Observing the Gravitational Universe with LISA

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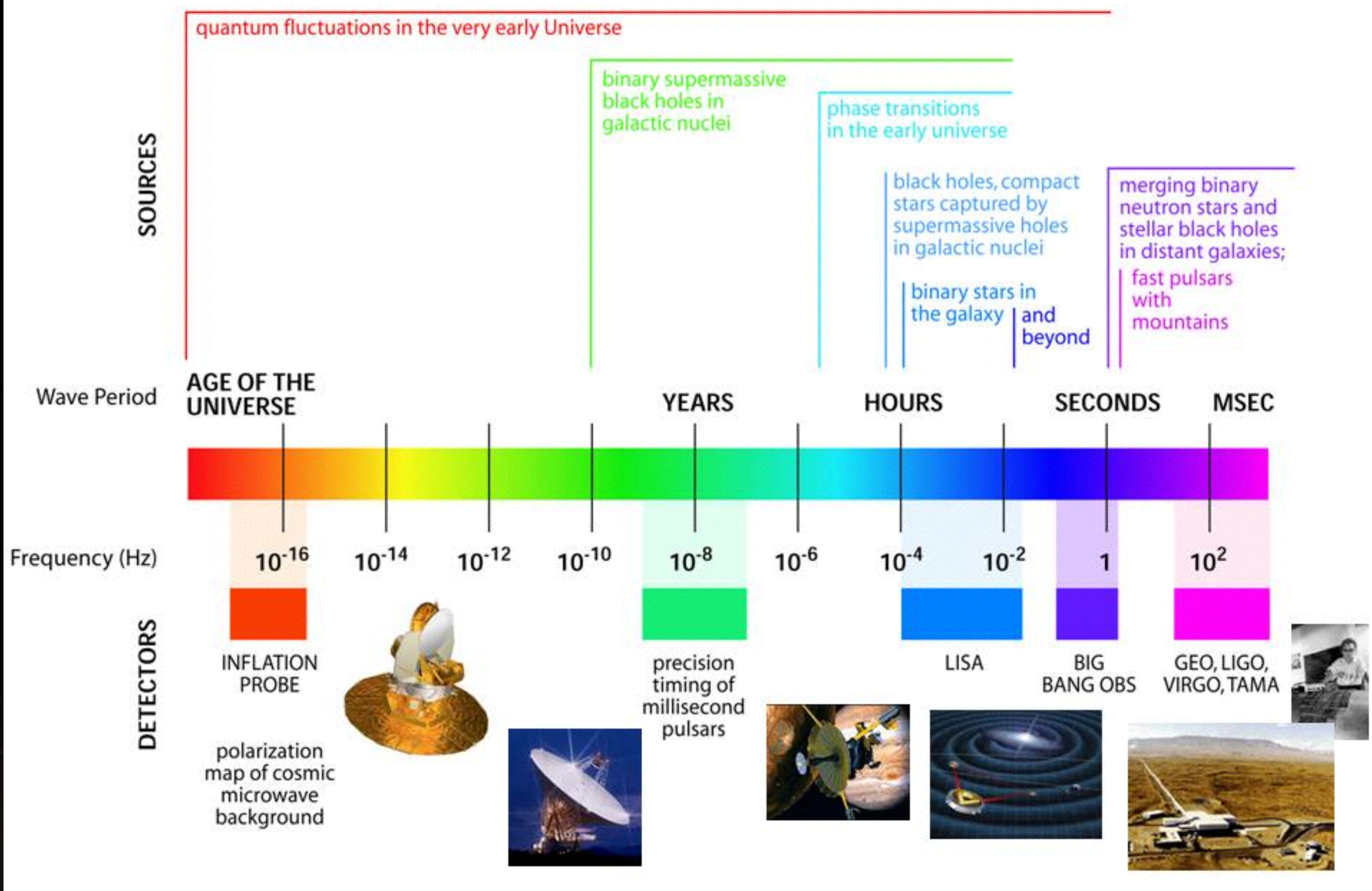
(APC – Université Paris-Diderot)
with contributions from Nikos Karnesis and Stas Babak

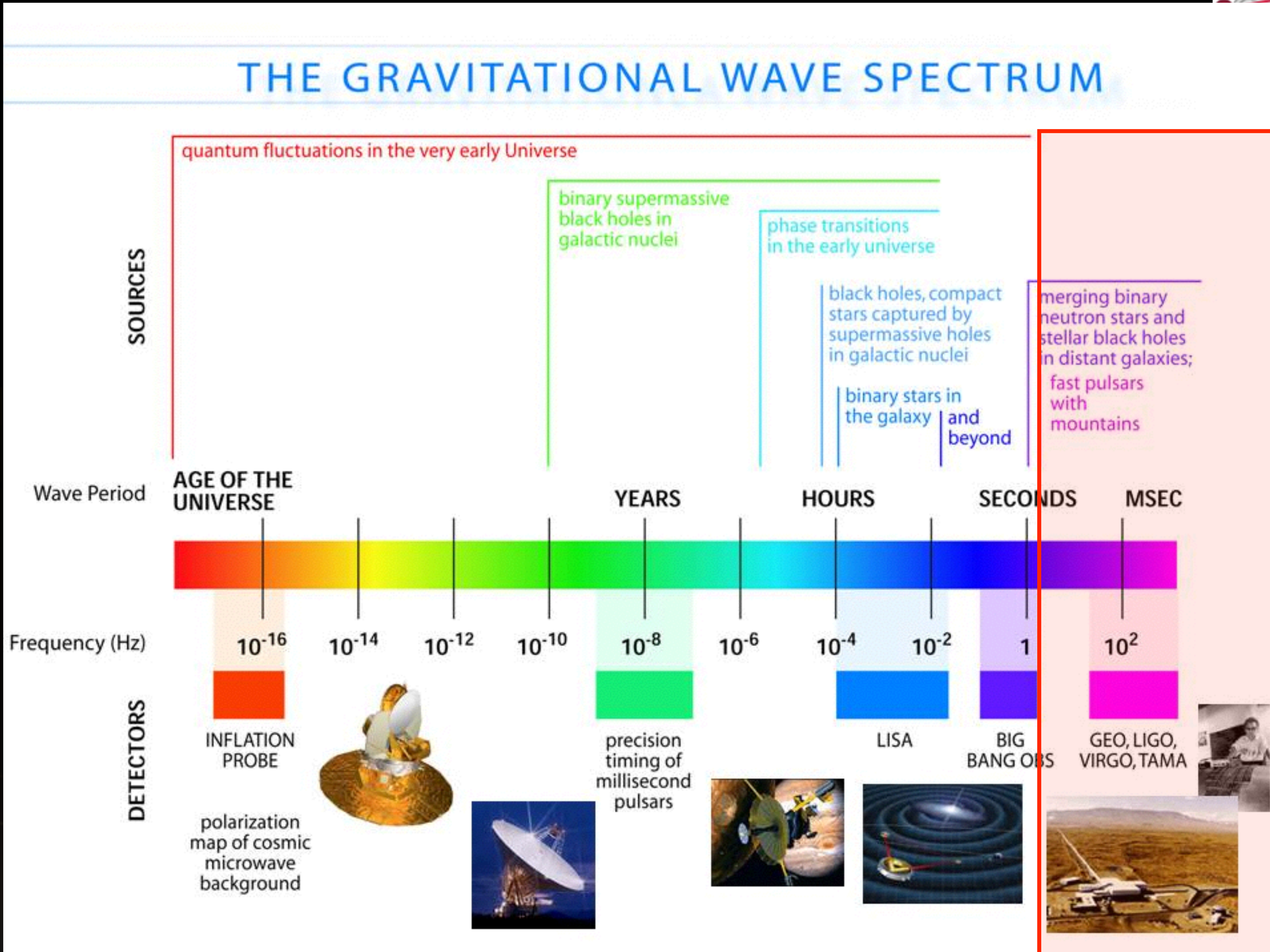
NORDITA
Gravitational Waves from the Early Universe
11th September 2019

Outline

- Gravitational wave sources in the millihertz regime
- LISA: a space-based gravitational wave observatory
- LISAPathfinder
- LISA status and organisation
- LISA scientific performances
- LISA Distributed Data Processing Center
- LISA Data Challenge
- An Example of Data Analysis for Stochastic Background

THE GRAVITATIONAL WAVE SPECTRUM

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quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
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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
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YEARS
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MSEC
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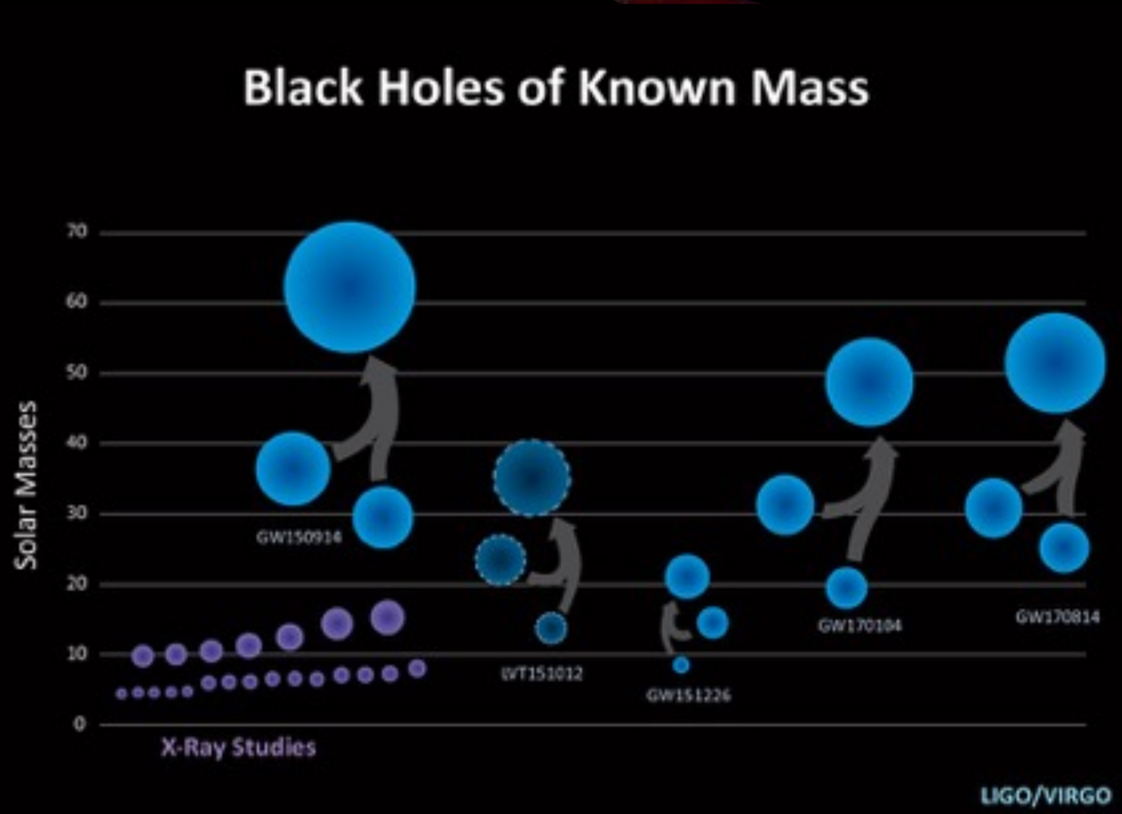
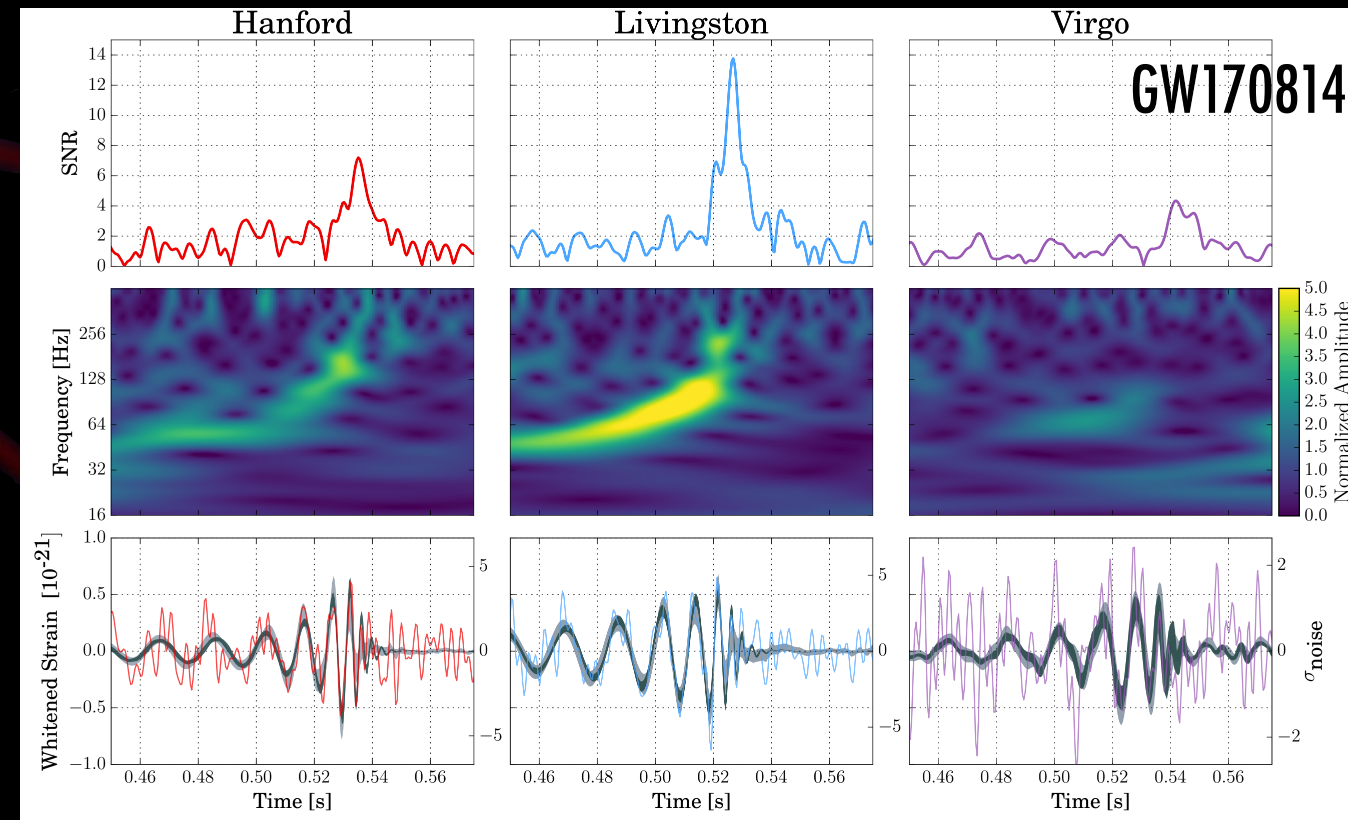
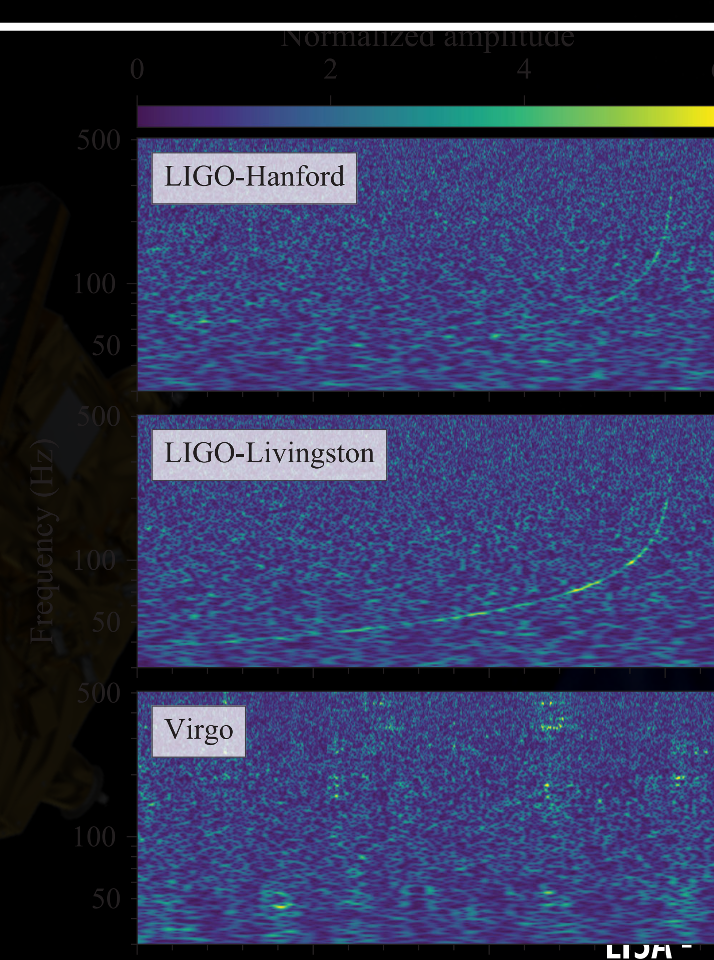
102
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA

Ground-based obs.: GWs detected





Binary Neutron Star - GW170817



NASA

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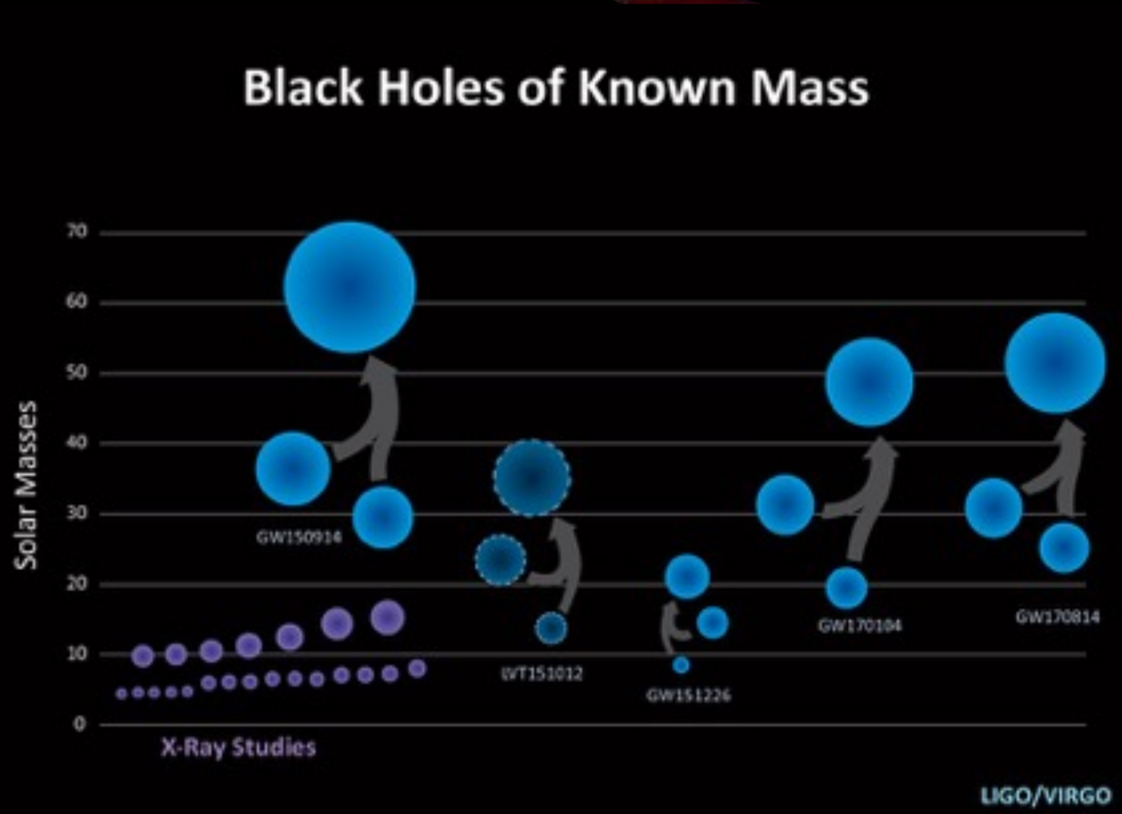

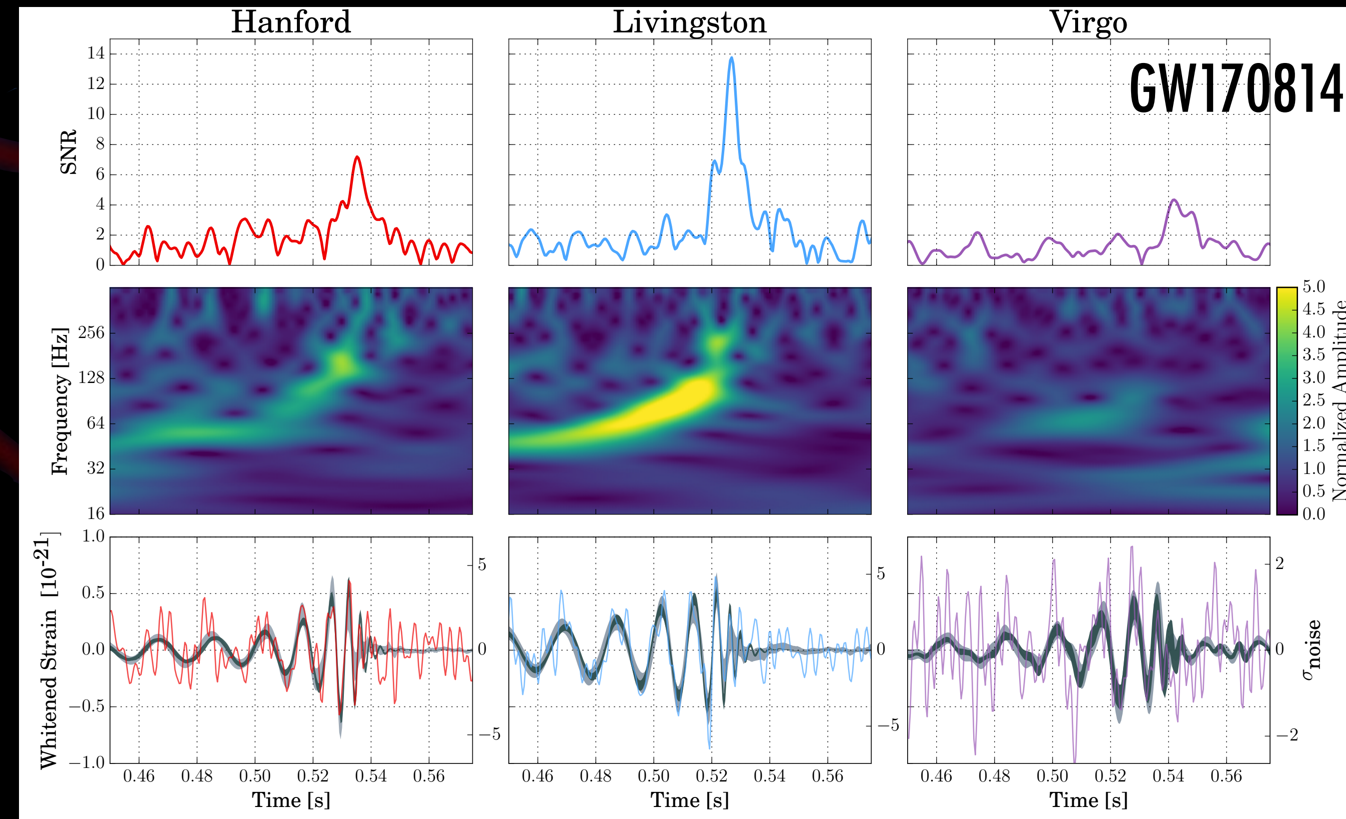

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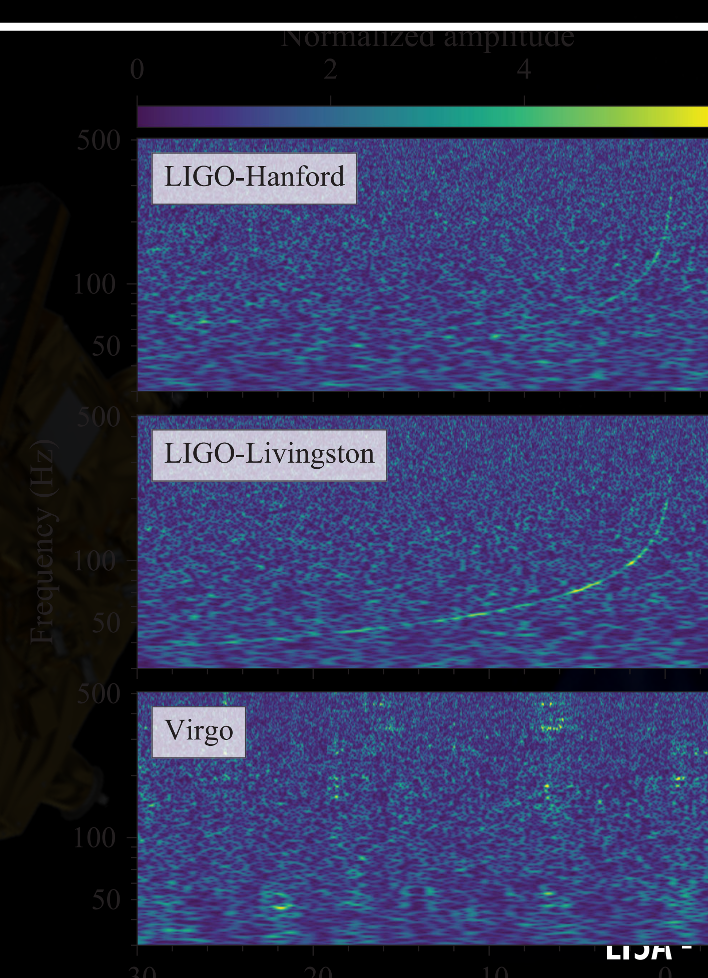

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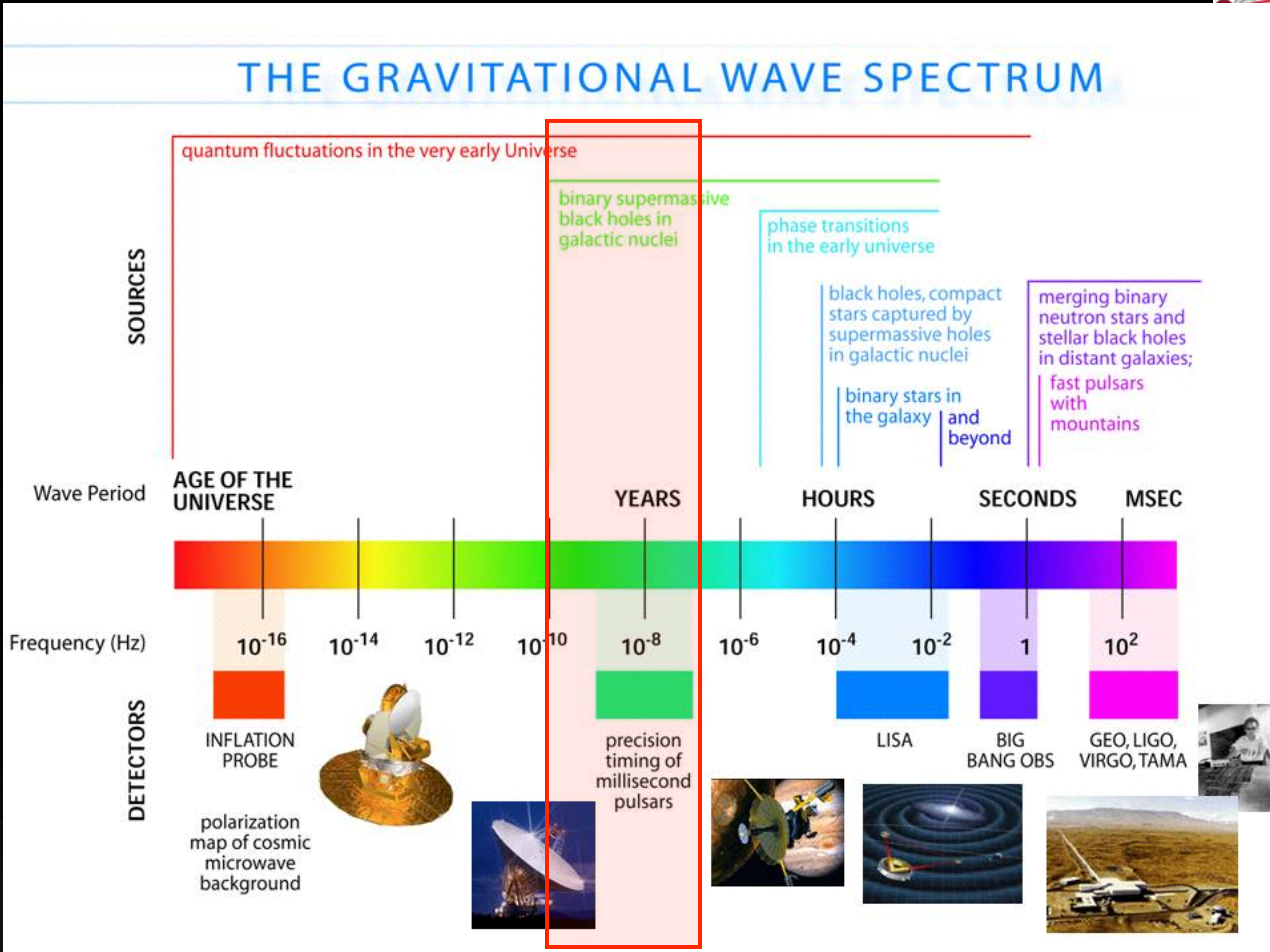
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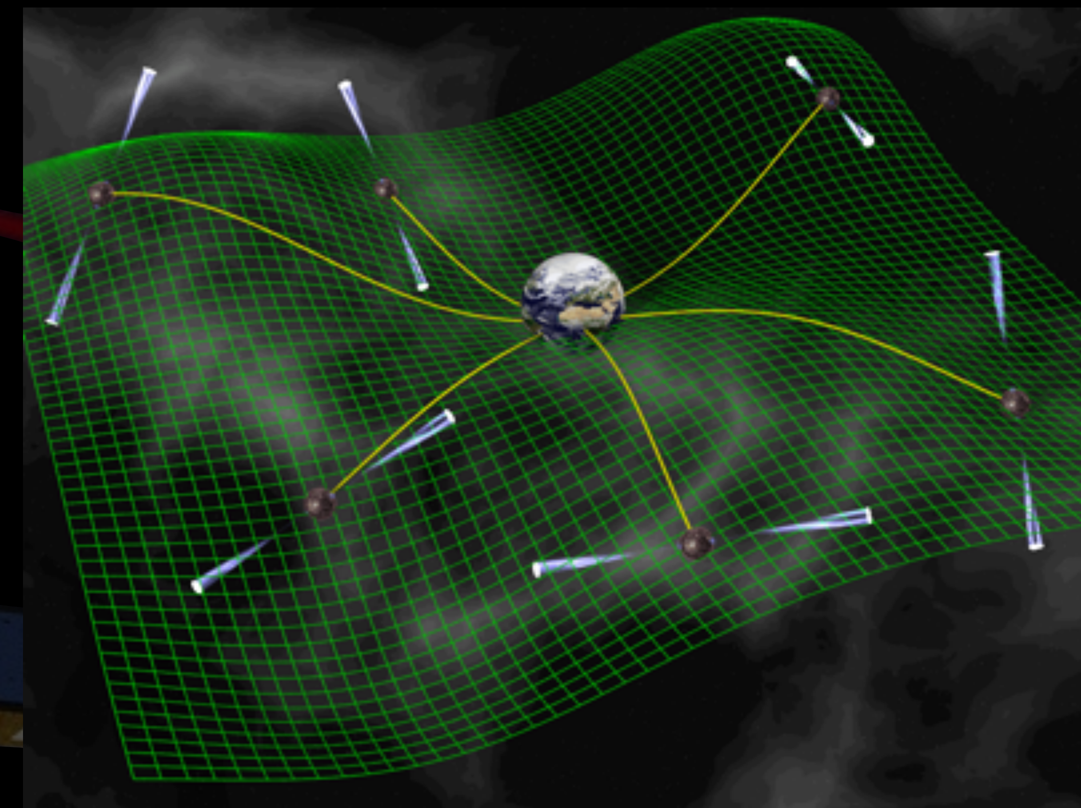
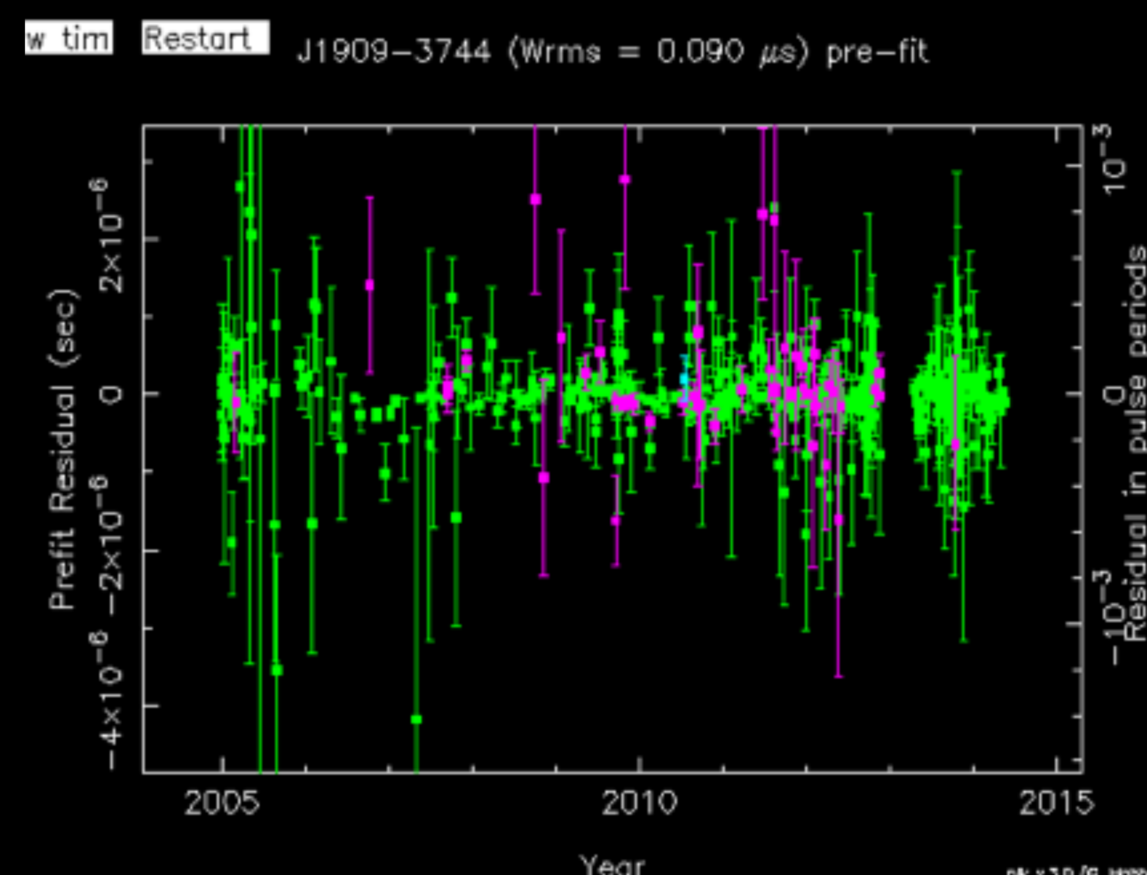
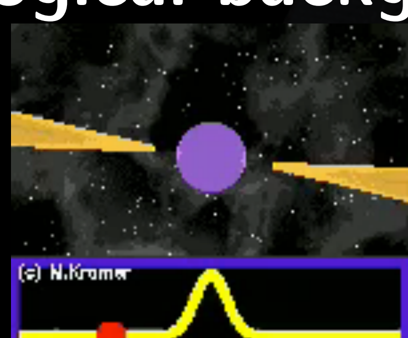
Pulsar Timing Array



- 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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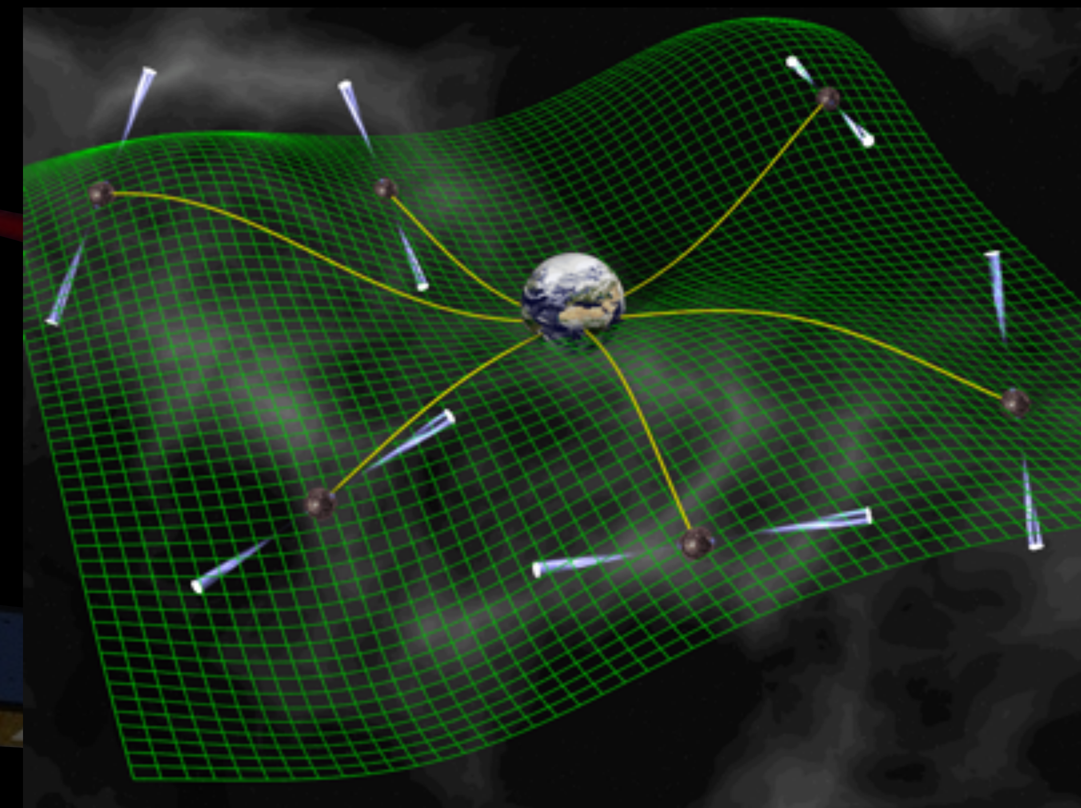

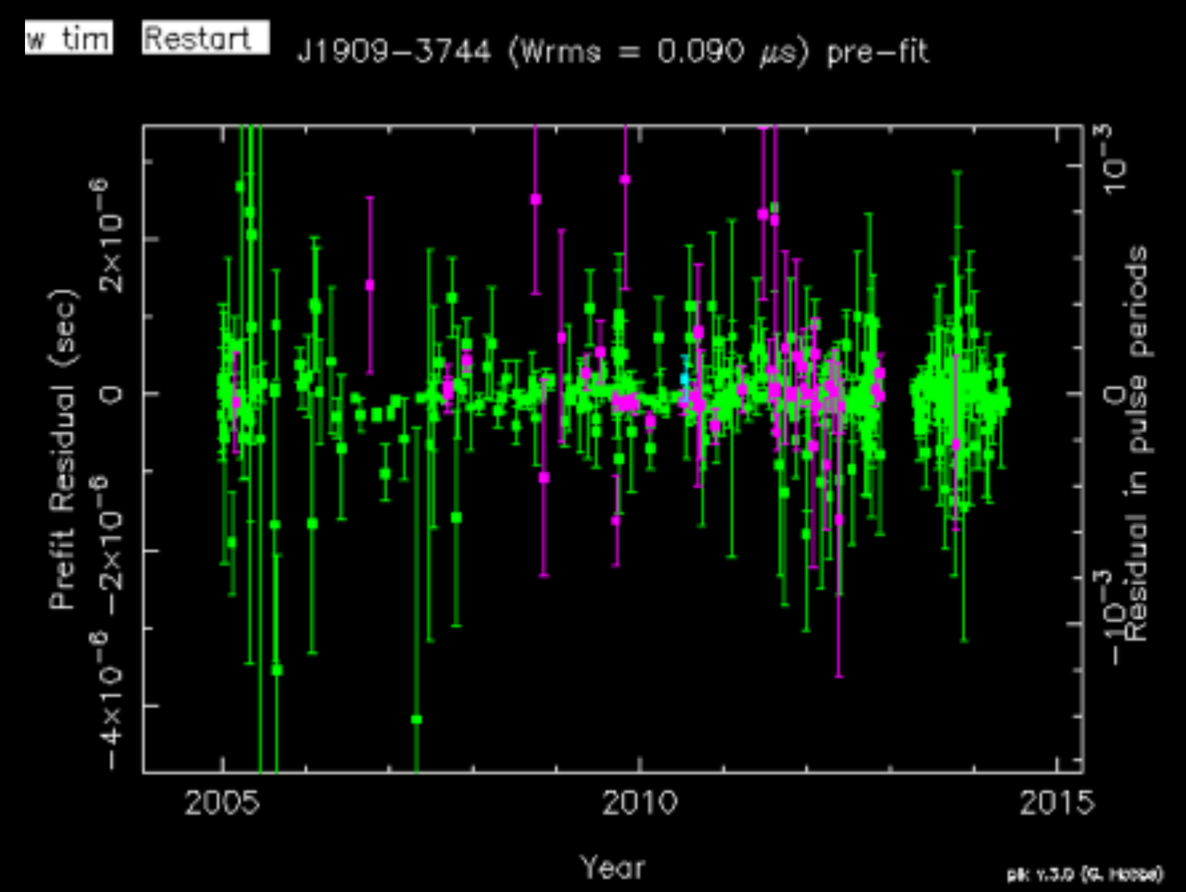

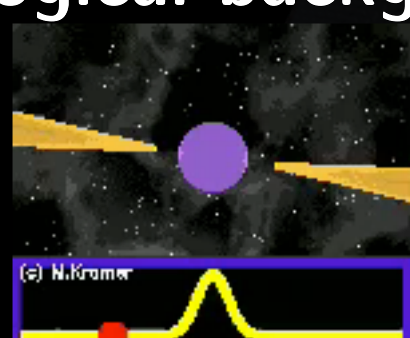

Pulsar Timing Array

- PTA-France collaboration: Nançay Radio Station, LPC2E, APC
- European PTA
- International PTA:
  - EPTA
  - NANOGrav (North America)
  - PPTA (Australia)
  - MeerKat (South Africa)
  - CPTA (China)
  - InPTA (India)

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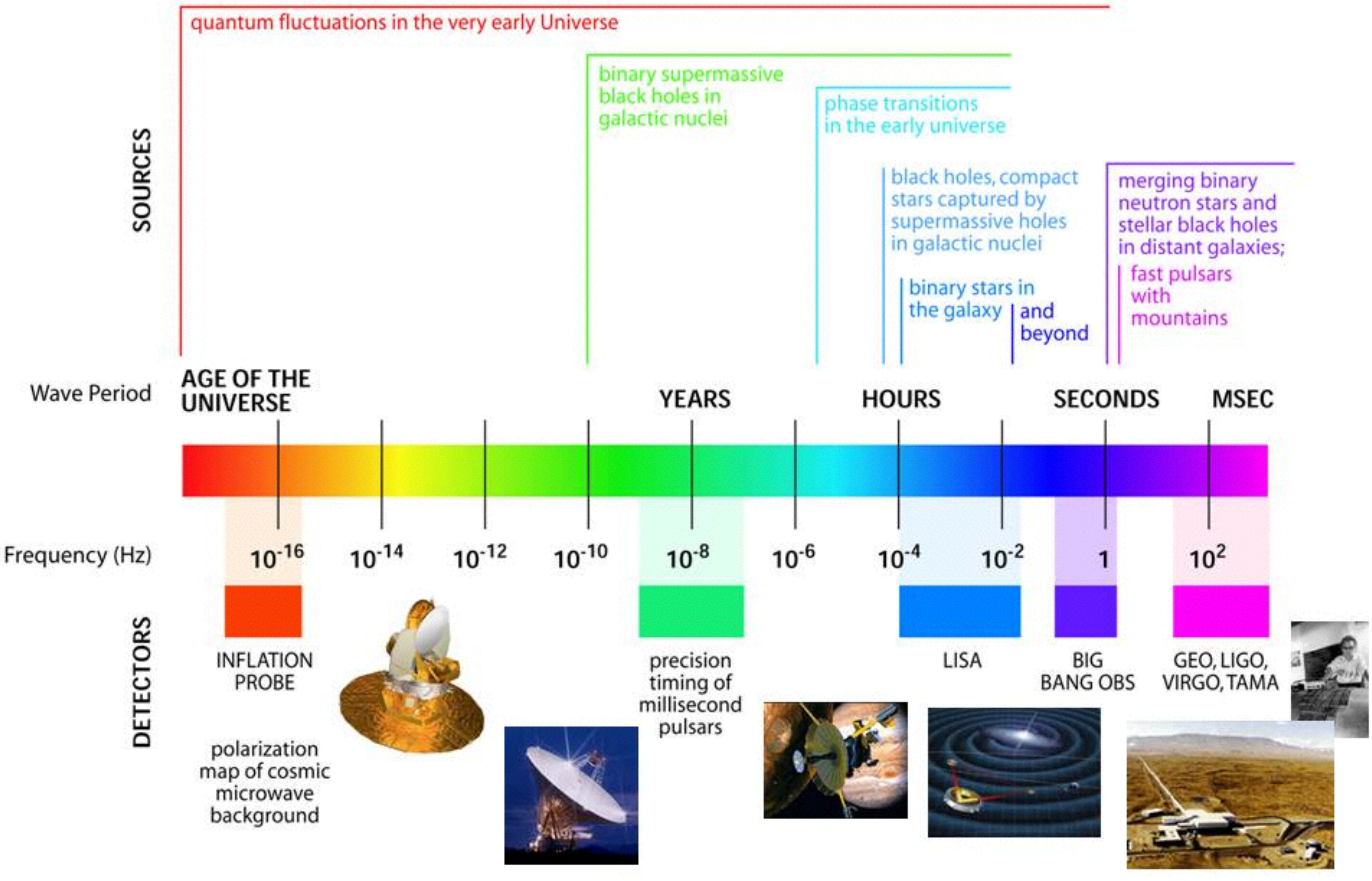

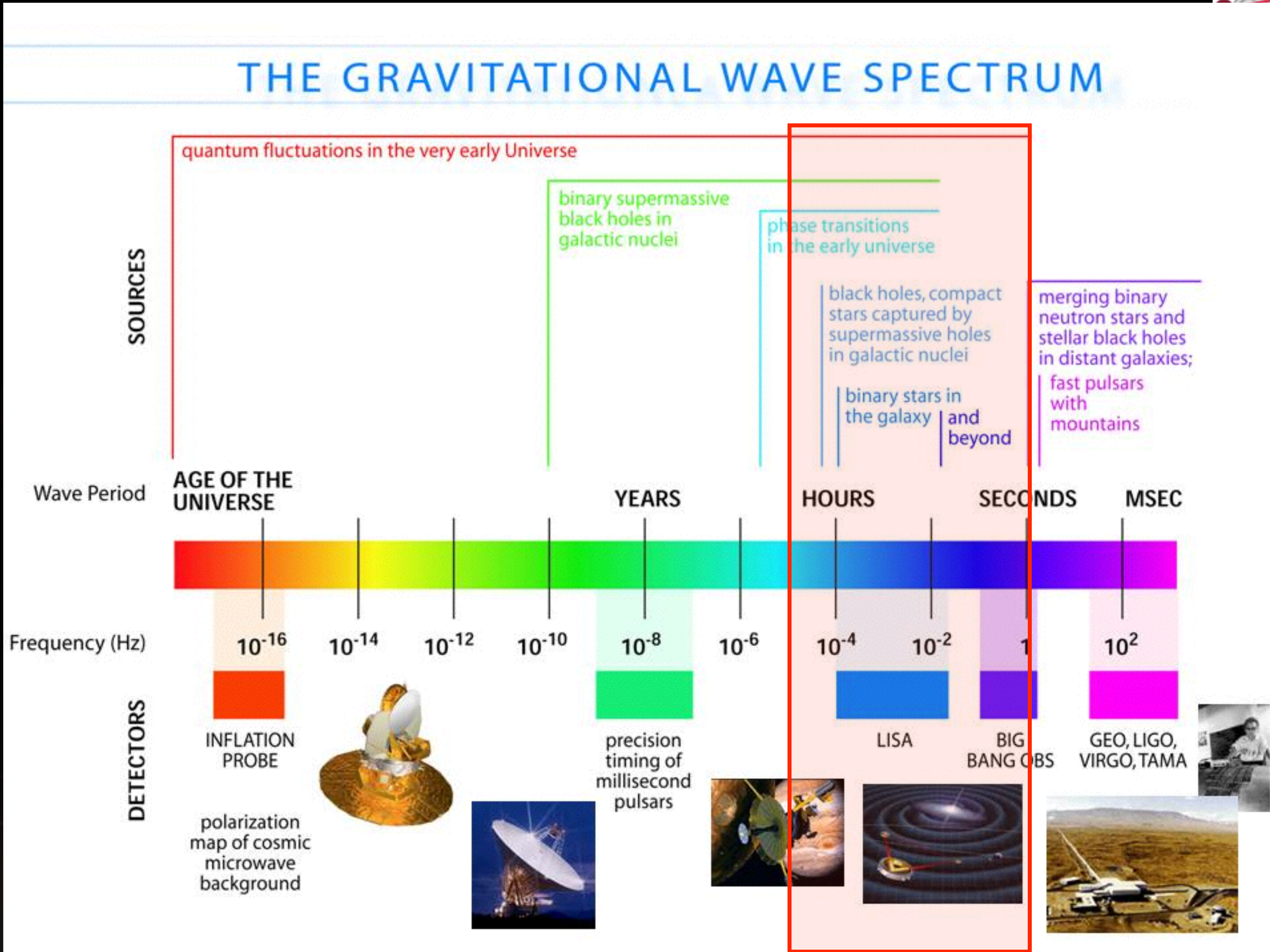
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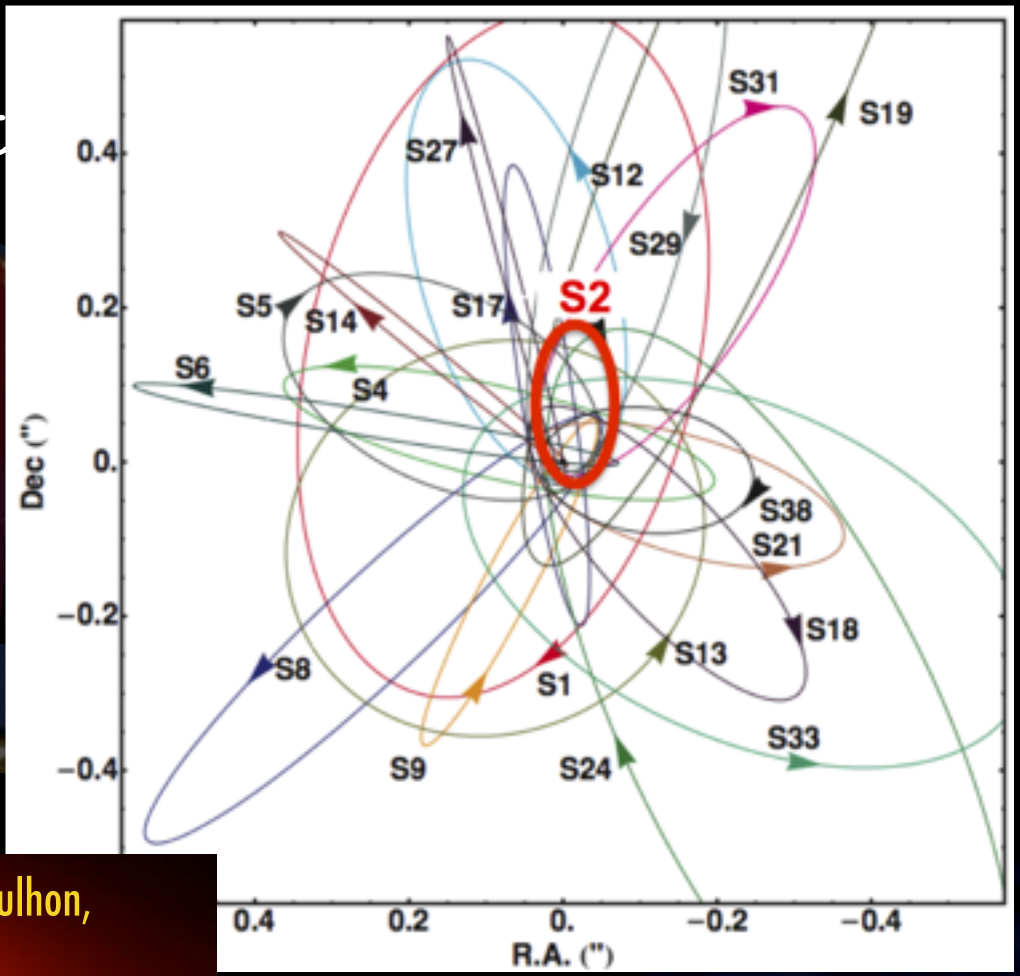
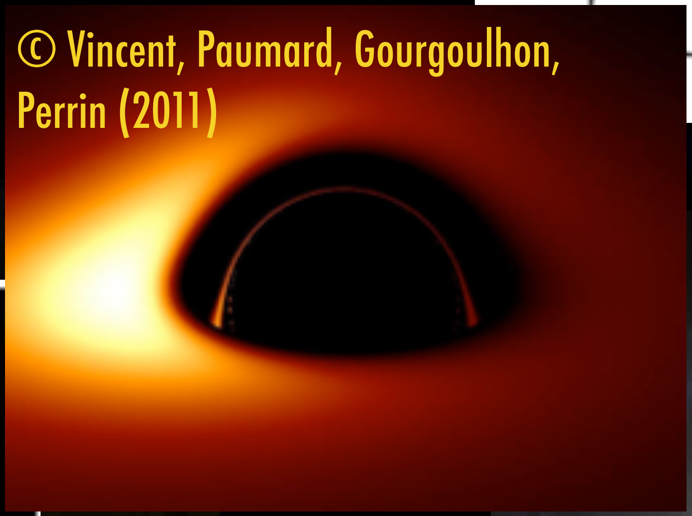
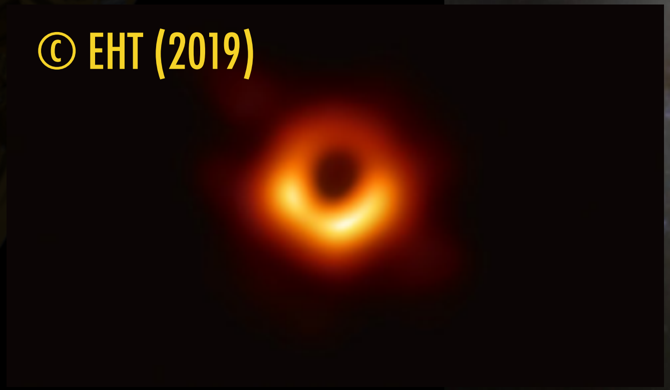
Supermassive black hole binaries

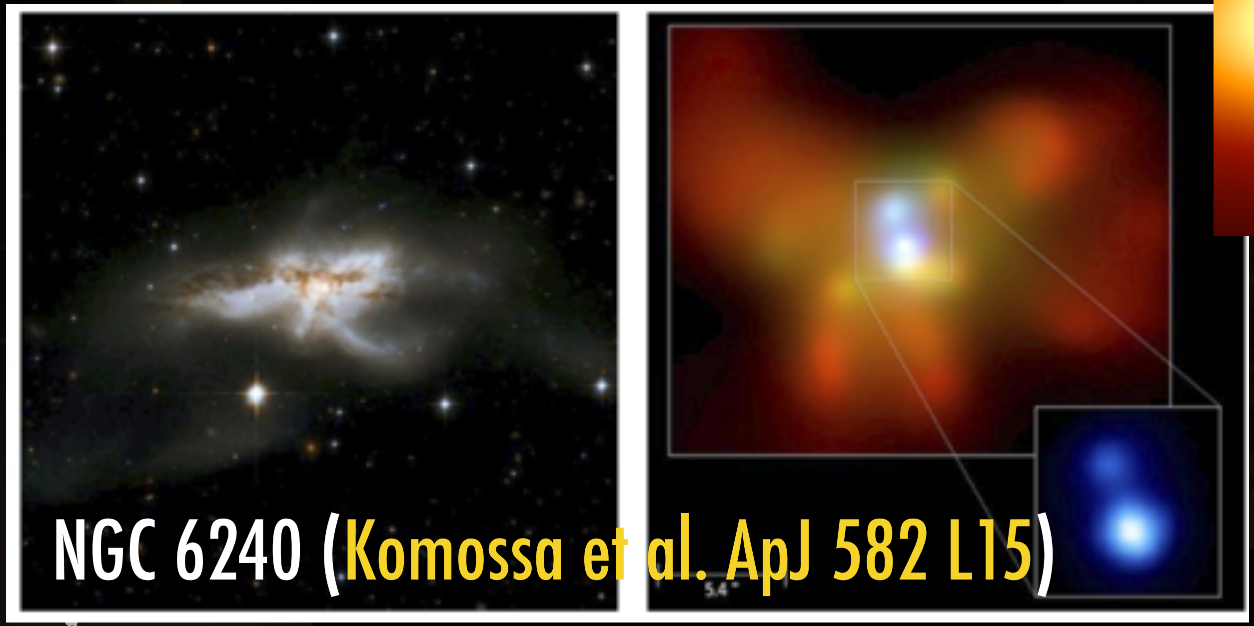
- Observations of Sgr A*, a dark massive object of 4.5×10^{6} M_{Sun} at the centre of Milky Way.
- Supermassive Black Hole are indirectly observed in the centre of a large number of galaxies (Active Galactic Nuclei).
- Observations of galaxies mergers.

  → MBH binaries should exist.
- Observations of double AGN





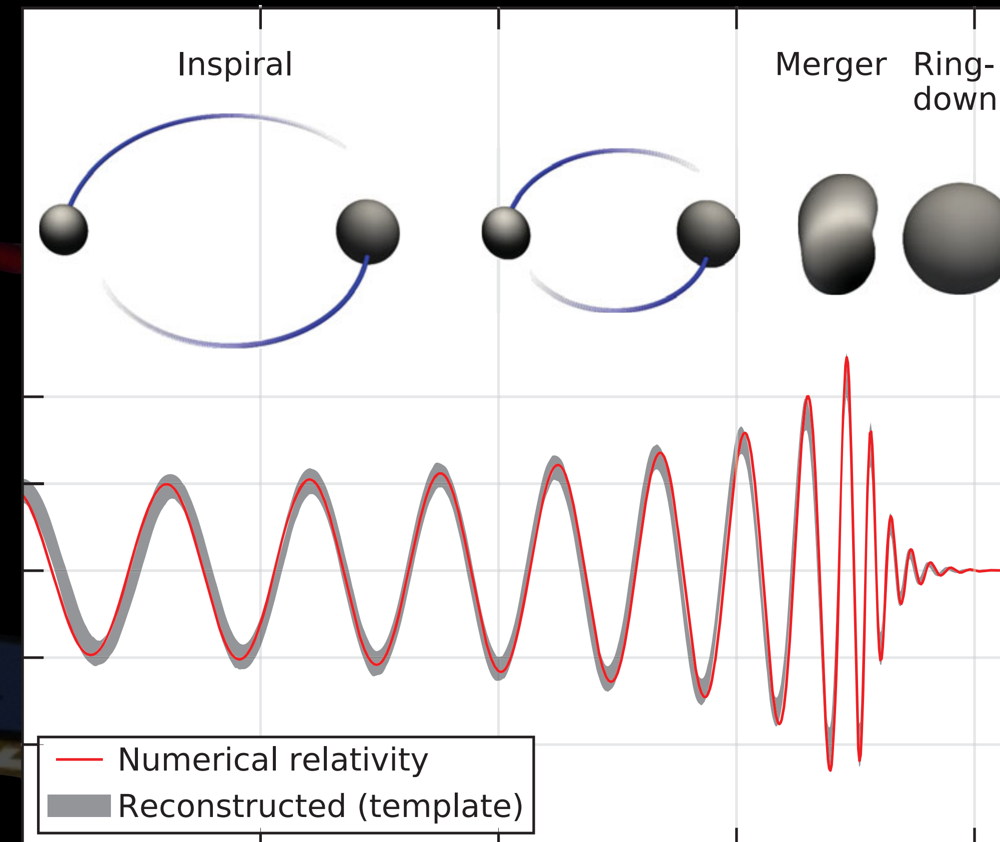



NGC 6240 (Komossa et al. ApJ 582 L15)

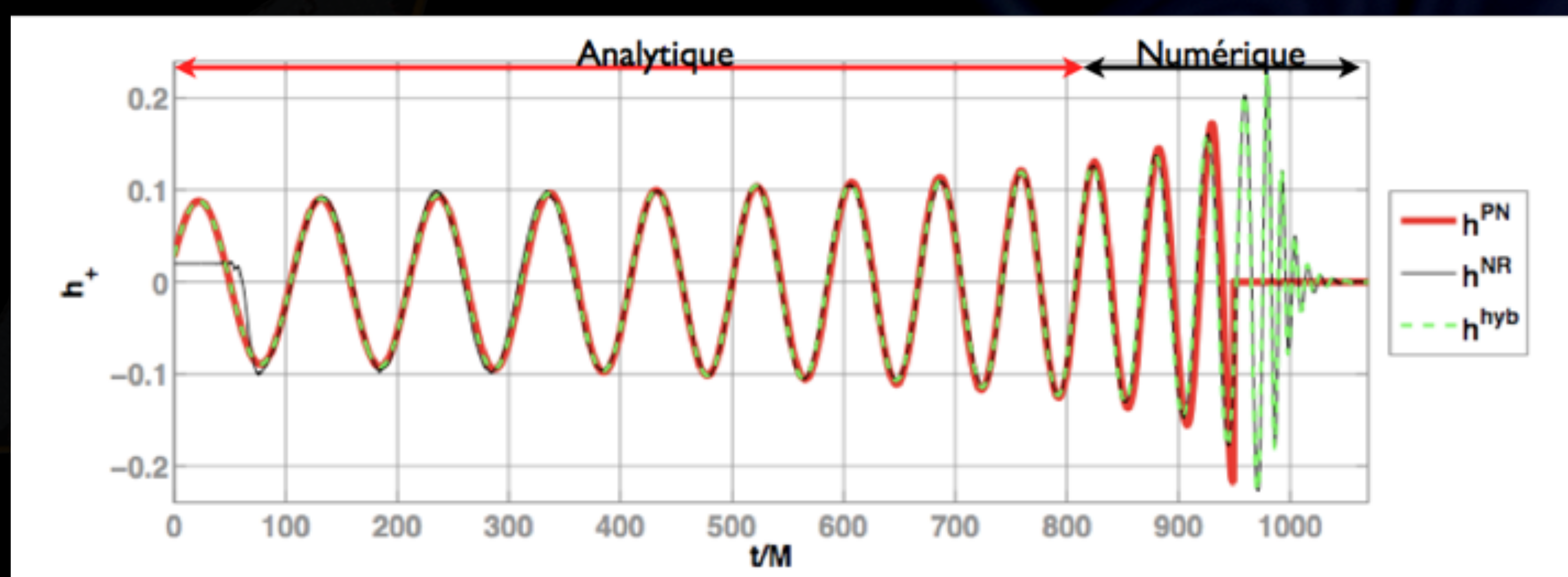

Antennae galaxies

Supermassive black hole binaries

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

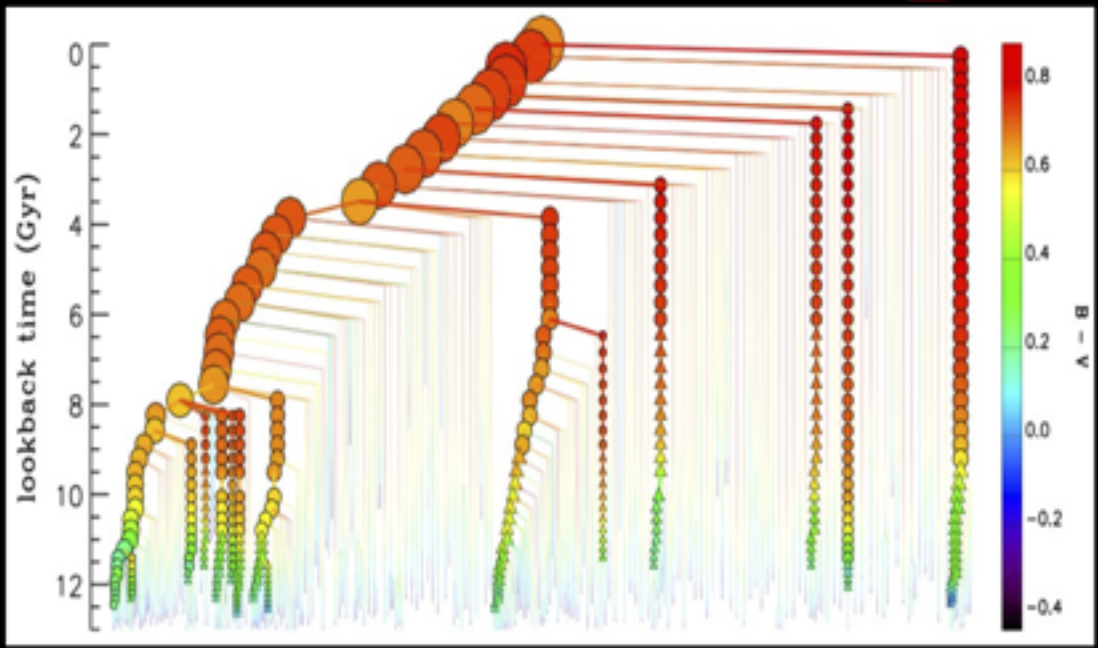


- No full waveform but several approximations exist :
  - Phenomenological waveform,
  - Effective One Body,
  - …



Supermassive black hole binaries

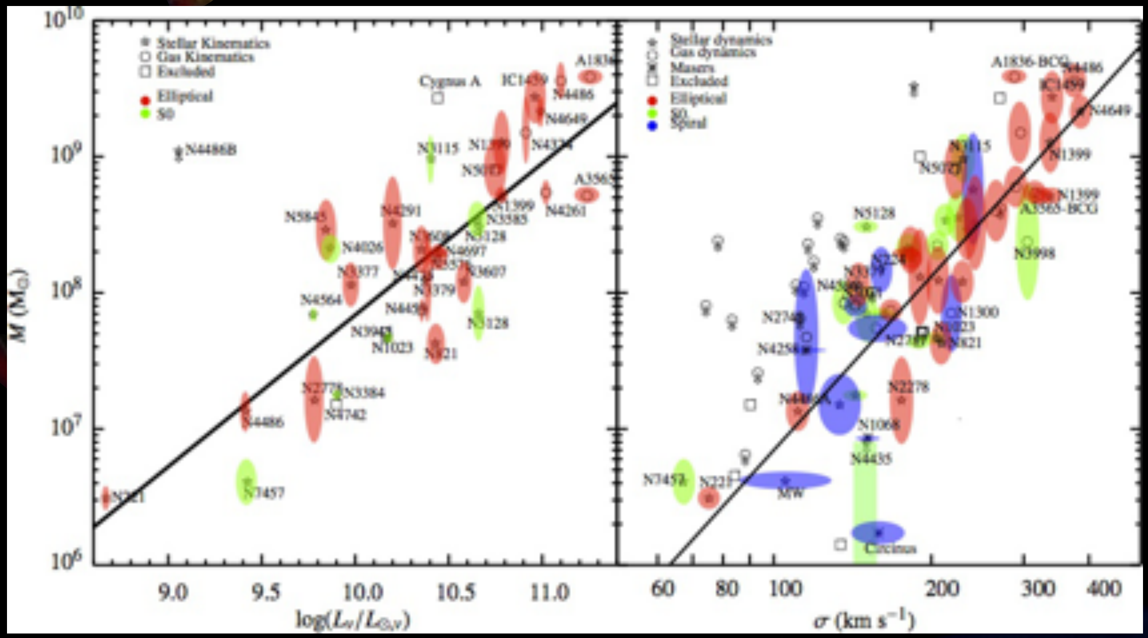
Galaxies merger tree
(cosmological simulation)



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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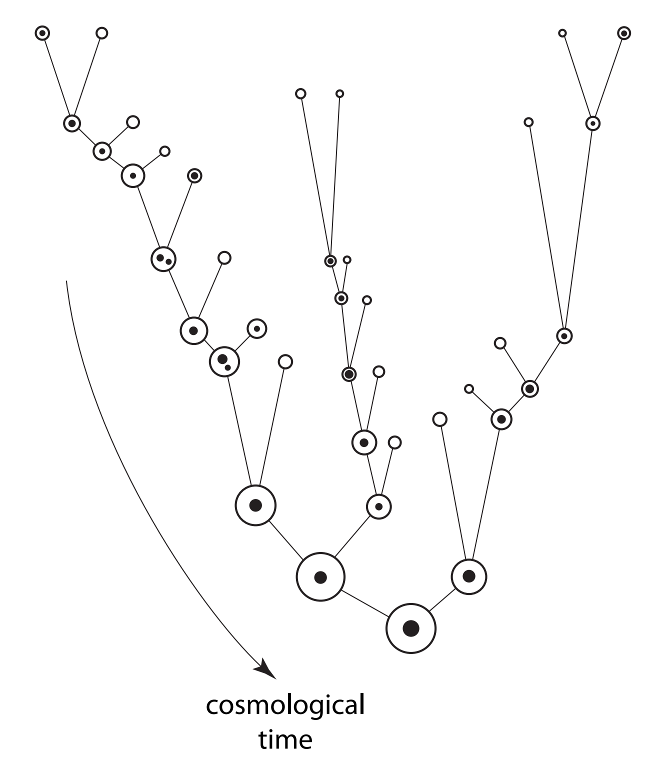
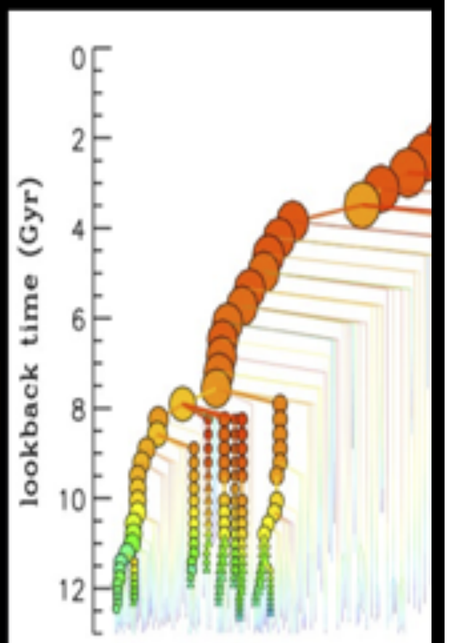


Supermassive black hole binaries

Galaxi
(cosmolo

speed of stars in
entral MBH mass

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



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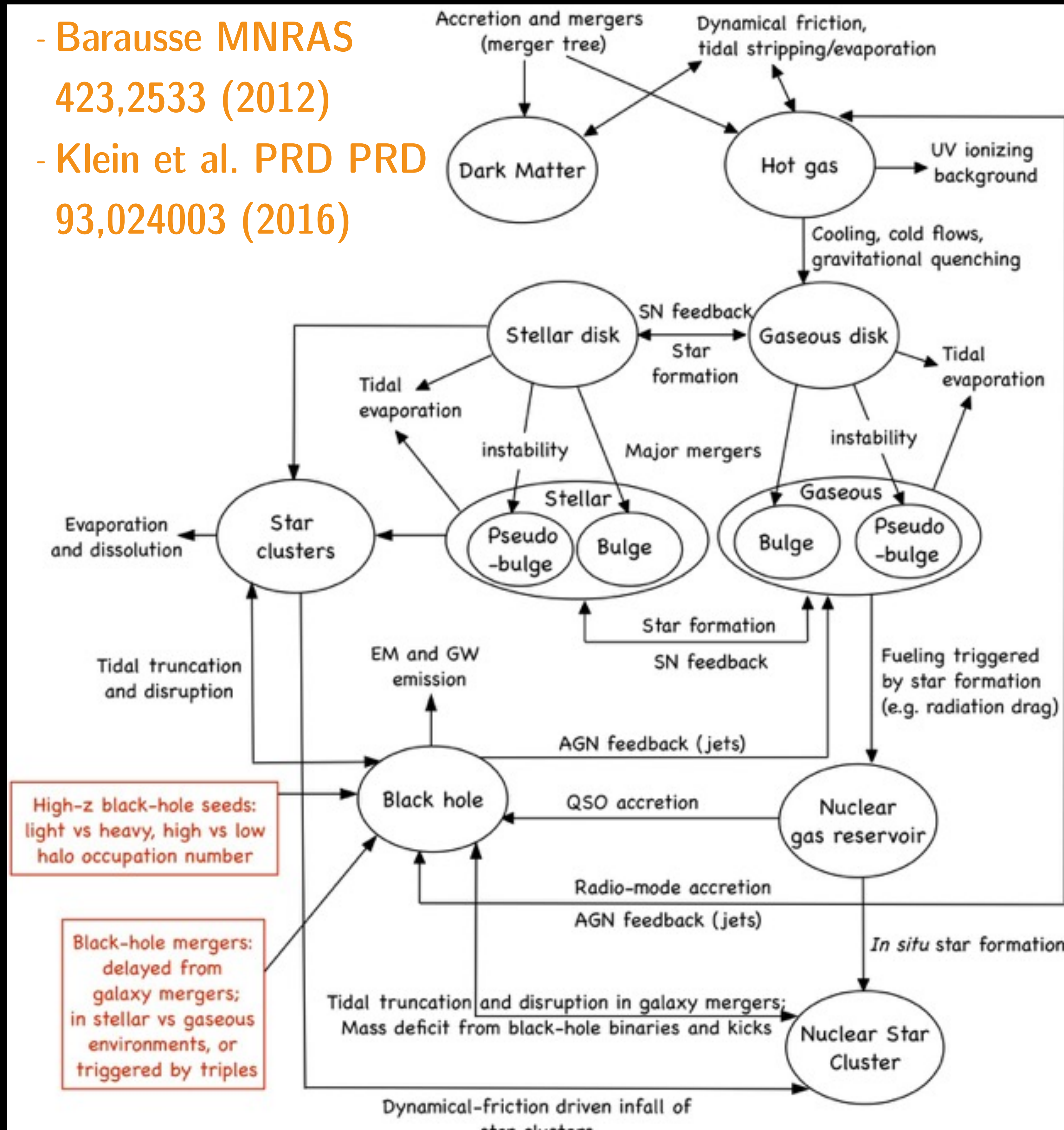
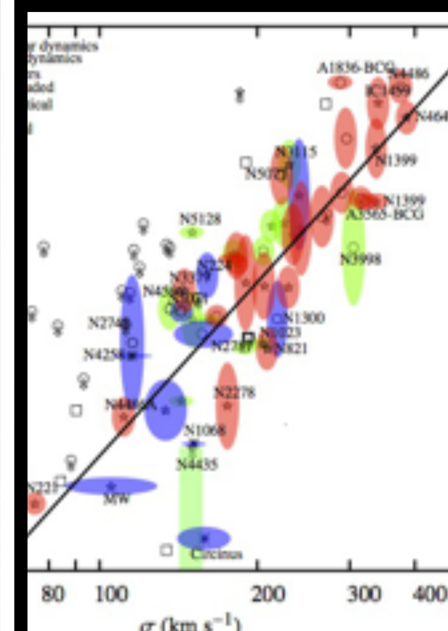
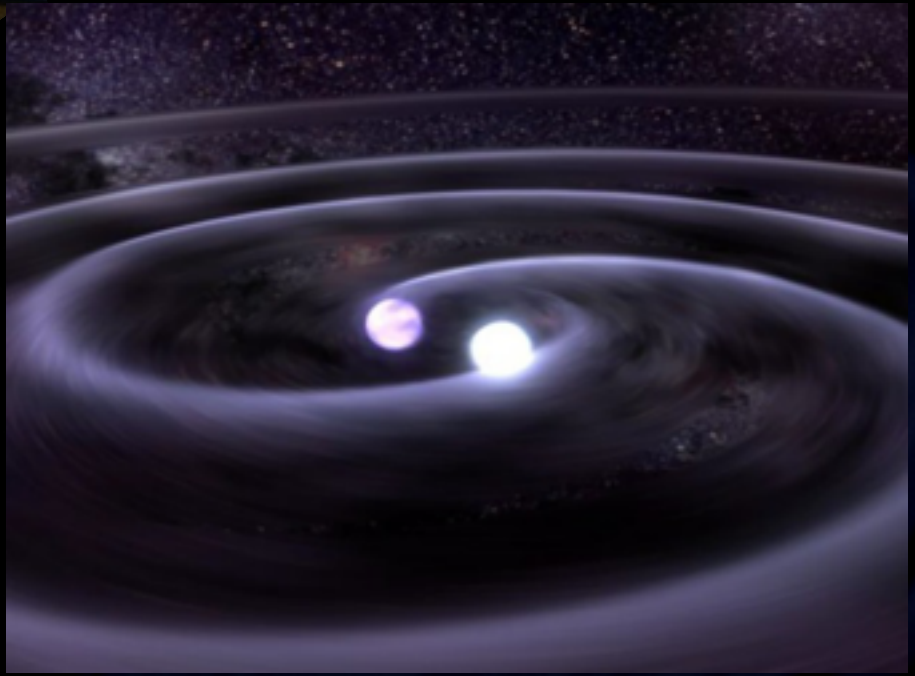




Compact solar mass binaries

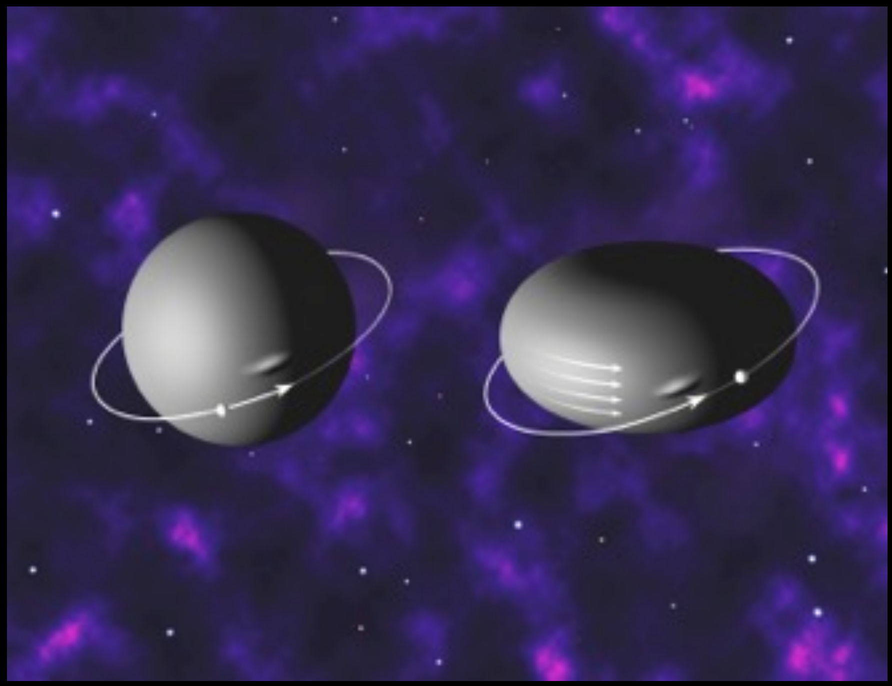
- Large number of stars are in binary system.
- Evolution in white dwarf (WD) and neutron stars (NS).
  => existence of WD-WD, NS-WD and NS-NS binaries
- Estimation for the Galaxy: 60 millions.
- Gravitational waves:
  - most part in the slow inspiral regime (quasi-monochromatic): GW at mHz
  - few are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

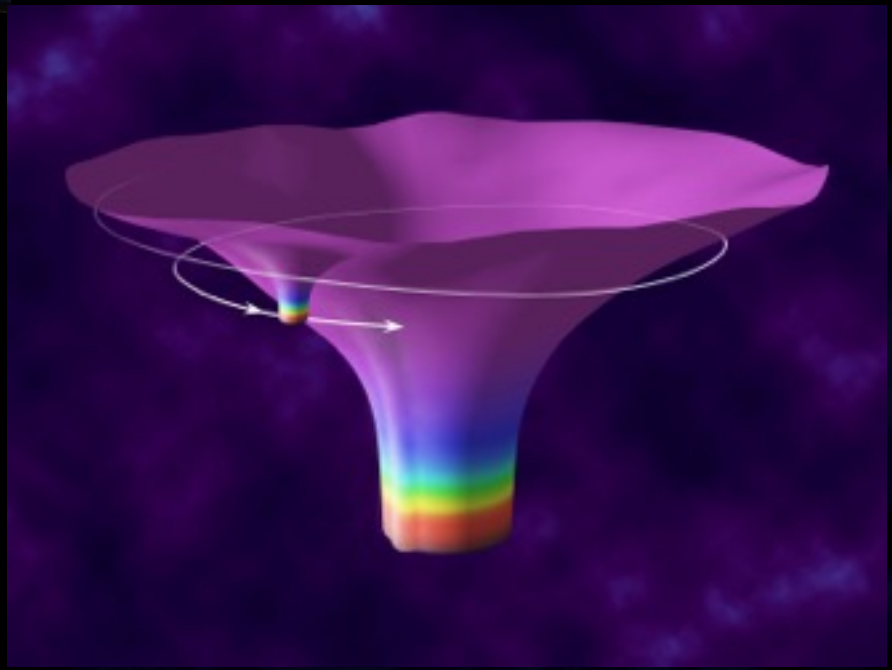


- Several known system emitting around the mHz
  => guaranteed sources

EMRIs

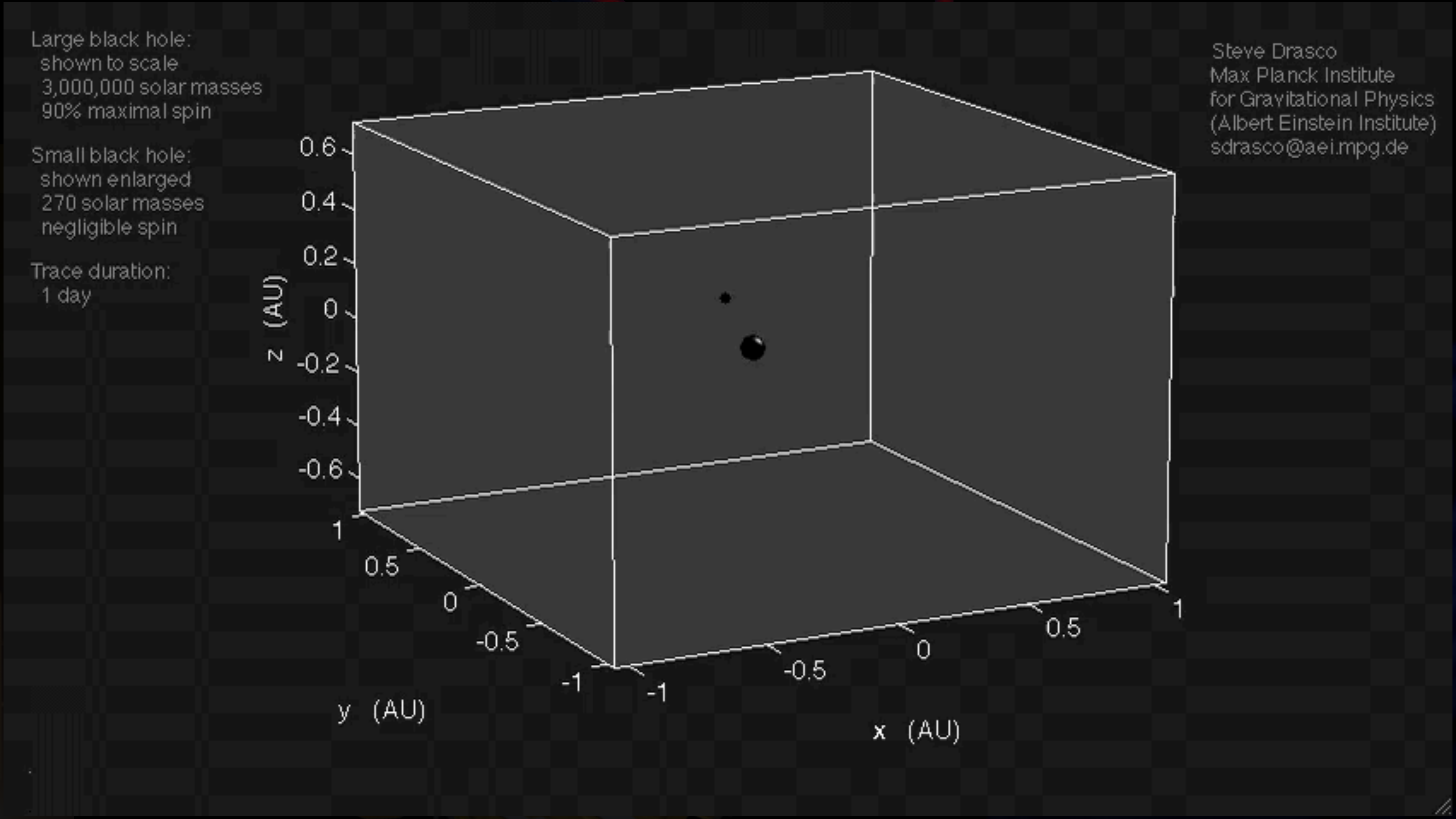
- Capture of a “small” object by massive black hole ($10 - 10^6\ M_{Sun}$)
  - Mass ratio > 200
  - GW gives information on the geometry around the black hole.
  - Test General Relativity in stong field
  - Frequency : 0.1 mHz to 0.1 Hz
  - Large number of source could be observed by space-based interferometer





EMRIs

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



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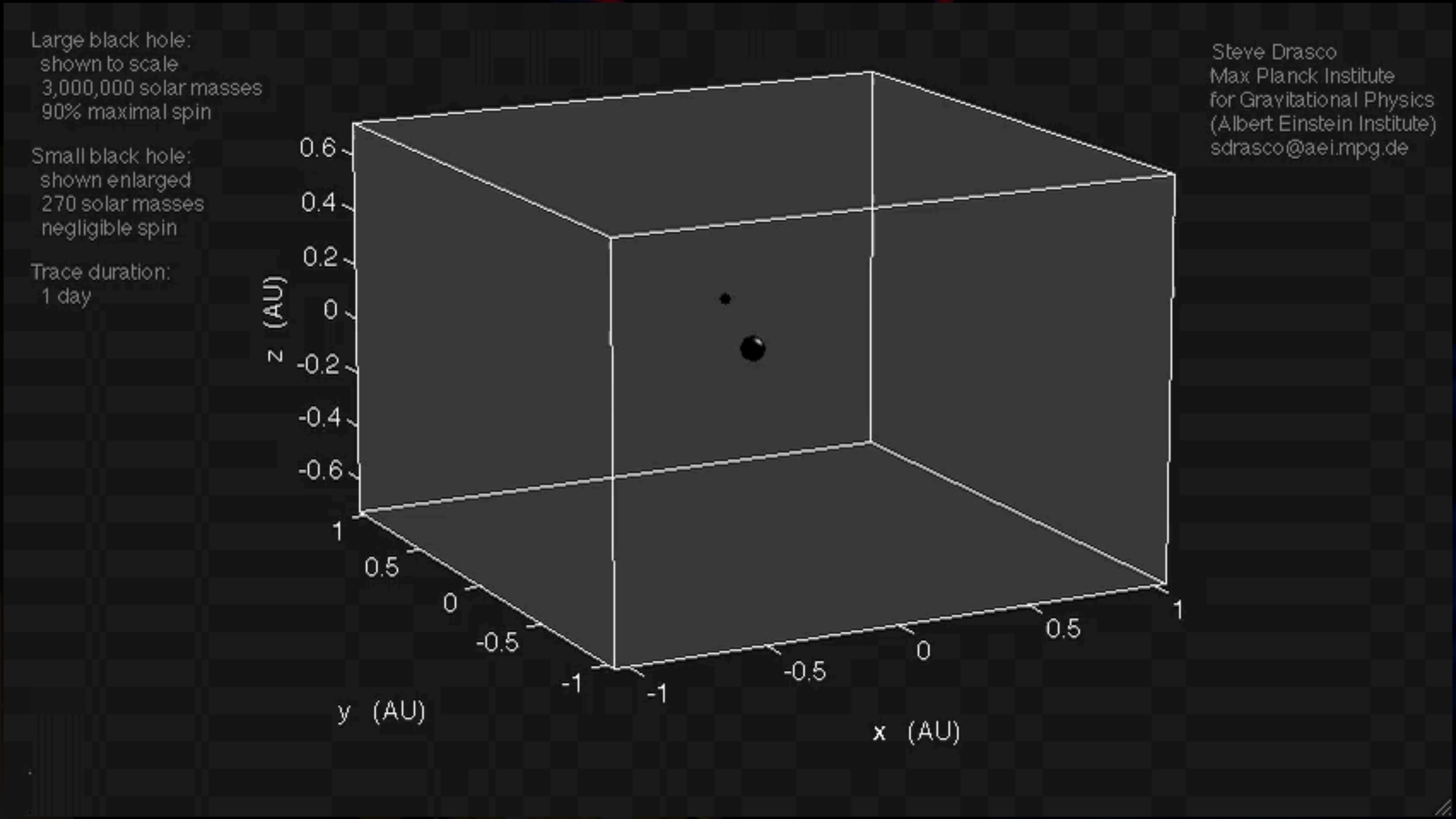
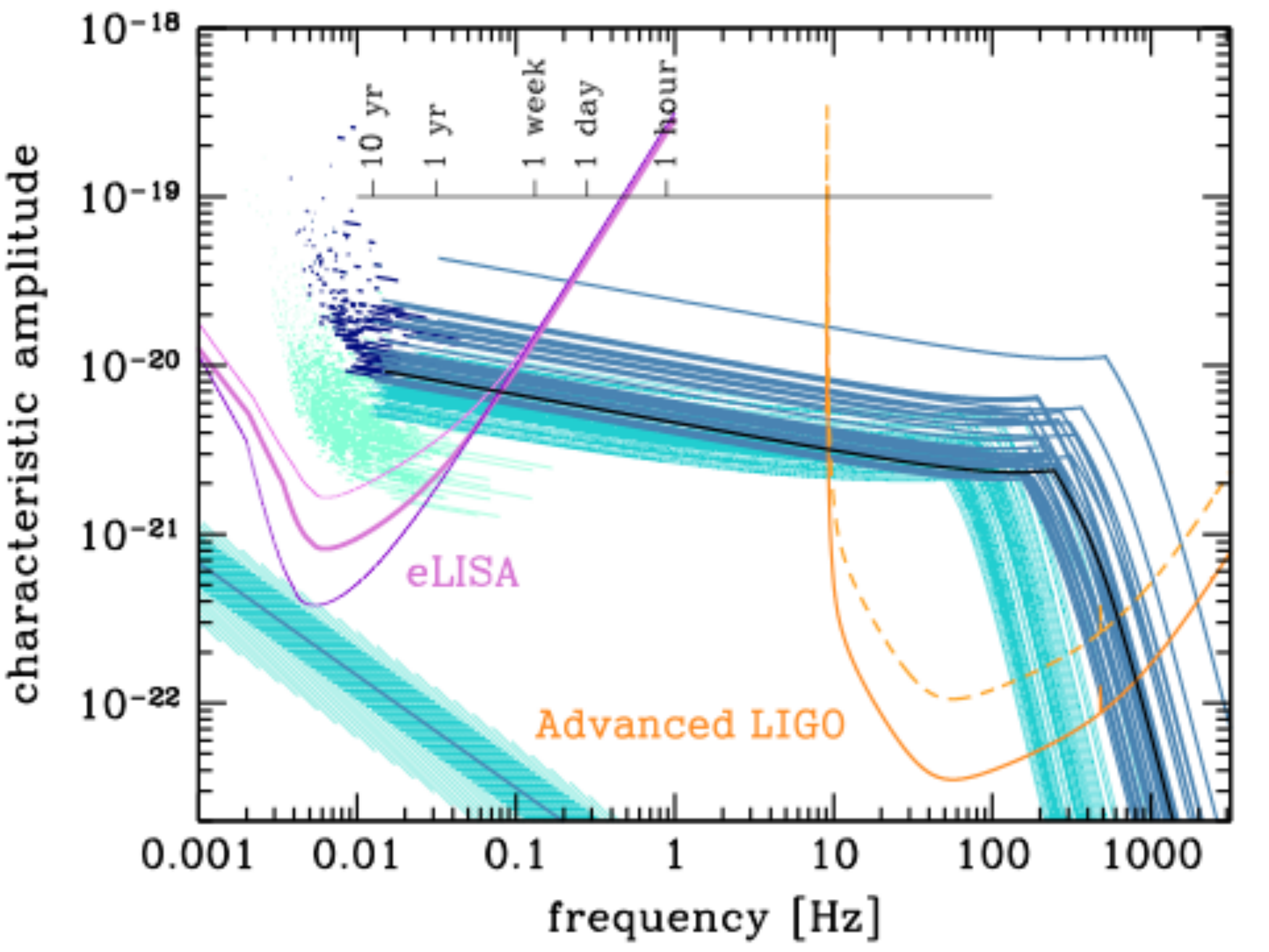


Black Hole Binaries

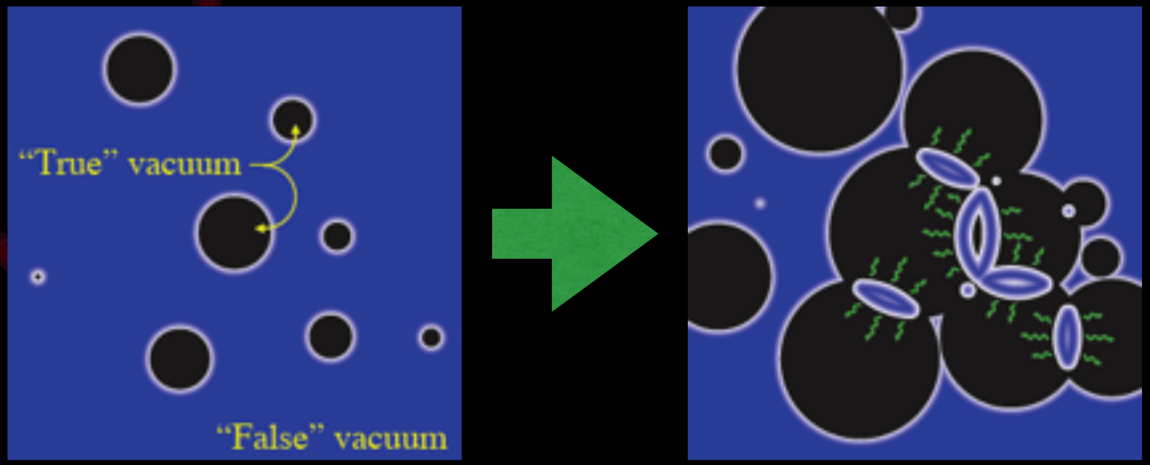
- LIGO/Virgo-type sources: binaries with 2 black holes of few tens solar masses.
- During most part of the inspiral time, emission in the mHz band
  => multi-observatories GW astronomy

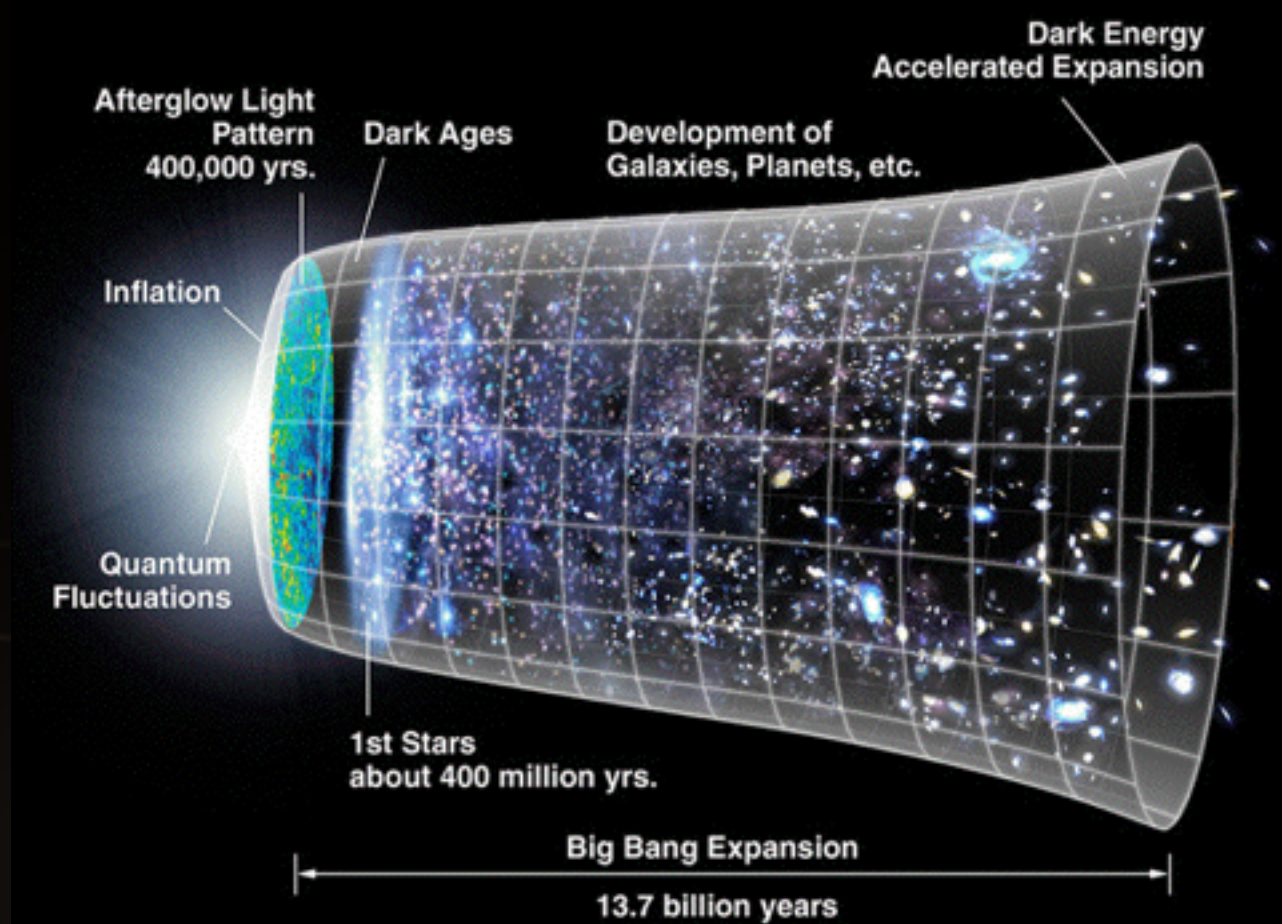
A. Sesana, PRL 116, 231102 (2016)

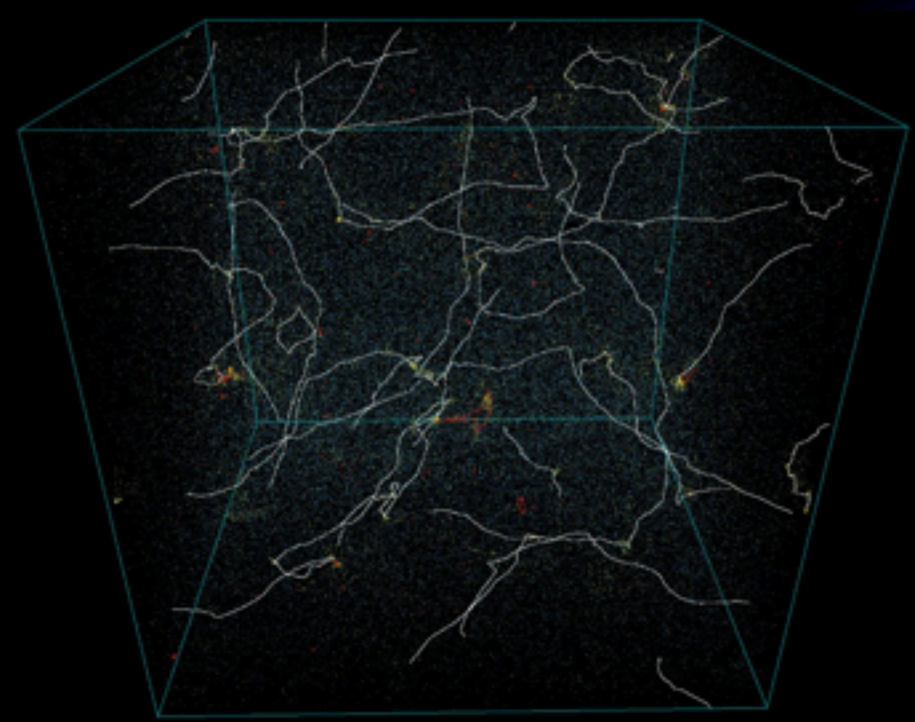


Cosmological backgrounds

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



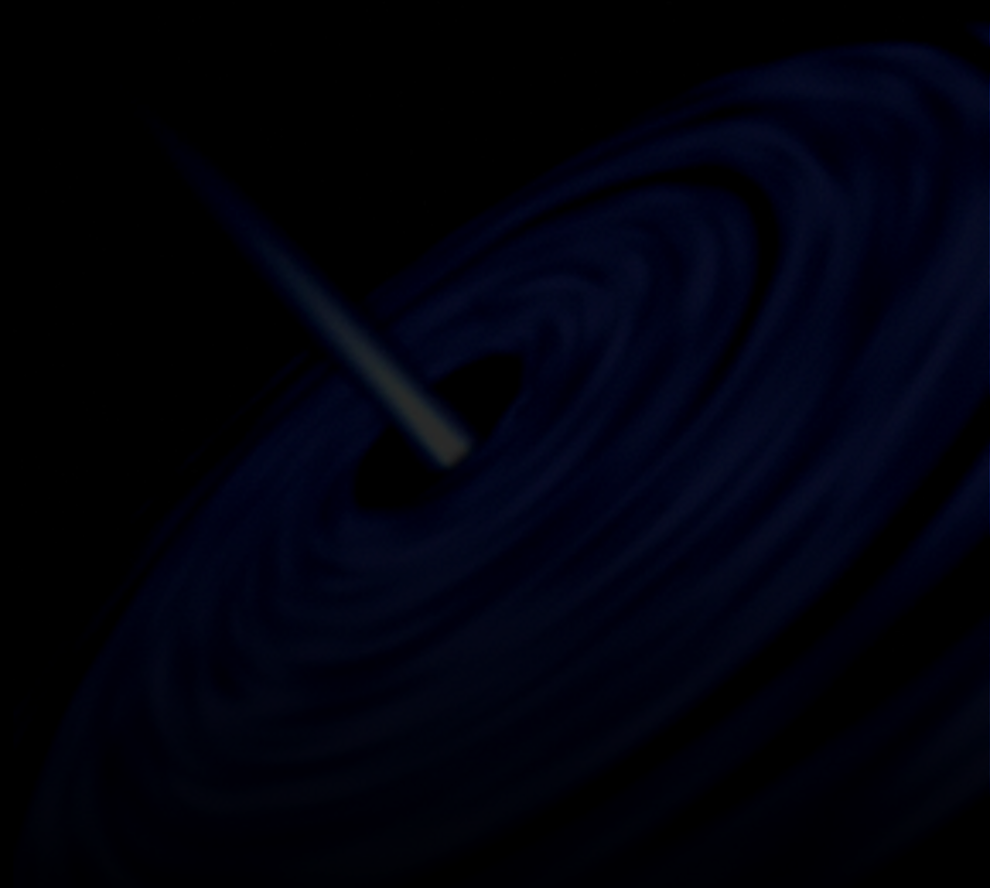




Unknown sources

- High potential of discovery in the mHz GW band ?

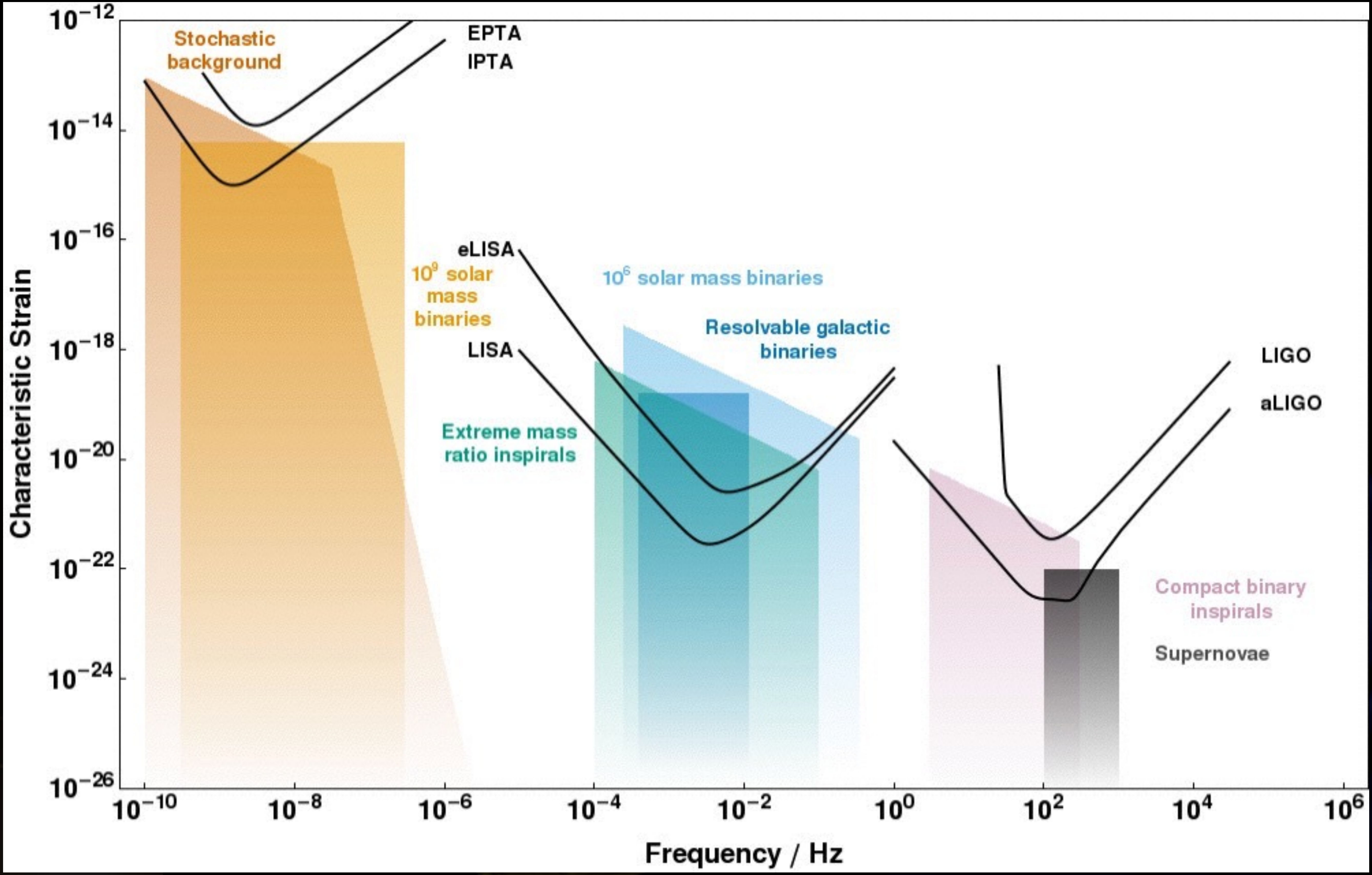
?



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 !



Stochastic background
EPTA
IPTA
eLISA
LISA
10^9 solar mass binaries
10^6 solar mass binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
LIGO
aLIGO
Compact binary inspirals
Supernovae
Characteristic Strain
Frequency / Hz
10^{-12}
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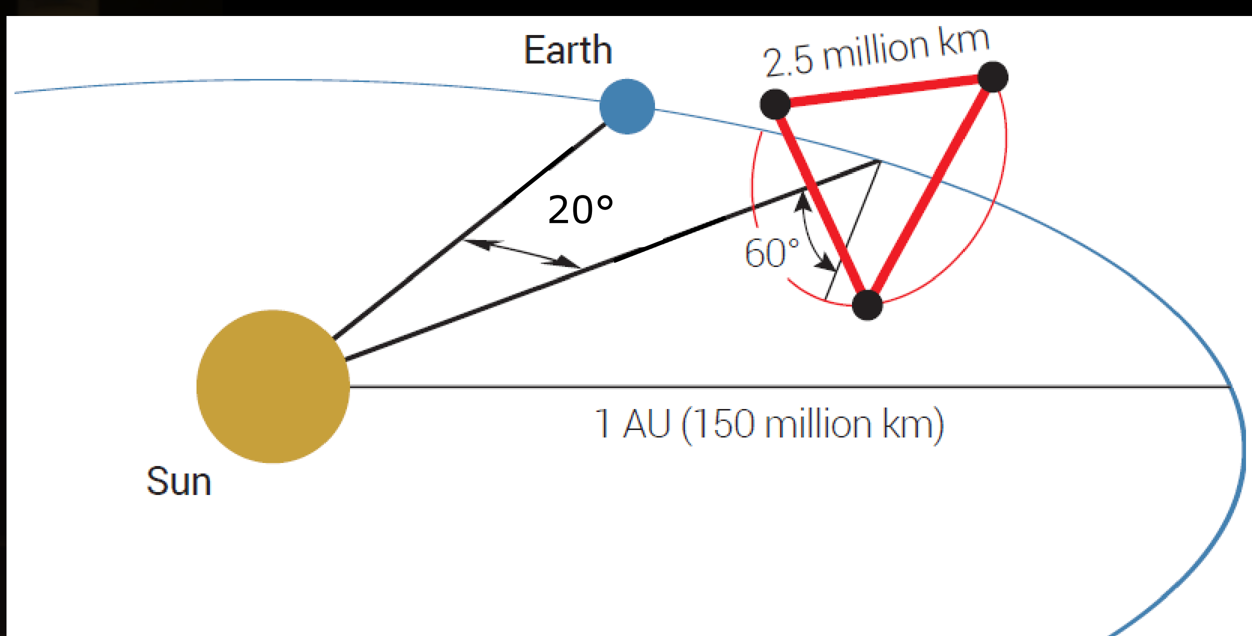
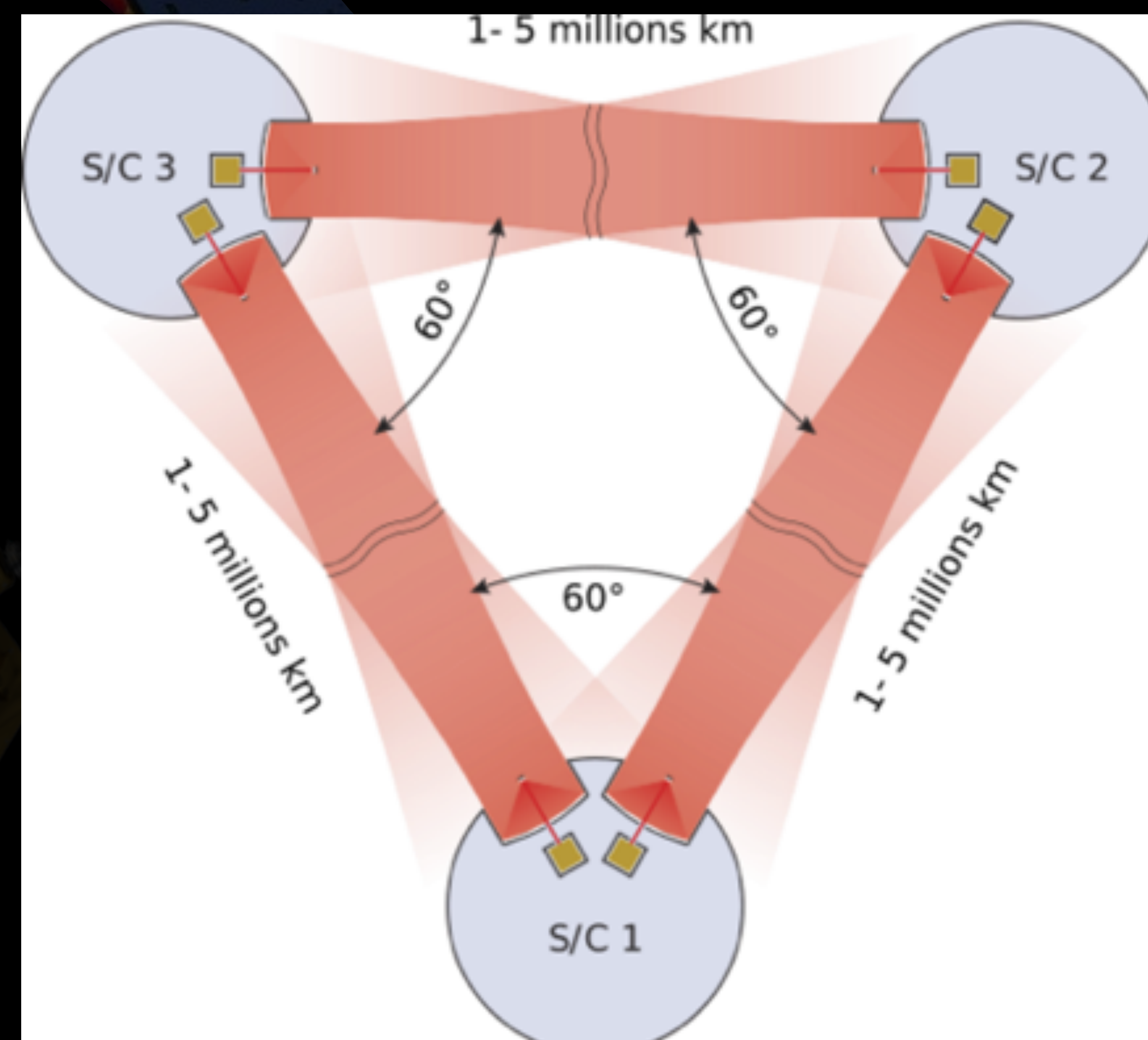
LISA

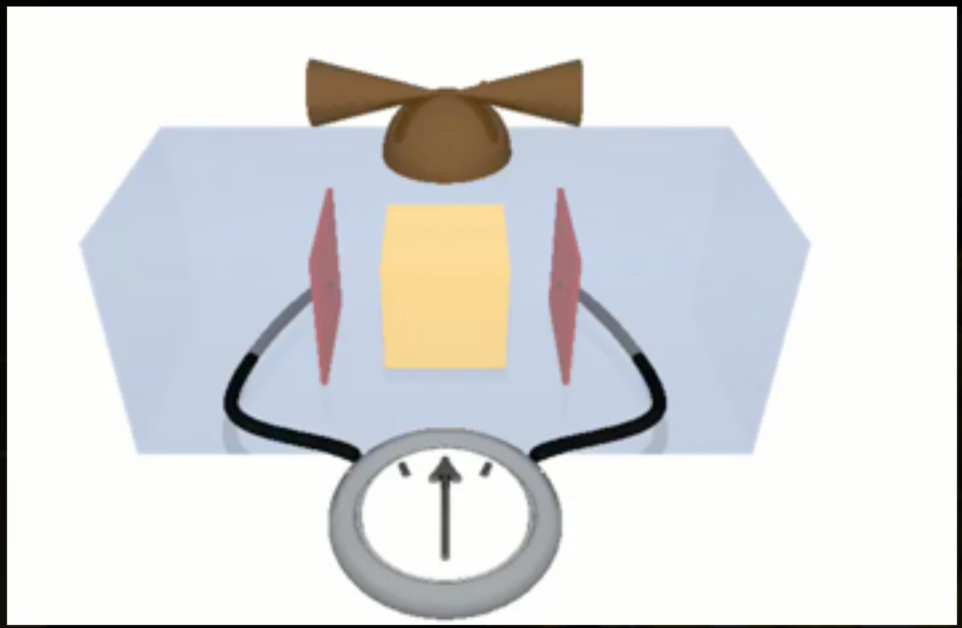
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of 10^{-21}: few picometers

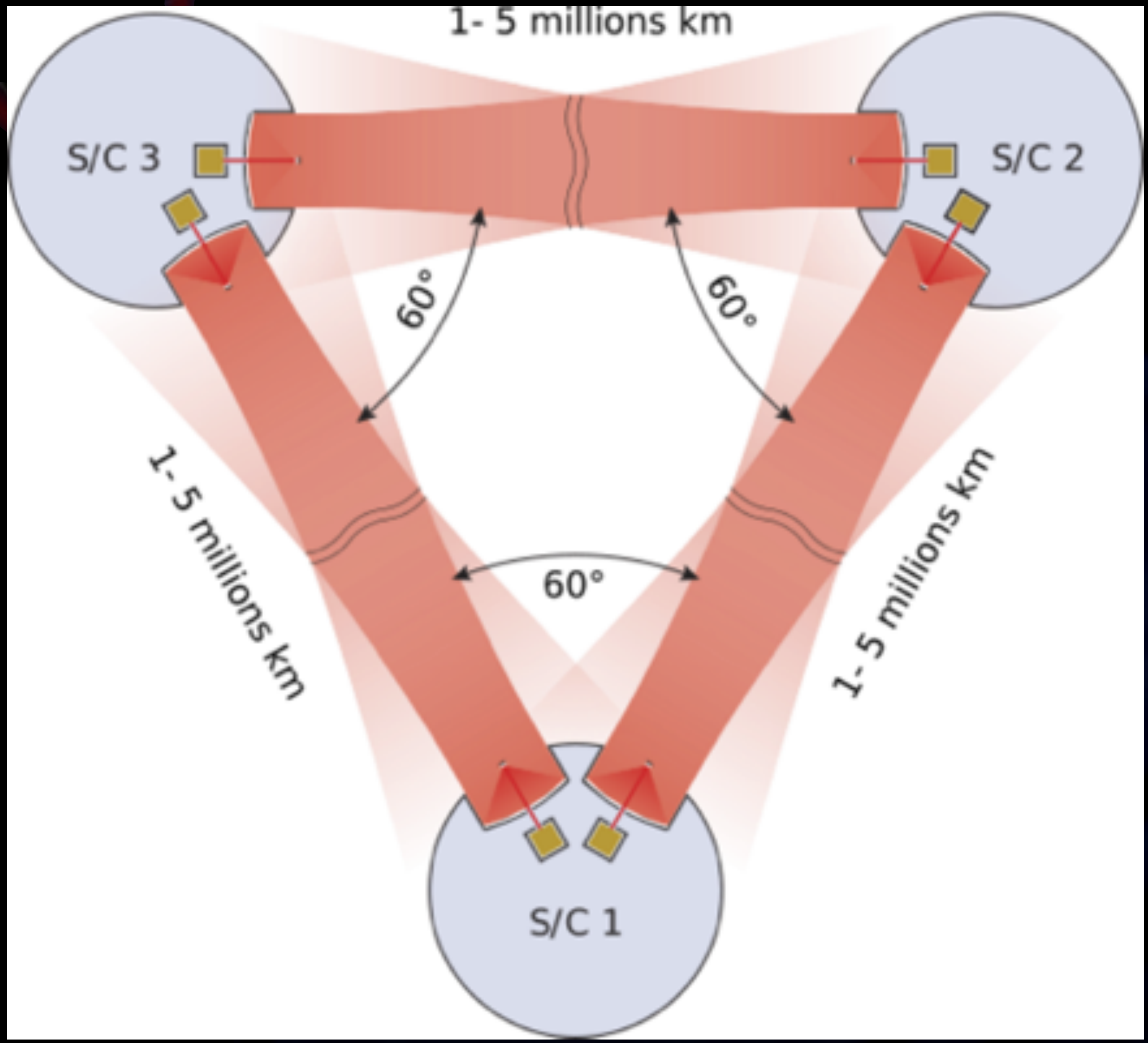




LISA

- 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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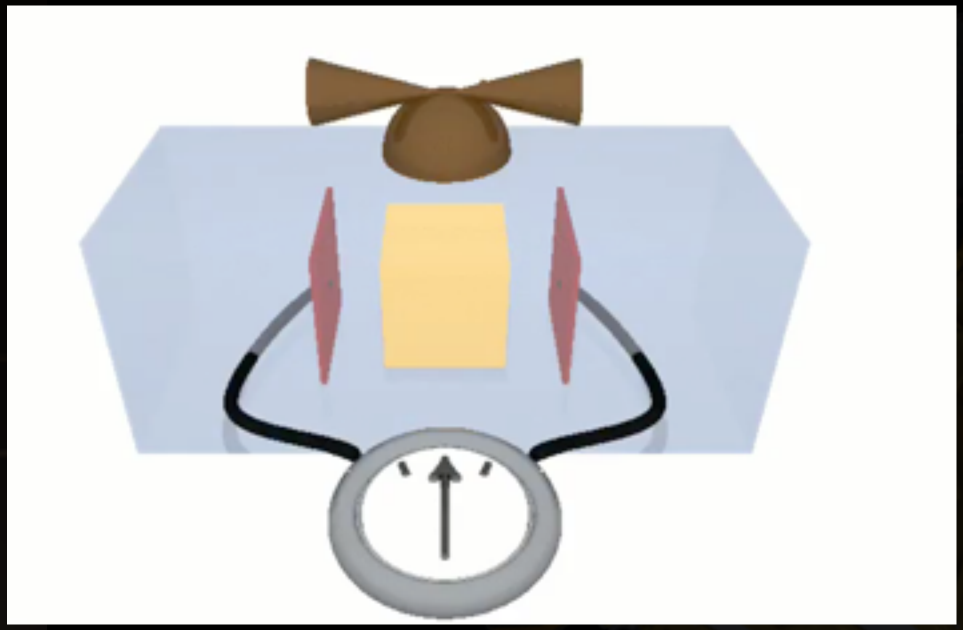
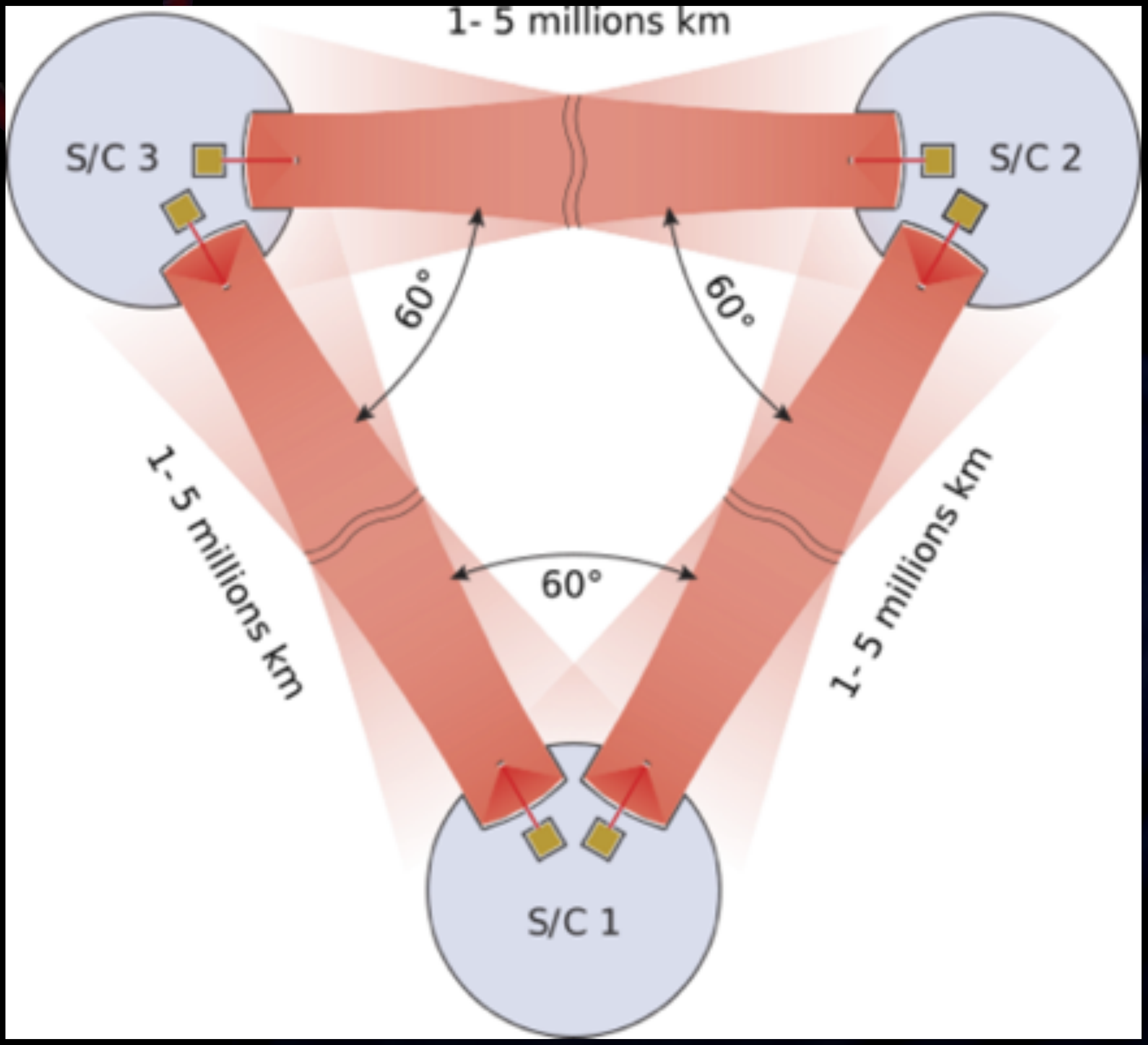
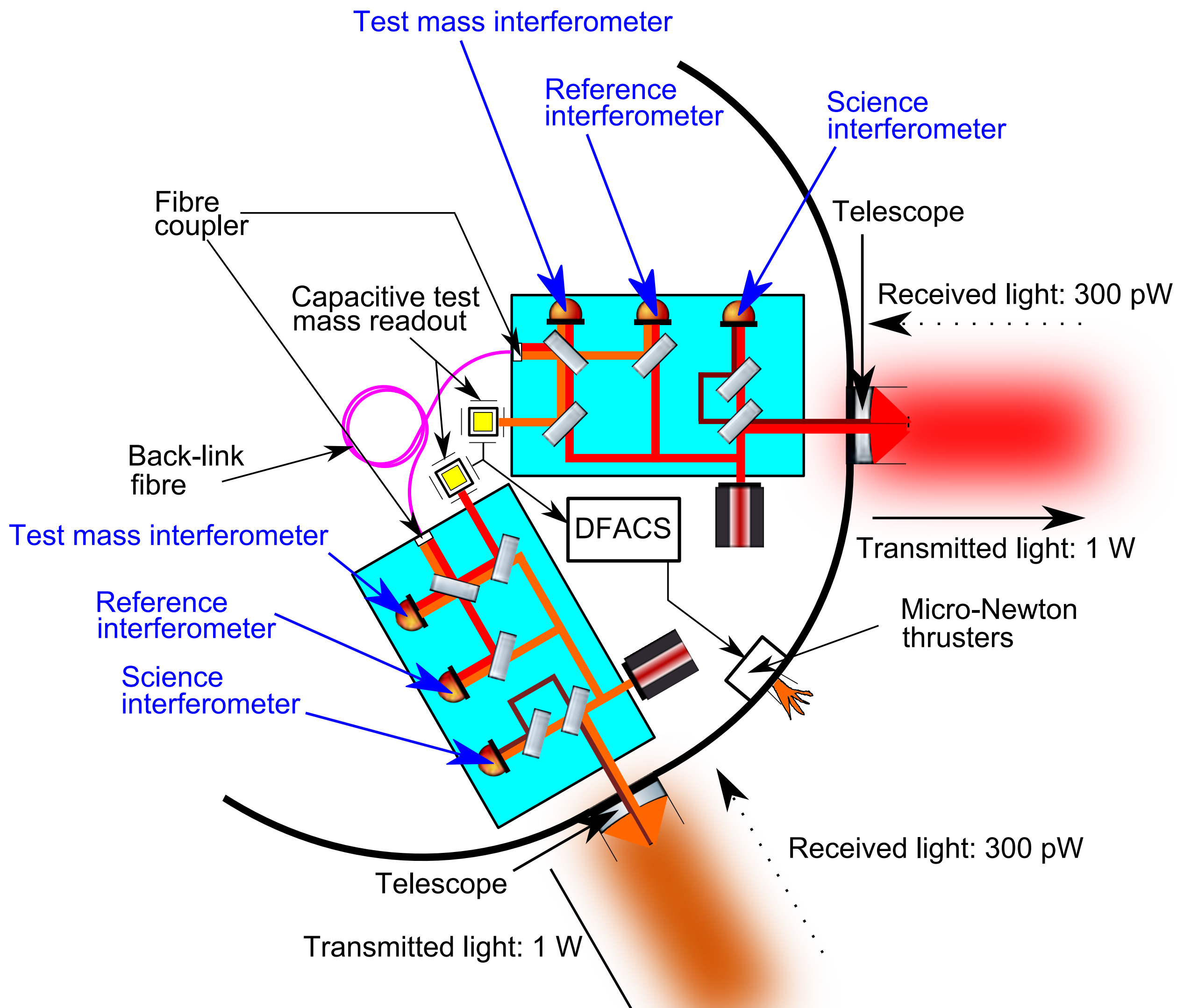




LISA

- 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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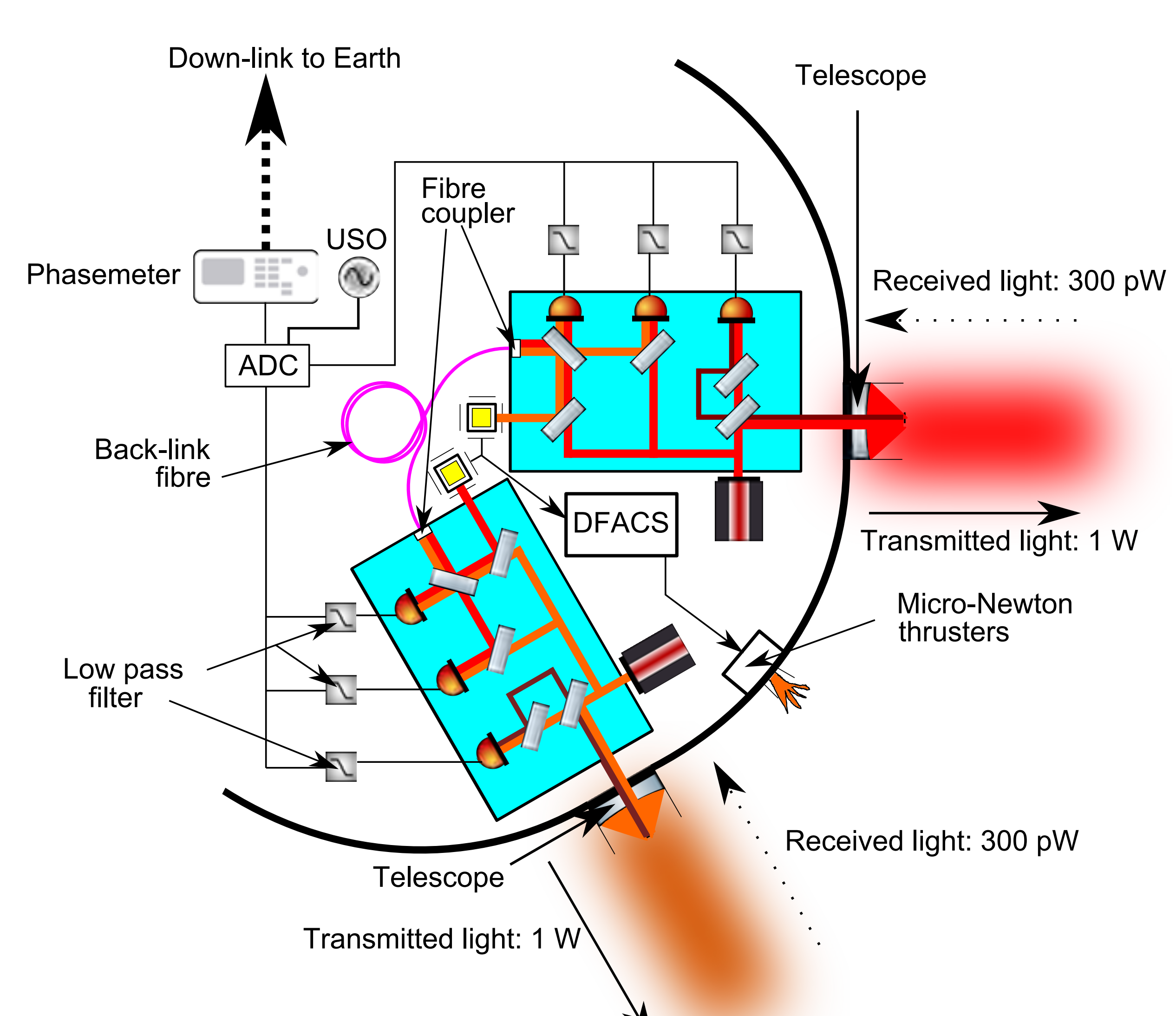

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LISA

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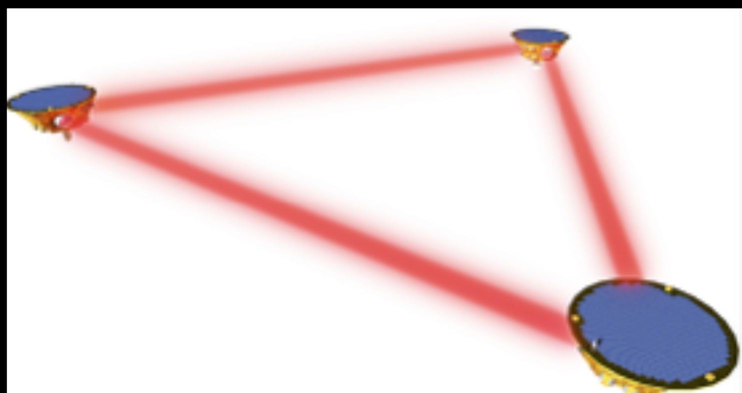

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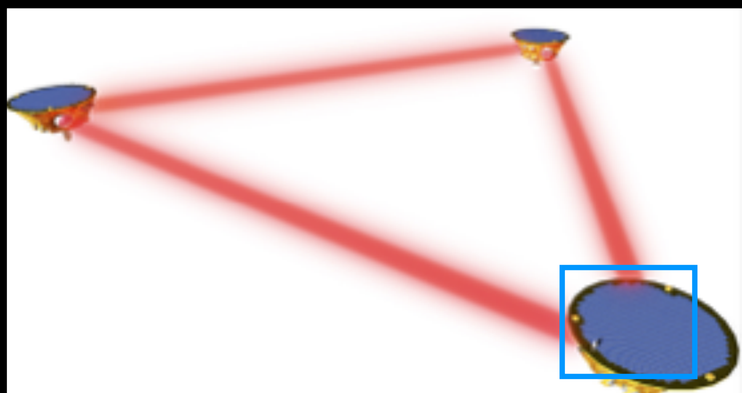
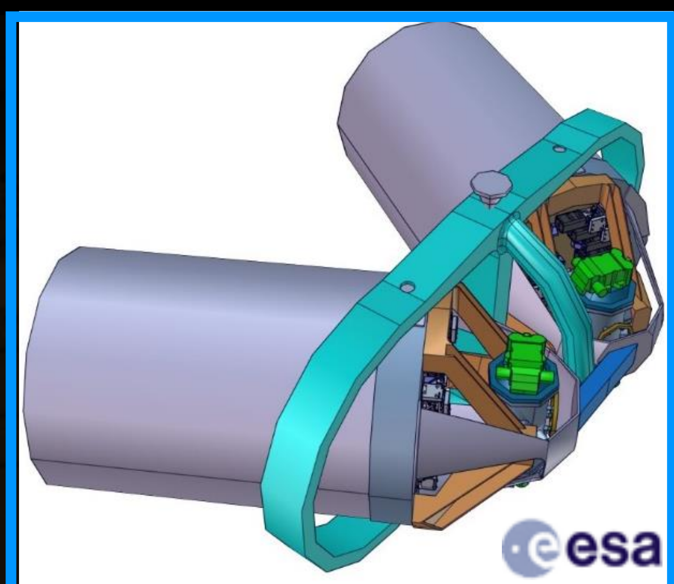
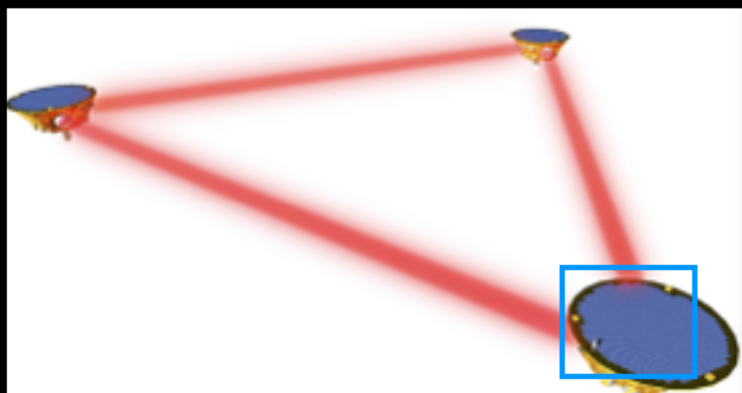
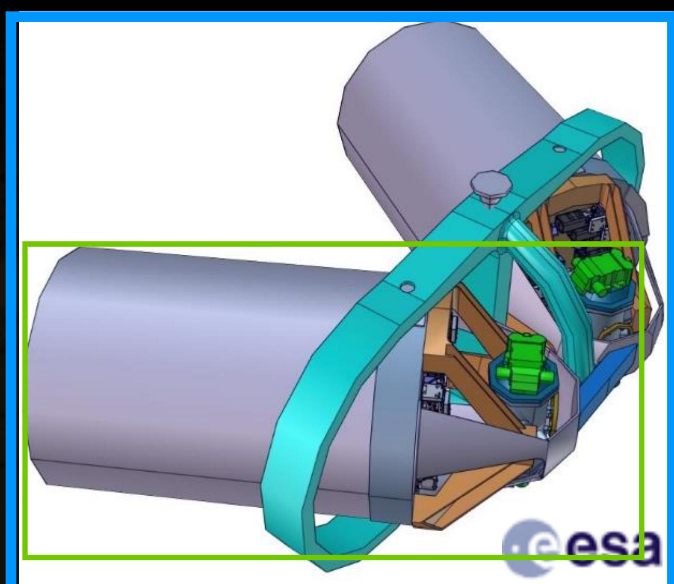


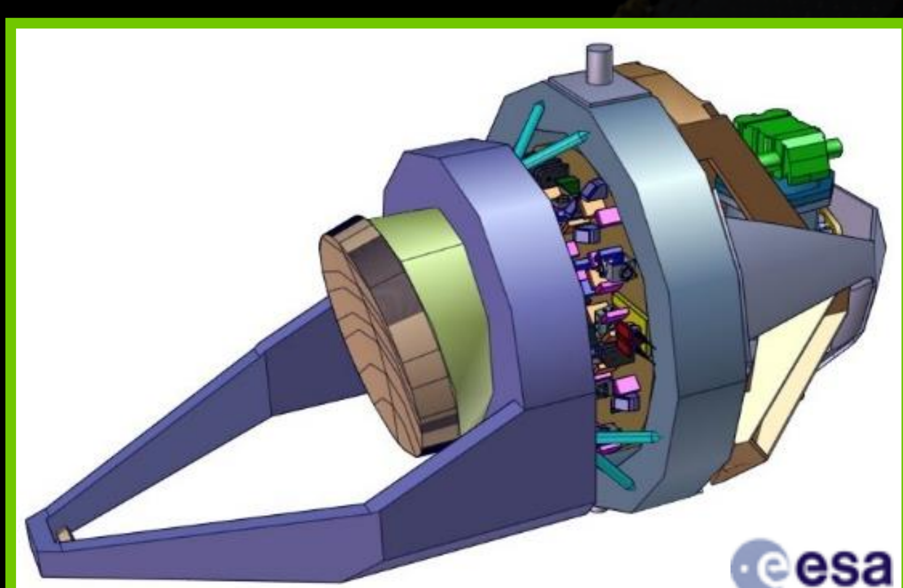


LISA

- A measurements in several steps

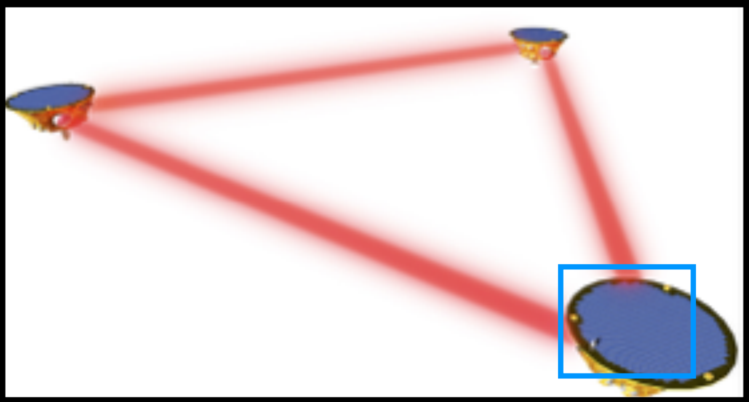


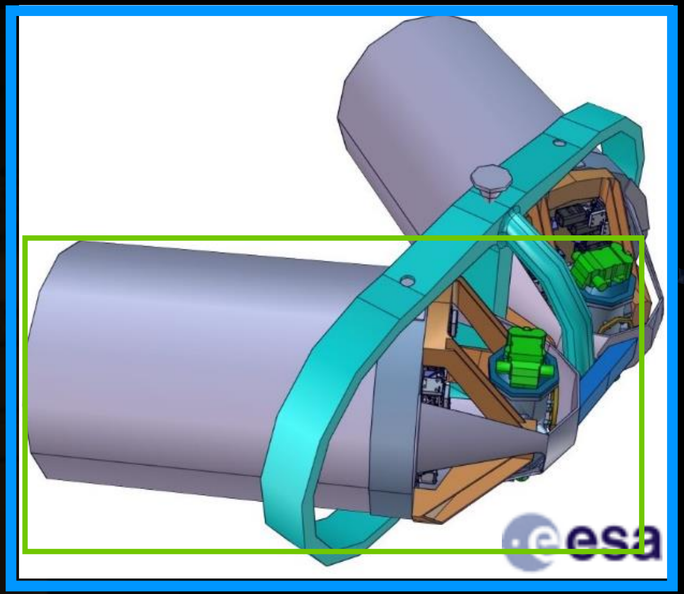


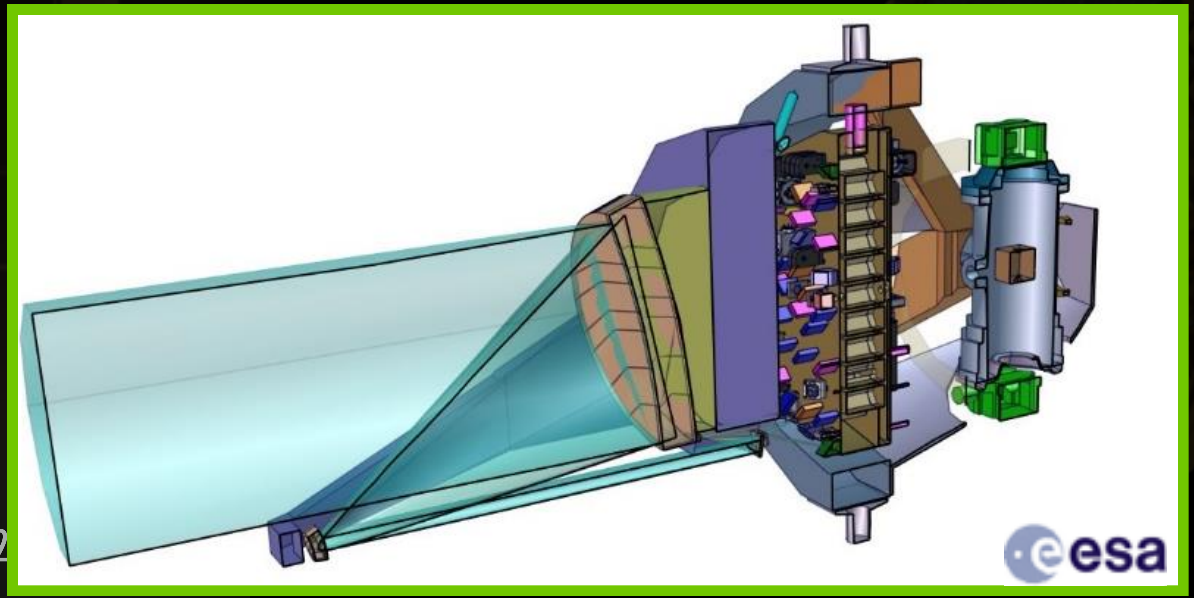


LISA

- A measurements in several steps







LISA

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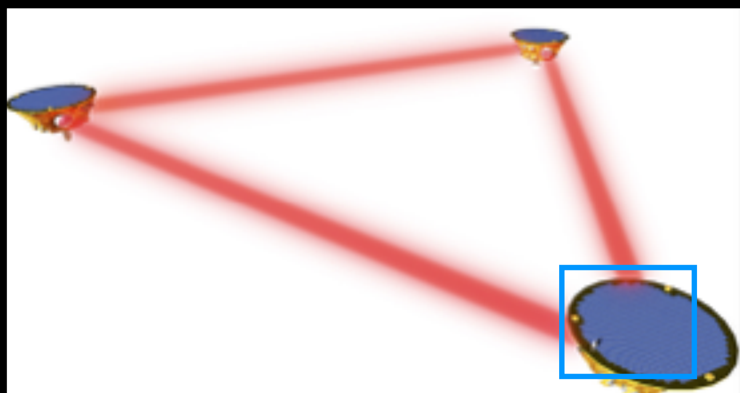
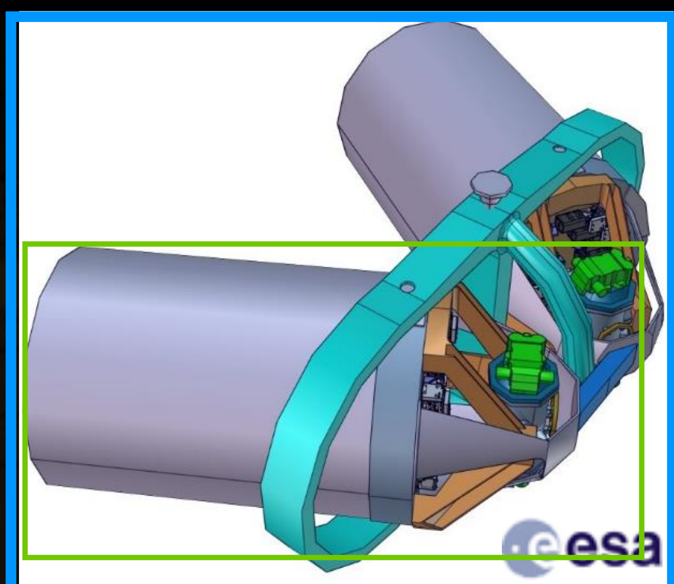
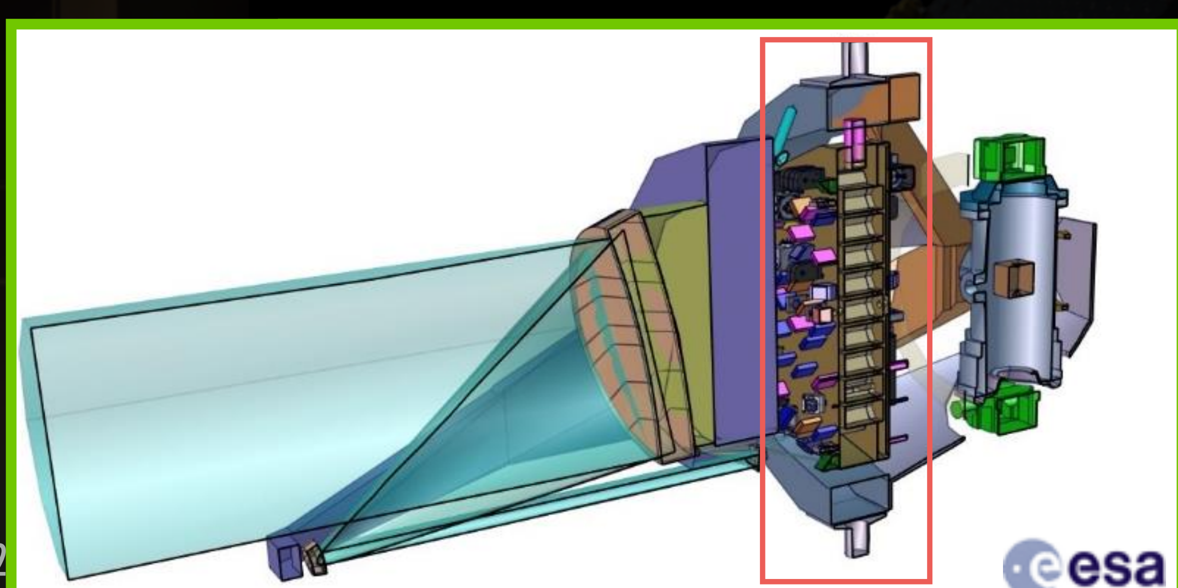


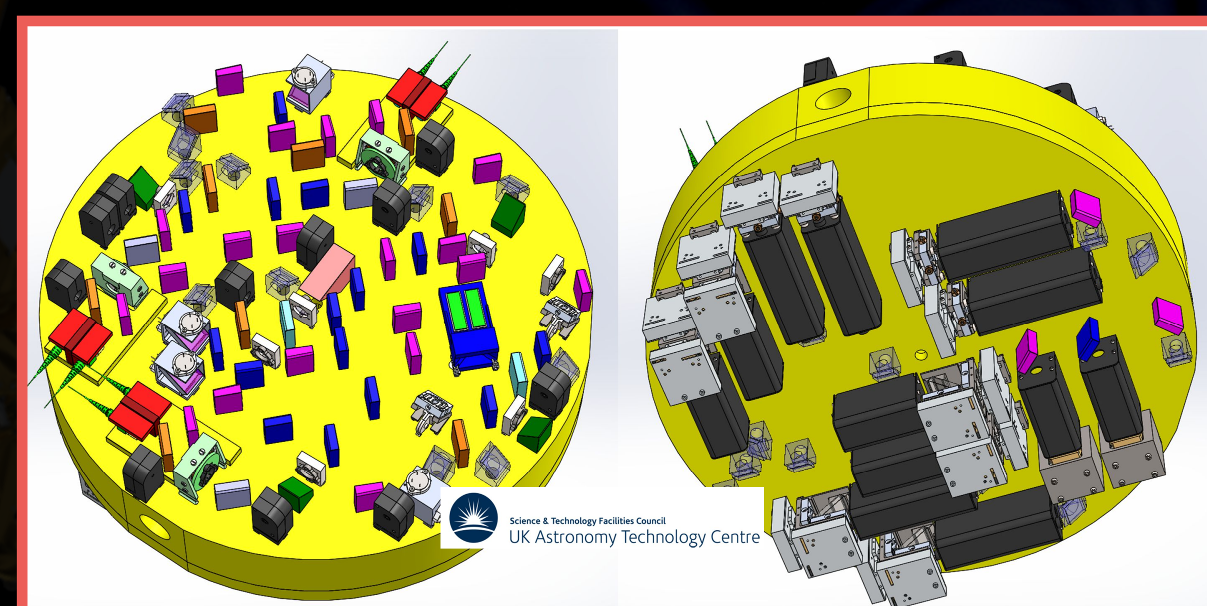




LISA:

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

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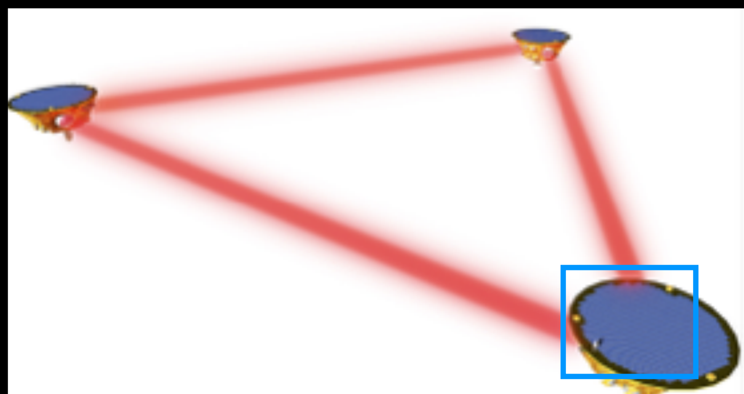
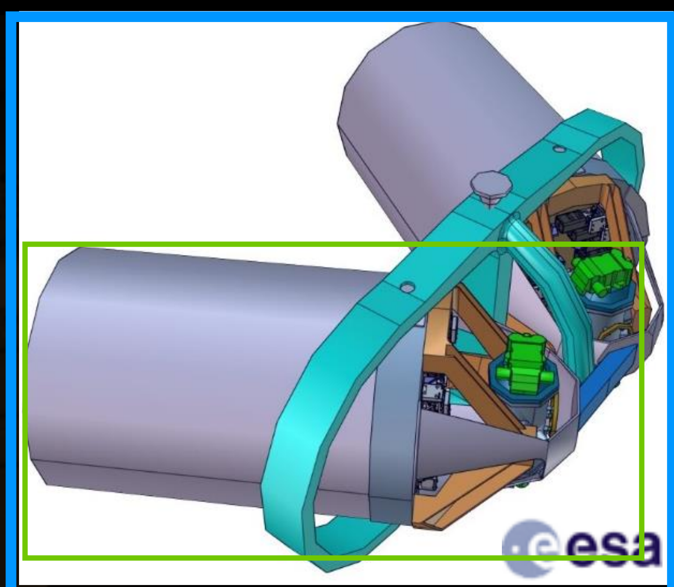
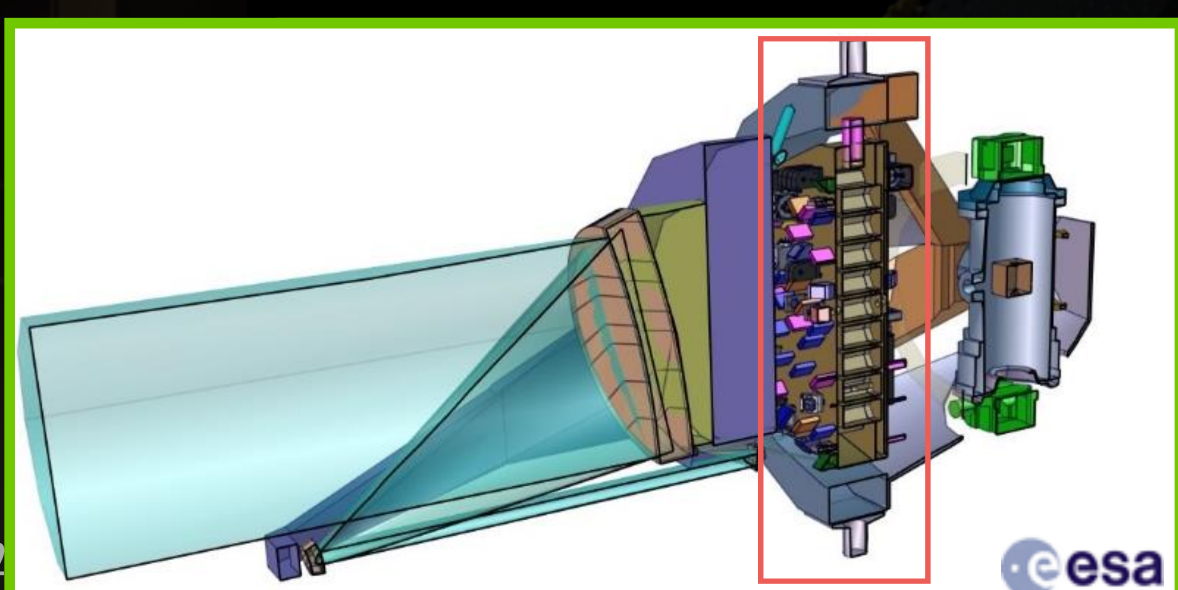
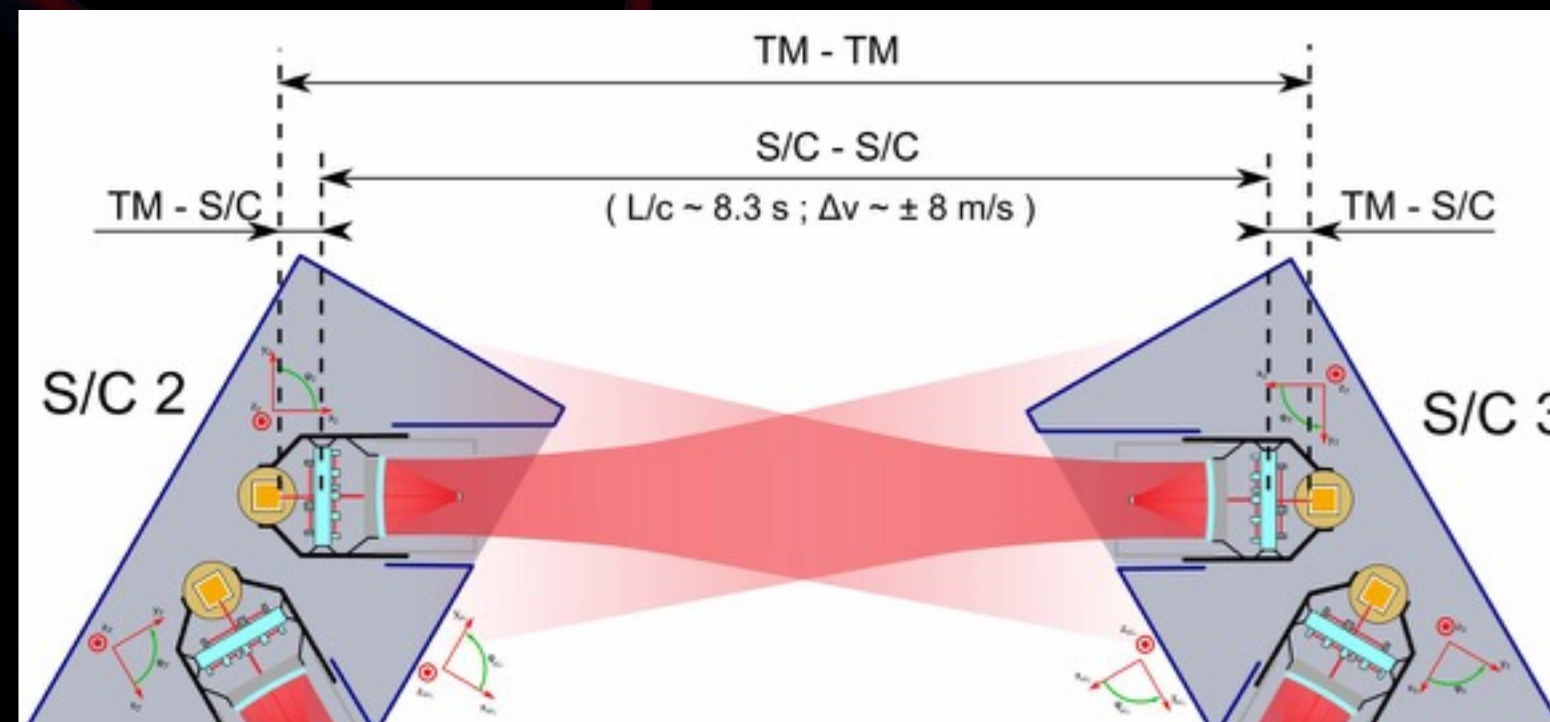
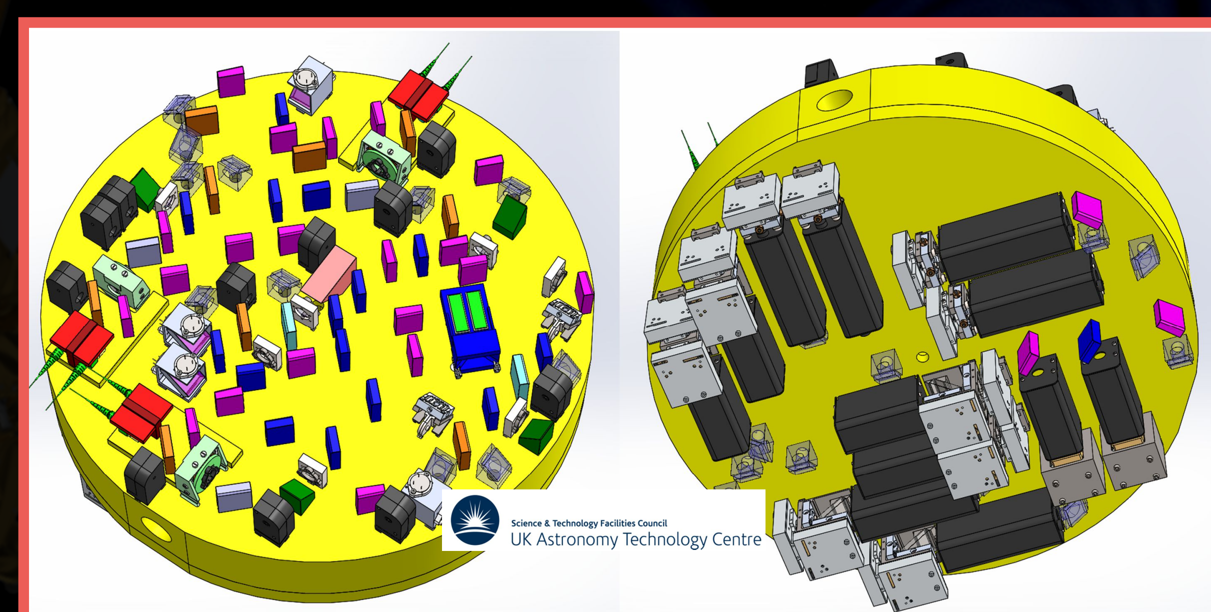






$$(TM2 \rightarrow SC2) + (SC2 \rightarrow SC3) + (SC3 \rightarrow TM3)$$





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
- 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)

Validated with LISAPathfinder

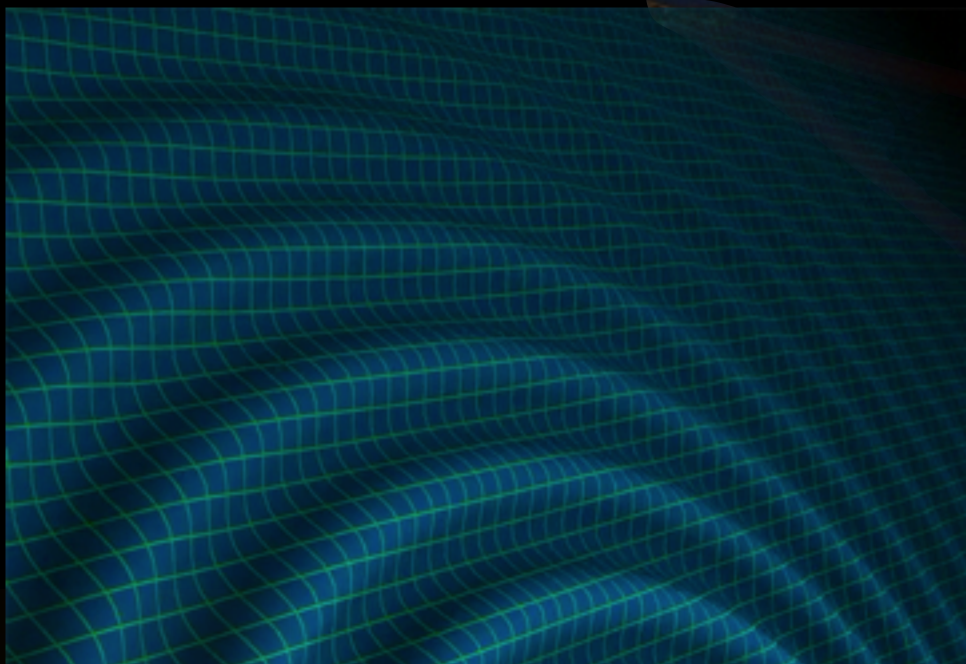
Ground-based demonstrators

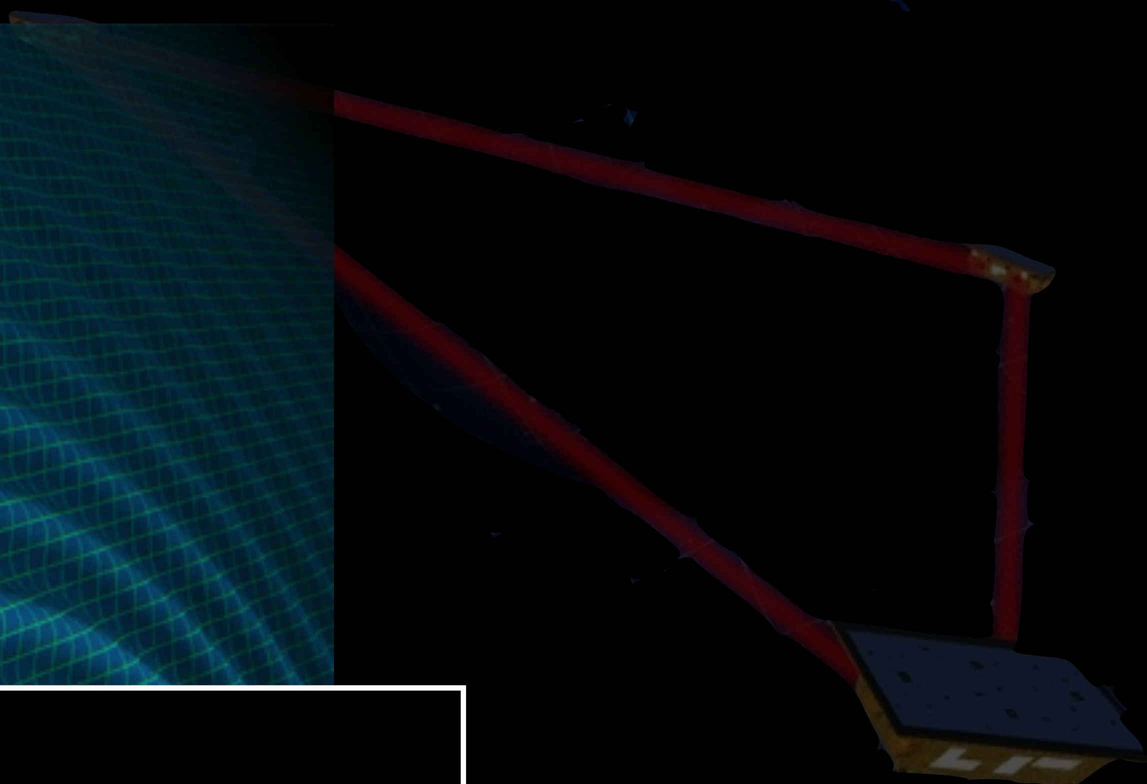
GRACE-FO

LISA data

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data





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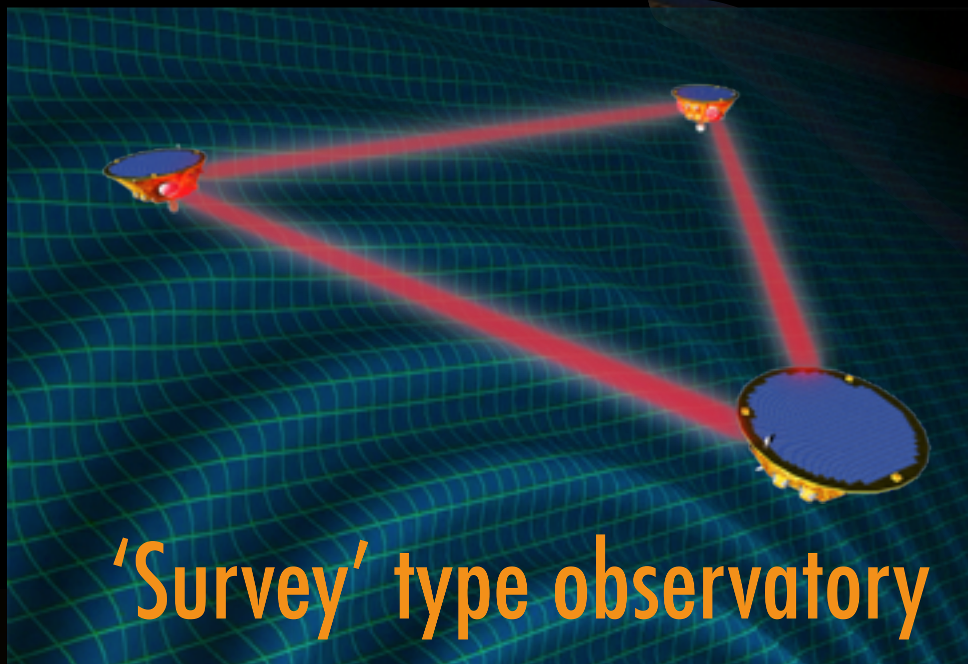

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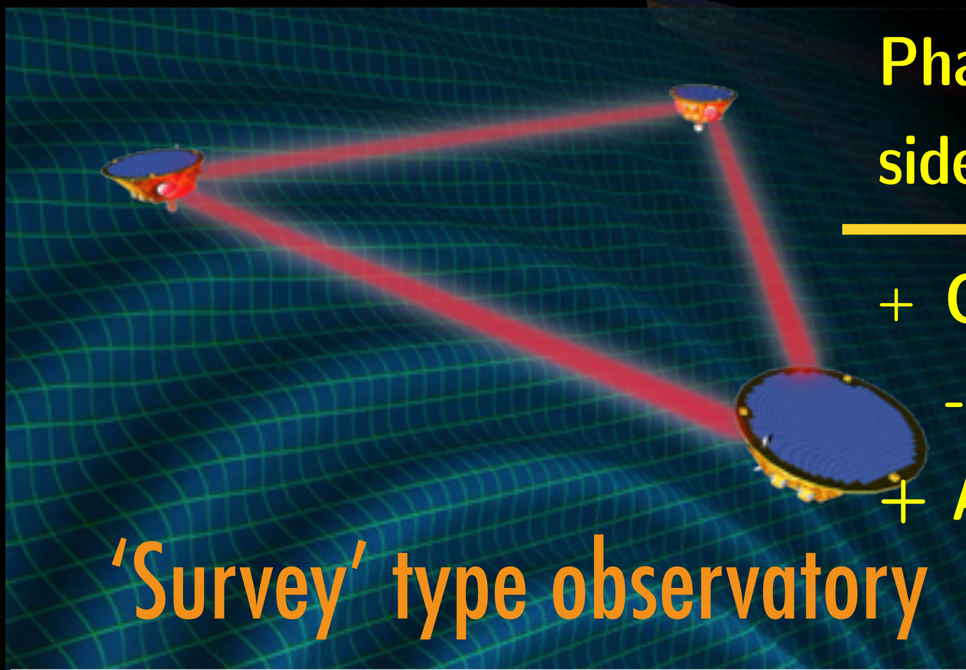


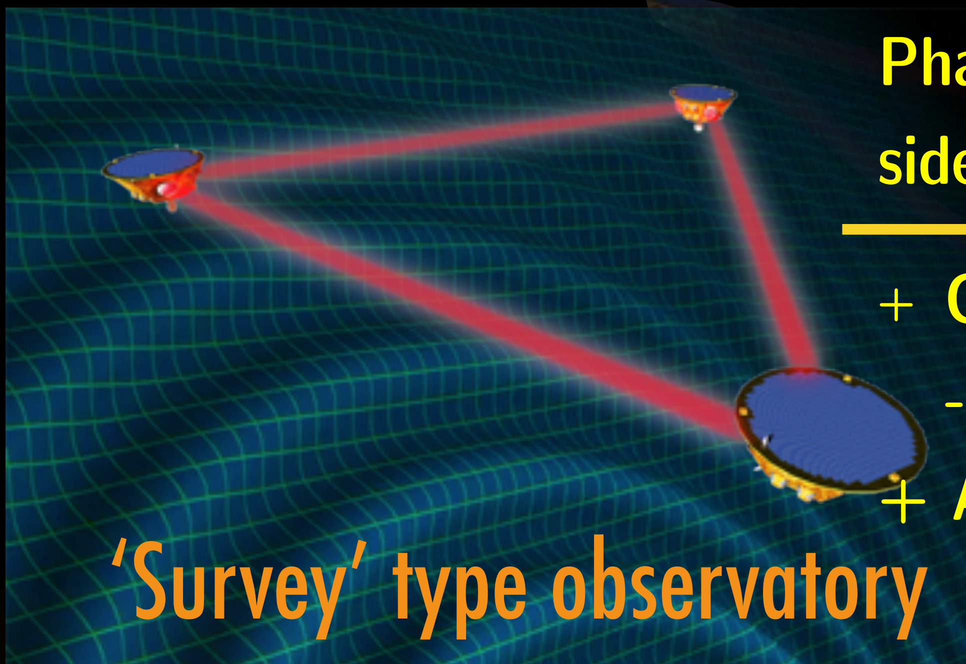
Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe--rence Sensor
+ Auxiliary channels

'Survey' type observatory

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



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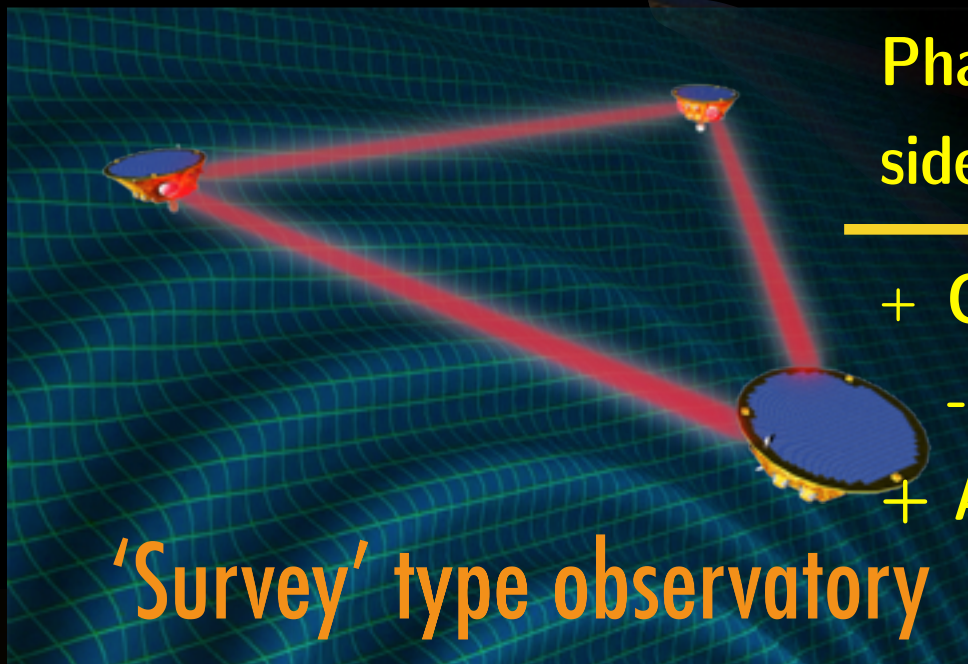

Phasemeters (carrier, sidebands, distance)

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'Survey' type observatory

Calibrations corrections

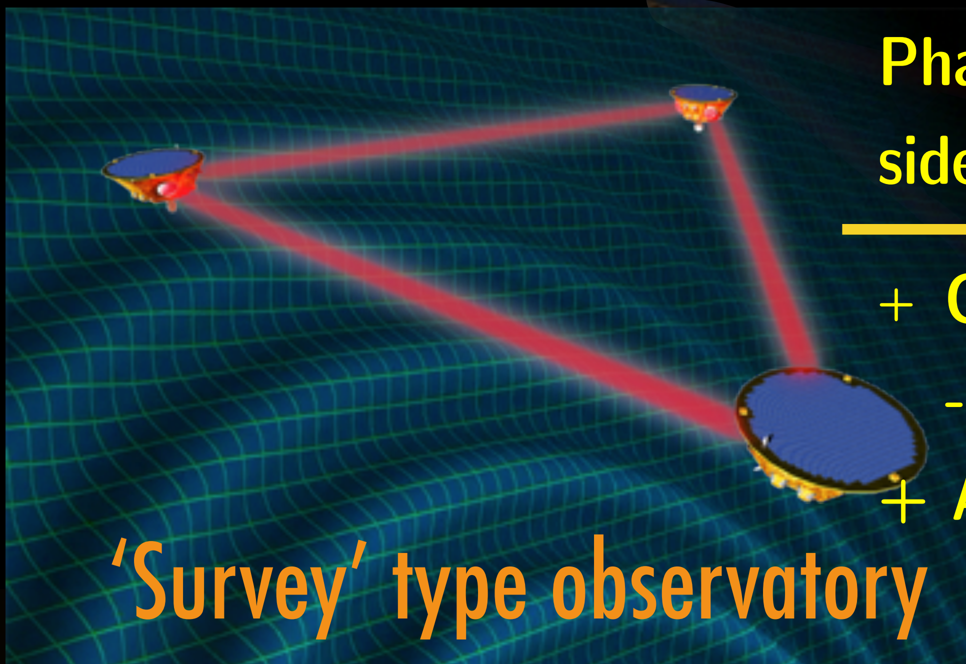
Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

3 TDI channels with 2 "~independents"

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



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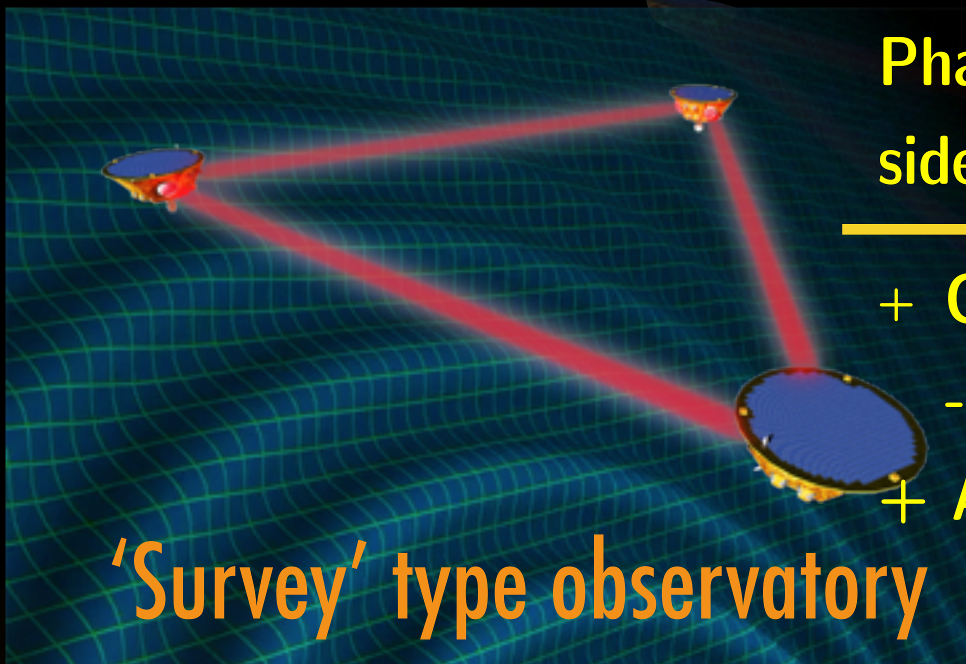
Data Analysis of GWs

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

3 TDI channels with 2 "~independents"

L2

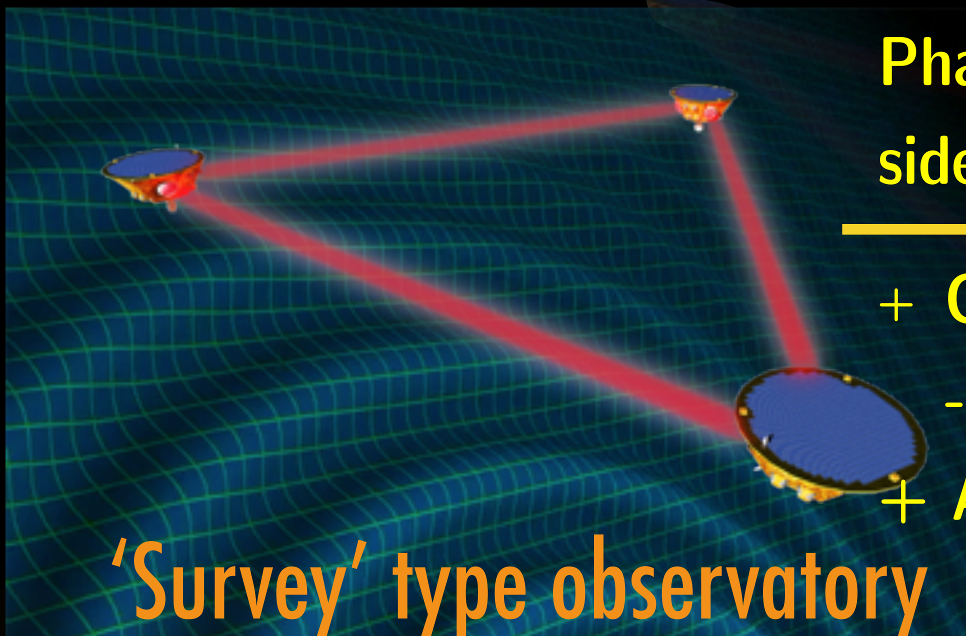
Data Analysis of GWs

L3

Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



'Survey' type observatory

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\+ Gravitational Reference Sensor

\+ Auxiliary channels

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

L1 3 TDI channels with 2 "~independents"

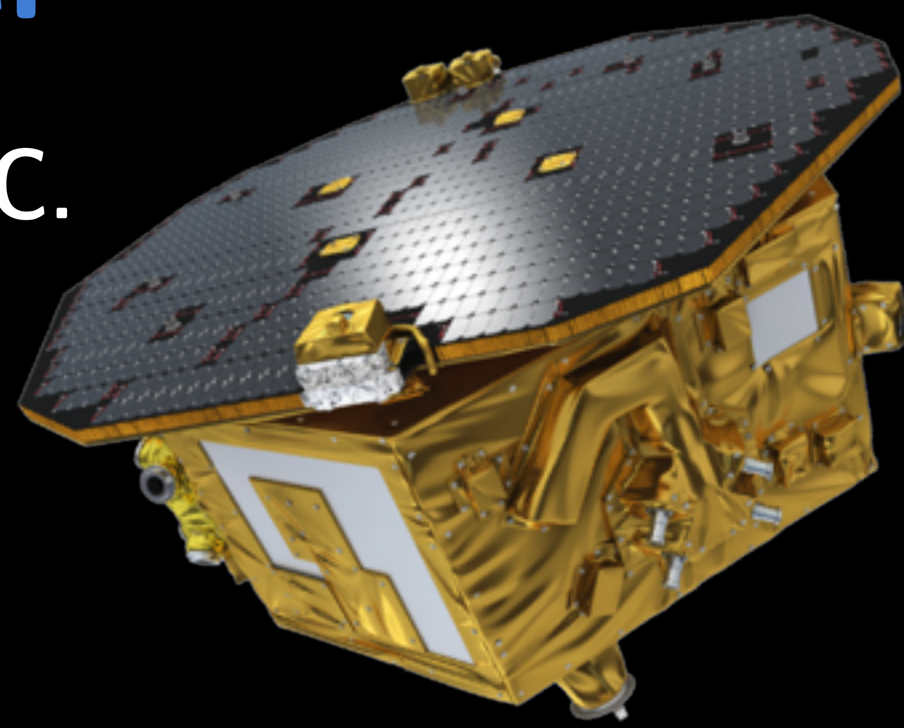
L2 Data Analysis of GWs

L3 Catalogs of GWs sources with their waveform

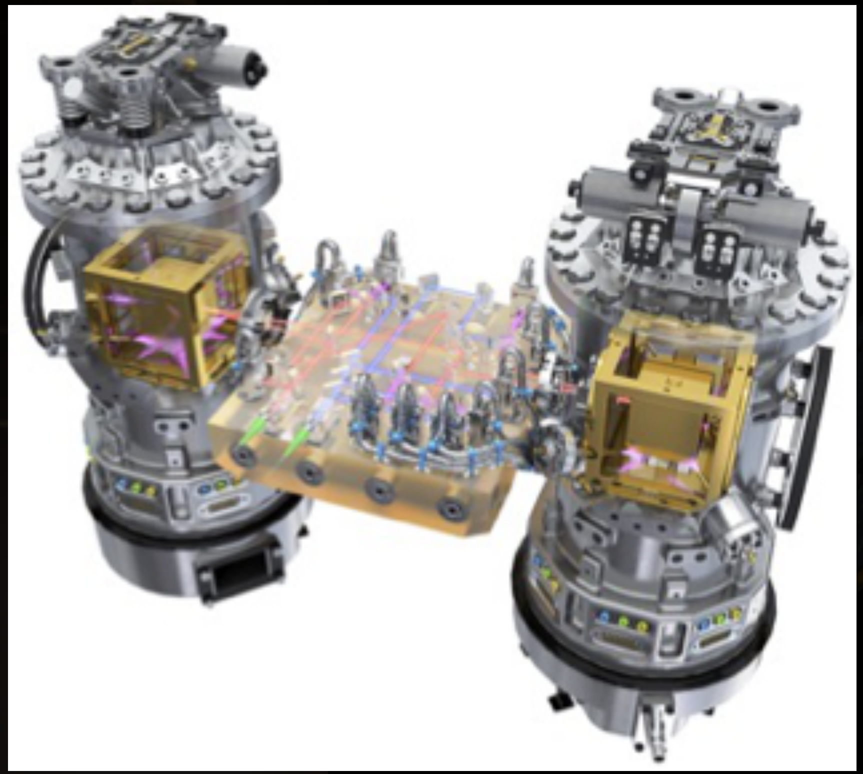
	Generation Rates	
System	Downlink rate [kbit/s]	Onboard rate [kbit/s]
Phasemeter	4,8	303,4
DFACS	1,1	107,5
GRS FEE	0,0	11,5
CGT	0,0	34,6
CMS	0,0	0,5
SciDiag	0,3	2,5
Housekeeping	4,0	4,0

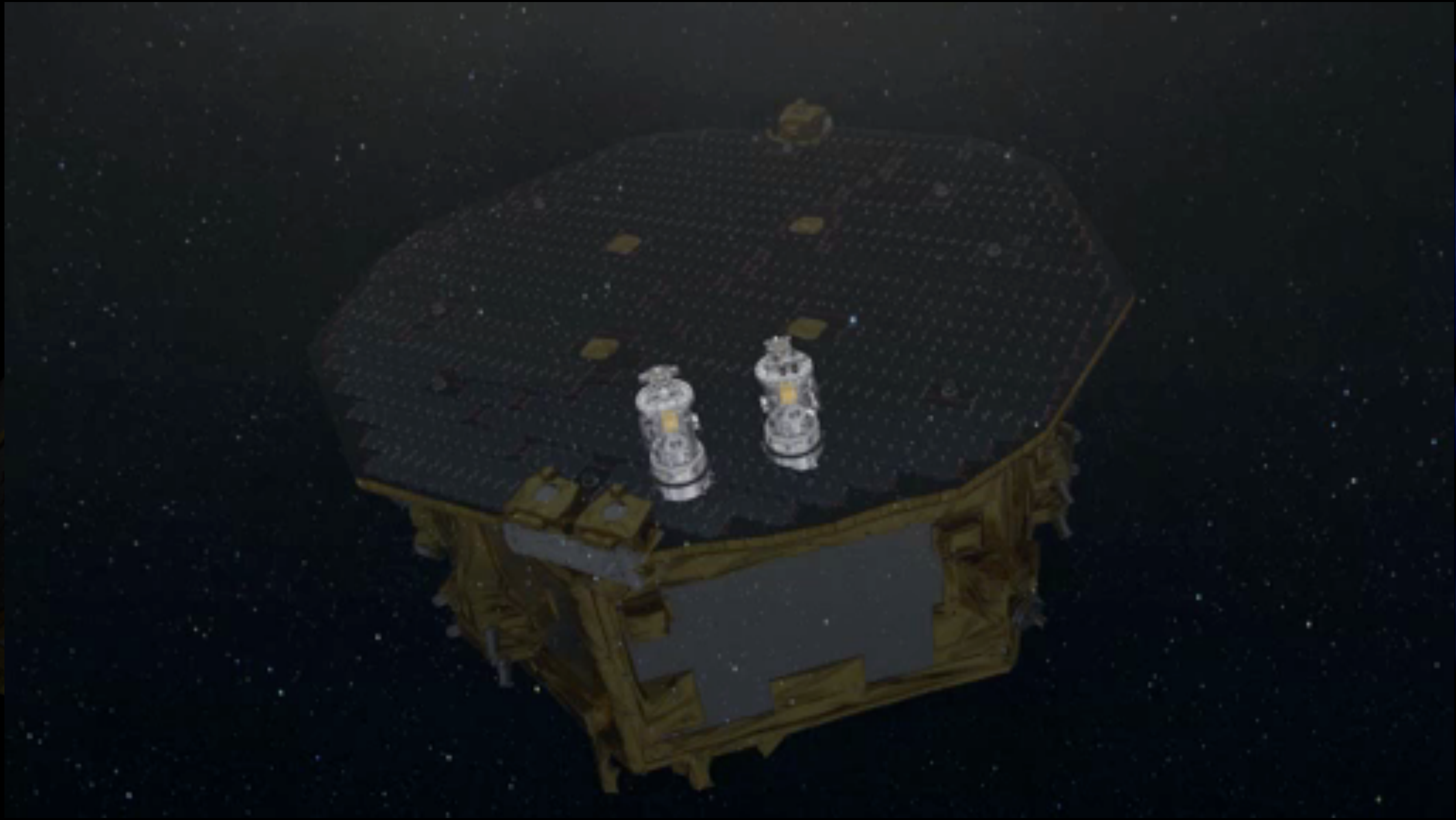
Generation Volumes	
Volume	GB
Telemetered volume generated per day per S/C	0,2
per day per S/C	11,0
Onboard Storage Required per S/C	154,4

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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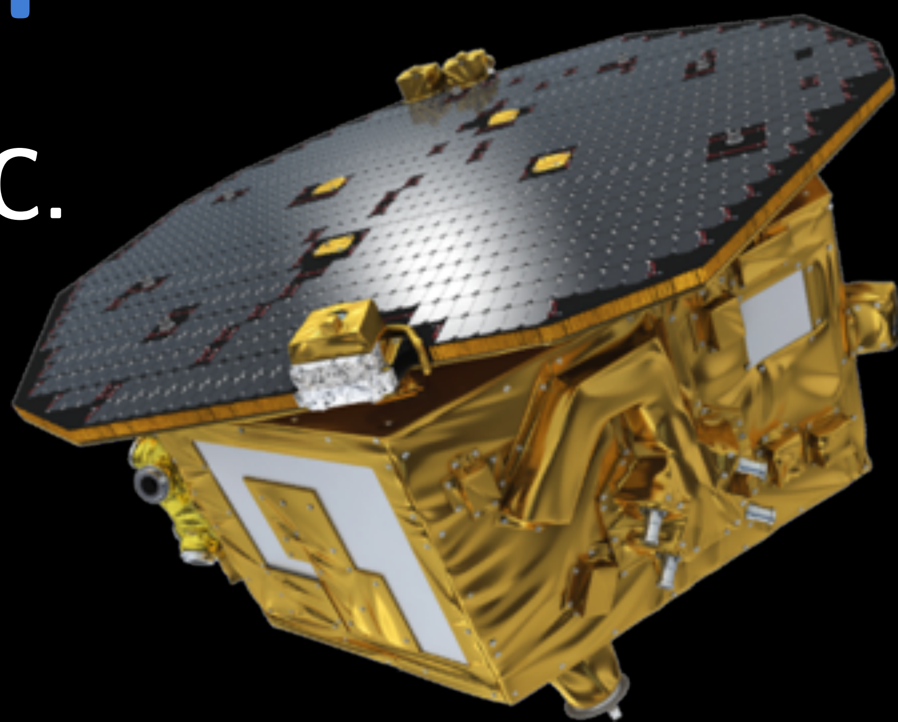
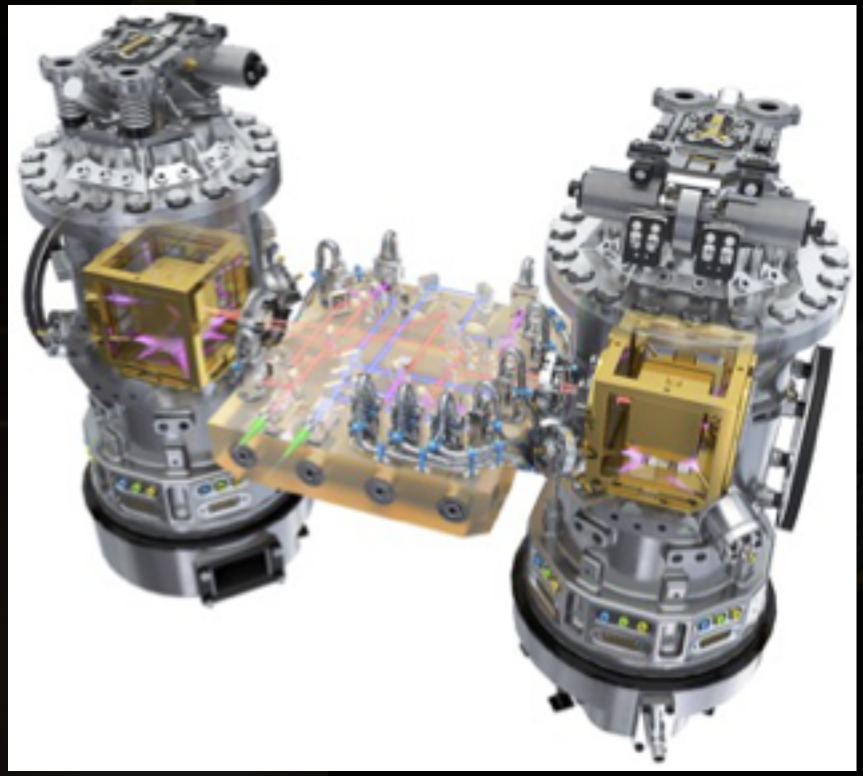
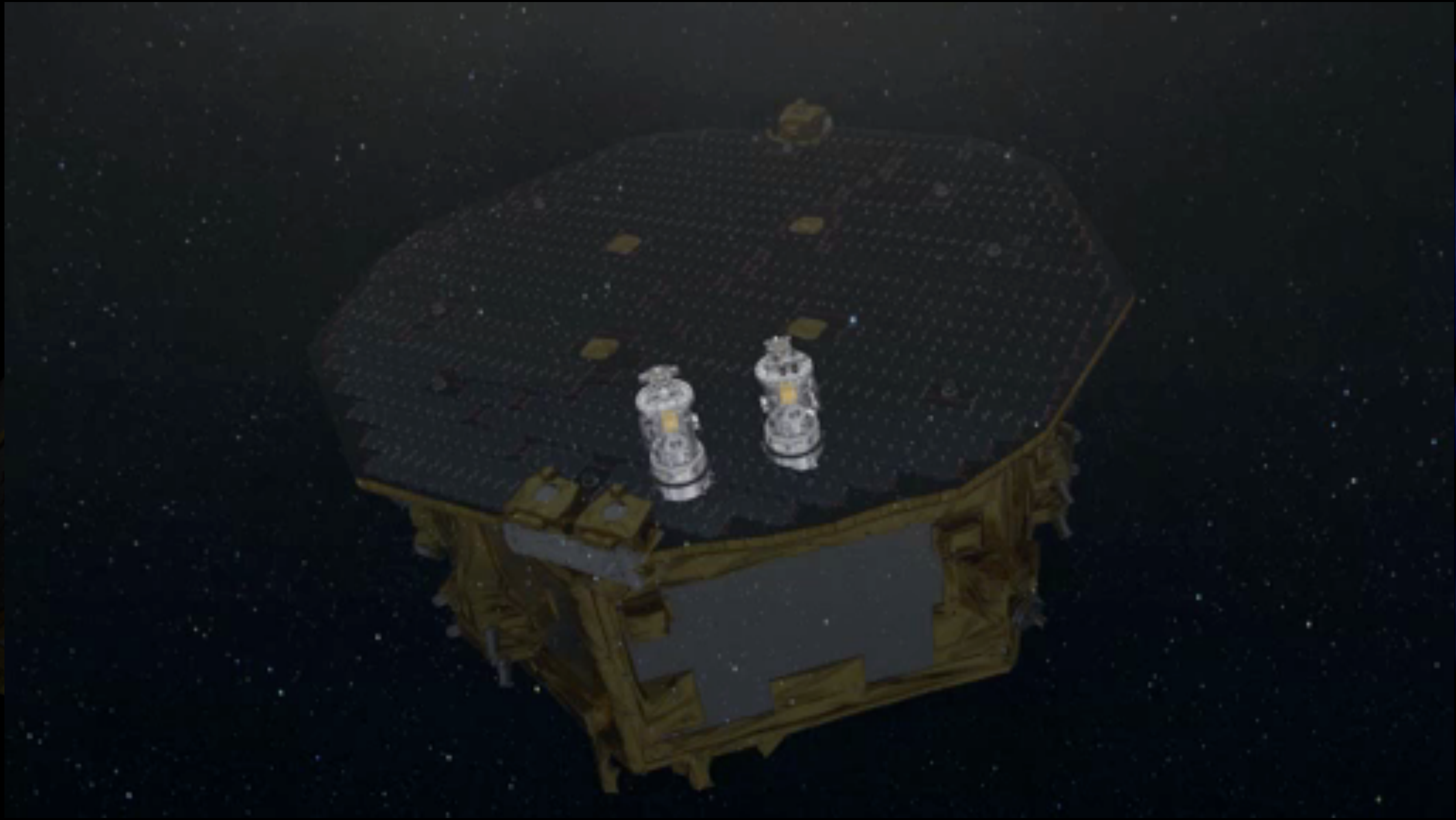
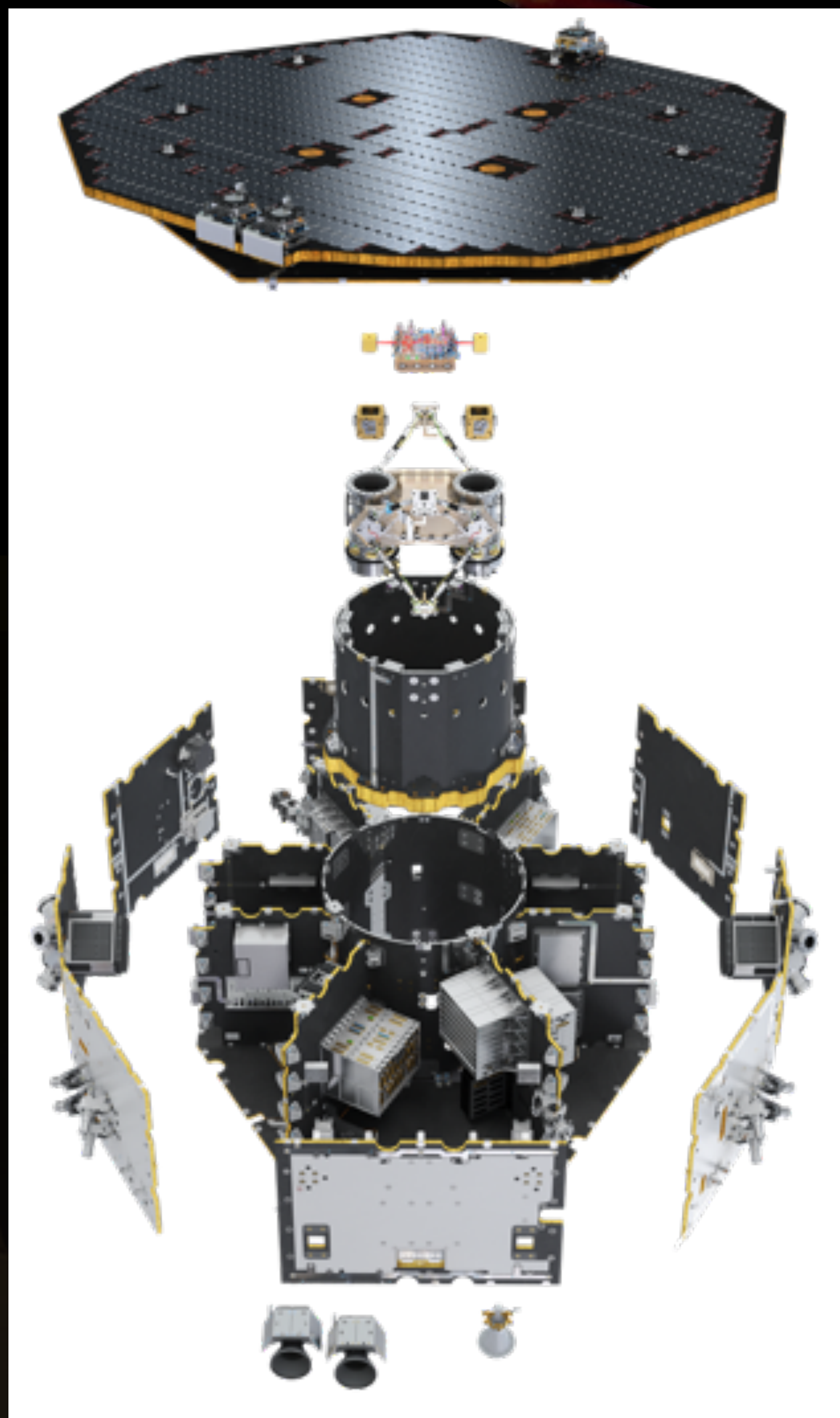




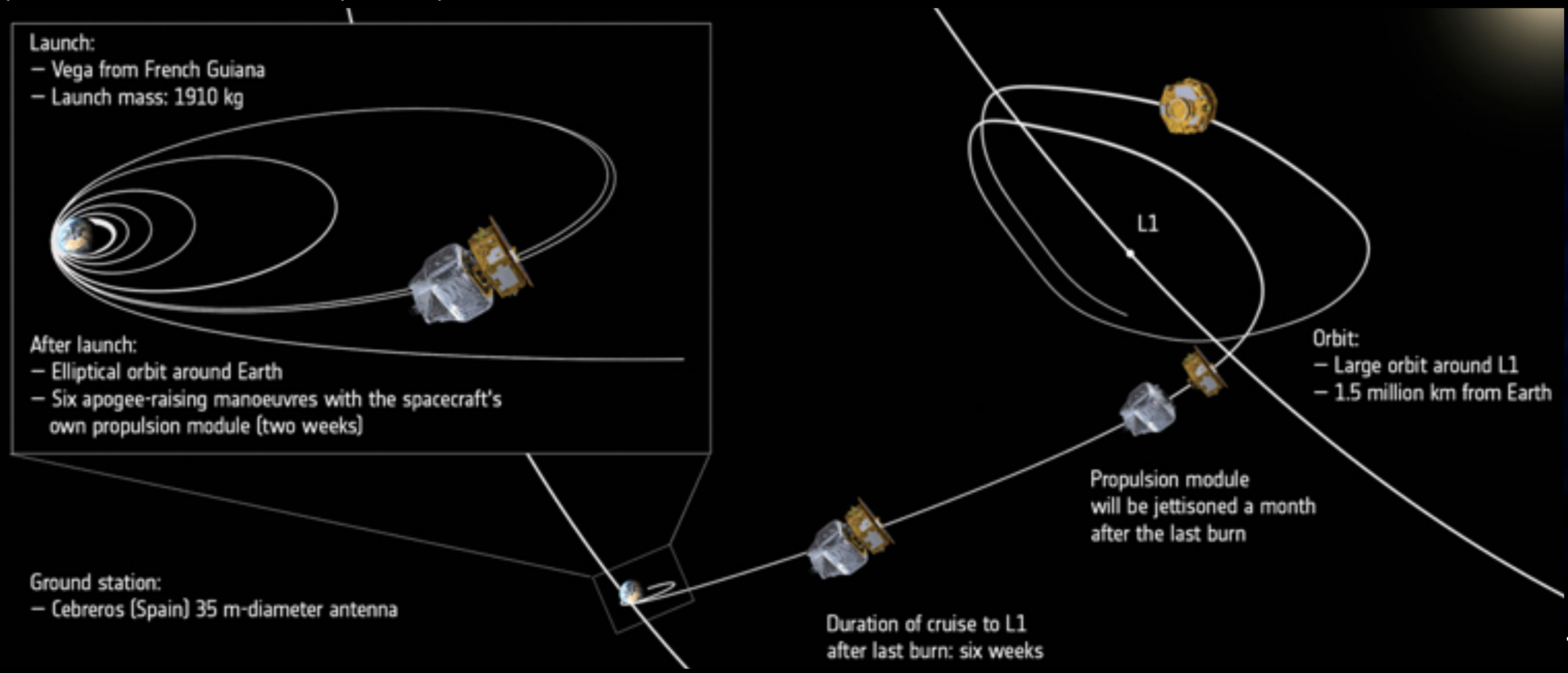


LISAPathfinder



LISAPathfinder timeline

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



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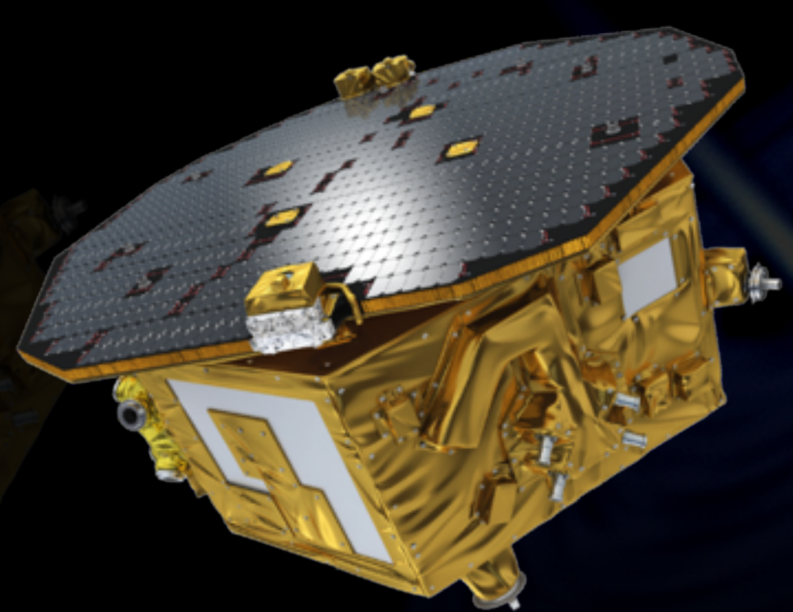
Last command: 18/07/2017



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The measurement - deltaG

by Joseph Martino

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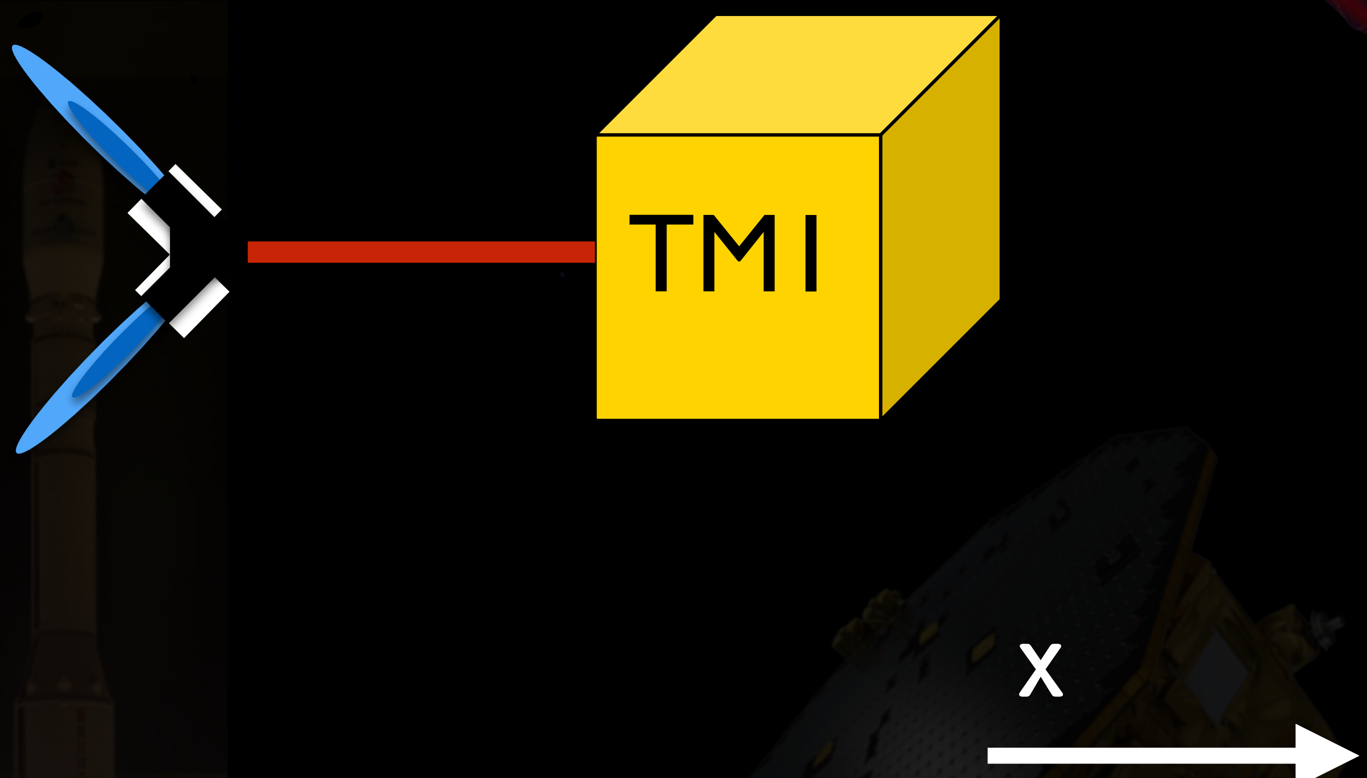

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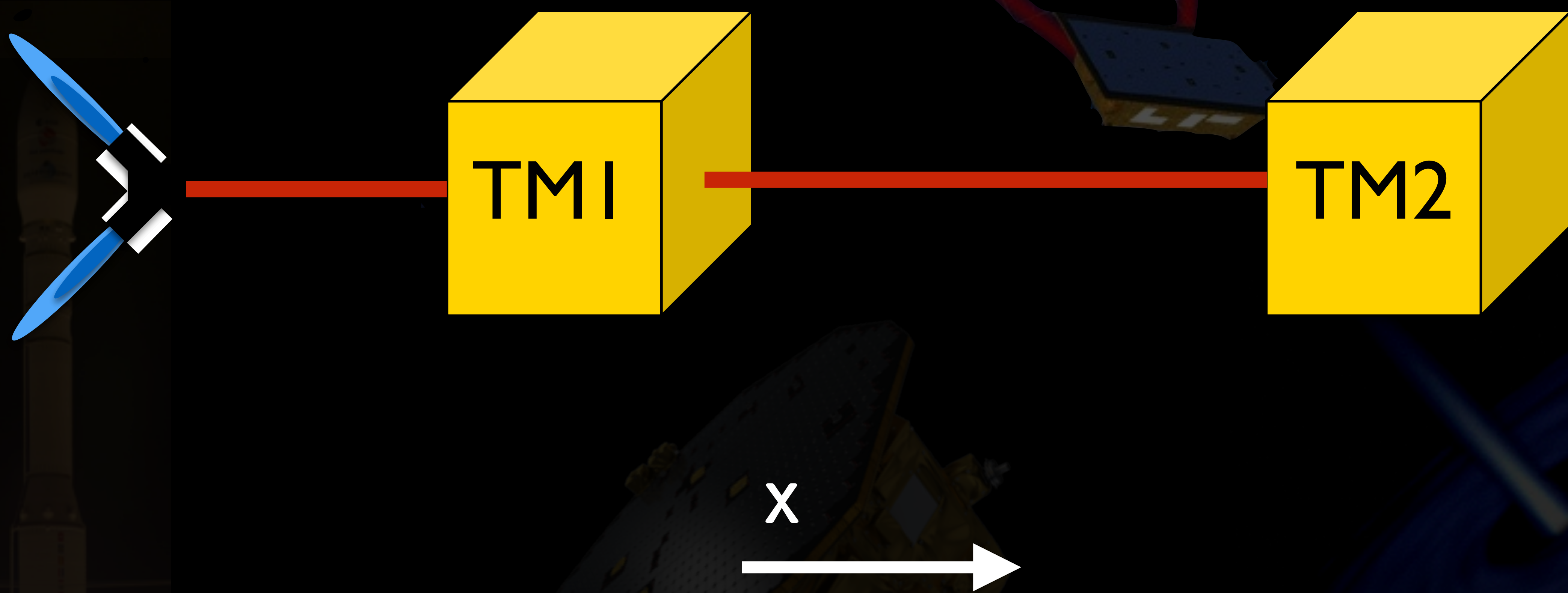

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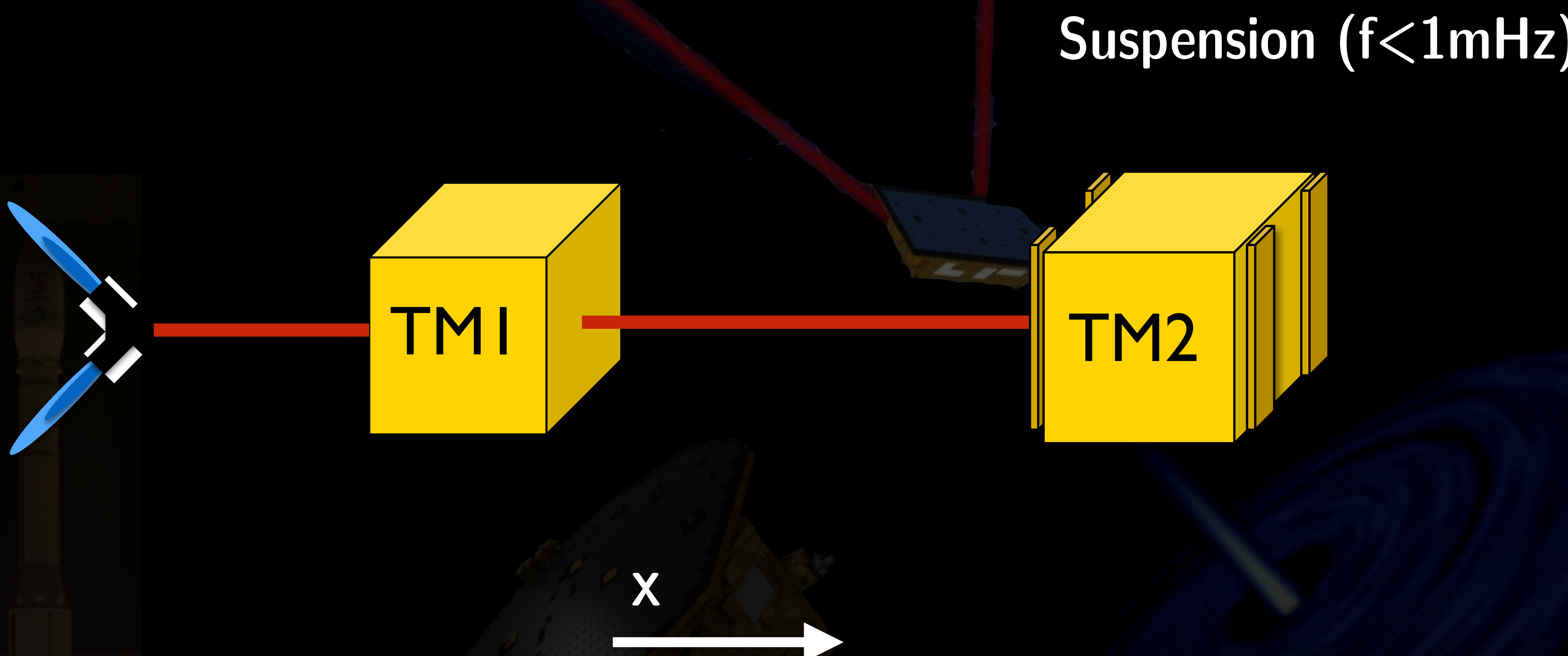

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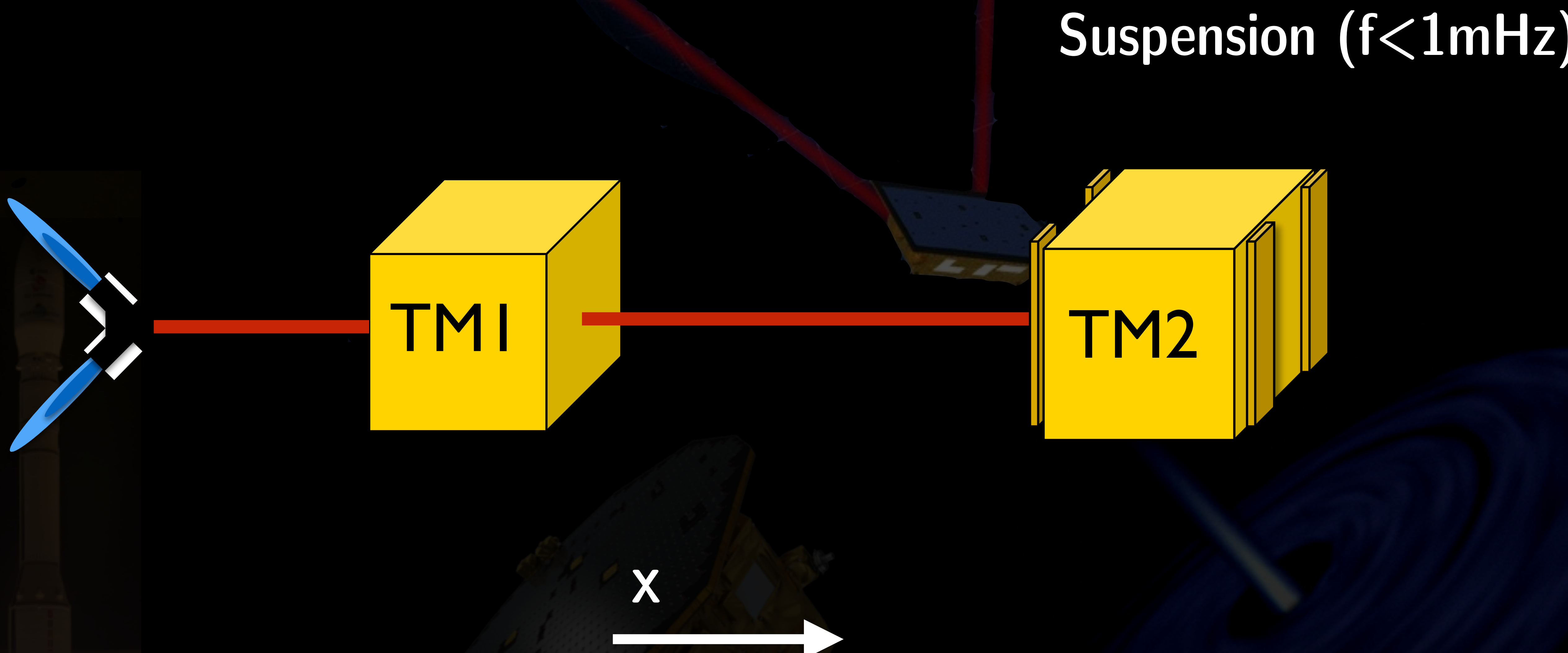
The measurement - deltaG

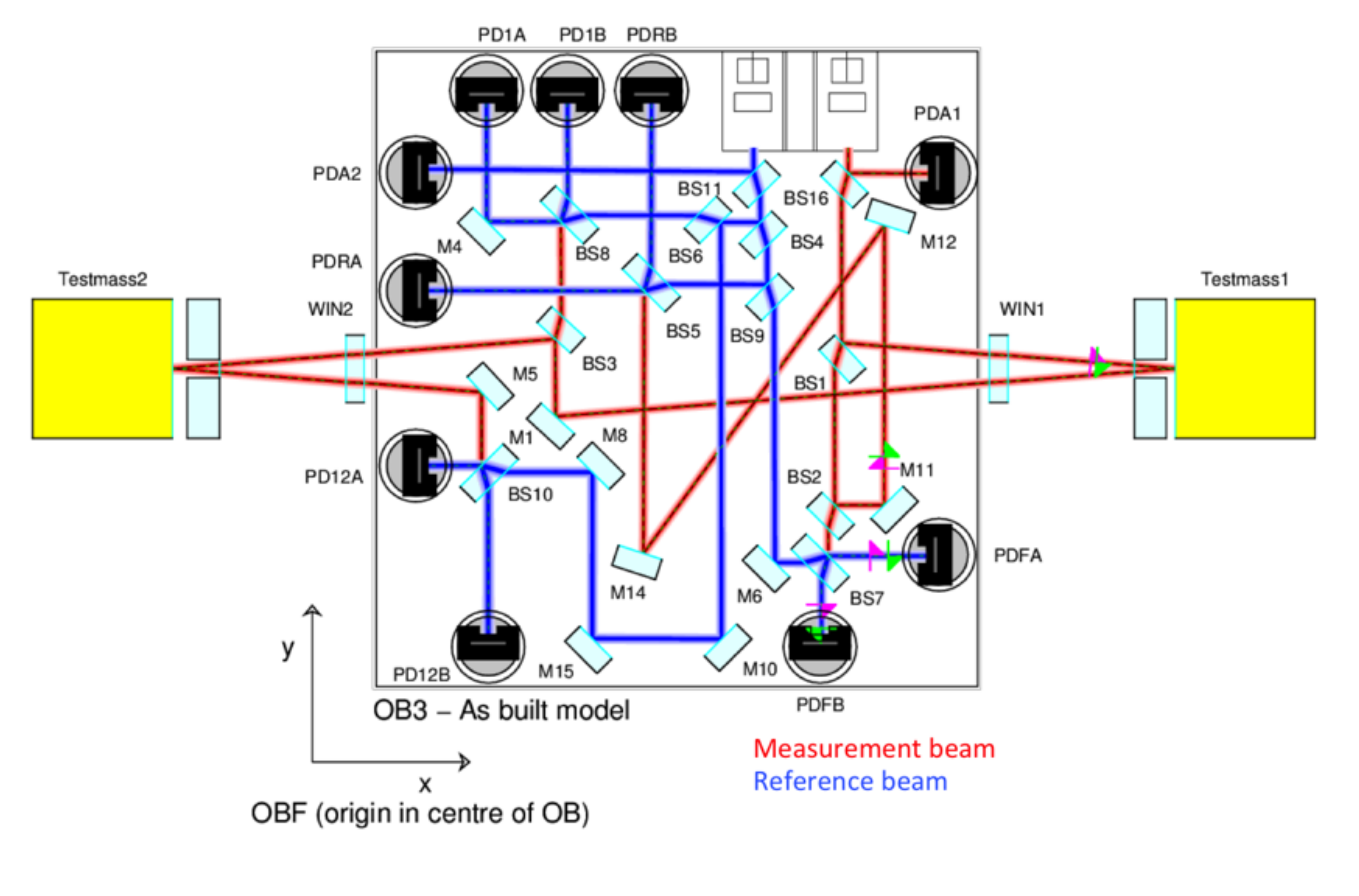
$$\mathrm{deltaG} = d^2(o12)/dt^2 - \mathrm{Stiff} * o12 - \mathrm{Gain} * Fx2$$



by Joseph Martino

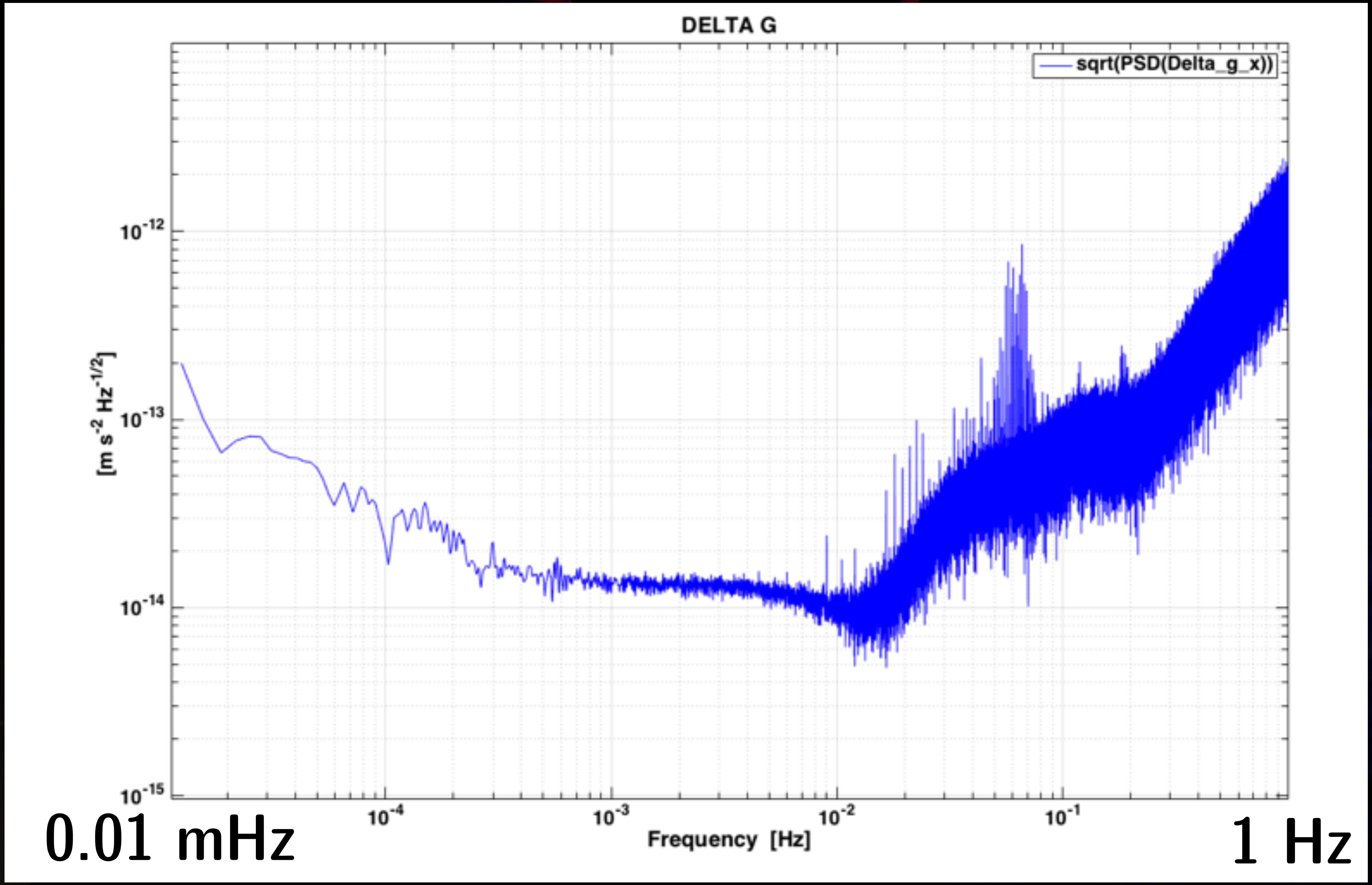
Optical bench

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



Δg - raw

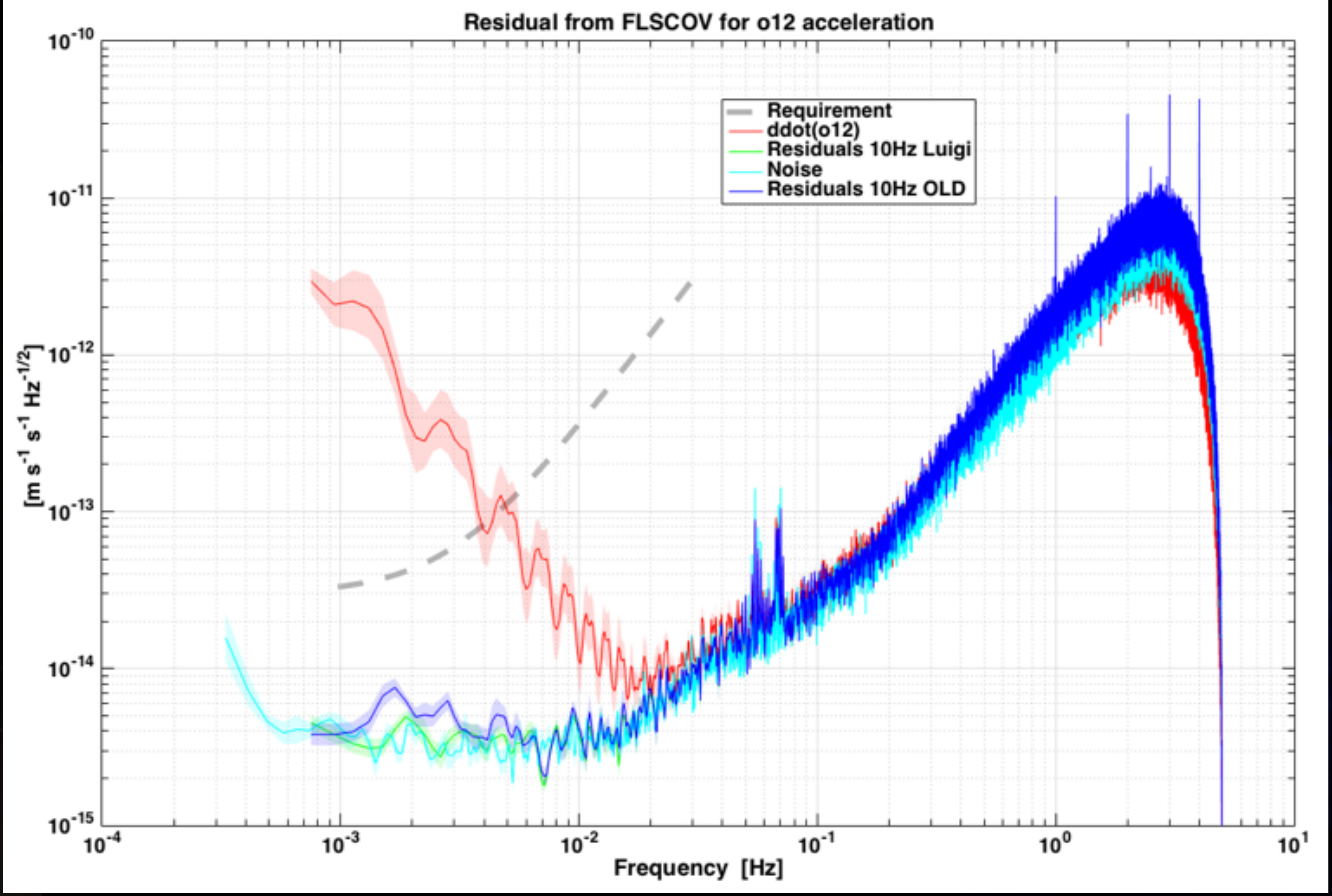
- Differential acceleration Test Mass1 - Test Mass2
- $\Delta g = d^2(o12)/dt^2$ - Stiff * o12 - Gain * Fx2



by Joseph Martino

System-Identification

- Measure gains and stiffness
- $\Delta g = d^2(o12)/dt^2$ - Stiff * o12 - Gain * Fx2



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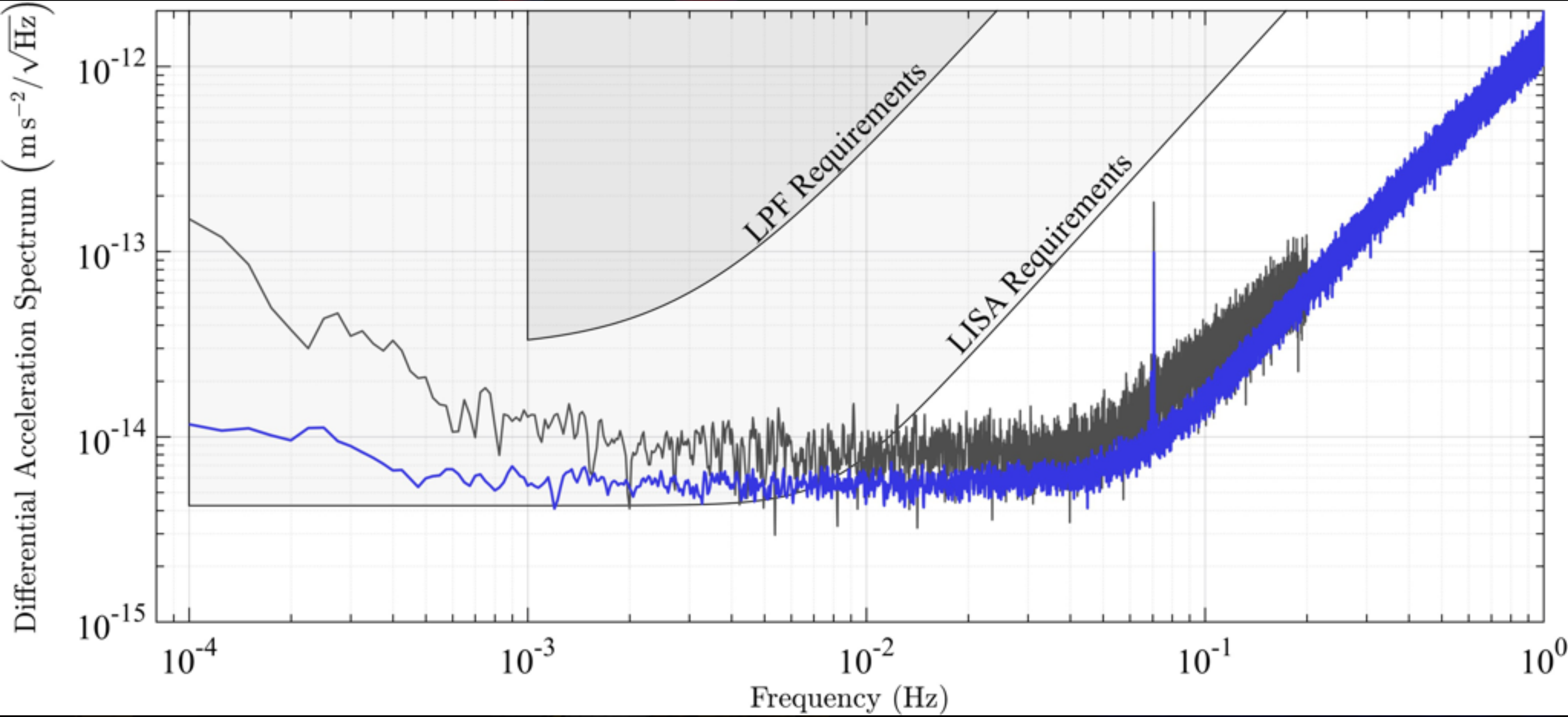
First results

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



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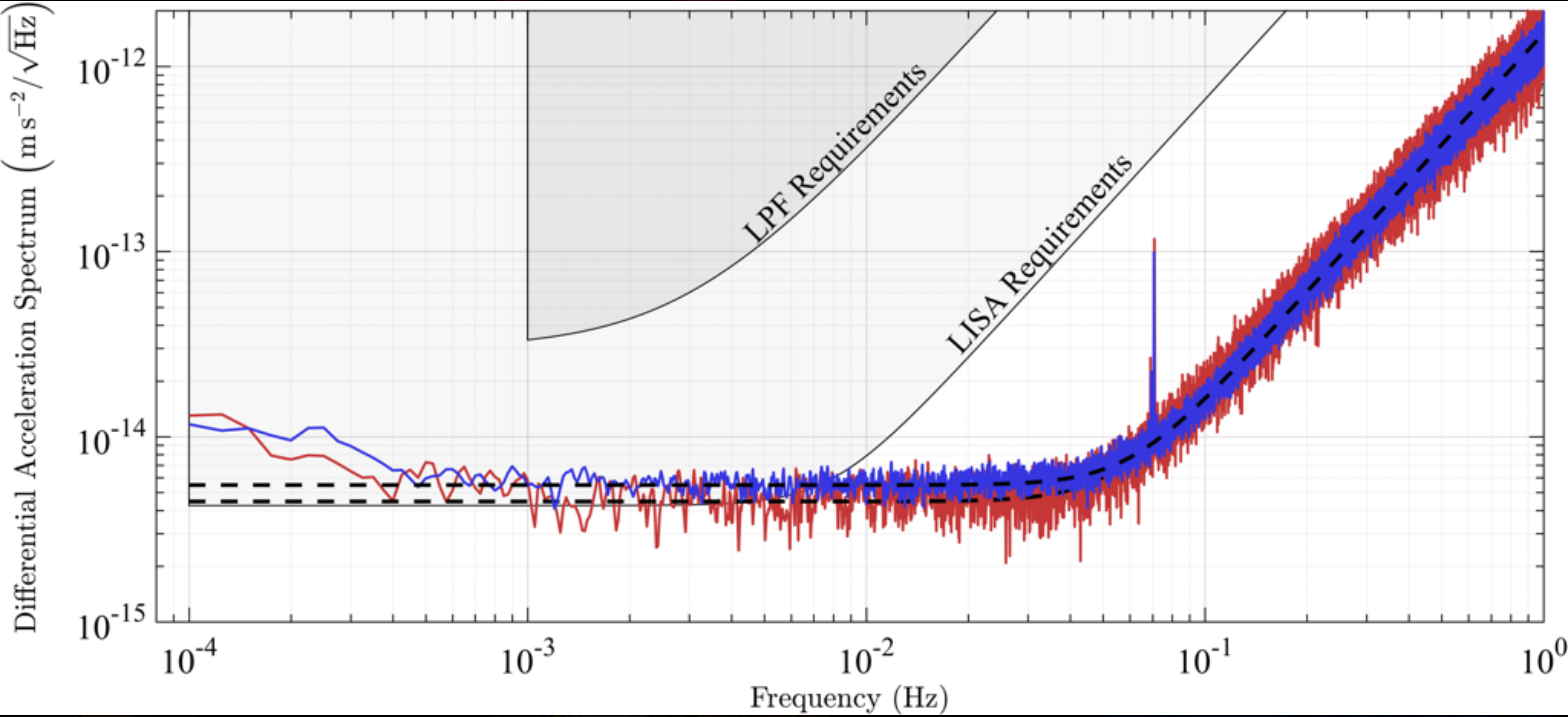

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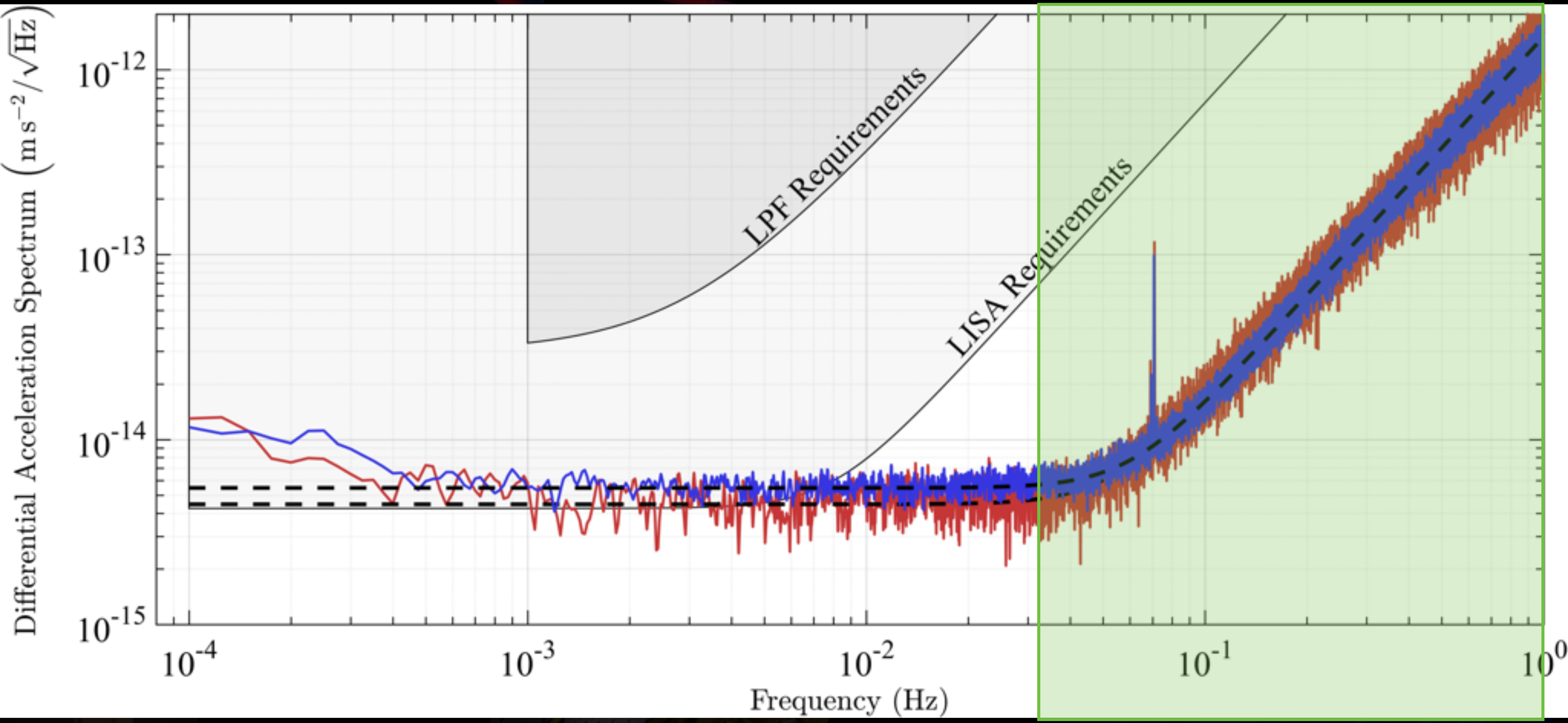
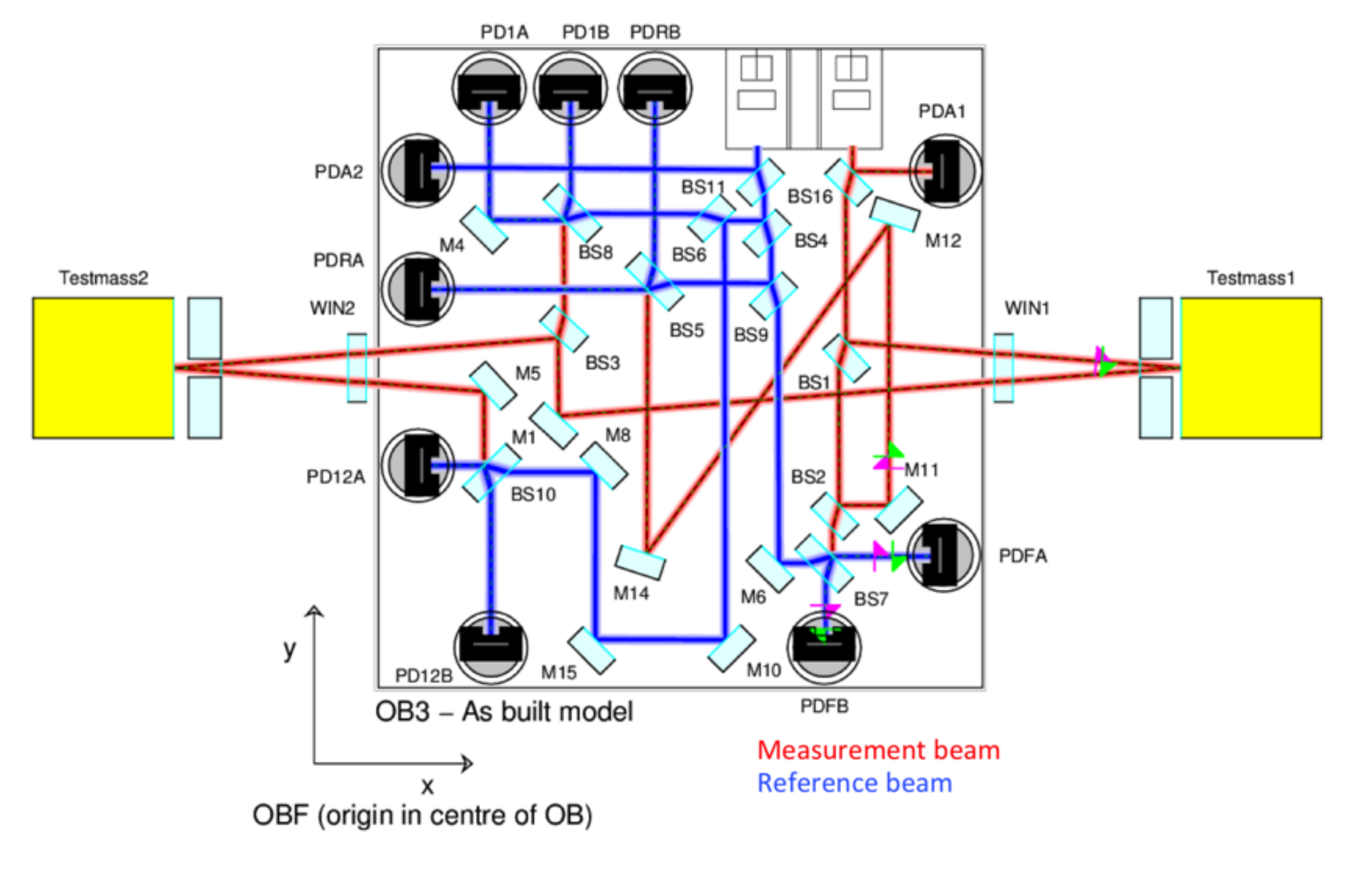
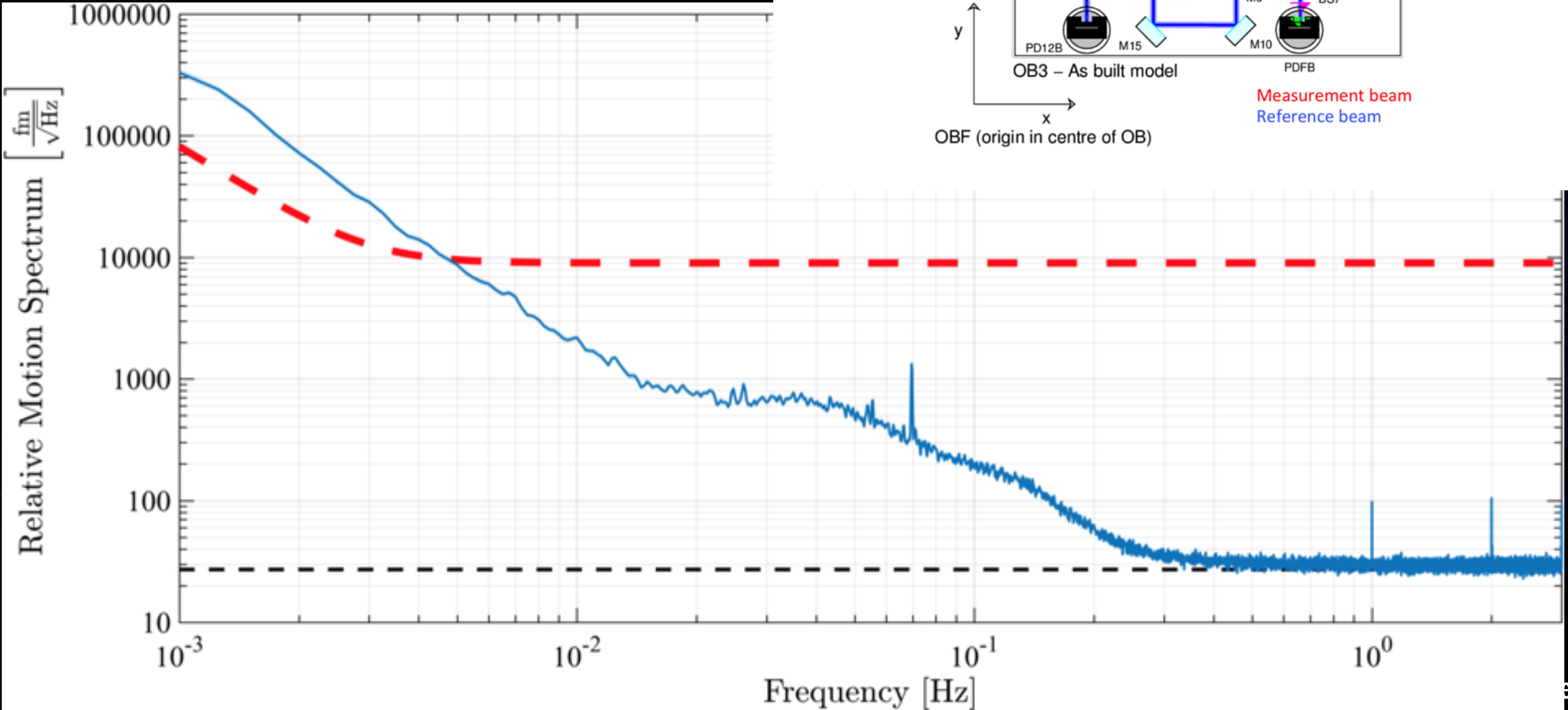


Interferometric noise
Not real test-mass motion

High frequency limit

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

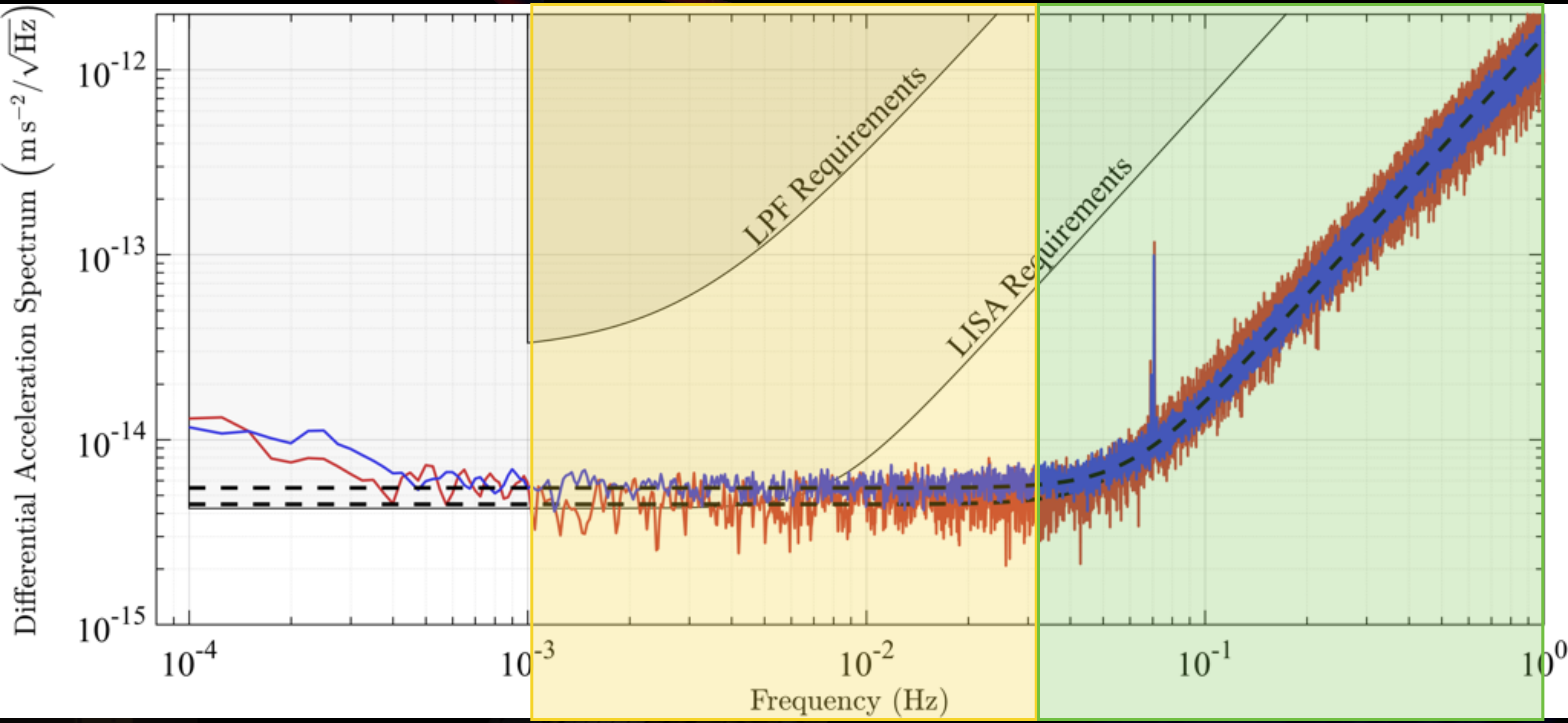




er 2019

First results

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

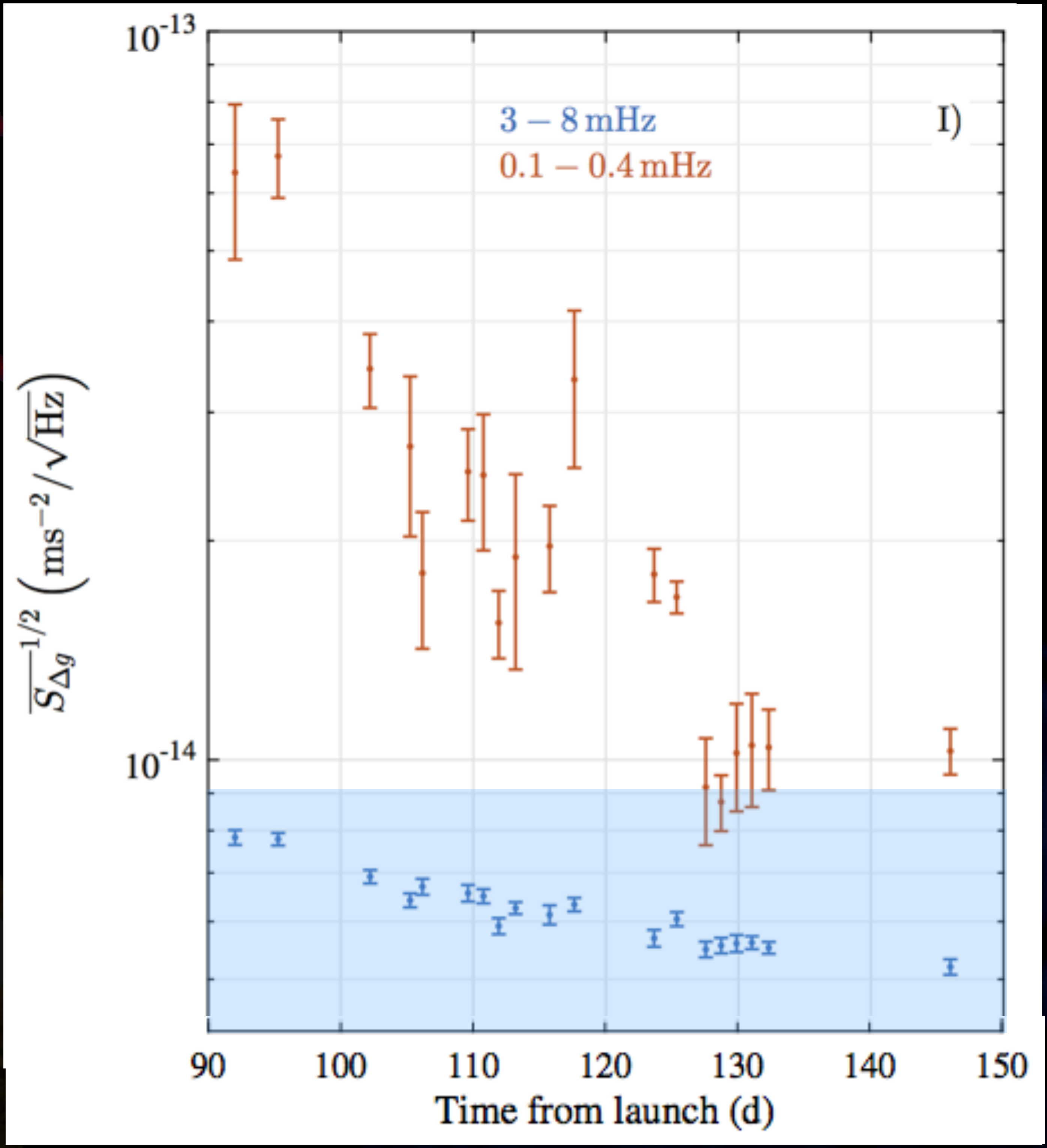


Brownian noise
Molecules within the noise hit test-masses

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 …



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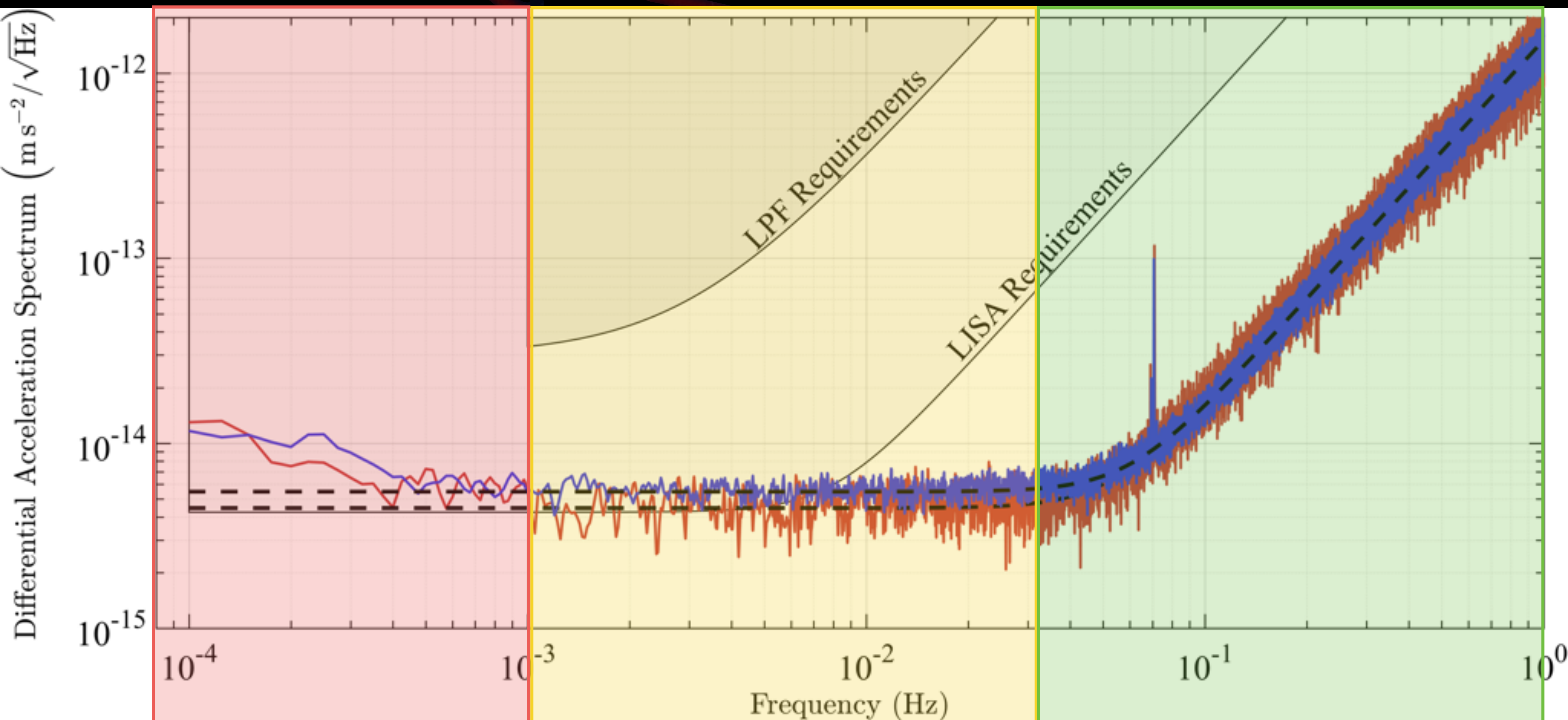


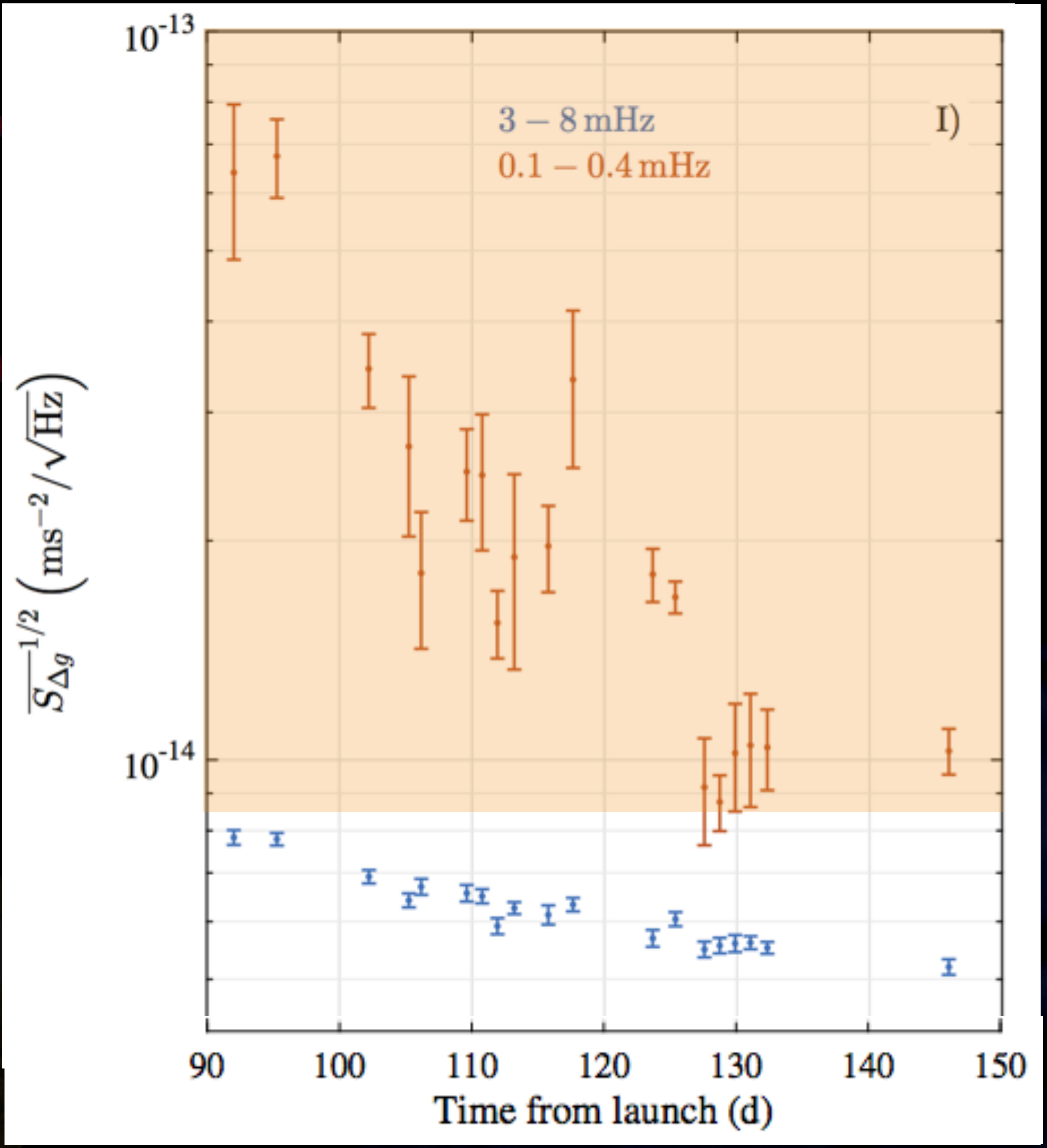
Low frequency noise
Investigation still in progress
...

Brownian noise
Molecules within the noise hit test-masses

Interferometric noise
Not real test-mass motion

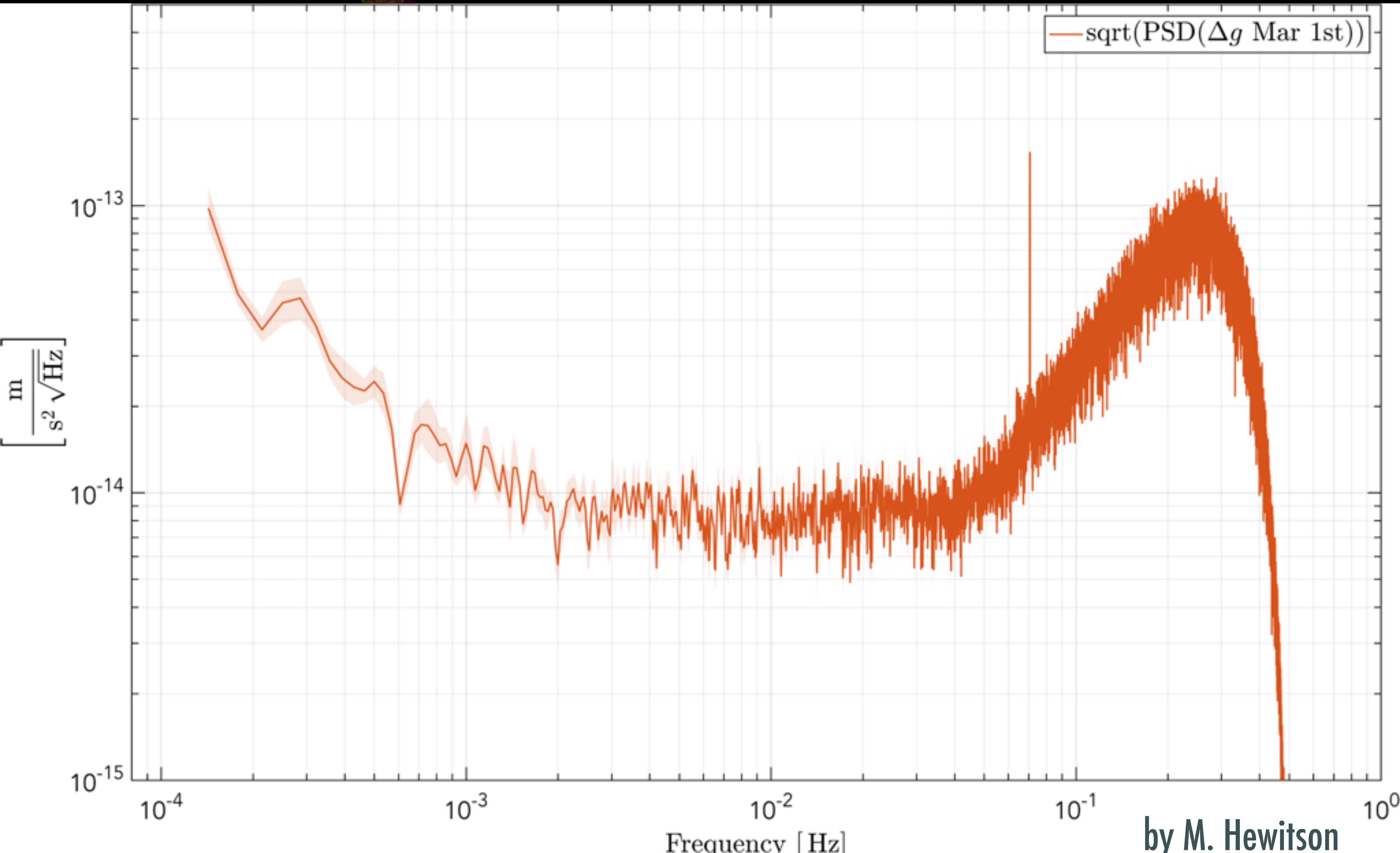
Low-frequency limit

- 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)

Time evolution of noises



by M. Hewitson

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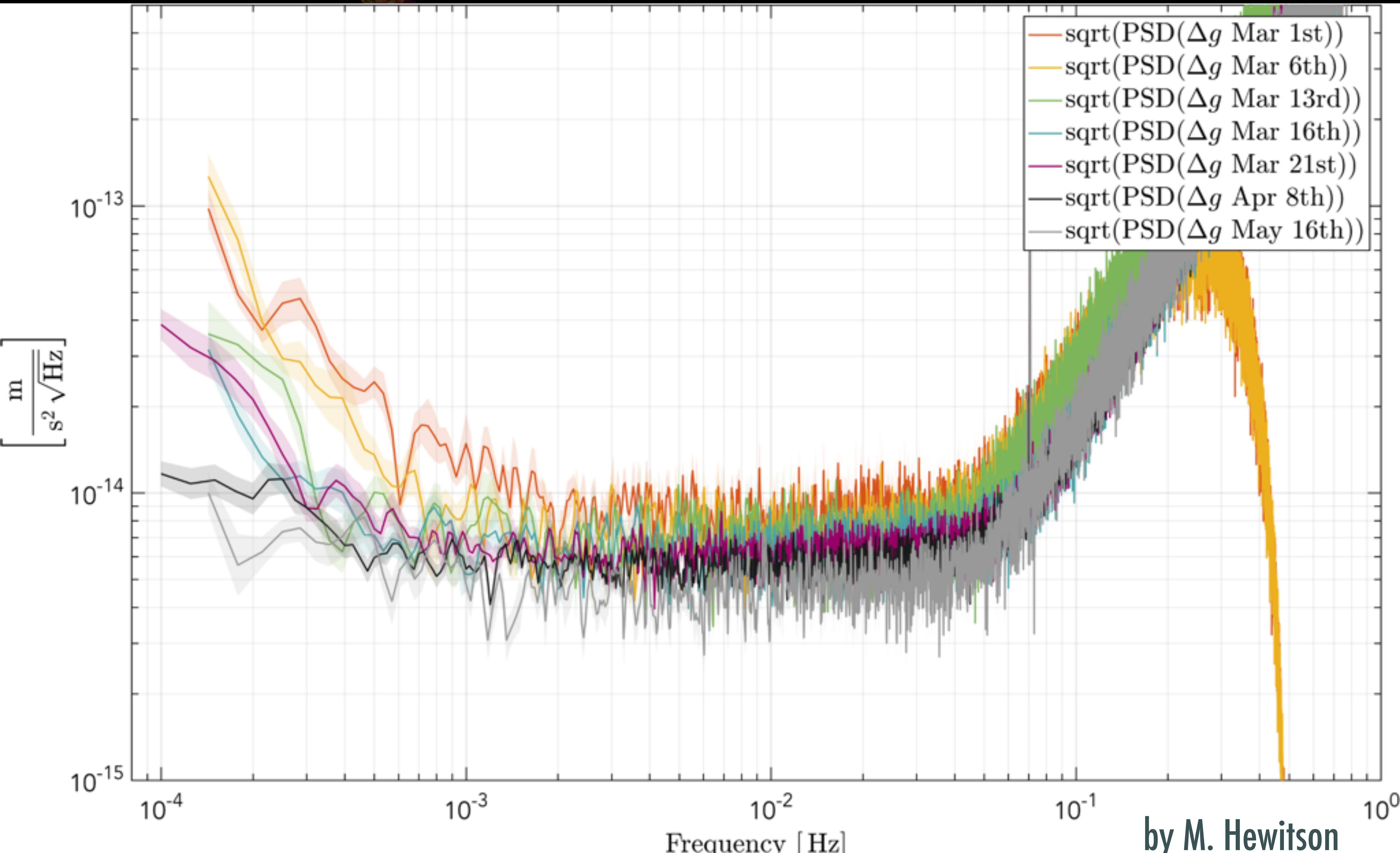
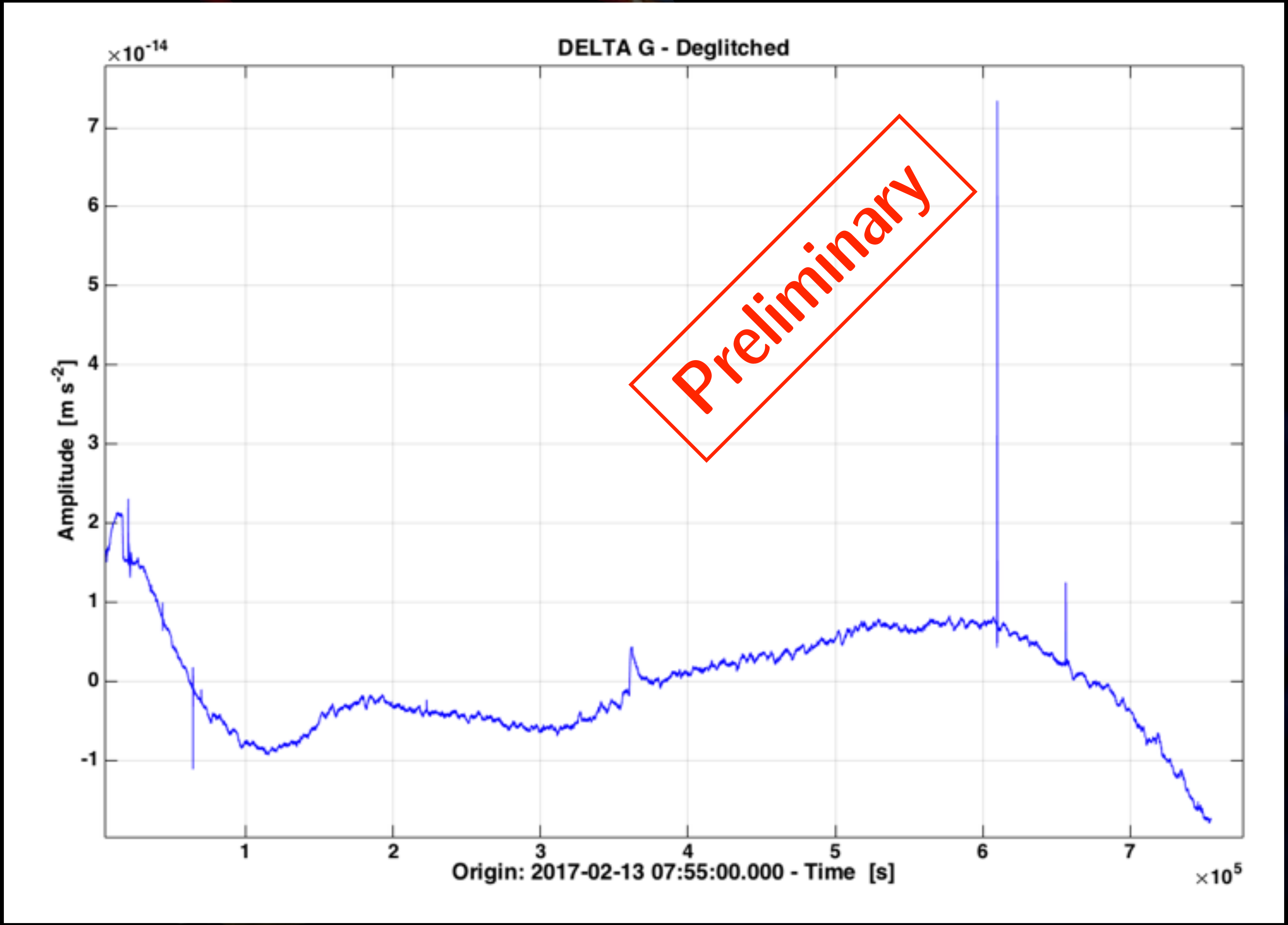
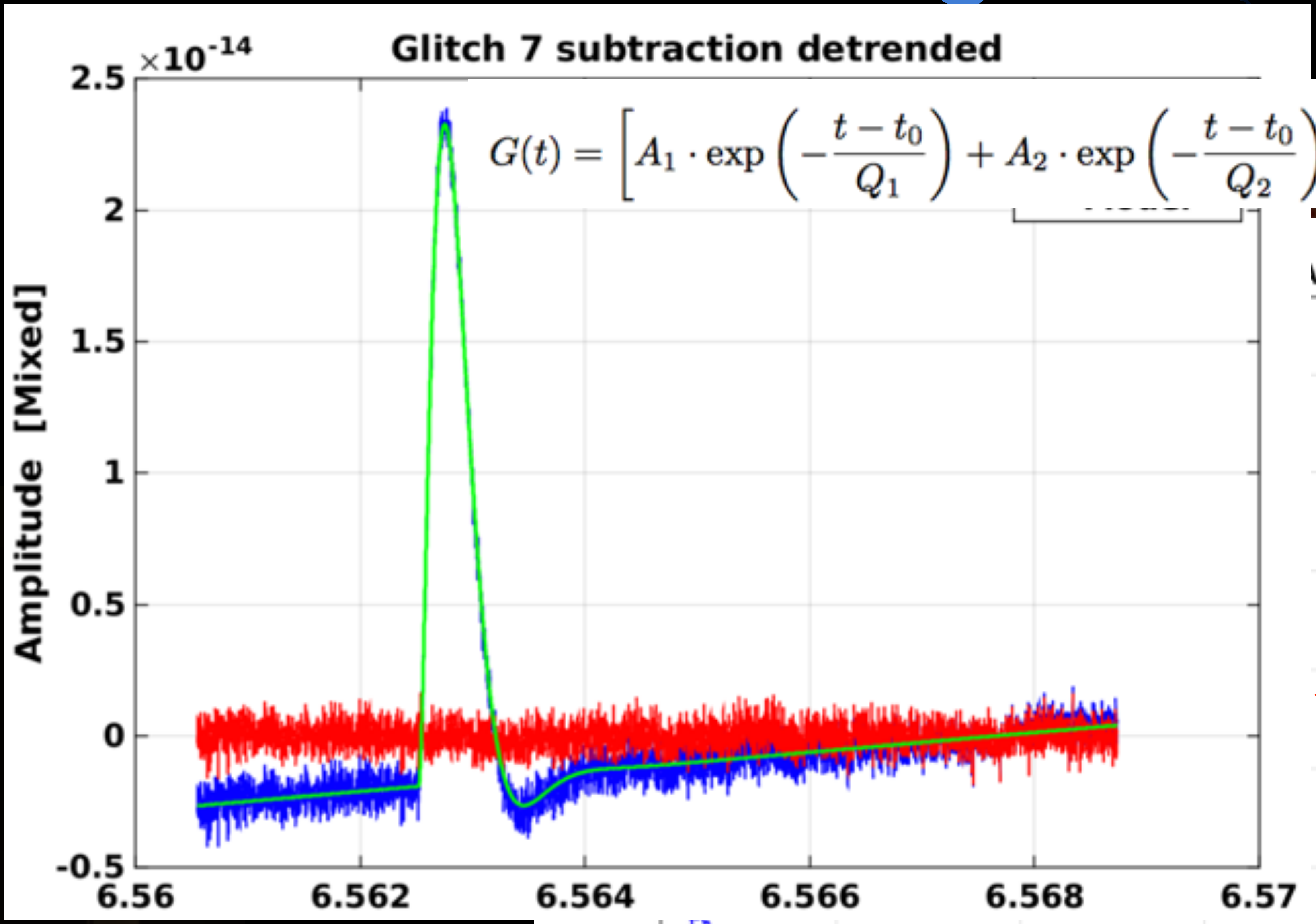


by M. Hewitson

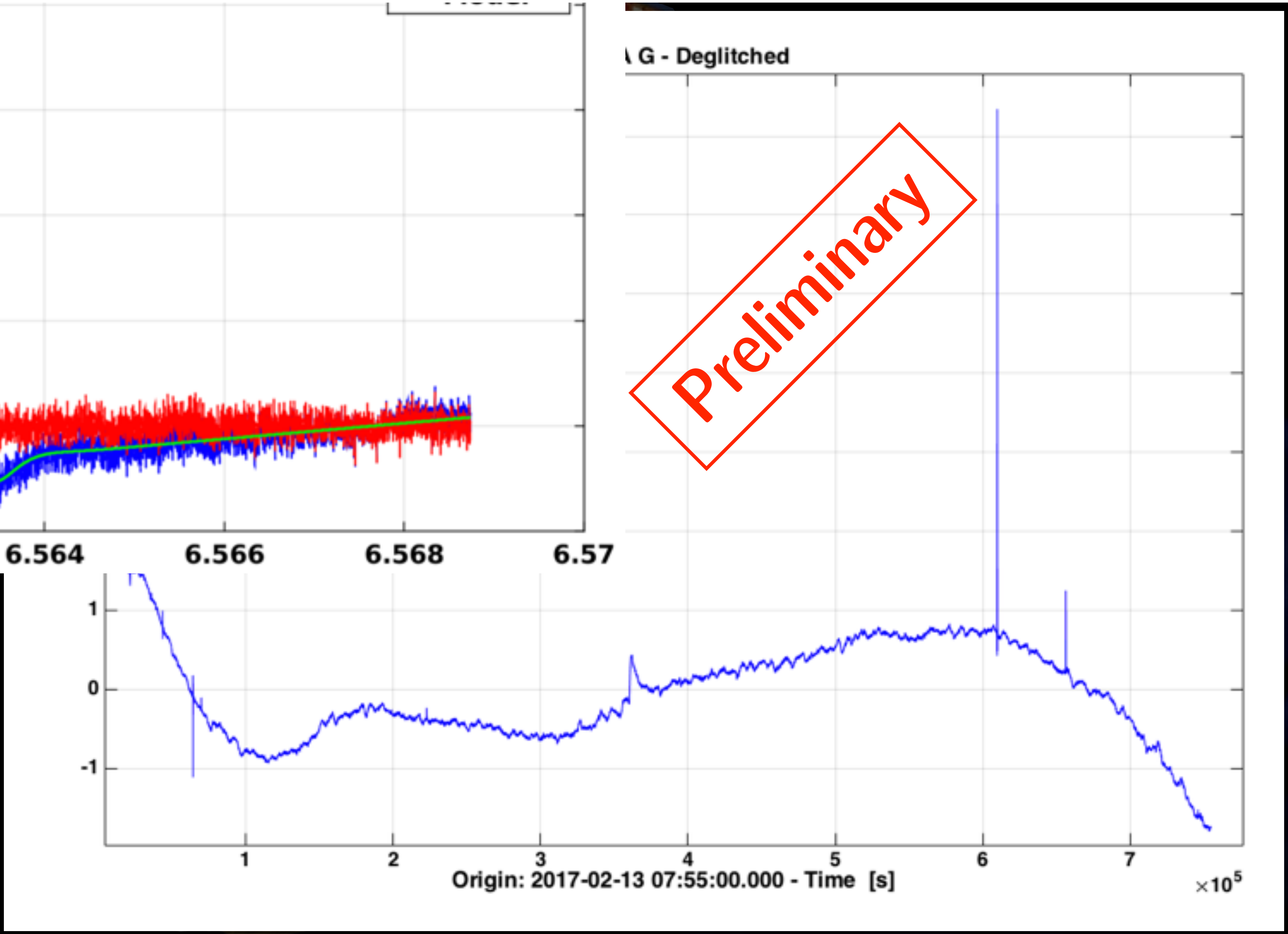
De-glitching



De-glitching

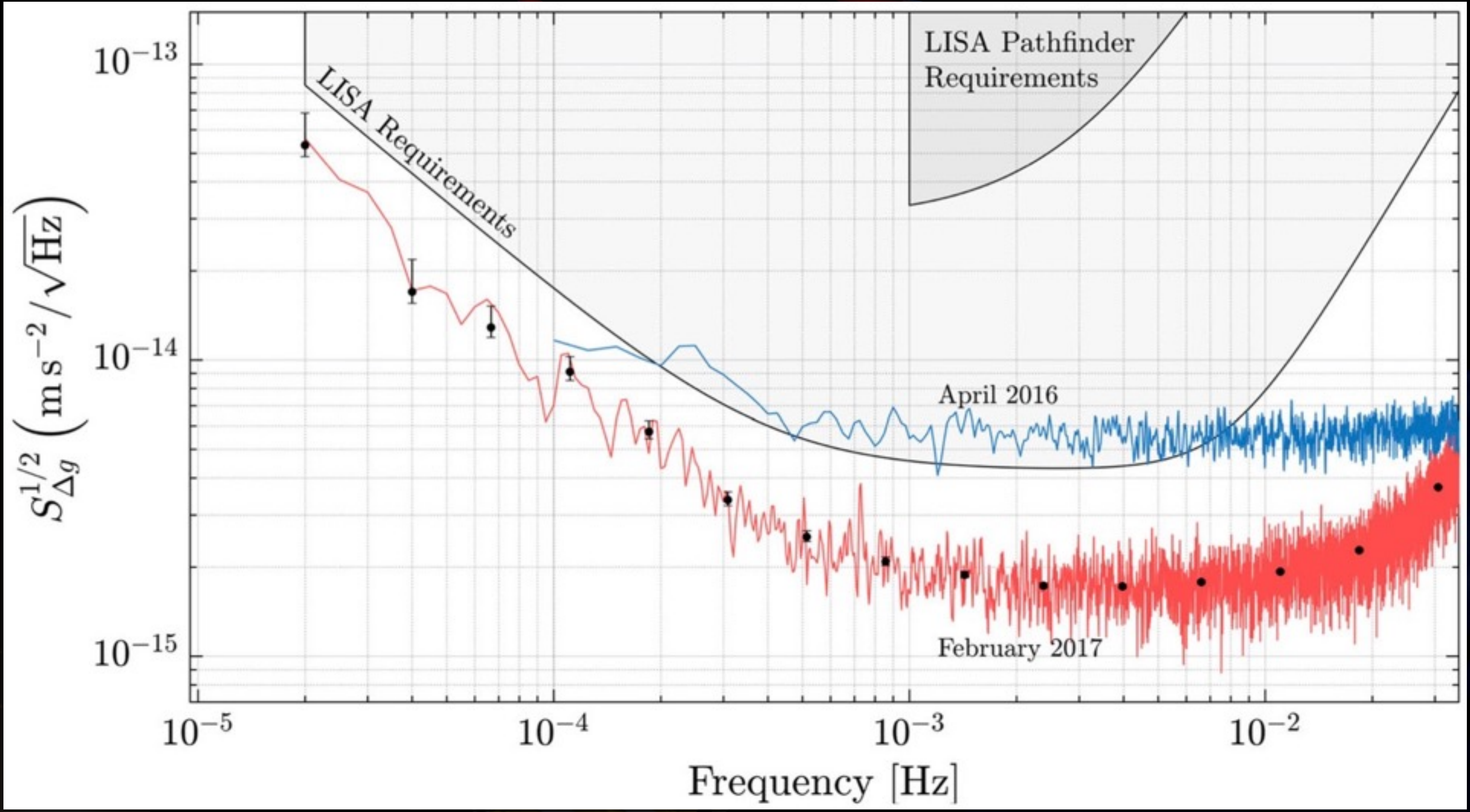


$$G(t) = \left[A_1 \cdot \exp\left(-\frac{t-t_0}{Q_1}\right) + A_2 \cdot \exp\left(-\frac{t-t_0}{Q_2}\right) + A_3 \cdot \exp\left(-\frac{t-t_0}{Q_3}\right)\right] * \left[1 - \exp\left(-\frac{t-t_0}{Q_0}\right)\right]^{\alpha}$$



LISAPAthfinder final main results

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



History of LISA

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

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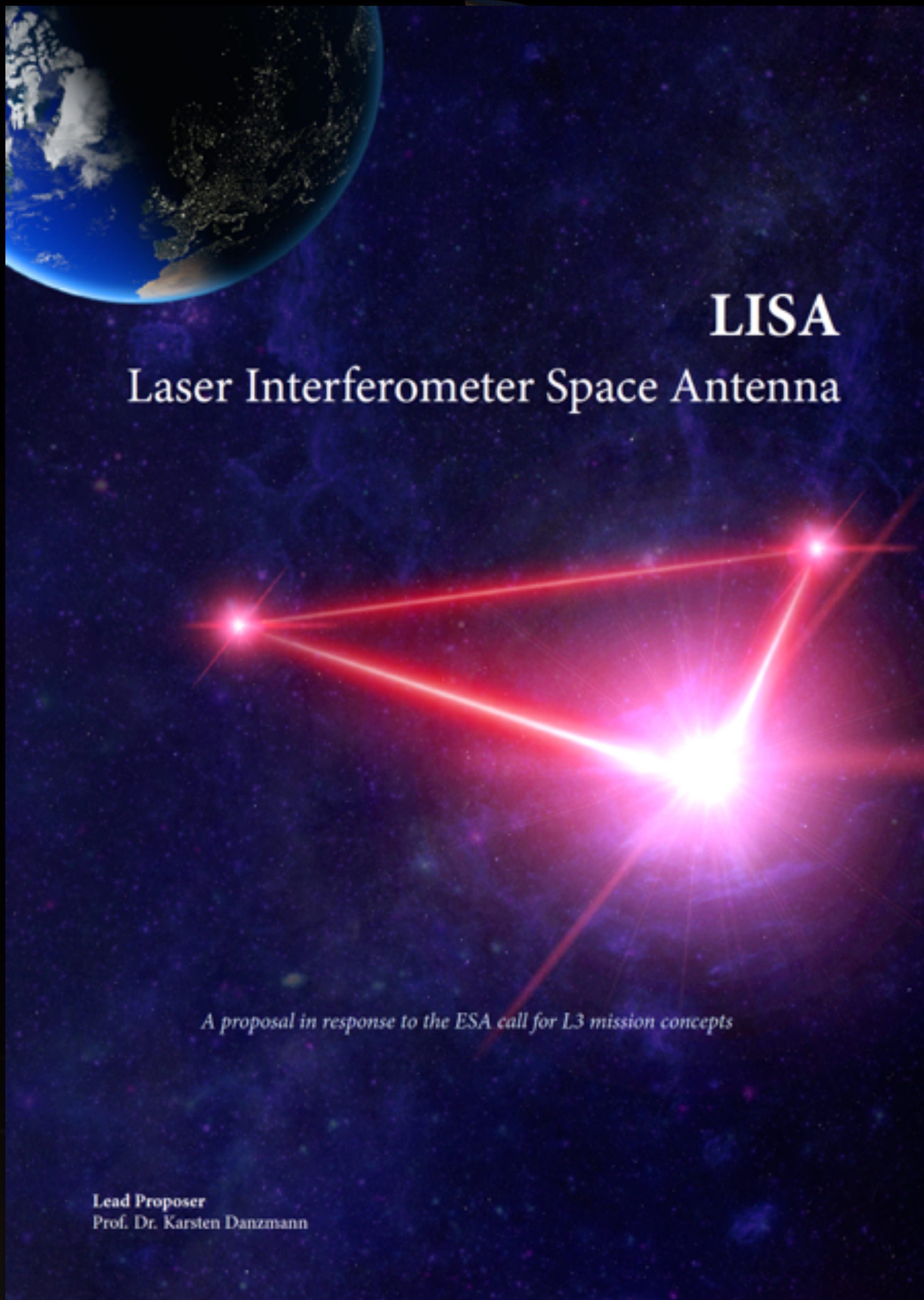
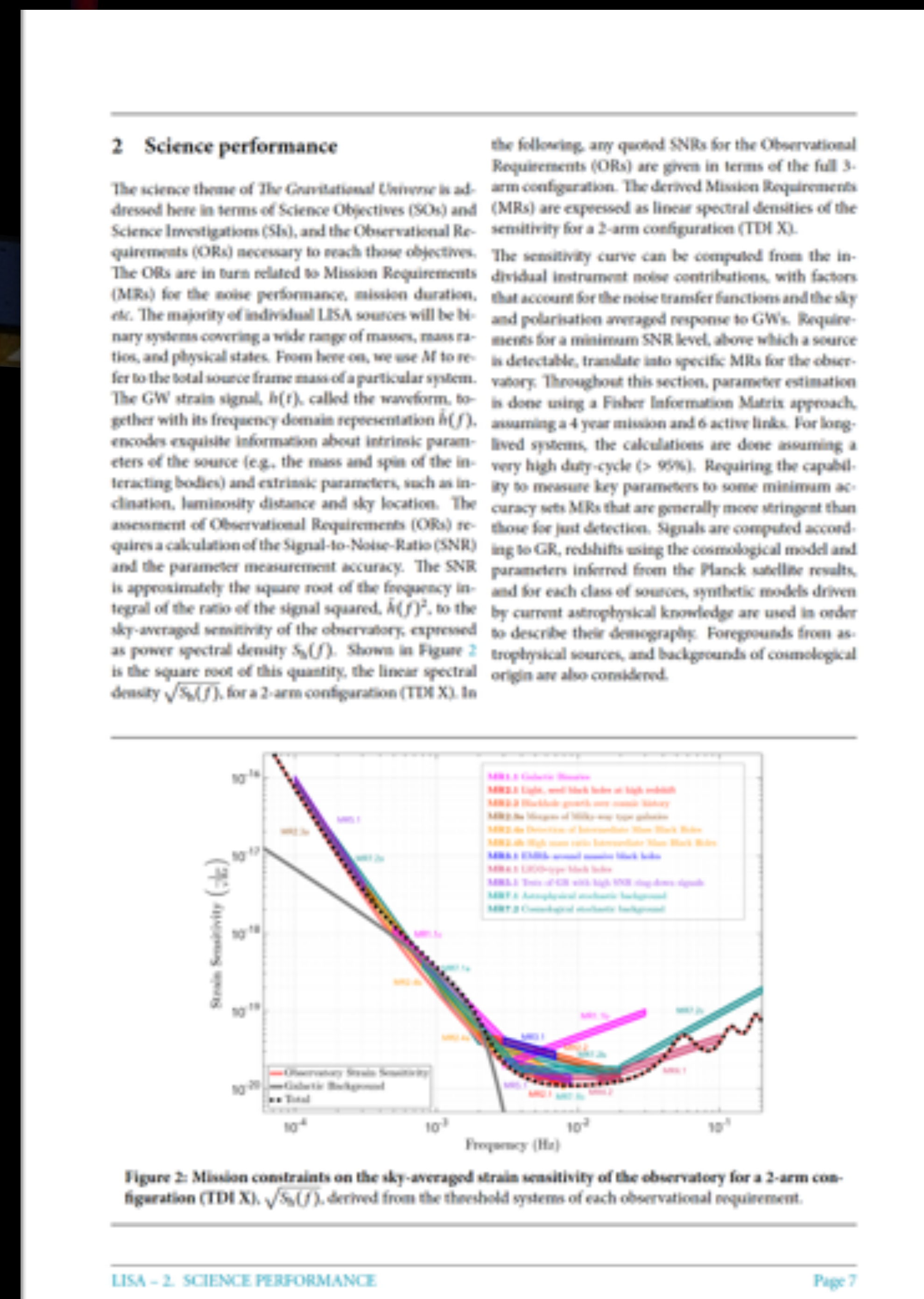
→ **Call for mission at ESA**

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.

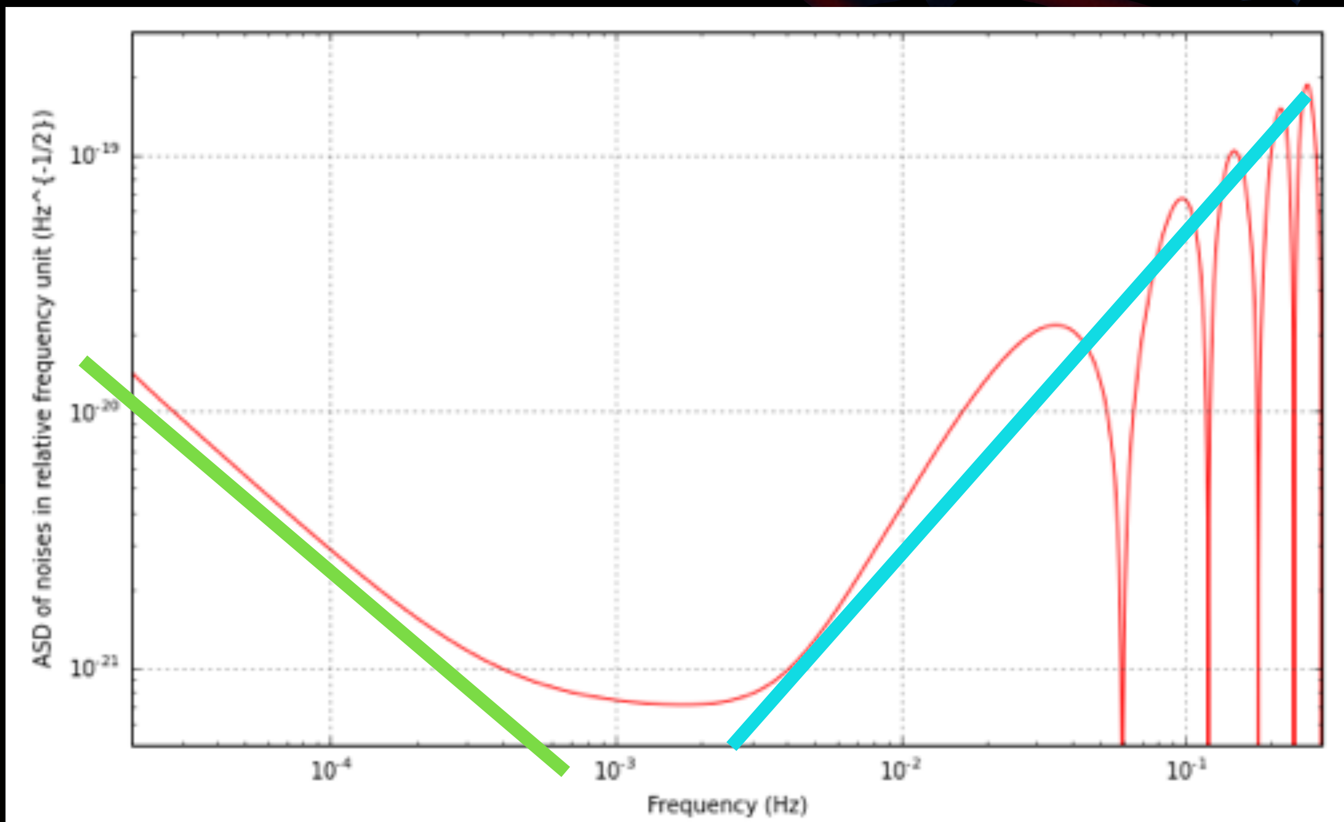
Strain Sensitivity
Frequency (Hz)
Observatory Strain Sensitivity
Galactic Background
Total

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

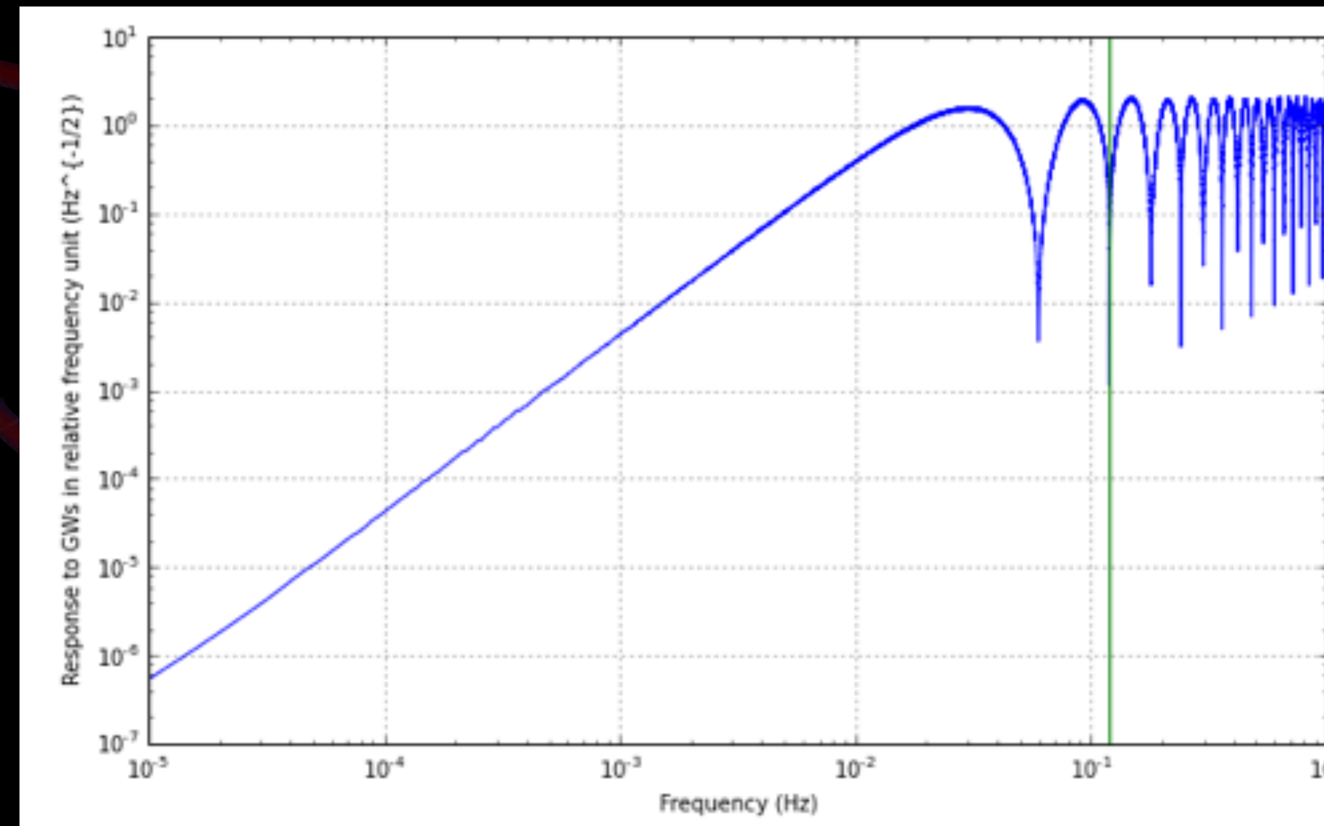
LISA – 2. SCIENCE PERFORMANCE Page 7

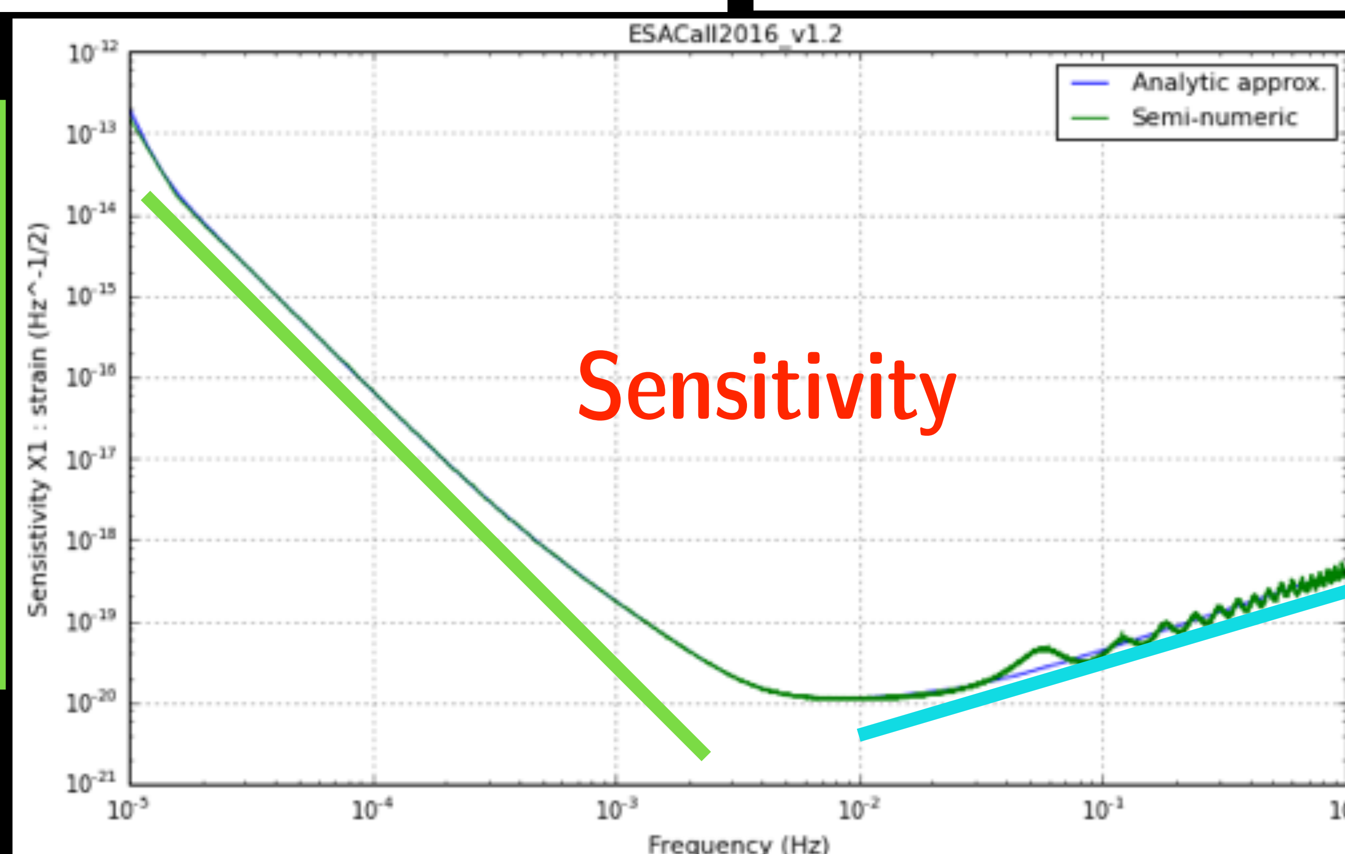
Sensitivity

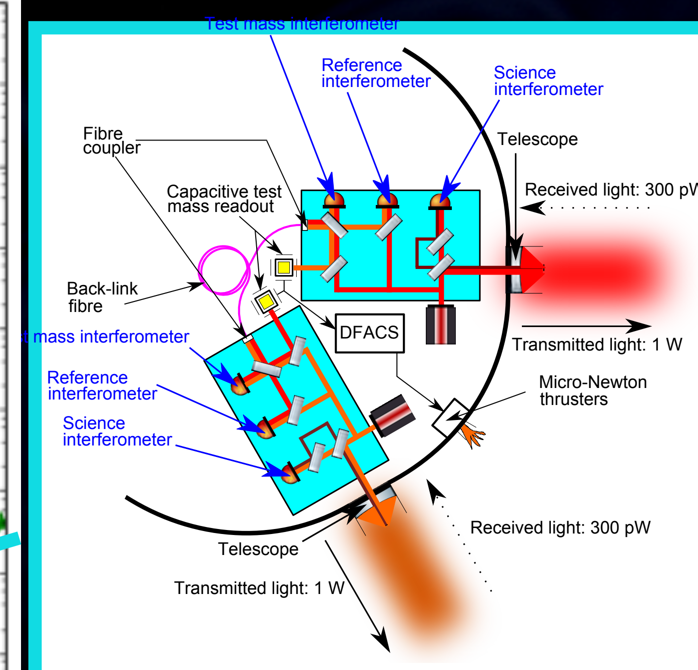
Noises



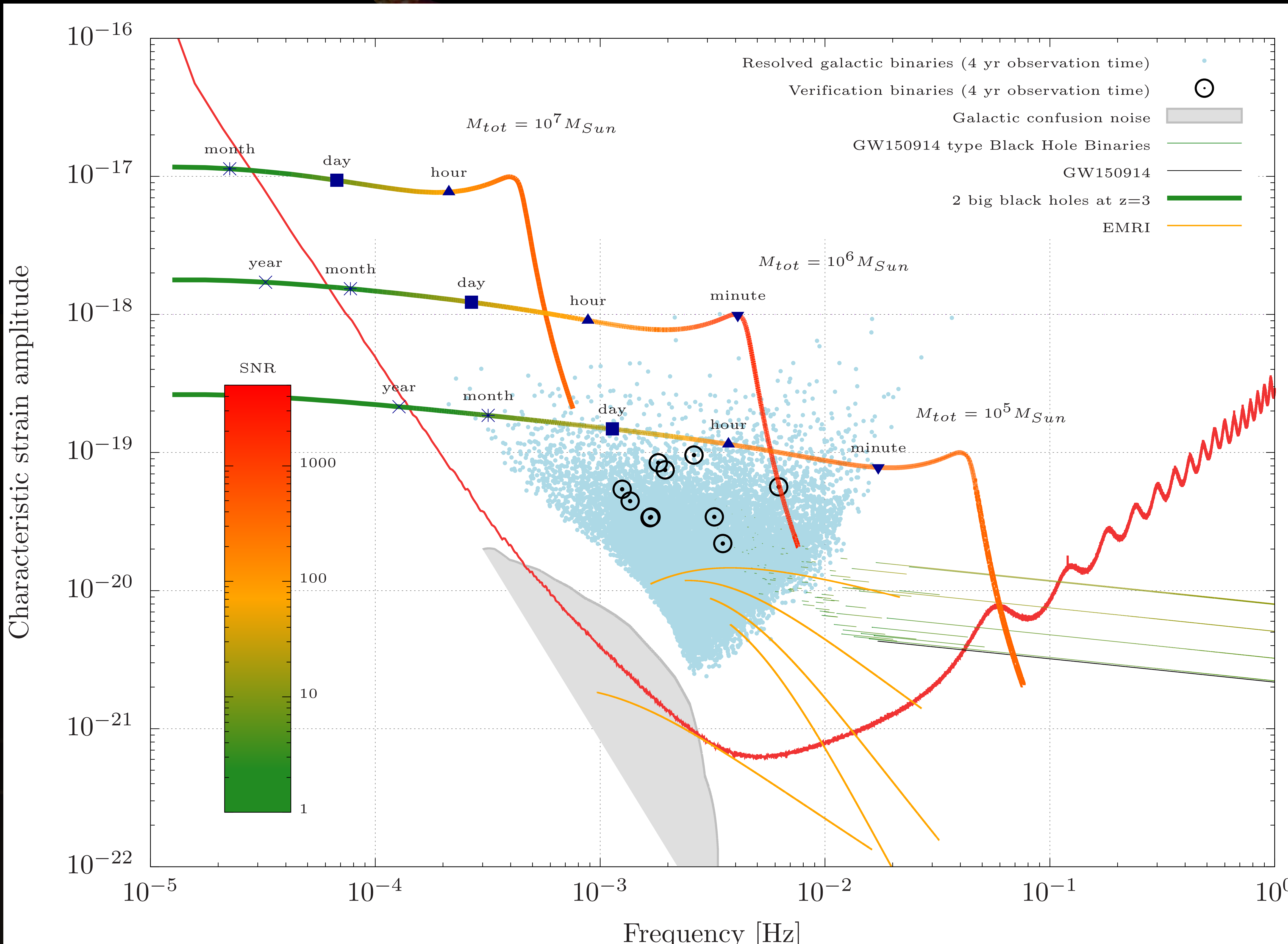
Response of the detector to GWs





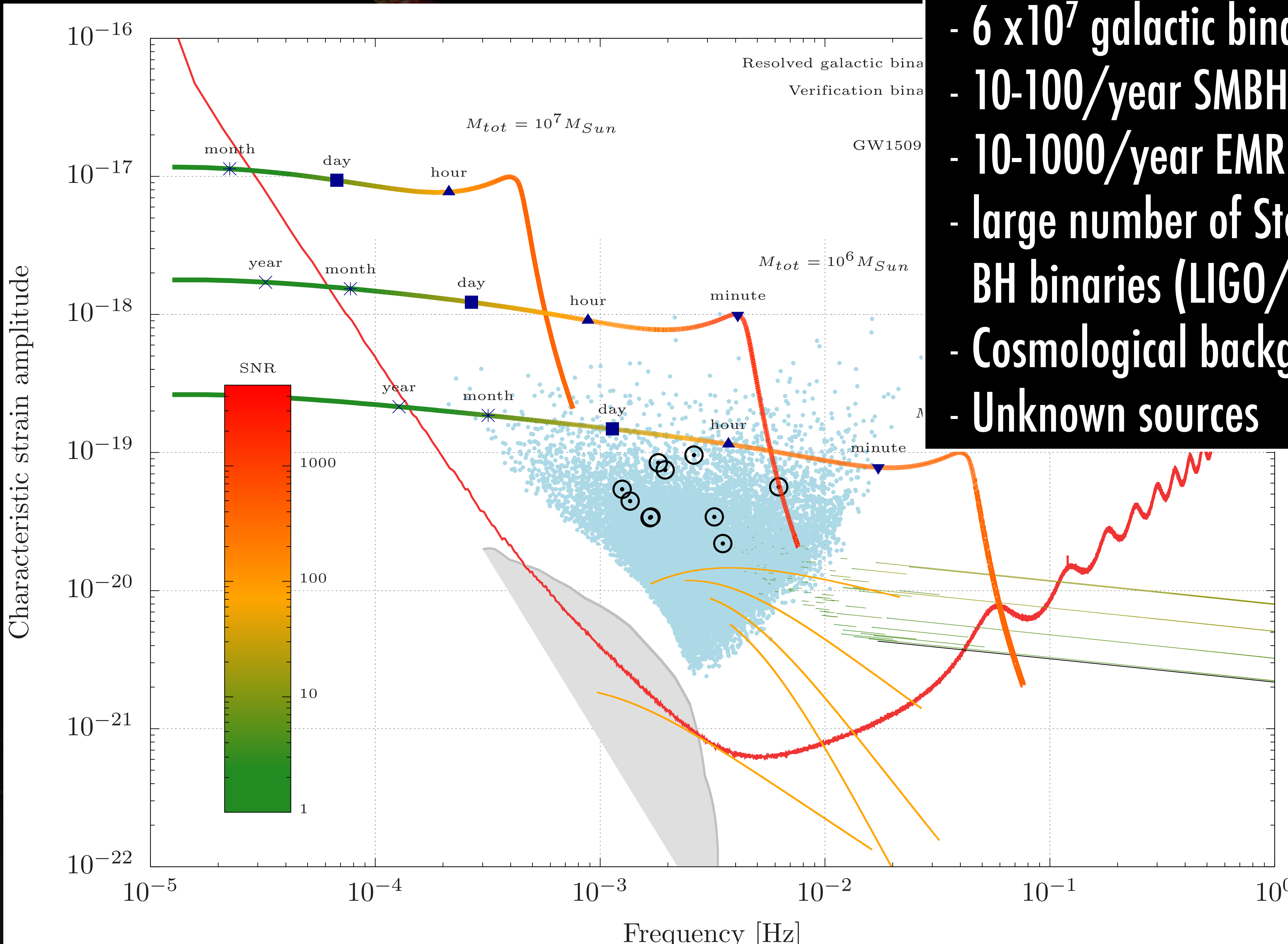


GW sources



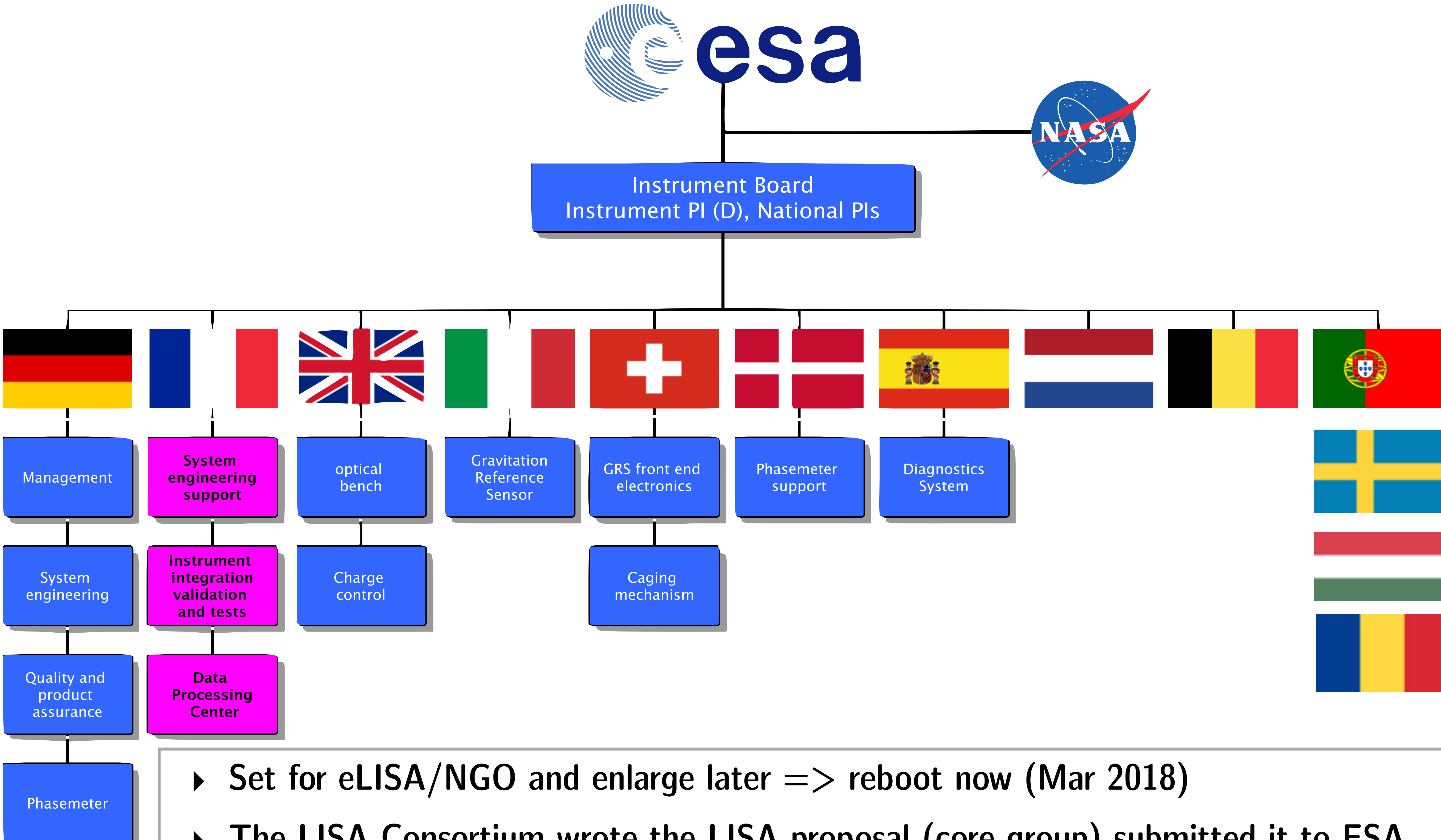
Characteristic strain amplitude
Frequency [Hz]
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Resolved galactic binaries (4 yr observation time)
Verification binaries (4 yr observation time)
Galactic confusion noise
GW150914 type Black Hole 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
year
month
day
hour
minute
SNR
1000
100
10
1

GW sources



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

LISA Consortium



- 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

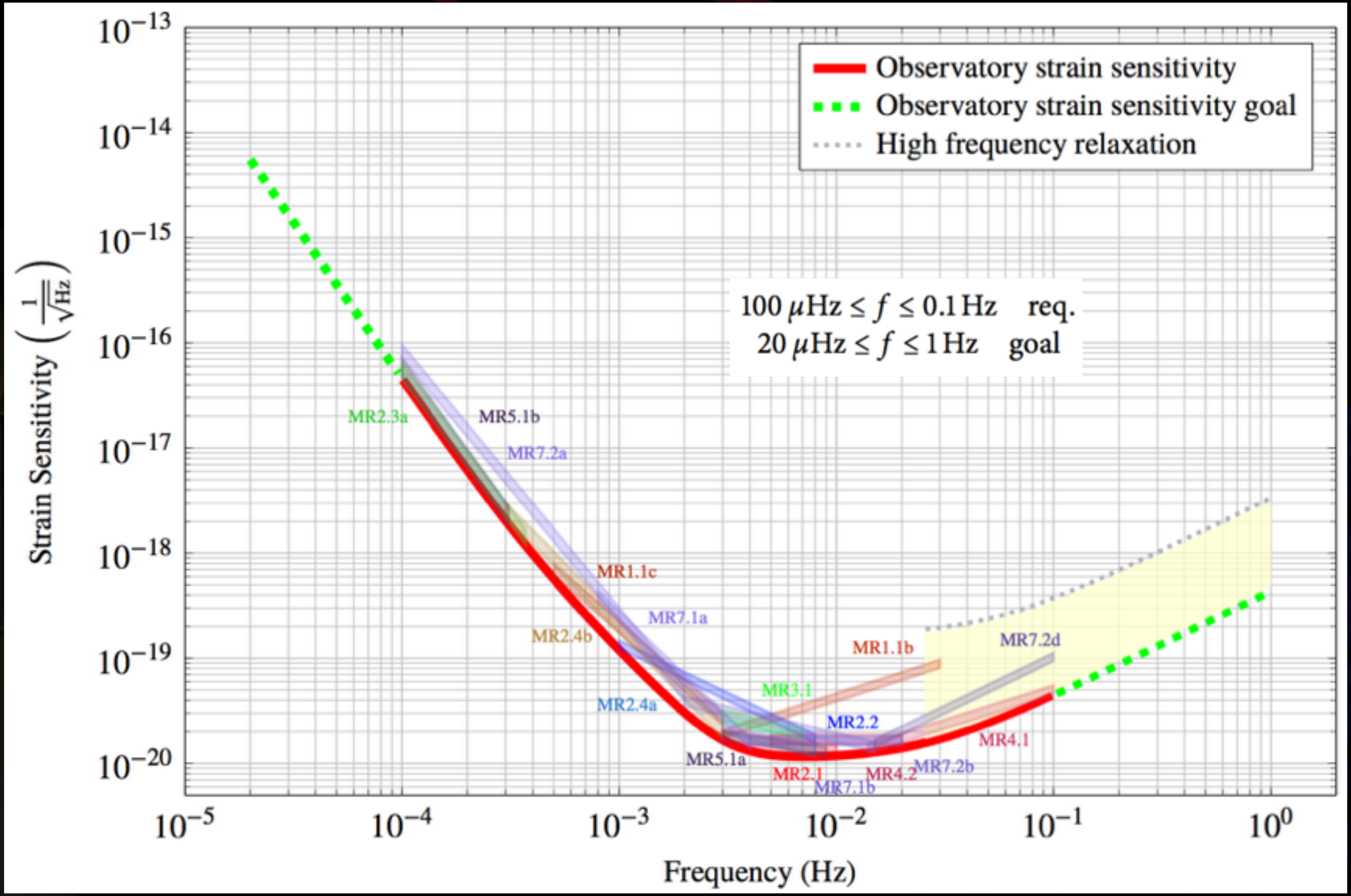
LISA science objectives

LISA Science Requirements Document:

- 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

LISA science objectives

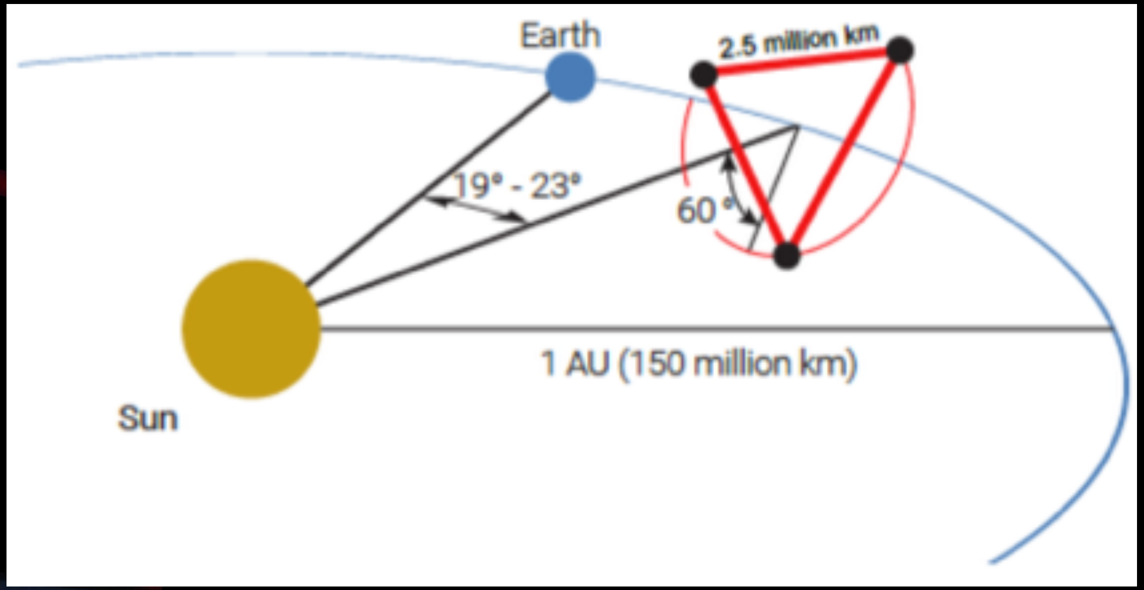
LISA Science Requirements Document:



LISA

LISA Mission Requirements Document:

- 3 arms, 2.5 km
- Launch Ariane 6.4



- Frequency band:

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

- Noise budget:
  - Low frequency: Acceleration (LISAPathfinder)

$$S_{\mathrm{a}}^{1/2} \le 2.4 \cdot 10^{-15} \frac{\mathrm{m\,s^{-2}}}{\sqrt{\mathrm{Hz}}} \cdot \sqrt{1 + \left(\frac{0.4\,\mathrm{mHz}}{f}\right)^2} \cdot \sqrt{1 + \left(\frac{f}{8\,\mathrm{mHz}}\right)^4}$$

  - High frequency: Interferometric Measurement System

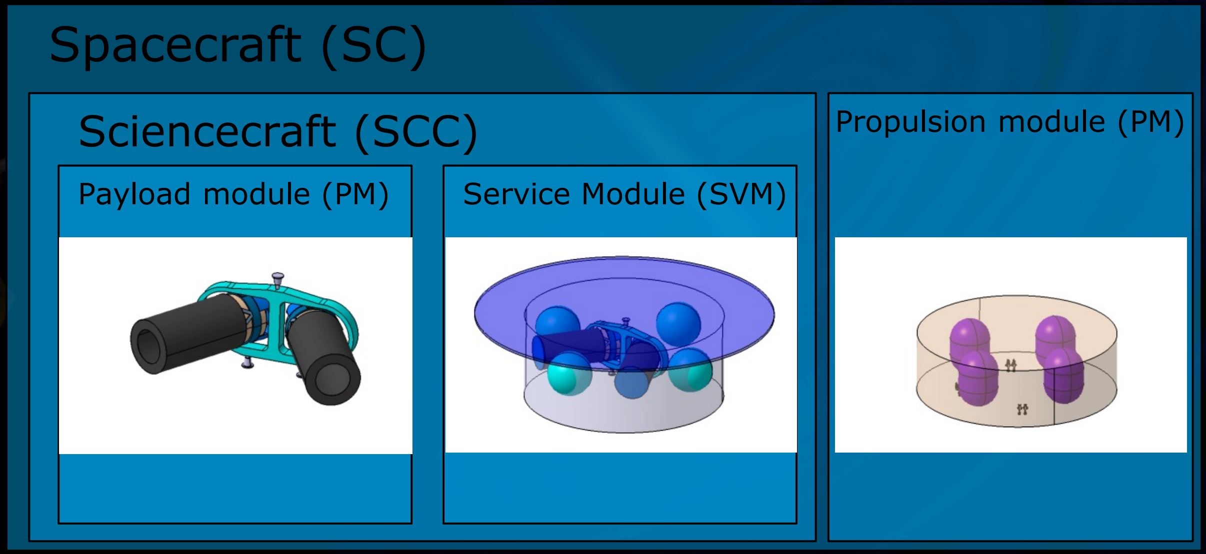
$$S_{\mathrm{IFO}}^{1/2} \le 10 \cdot 10^{-12} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \cdot \sqrt{1 + \left(\frac{2\,\mathrm{mHz}}{f}\right)^4}$$

LISA timeline

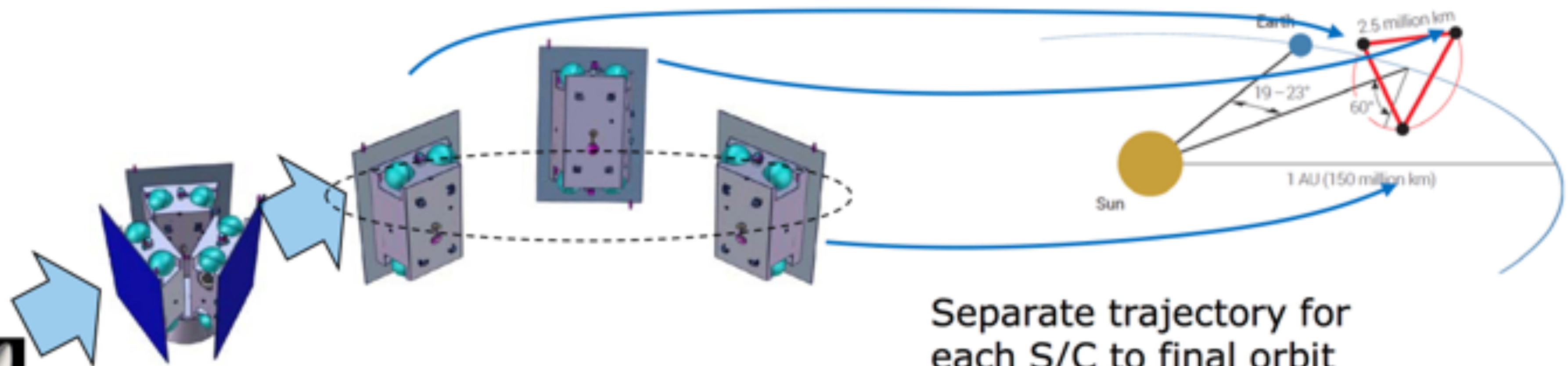
- 25/10/2016 : Call for mission
- 13/01/2017 : submission of «LISA proposal» (LISA consortium)
- 8/3/2017 : Phase 0 mission (CDF 8/3/17 → 5/5/17)
- 20/06/2017 : LISA mission approved by SPC
- 8/3/2017 : Phase 0 payload (CDF June → November 2017)
- 2018→2020 : competitive phase A: 2 companies compete
- 2020→2022 : B1: start industrial implementation
- 2023 : mission adoption
- During more than 8 years : construction
- 2032-2034 : launch Ariane 6.4
- 1.5 years for transfert
- 4 years of nominal mission → GW observations !
- Possible extension to 10 years

Phase 0

- Studied from March to November 2017
- Drivers: thermal stability/range, mechanical stability, mass, power, data rate, volume, integration, ...
- Several studied options:
  - Propulsion: chemical (CP) / electrical (EP & EP+)
  - Micro-propulsion: cold-gas (CP & EP)/ electrical (EP+)
  - Communication,
  - Shape,
  - Launch strategies, orbits,
  - ...



ESA Phase 0 mission

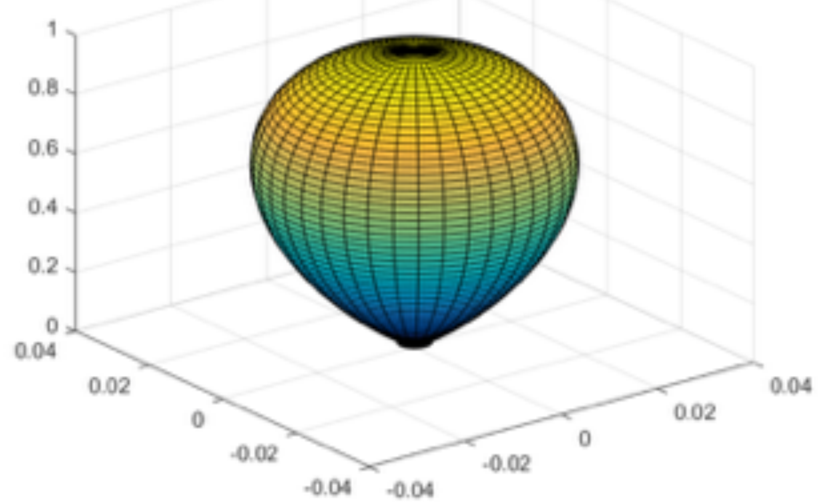


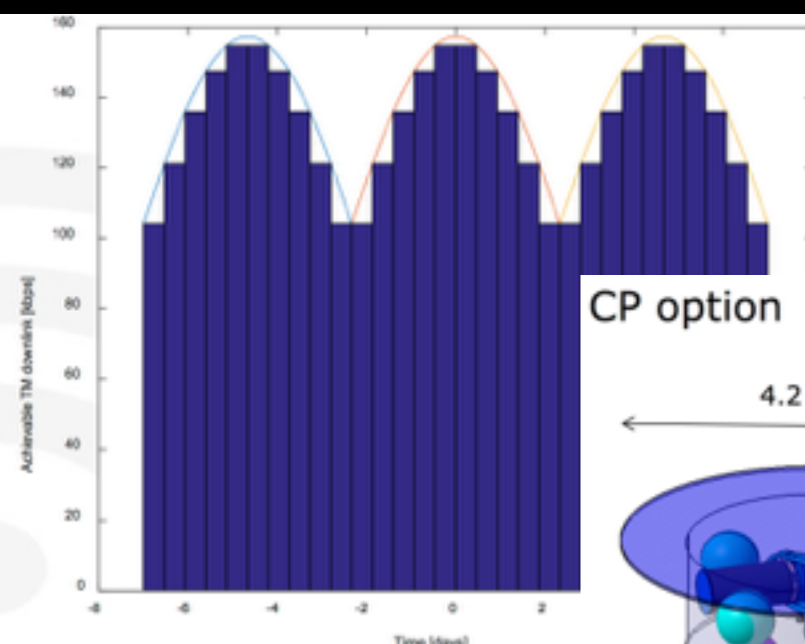
Separate trajectory for each S/C to final orbit

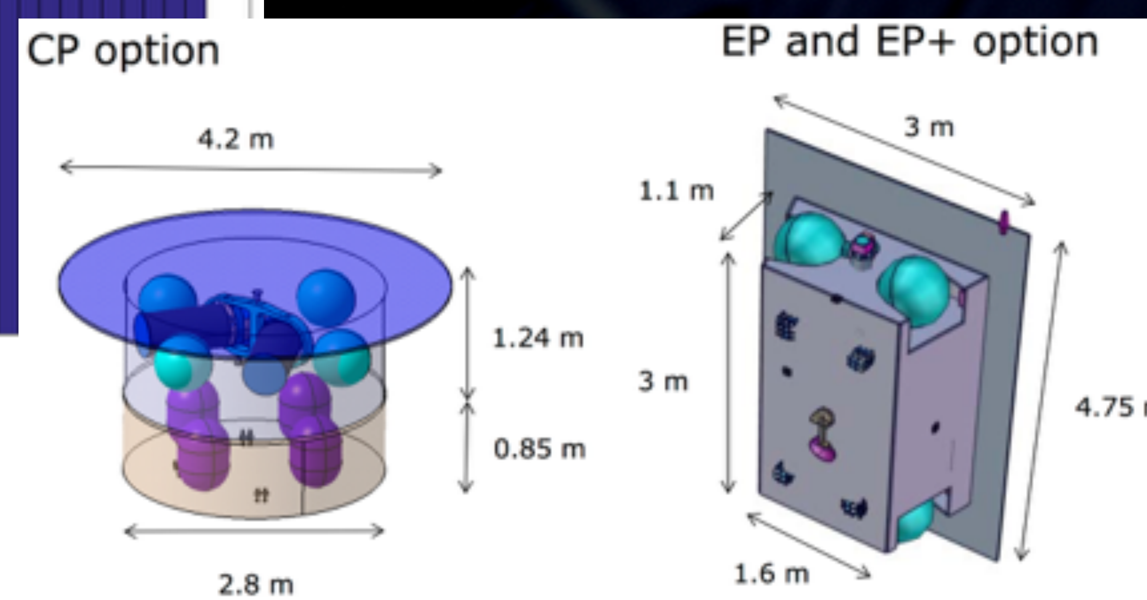
Separation of the stack right after launch

Launch in stacked configuration
Direct injection into escape trajectory

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







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

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

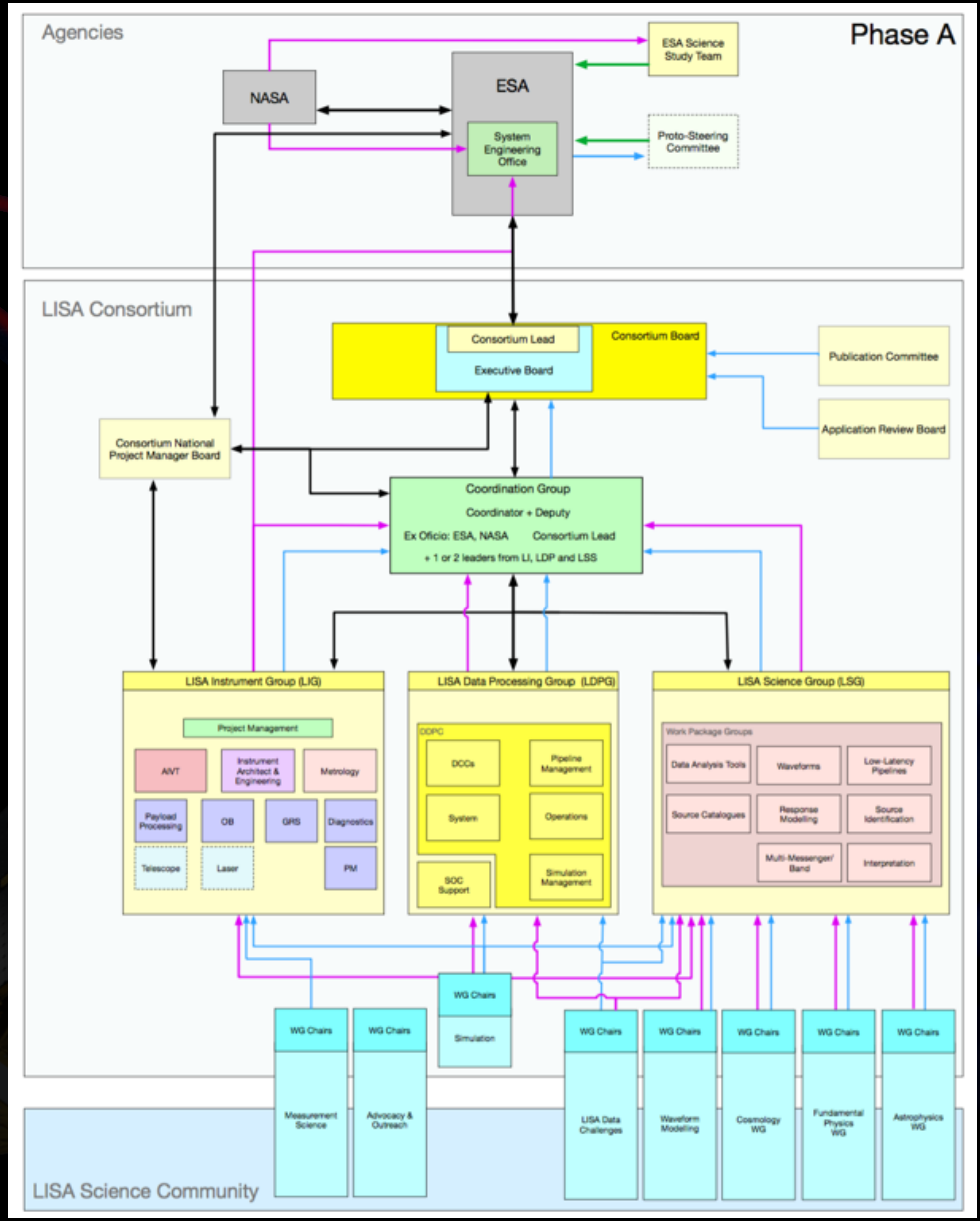
LGA
Max rate: 52 bps
Margin: 3.1 dB

Phase A

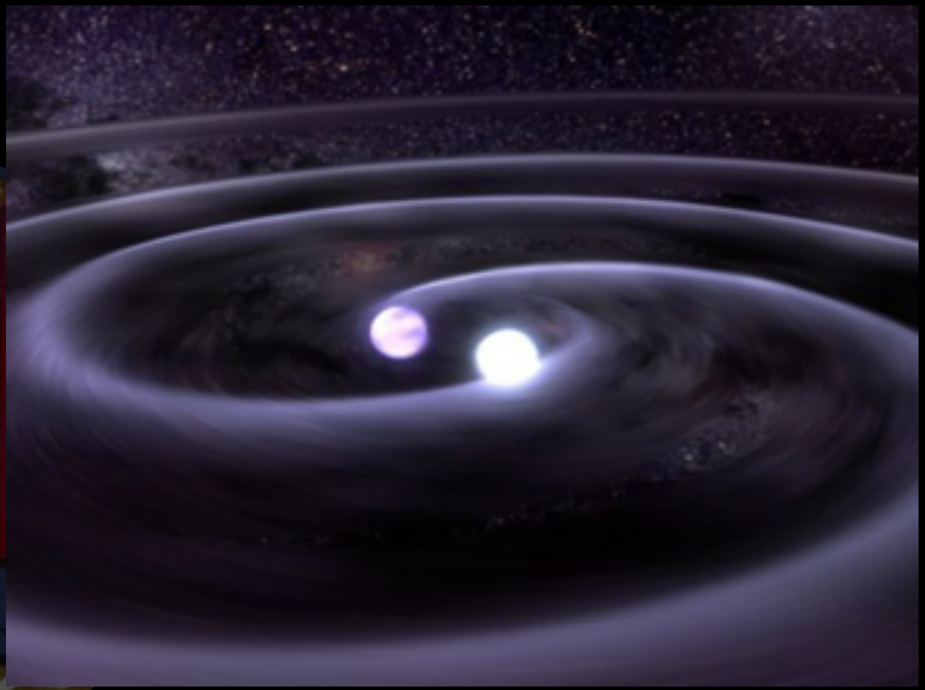
- From April 2018 to Summer 2020: detailed studies of the mission, the payload, the organisation, the plannings, ...
- Importance of performances studies and control from subsystem to science: particularly important and complex for LISA because highly integrated, i.e. instrument = whole 3 spacecrafts + ground segment
- Plateform: competitive between Airbus and Thales
- Payload:
  - Laser
  - Diagnostics
  - Gravitational Reference Sensor
  - Mechanisms
  - Optical Bench
  - Telescope
  - Constellation Acquisition Sensor
  - PhaseMeter
  - Payload Processing Unit

LISA Consortium

- About 1146 members:
  - 552 full (FTE>0.05)
  - 594 associates
- More than 150 groups (institutes)

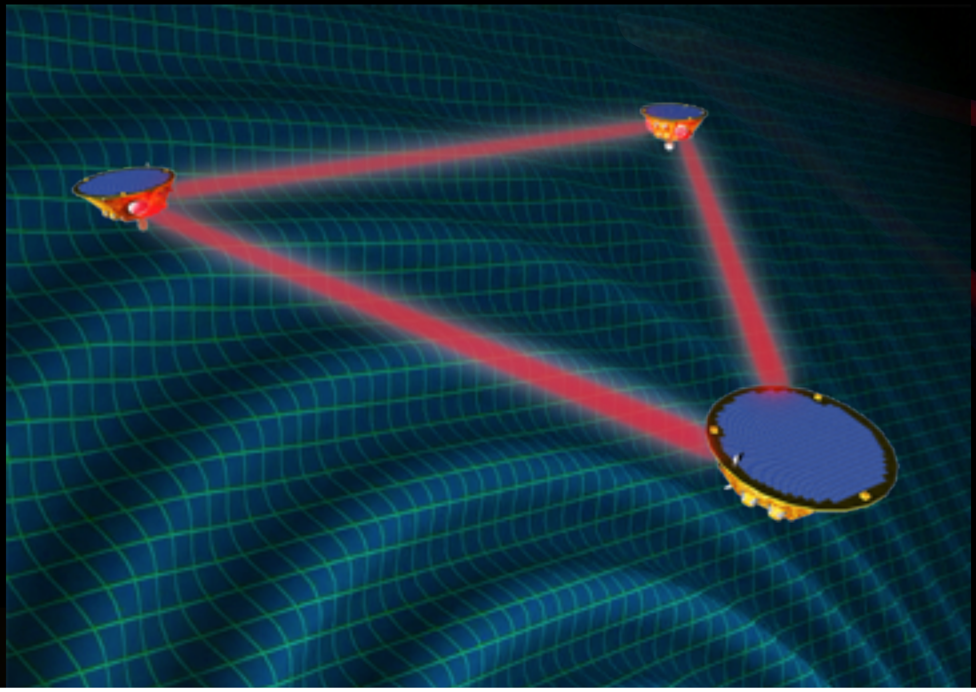


Galactic binaries



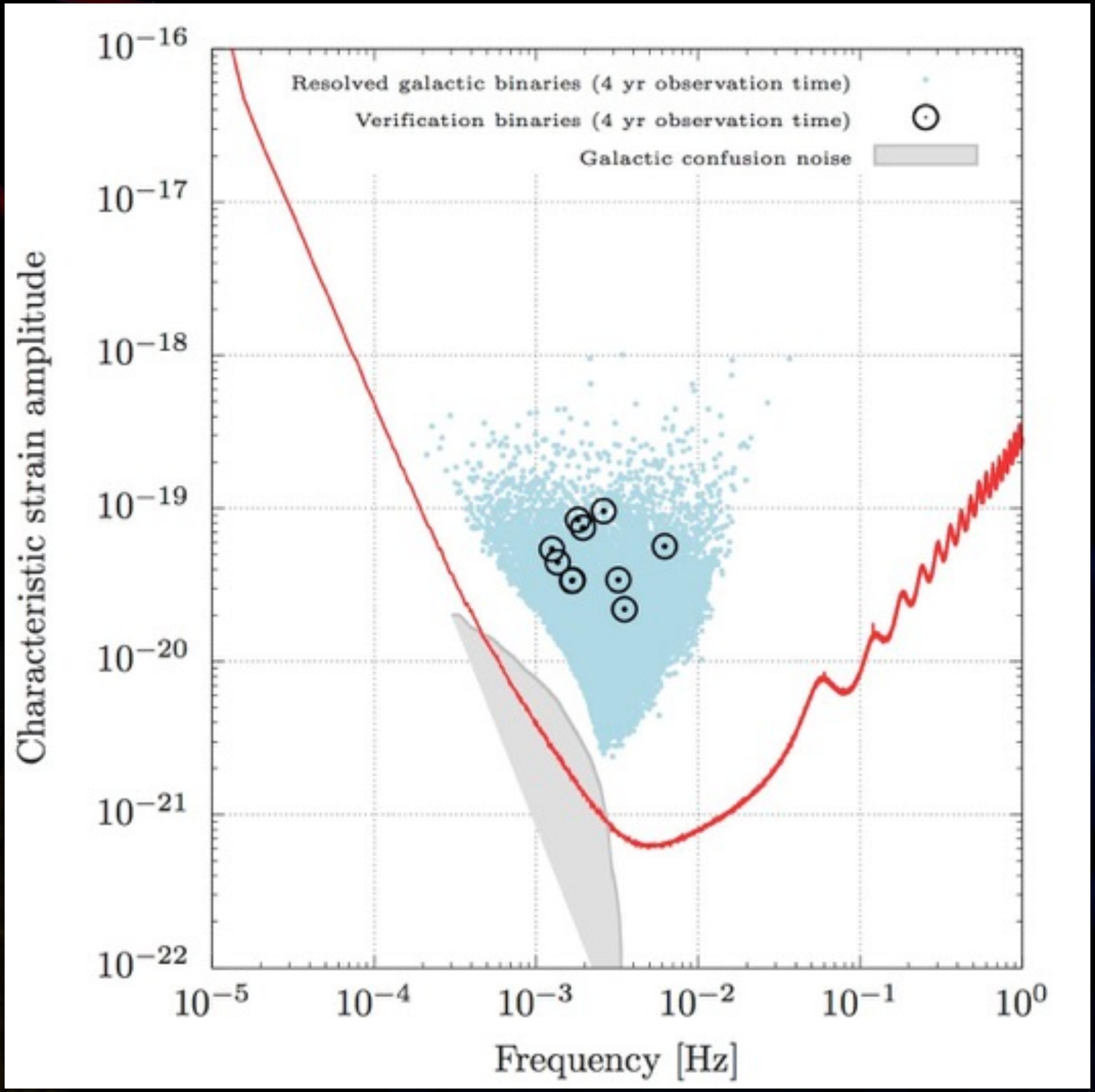
- Gravitational wave:
  - quasi monochromatic
- Duration: permanent
- Signal to noise ratio:
  - detected sources: 7 - 1000
  - confusion noise from non-detected sources
- Event rate:
  - 25 000 detected sources
  - more than 10 guarantied sources (verification binaries)

Galactic binaries



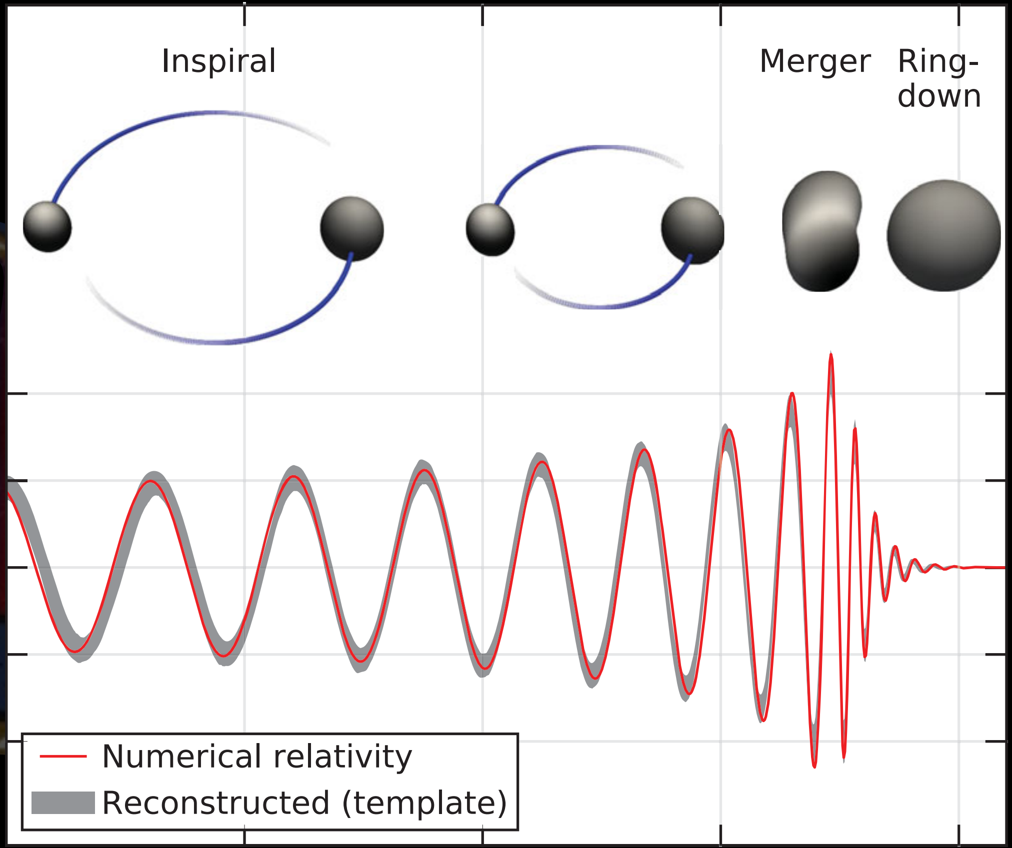
GW sources

- 6 x10^7 galactic binaries



Super Massive Black Hole Binaries

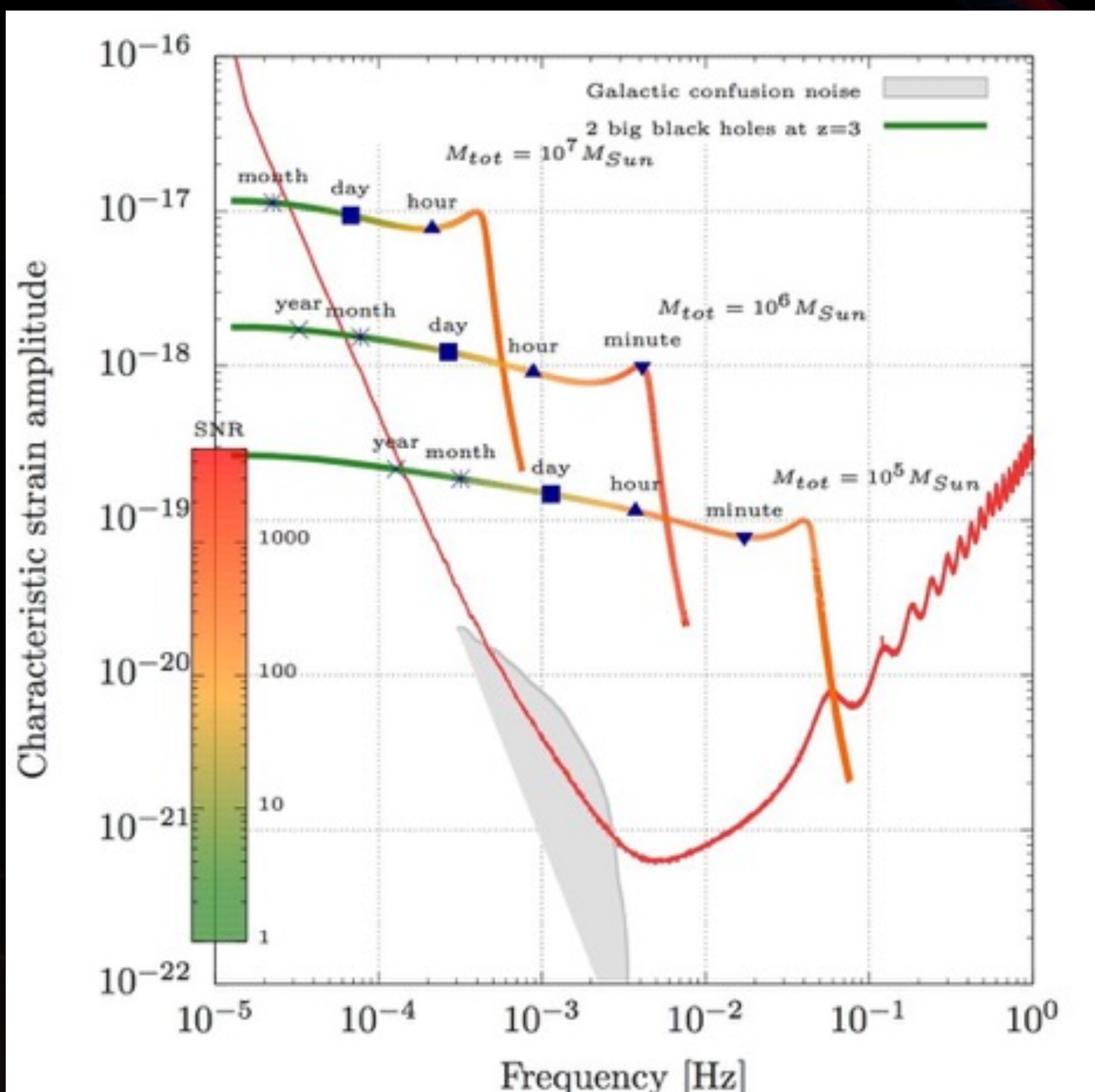
- Gravitational wave:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.

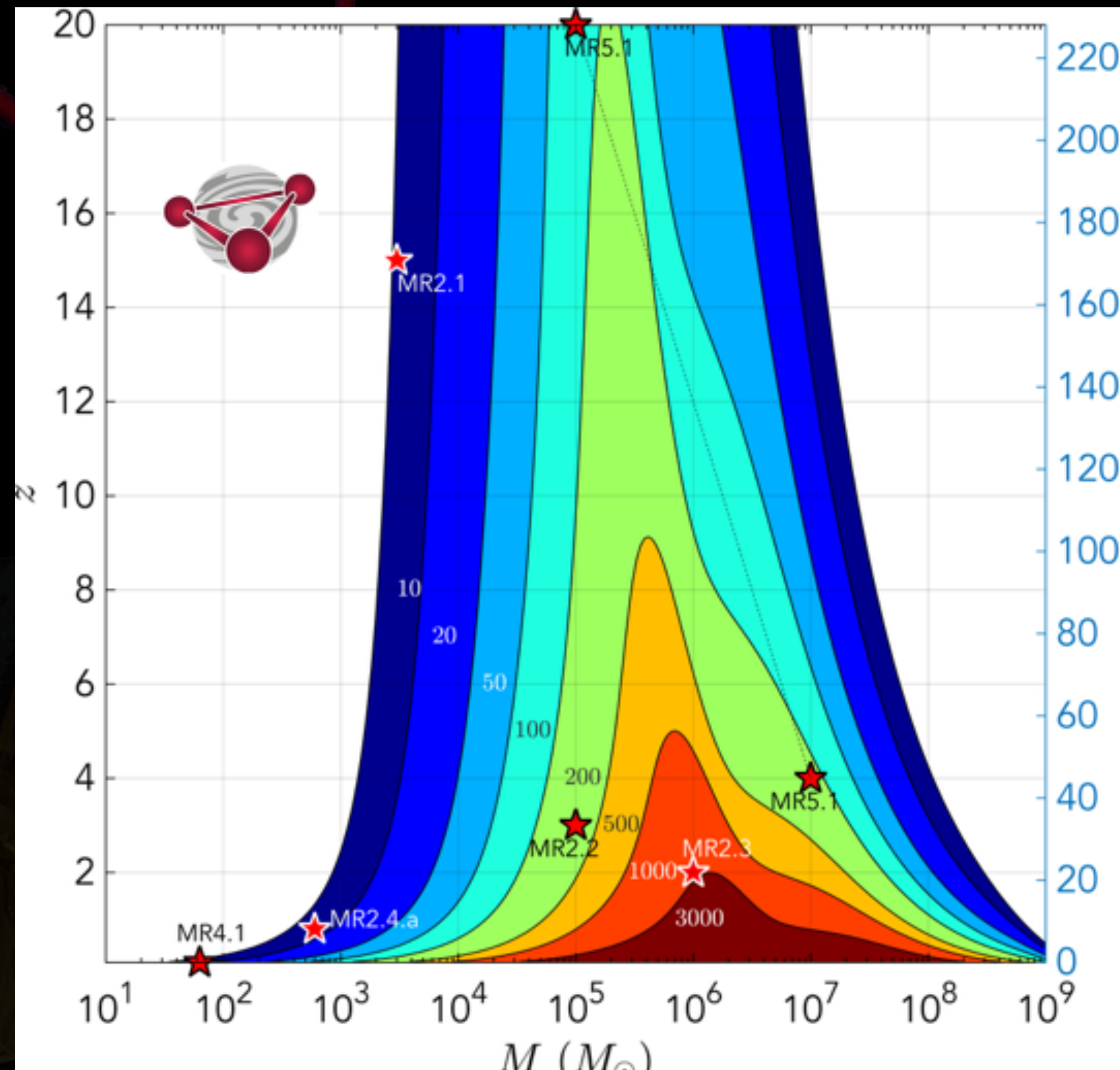


- Duration: between few hours and several months
- Signal to noise ratio: until few thousands
- Event rate: 10-100/year

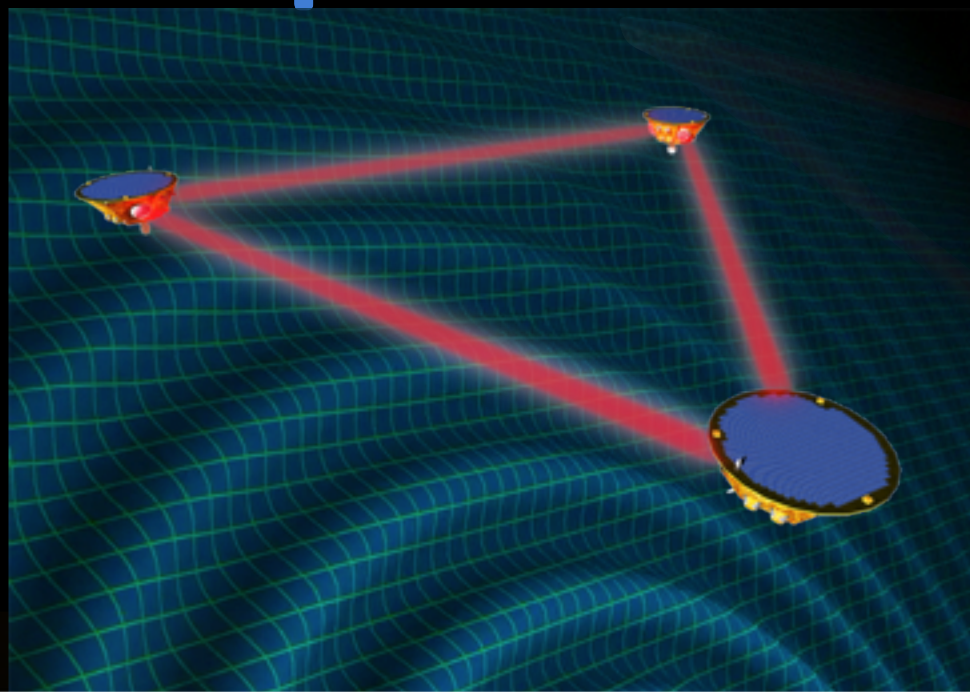
Super Massive Black Hole Binaries

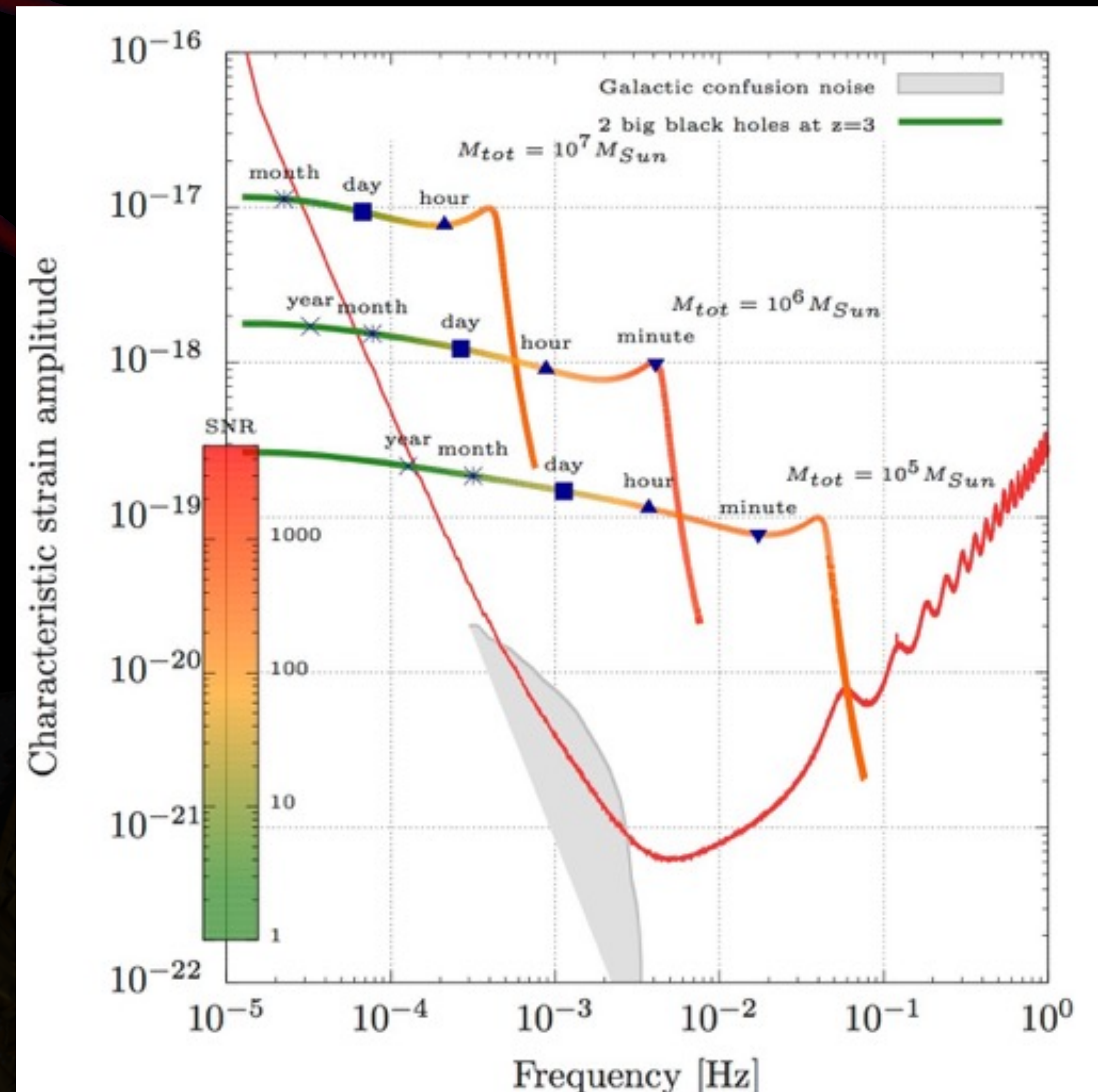
LISA: SMBHB from 10^4 à 10^7 solar masses in "all" Univers





Super Massive Black Hole Binaries





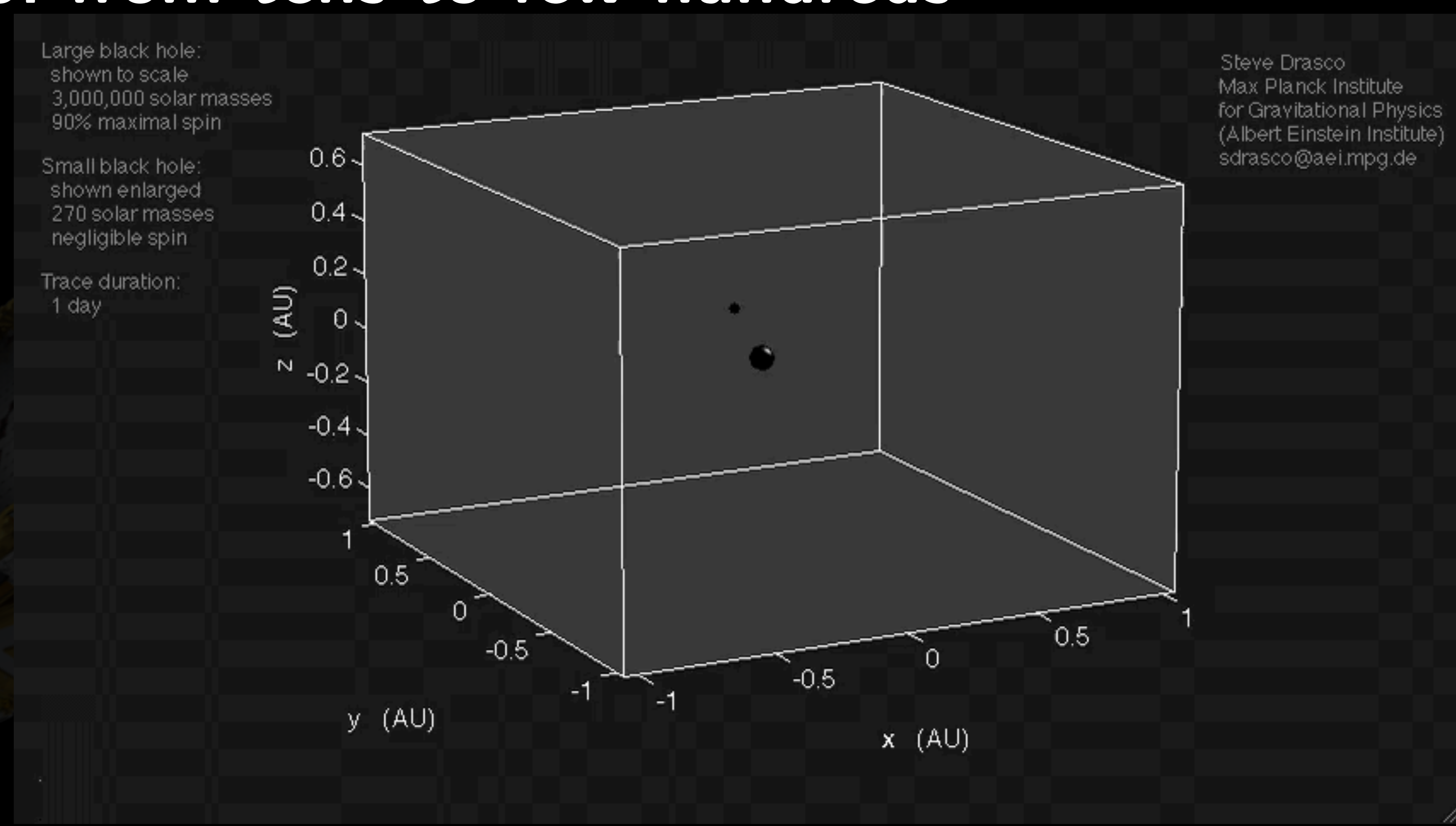
GW sources

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

EMRIs

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

  from few events per year to few hundreds



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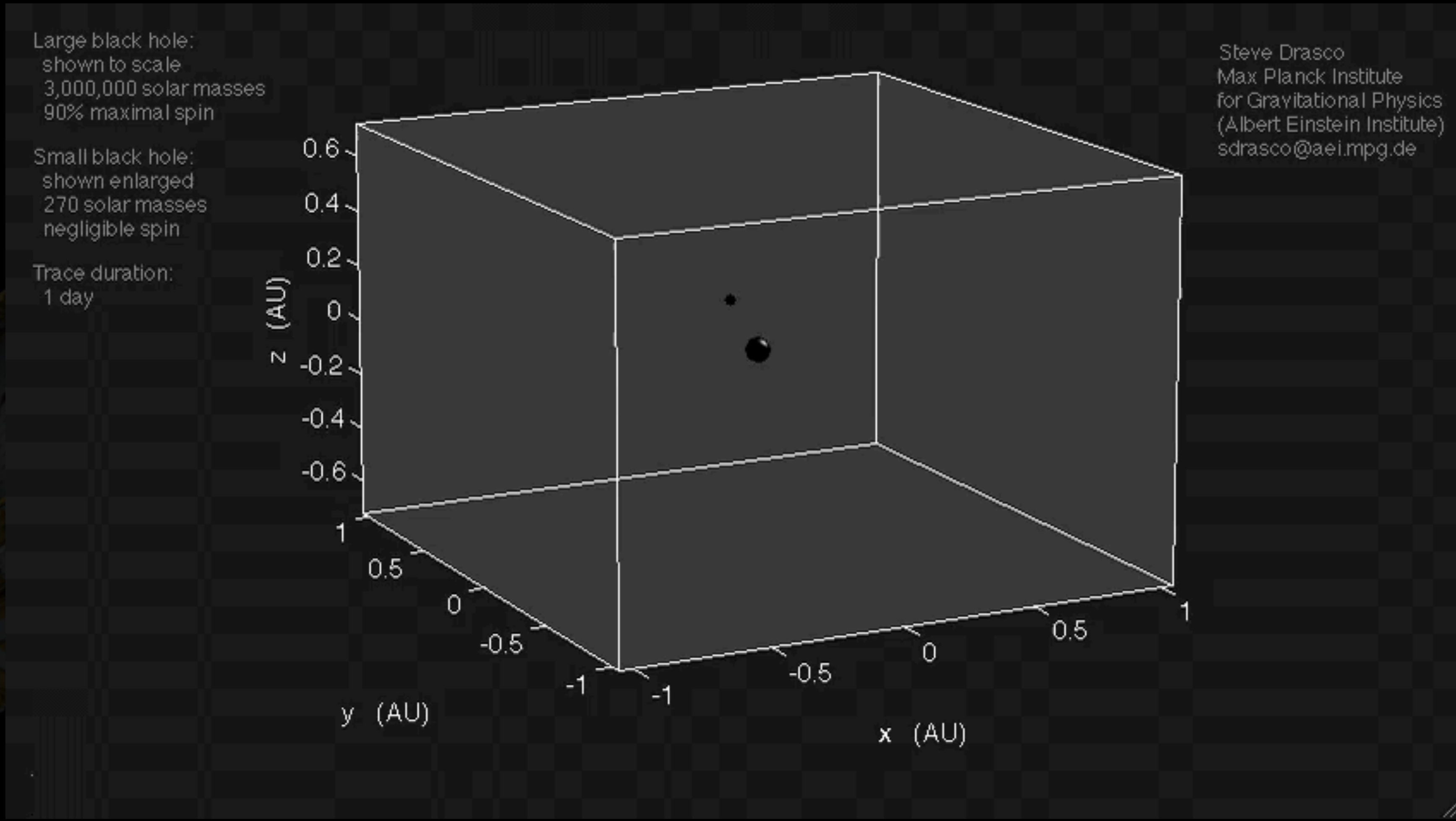
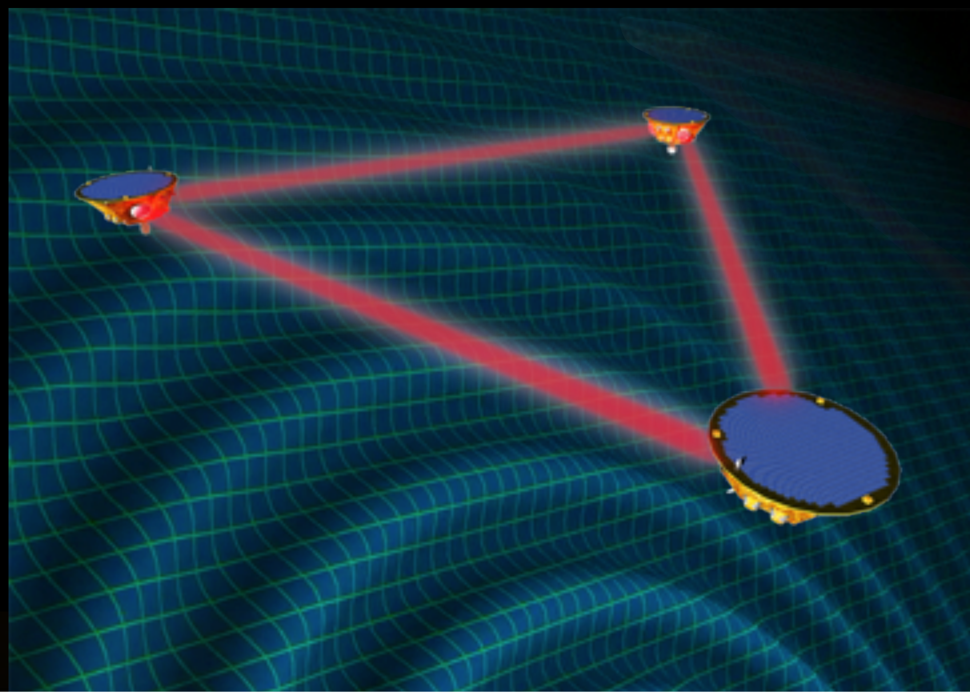


EMRIs



GW sources

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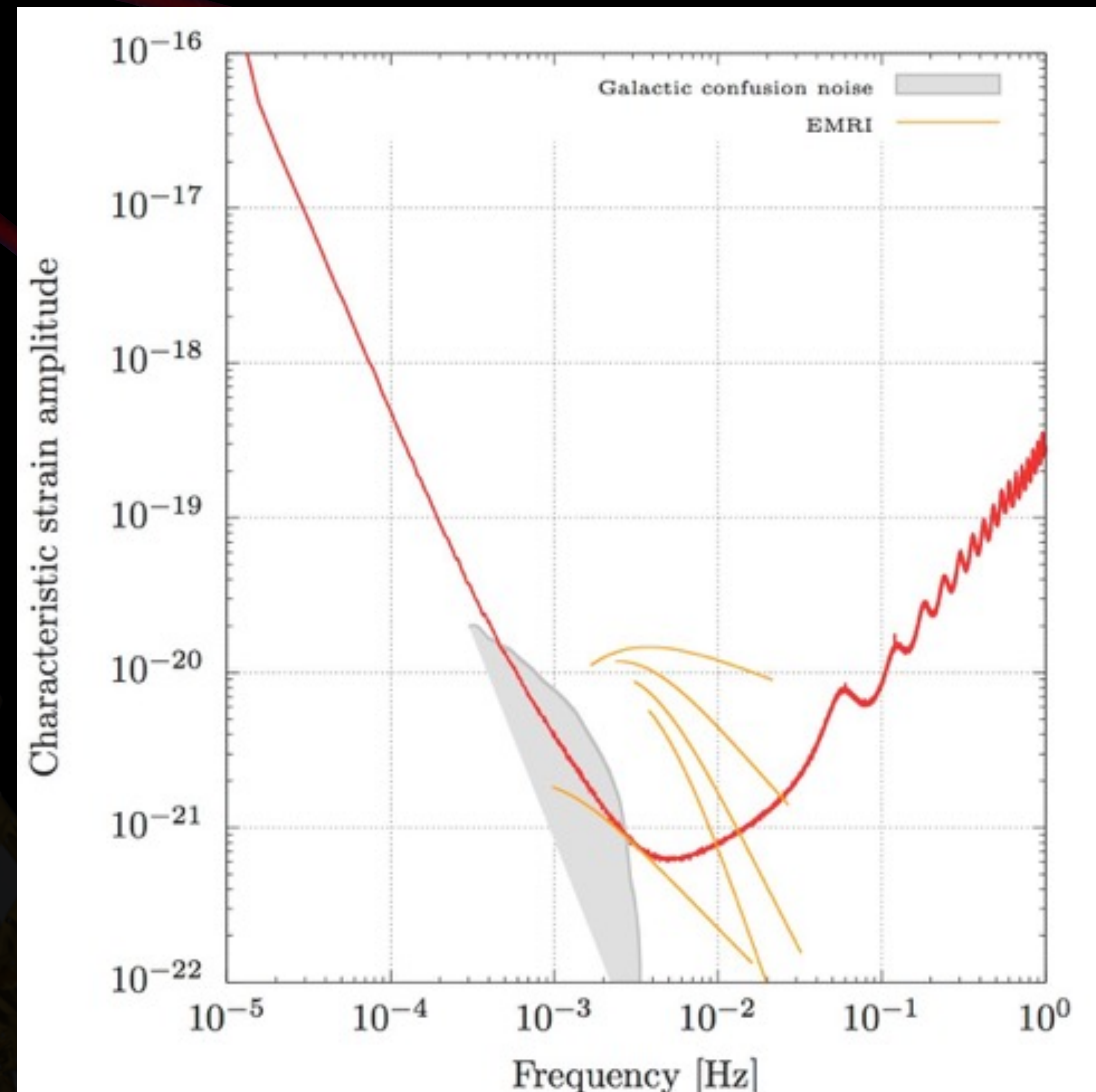
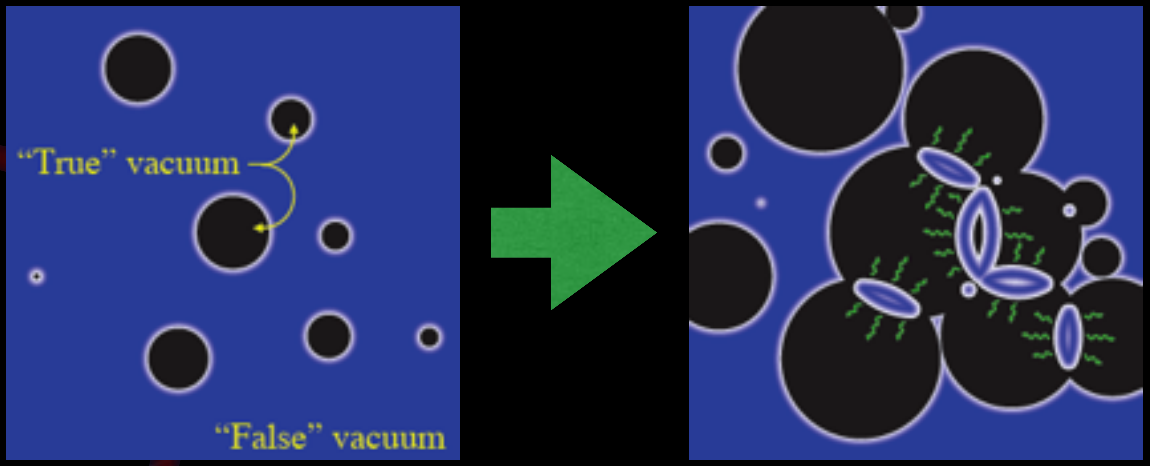
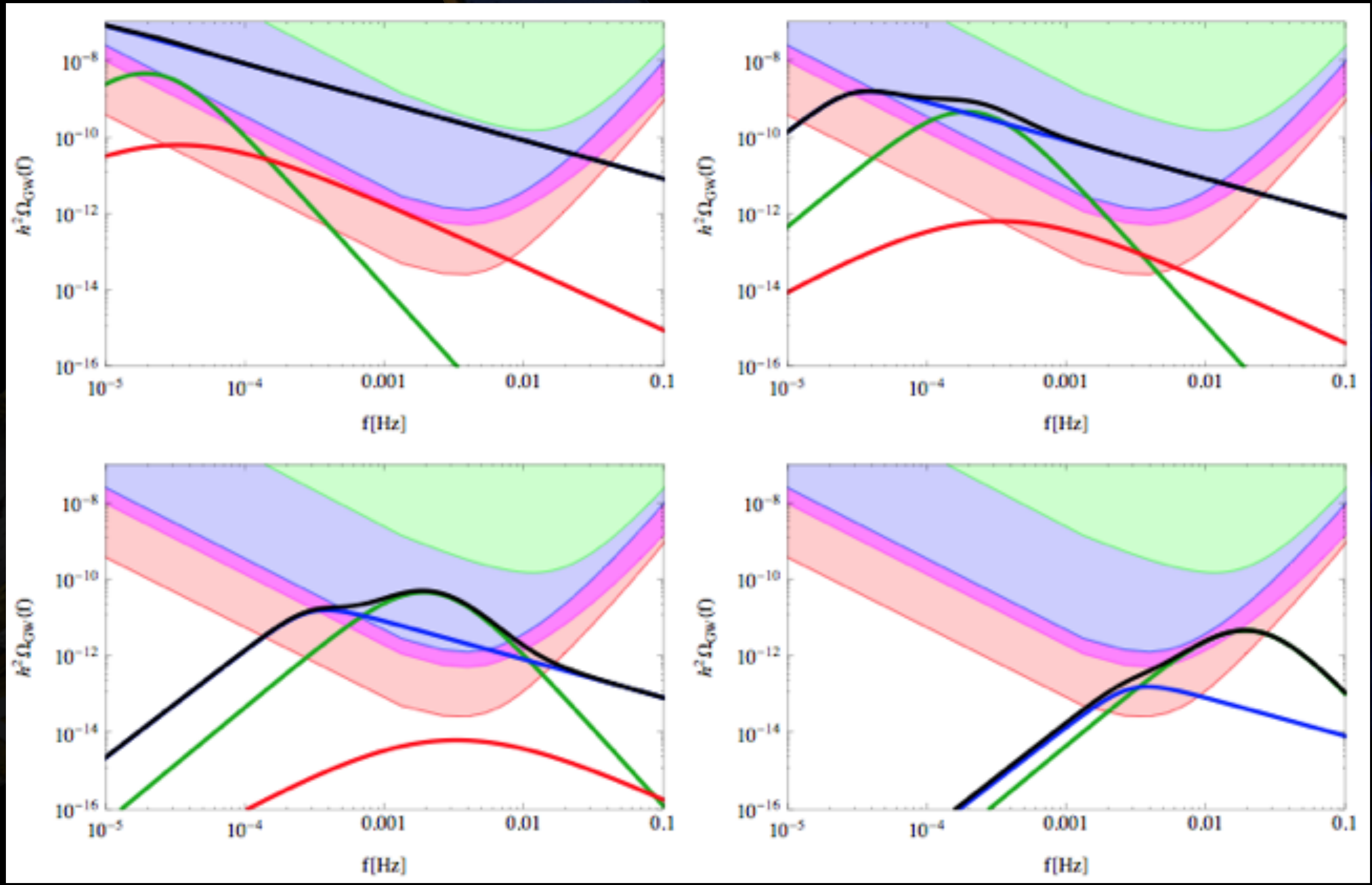


Cosmological backgrounds

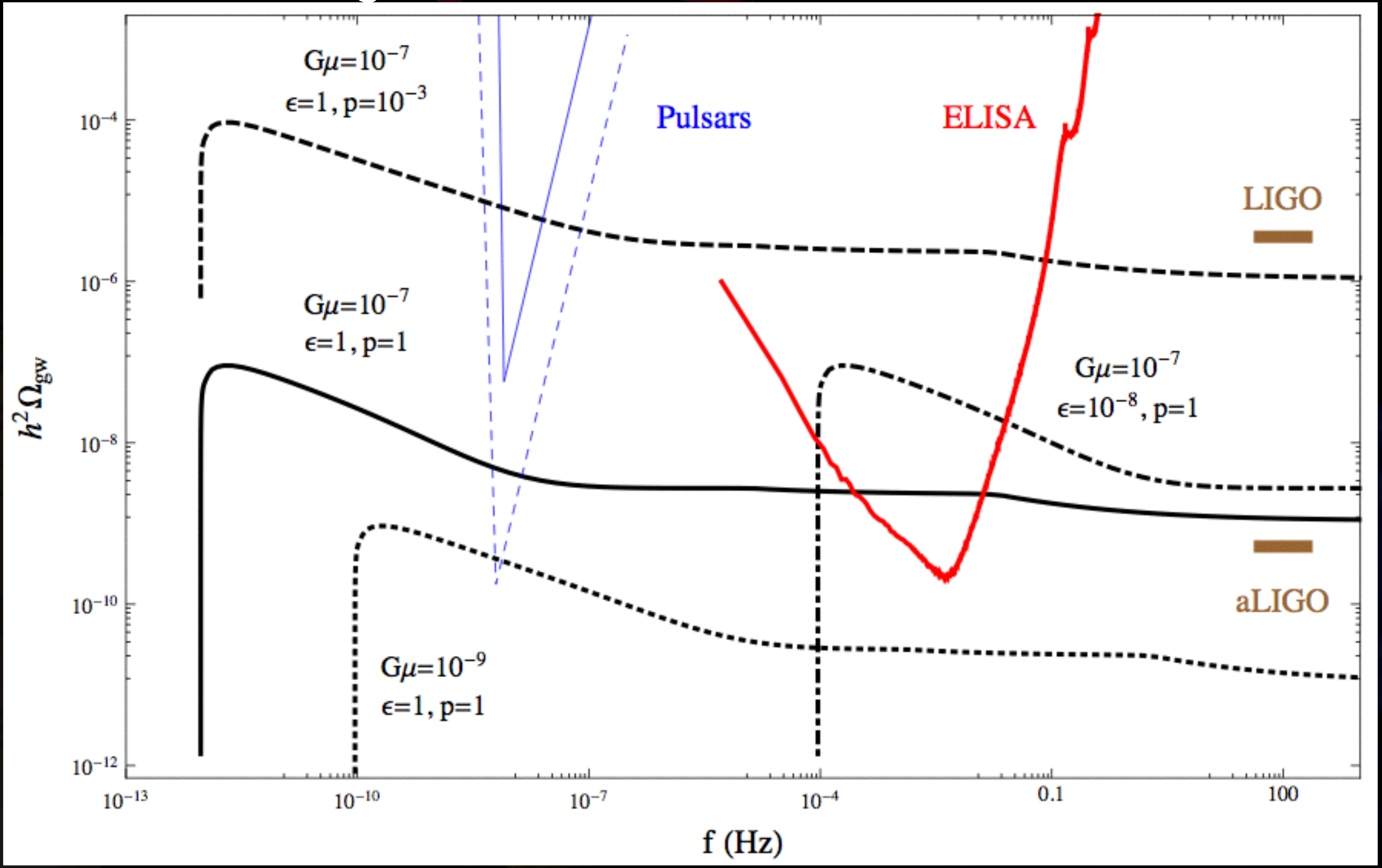
- Work in progress for LPF-LISA …
- Studies within the LISA Cosmology Working Group:
  - Ex: first order phase transition in the very early Universe
    Caprini et al. JCAP 04, 001 (2016)
  - Cosmic strings network
  - …





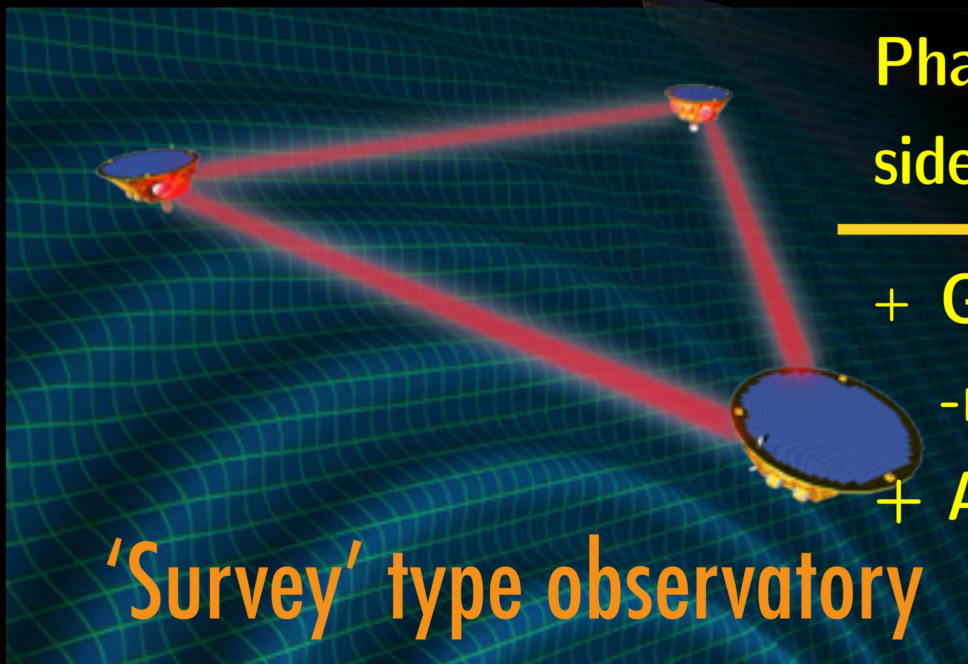
Cosmic string networks

- Stochastic background + bursts



© Binétruy et al.

LISA data



'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor

+ Auxiliary channels

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

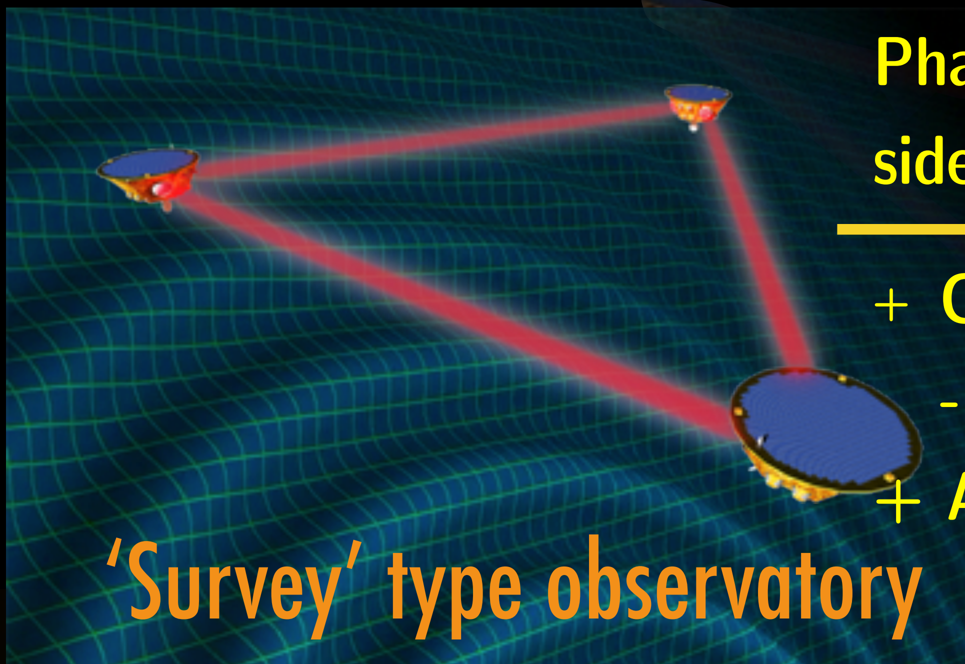
3 TDI channels with 2 "~independents"

Data Analysis of GWs

Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data



Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor
+ Auxiliary channels

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

L1

3 TDI channels with 2 "~independents"

L2

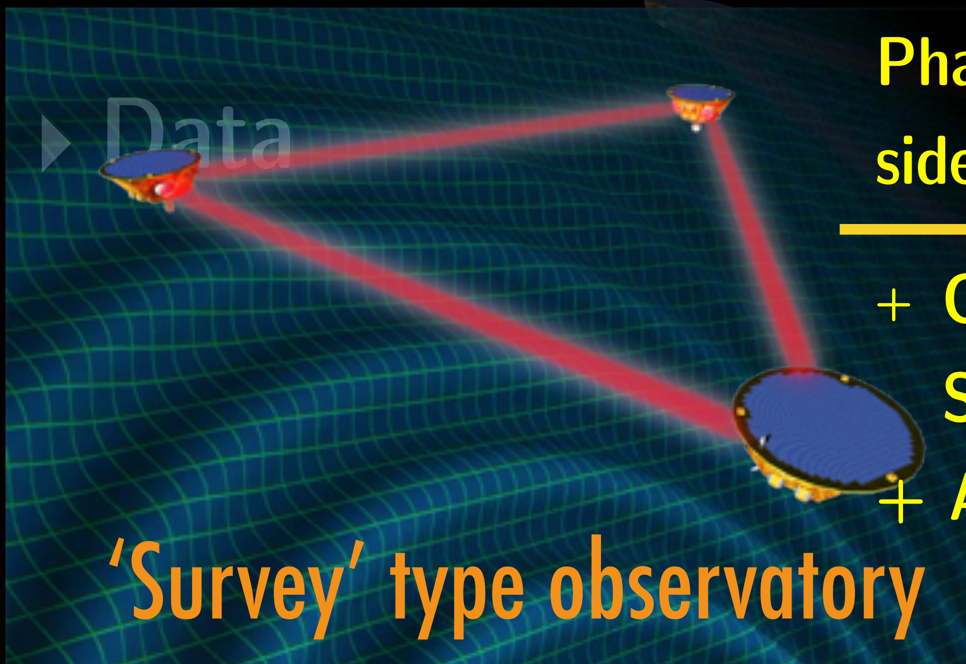
Data Analysis of GWs

L3

Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

LISA data flow



Phasemeters (carrier, sidebands, distance)

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L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

L1 — 3 TDI channels with 2 "~independents"

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

GW sources

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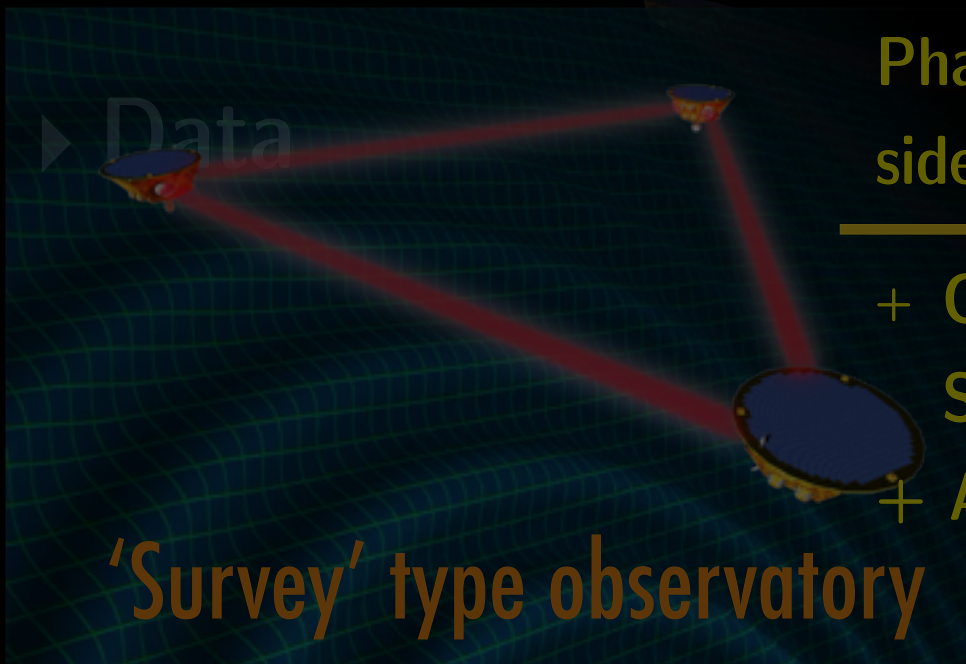
- 10-1000/year EMRIs
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources

LISA data flow



Phasemeters (carrier, sidebands, distance)

+ Gravitational Reference Sensor

+ Auxiliary channels

'Survey' type observatory

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

L1

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LISA data flow

Mission Operation Centre

(carrier,
stance)

+ Gravitational Reference Sensor
+ Auxiliary channels

'Survey' type observatory

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

L1

3 TDI channels with 2 "~independents"

L2

Data Analysis of GWs

L3

Catalogs of GWs sources with their waveform

Science Operation Centre

- $6\ x10^7$ galactic binaries
- 10-100/year SMBHBs
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- Unknown sources

LISA data flow

Mission Operation Centre

(carrier,
stance)

+ Gravitational Reference Sensor

+ Auxiliary channels

'Survey' type observatory

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

L1 3 TDI channels with 2 "~independents"

L2 Data Analysis of GWs

L3 Catalogs of GWs sources with their waveform

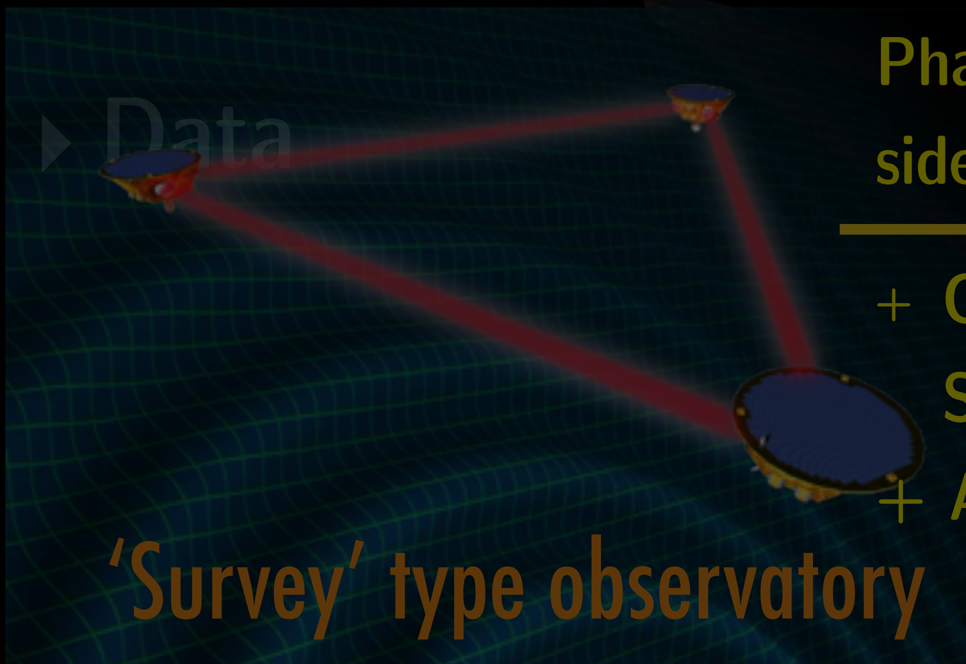
Science Operation Centre

- 6×10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin

Distributed Data Processing Centre

- Unknown sources

LISA data flow



Phasemeters (carrier, sidebands, distance)

+ Gravitational Reference Sensor

+ Auxiliary channels

'Survey' type observatory

L0

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Time-Delay Interferometry reduction of laser noise

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Data Analysis of GWs

L2

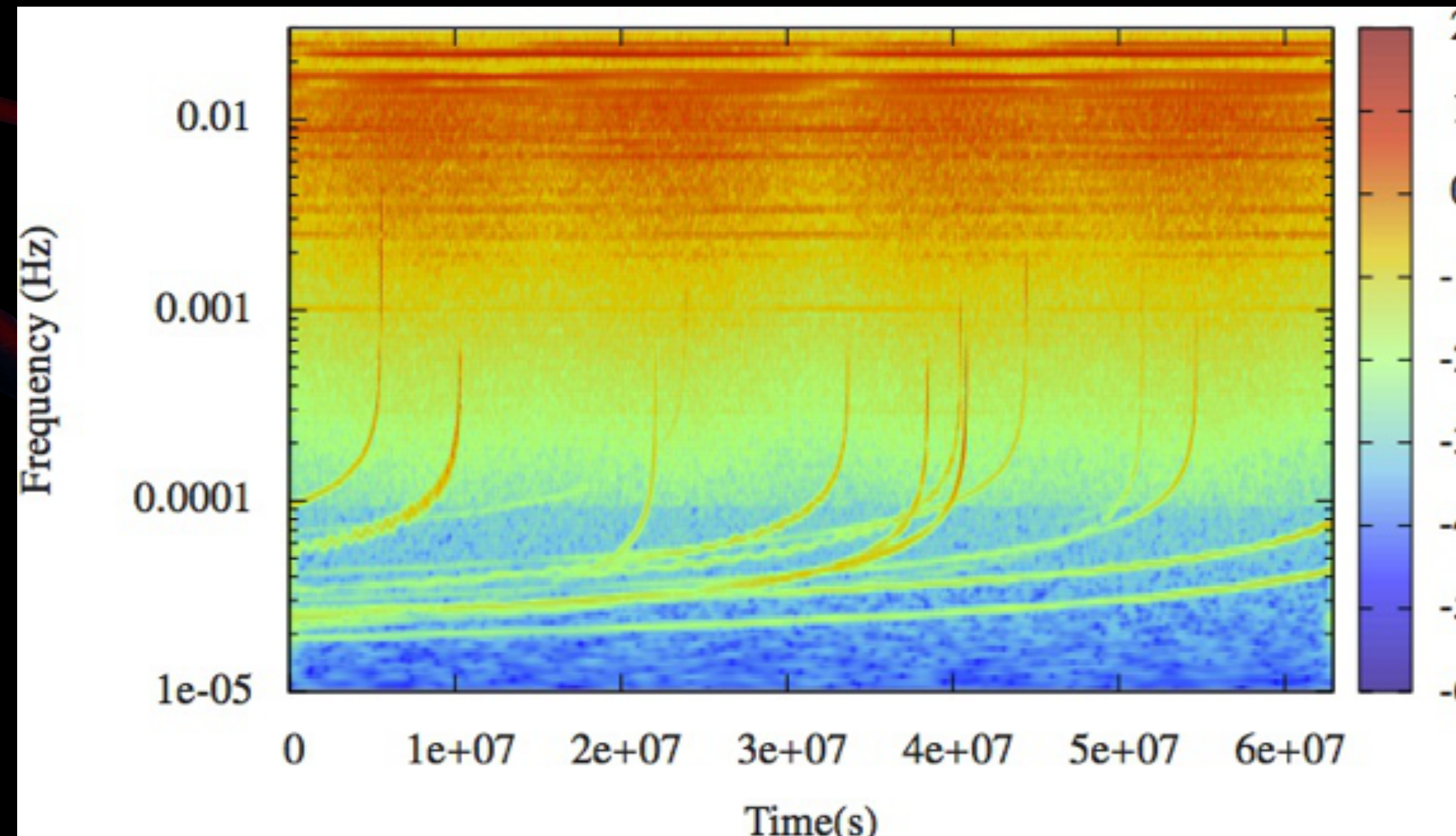
L3 Catalogs of GWs sources with their waveform

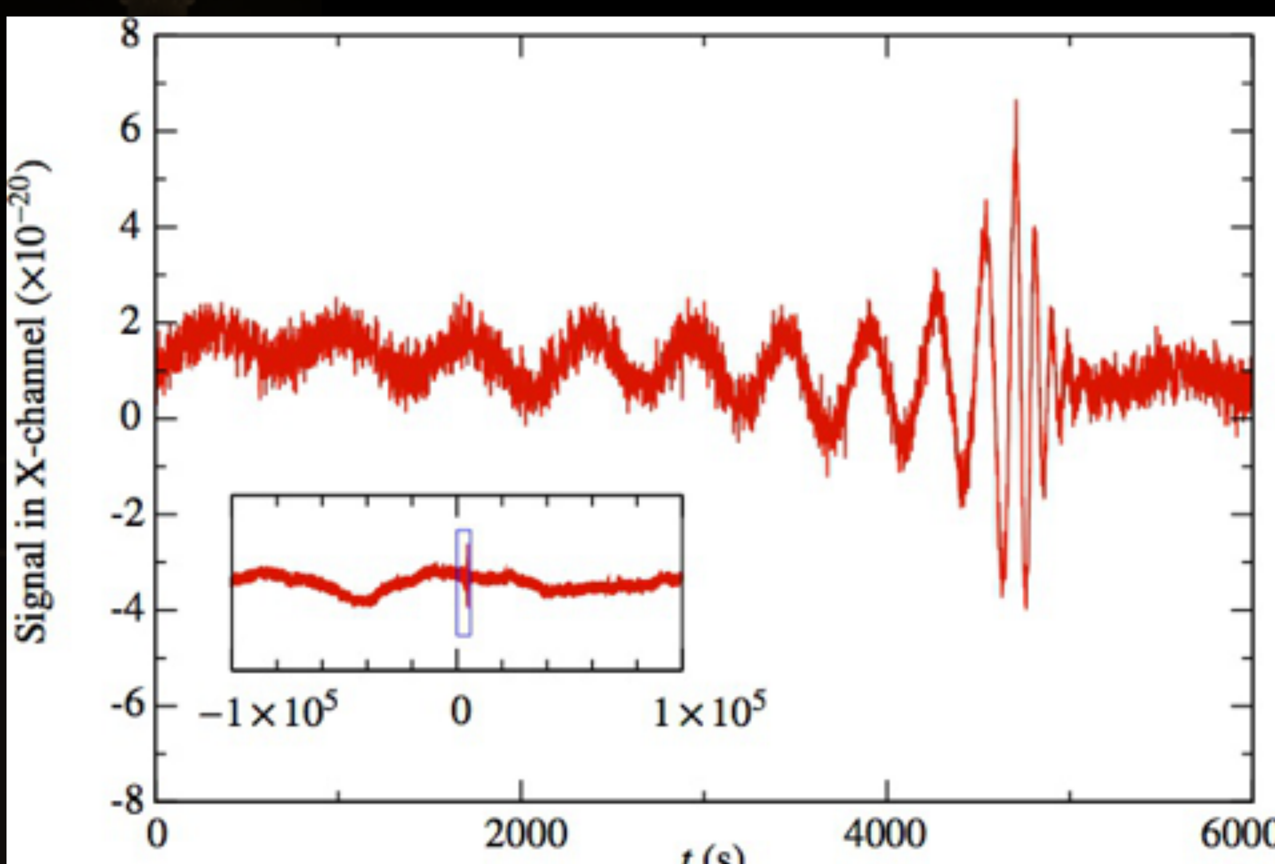
GW sources

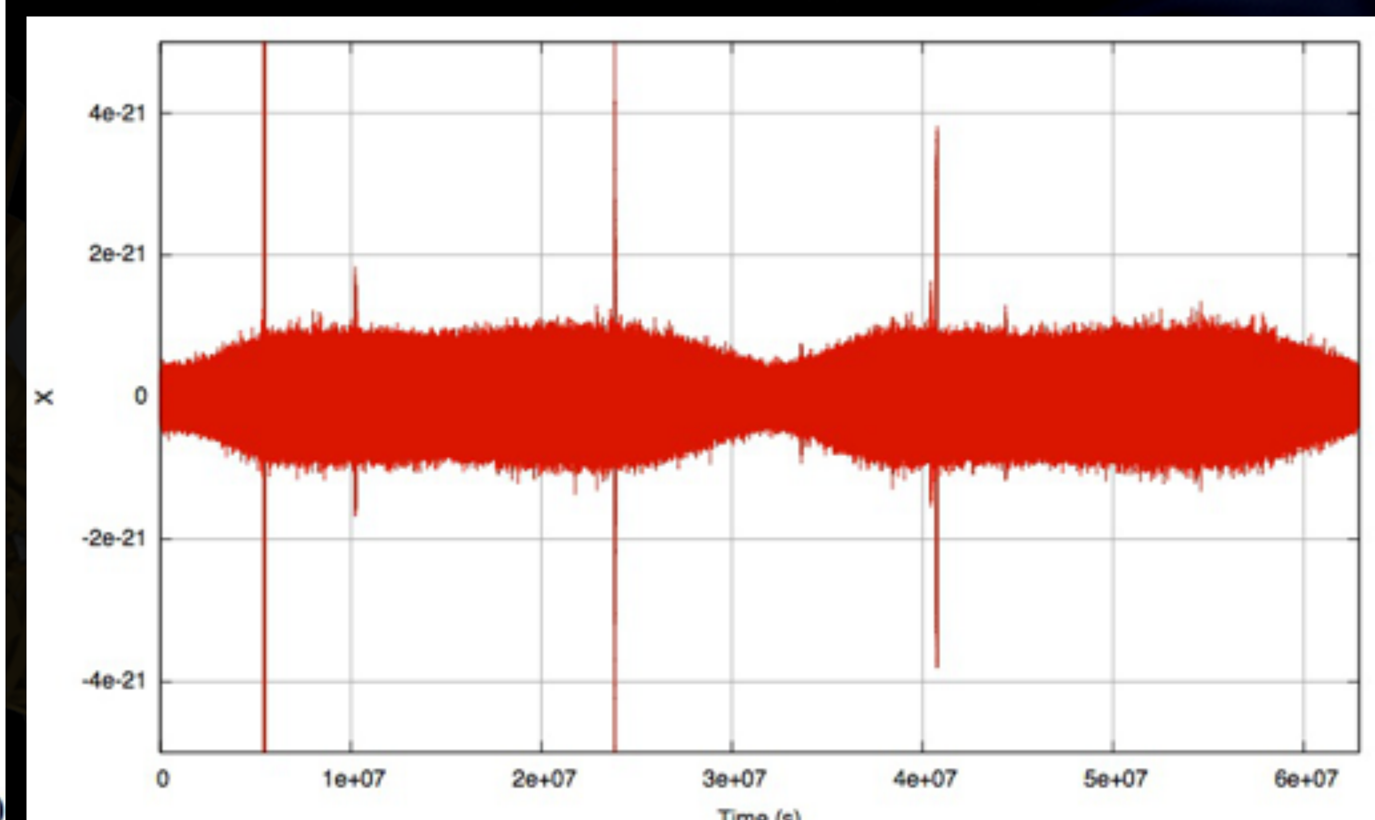
- 6 x10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources

GWs in LISA data

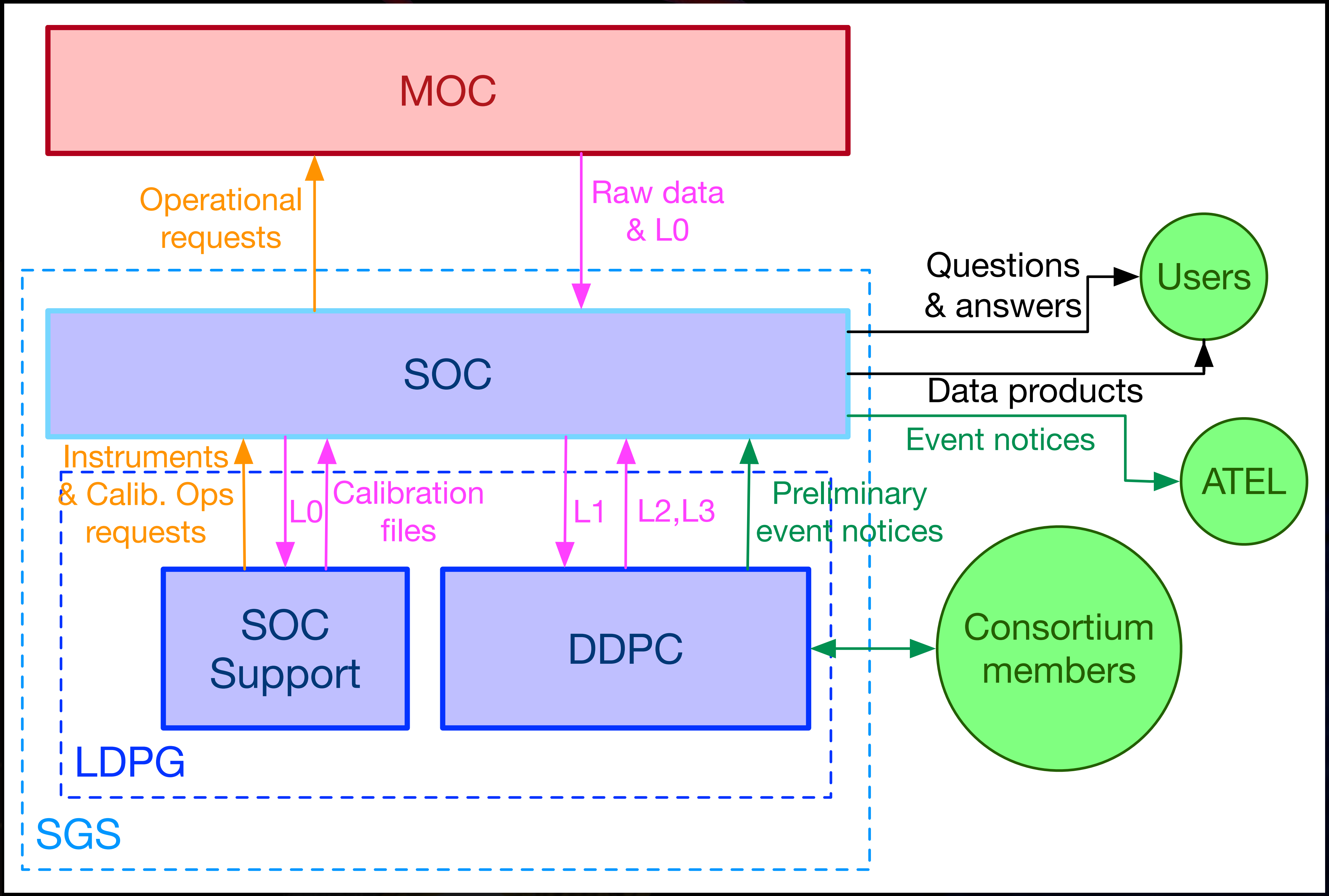
- Example of simulated data (LISACode):
  - about 100 SMBHs,
  - Galactic binaries







LISA Ground Segment



From L0 to L1

- Input (L0): “raw” data from the MOC
- Output (L1): TDI + all data “cleaned”
- Responsibility: SOC (ESA)
- With Consortium support => SOC Support group
- Activities / Challenges:
  - Processing ————————>
    - Calibration
    - Clock synchronisation
    - Ranging (estimation of delays)
    - TDI
  - Hardware monitoring
  - Quick-look of instrument data
  - …

From L1 to L3

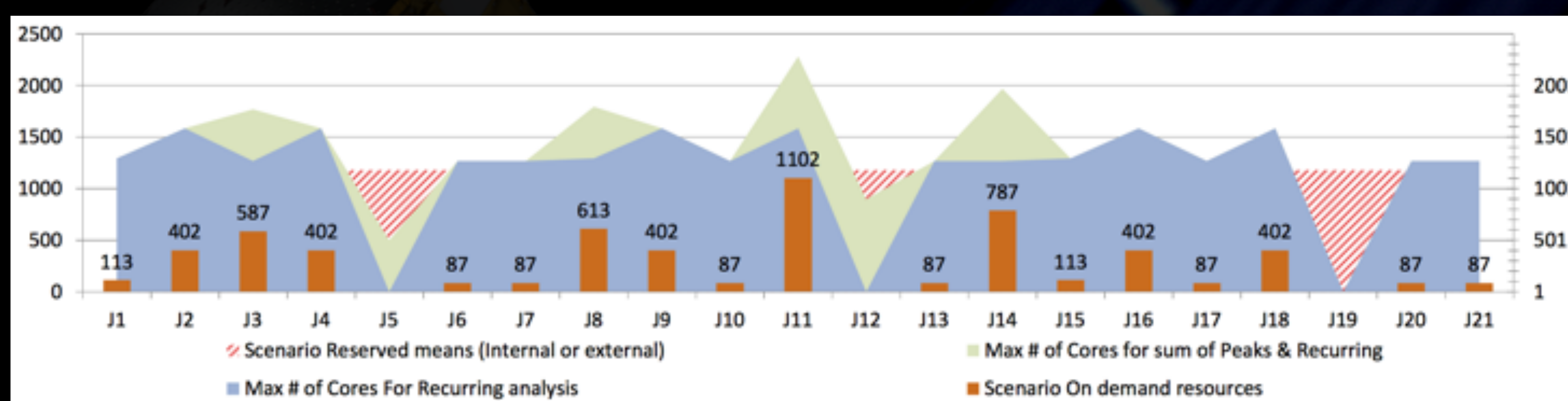
- Inputs: TDI + all data "cleaned"
- Outputs: final science products (catalogs, ...)
- Responsibility: Consortium => DDPC
- Activities:
  - Data analysis pipelines and simulation:
    - Prepare, Implement, Operate;
    - Support (LSG, SimWG, LDC) design and prototyping;
  - Define, coordinate and implement software framework and management structure for data and products
  - Coordinate and operate the DCCs
  - Define, implement and maintain dev. and op. environment

Data analysis & simulations

- **Simulations**:
  - Simulations at different scales: micro-sec to years in reasonable time
  - Coherently simulate control loops, integrate discretization/ interpolation, precisions, ...
- **Data pre-processing**: clock, ranging, TDI
- **Data processing**: extracting science
  - For the matched filtering: optimisation of likelihood computation, variety of samplers, possibly large number of parameters, evolving number of parameters, ...
  - Orchestration of multiple pipelines in parallel
  - Keep track of all produced data
  - Incremental data: new data to integrate every day
  - Fast pipeline for alerts, ...

LISA Data Processing

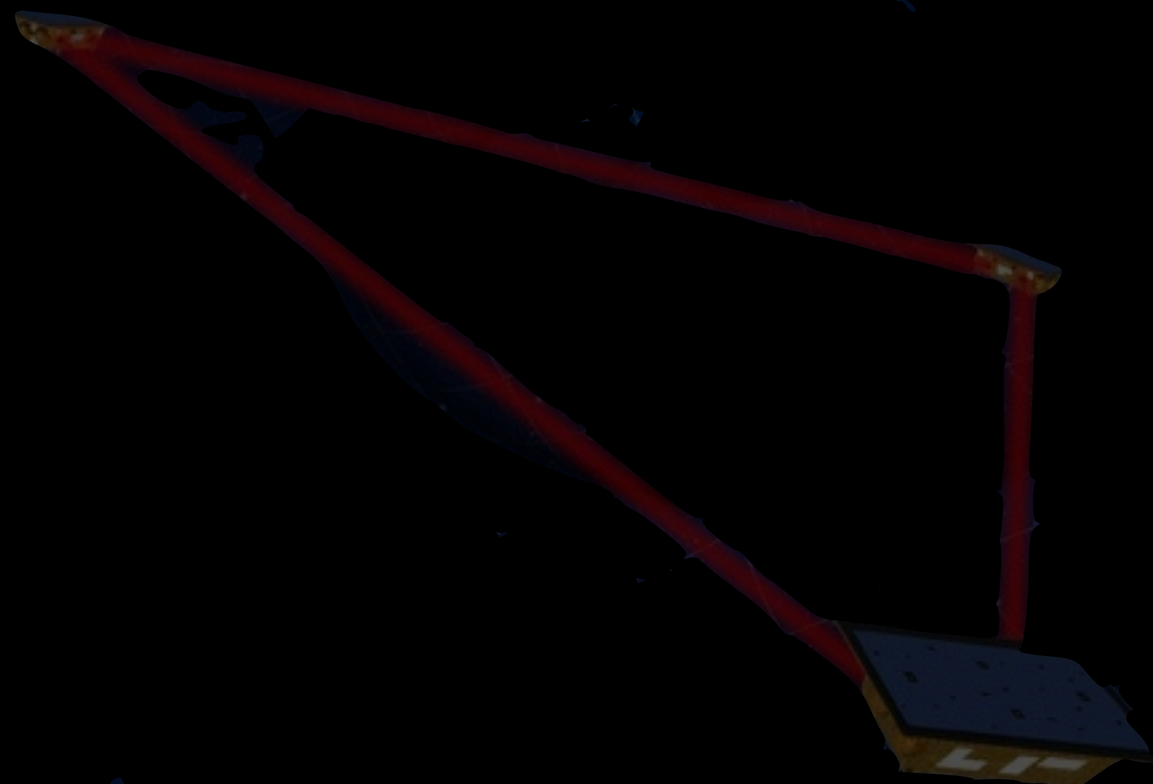
- First data and analysis of this kind + potential unknown sources
  => Keep flexibility + continuous evolution
- Permanent sources + transient sources + continuous evolution of codes, i.e. full reprocessing phase
  => fluctuations of the computational charge: mixed infrastructure (standard clusters + on demand, i.e. Cloud)
- Data analysis challenges: large number of mixed sources + no direct calibration of instrument
  => need to start the studies now!
  - Simulations
  - LISA Data Challenge

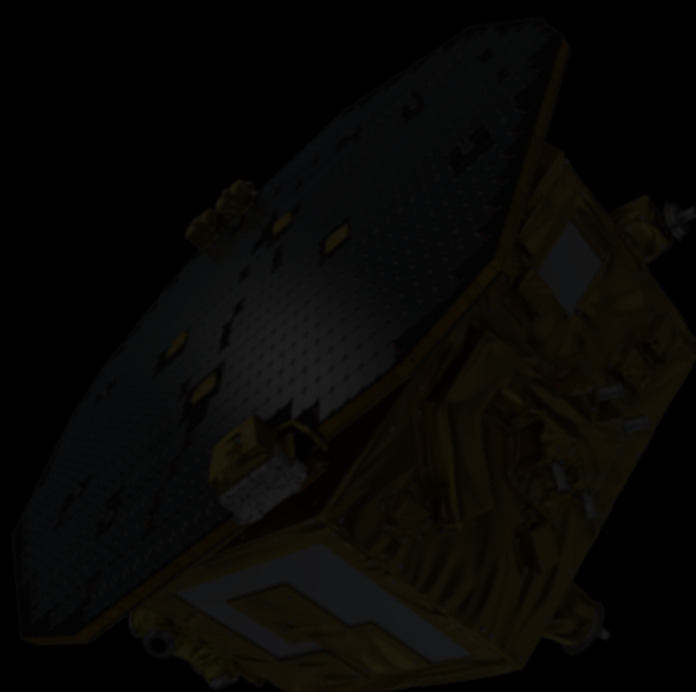


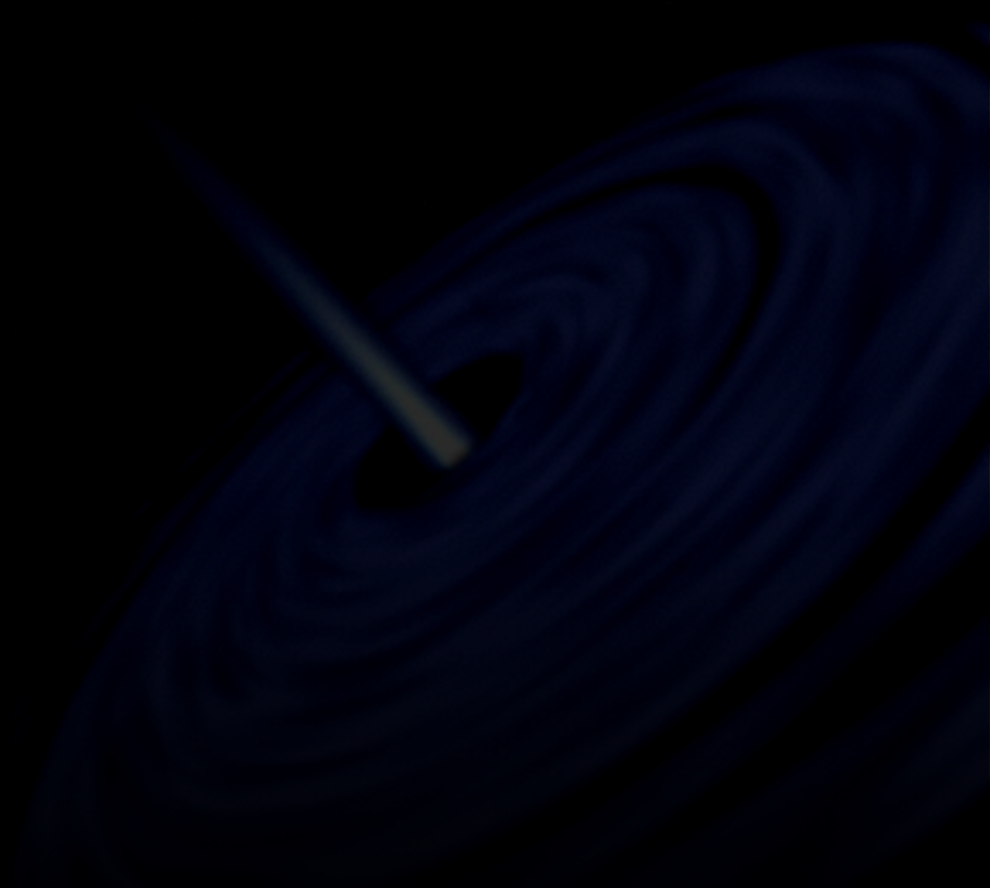
Current vision of the DDPC

- DDPC: unique entity responsable for the data processing (driving, integration of software blocks, ...)
- DDPC 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 DDPC software « suite » can run on "any" DCC.
  - Software: codes (DA & Simu.) + services (LDAP, wiki, database) + OS.
- First solutions:
  - Separation of hardware and software: light virtualization, ...
  - Collaborative development: continuous integration, ...
  - Fluctuations of computing load: hybrids cluster/cloud

Proto-DPC: basics







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- Development environment: in production
  - Collaborative work, reproducibility of a rapidly evolving & composite DA pipeline; Keep control of performance, precision, readability, etc
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GitLab jupyter

- Data basis & data model: in R&D
  - 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

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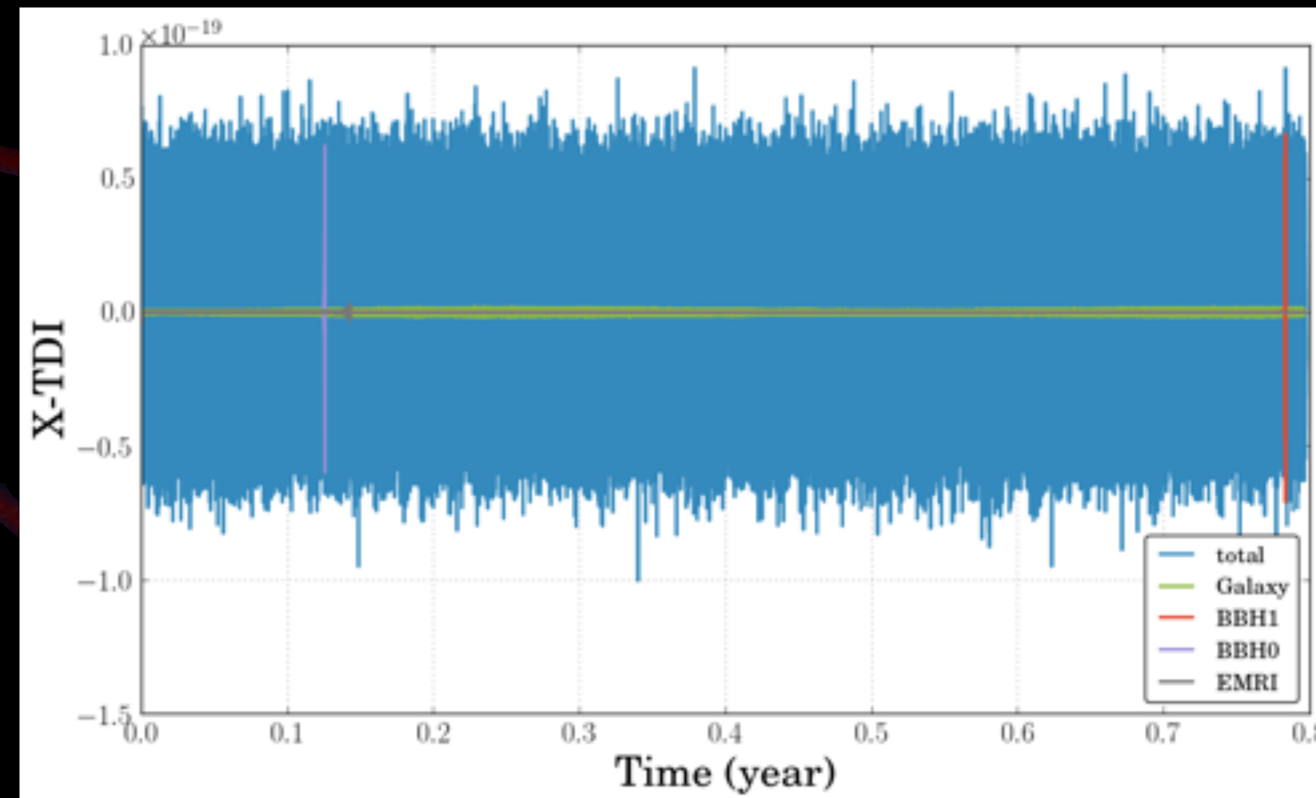
- Execution environment: in R&D (singularity, …)

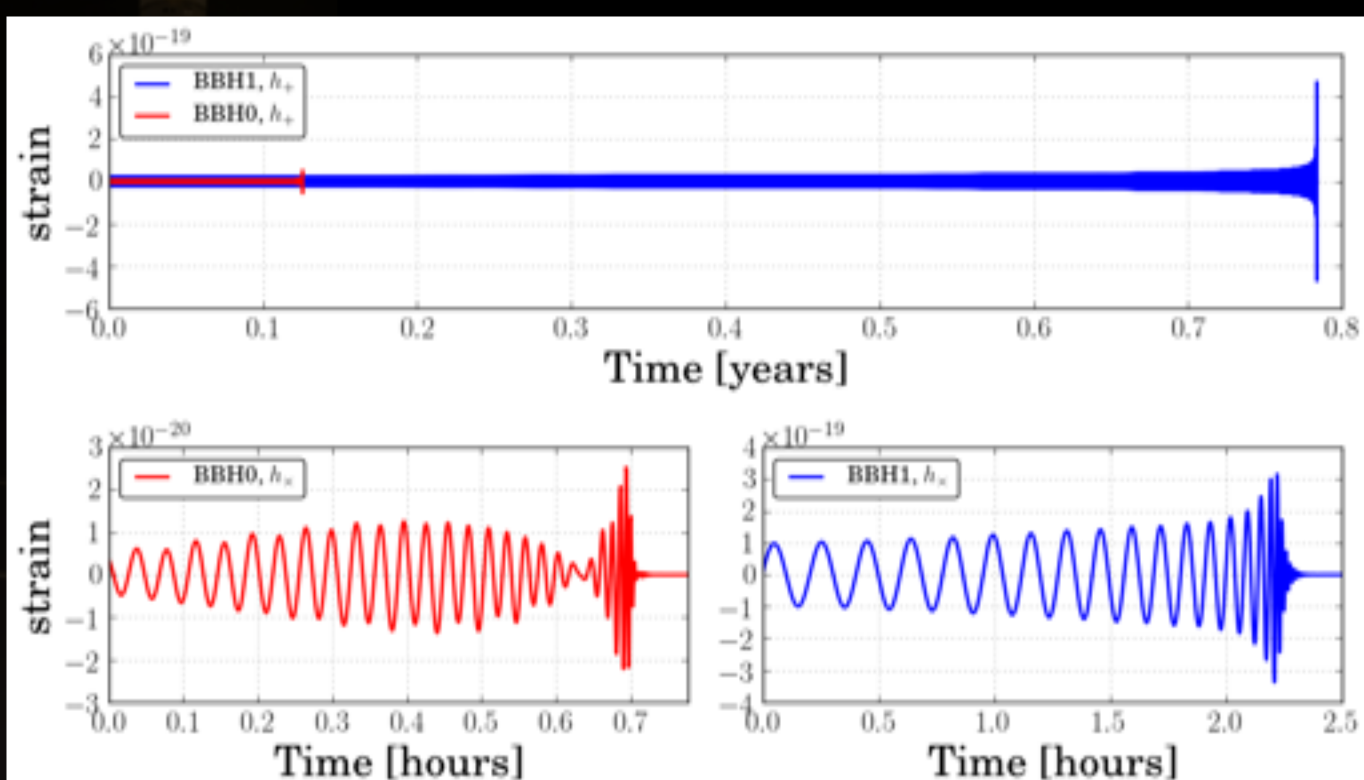
Support LISA Consortium today

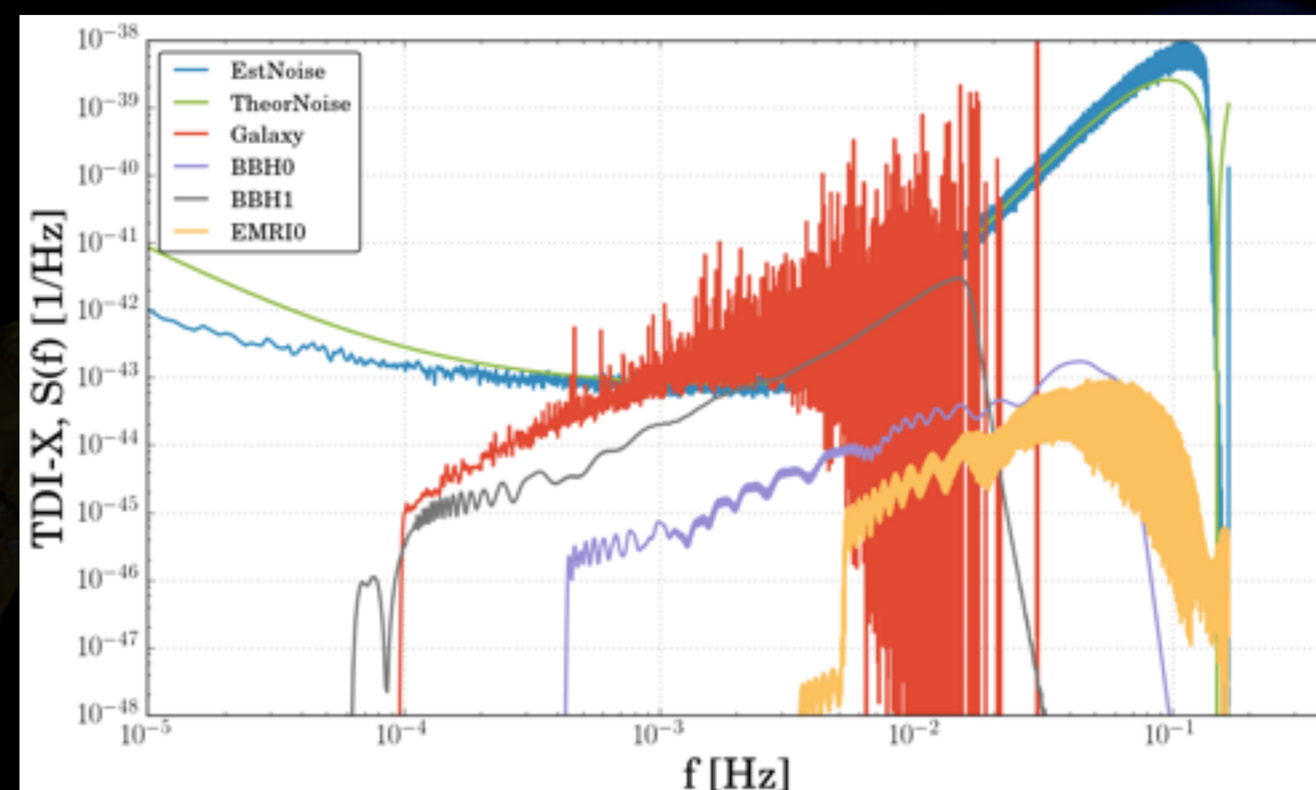
- Simulation:
  - LISACode and LISANode: git with continuous integration, docker image, singularity, documentation, ...
    => realistic data used for ex for performance, pre-processing, ...
- Exchange: LDC database, Virtual Machine on demand
- IT: Repositories, Document Management System, wikis
- Coming soon:
  - Jupyter hub available soon: share scripts
  - Singularity hub: share image containing all LDC tools
  - Computing facilities (prototyping DCCs)
  - Integration of LDC DA methods submitted with responses

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







History: the MLDC

Jan 2006
Works begins!

Jun 2006
Challenge 1 datatsets released at 6th LISA Symposium
[in proc. ,gr-qc/0609105-6]

Dec 2006
Challenge 1 results presented in GWDAW-11
[CQG 24, S529 (2007)]

Jan 2007
Challenge 2 datatsets released
[CQG 24, S551 (2007)]

Jun/Jul 2007
Challenge 2 results presented at Amaldi
[CQG 25, 114037 (2008)]
Challenge 1B released

Dec 2007
Challenge 1B results presented at GWDAW-12
[CQG 25, 184026 (2008)]

Apr 2008
Challenge 3 released
[CQG 25, 184026 (2008)]

Jun 2009
Challenge 3 results at Amaldi
[CQG 27, 084009 (2009)]

Nov 2009
Challenge 4 released
[CQG 27, 084009 (2009)]

Dec 2010
Challenge 4 deadline

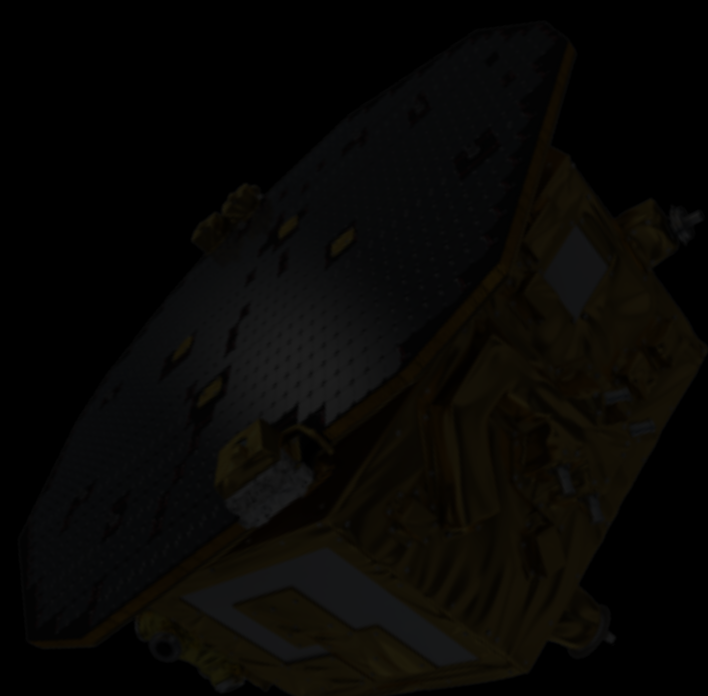
2006 2007 2008 2009 2010

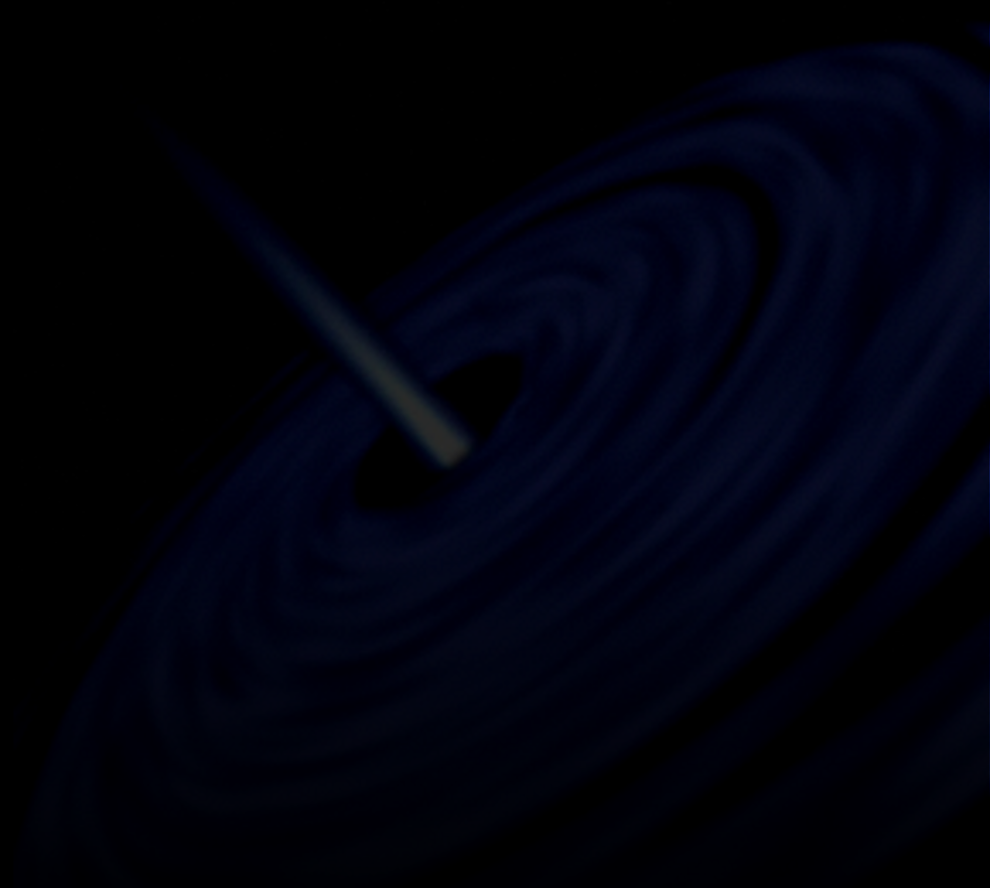
by M. Vallisneri

Previous MLDC

	MLDC 1	MLDC 2	MLDC 1B	MLDC 3	MLDC 4
Galactic binaries	• Verification • Unknown isolated • Unknown interfering	Galaxy $3x10^6$	• Verification • Unknown isolated • Unknown interfering	Galaxy $6x10^7$ chirping	Galaxy $6x10^7$ chirping
Massive BH binaries	• Isolated	4-6x, over "Galaxy" & EMRIs	• Isolated	4-6x spinning & precessing over "Galaxy"	• 4-6x spinning & precessing, extended to low-mass
EMRI		• Isolated • 4-6x, over "Galaxy" & MBHs	• Isolated	• 5 together, weaker	• 3 x Poisson(2)
Bursts				• Cosmic string cusp	• Poisson(20) cosmic string cusp
Stochastic background				• Isotropic	• Isotropic

Aim of the LDC





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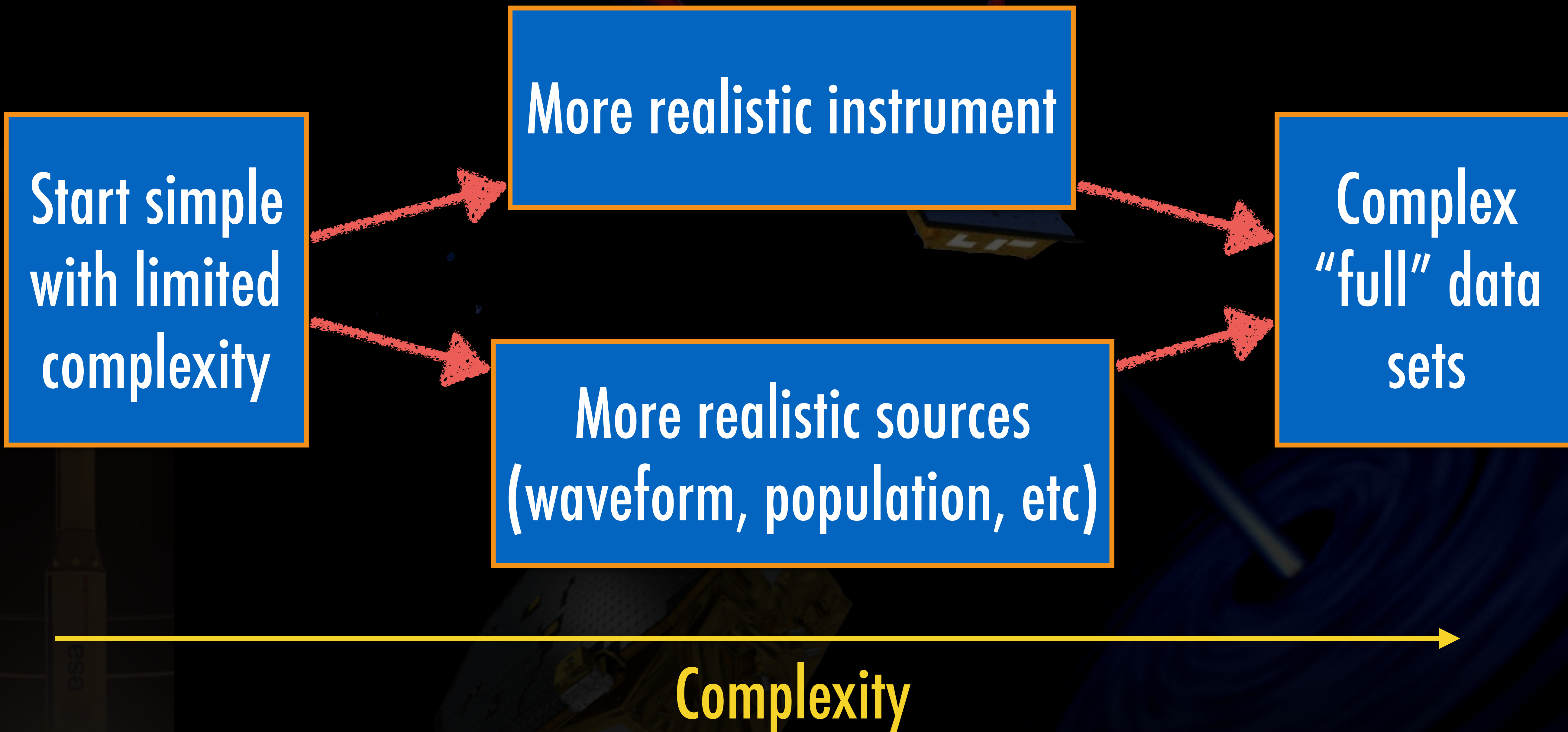
- To make a common platform for evaluation and performance comparison of various algorithms
- To address the science requirements: project oriented challenges
- To introduce the software development standards for the data analysis pipeline
- To prototype and develop the end-to-end data analysis pipeline (integration into DDPC -- Distributed Data Processing Center).

Philosophy of the challenges

- Two parallel studies



“Radler” data set

- Noise: very simple (Gaussian),
- Orbit: analytic LISA orbit,
- TDI: 1.5 generation TDI (rigid LISA)
- Response of instrument:
  - Full simulation (time domain - LISACode - slow)
  - and/or approximation (evolved low frequency approximation - fast)
- Data ready and available
- Problem of conventions for polarisation between various sources and waveforms => a new version will be generated after correcting conventions

“Radler” data set: MBHB

Radler #1: one MBHB

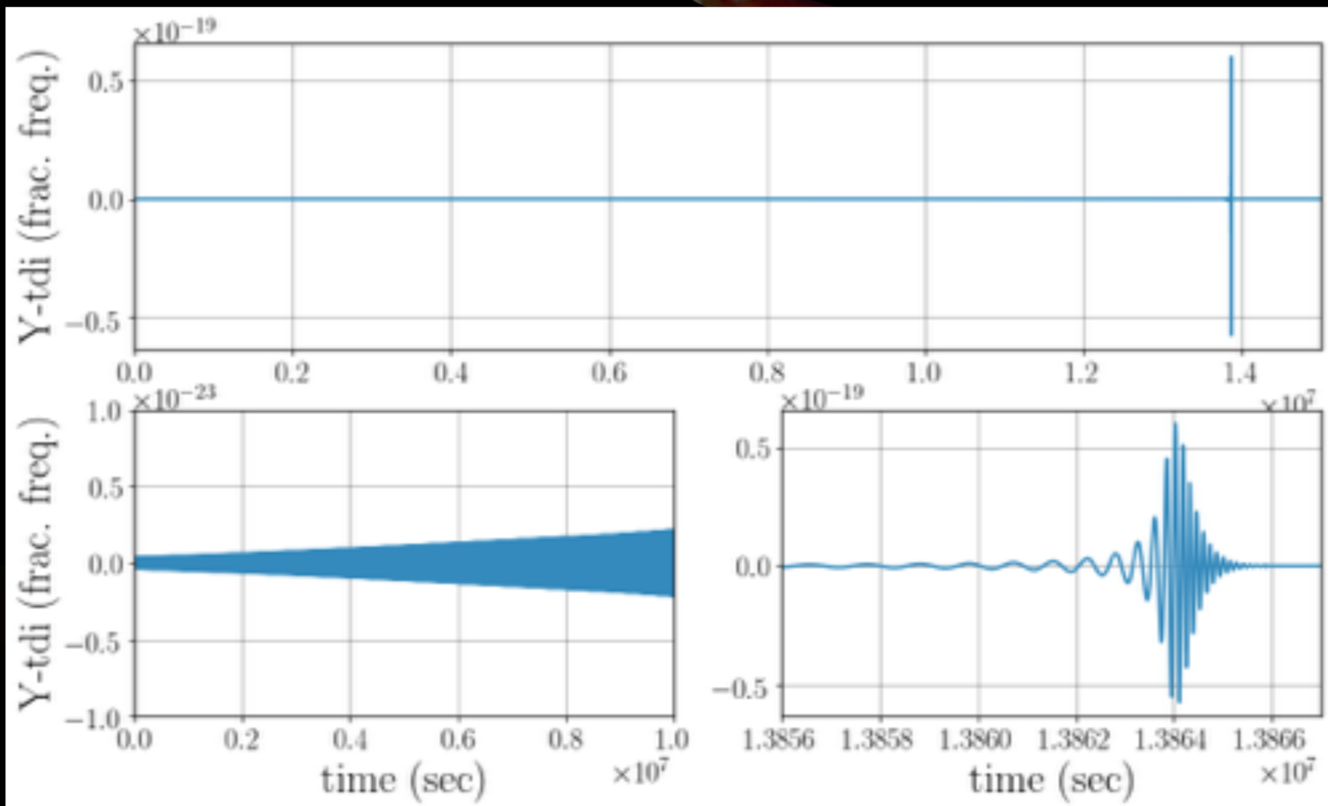
- Duration of the signal: 0.6-1.2 years
- SNR = 100-500
- Time domain using LISACode (for the response)
- Waveform: IMRPhenomD
  - inspiral-merger-ringdown
  - non-precessing: spins parallel orbital angular momentum.
  - only the dominant mode: $l = 2, m = \pm 2$
  - $h_+, h_\times$ in frequency domain and Fourier transformed
- Observation: 1.4 years @ 10s

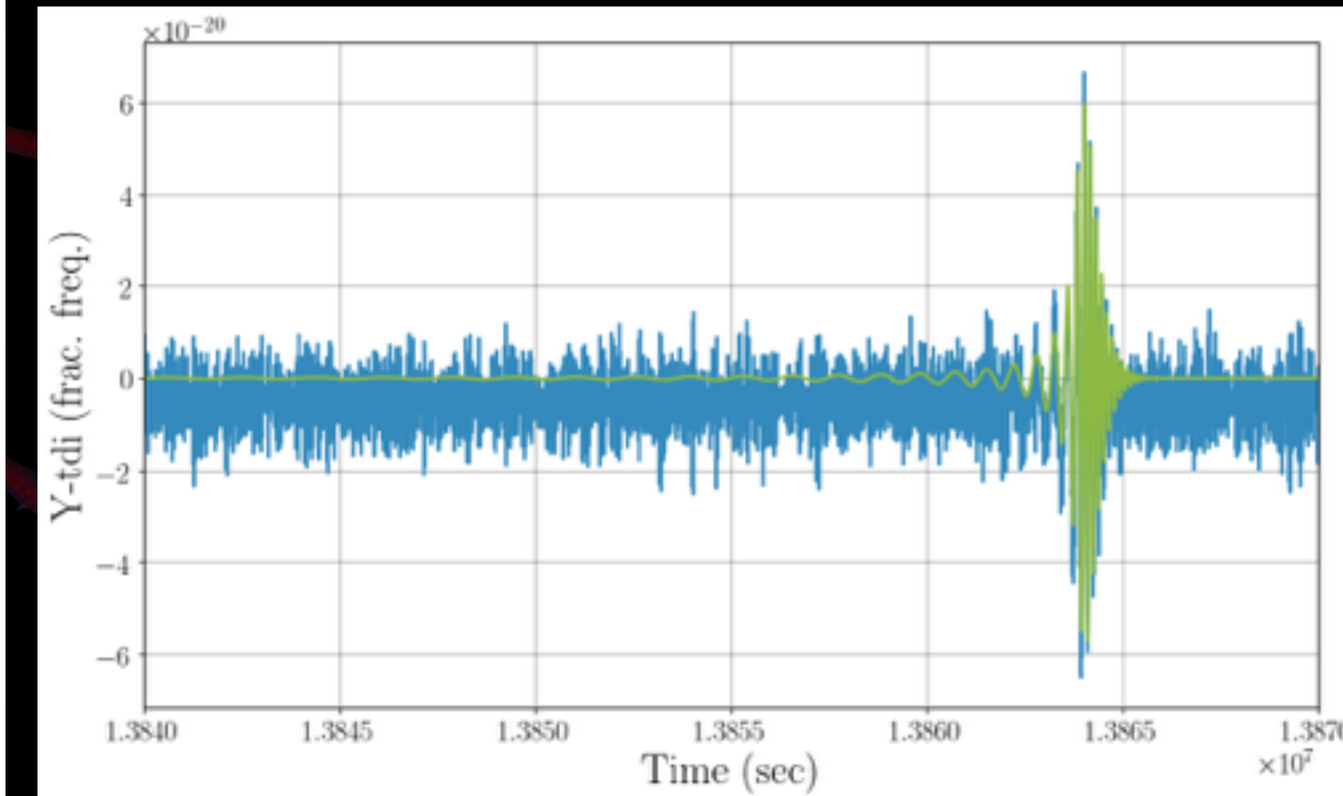
"Radler" data set MBHB

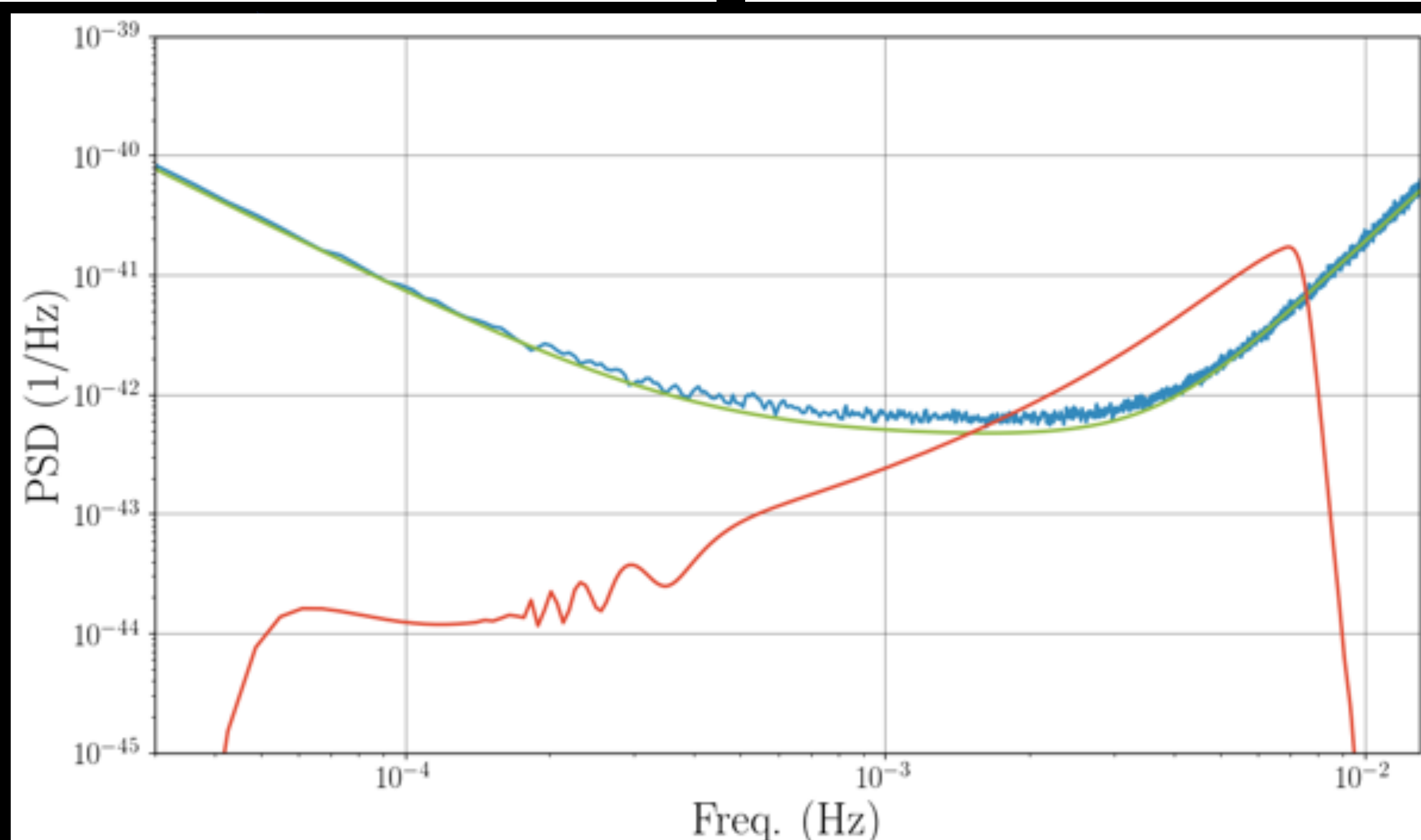
- Radler #2: one MBHB idem as #1 but
  - generated completely in the frequency domain,
  - including approximative TDI response (frequency domain)

- Radler #3 (?): one MBHB idem as #1 but noise
  - instrumental noise will be assumed gaussian but its level will be chosen uniform U[1,2] of the nominal value for each link.
  - => We do not know the level of the noise in each link and one cannot easily construct the TDI combination A, E, T with uncorrelated noise.

"Radler" data set: MBHB





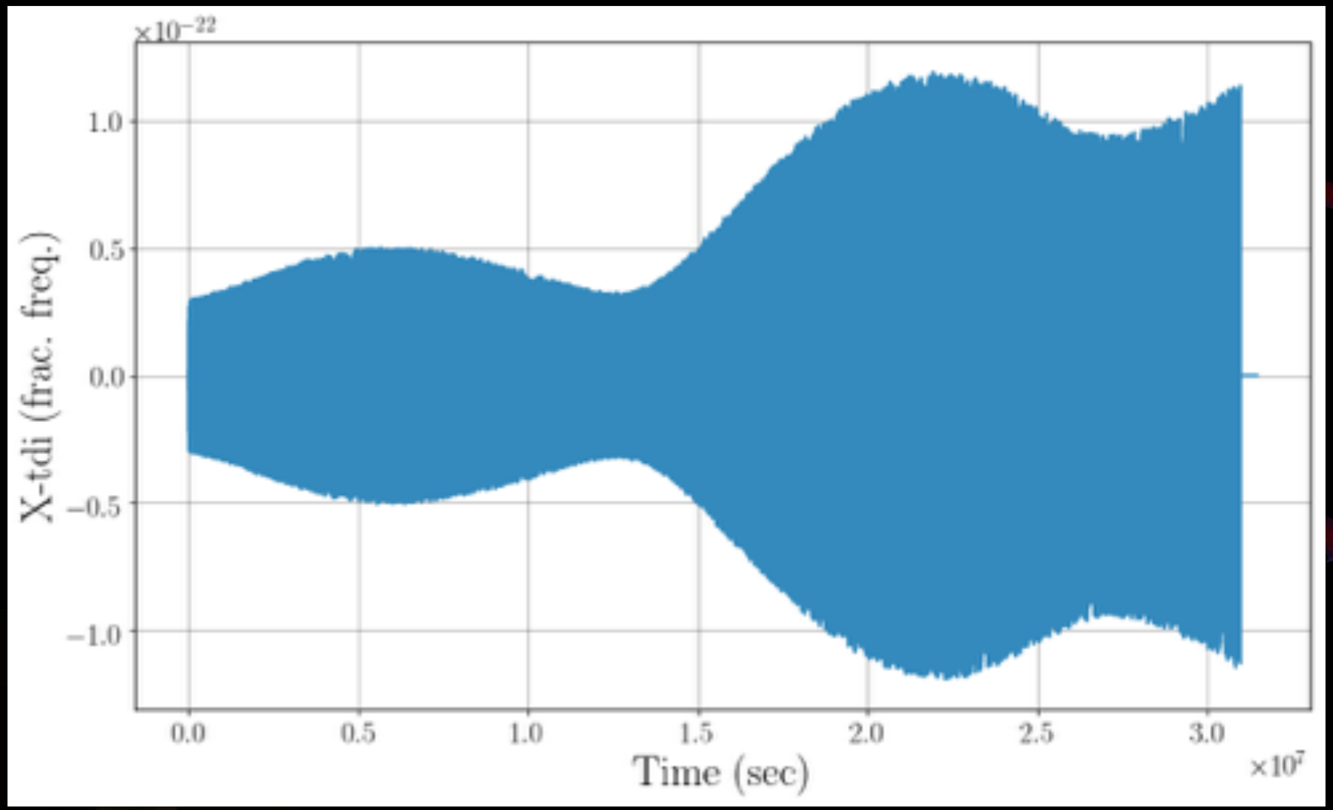


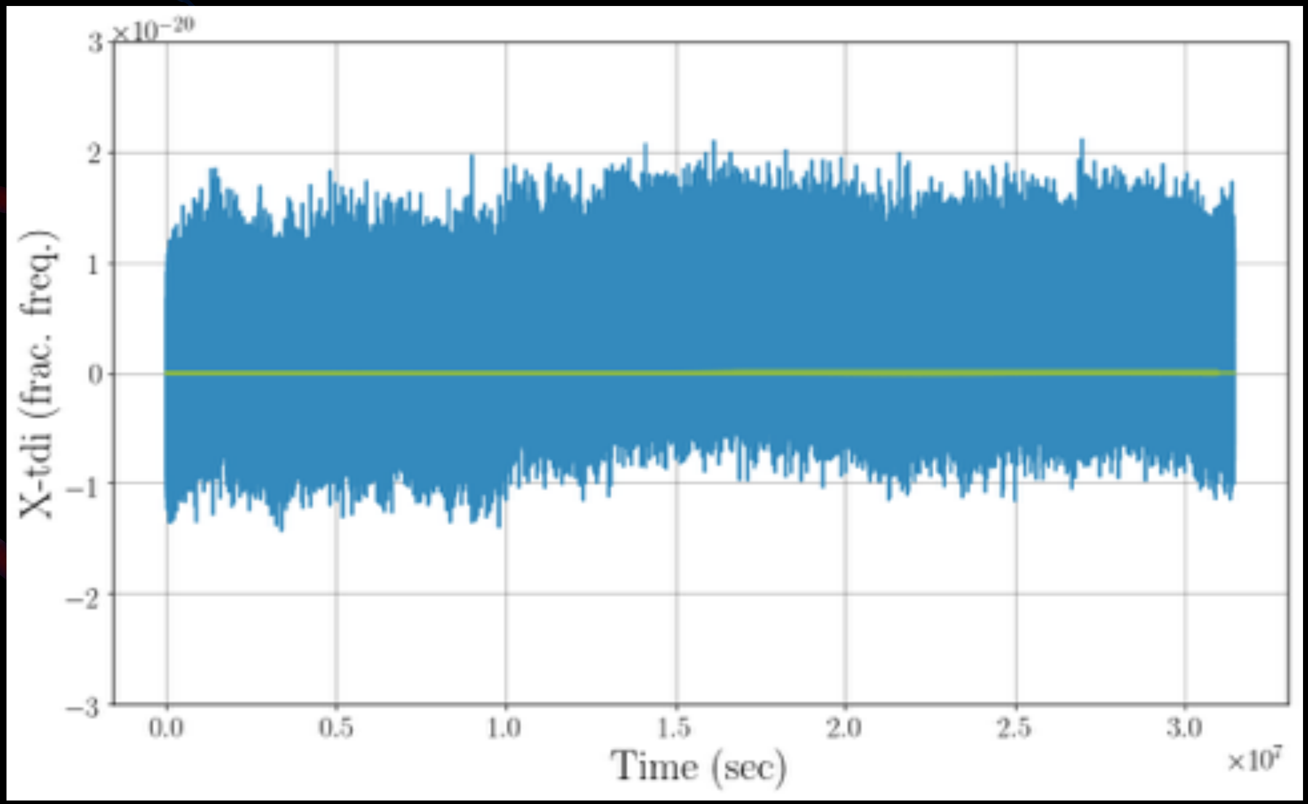
“Radler” data set: EMRIs

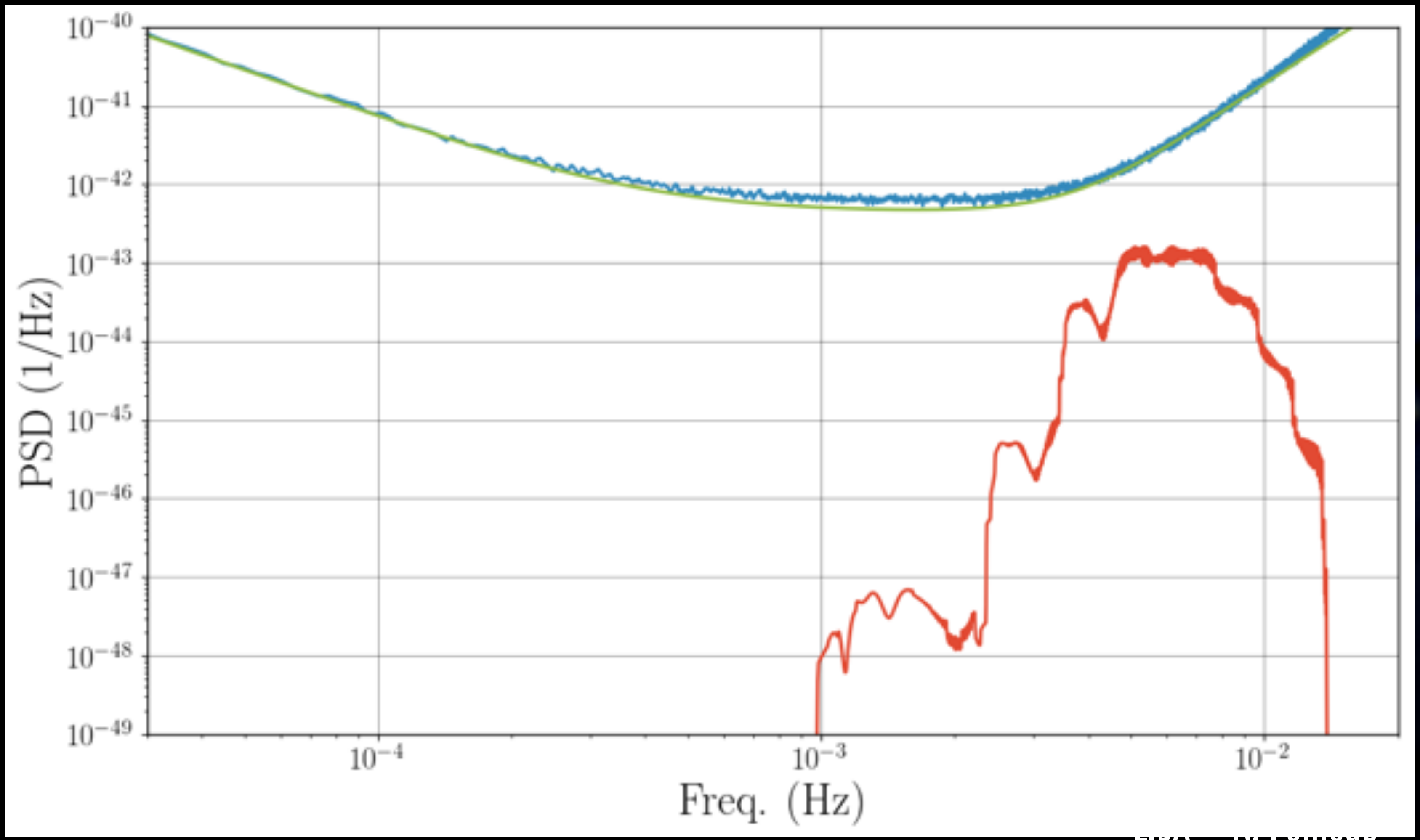
- Radler #4: Extreme Mass-Ratio Inspiral (EMRI)
  - one EMRI GW signal
  - waveform: idem as in the old MLDC: not a faithful representation of the expected GW signal but fast to produce => participants should not rely strongly on the model for the detection purposes
  - SNR: 40-70
  - duration 1-1.5 years
  - Observation: 2 years @ time step is 15 sec

- Radler #5: EMRI: idem #4 but:
  - waveform: AAK (augmented analytic kludge)

“Radler” data set: EMRIs



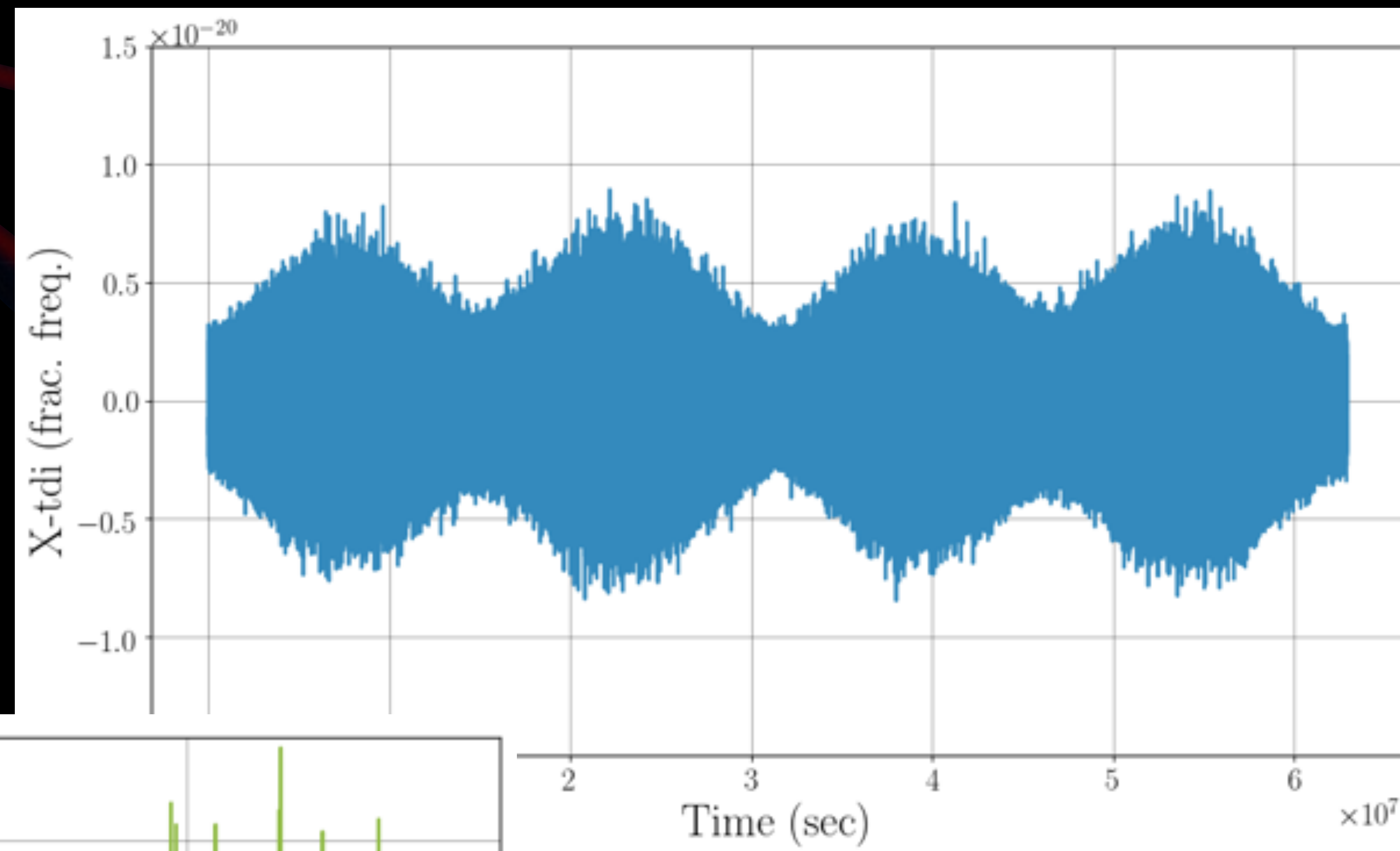


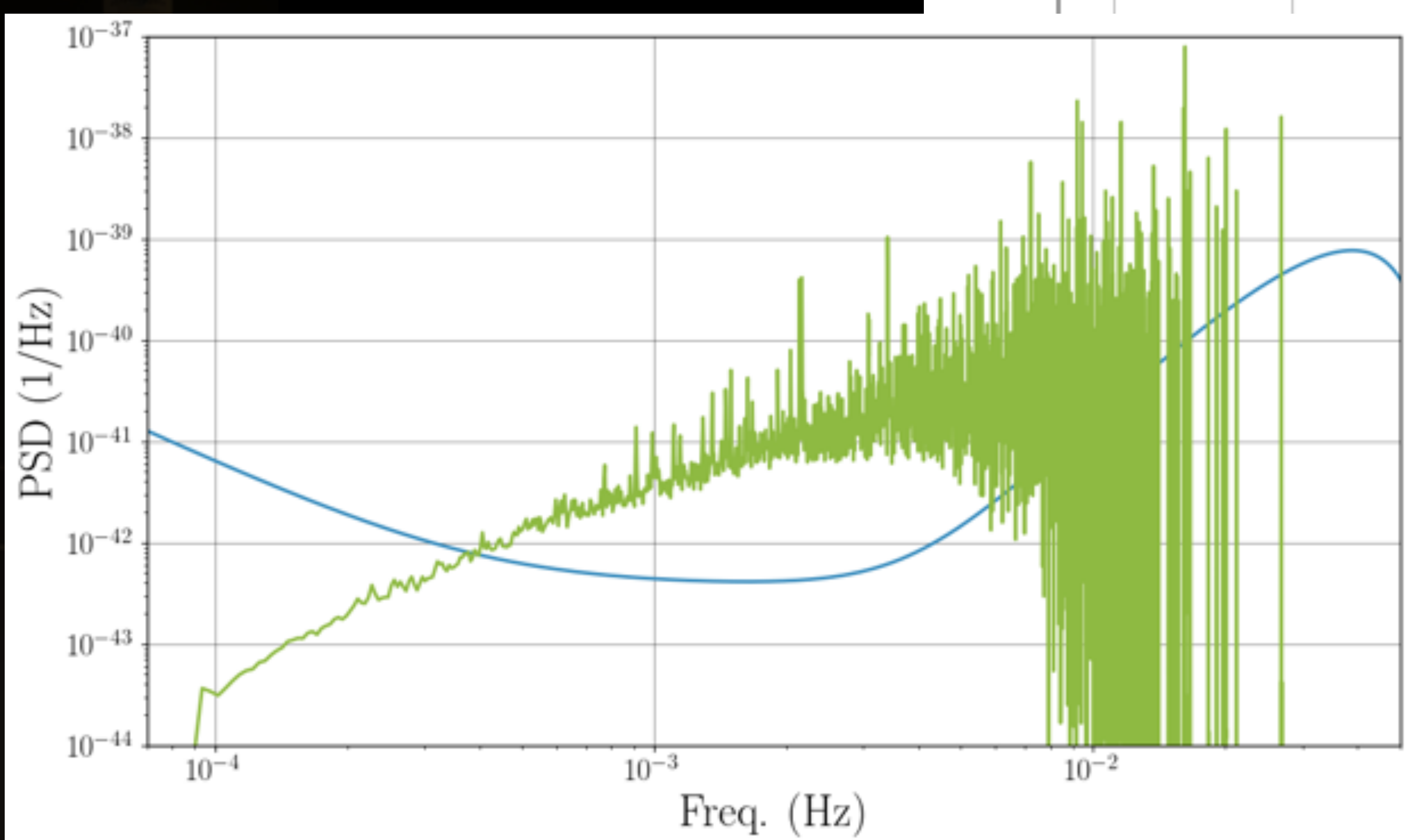


“Radler” data set: GBs

- Radler #6: Galactic binaries:
  - population of Galactic white dwarf binaries: about 30 millions of binary systems
  - waveform : h+, h× is produced by Taylor expansion of the phase (up to first derivative in frequency) at the t0 (beginning of observations).
  - LISA response function: approximate
  - Observation: 2 years @ 15 sec.

"Radler" data set: GBs





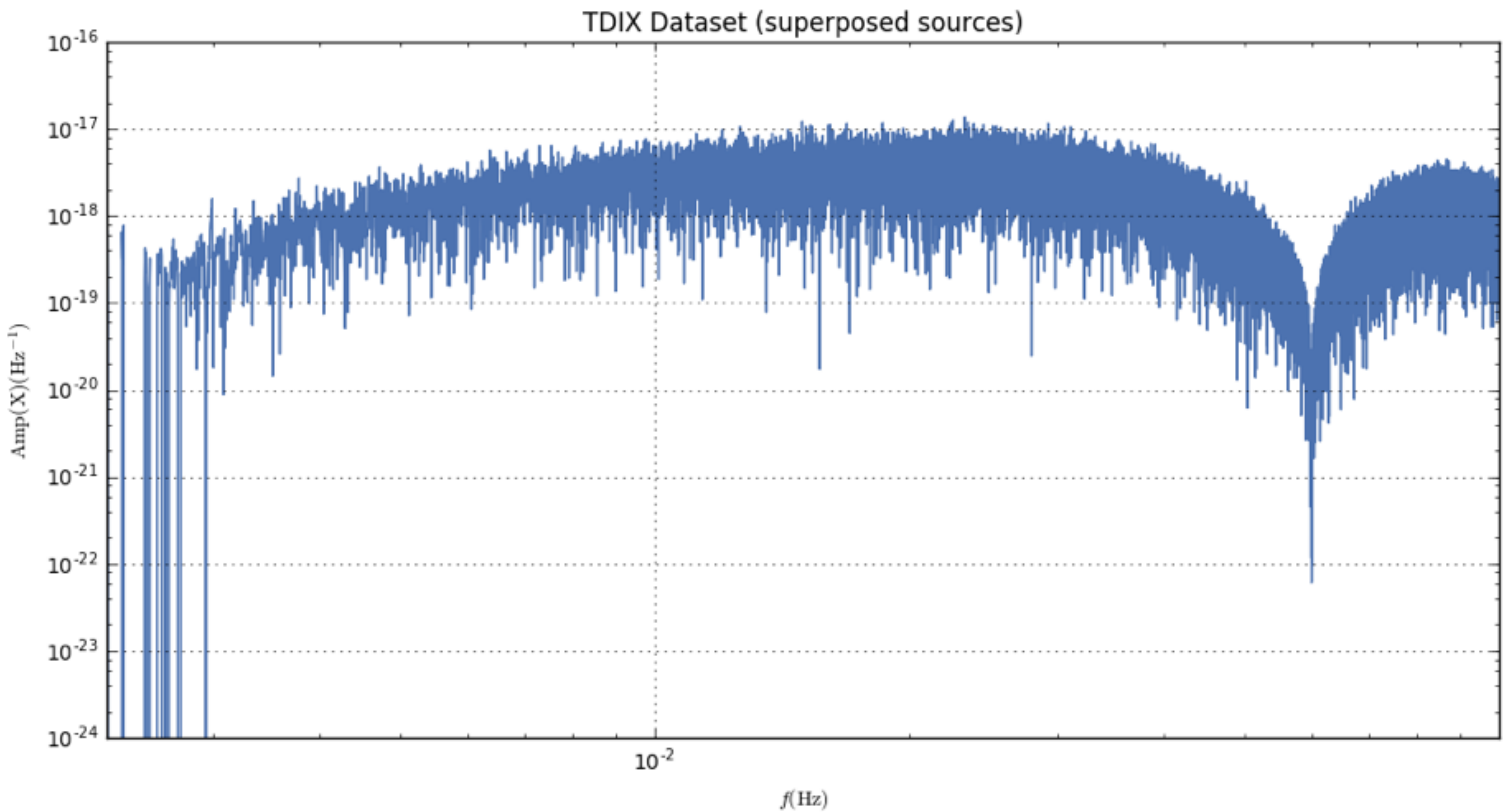
"Radler" data set: GBs

- Radler #5: one MBHB idem as #1 but
  - Galactic binaries: The gaussian noise and GW signals from the population of Galactic white dwarf binaries. The population contains about 30 millions of binary systems. The waveform (h_+, $h_\times$) is produced by Taylor expansion of the phase (up to first derivative in frequency) at the t0 (beginning of observations). The response function is approximate and described in details [5]. Time step is 15 sec. Duration of observation is assumed to be 62914560 seconds.

“Radler” data set: sMBHB

- Radler #7: stellar Mass Black Hole Binaries (or SOBHB):
  - Population of sMBHB (similar LIGO-Virgo): 21721 sources
  - Some of those binaries will be detectable in the band of ground based detectors several years after being observed in LISA
  - Waveforms: h+, h× (IMRPhenomD) model => frequency domain then transformed into time domain.
  - Observation: 2.6 years @ 5s
- Radler #8: bright stellar mass black hole binaries:
  - Similar to #7 but with only the signals which have the total SNR above 5.0 (against the instrumental noise!).
  - Same population as #7 => can be subtracted from #6 in

“Radler” data set: sMBHB



“Radler” data set: SGWB

- Radler #8: Stochastic GW signal
  - Gaussian instrumental noise only
  - Isotropic
  - Power Law: amplitude and slope similar to the one expected from sMBHB

- Radler #9: Stochastic GW signal
  - Idem #8 but with a broken power law

Radler LDC-1

- The main aim of "Radler" is to dust-off old and/or develop new data analysis tools, however we can use these datasets to
  - to study the time-iterative data analysis (low latency prototyping)
  - to check robustness of the algorithm to gaps
  - to develope modular structure for the DA pipeline
  - catalogues building and releases
- Projects using LDC tools / infrastructure:
  - Waveform systematics study
  - SNR computation, parameter estimation
- Tutorials on LISA data analysis
- Evaluation of the results and algorithms.
- Visuzalization tools

Radler LDC-1

- Projects using LDC tools / infrastructure:
  - Waveform systematics study
  - SNR computation, parameter estimation
- What else do we expect from LDC-1:
  - Tutorials on LISA data analysis
  - Evaluation of the results and algorithms.
  - Visuzalization tools
  - Pipeline construction and management tools

Beyond the first data set

- Improve sources and populations
  - more precise waveforms
  - different populations

    => test the ability to constrain the population model
  - several type of sources in the same data

Beyond the first data set

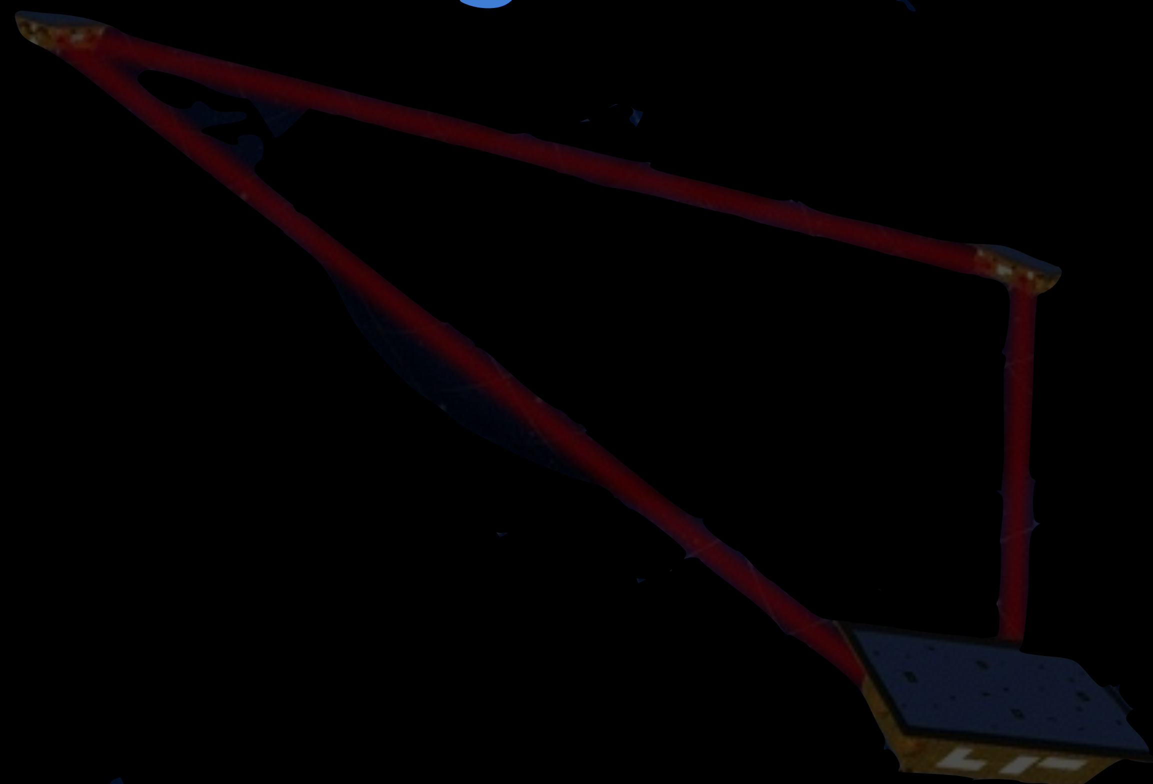
- We need to move away from the simplistic assumption about the noise:
  - Develop pipelines to produce L1 data (TDI) from raw data (L0):
  - Calibrations, remove / reduce noises, gaps, frequency planning, non-stationarity, unexpected events
  - Use LPF results to mimic instrumental artefacts in LISA simulations (gaps, glitches, non-stationarity)
  - Work together with the simulation WG: end-to-end simulation
  - Work on the estimation effect of gaps is under way

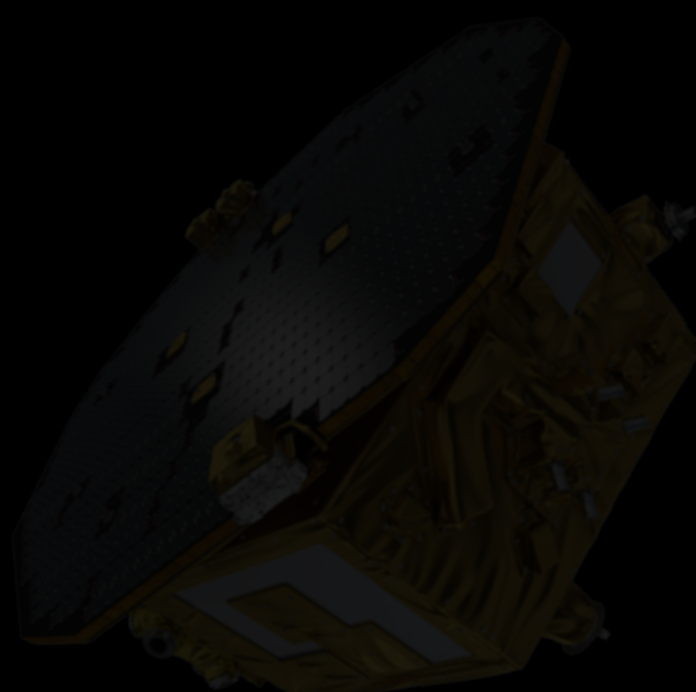
  => For each astrophysical source we need to revisit the detection (Gaussian) algorithms with realistic noise

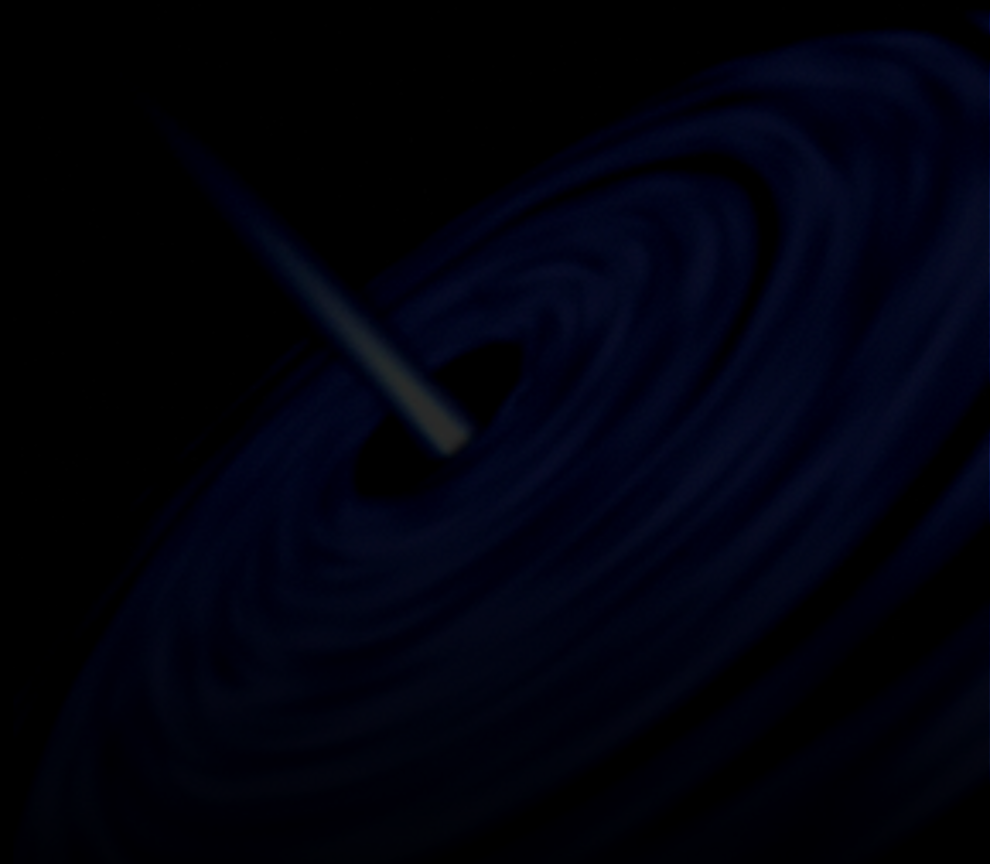
Next ... LDC-2

- Spritz: Non-stationary instrum. noise + light astrophysical content
  - to address robustness of algorithms used in Radler for non-stationary noise
  - to help setting some requirements on the instrument performance/artifacts
- Sangria: Mild Enchilada: Galaxy + MBHBs + EMRI+ Gaussian stationary noise
  - Start prototyping global fit pipeline
  - Investigation: are signals aware of each other?
  - Building the catalogues
  - Assessment of required resources and hardware structure (HPC

Generating LDC data sets







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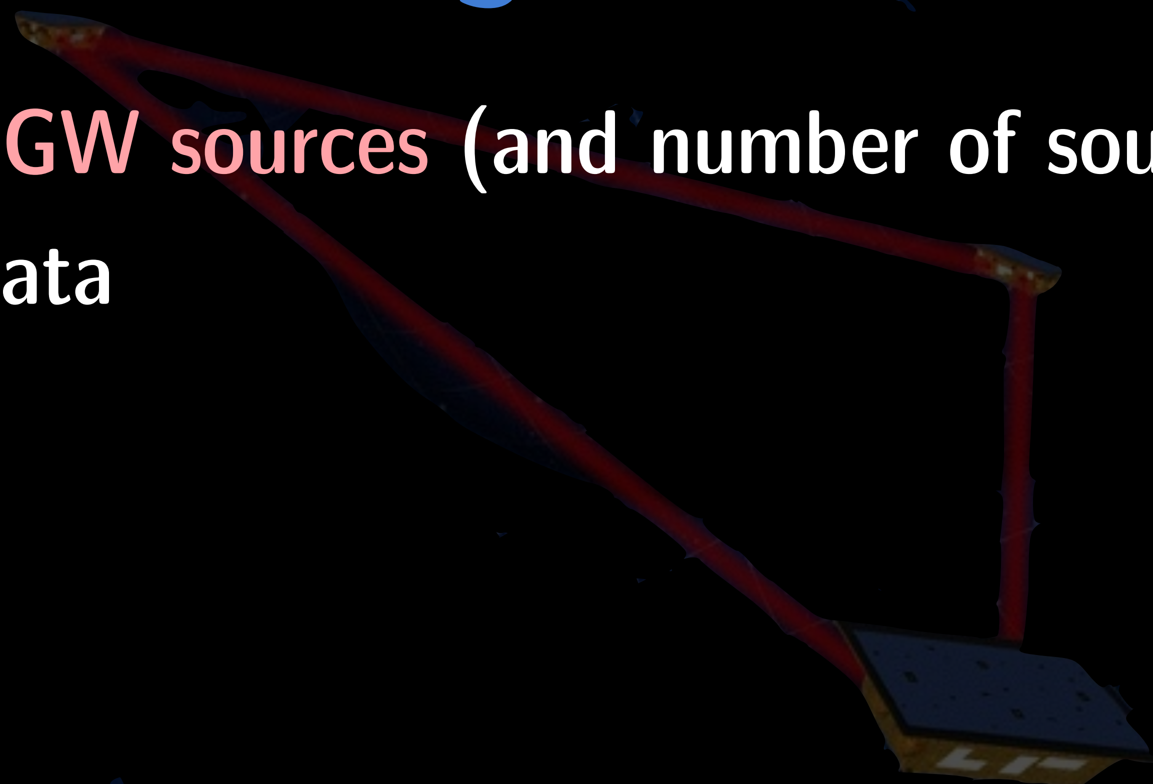
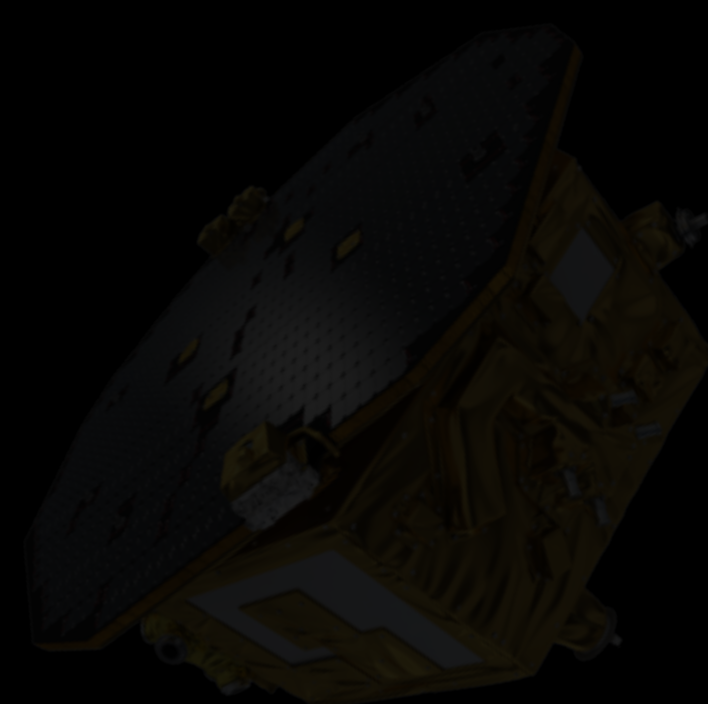
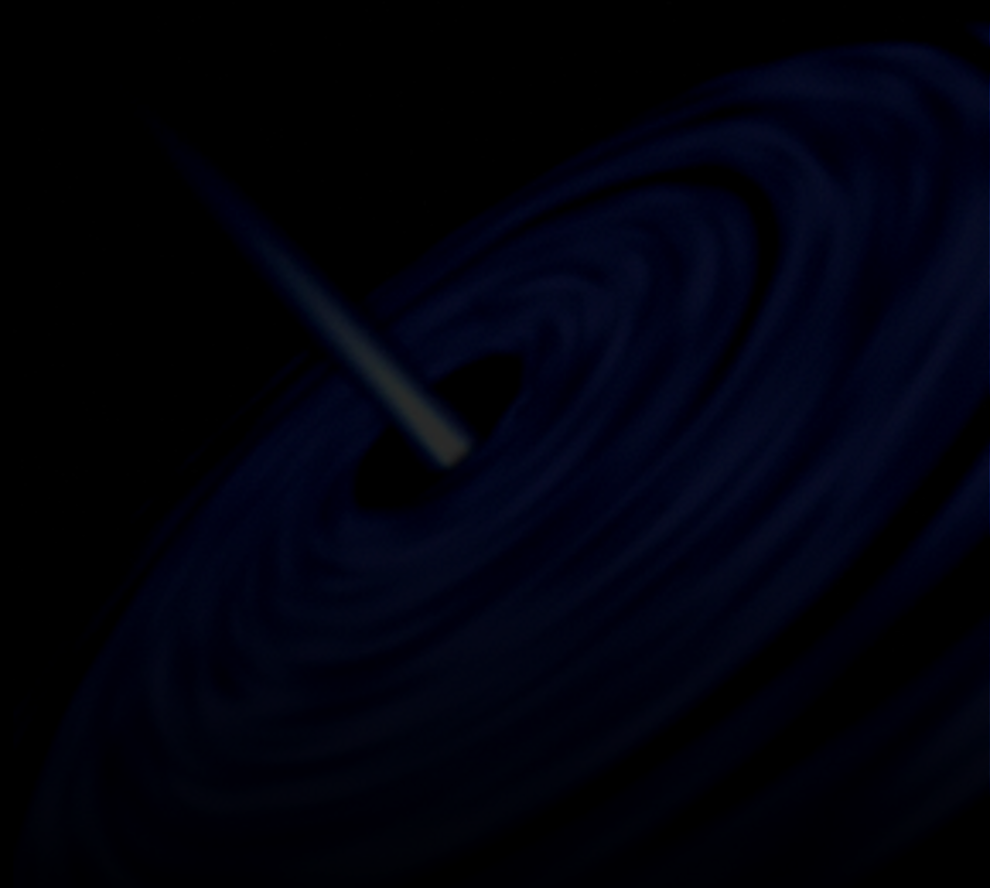


- Decide on the GW sources (and number of sources) which we want to put in the data





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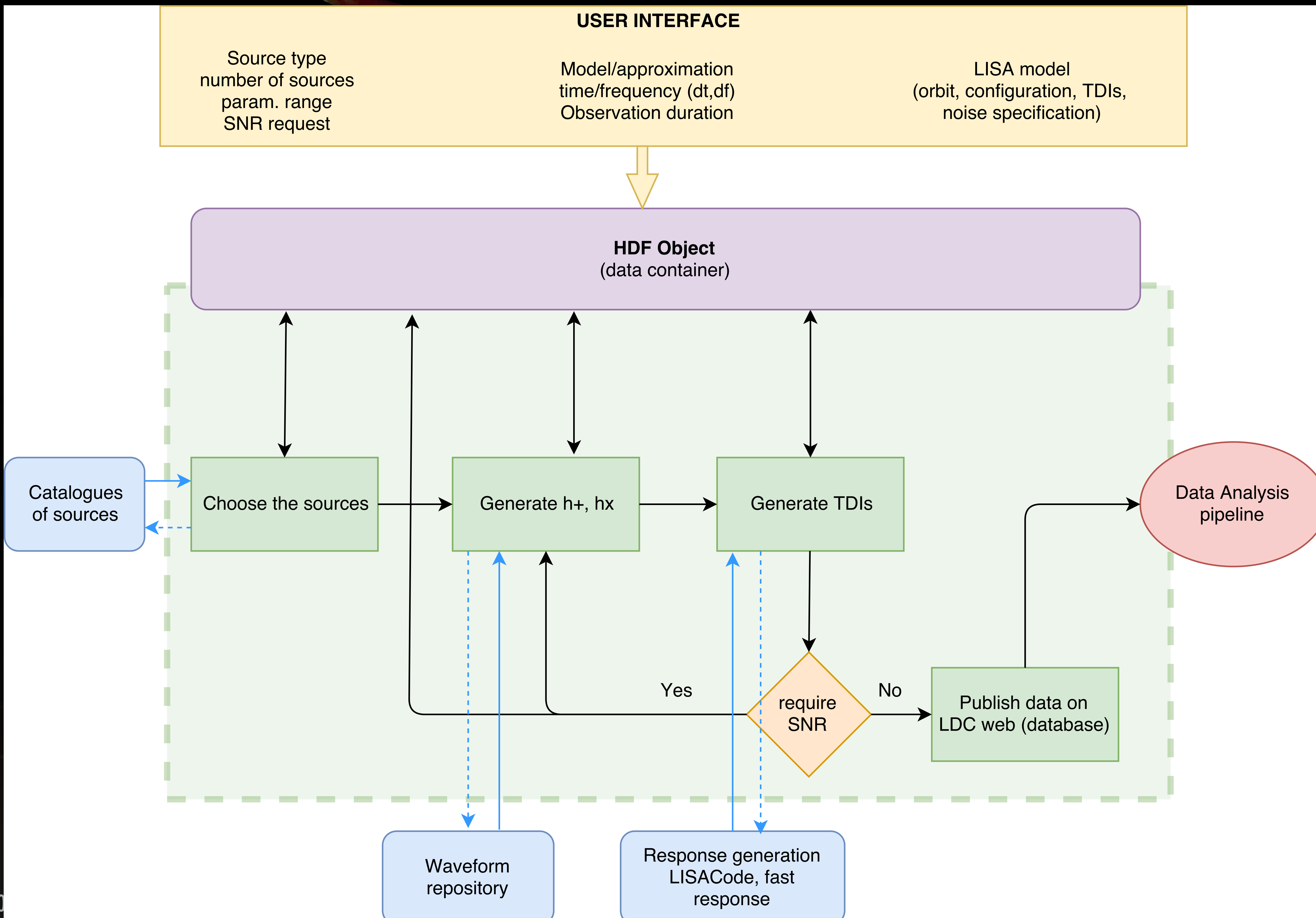
- Produce the noise with the signal(s)

LDC production pipelines

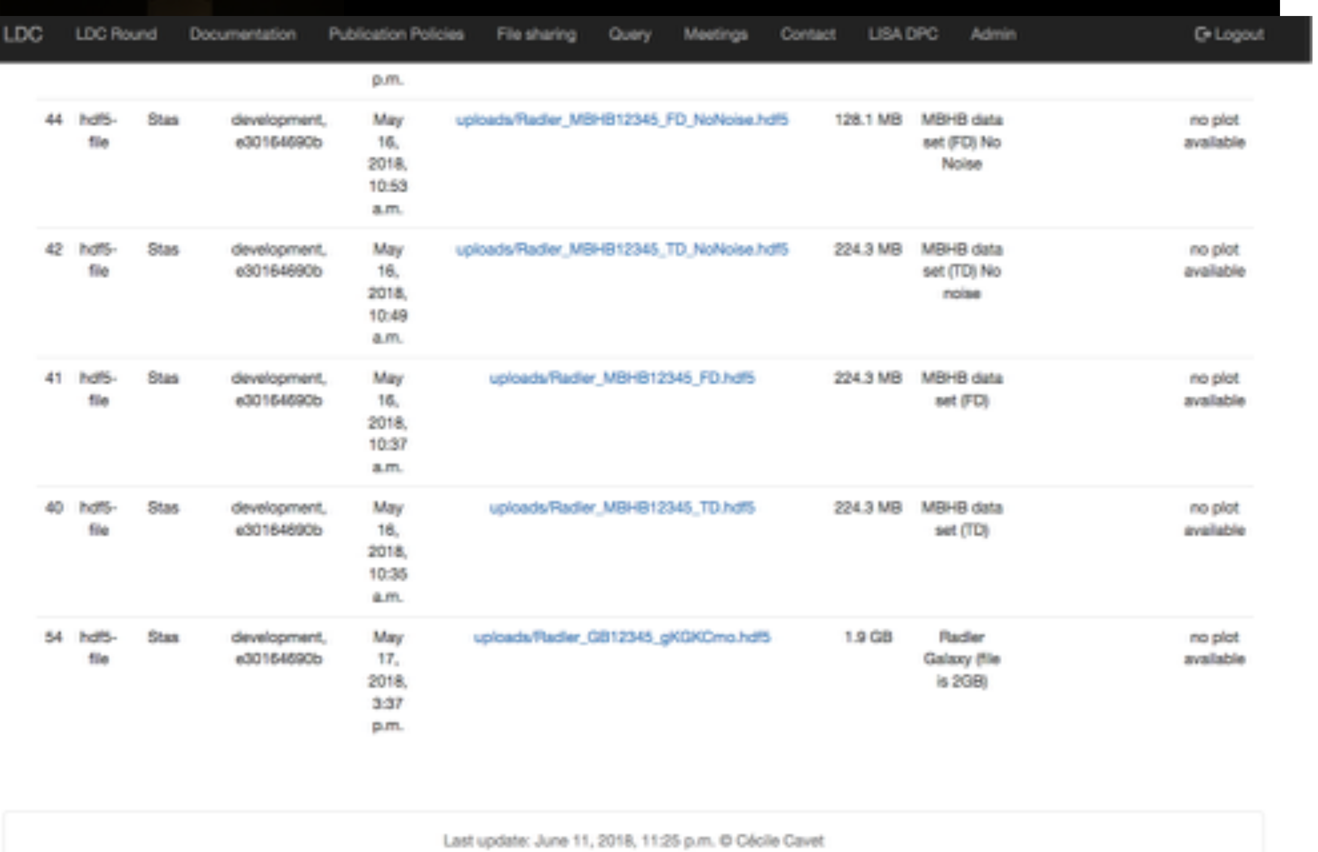


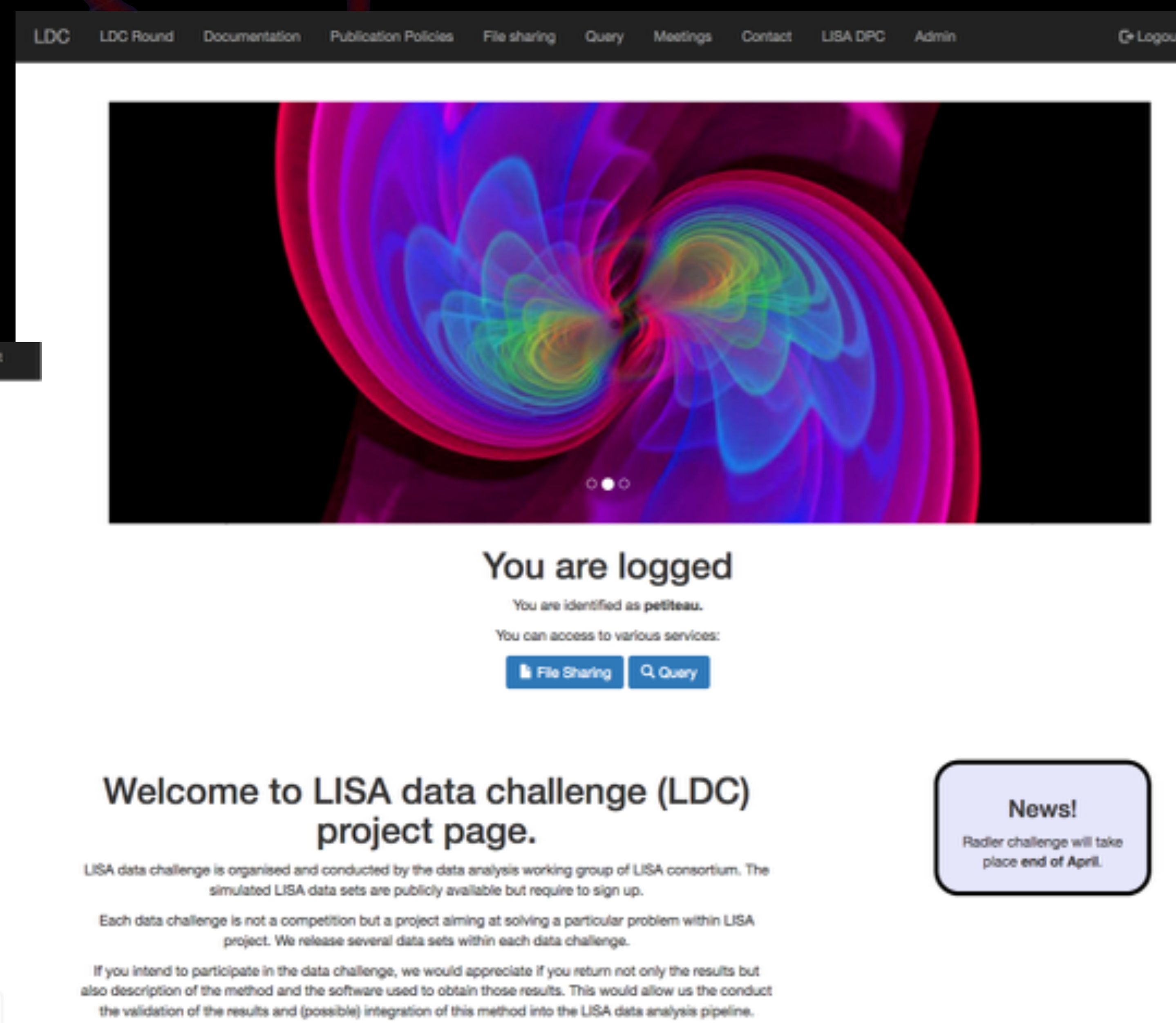
Tools for the LDC from LDPG

- Webpage connected to a data base:

  https://lisa-ldc.lal.in2p3.fr/

  - Upload/download the data
  - Description
  - Web portal





Tools for the LDC from LDPG

- Repository: gitlab.in2p3.fr:stas/MLDC (registration required)
  - Codes
  - Continuous Integration to run
    - tests
    - build documentation
    - build docker image
  - Wiki
  - Issues
  - Features

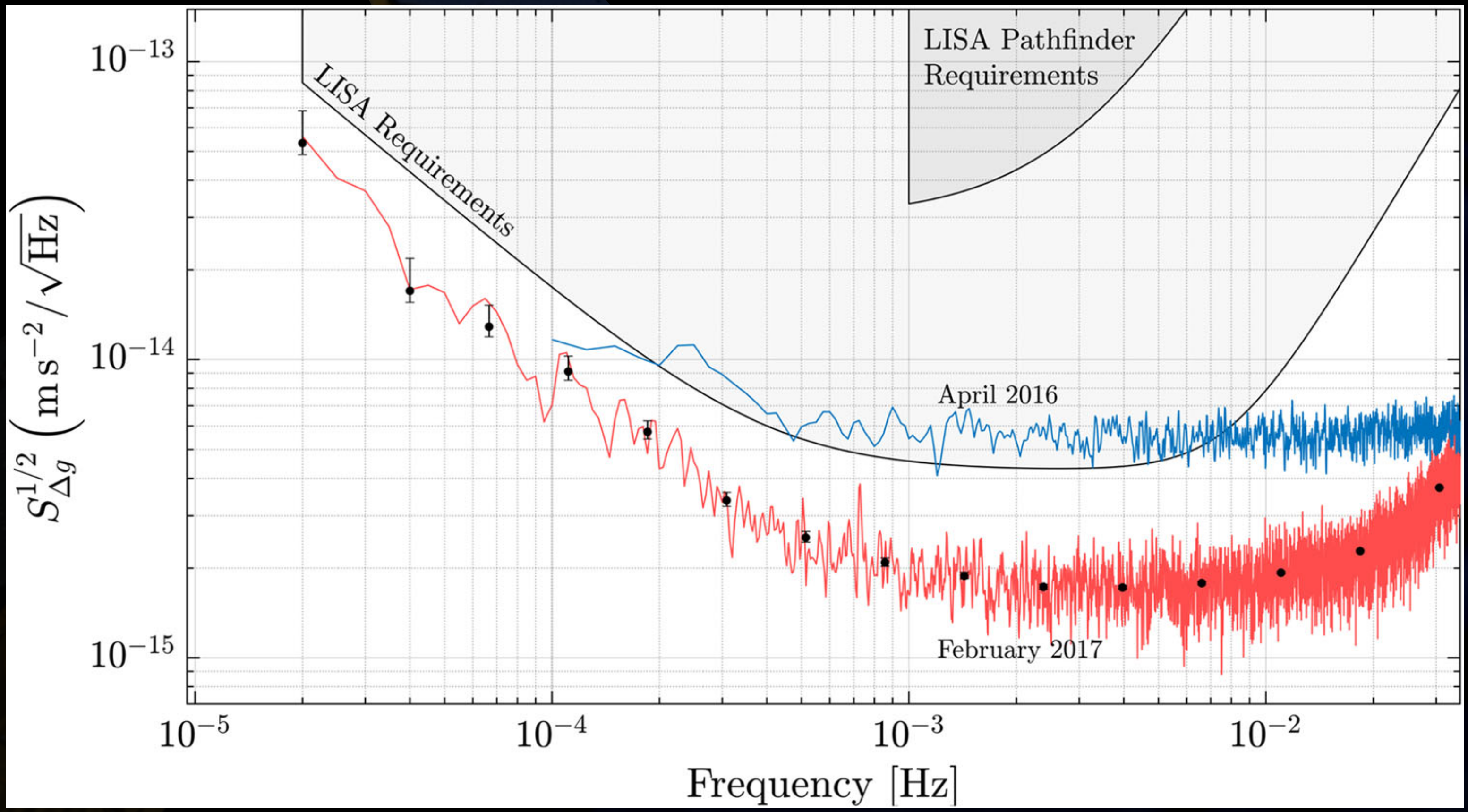
Tools for the LDC from LDPG

- Repositories:
  - git
  - database
- The core pipeline:
  - hdf5 for data
  - steps for producing data:
    - Choose sources
    - Generate waveform
    - Configure instrument
    - Configure noises
    - Run simulations
- Users:
  - docker
  - singularity
  - jupyter
  - jupyterhub (soon)
  - singularity hub (soon)
  - documentation
- Developpers
  - docker
  - workflow
  - tests

Example of SGWB analysis 1

Karnesis, Petiteau, Lilley (2019) submitted , arXiv:1906.09027

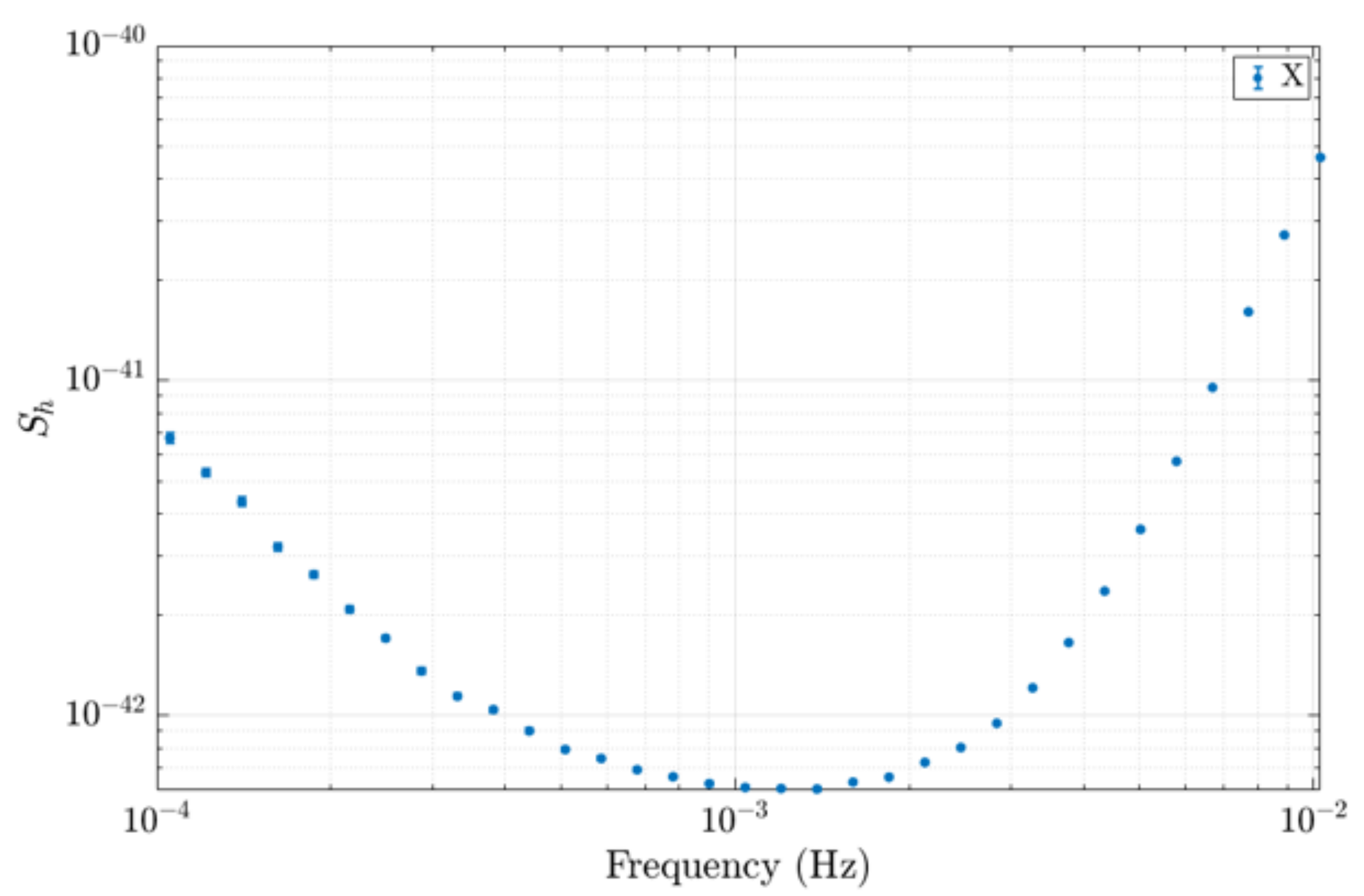
- A methodology adapted/evolved from LPF data analysis: 10.1103/PhysRevLett.120.061101
- Throughout the mission we were measuring a noise excess of unknown origin (no models) at the lower part of the differential acceleration spectrum.
- So, we set up this methodology to estimate this excess for all runs: needed to take into account the variability of the noise, i.e. the Brownian levels, inertial forces, etc.



Example of SGWB analysis 1

Karnesis, Petiteau, Lilley (2019) submitted , arXiv:1906.09027

- The same philosophy can be applied to the TDI channels of LISA, looking for an excess in power that, for the case of Radler, is caused from a SGWB.
- We start by this "ideal case" data (no bright sources, no data artefacts, only isotropic & stationary SGWB) by calculating the logPSD.
- Equally spaced bins in frequency i, different number of averages for each bin N_i.



Example of SGWB analysis 1

Karnesis, Petiteau, Lilley (2019) submitted , arXiv:1906.09027

- Then, if D is the data averaged power spectrum (logPSD), we get

O M Solomon, Jr. Psd computations using welch's method. [power spectral density (psd)]

$$p(\overline{D}_k|\vec{\theta}_{\rm n}, S_{\rm m}) = \frac{e^{-\frac{\sum_{j=1}^{N} D_{k,j}}{S_{\rm m}}}}{S_{\rm m}^N} = \frac{e^{-N\frac{\overline{D}_k}{S_{\rm m}}}}{S_{\rm m}^N}$$

- Where S_m is the theoretical power spectrum we are interested in. Then if we assume

$$S_{\rm m}[i] = S_{\rm o}[i] + S_{\rm n}[i, \vec{\theta}_{\rm n}]$$

and that we have a prior knowledge of S_n around ε, we can try to marginalise it out by

$$p(\overline{D}_k|\vec{\theta}_{\rm n}, S_{\rm n}, S_{\rm o}) \propto \int_{\bar{S}_{\rm n}-\epsilon}^{\bar{S}_{\rm n}+\epsilon} \frac{e^{-N\frac{\overline{D}_k}{S_{\rm o}+S_{\rm n}}}}{(S_{\rm o}+S_{\rm n})^N} {\rm d}S_{\rm n}$$

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- Then, taking into account the definition of Gamma functions, we can derive the posterior of the underlying signal as

$$p(S_{\mathrm{o}}|\overline{D}_k, S_{\mathrm{n}}) \propto \left(\Gamma_{N-1}\left(A^+\right) - \Gamma_{N-1}\left(A^-\right)\right)$$

with

$$A^{\pm} = \frac{N\overline{D}_k}{\bar{S}_{\mathrm{n}} + S_{\mathrm{o}} \mp \epsilon},$$

We can then sample the posterior via MCMC, or simply map it with a grid. Reminder: this is per frequency bin, so we estimate $S_o(f_i)$.

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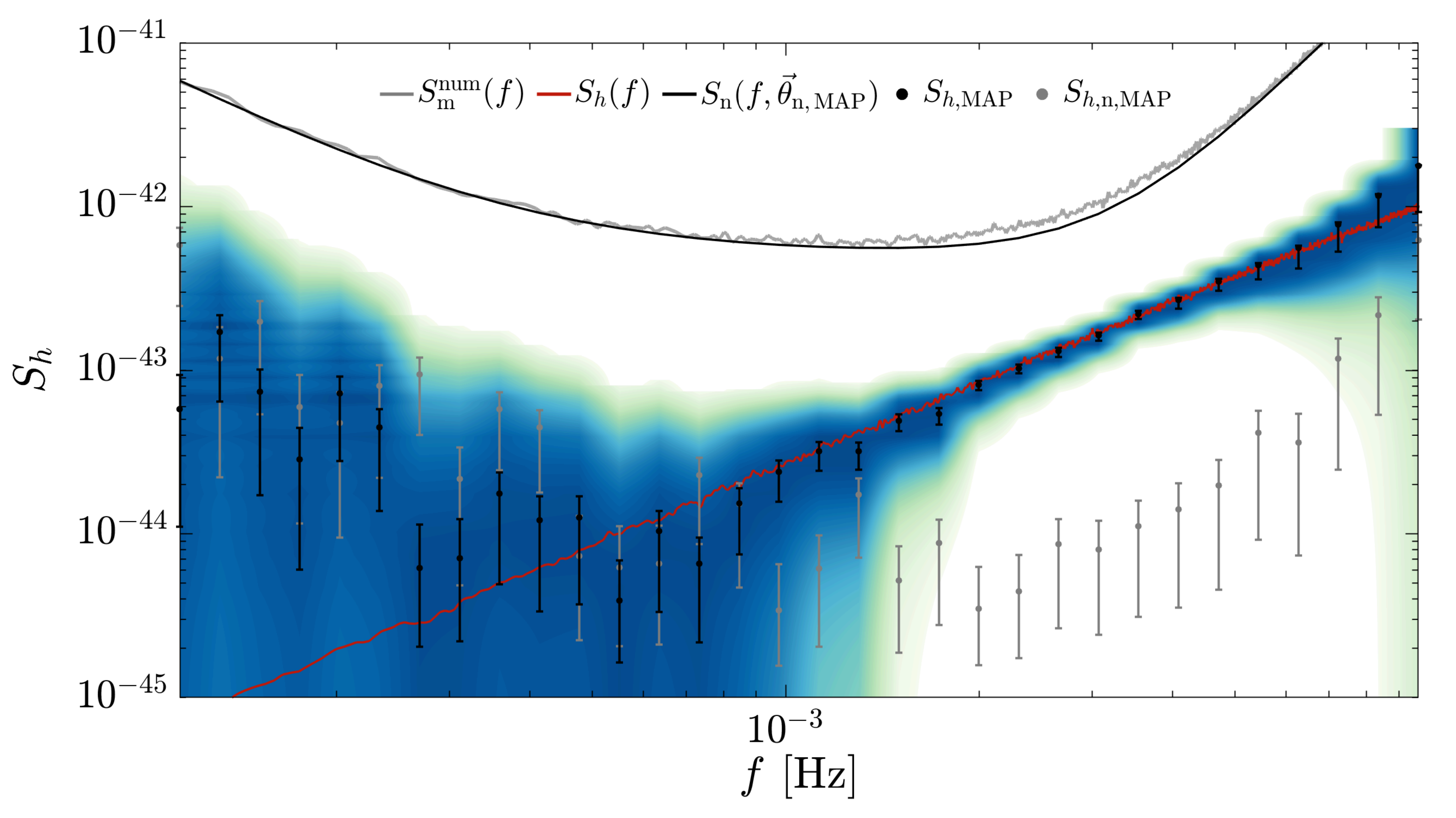


Example of SGWB analysis 1

Karnesis, Petiteau, Lilley (2019) submitted , arXiv:1906.09027

- We can go a little further, and try to assess the detectability of a given signal, depending on our level of knowledge of the noise PSD (parametrised by ε).

- Bayes factor:
  - M1: Instrumental noise + SGWB signal
  - M0: Instrumental noise only

- Since we have nice closed forms of the posteriors, we marginalise so that:

$$\mathcal{B}_{10}(\epsilon) = \frac{P(\bar{D}|\mathcal{M}_1)}{P(\bar{D}|\mathcal{M}_0)} = \frac{\bar{D}N\left(\Gamma^{+}-\Gamma^{-}\right)}{(N-2)(\bar{D}-S_{\mathrm{n}})(\Gamma^{-}-\Gamma^{+})} + \frac{\bar{S}_{\mathrm{n}}+\epsilon}{\bar{D}-\bar{S}_{\mathrm{n}}} + \frac{2\epsilon(N-2)\left(\Gamma_{N-2}(N)-\Gamma^{-}\right)}{(N-2)(\bar{D}-\bar{S}_{\mathrm{n}})(\Gamma^{-}-\Gamma^{+})} \quad (13)$$

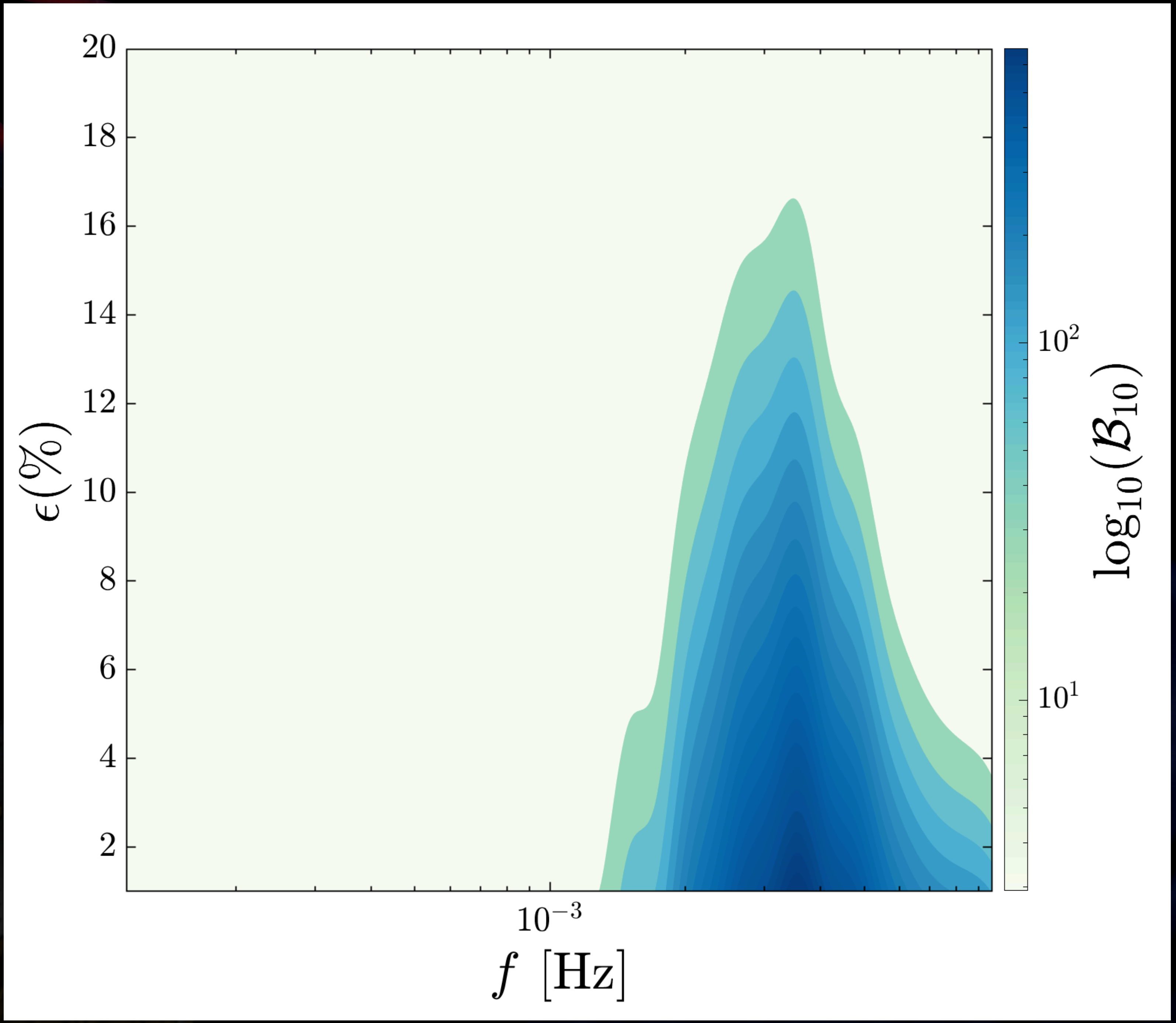
$$\Gamma^{\pm} = \Gamma_{N-2}\left(\left(N\bar{D}\right) / \left(\bar{S}_{\mathrm{n}} \pm \epsilon\right)\right)$$

- In the above expression we know D, S_n, N, and we can play with ε

Example of SGWB analysis 1

Karnesis, Petiteau, Lilley (2019) submitted , arXiv:1906.09027

- Bayes factor as a function of the uncertainty on the noise model



Example of SGWB analysis 1

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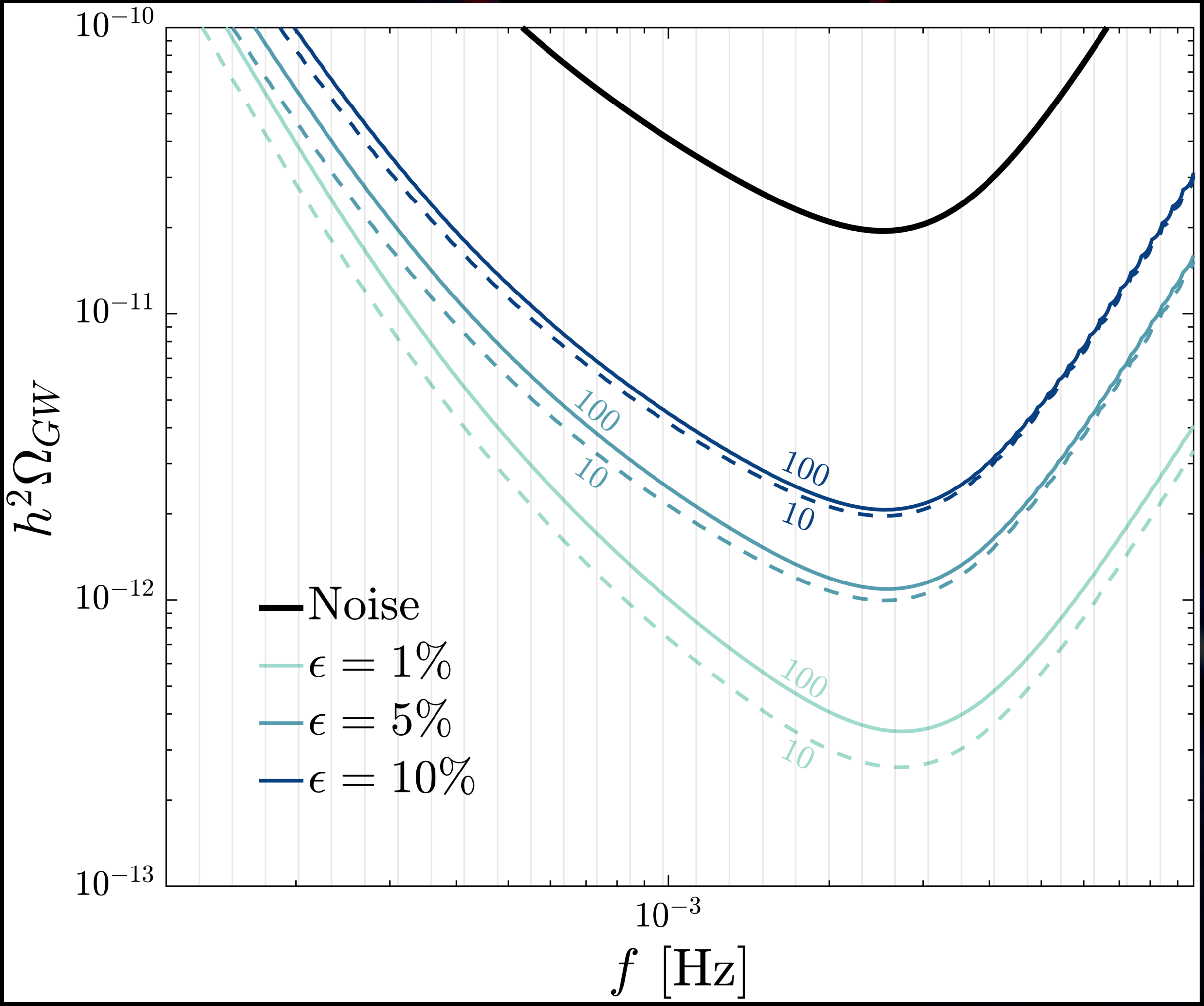
- The logarithm of the Bayes factor as a function of the GW signal power.



Example of SGWB analysis 1

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- To conclude on this example ...
  - Fast and model-free approach to analyse stochastic backgrounds.
  - It can be a very useful tool to quickly assess the detectability of a given model given the LISA noise uncertainty.
  - It can be used in combination with other methods for dealing with the foreground noises.
  - It can be very useful for helping us define priors for models based searches.

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: physic, astrophysics, cosmology, ...
- LISAPathfinder: success
  - Performances > 7 times better than the requirements
- LISAPathfinder + detections of Ground-based observatories

  => Green light for LISA: complementarity with PTA and LIGO/Virgo

  => speed-up of the ESA planning:
  - Done: call for mission, selection, phase 0
  - Now:
    - Phase A => on time for 2032-2034 !
    - Adoption 2023 => busy time because all scientific studies have to be

Thank you !