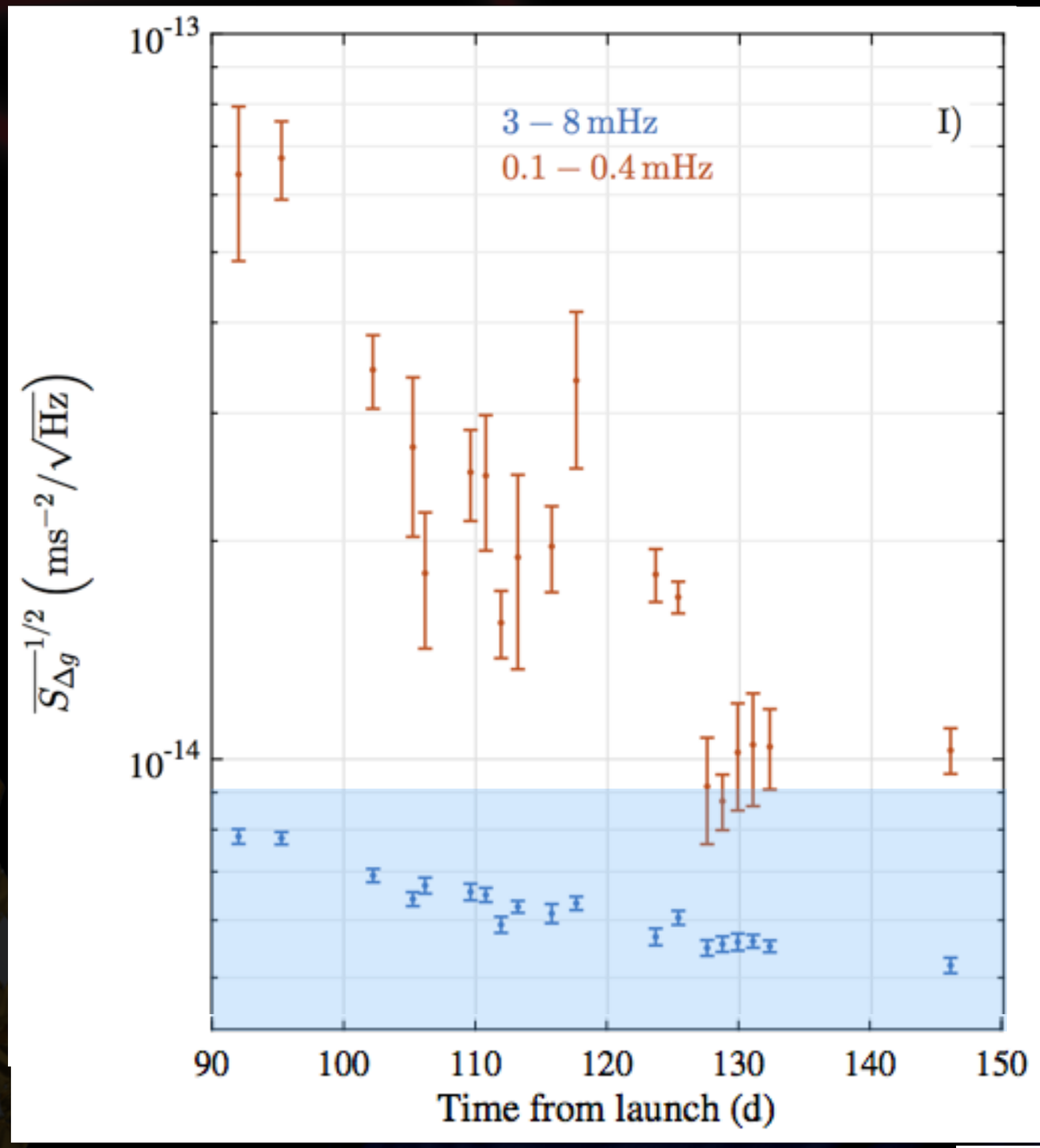


Brownian noise
Molecules within the noise
hit test-masses

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 ?



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First results

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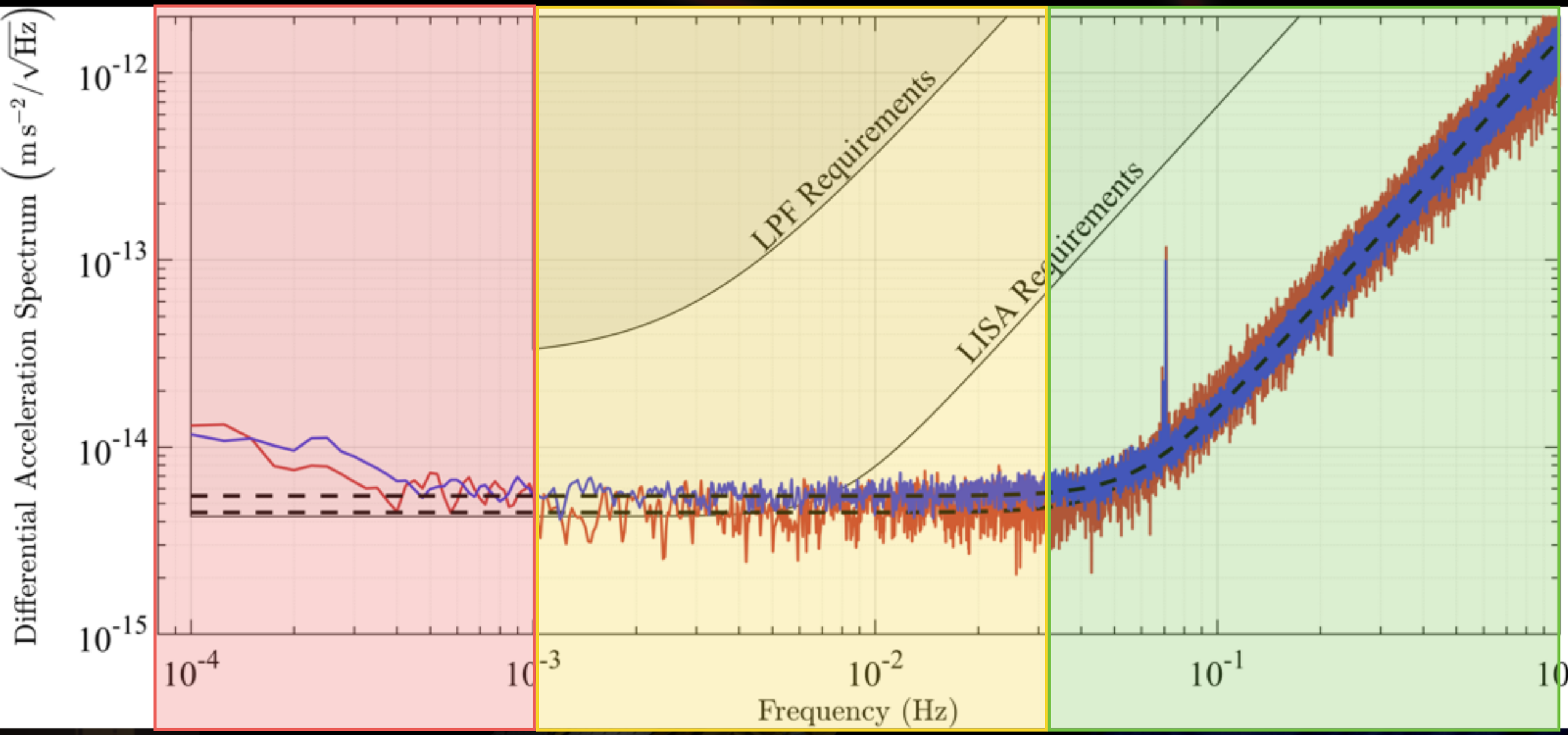


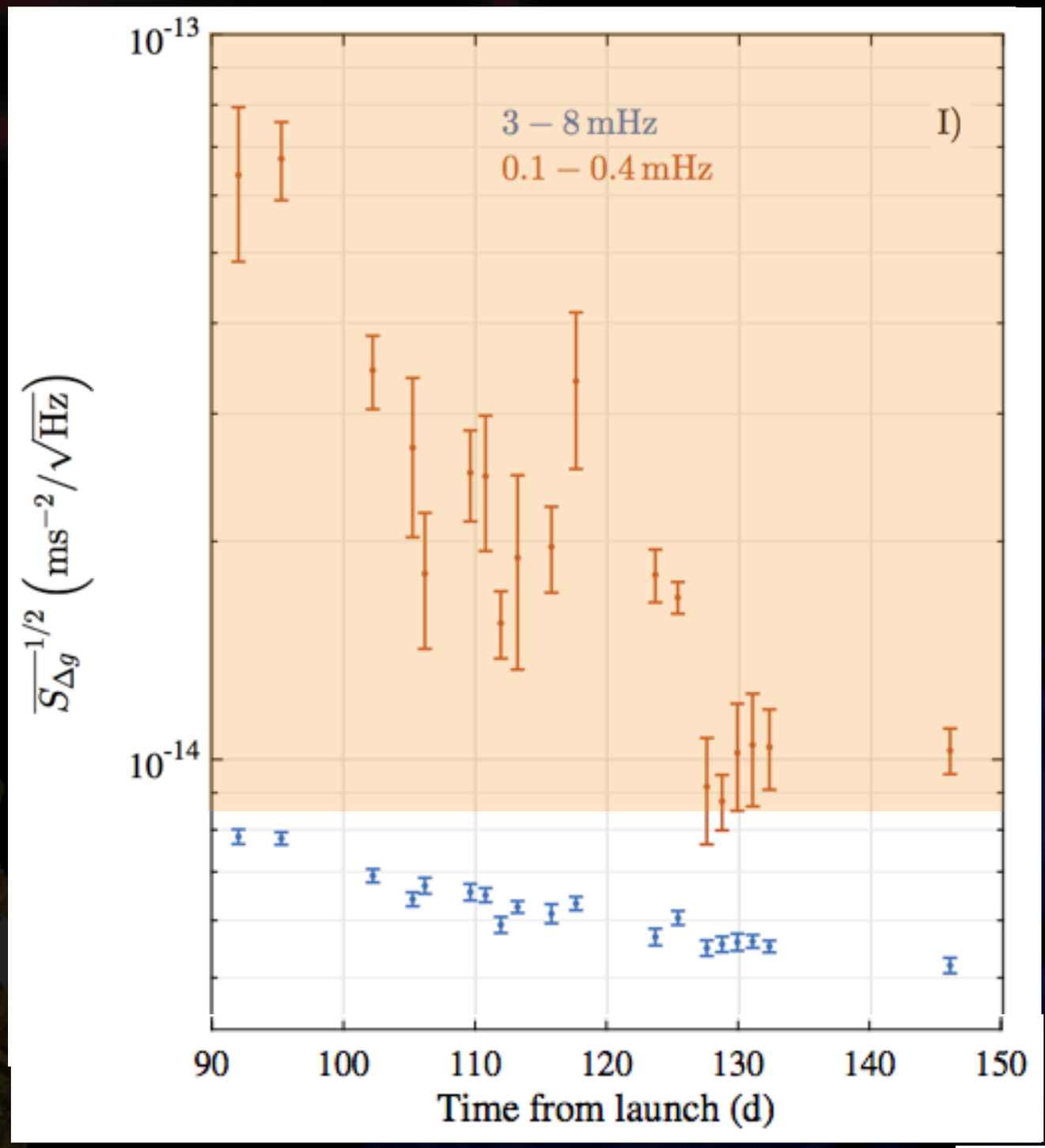
Low frequency noise
Investigation in progress
...

Brownian noise
Molecules within the noise
hit test-masses

Interferometric noise
Not real test-mass motion

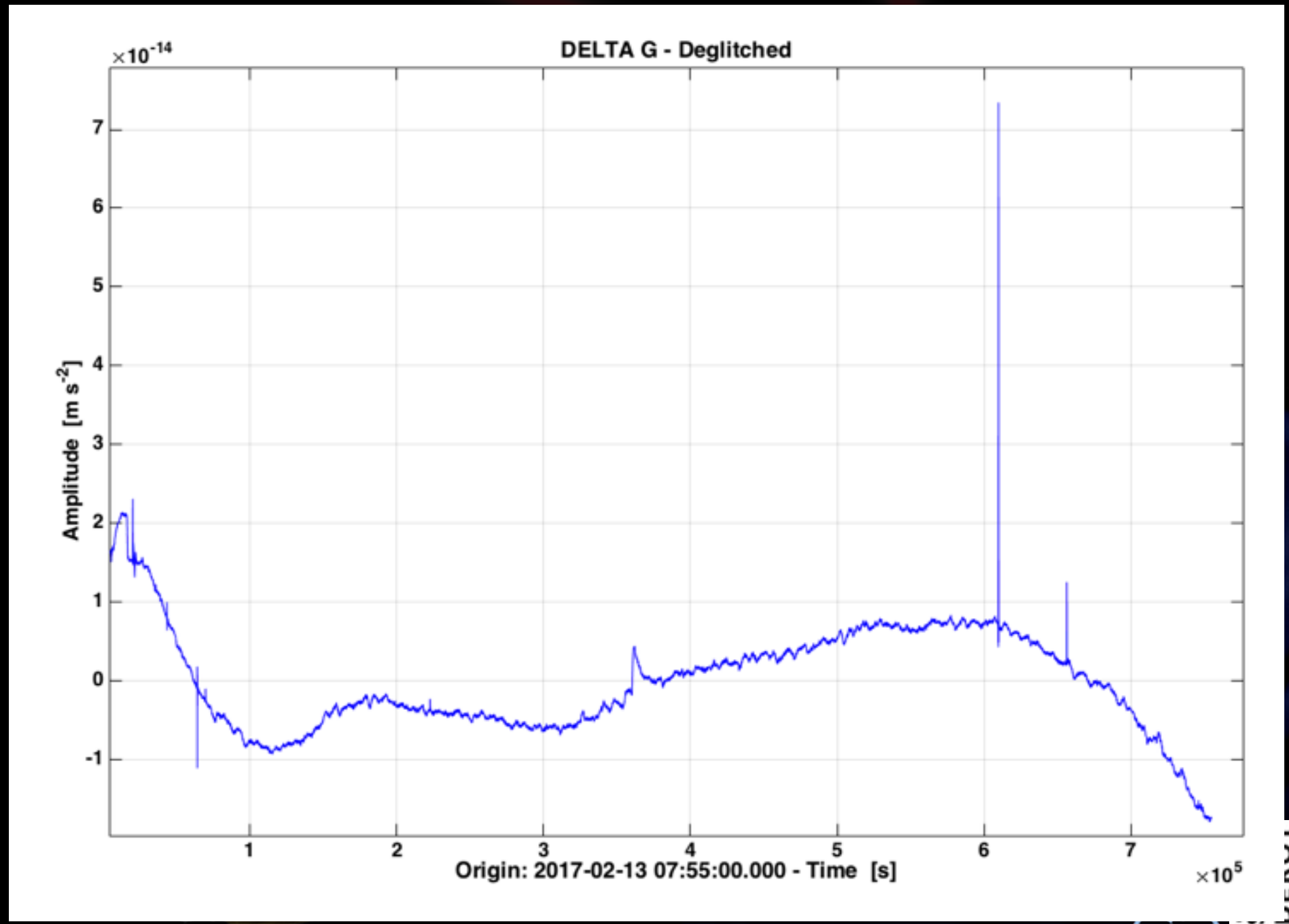
Low-frequency limit

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



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

de-glitching



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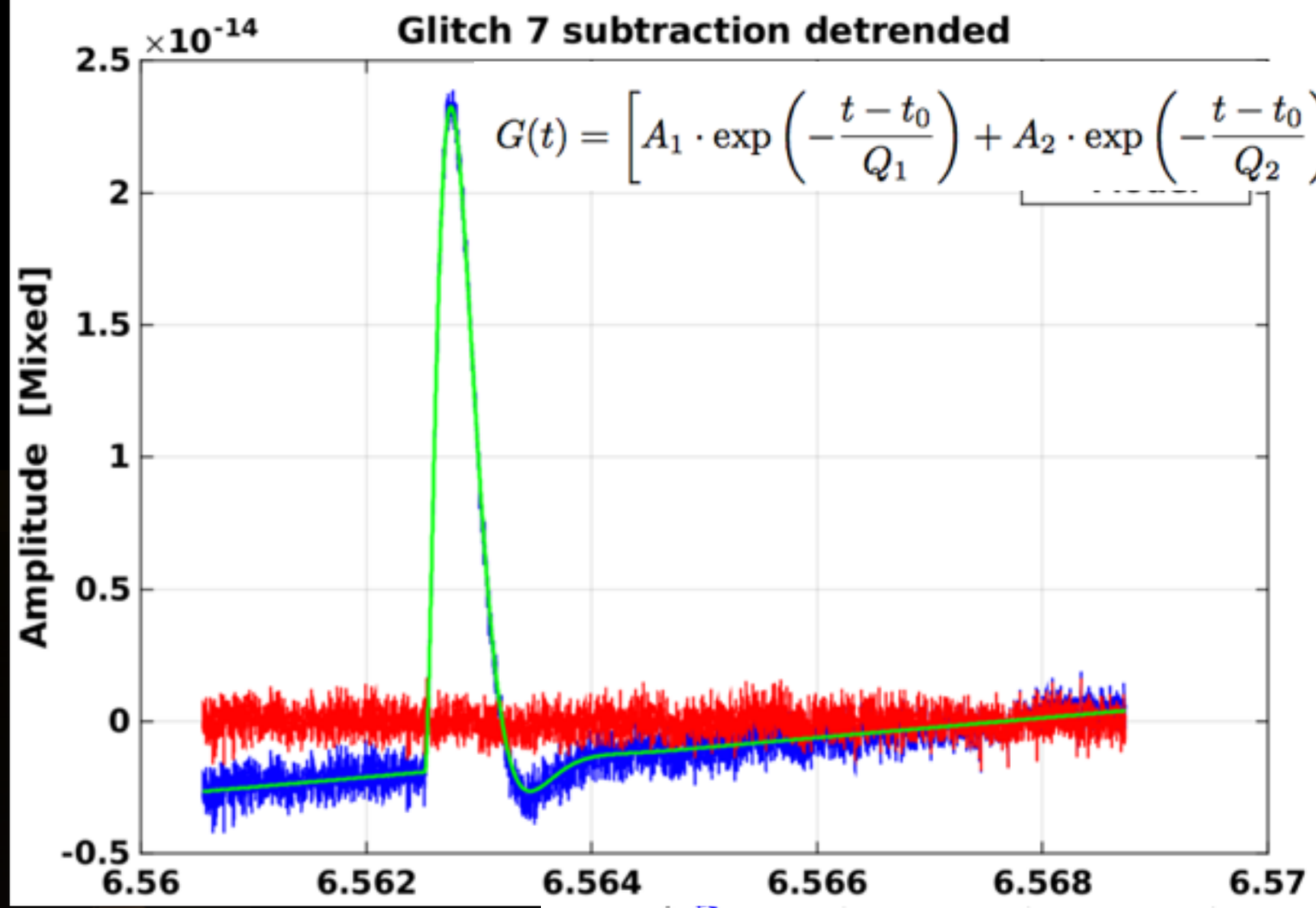
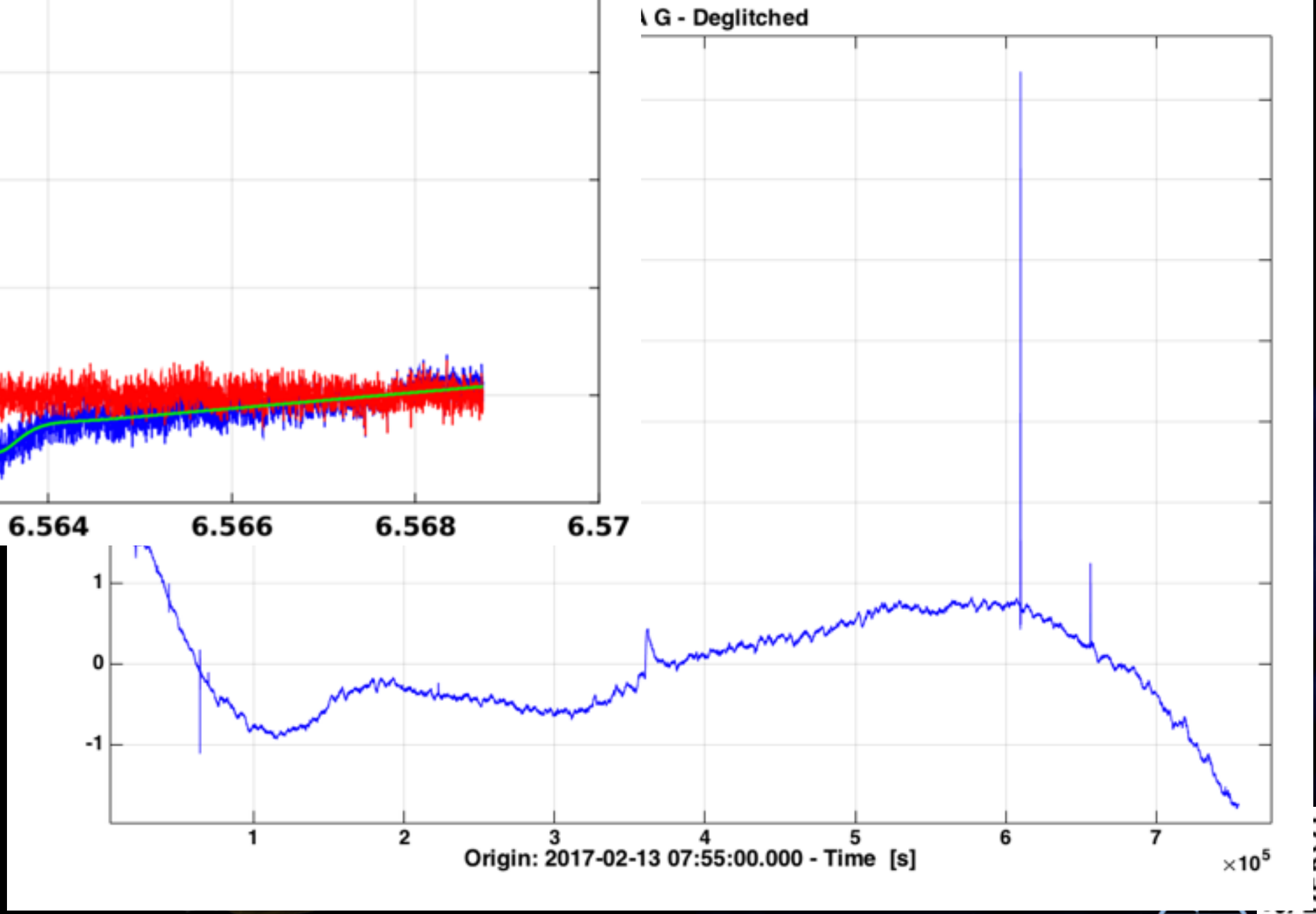
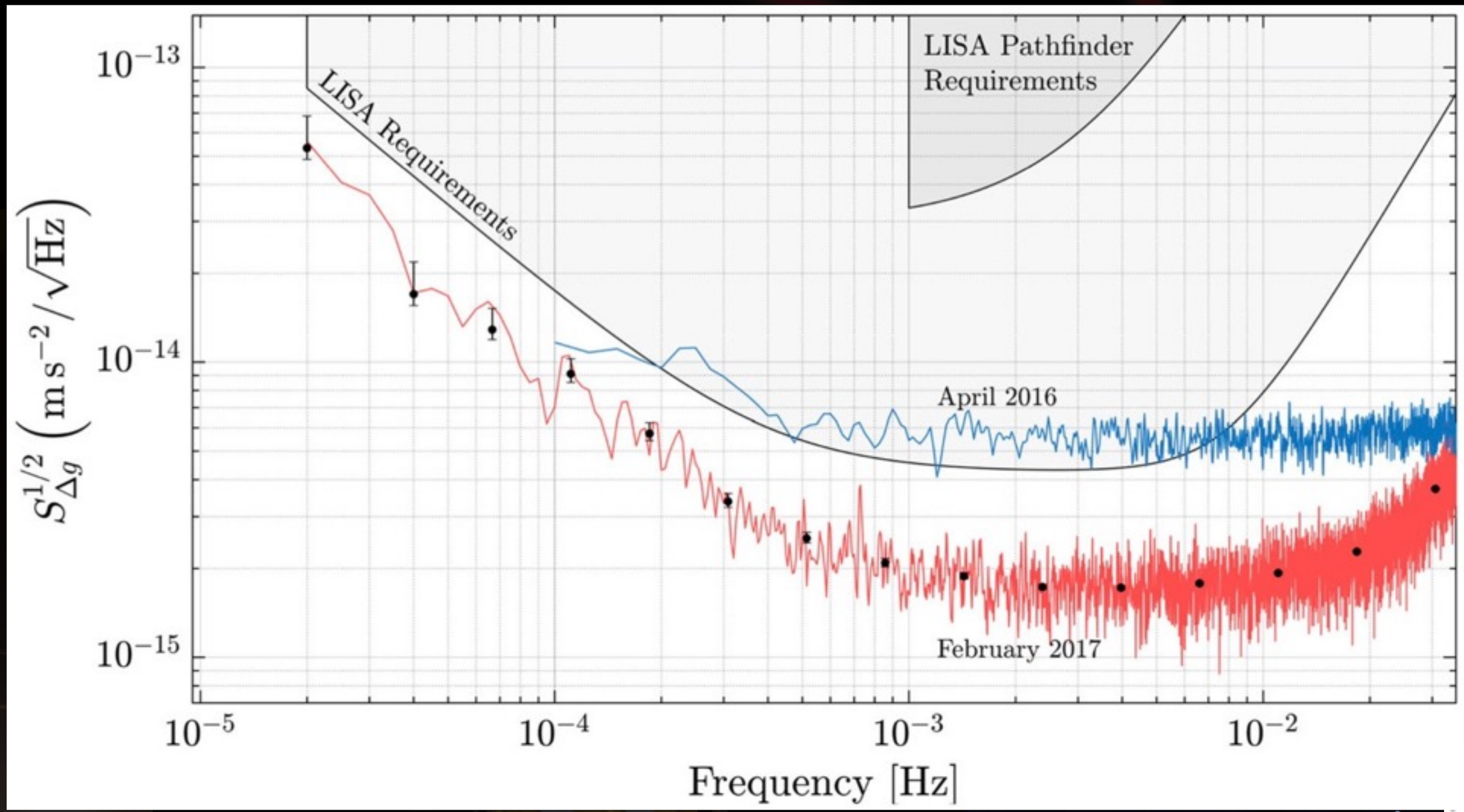


$$G(t) = \left[A_1 \cdot \exp\left(-\frac{t-t_0}{Q_1}\right) + A_2 \cdot \exp\left(-\frac{t-t_0}{Q_2}\right) + A_3 \cdot \exp\left(-\frac{t-t_0}{Q_3}\right)\right] * \left[1 - \exp\left(-\frac{t-t_0}{Q_0}\right)\right]^{\alpha}$$



LISAPAthfinder final main results

M. Armano et al. PRL 120, 061101 (2018)



Outline

- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISAPathfinder
- LISA status and organization
- LISA scientific performances
- LISAFrance
  - Distributed Data Processing Center
  - AIV(T)
- Conclusion and perspectives

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

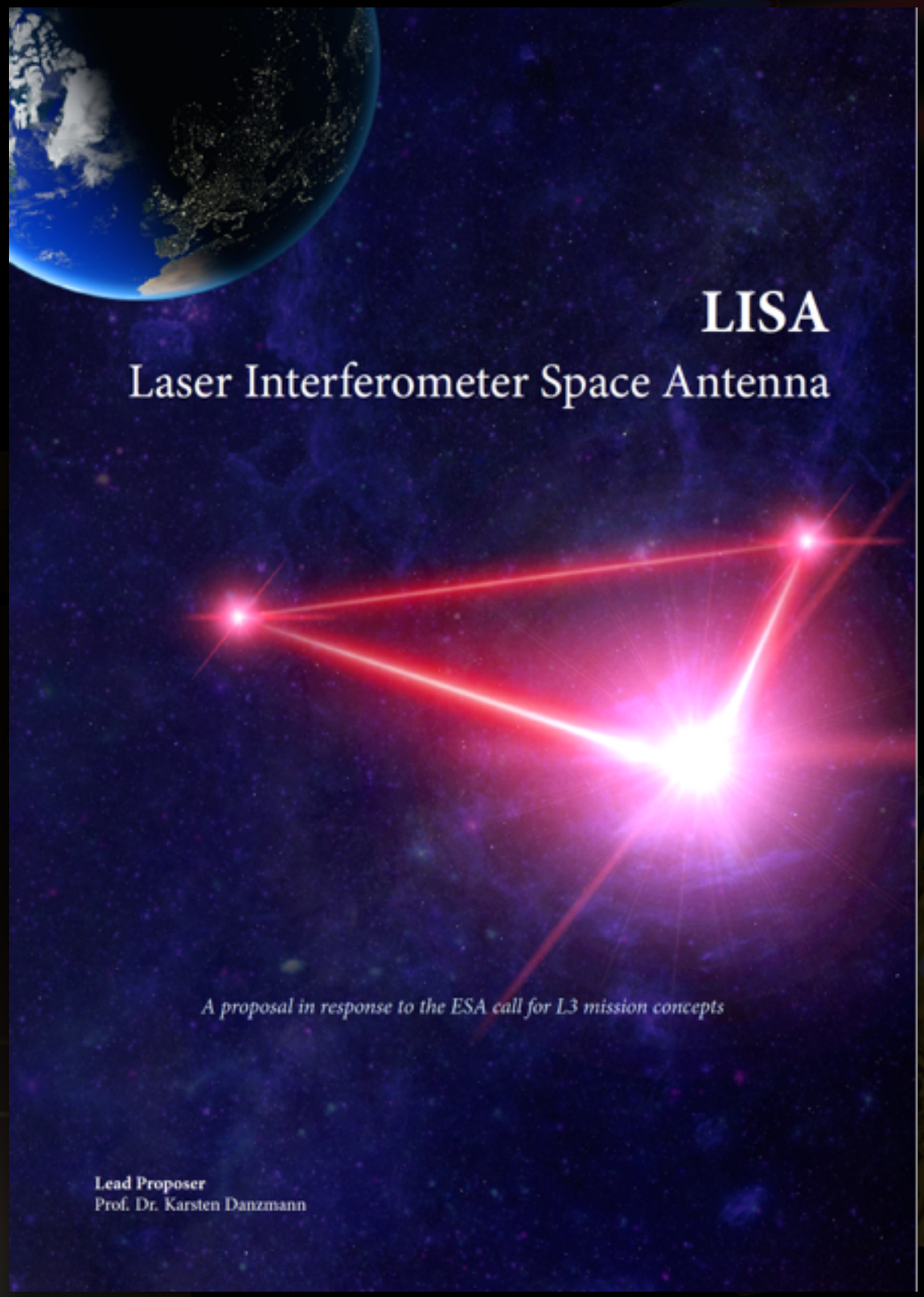
LISA at ESA

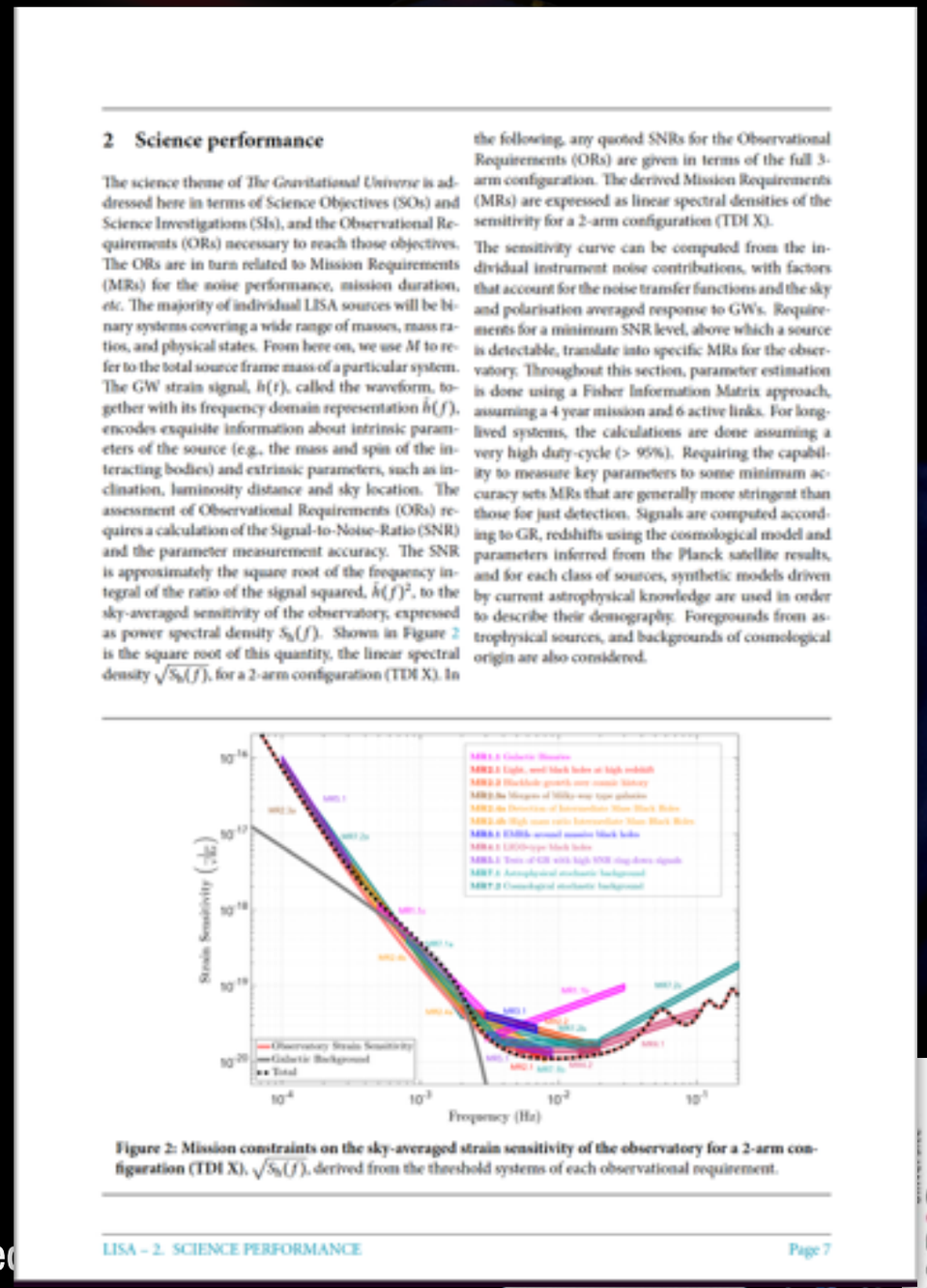
- 25/10/2016 : Call for mission
- 13/01/2017 : submission of «LISA proposal» (LISA consortium)
- 8/3/2017 : Phase 0 mission (CDF 8/3/17 → 5/5/17)
- 20/06/2017 : LISA mission approved by SPC
- 8/3/2017 : Phase 0 payload (CDF June → November 2017)
- 2018→2020 : competitive phase A: 2 companies compete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

→ GW observations !

The LISA Proposal

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





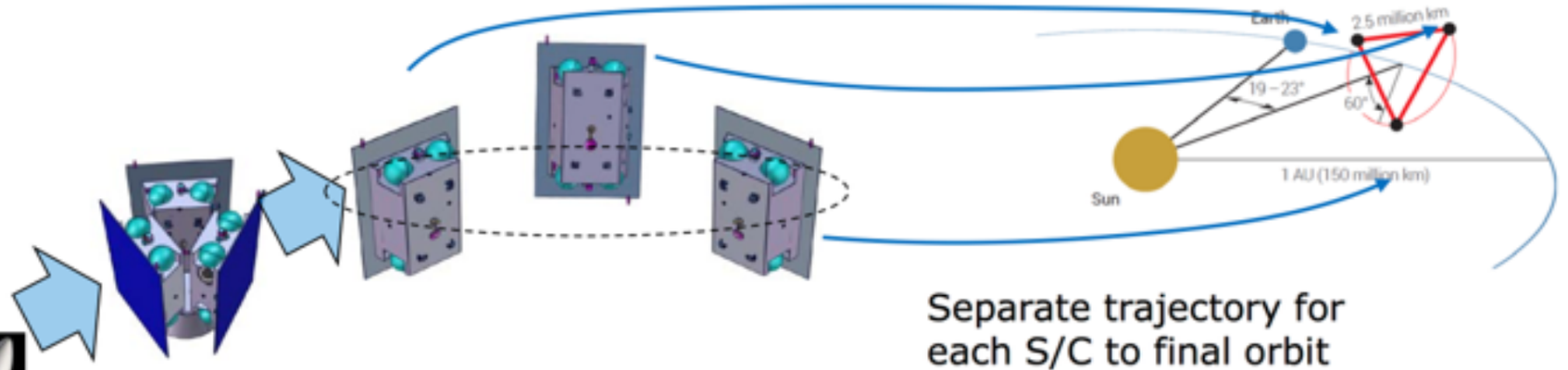
2 Science performance

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.

ESA Phase 0 mission

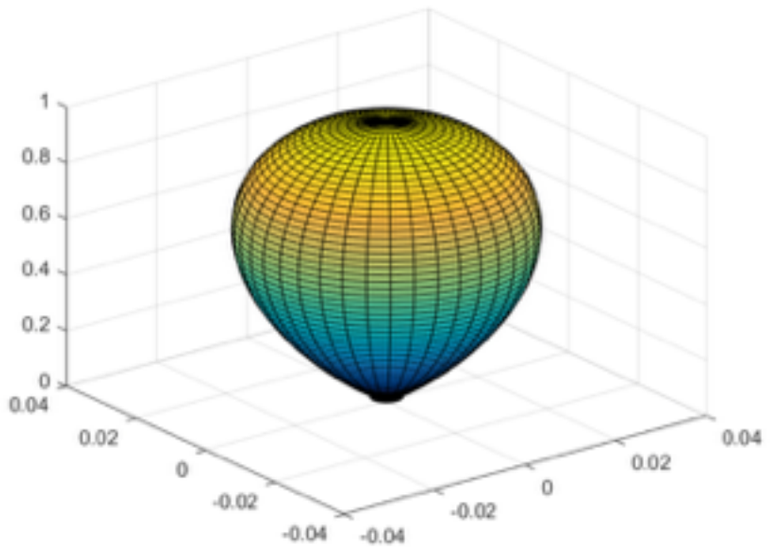


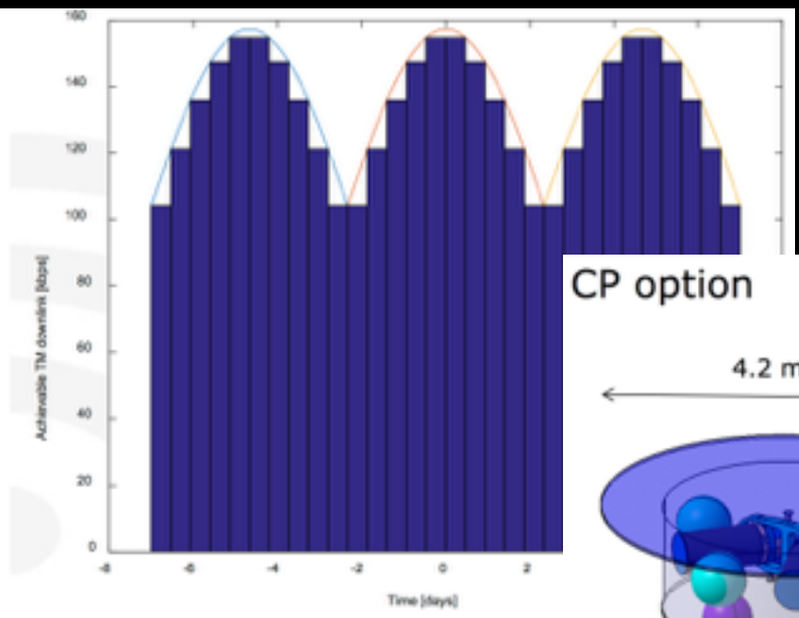
Separate trajectory for each S/C to final orbit

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**



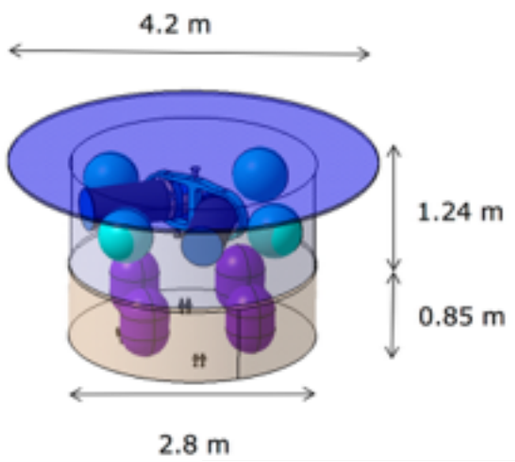


Dish
Average rate: 132.7 kbps
Max rate: 154.8 kbps
Min rate: 104.2 kbps
Margin: 4.1 dB (>3 dB)

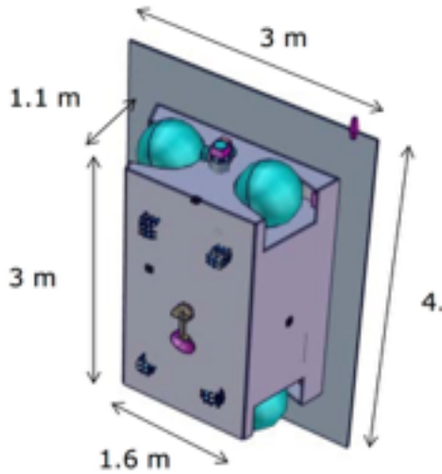
MGA (CP option)
Max rate: 13 kbps
Margin: 4.0 dB (>3 dB)

LGA
Max rate: 52 bps
Margin: 3.1 dB

CP option



EP and EP+ option



LISA Consortium

esa

NASA

Instrument Board
Instrument PI (D), National PIs

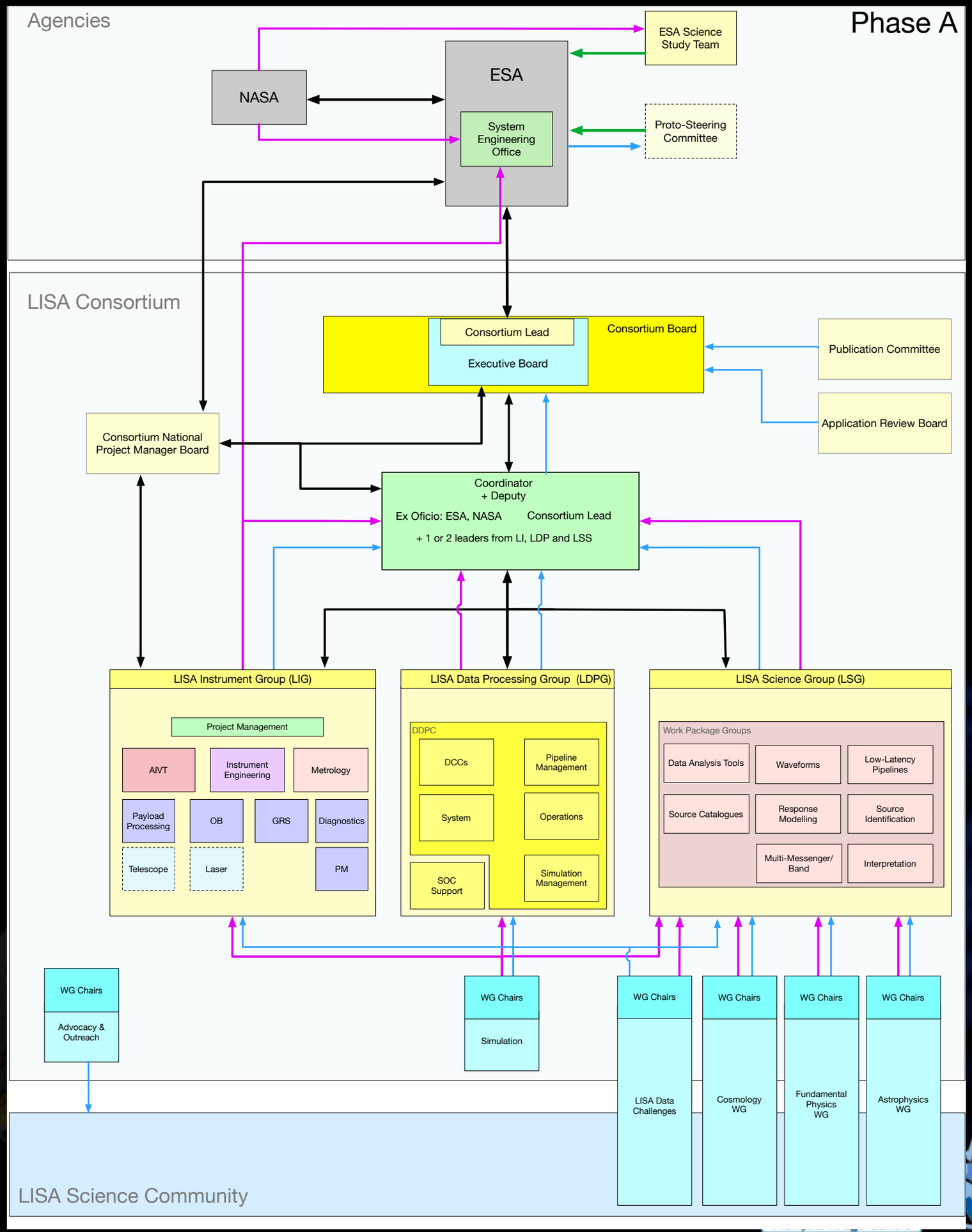
- Management
  - System engineering
    - Quality and product assurance
      - Phasemeter
- **System engineering support**
  - **Instrument integration validation and tests**
    - **Data Processing Center**
- optical bench
  - Charge control
- Gravitation Reference Sensor
- GRS front end electronics
  - Caging mechanism
- Phasemeter support
- Diagnostics System

- Set for eLISA/NGO and enlarge later => reboot now (Mar 2018)
- The LISA Consortium wrote the LISA proposal (core group) submitted it to ESA
- Letter of endorsement from National Agencies to ESA

François Arago Centre

Consortium organisation

- Reboot:
  - 415 members
  - 432 associates



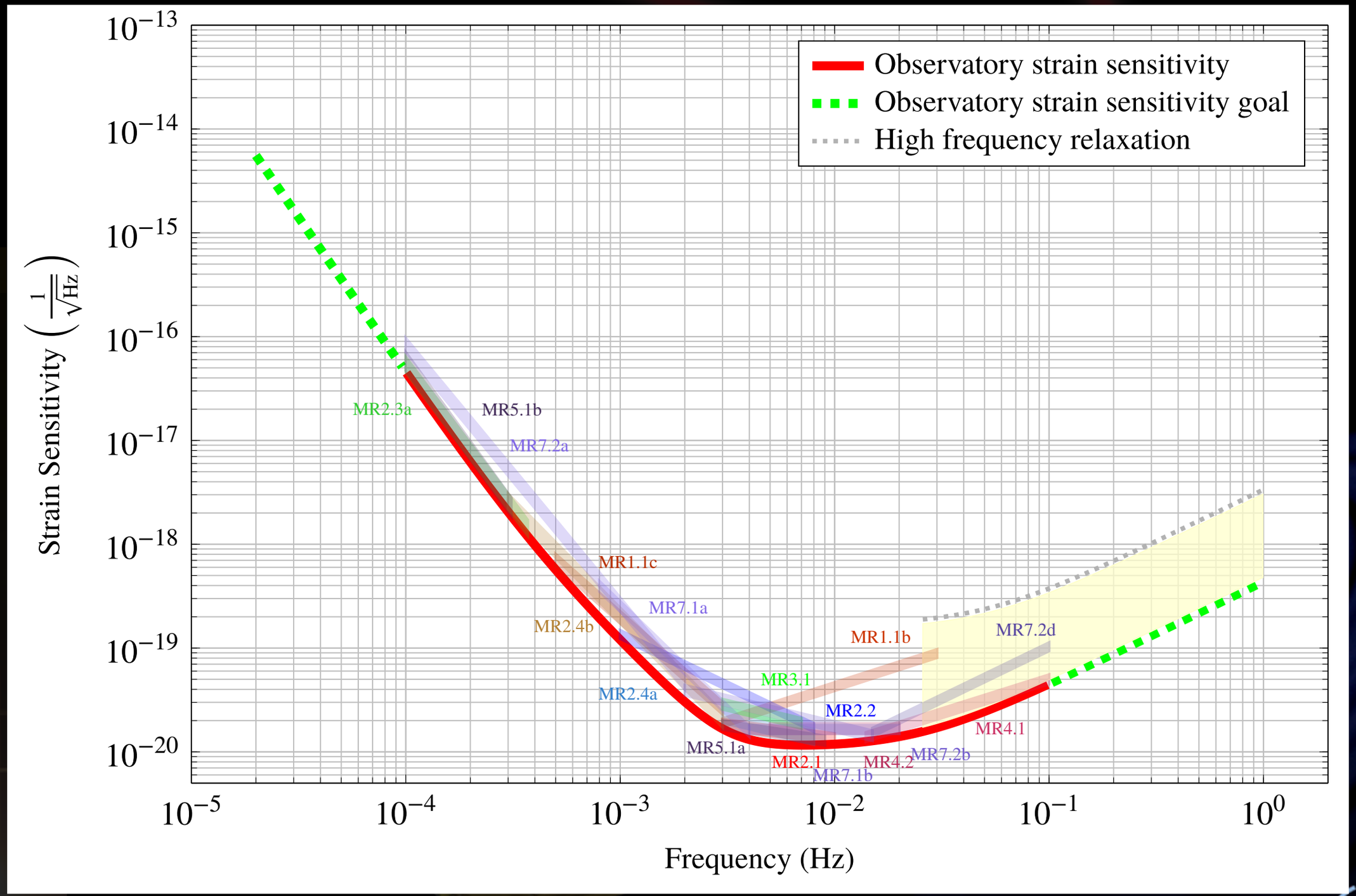
Science Objectives

LISA Science Requirement Document (ESA)

- 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
- SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics
- SO8: Search for GW bursts and unforeseen sources

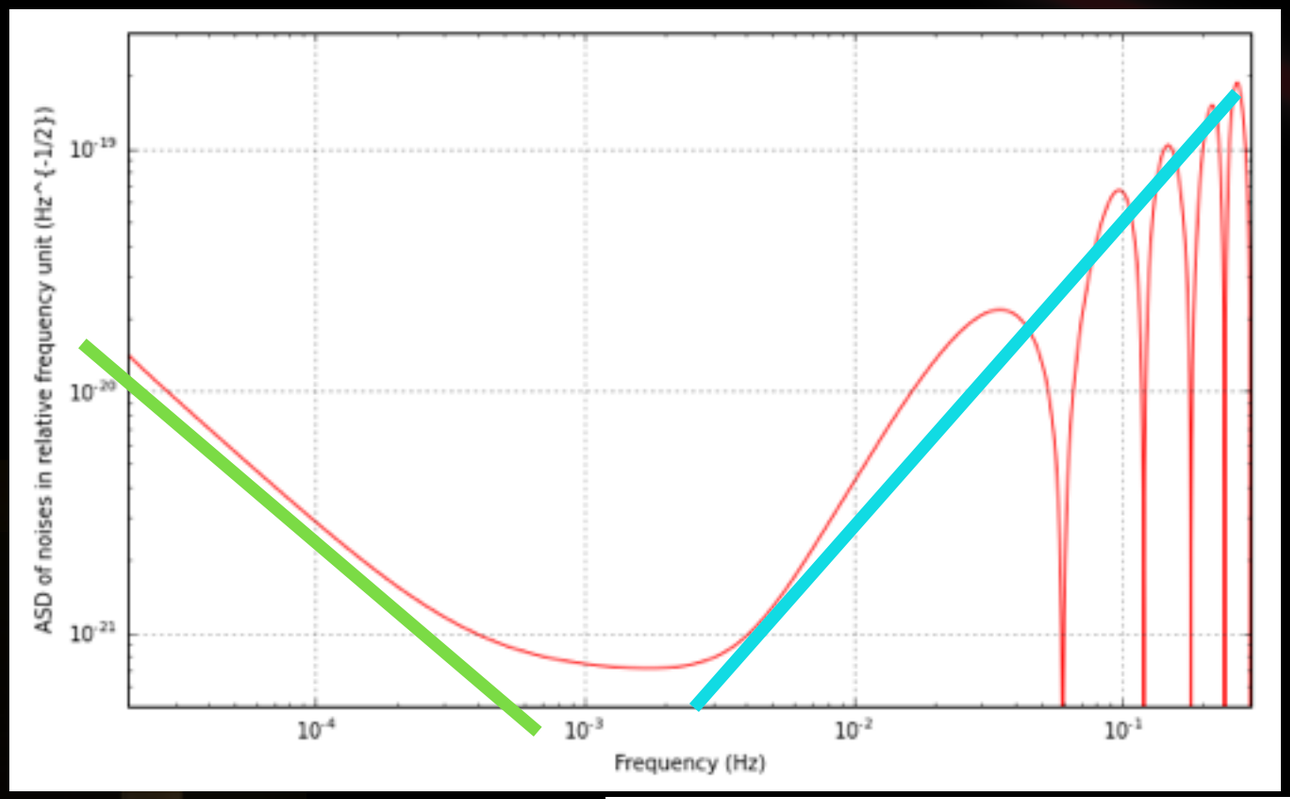
Sensitivity

- Science Requirement Document from ESA Science Study Team

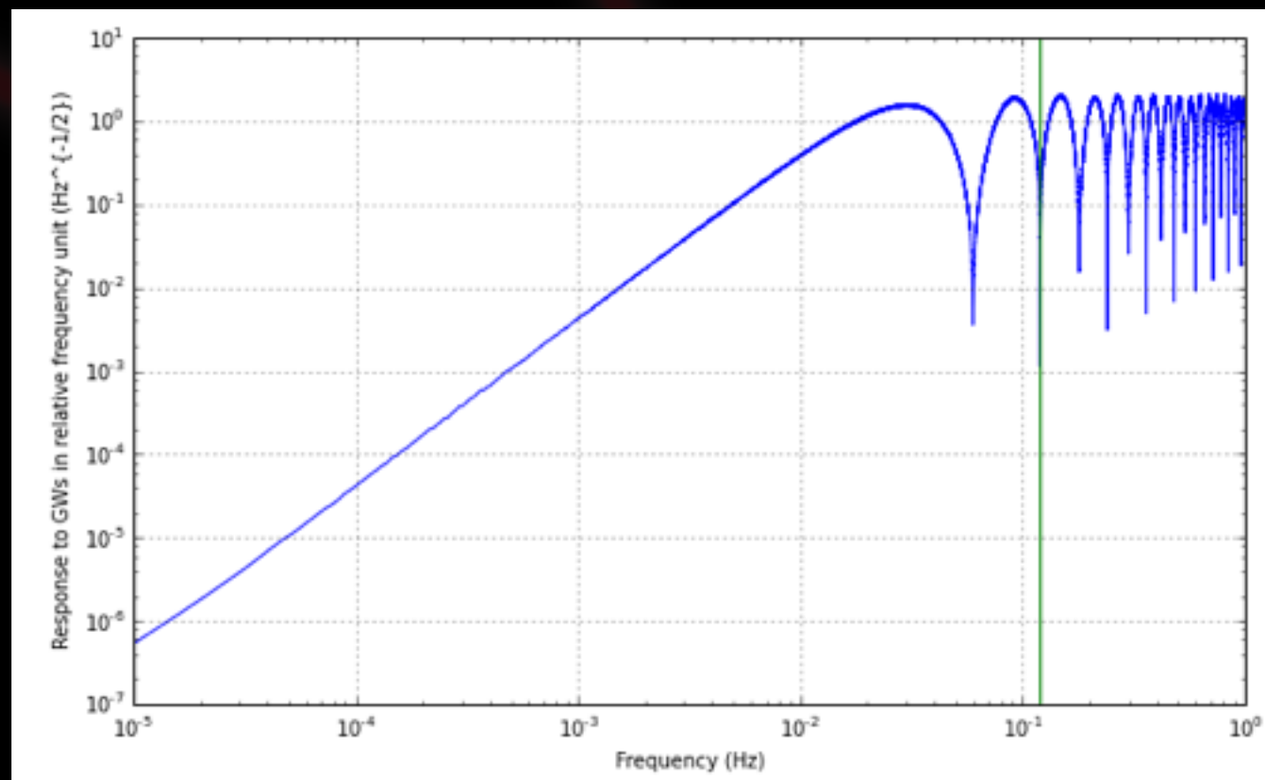


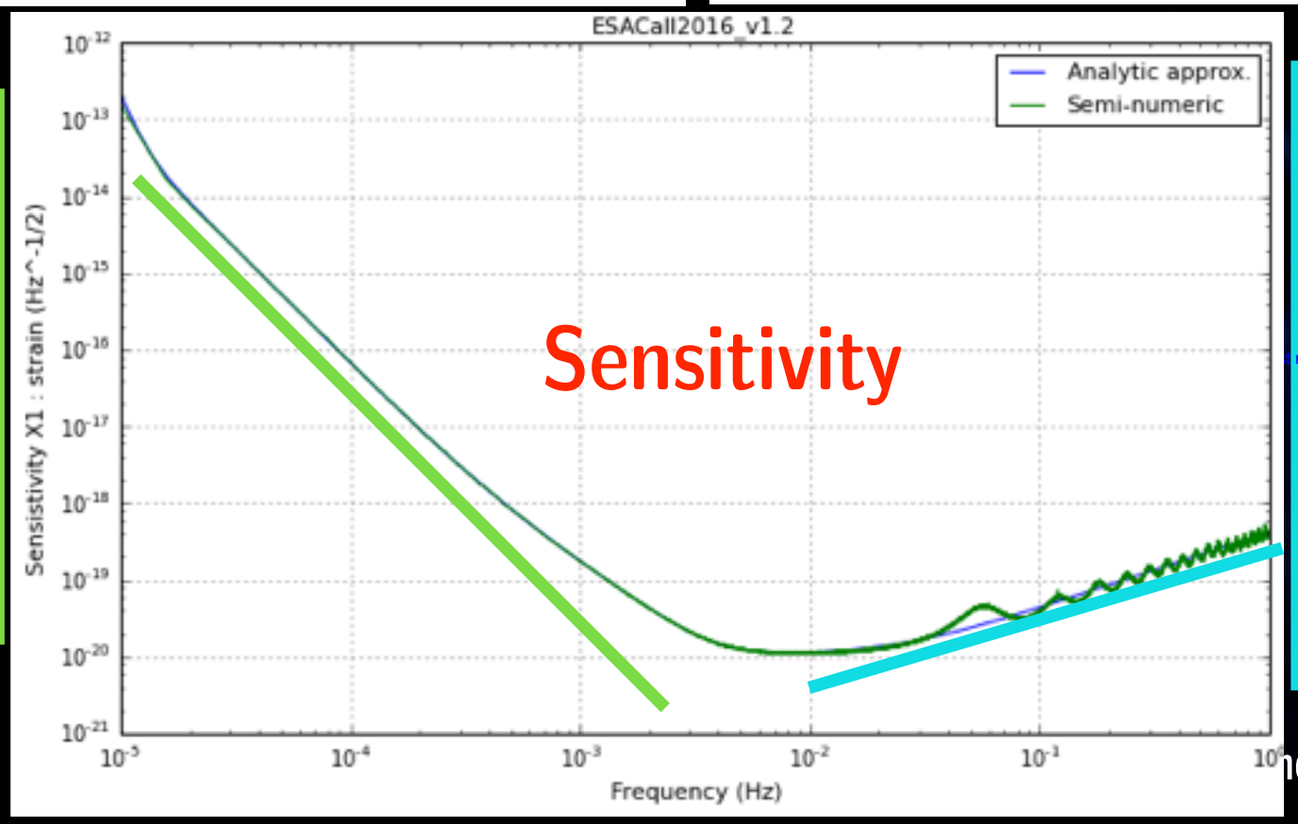
Sensitivity

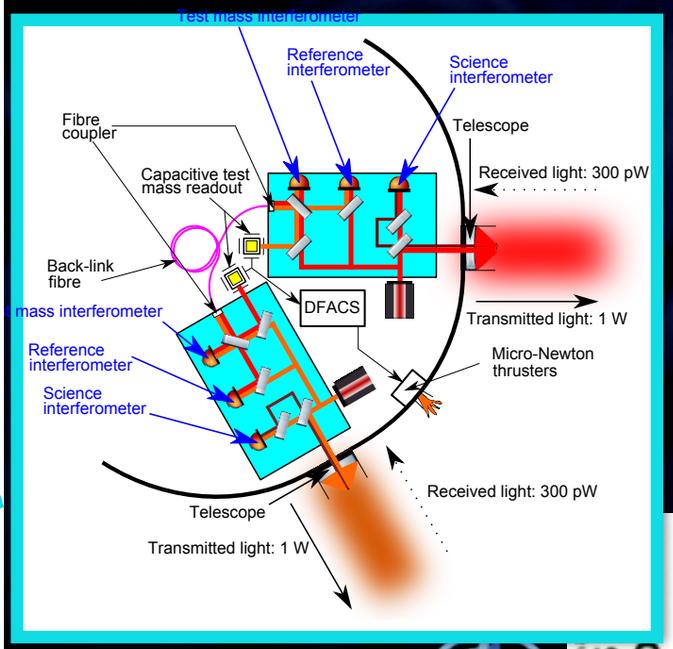
Noises



Response of the detector to GWs





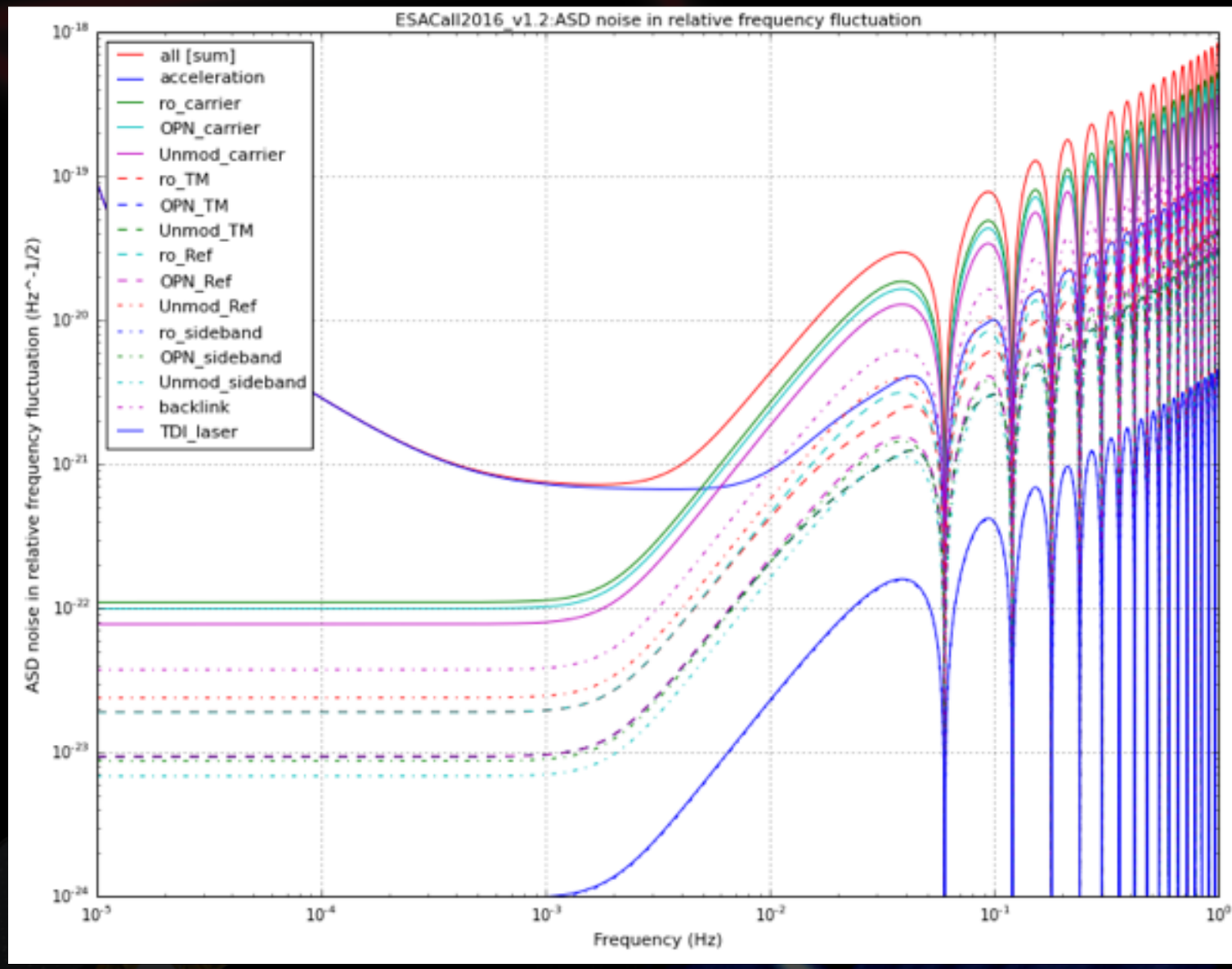


LISA concept in the proposal

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

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

- Noise budget:
  - Acceleration => LISAPathfinder
  - Interferometric Measurement System



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

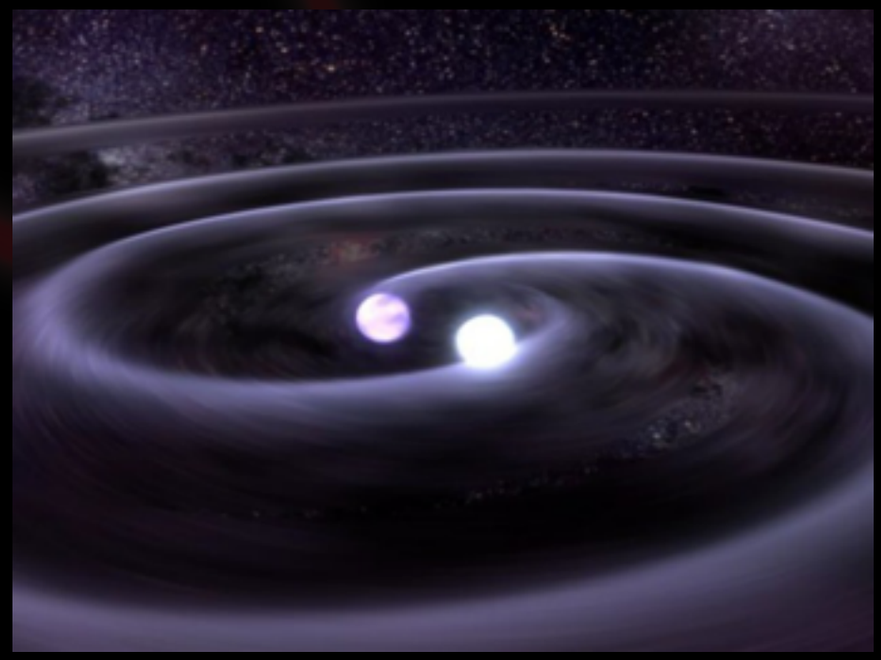
$$S_{\text{IFO}}^{1/2} \le 15\cdot 10^{-12}\frac{\text{m}}{\sqrt{\text{Hz}}}\cdot\sqrt{1+\left(\frac{2\,\text{mHz}}{f}\right)^4}$$

Outline

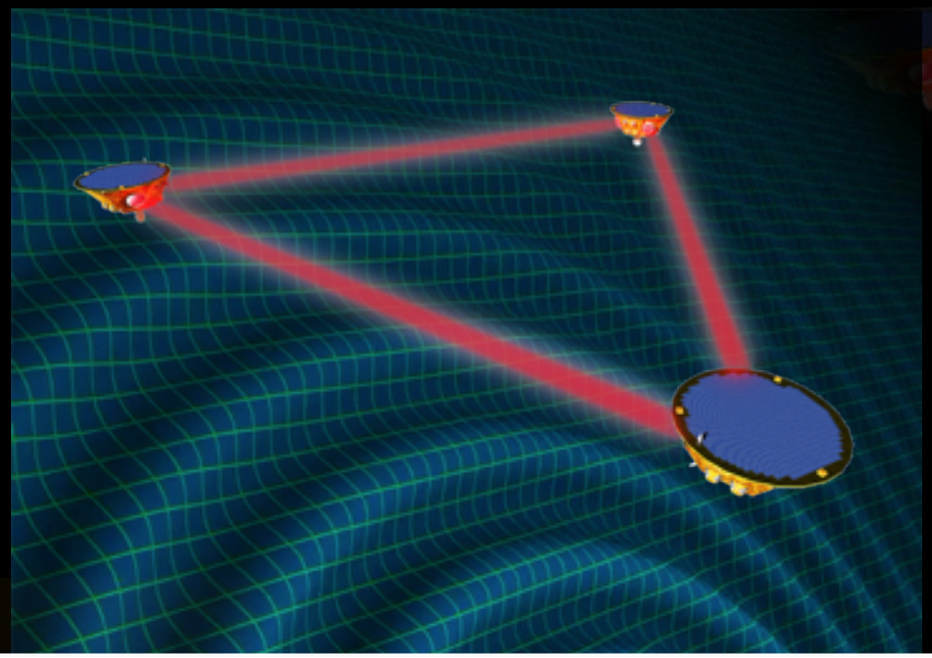
- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISAPathfinder
- LISA status and organization
- LISA scientific performances
- LISAFrance
  - Distributed Data Processing Center
  - AIV(T)
- Conclusion and perspectives

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)

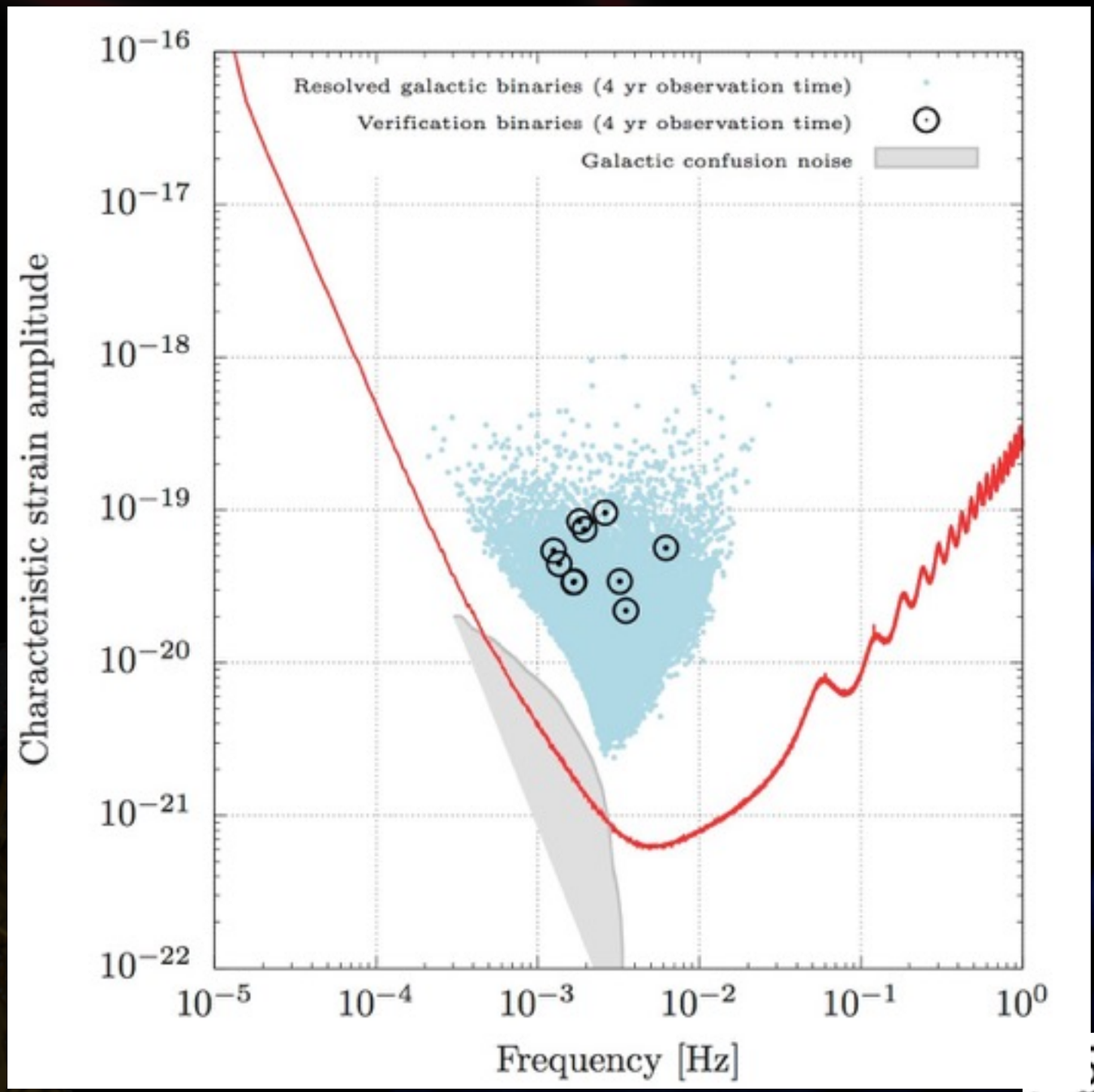


Galactic binaries



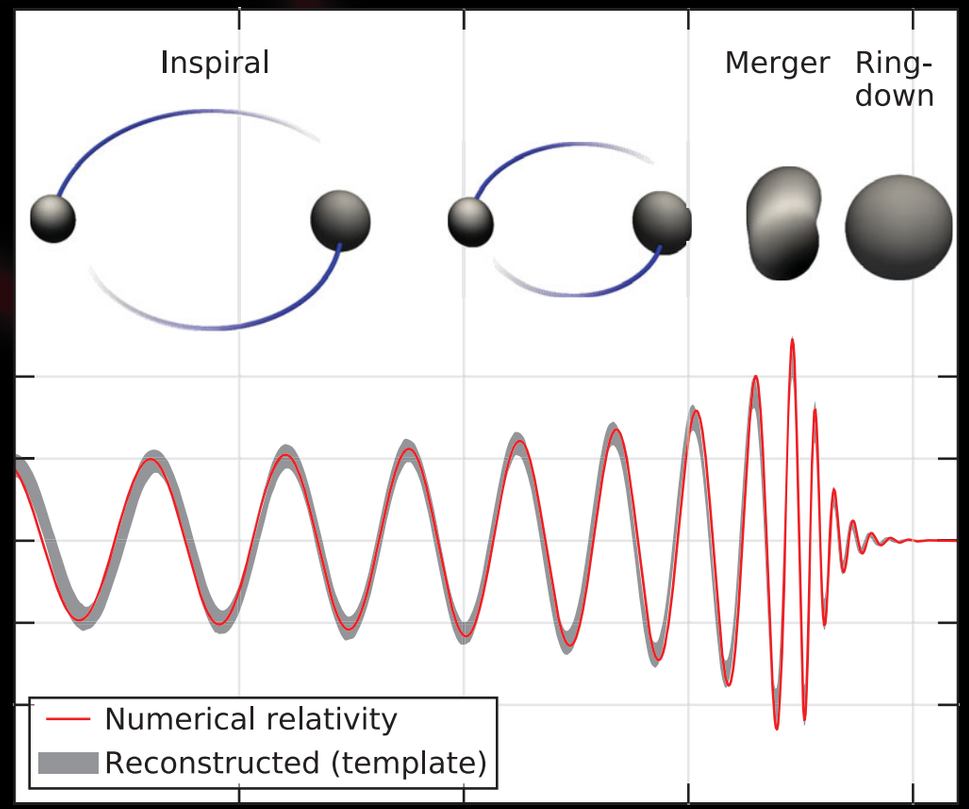
GW sources

- 6 x10^7 galactic binaries



Super Massive Black Hole Binaries

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

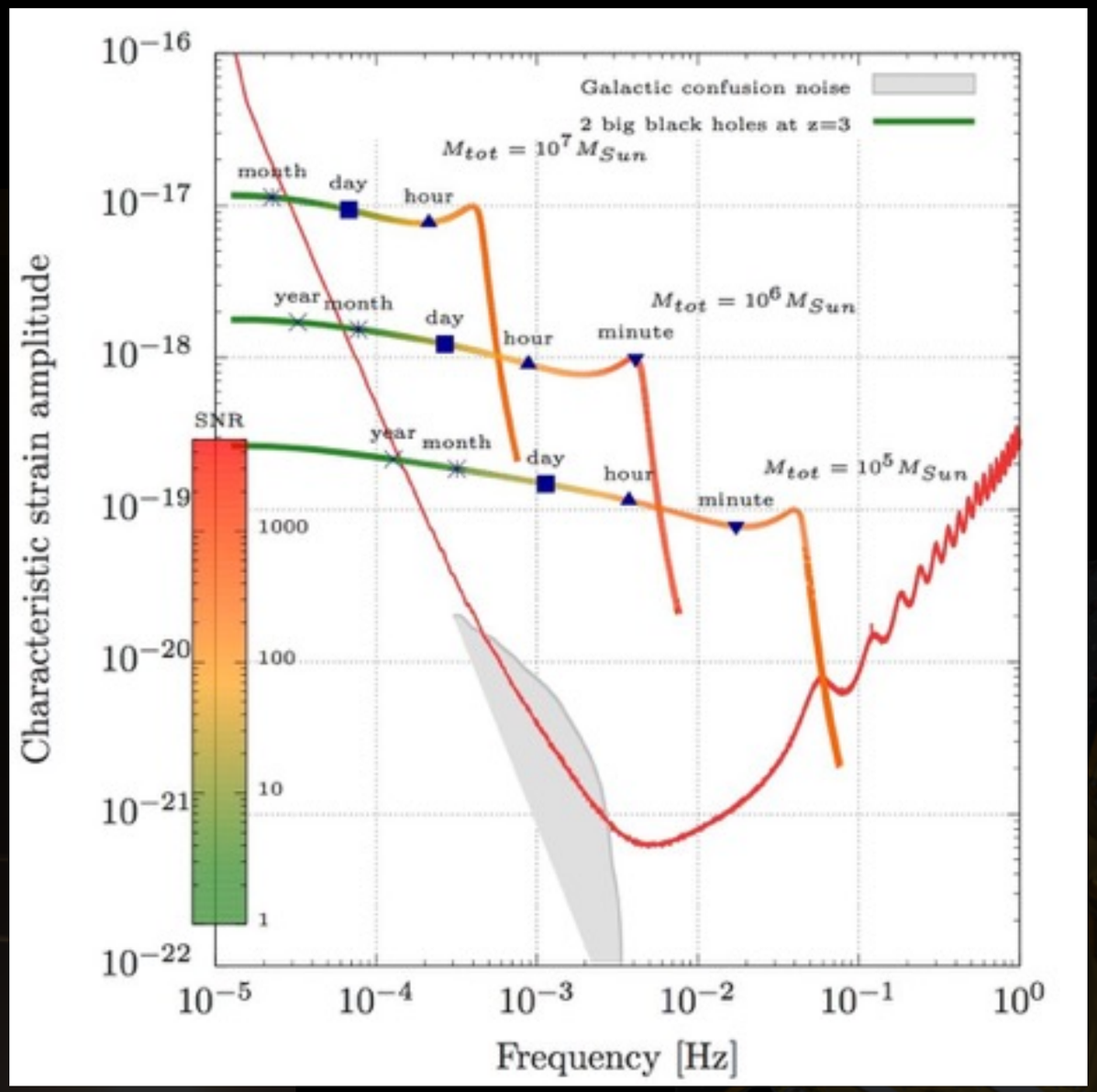


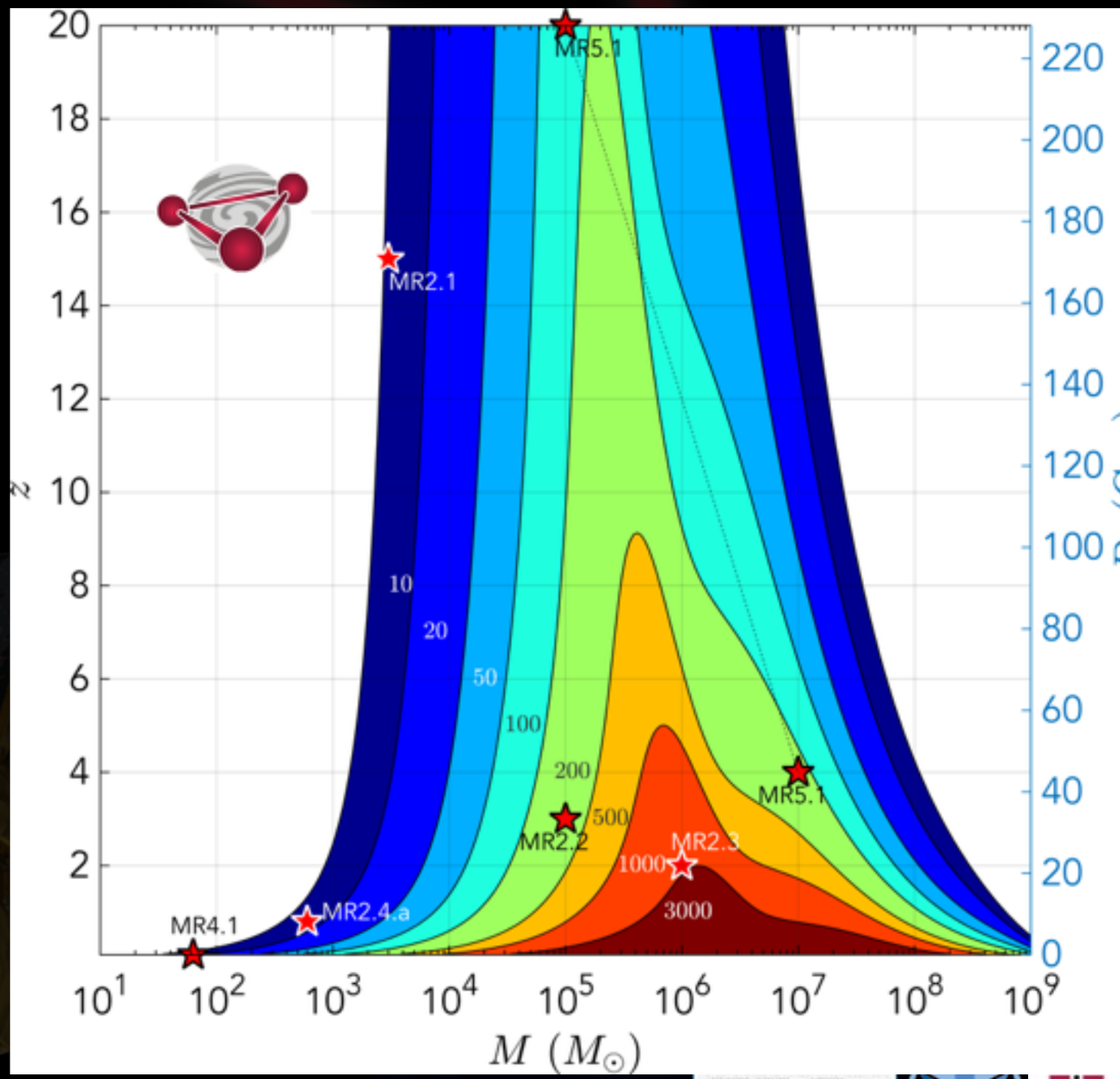
- Duration: between few hours and several months
- Signal to noise ratio: until few thousands
- Event rate: 10-100/year

Super Massive Black Hole Binaries

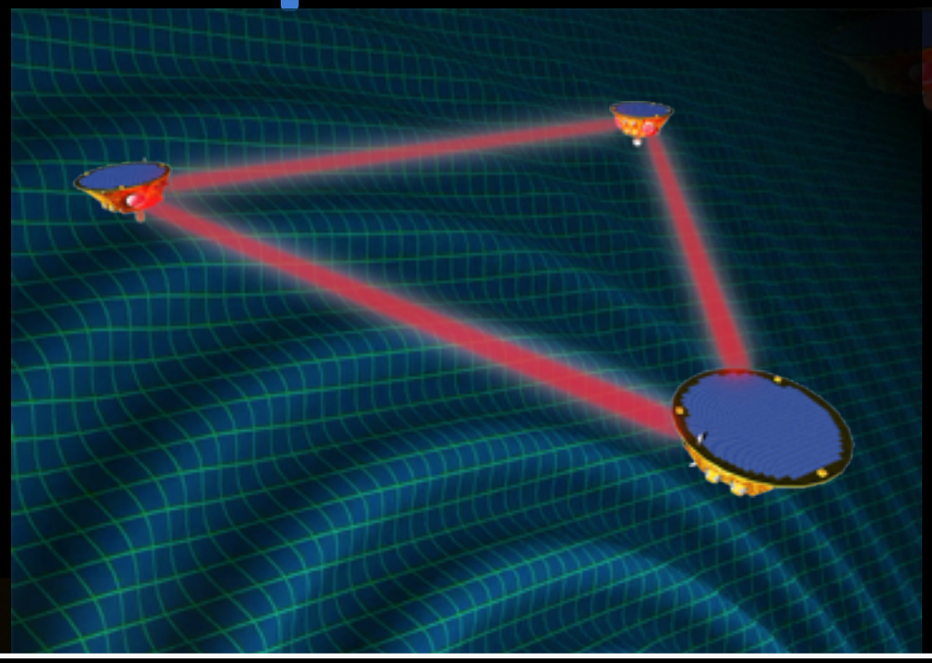
- Data

LISA: SMBHB from 10^4 à 10^7 solar masses in "all" Univers



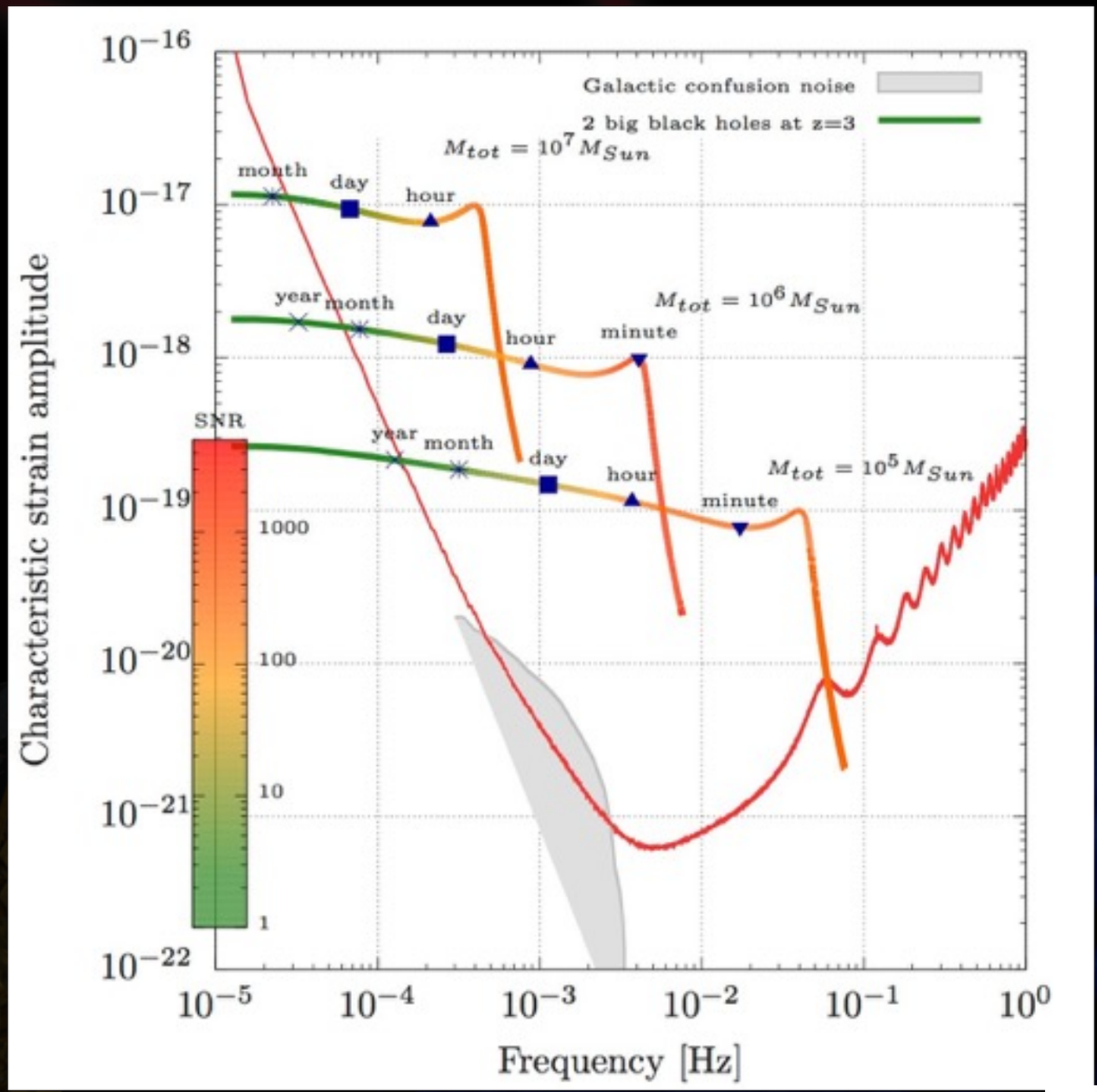


Super Massive Black Hole Binaries



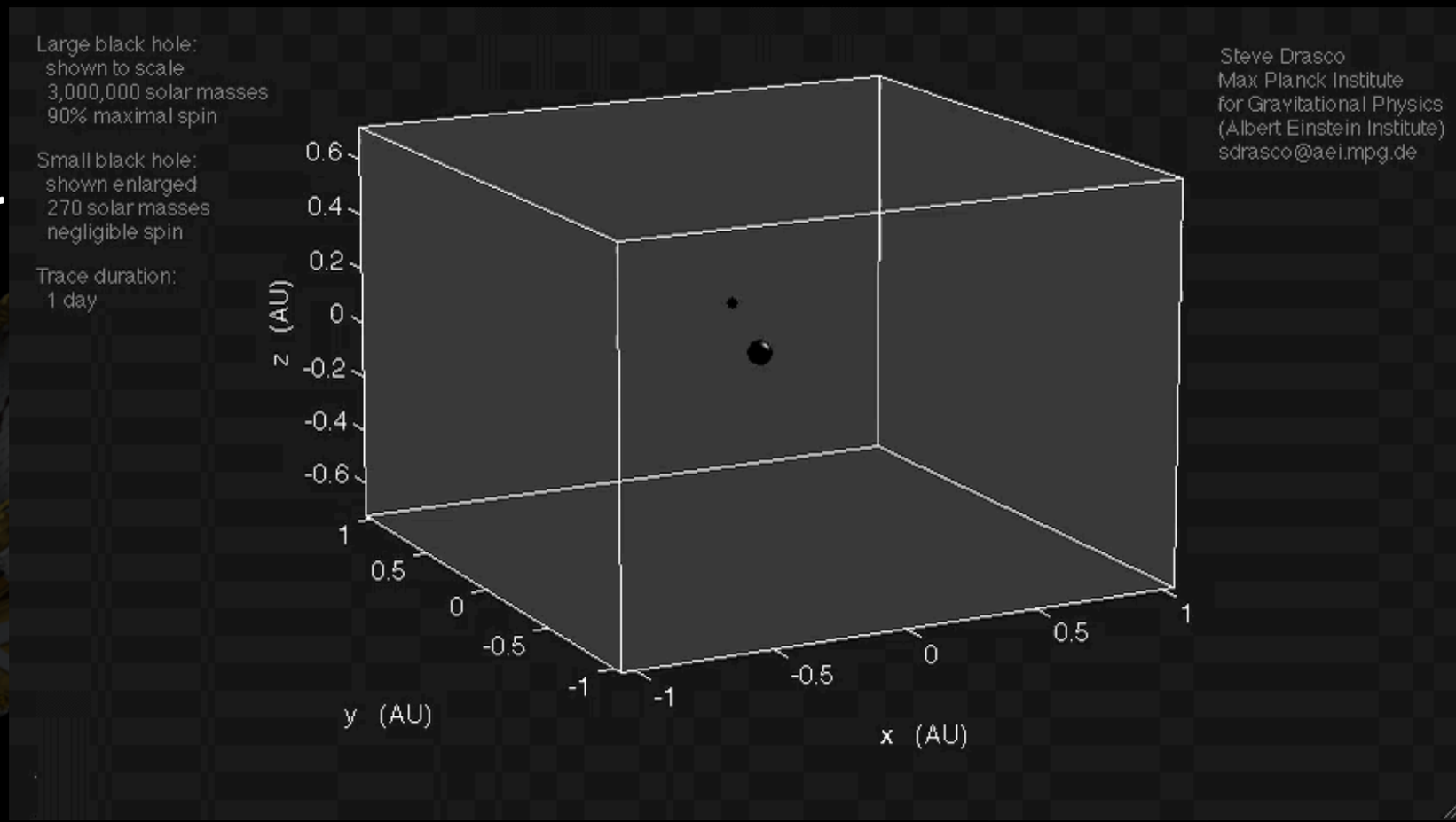
OG sources

- 6 x10^7 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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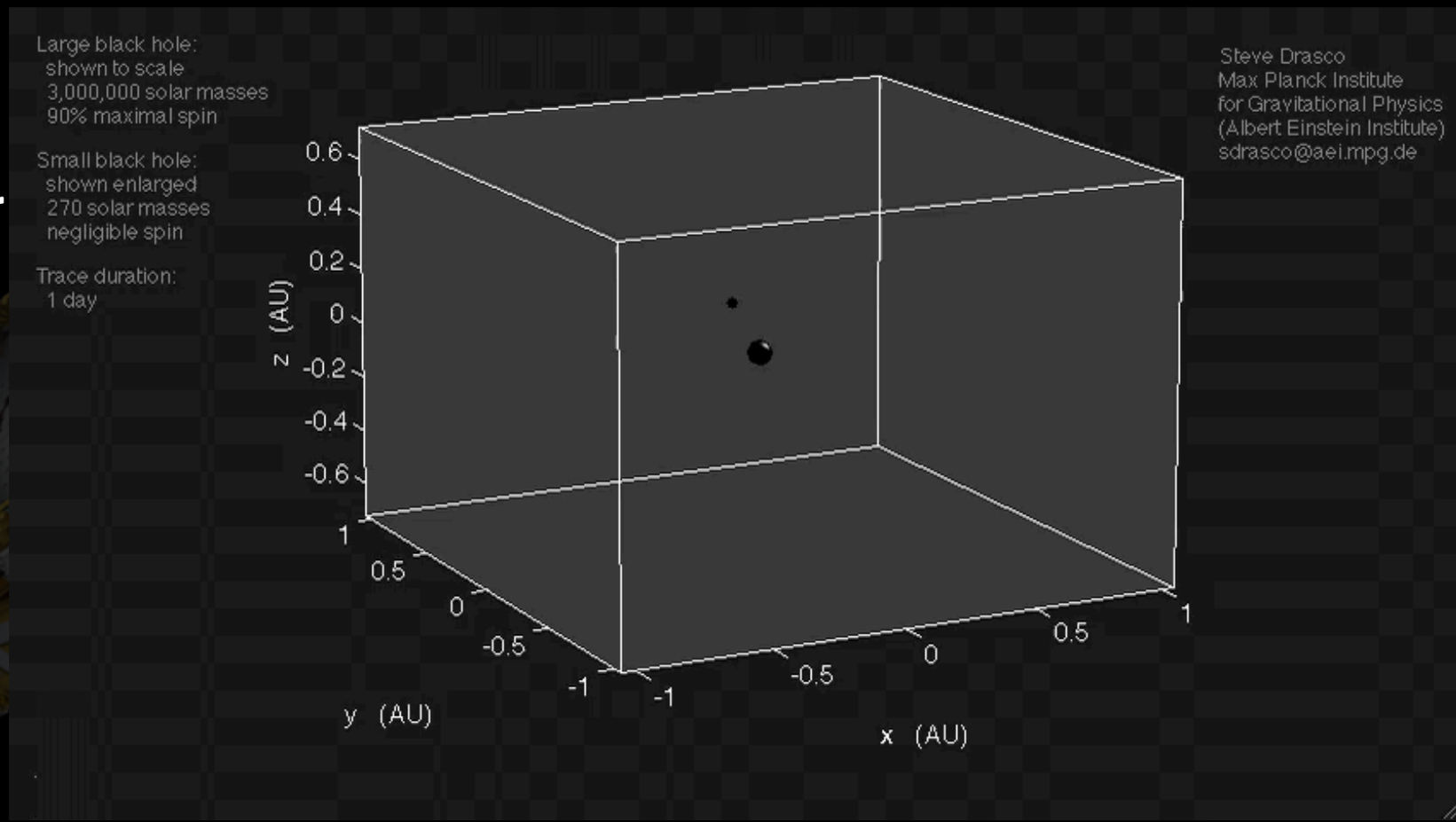
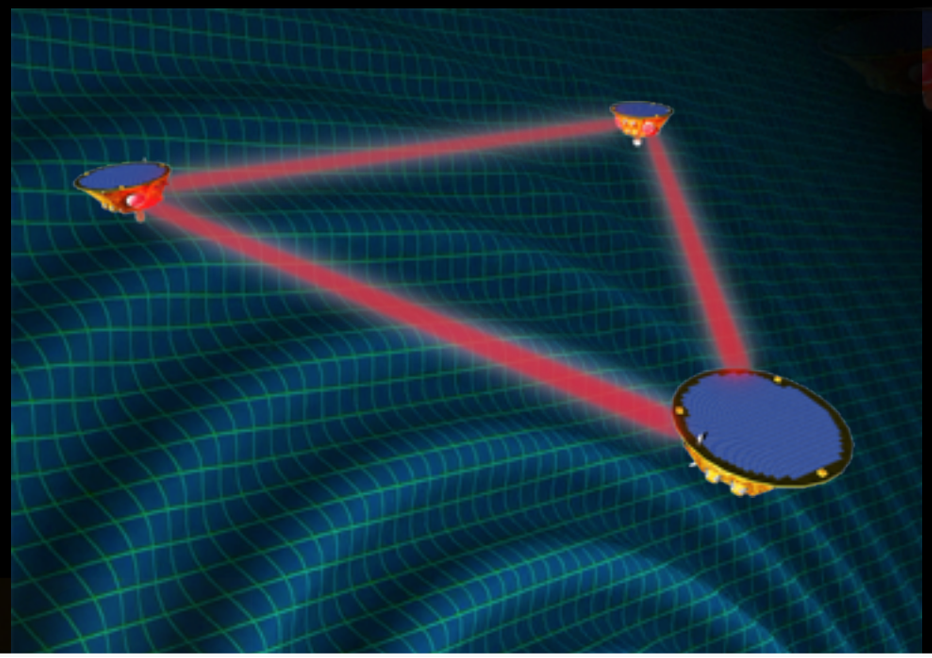
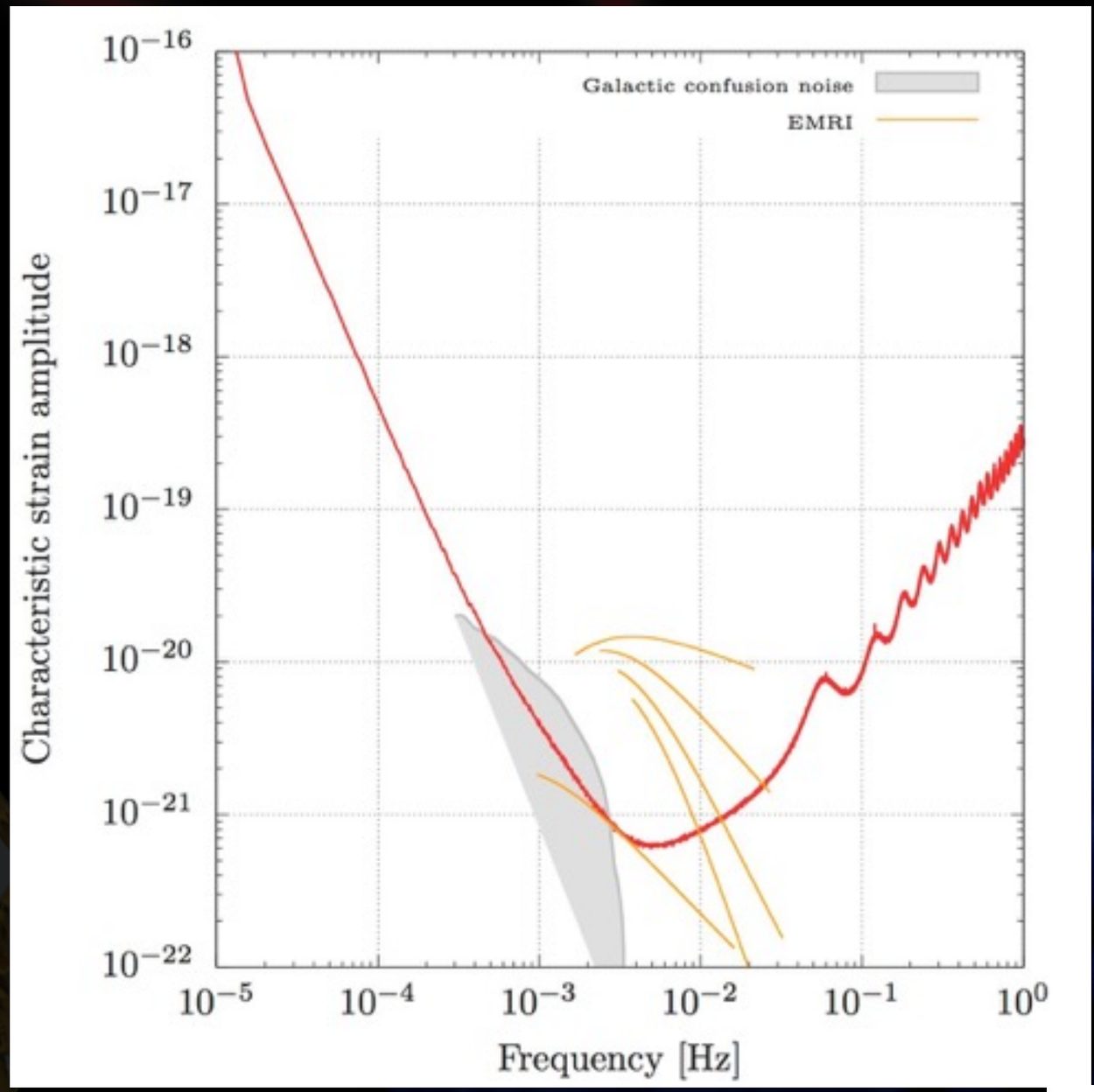


EMRIs



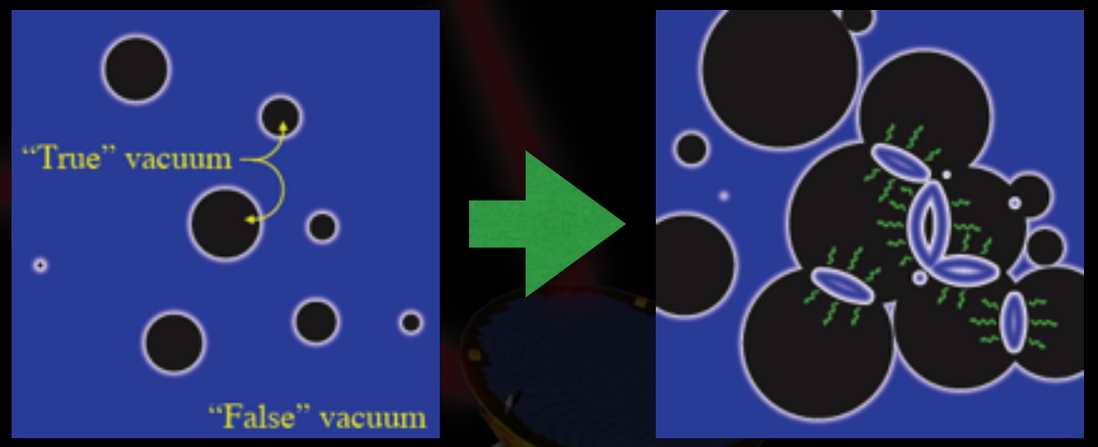
OG sources

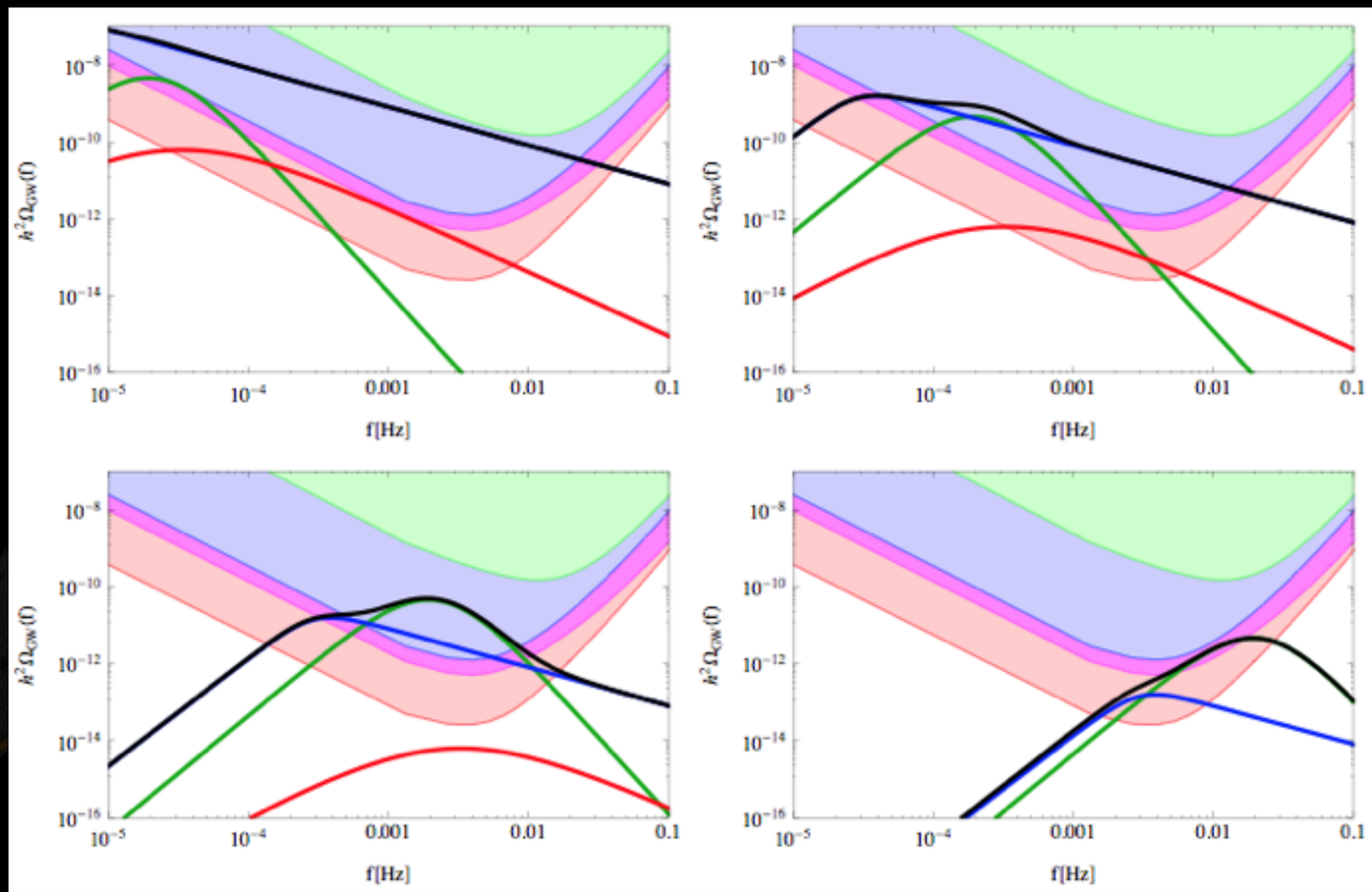
- 6 x10^7 galactic binariess
- 10-100/year SMBHBs
- 10-1000/years EMRIs



Cosmological backgrounds

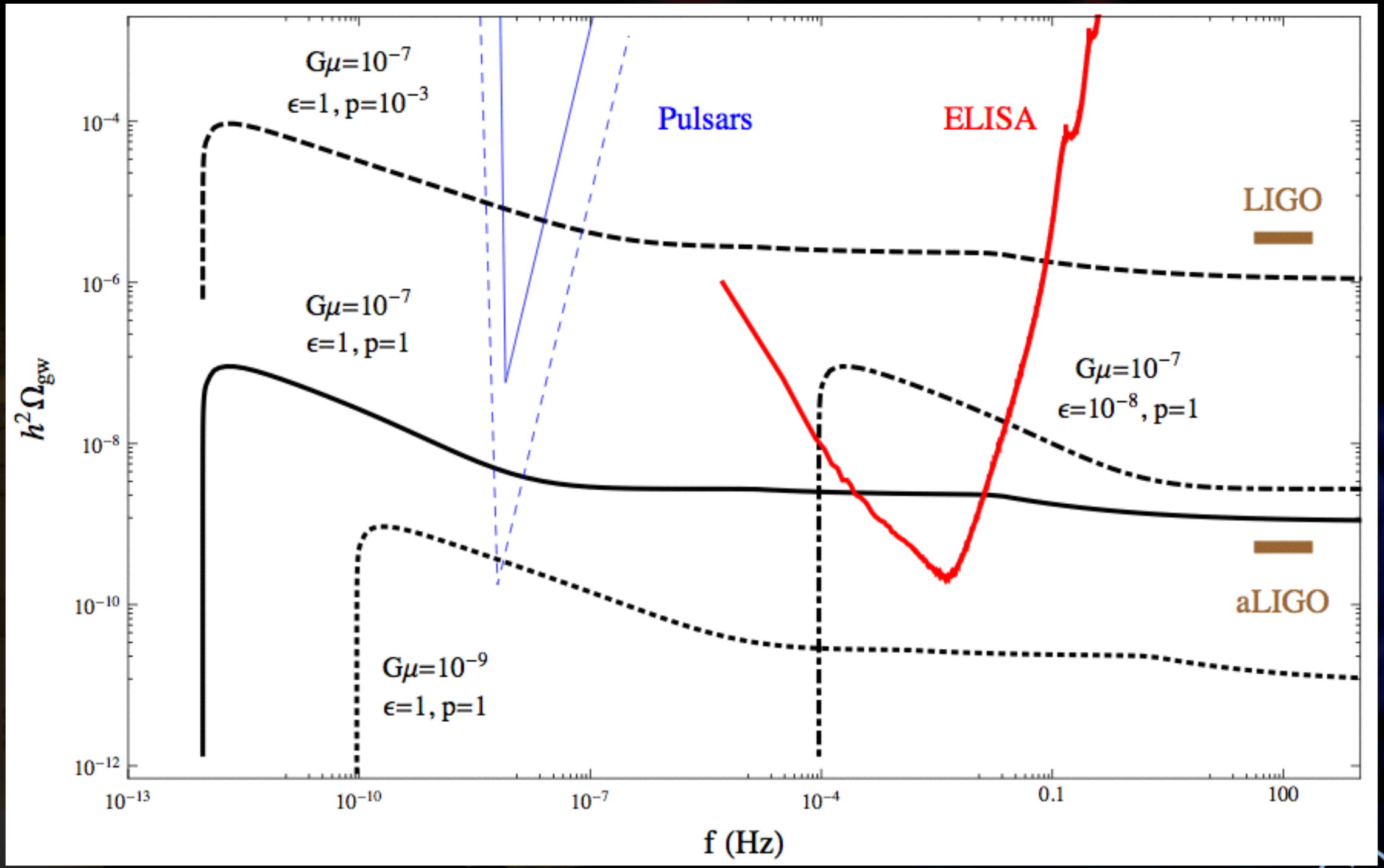
- Work in progress for LISA ...
- But studies done in the context of eLISA already showed:
  - Ex: first order phase transition in the very early Universe Caprini et al. JCAP 04, 001 (2016)
  - Cosmic strings network
  - ...





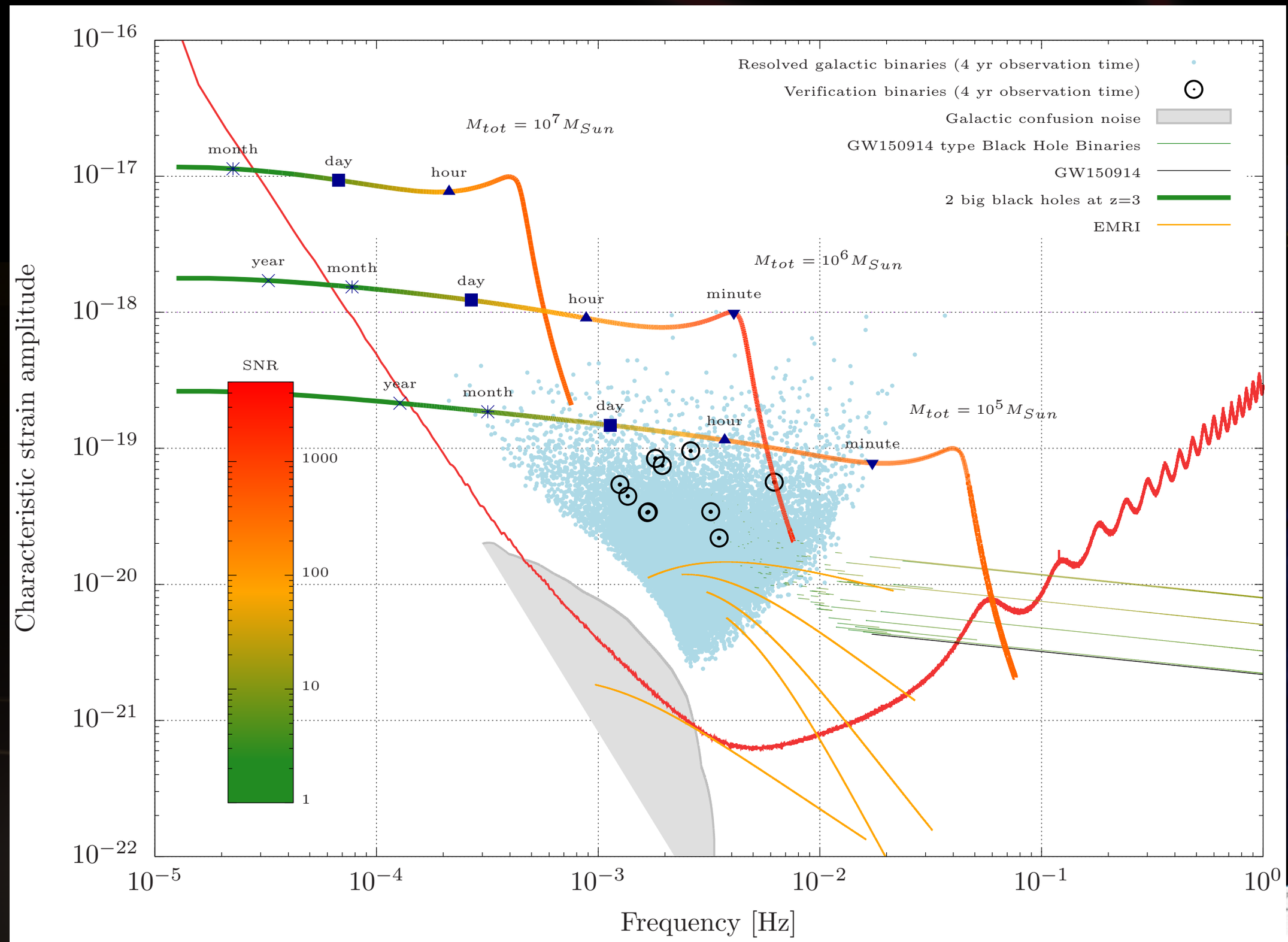
Cosmic string networks

- Stochastic background + bursts



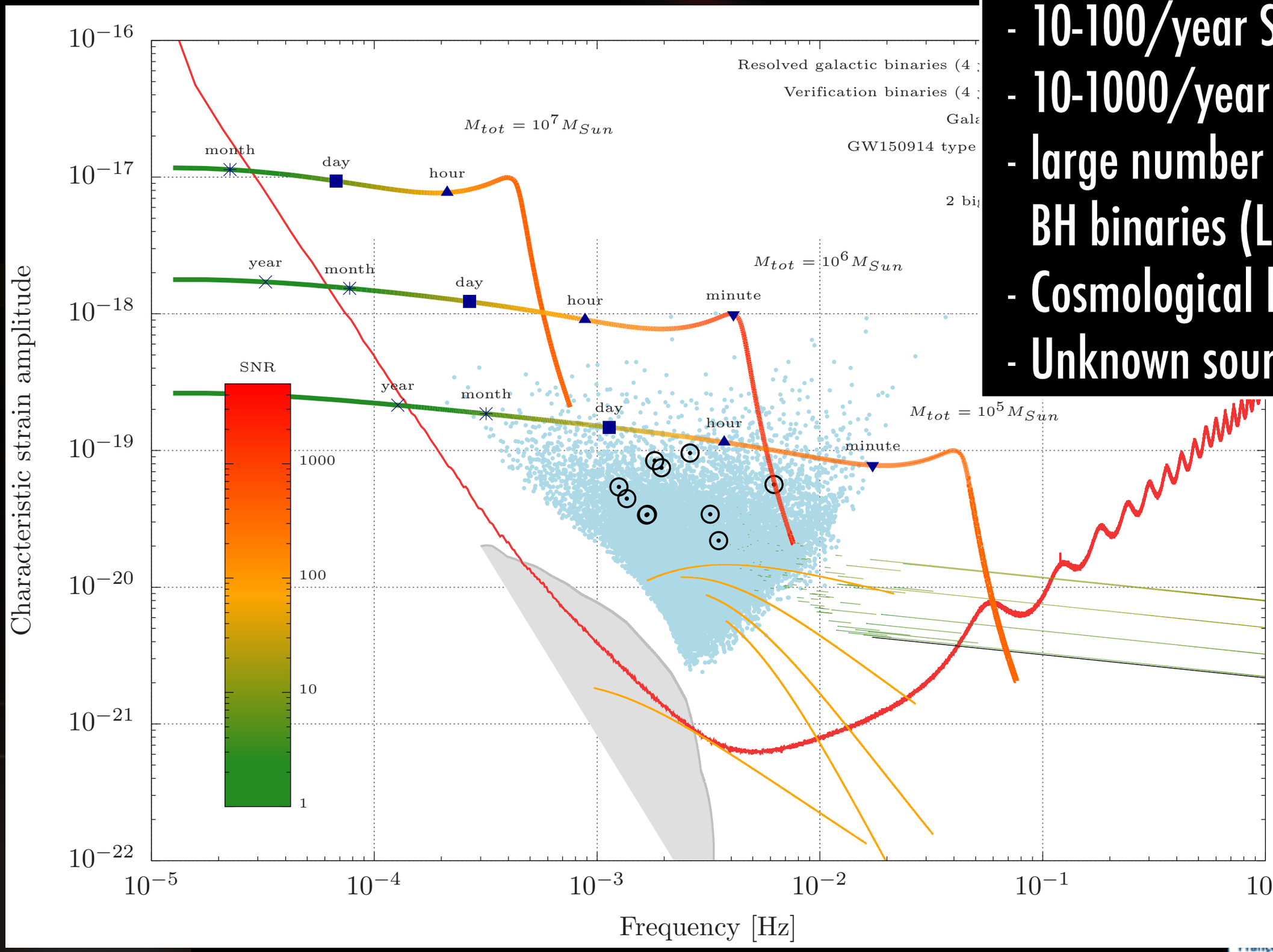
© Binétruy et al.

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
month
day
hour
minute
SNR
year
month
day
hour
minute
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



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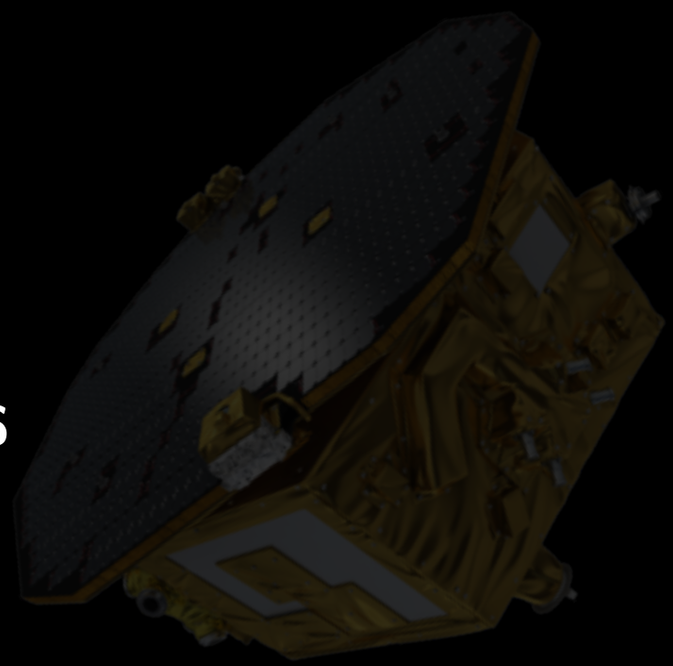
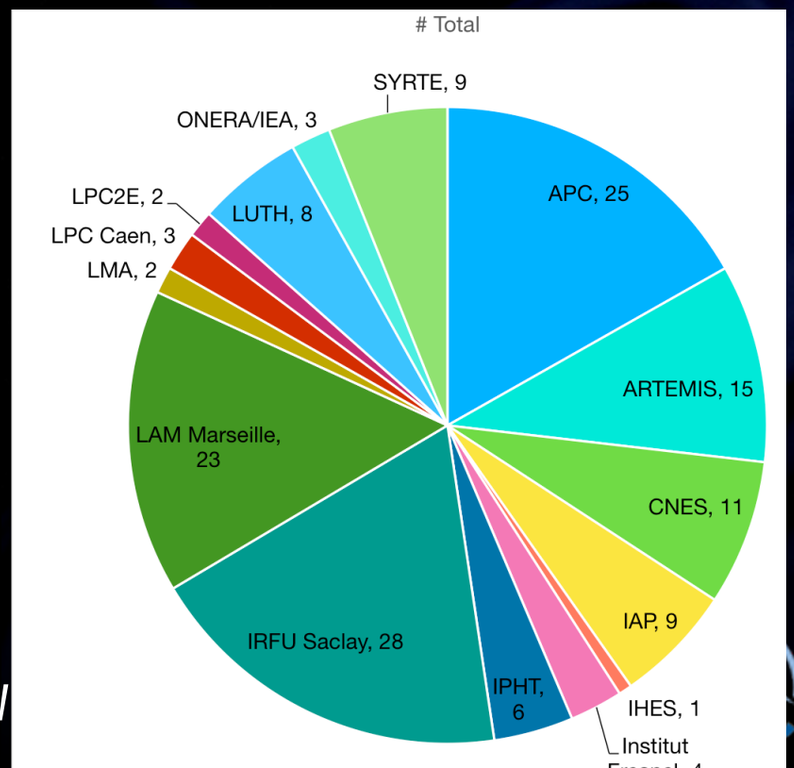
LISA France

- Started in 2006
- Supported by CNES
- Recent “restart” with strong interest of “new” lab:
  - 15 french institutes: APC, ARTEMIS, CEA/IRFU (DAp, DEDIP, DIS, DPhP, DPhN), CEA/DSM (IPhT), CNES, CPPM, IAP, Fresnel, LAM, LMA, LPC Caen, LPC2E, LUTh, ONERA, SYRTE
- Activities centered on Consortium deliverables:
  - DDPC
  - AIV(T)
  - GW Science
  - Data analysis
  - Simulation

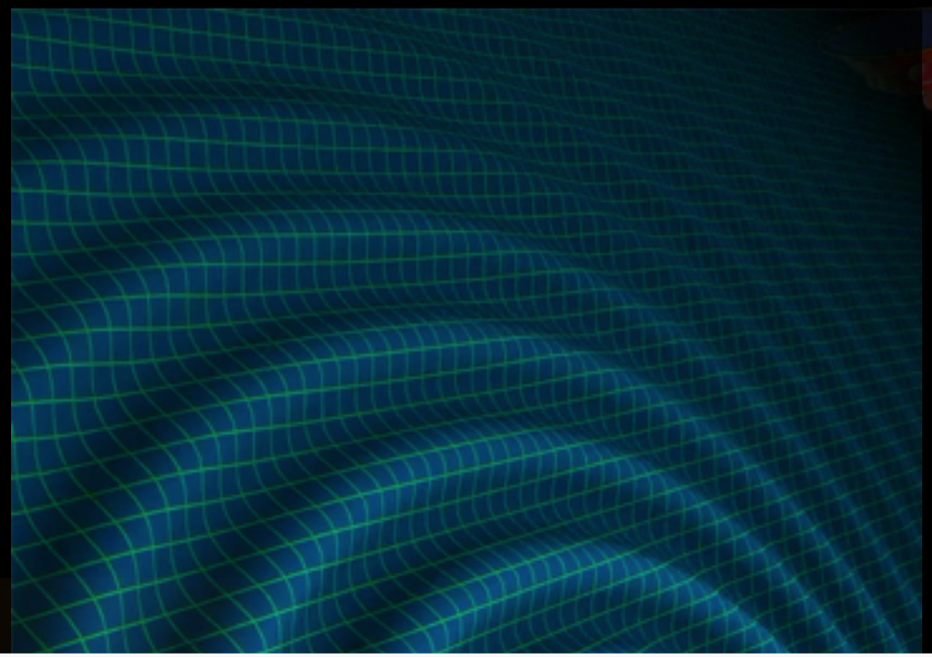




LISA data

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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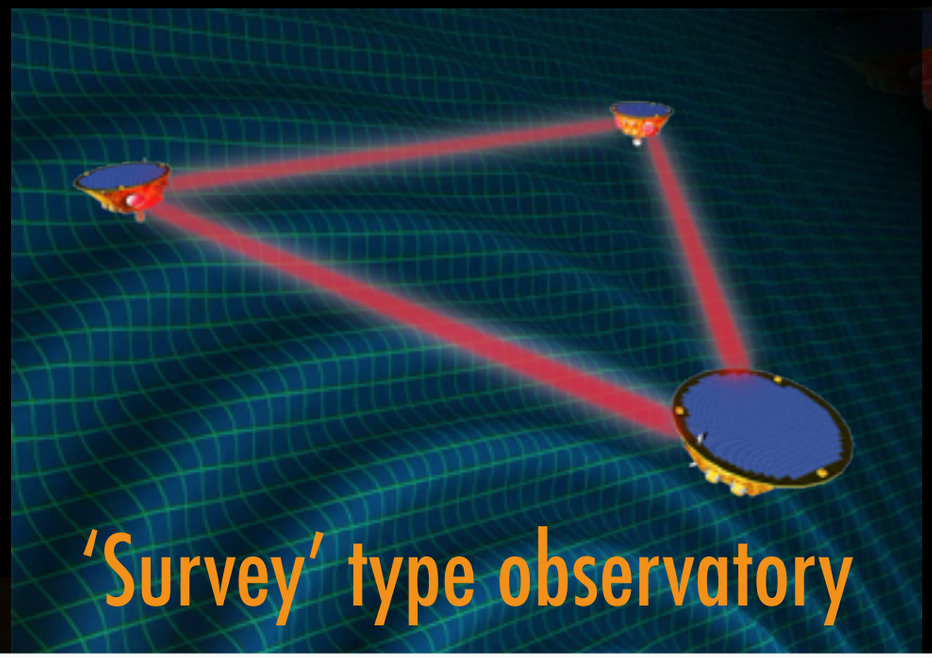

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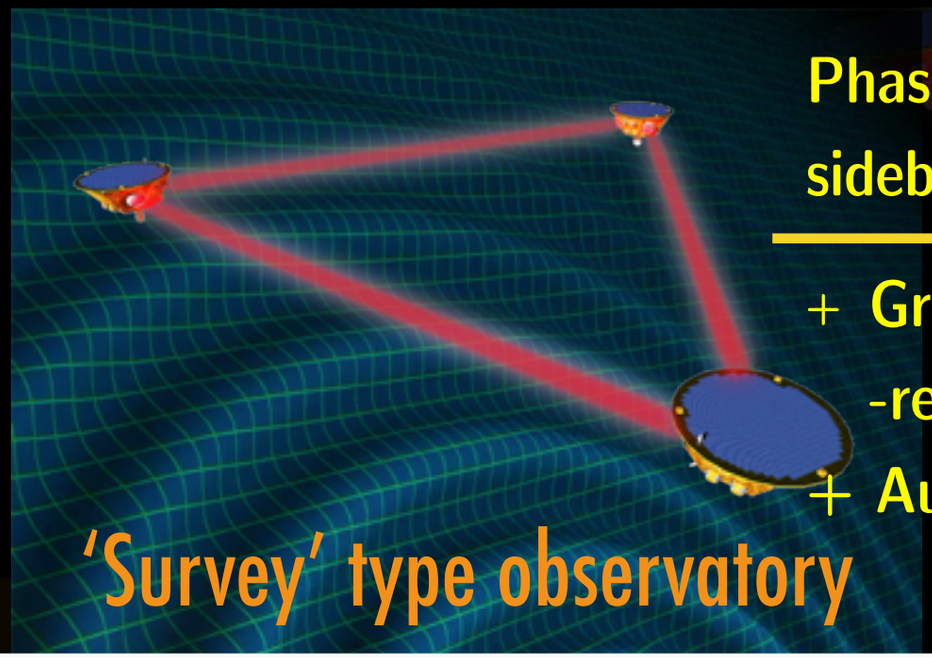


'Survey' type observatory

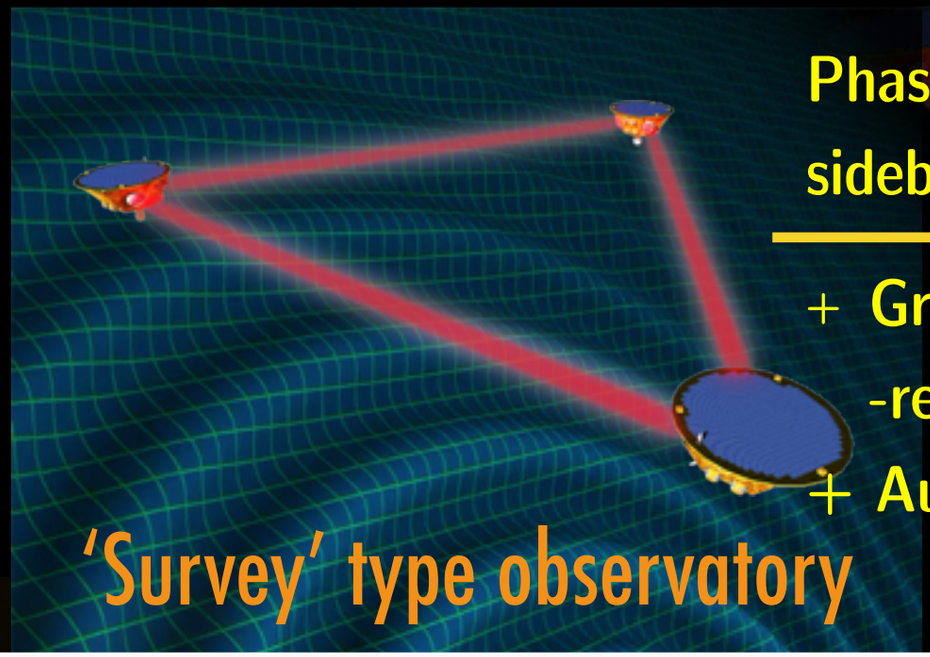
Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe--rence Sensor

+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



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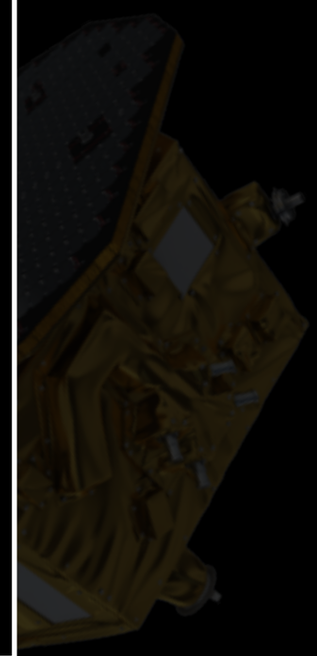
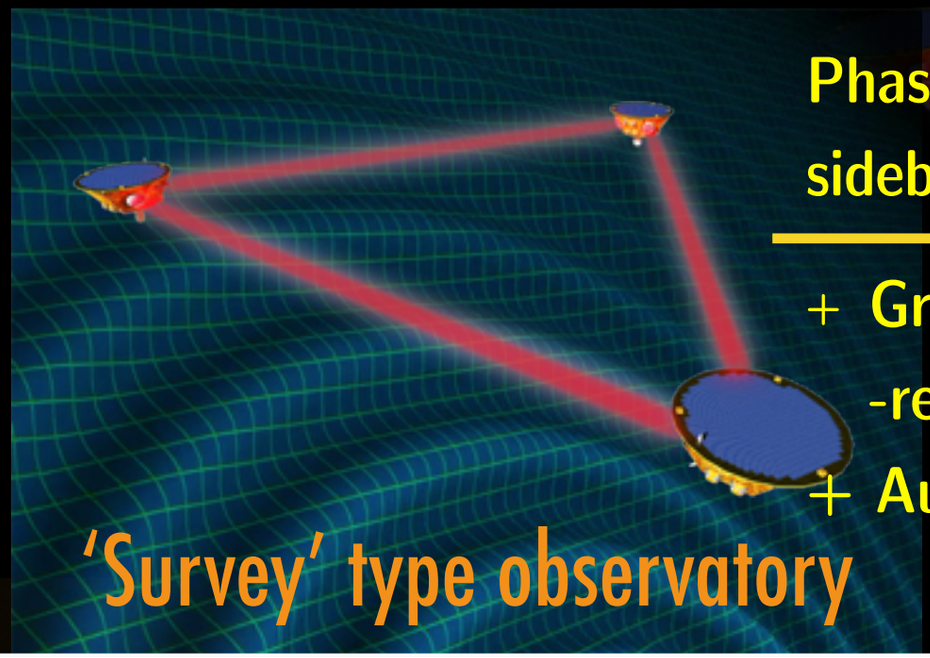


LISA data



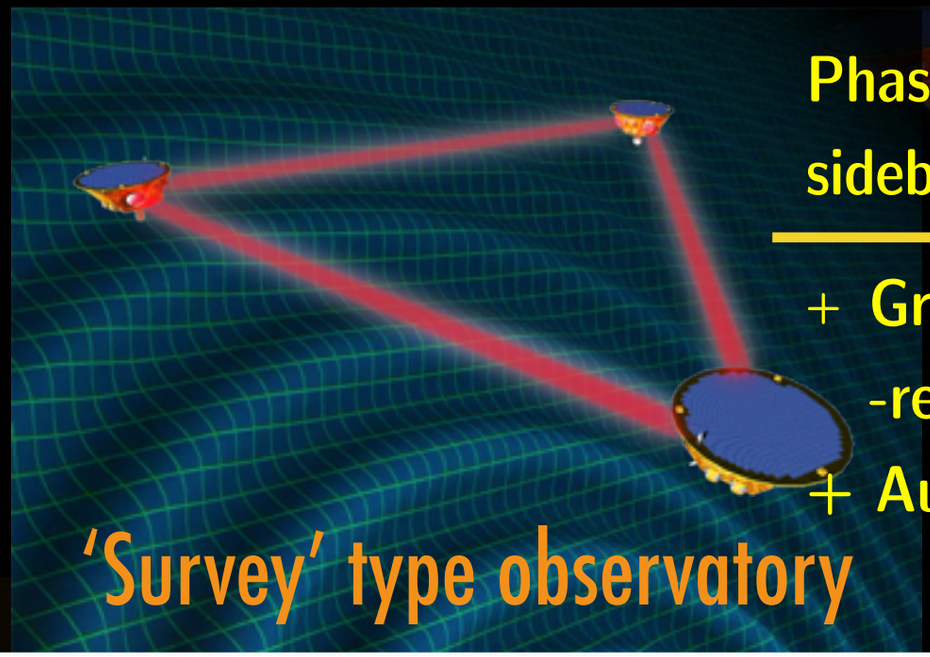
Phasemeter
sidebands, c
+ Gravitati
-rence Se
+ Auxiliary

'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



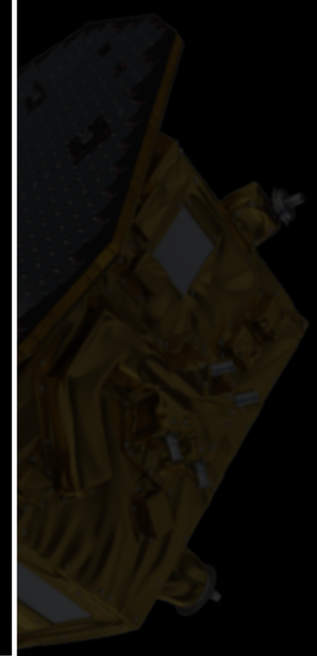
'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

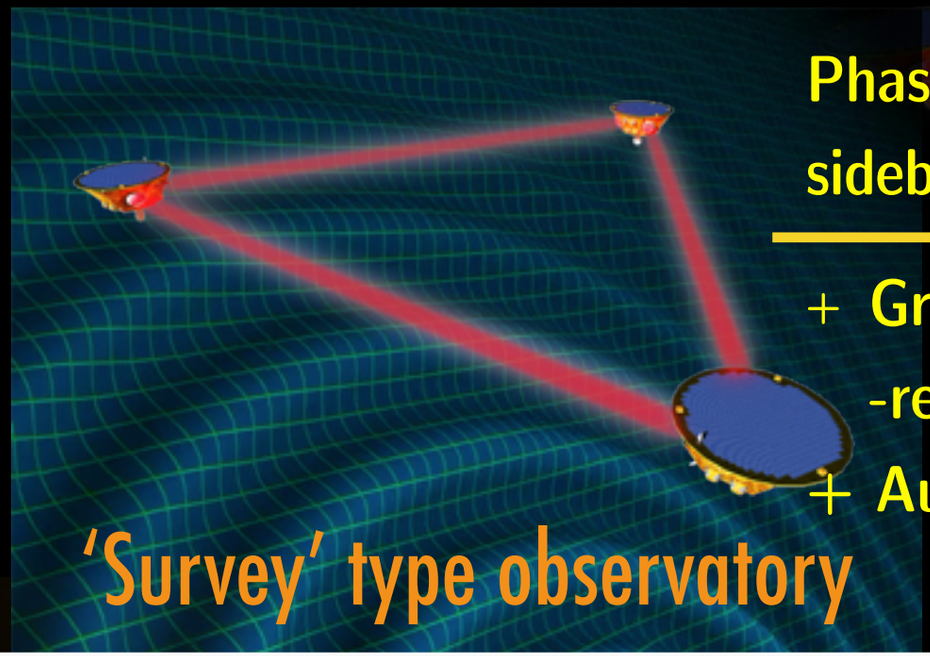
+ Gravitational Refe--rence Sensor

+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz



LISA data



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Calibrations corrections

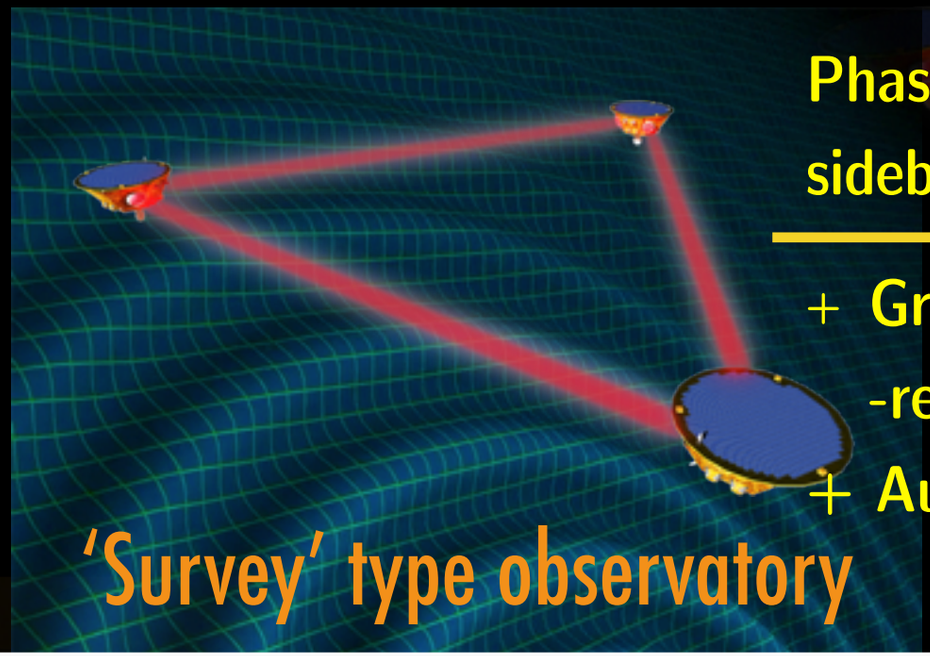
Resynchronisation (clock)

Time-Delay Interferometry
reduction of laser noise

2 data channels TDI non-correlated

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



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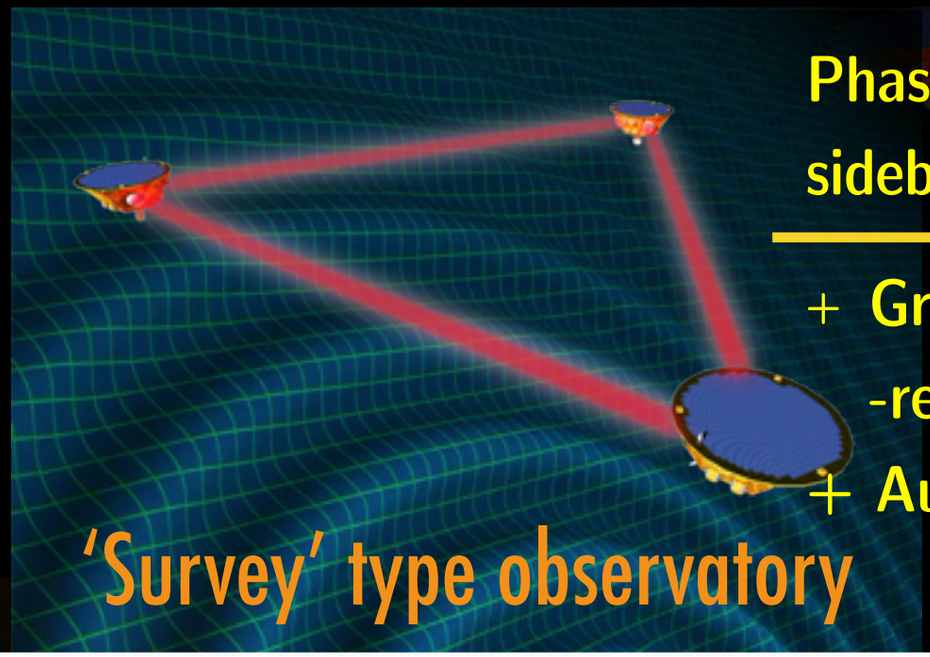
Data Analysis of GWs

Catalogs of GWs sources
with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe--rence Sensor

+ Auxiliary channels

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry
reduction of laser noise

L1 2 data channels TDI non-correlated

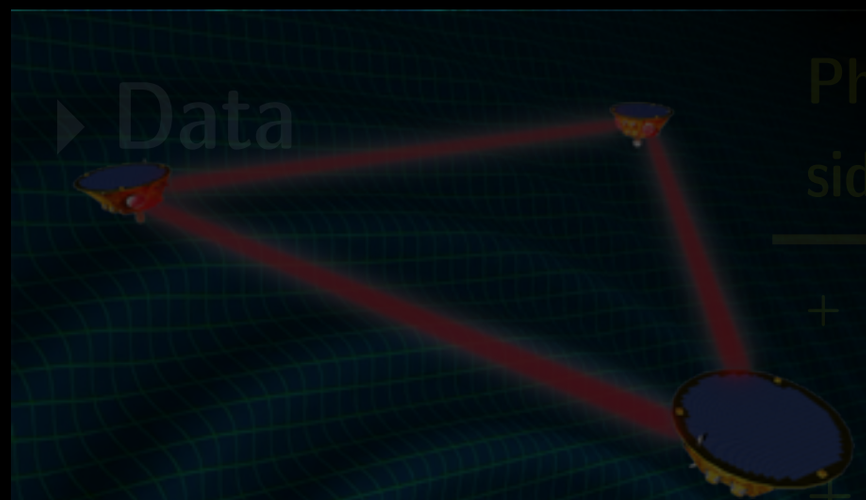
Data Analysis of GWs

L2

L3 Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA DDPC

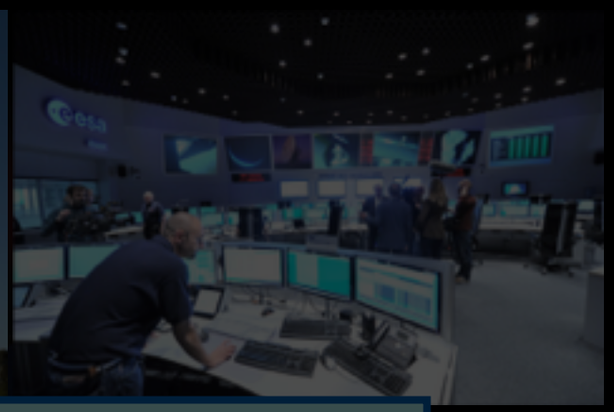


'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ Gravitational Reference Sensor

+ Auxiliary channels



L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry
reduction of laser noise

L1 — 2 data channels TDI non-correlated

L2 — Data Analysis of GWs

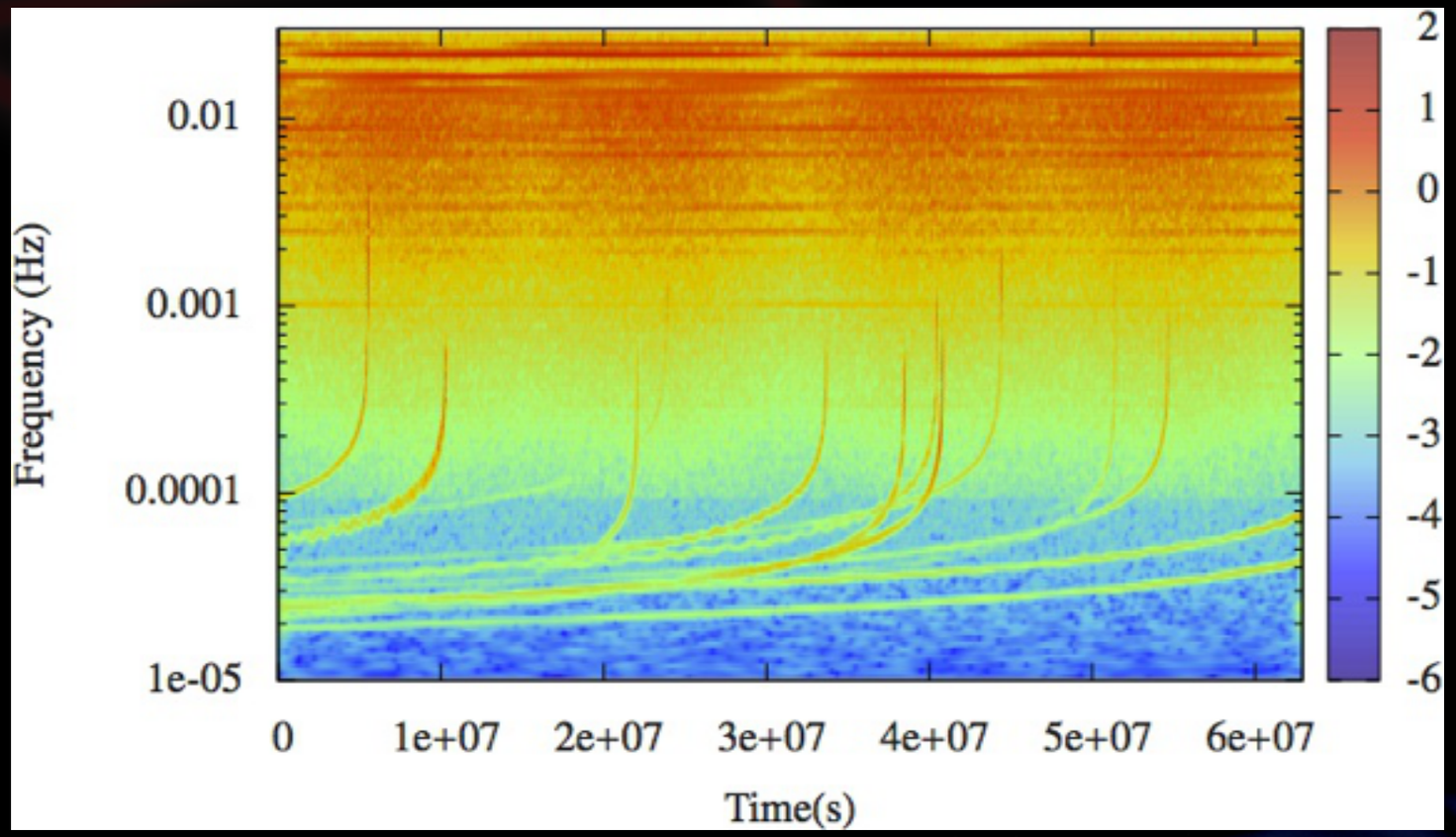
L3 — Catalogs of GWs sources with their waveform

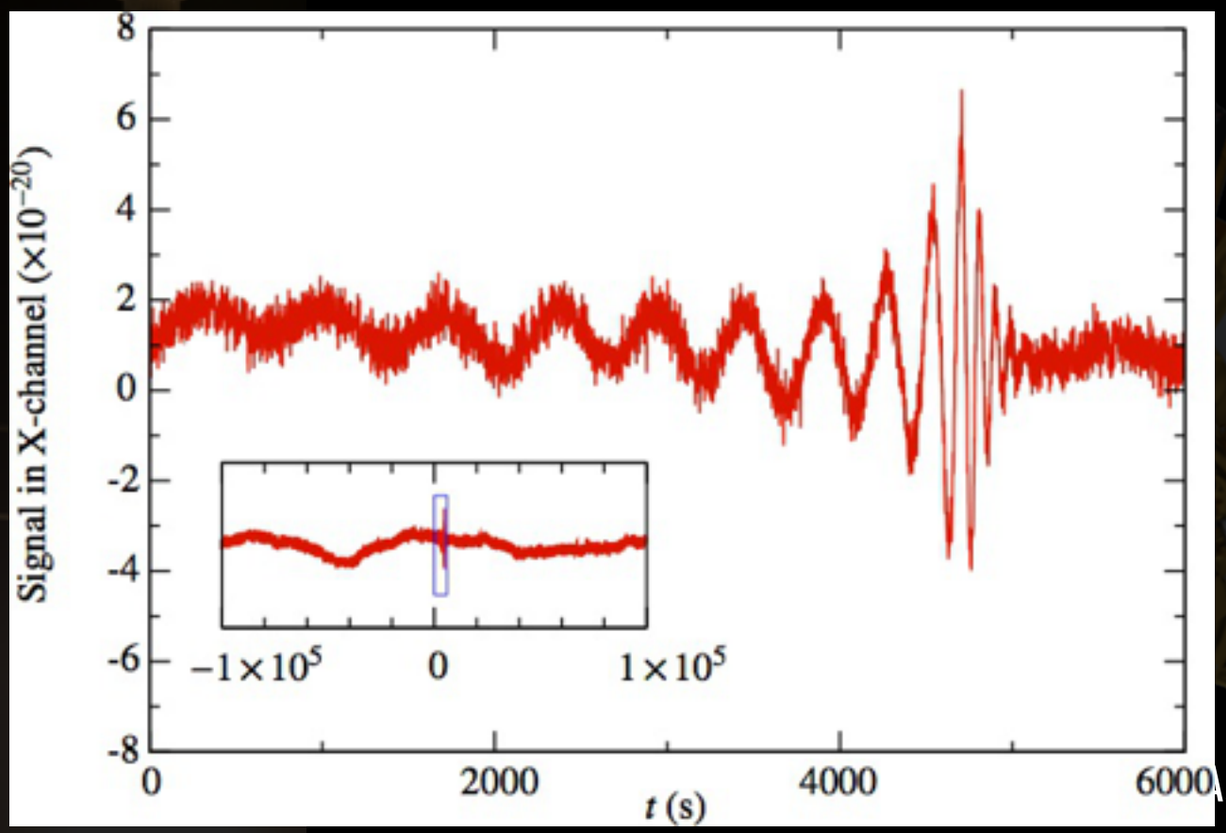
GW sources

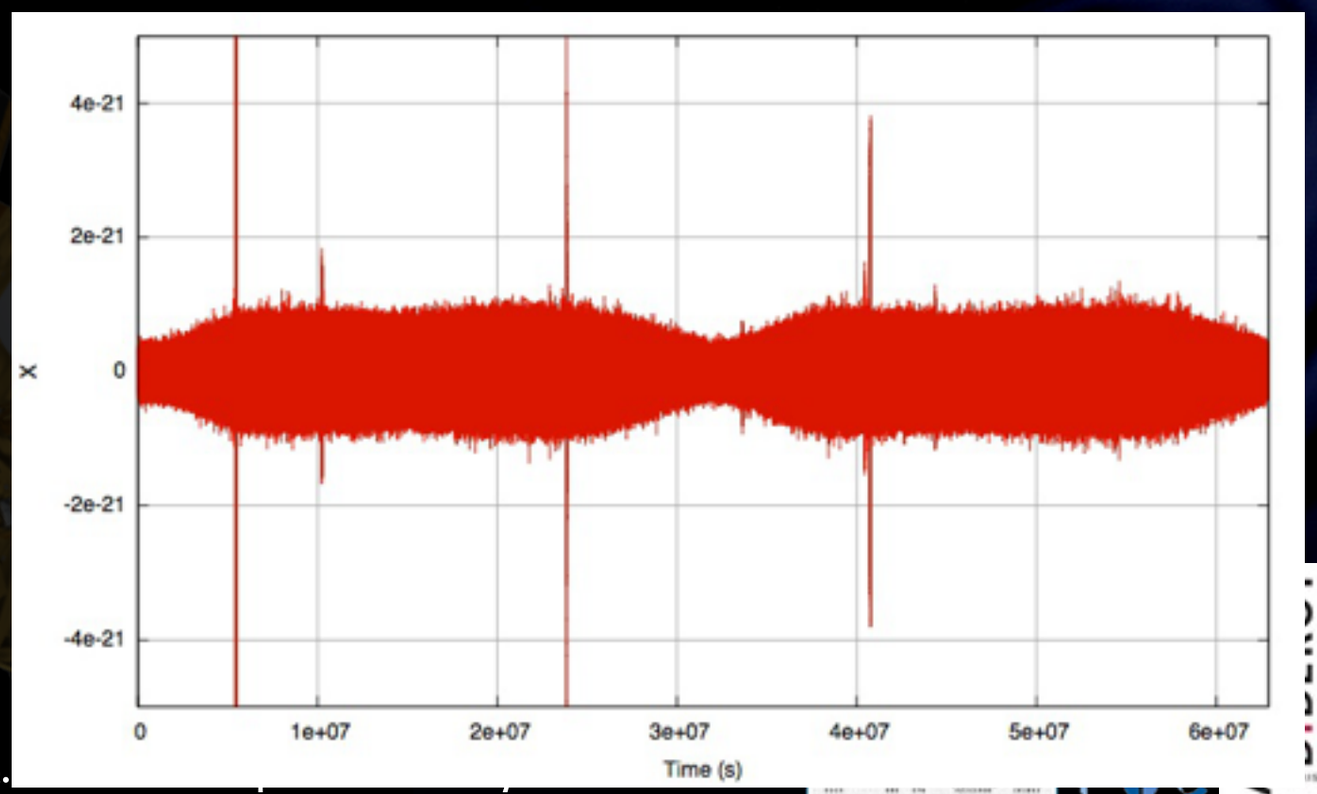
- 6 x10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources

GWs in LISA data

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







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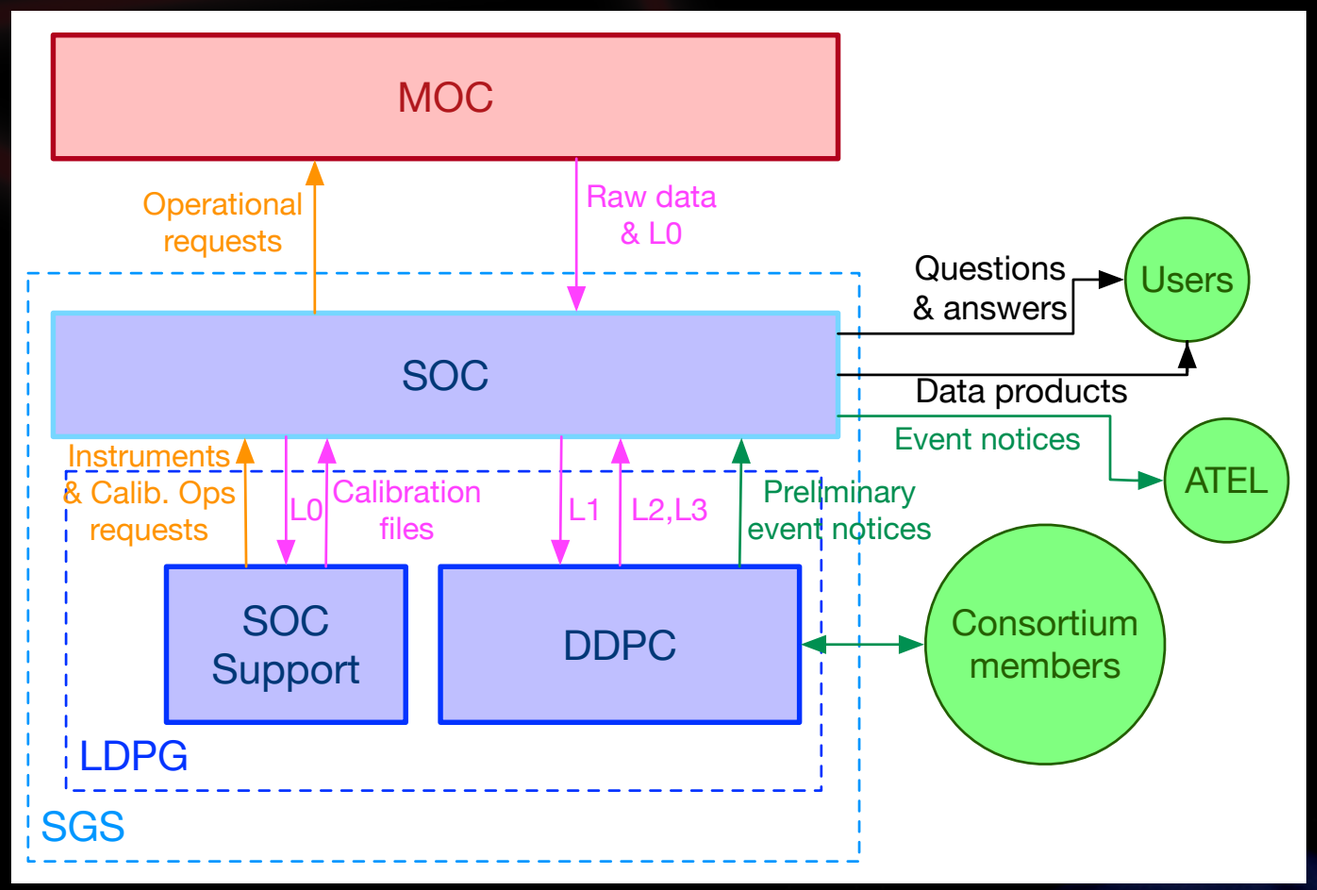
DDPC

- LISA Ground Segment:



- Results of CNES Phase-0:
  - First analysis of this kind + potential unknown sources
    =>Keep flexibility + continuous evolution
  - Permanent sources + transient sources + continuous evolution of codes (full reprocessing phase)
    => fluctuations of the computational charge: mixed infrastructure (cluster + cloud)

Current vision of the DDPC

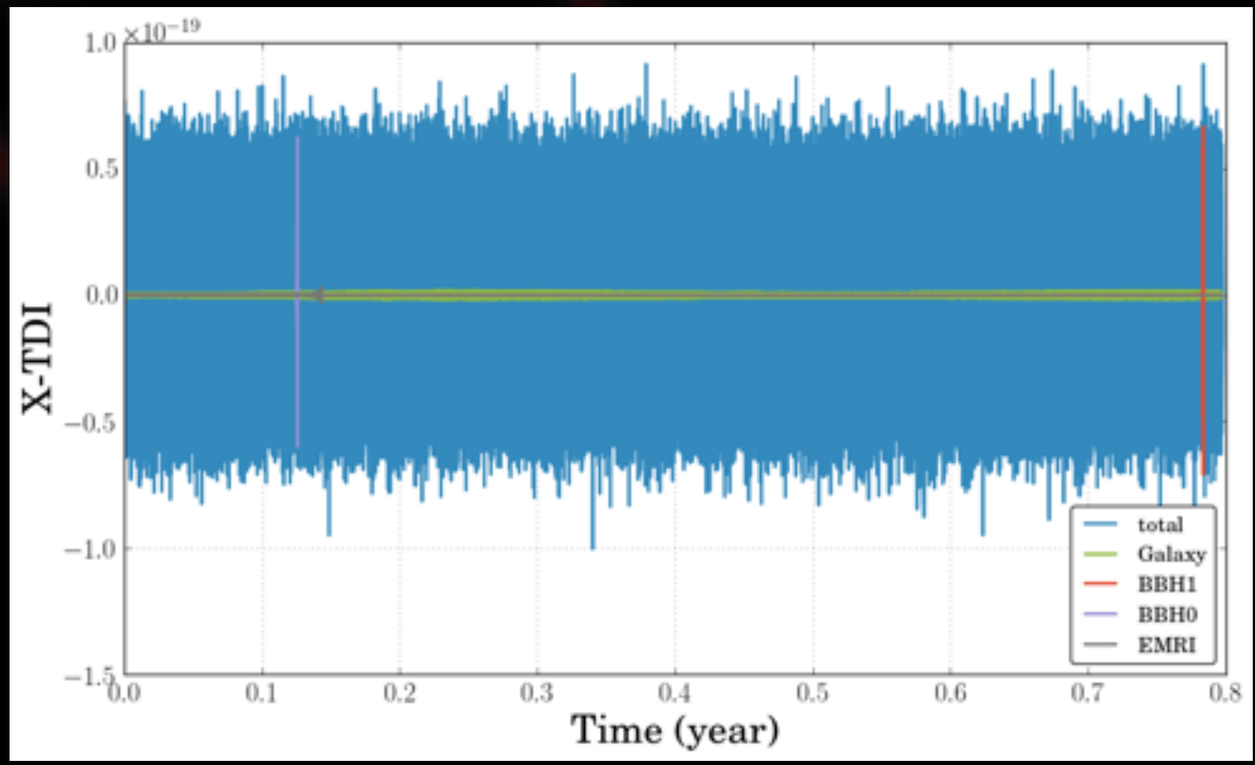
- DPC: unique entity responsable for the data processing (driving, integration of software block, ...)
- DPC in charge of delivering L2 & L3 products + what's necessary to reproduce/refine the analysis (i.e. input data + software + its running environment + some CPU to run it).
- Data Computing Centres (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, ...
  - Fluctuations of computing load: hybrids cluster/cloud

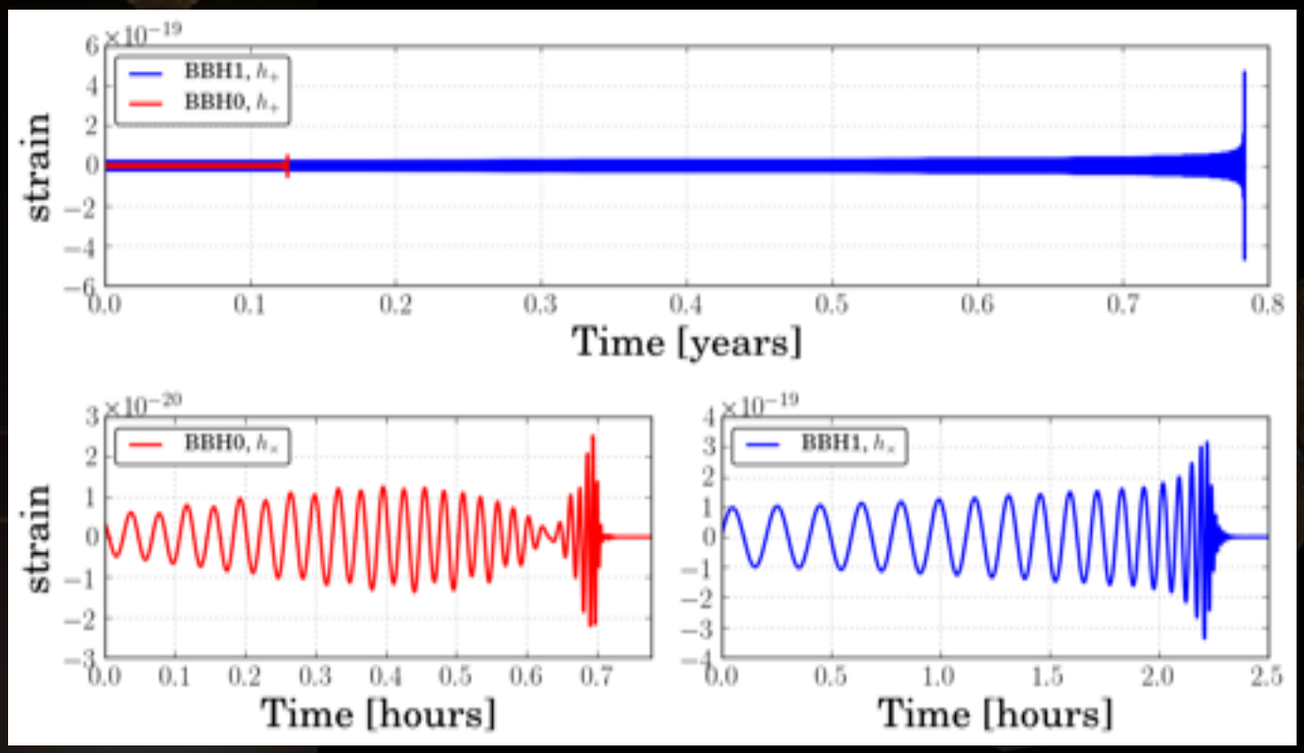
Proto-DPC: basics

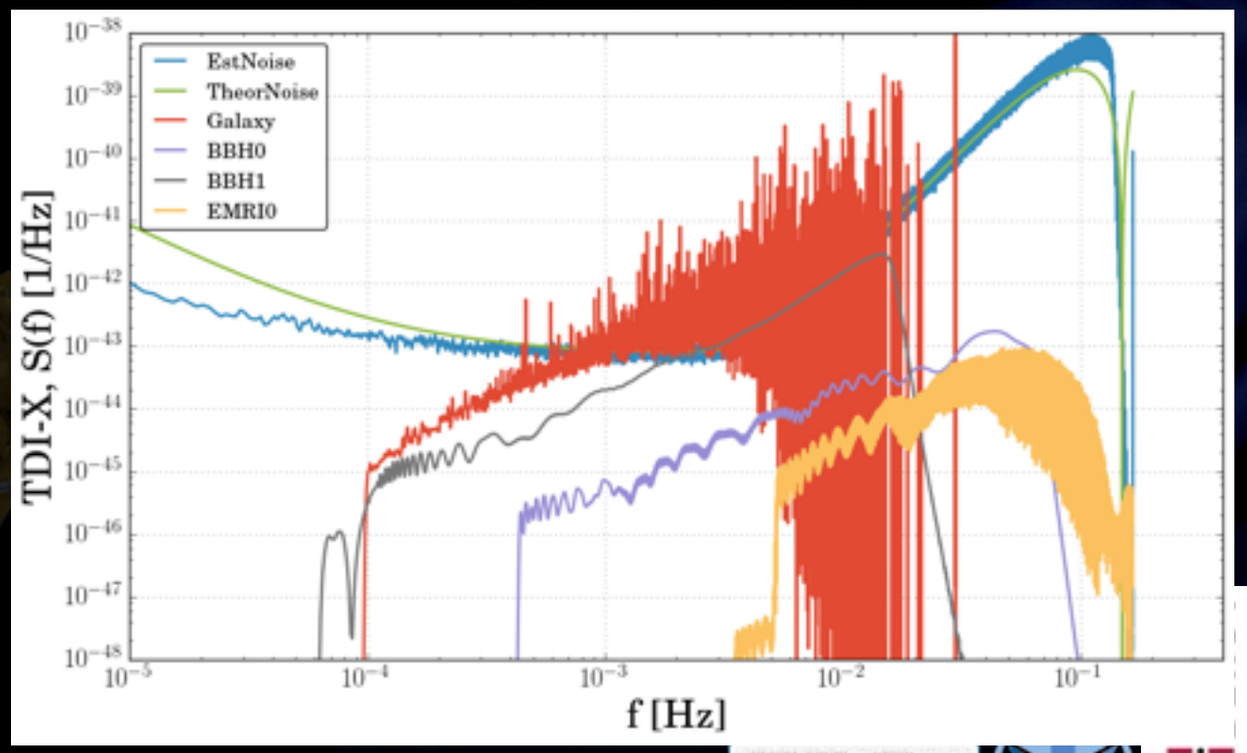
- Development environment: in production
  - Collaborative work, reproducibility of a rapidly evolving & composite DA pipeline; Keep control of performance, precision, readability, etc
  - Use existing standard tool (version control, Continuous integration, Docker)
- Data basis & data model: in R&Dn
  - Data sharing, a lot of information (search engine, DB request, tree view);
  - Context: Not very big data volume for data itself but large number of sub-products, simulations, ... => LDC, simulations, LPF data
- Execution environment: in R&D

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







Outline

- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISAPathfinder
- LISA status and organization
- LISA scientific performances
- LISAFrance
  - Distributed Data Processing Center
  - AIV(T)
- Conclusion and perspectives

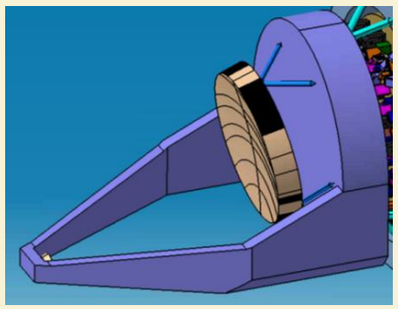
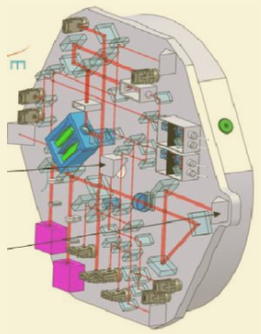
Integration & performance model

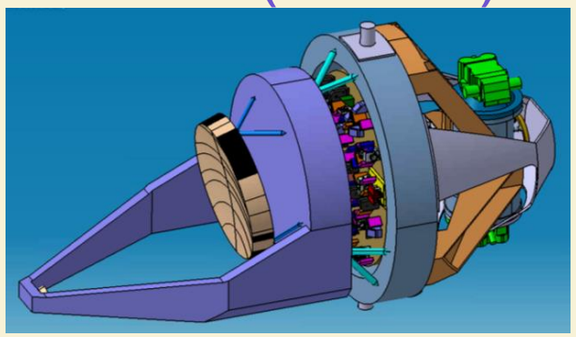
- In LISA, the "instrument" is the satellites' constellation !
  - Highly integrated spacecraft
  - Strong interactions between subsystems (payload & platform)
- A (very) precise knowledge of the noise sources and detector response is required.
- The Consortium must have the hands on a complete and precise 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

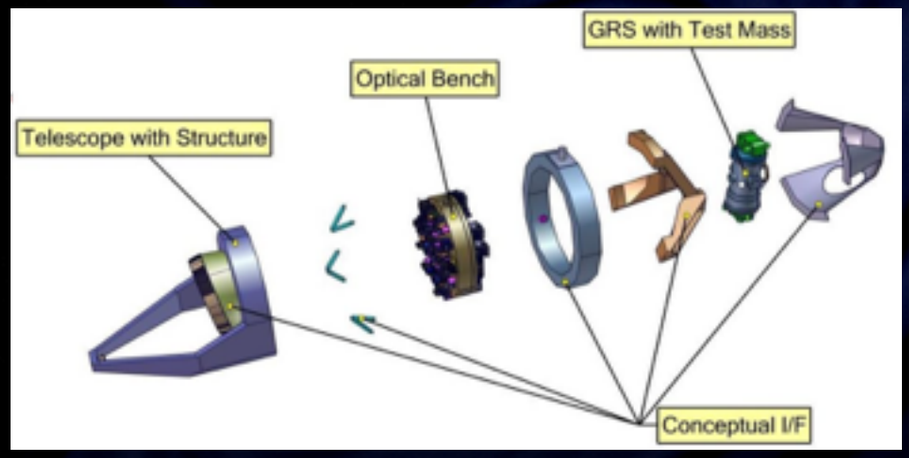
- Consortium is responsible for delivering integrated/tested/validated MOSA

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



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



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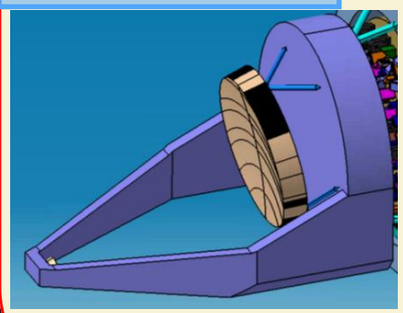
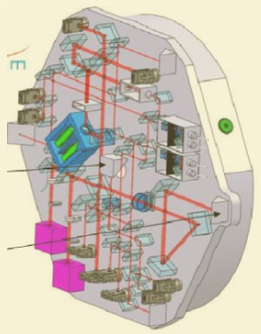

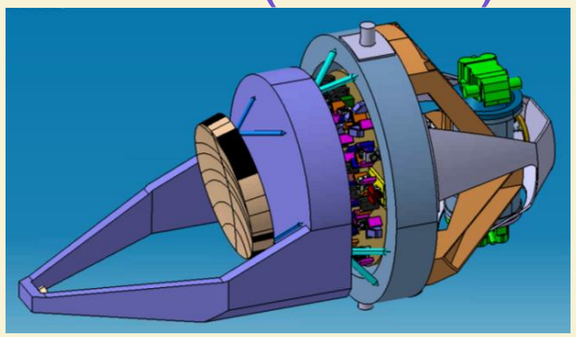

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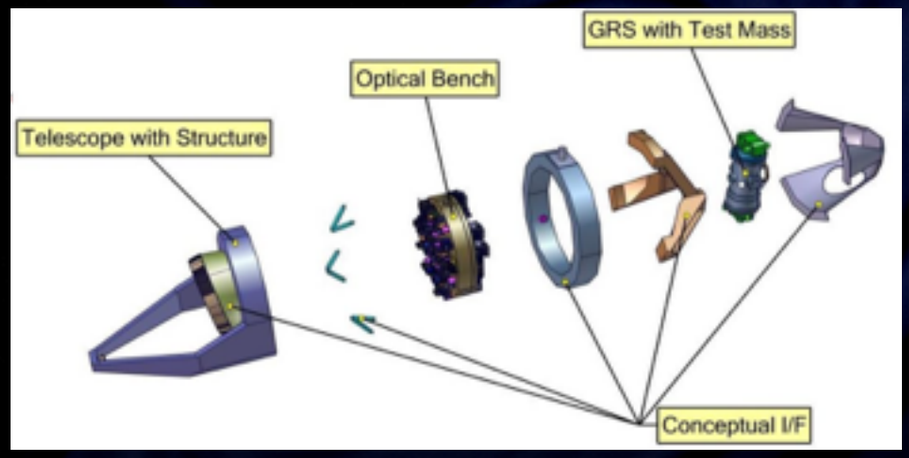


AIV(T) / perfos

- Start to be organized with Working Groups:
  - Straylight
  - Performances
  - Infrastructure & integration tools
  - Optical Ground Segment Equipement
  - Laser Ground Segment Equipement
  - Monitoring & control des GSEs
  - Integration procedures
  - Contamination control

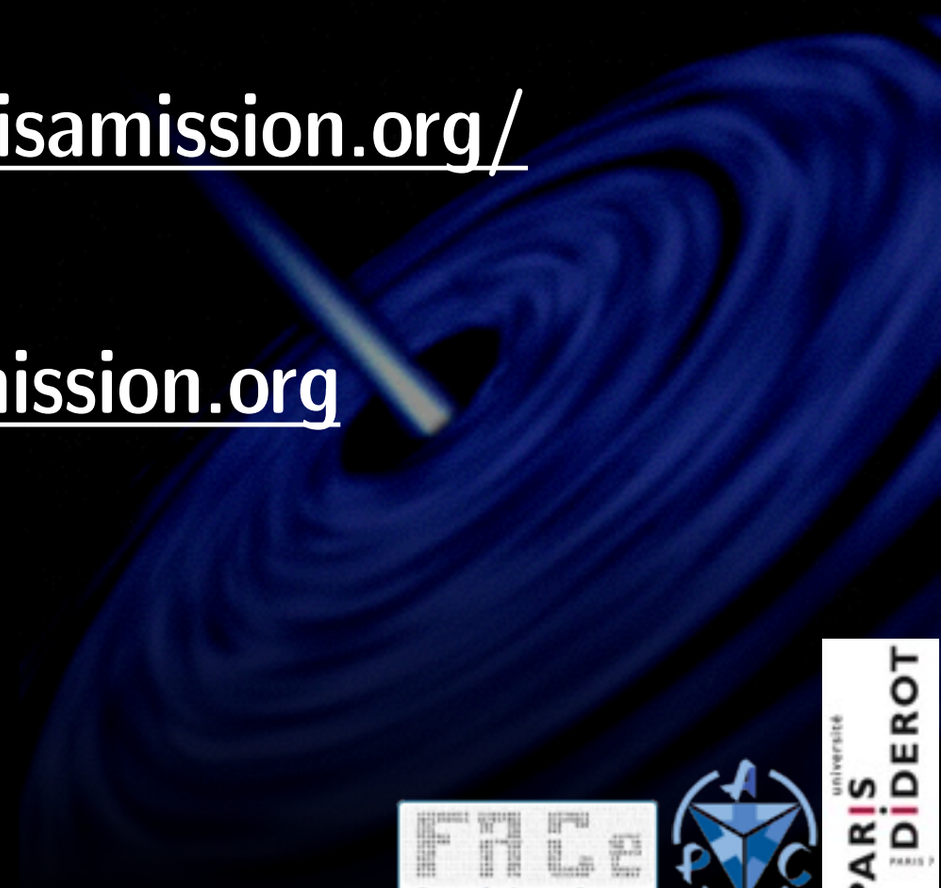
Summary

- 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: physics, astrophysics, cosmology, ...
- LISAPathfinder: success
  - Performances $>$ 7 times better than the requirements
- LISAPathfinder + detections of Ground-based observatories
  $\Rightarrow$ Green light for LISA: large extension of the new window opened with LIGO/Virgo
  $\Rightarrow$ speed-up of the ESA planning:
  - Already done: call for mission, selection, phase 0
  - Now: phase A starting in April-May 2018

Thank you !

More informations: https://www.lisamission.org/

Sign-up: http://signup.lisamission.org



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