LISA

Observing GW Universe from space

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(APC - Université de Paris)

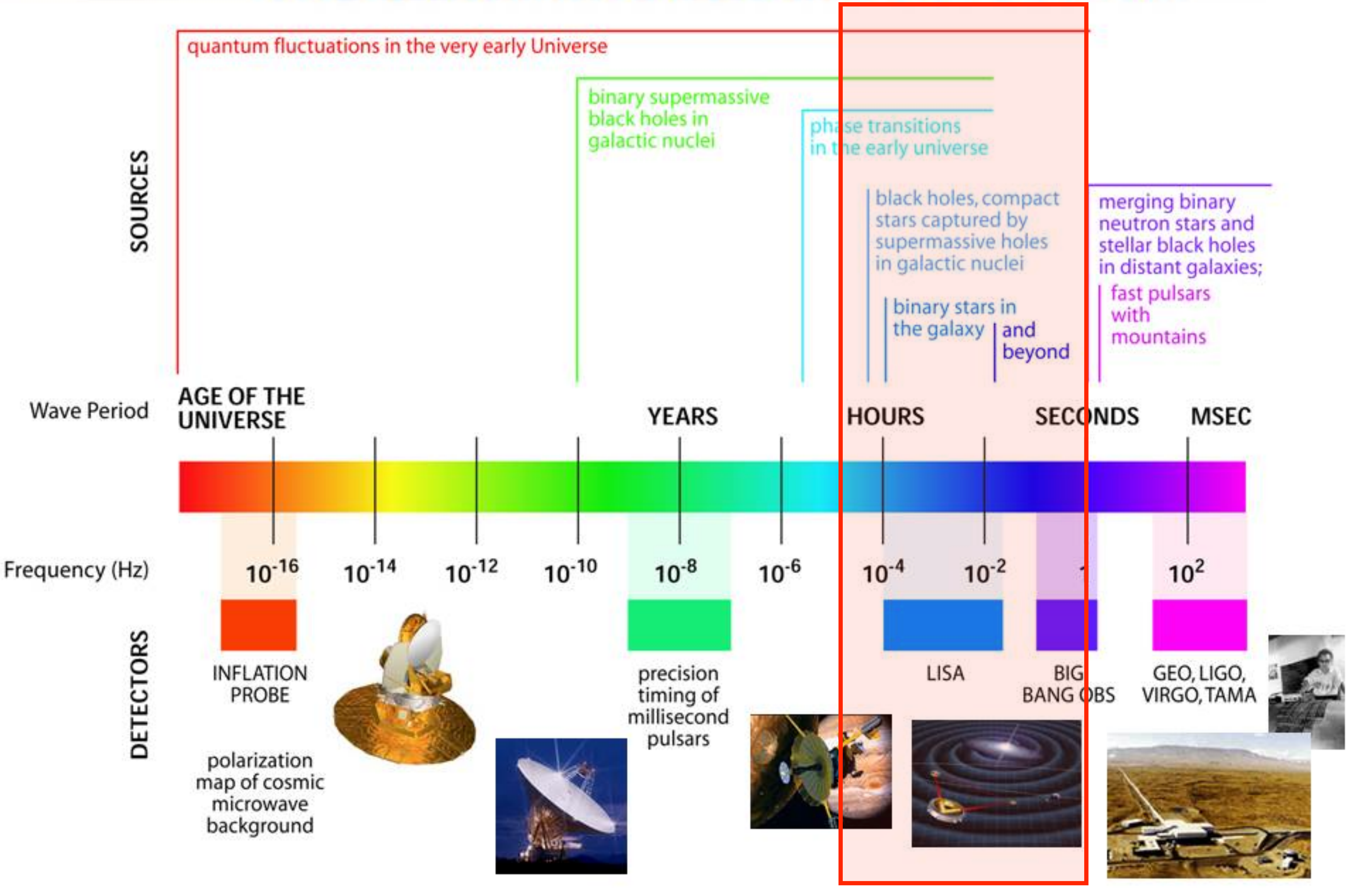
Workshop GW Probes of Physics Beyond Standard Model

Remote - 16th July 2021

Overview

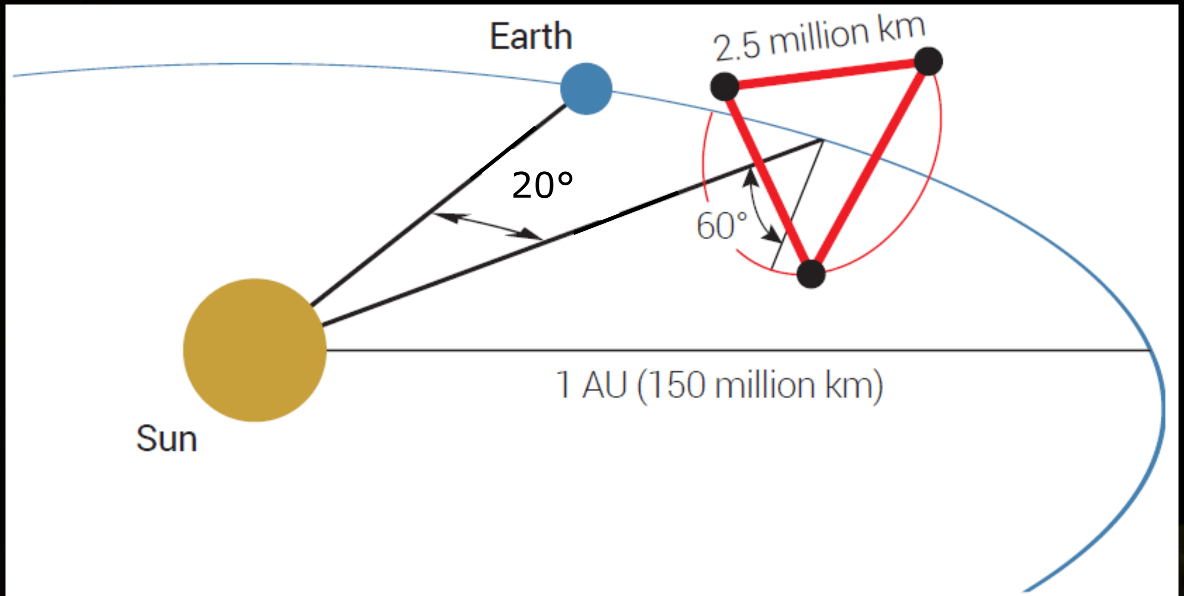
- Instrument
  - Space segment ("hardware")
  - Ground segment ("data processing")
- GW Science with LISA
- Organisation and status

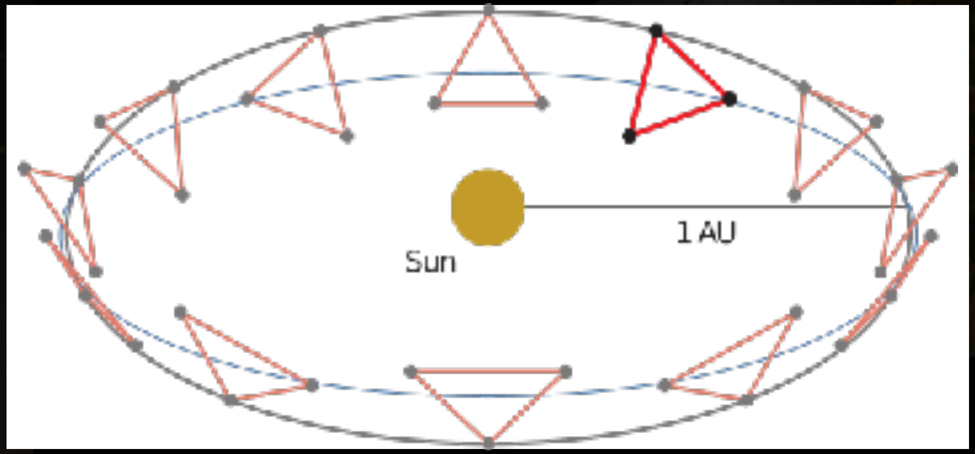
THE GRAVITATIONAL WAVE SPECTRUM

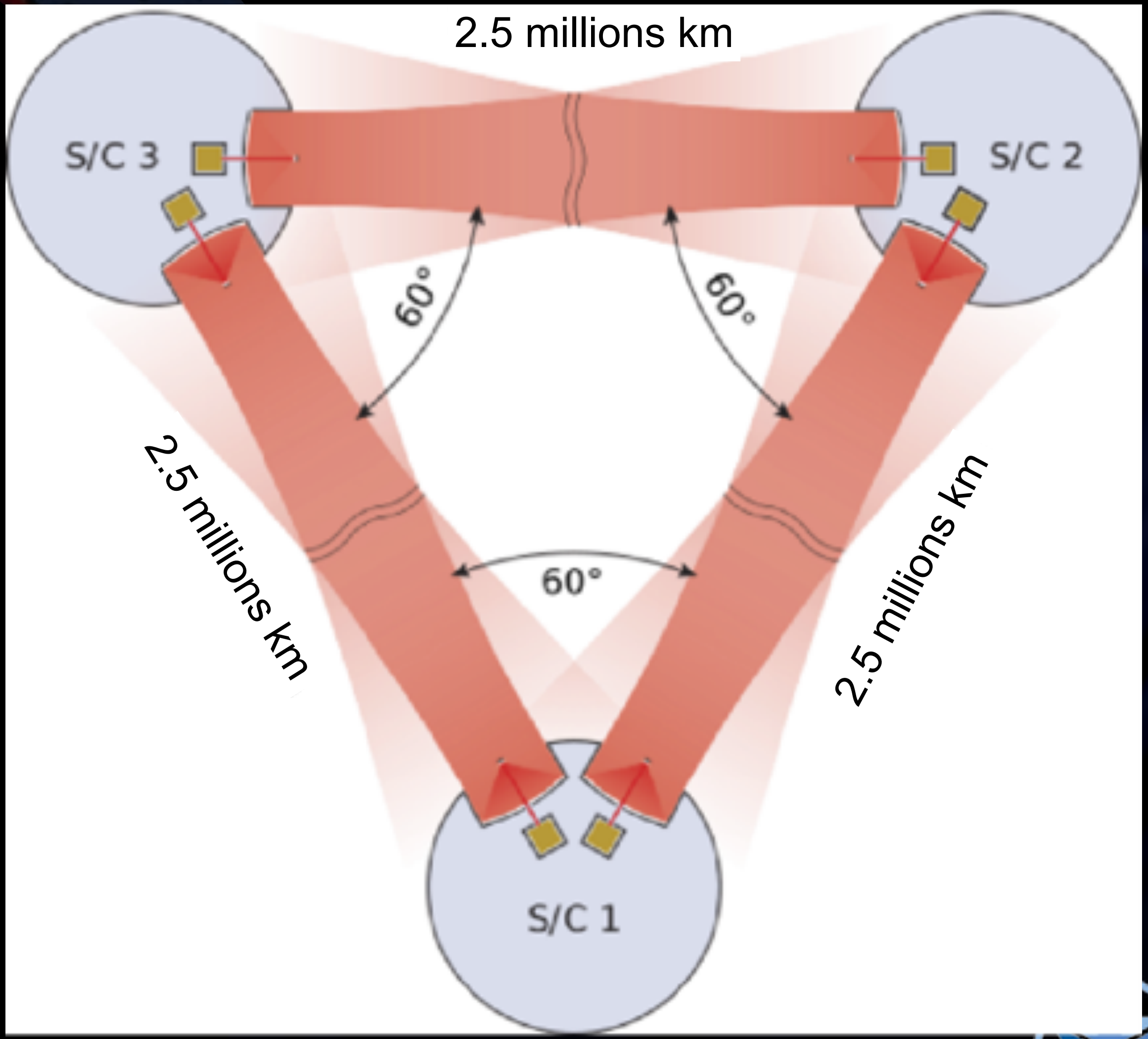


LISA mission

- 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

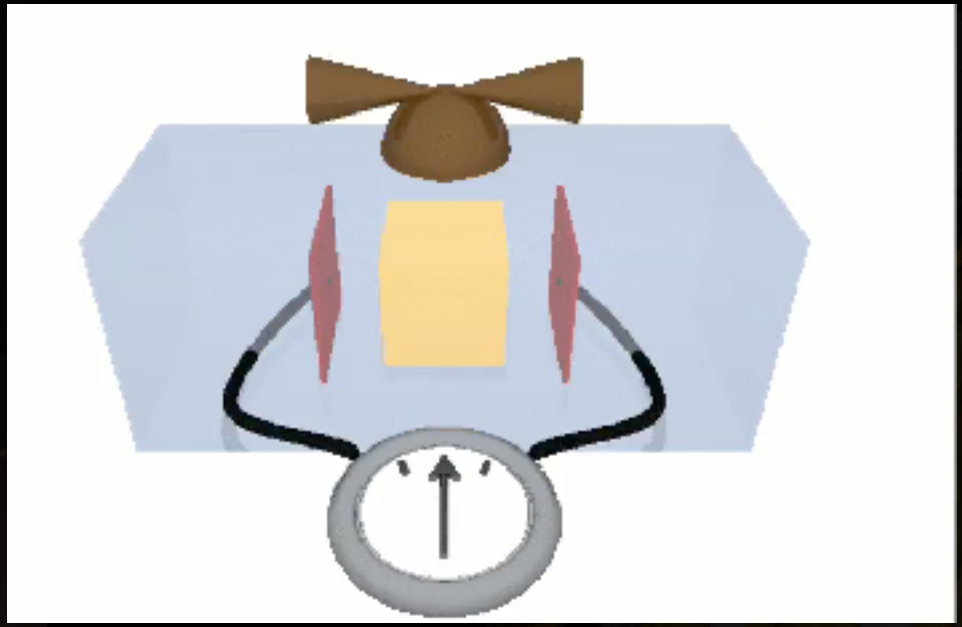


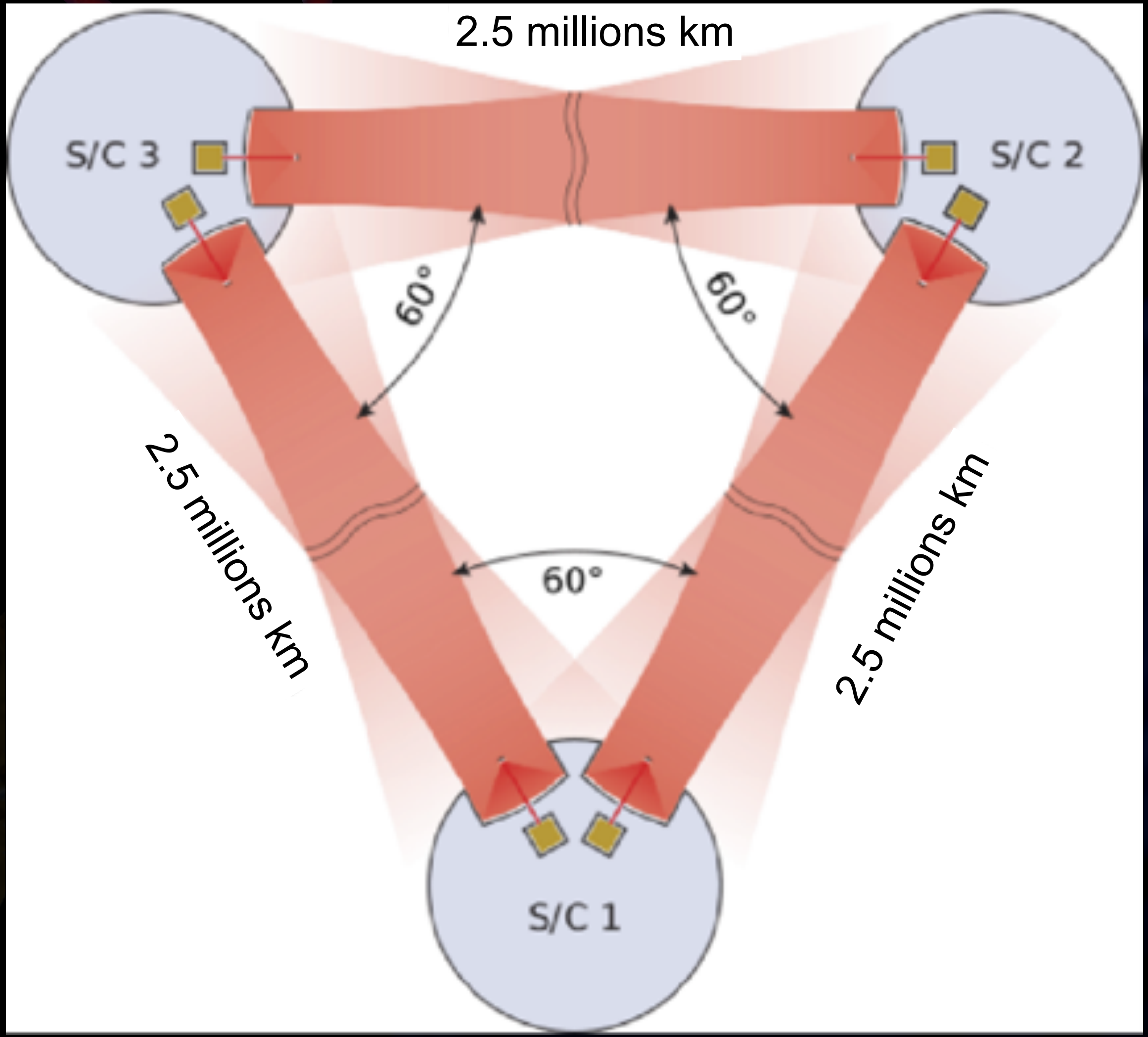




Being sensitive "only" to gravity

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





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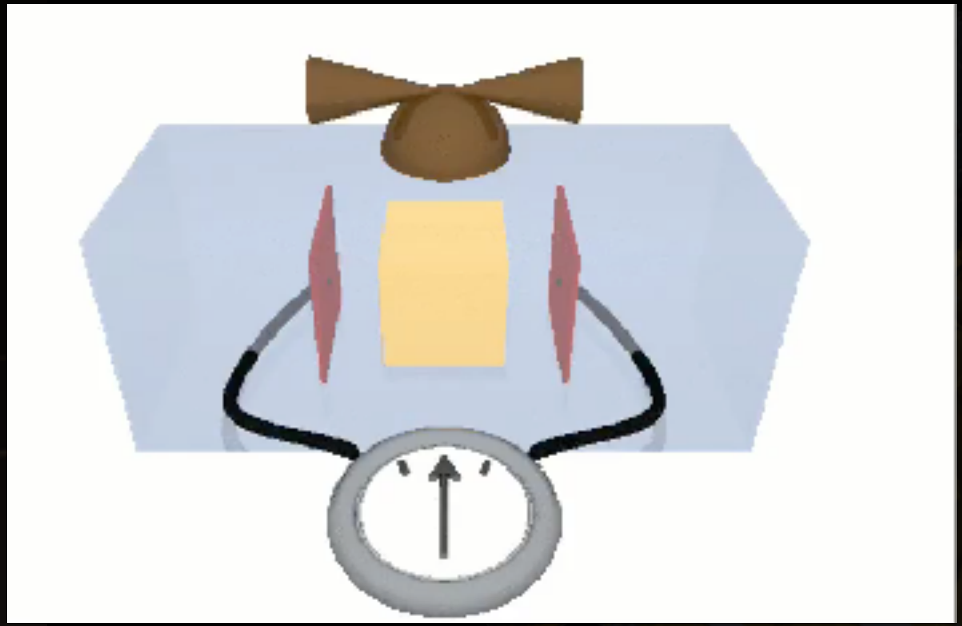
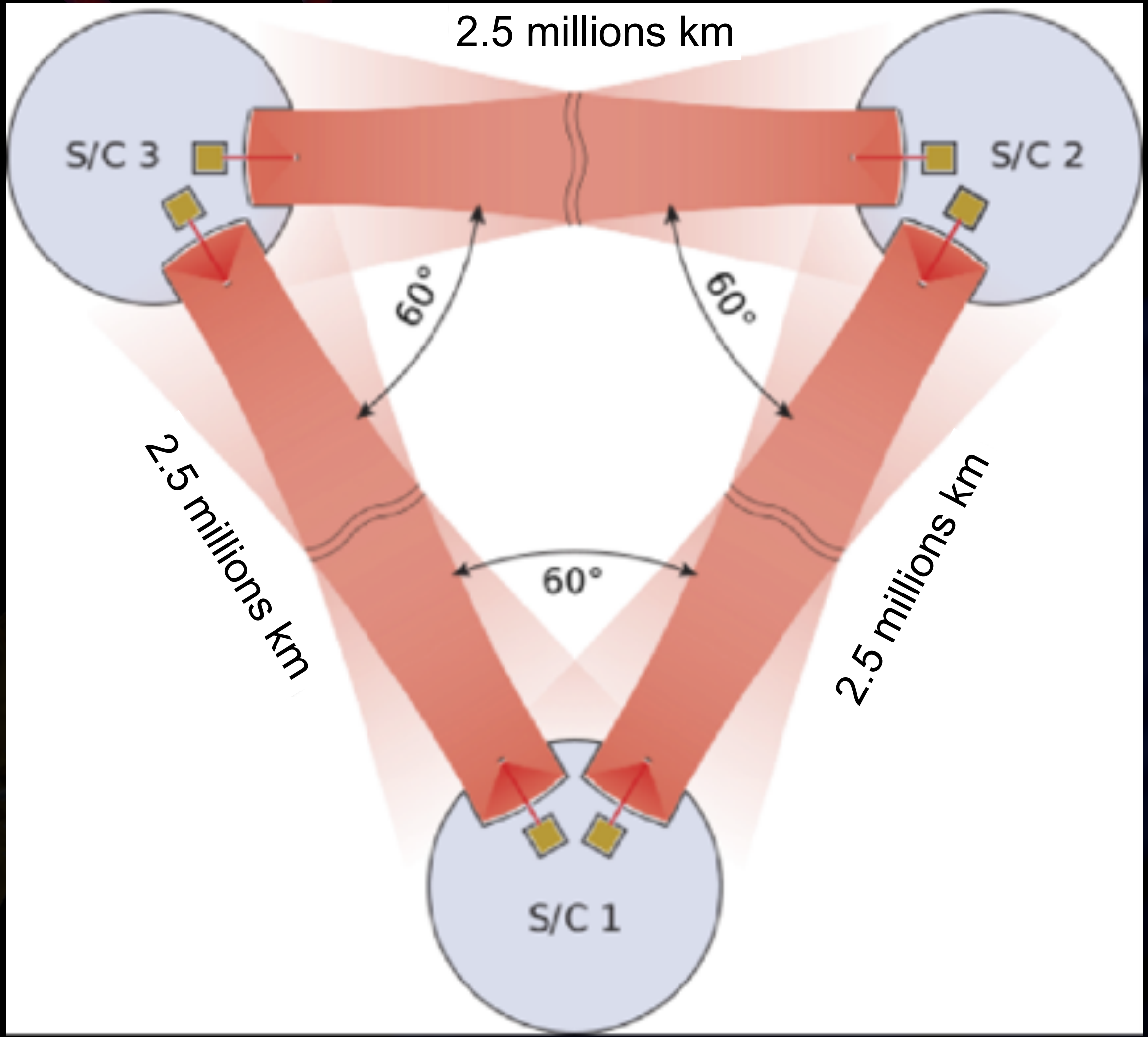
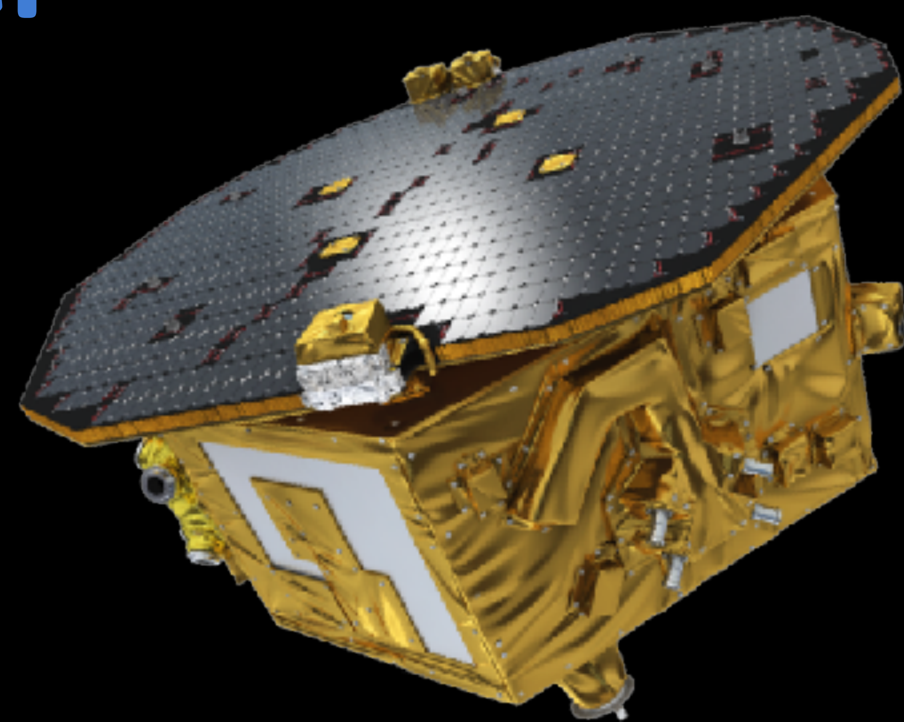




LISAPathfinder



- Basic idea: Reduce one LISA arm in one SC.
- Operations: March 2016 to June 2017
- LISAPathfinder is testing:
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
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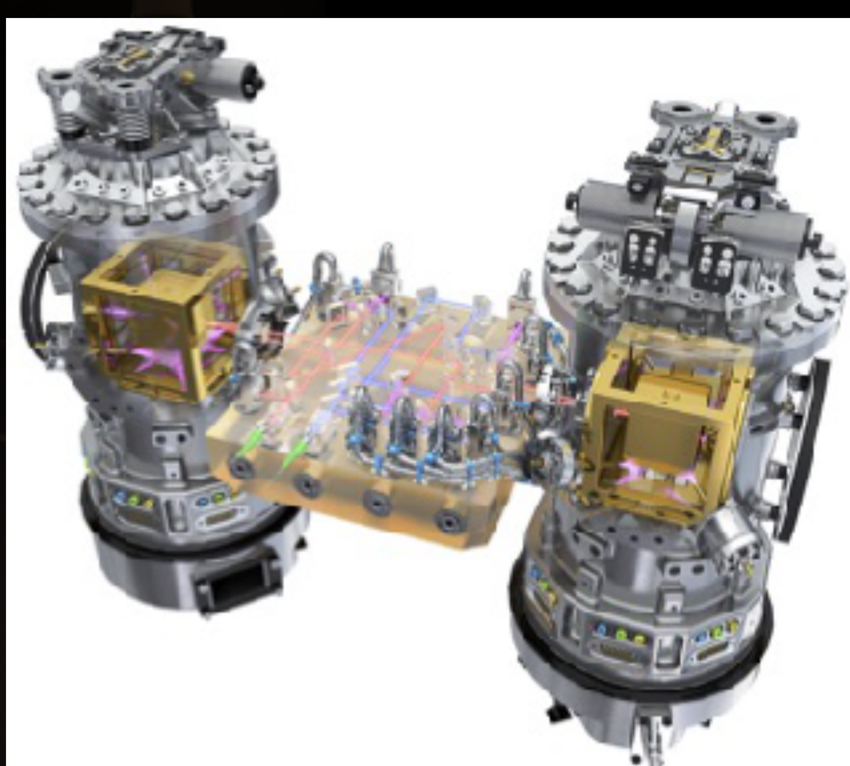

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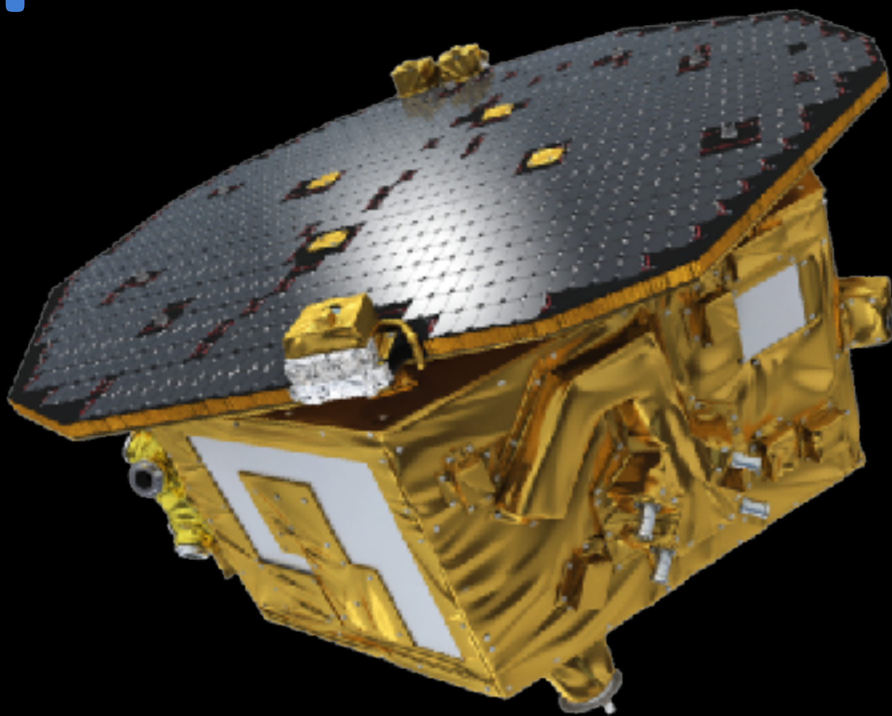

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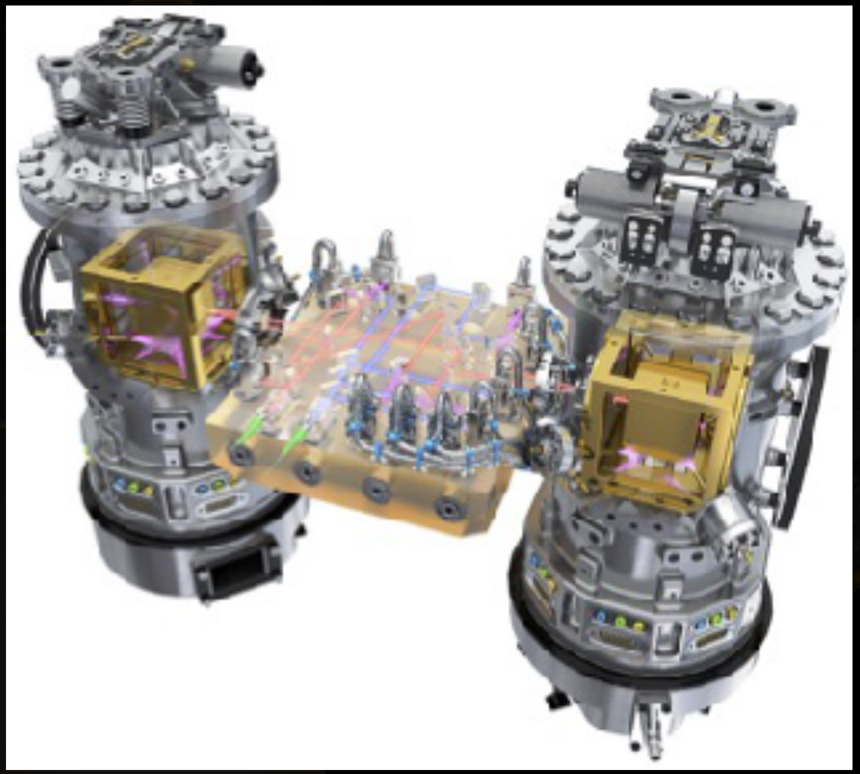
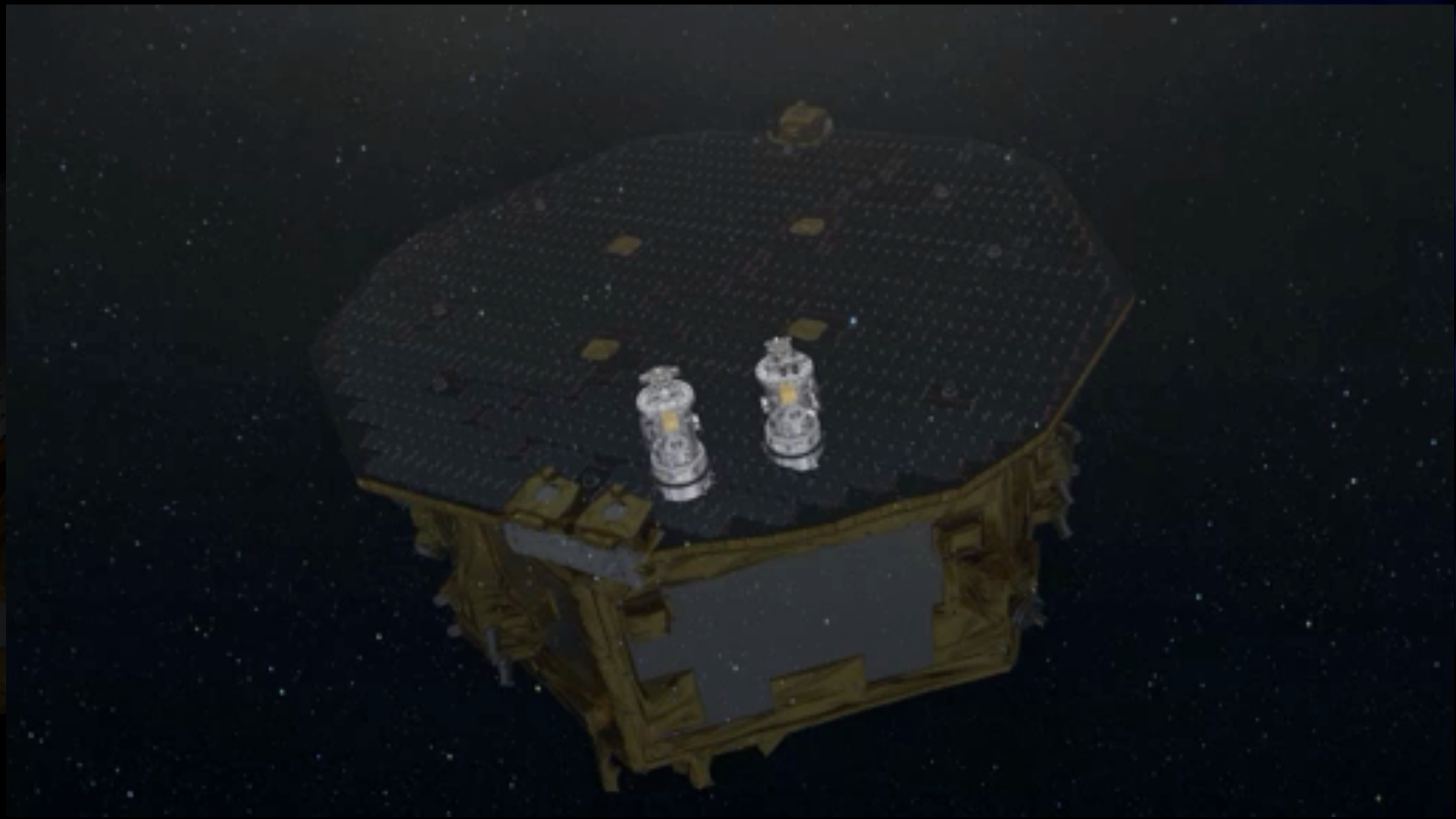
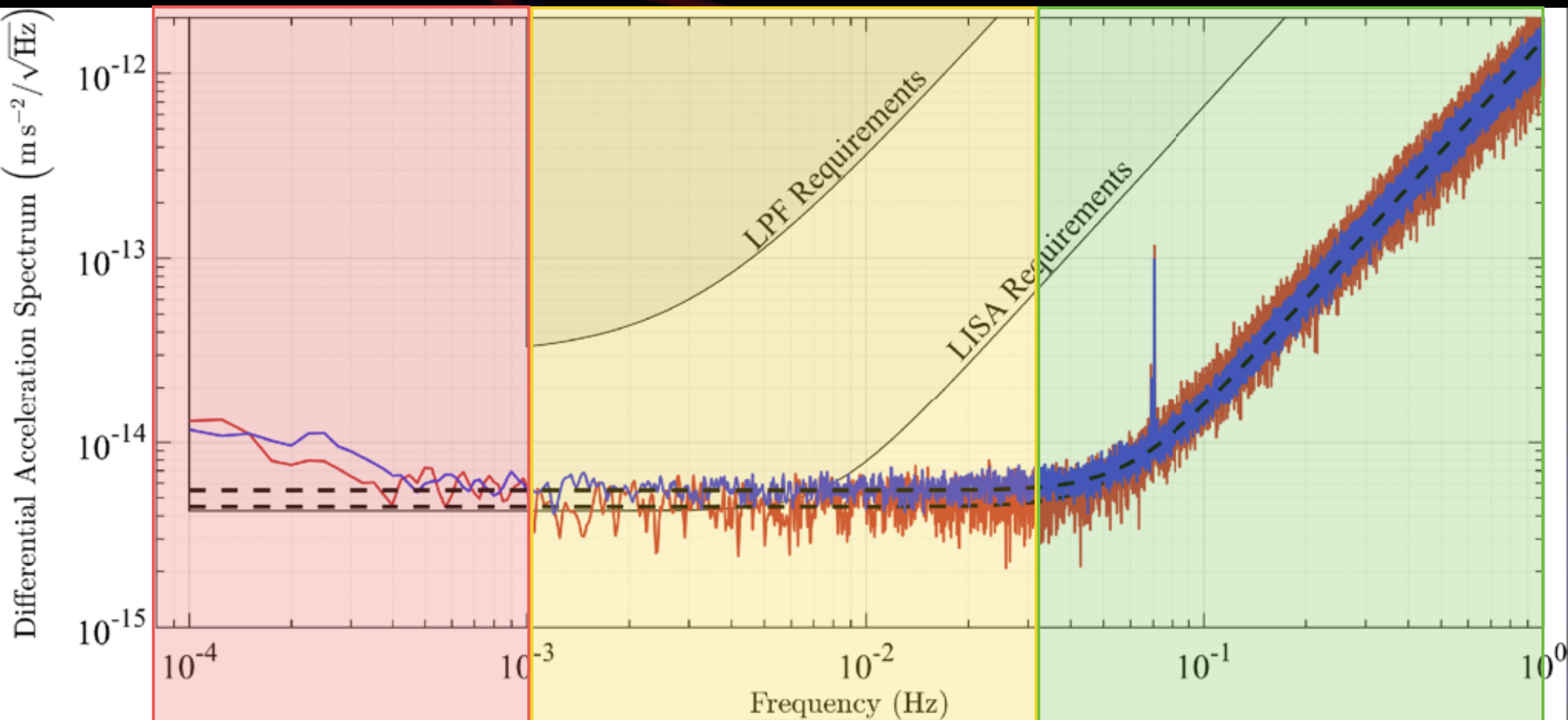




LISA Pathfinder first result

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



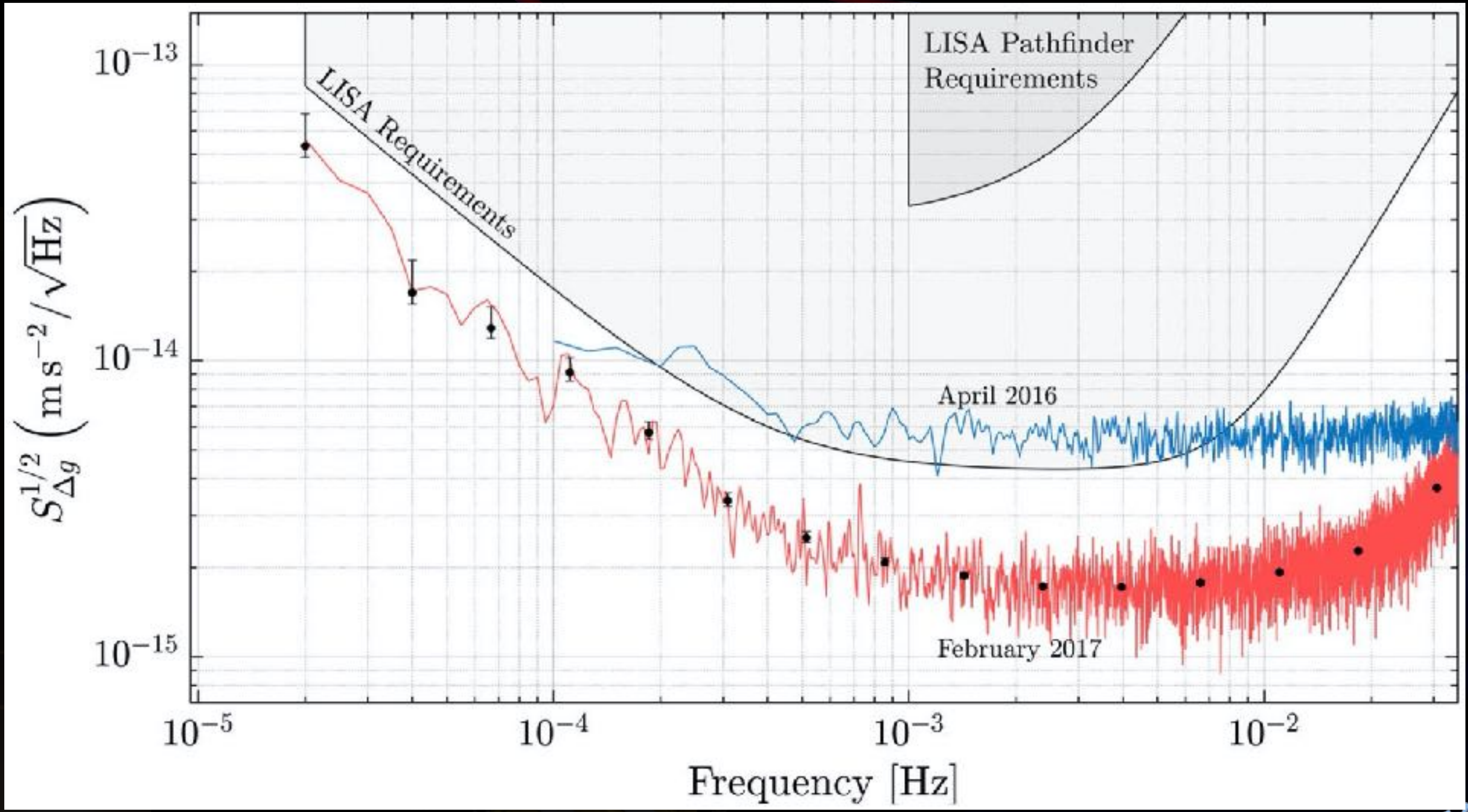
Low frequency noise
Investigation still in progress
...

Brownian noise
Molecules within the noise hit test-masses

Interferometric noise
Not real test-mass motion

LISAPathfinder final main results

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



Interferometric measurements

- Several steps for an extremely precise measurements

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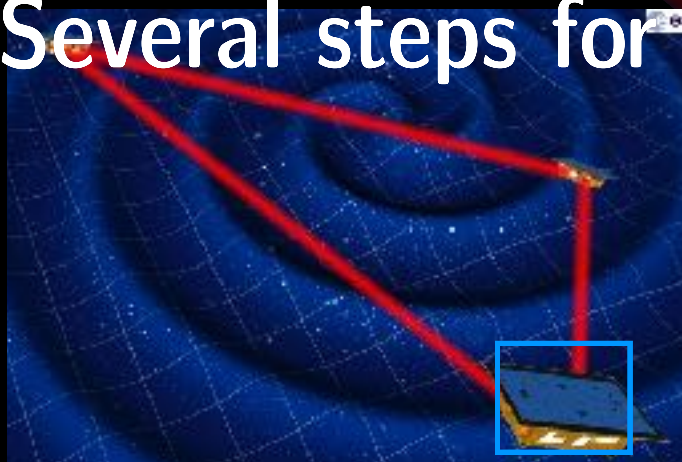

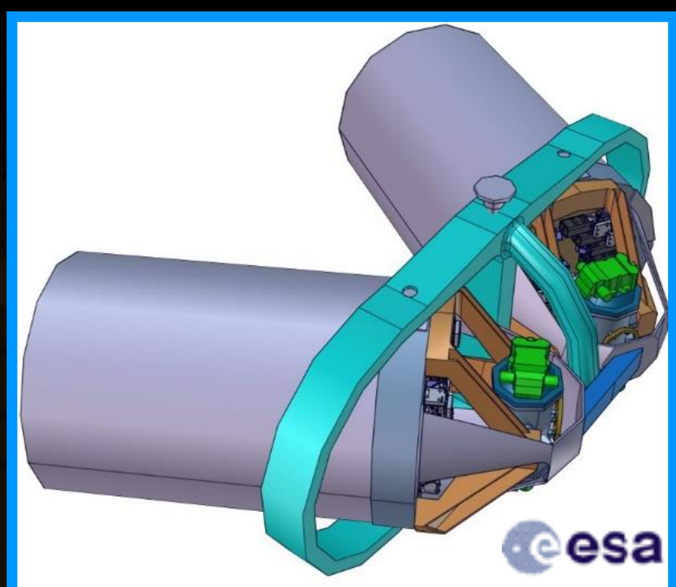

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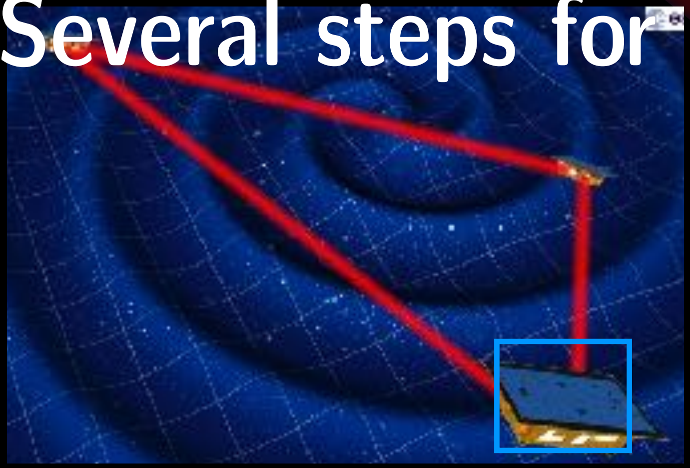

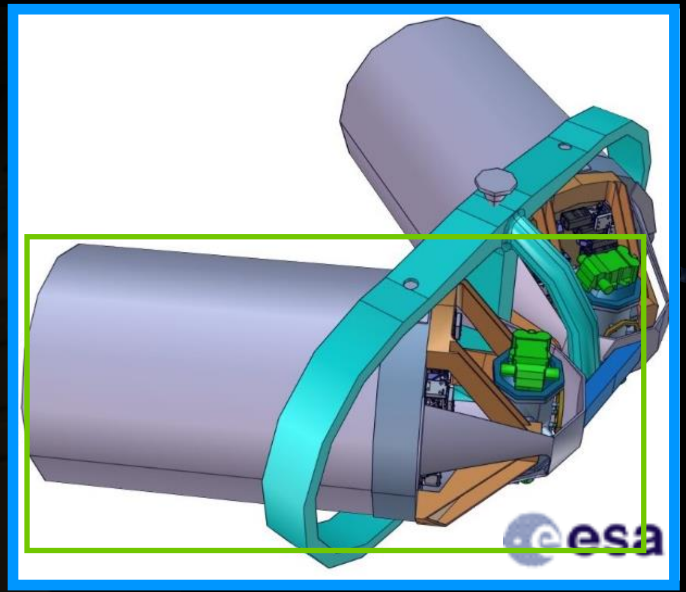

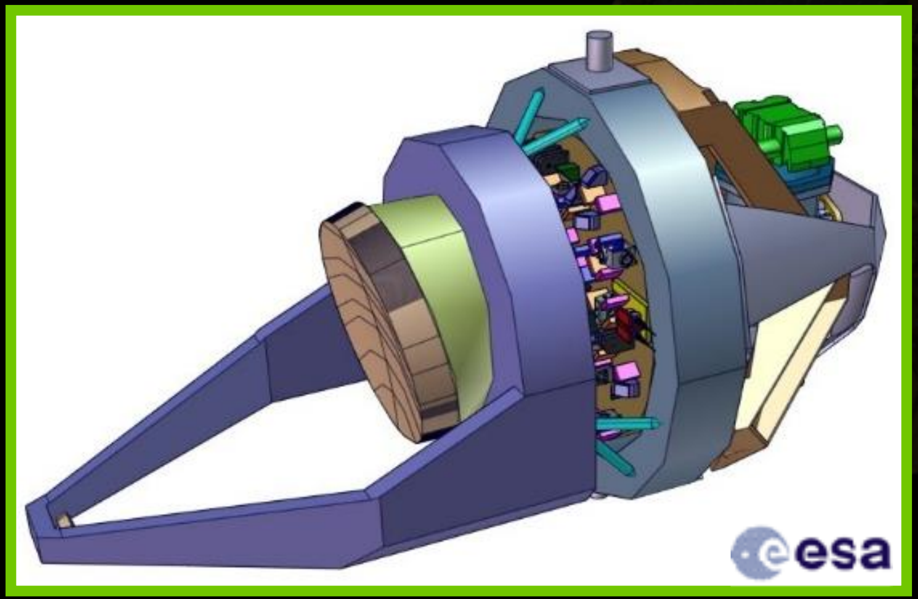

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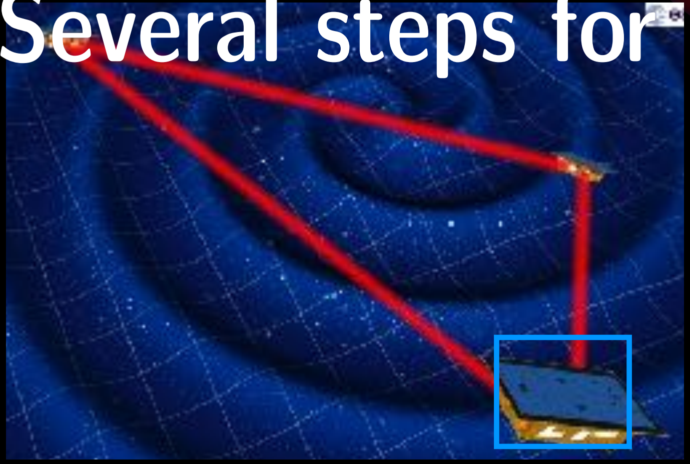

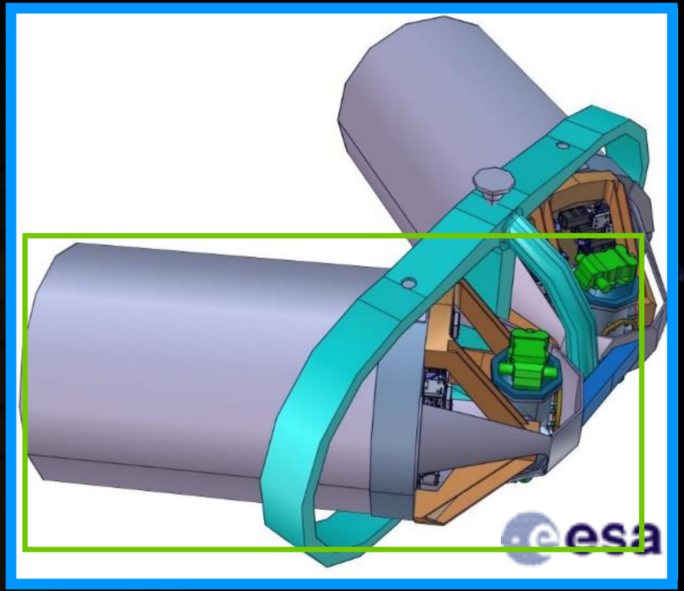

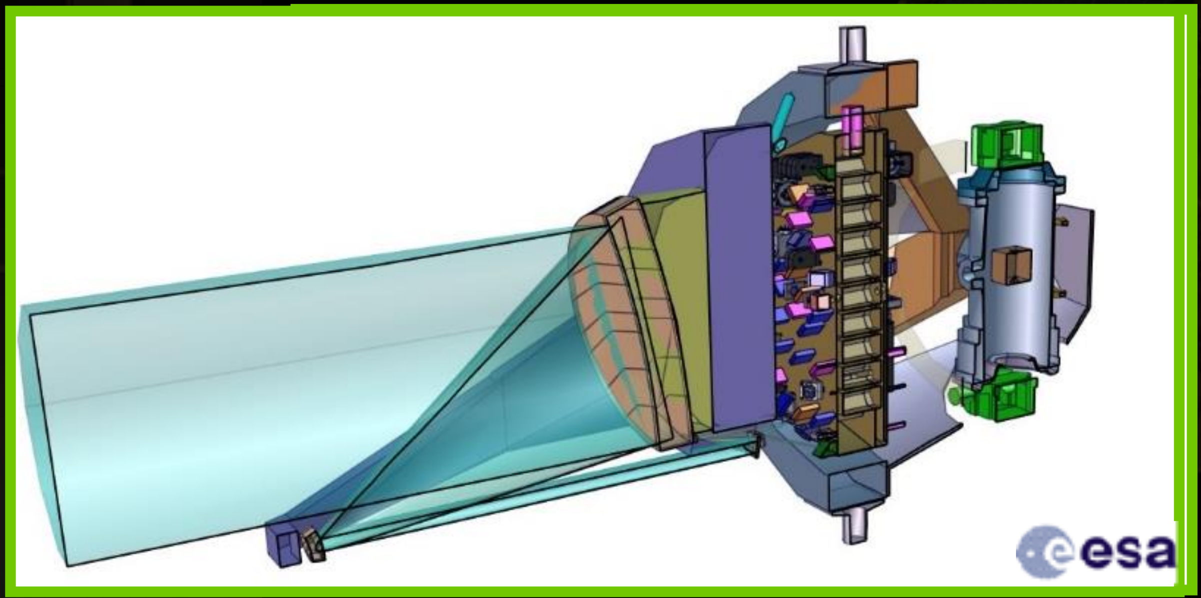

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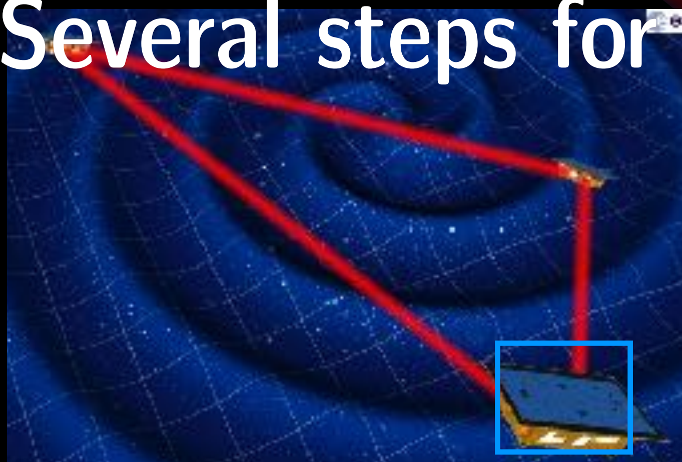
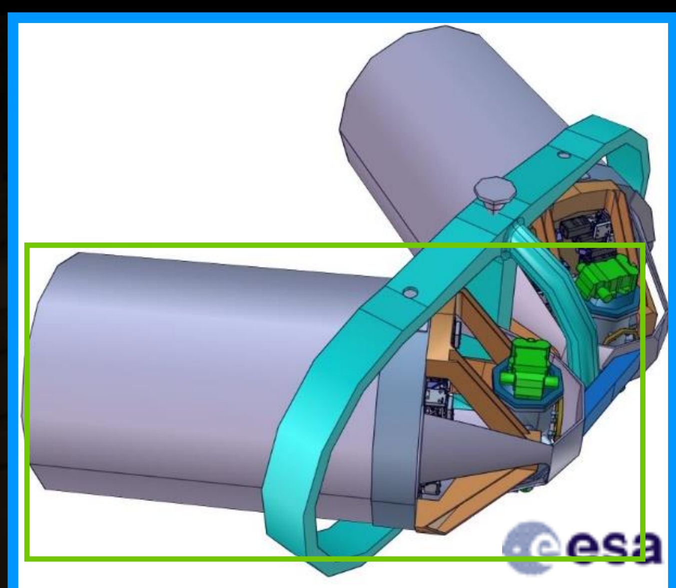
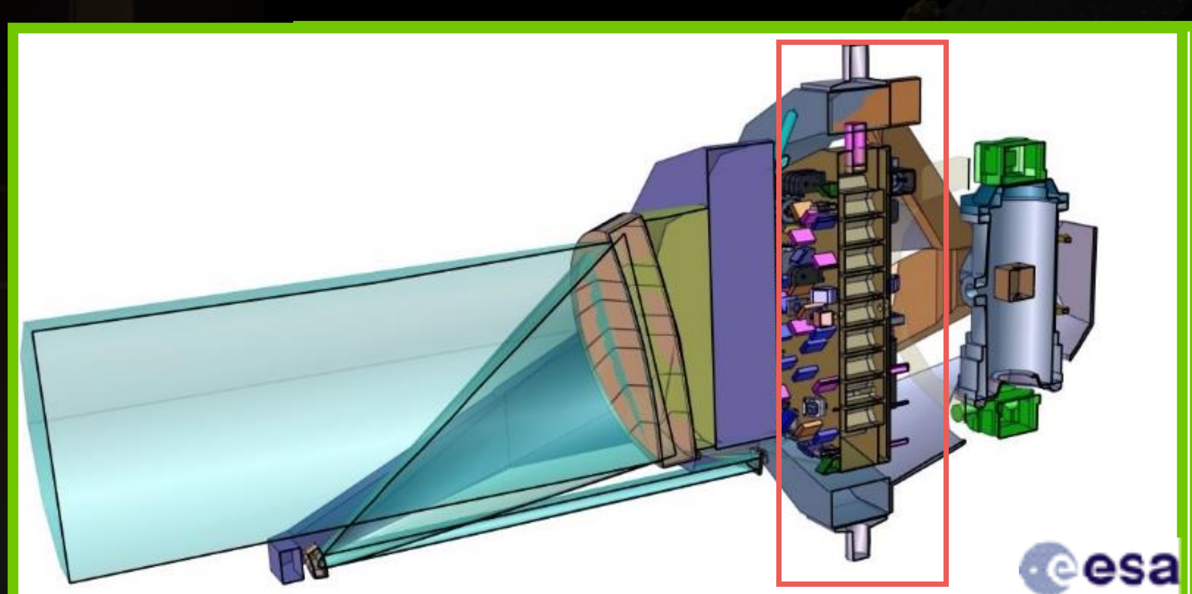
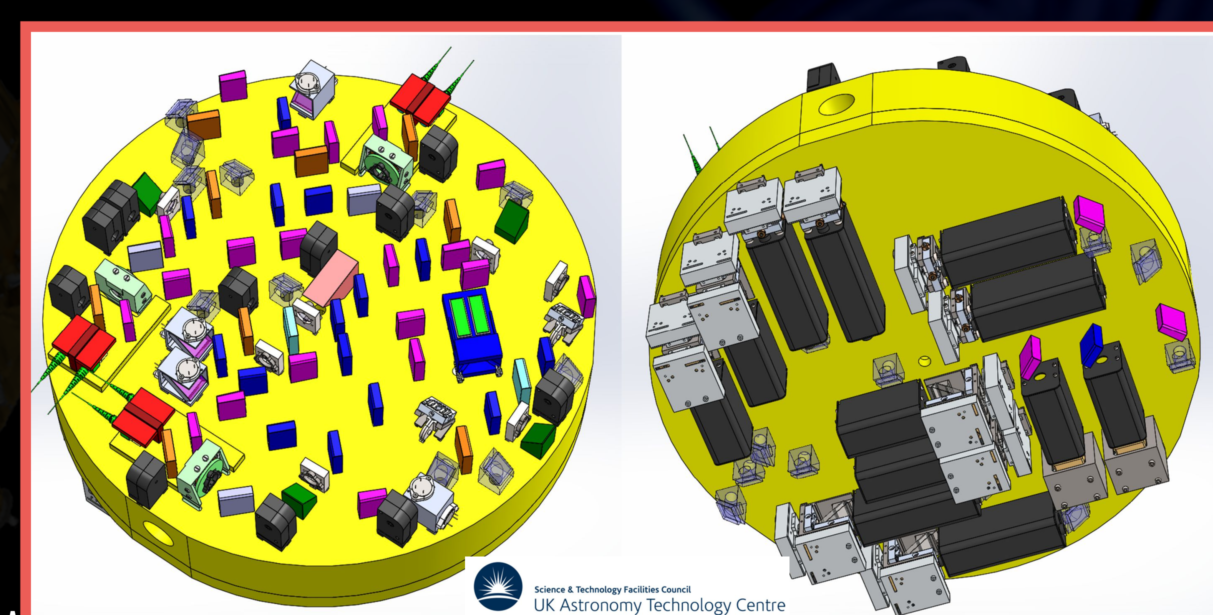


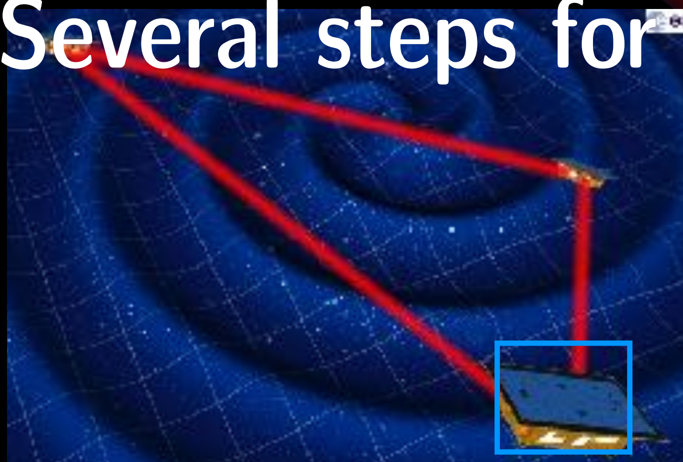


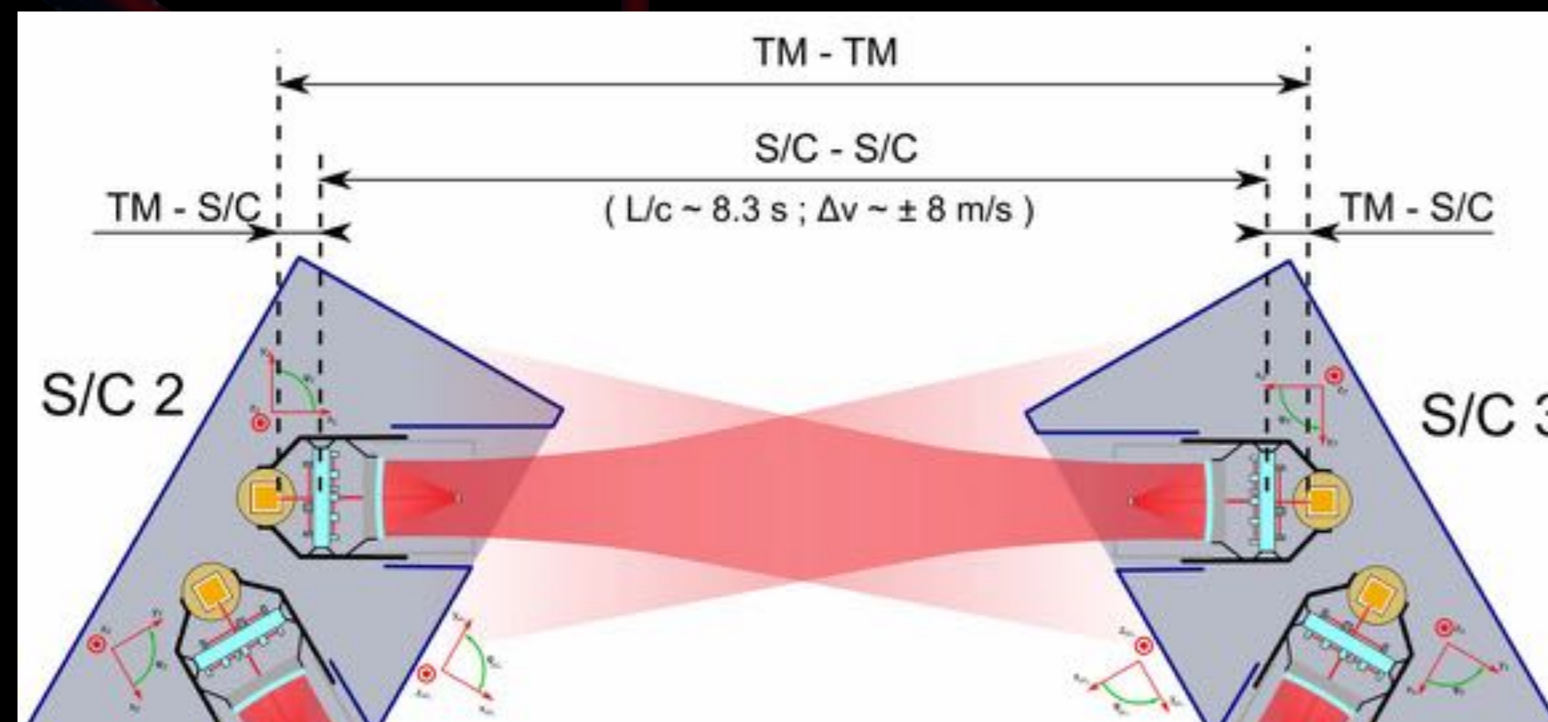


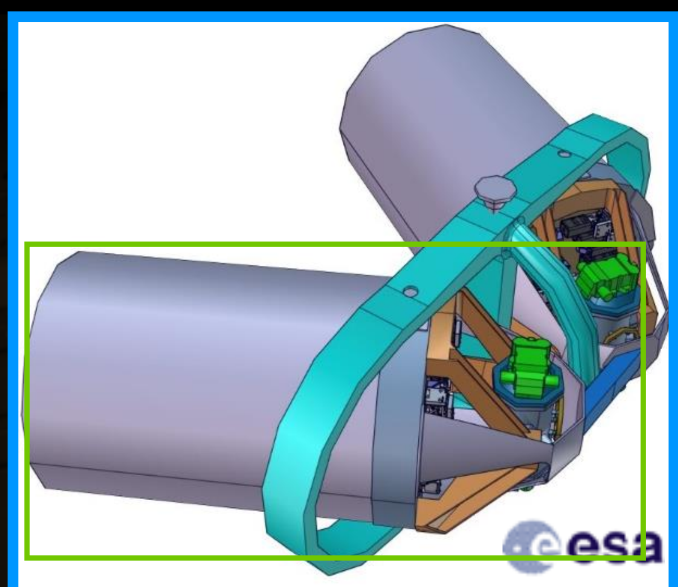


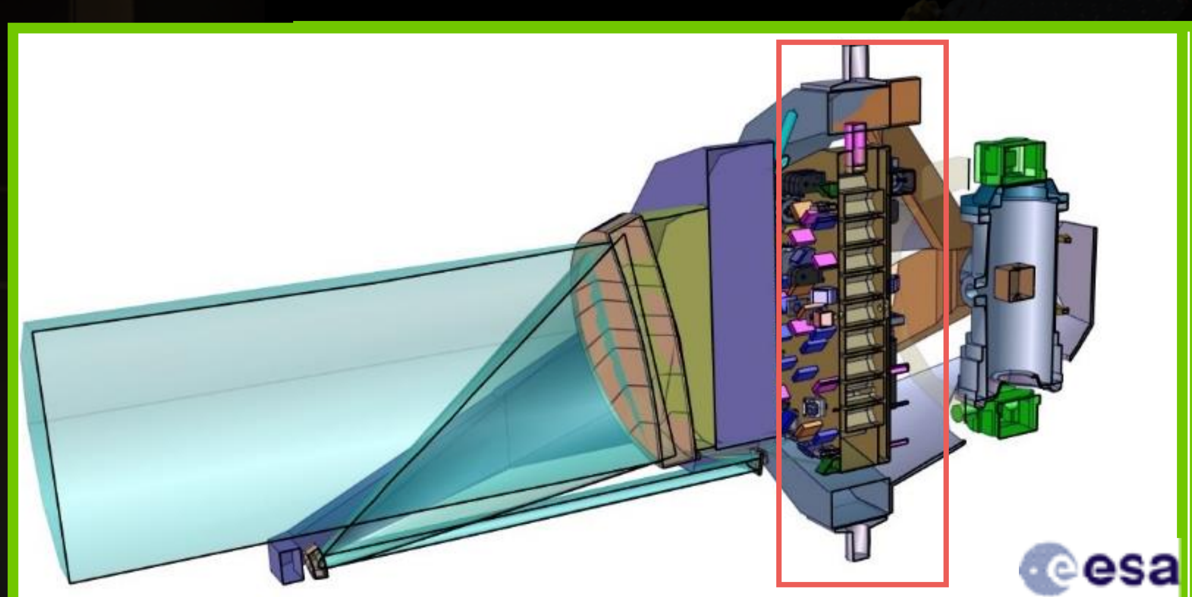
Interferometric measurements

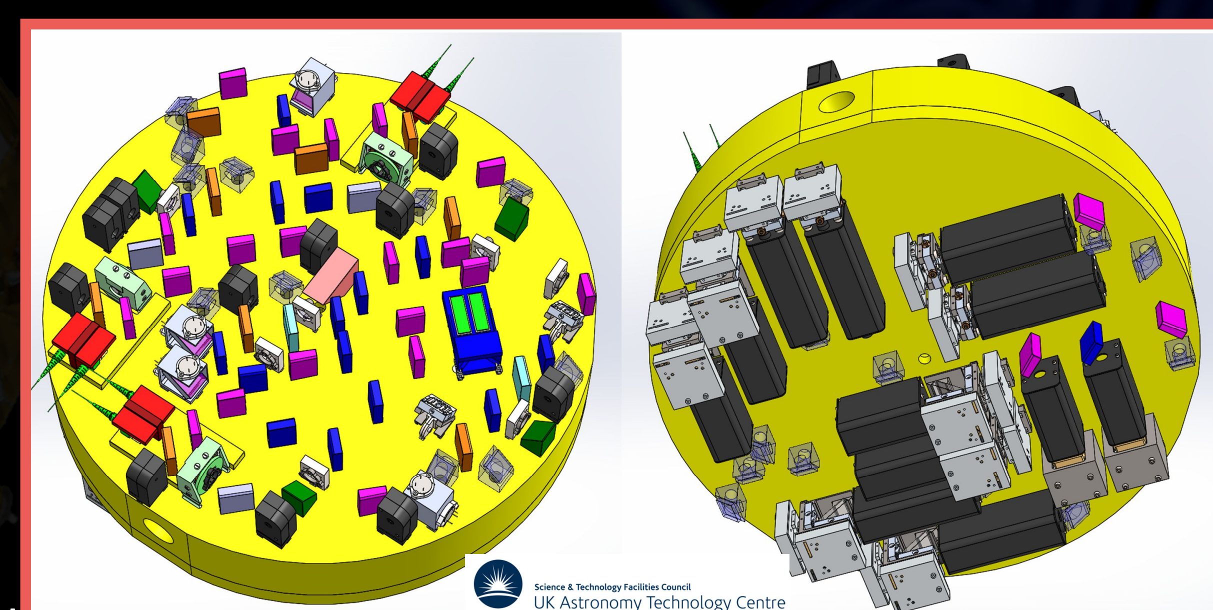
- Several steps for an extremely precise measurements
  (TM2→SC2) + (SC2→SC3) + (SC3→TM3)





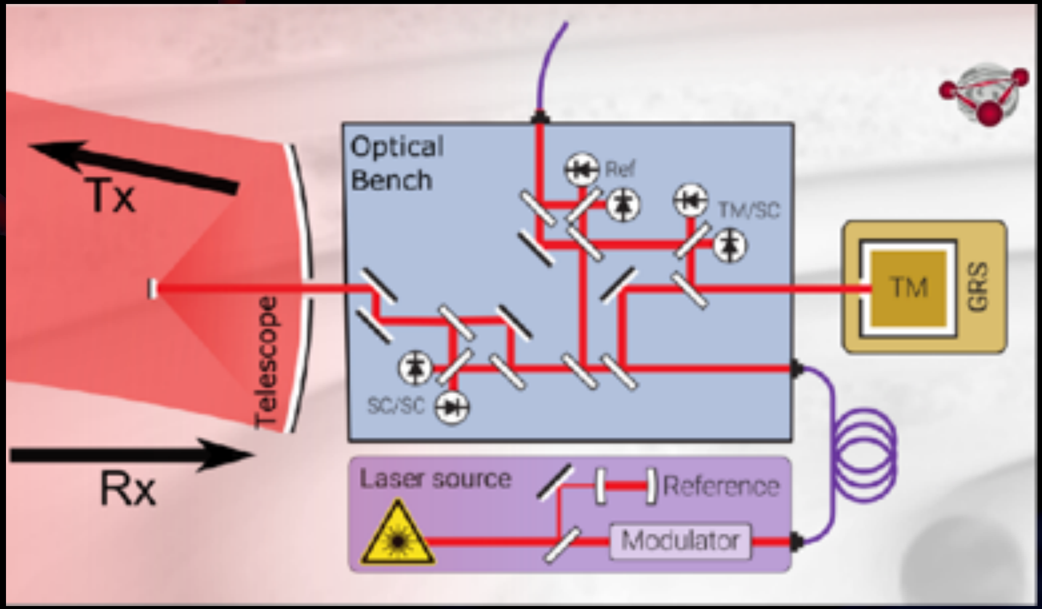


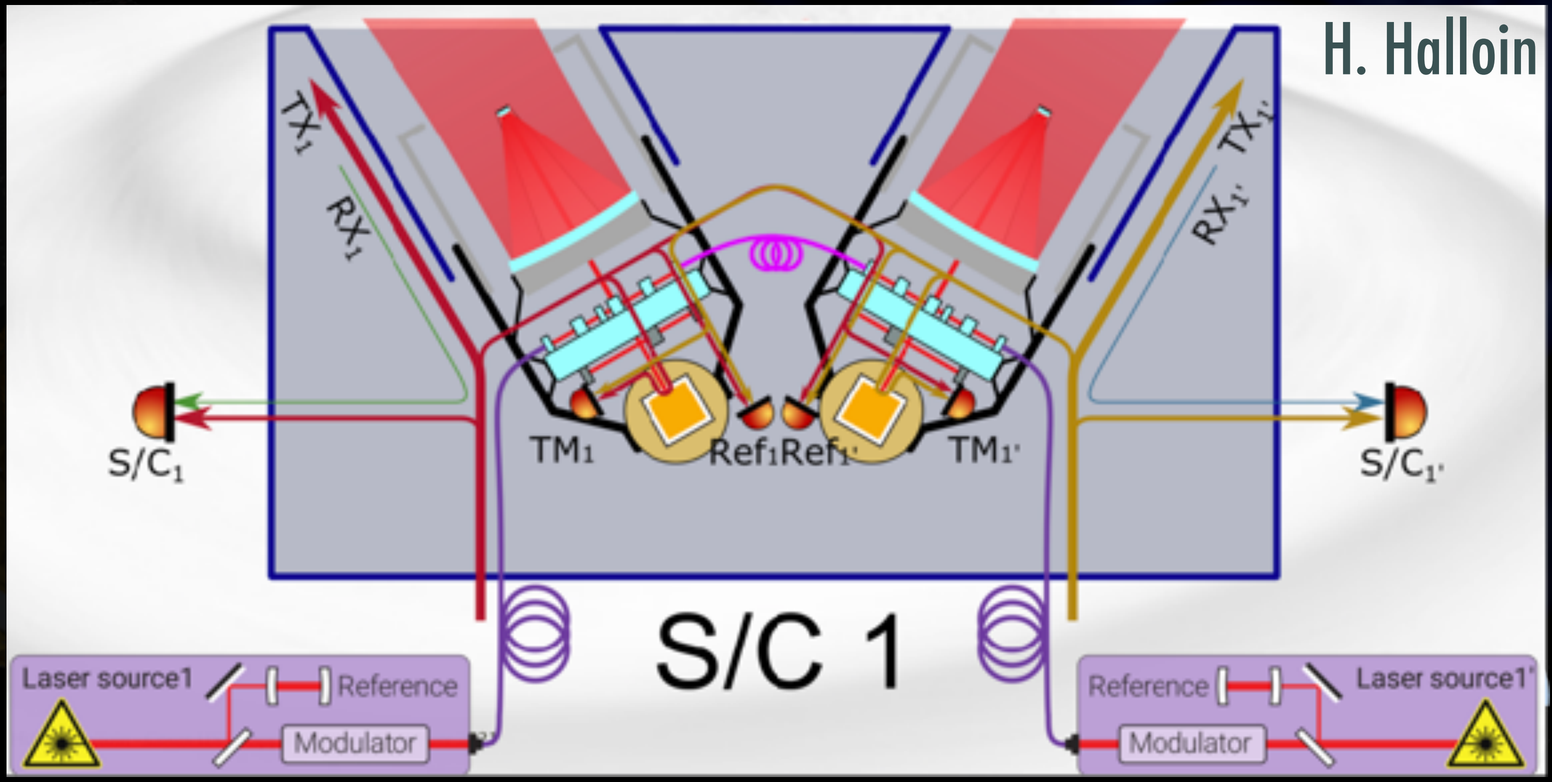




Interferometric measurements

- Exchange of laser beams 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





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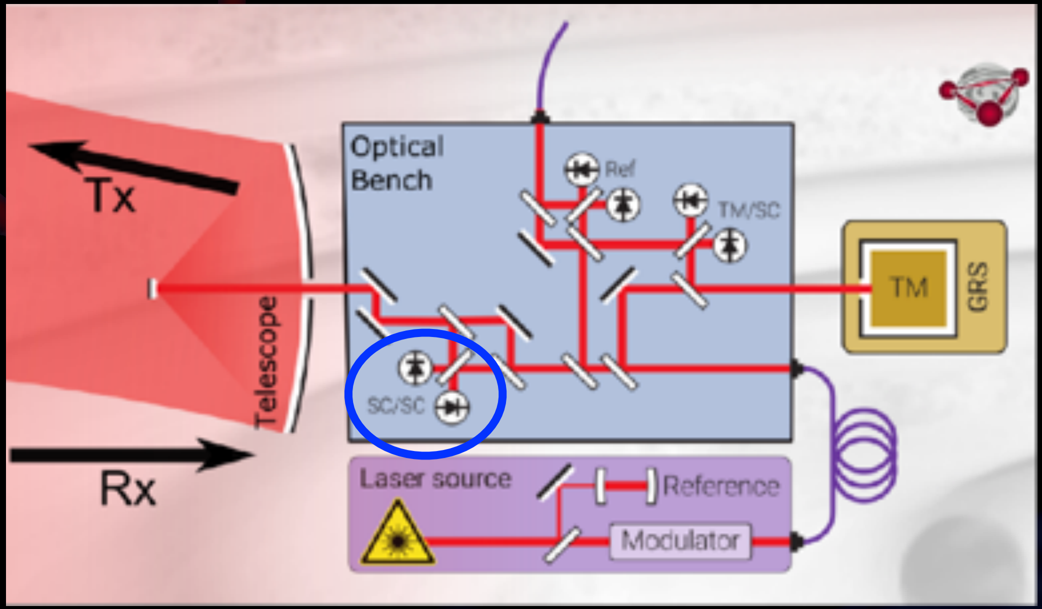

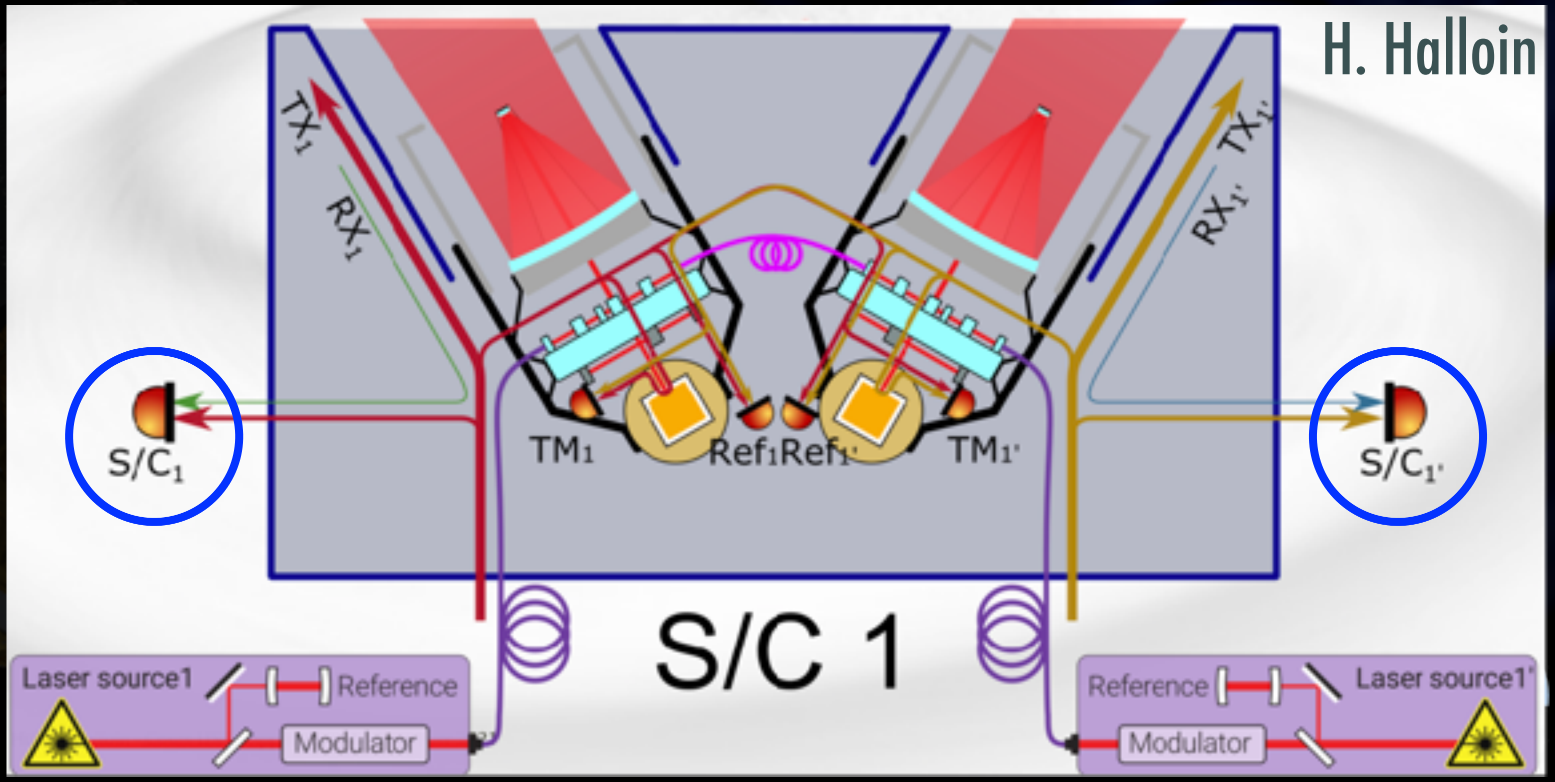

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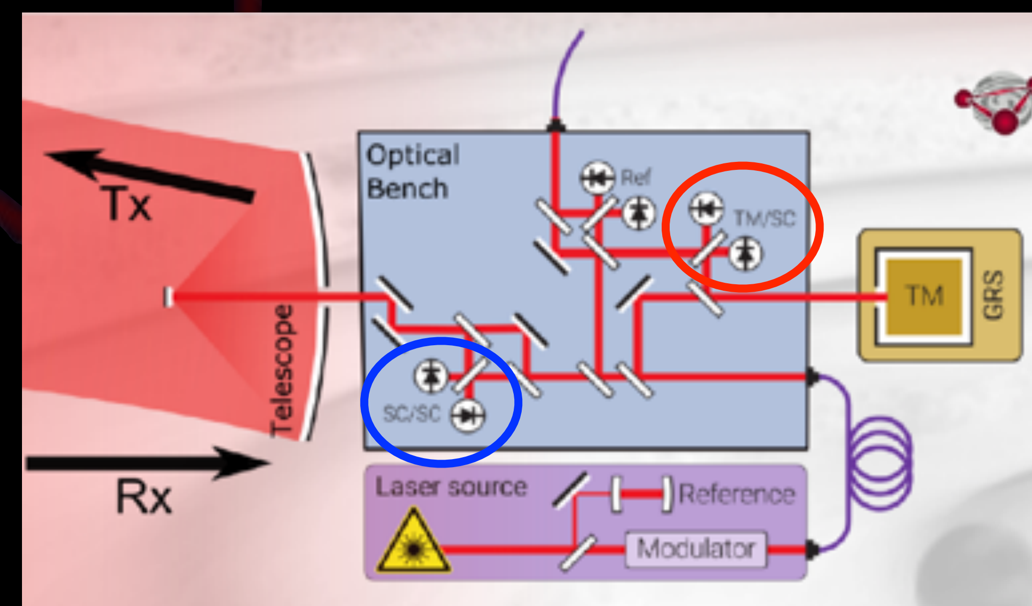

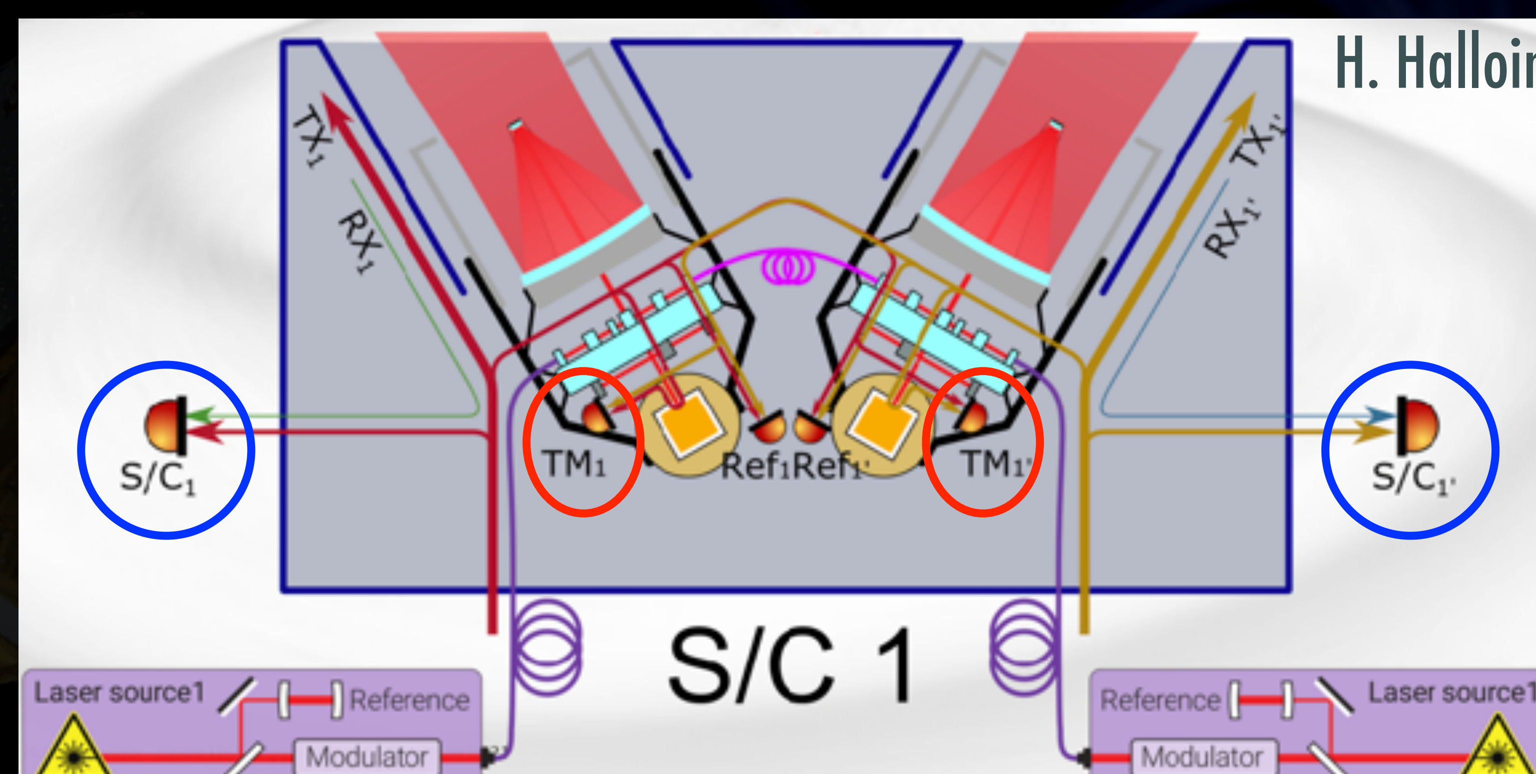

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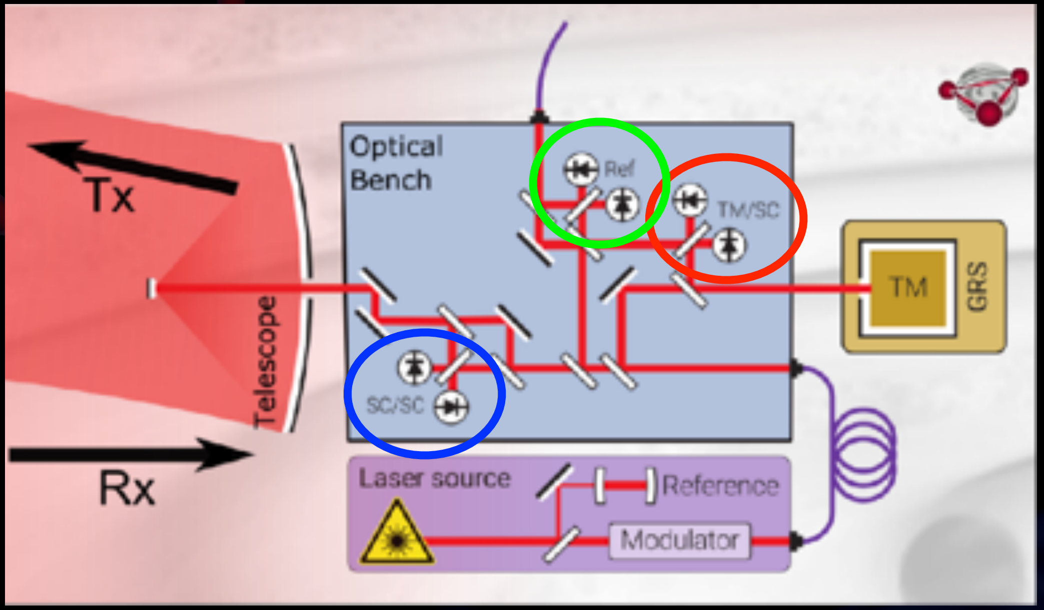
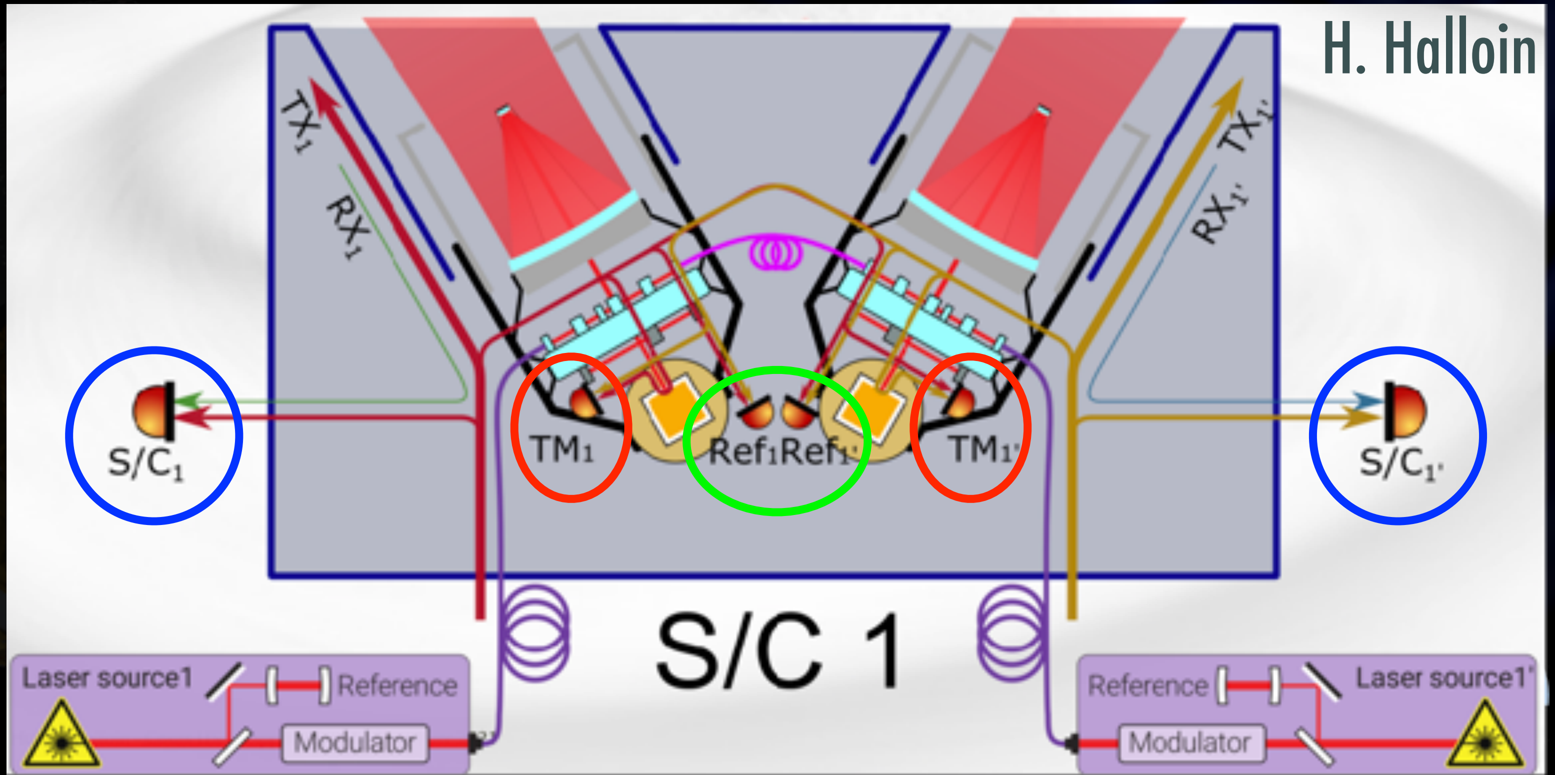
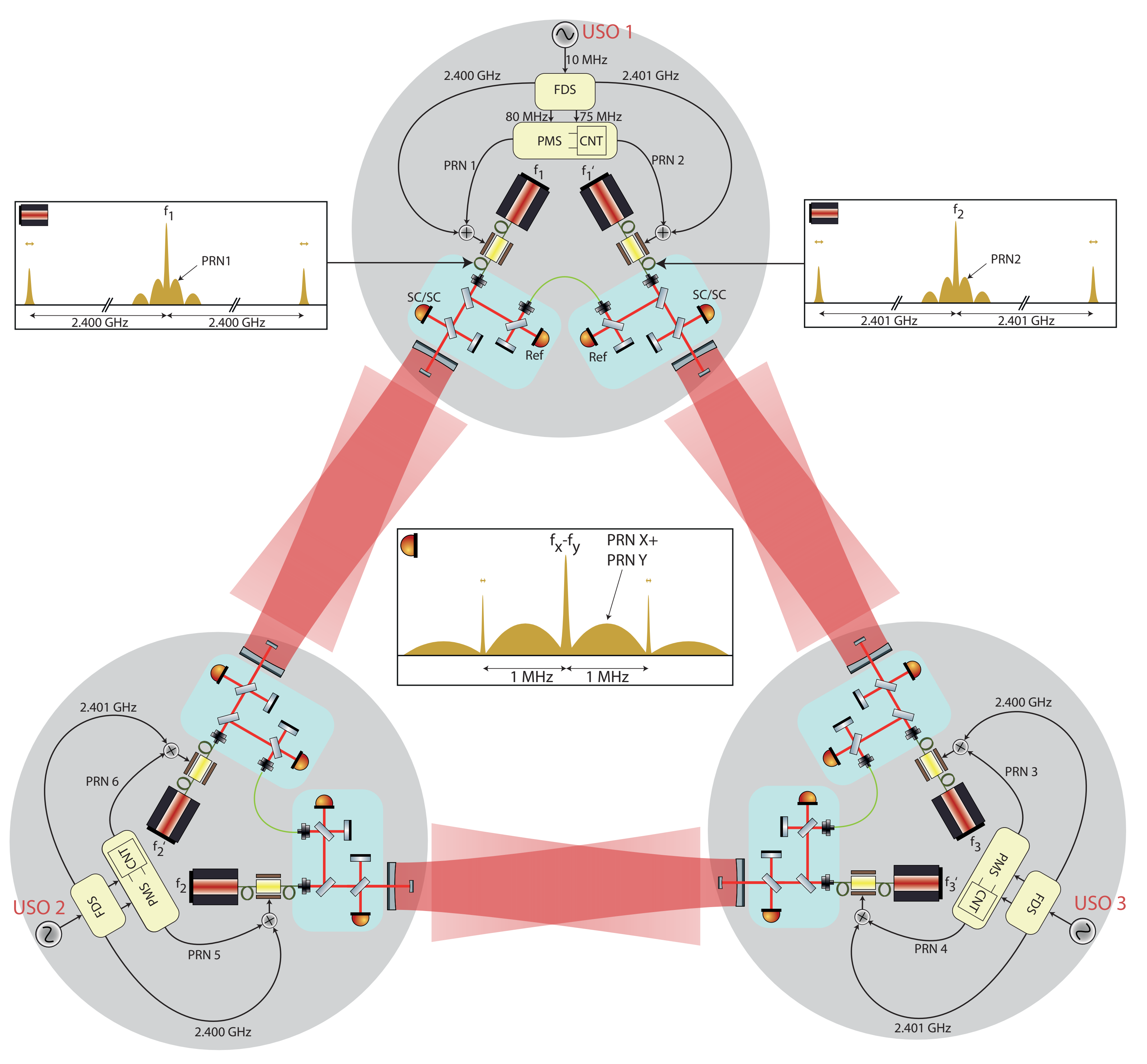




Interferometric measurements

- Measurements via exchange of beams:
  - Heterodyne interferometry with carrier for inter-spacecraft measurement => GWs
  - Sideband for transferring amplified clock jitter => correction of additional clock jitter
  - Pseudo-Random Noise => ranging (measure arm length)
  - Laser locking



Interferometric measurements

- Quadrant Photodiodes for measuring phase and angle (DWS)
- Phasemeter: the core of the measurement: complex phase-locked loop system, followed by multiple filters to provide data around 16Hz
- Several mechanisms are necessary:
  - PAAM: Point Ahead Angle Mechanism: emission & reception not in the same direction
  - OATM: Optical Assembly Tracking Mechanism: pointing of the MOSA
  - BAM: Beam Alignment Mechanism
  - FSU: Fiber Switching Unit
- Science diagnostics: temperature, magnetic field, charge, …
- For constellation acquisition, a Constellation Acquisition System (very sensitive camera) is necessary

LISA technology requirements

- Free flying test mass subject to very low parasitic forces:
  - ✓ Drag free control of spacecraft (non-contacting) with low noise microthruster
  - ✓ 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 accuracy laser frequency stabilisation + noise suppression with TDI
  - ➡ "Tilt to length" coupling (control of alignement + ground correction)
  - ➡ Low level of stray-light
  - ➡ High stability telescopes
  - ➡ High accuracy phase-meter and frequency distribution
  - ➡ Constellation acquisition

Validated with LISAPathfinder

On-ground demo. ✗

simulation

GRACE-FO

LISA noises

- In the on-board interferometric measurements the main noises sources are
  - Laser noise : 10^{-13} (vs 10^{-21})
  - Clock noise (3 clocks)
  - Longitudinal SC jitter
  - Tilt-to-Length
  - Modulation error
  - Acceleration noise
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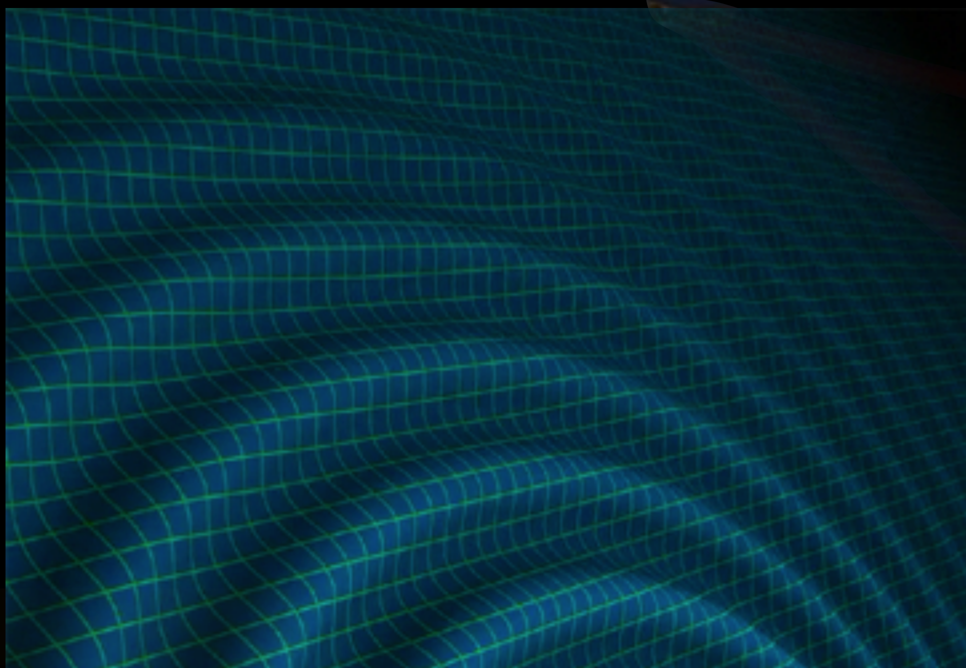
To be suppressed with on-ground processing: Initial Noise REduction Pipeline (INREP)

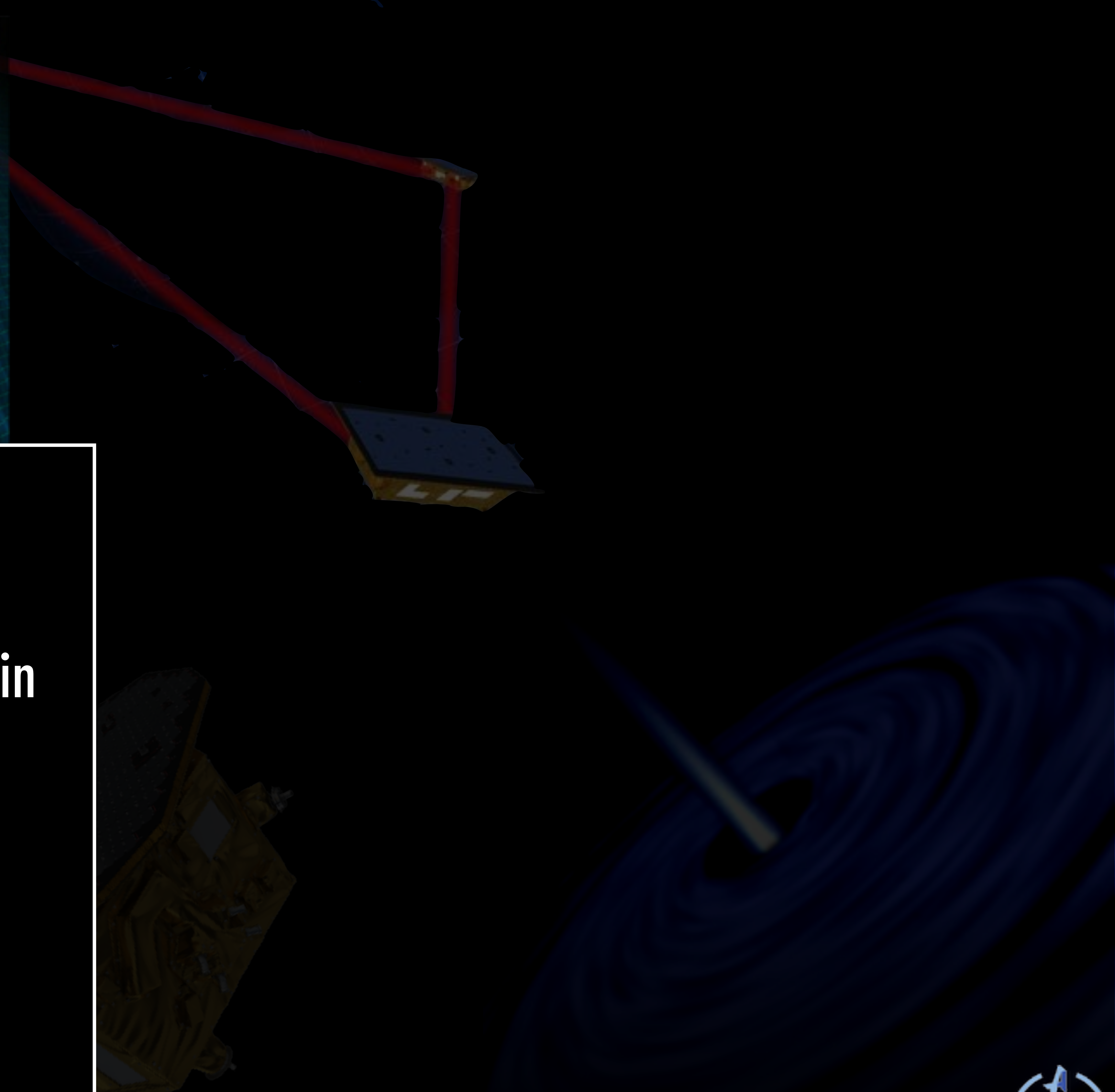
LISA data

GW sources

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

LISA data





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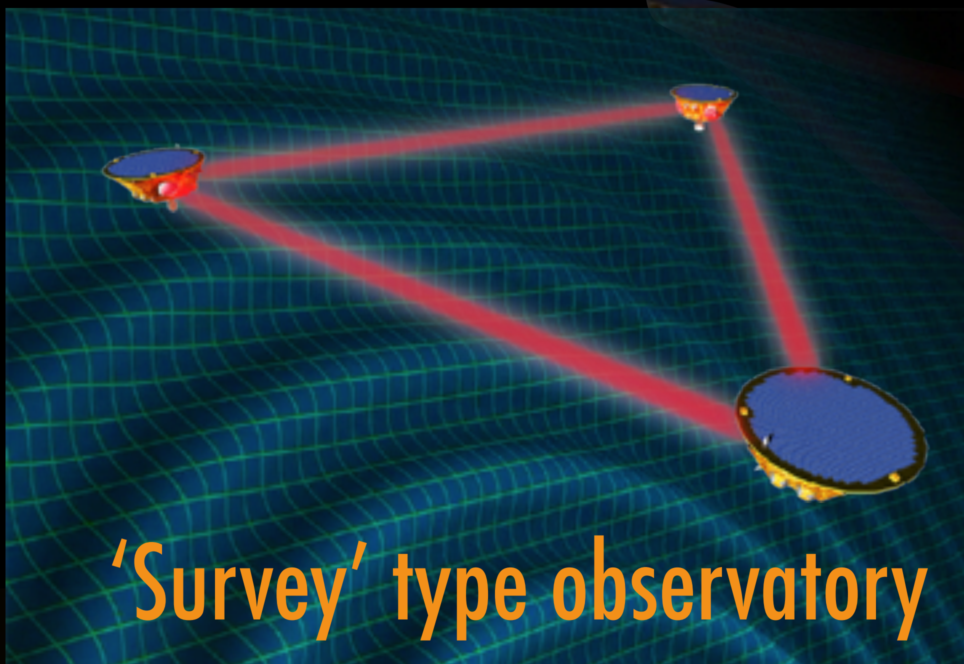

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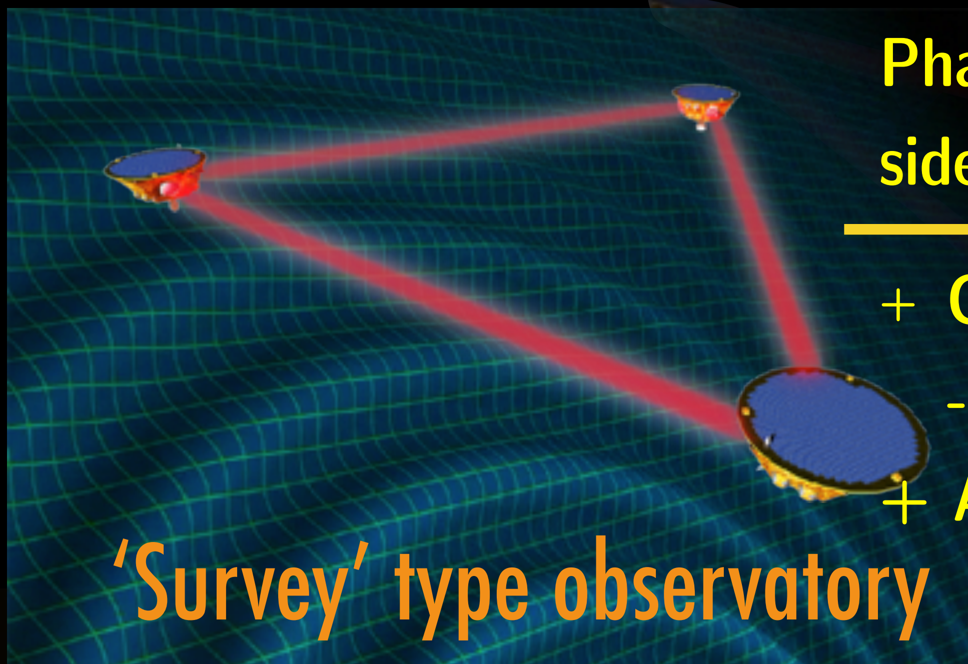

Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe- -rence Sensor
+ Auxiliary channels

'Survey' type observatory

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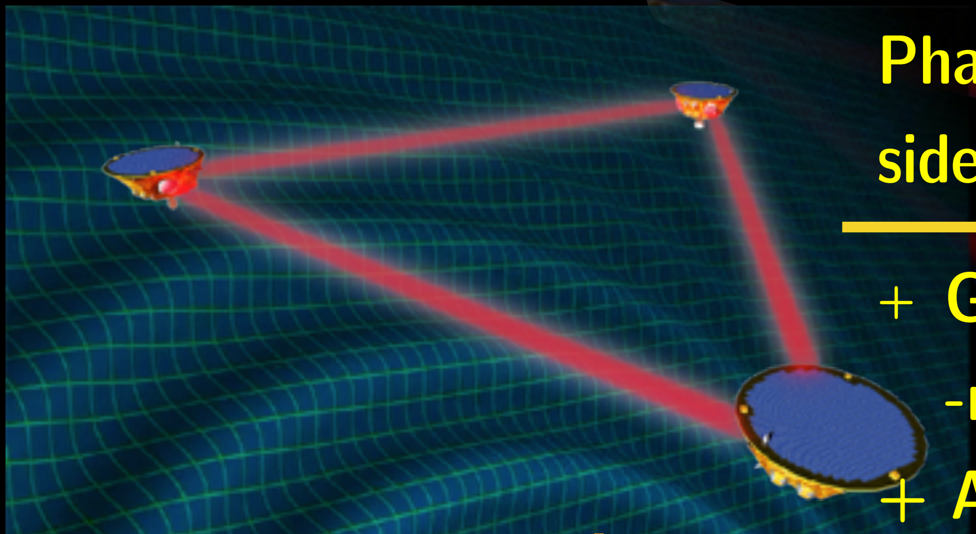

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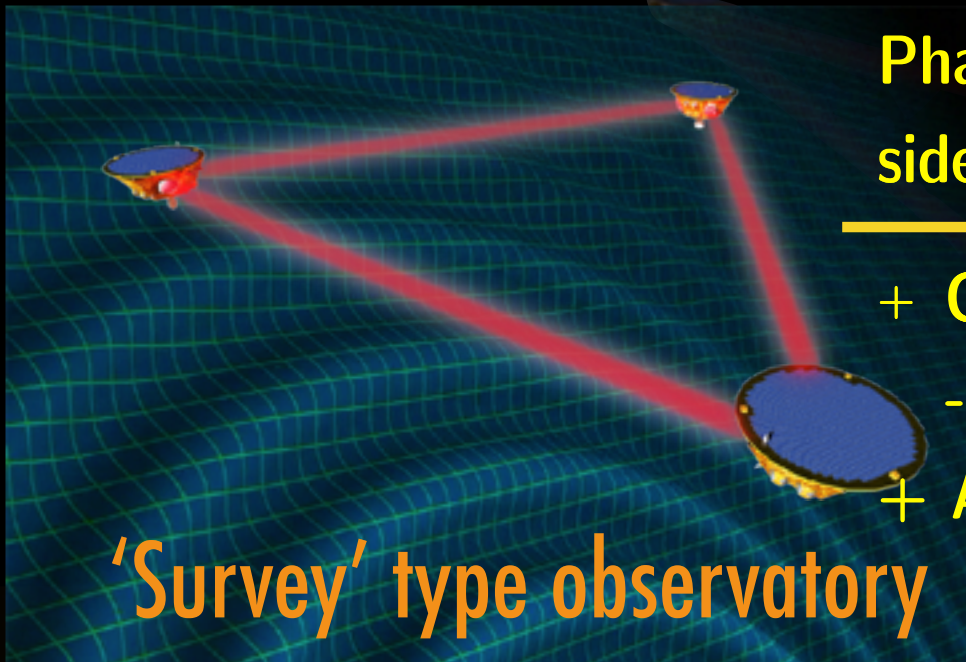

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Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

3 TDI channels with 2 "~independents"

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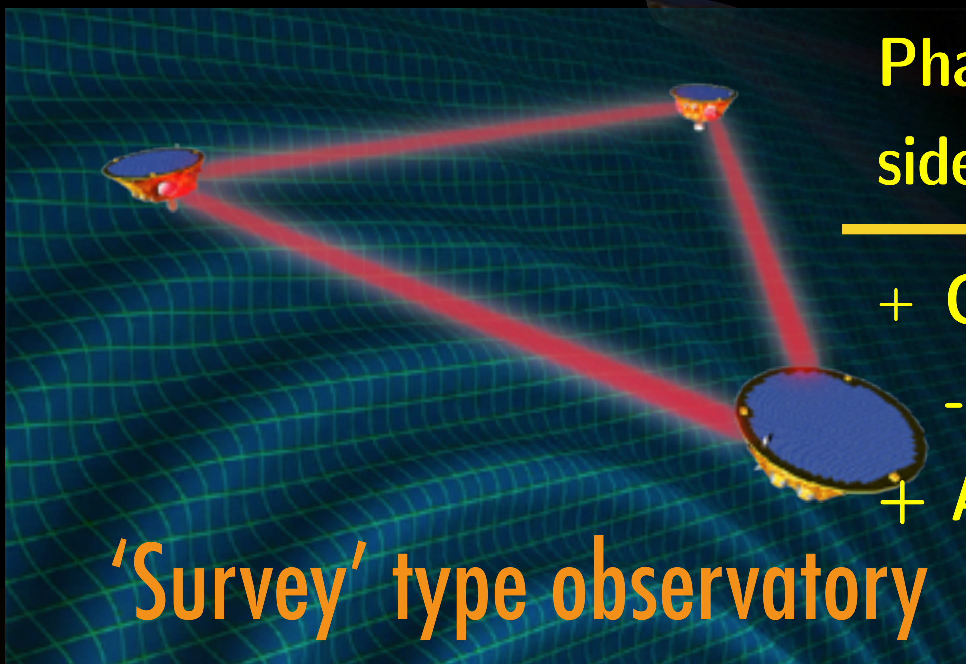

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Data Analysis of GWs

Catalogs of GWs sources with their waveform

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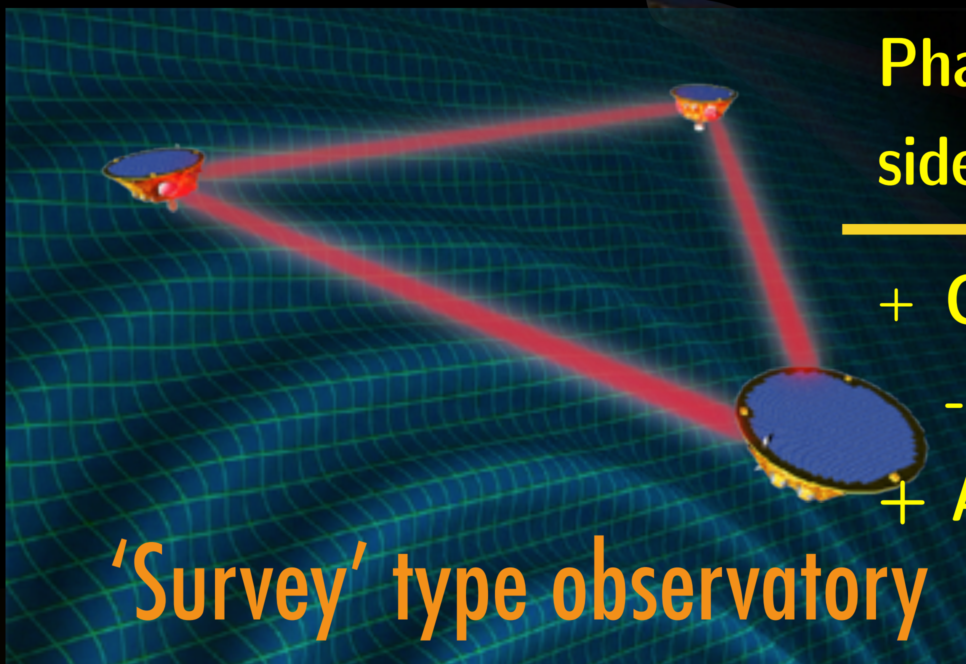

Phasemeters (carrier, sidebands, distance)

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L0

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Time-Delay Interferometry reduction of laser noise

L1 3 TDI channels with 2 "~independents"

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L3 Catalogs of GWs sources with their waveform

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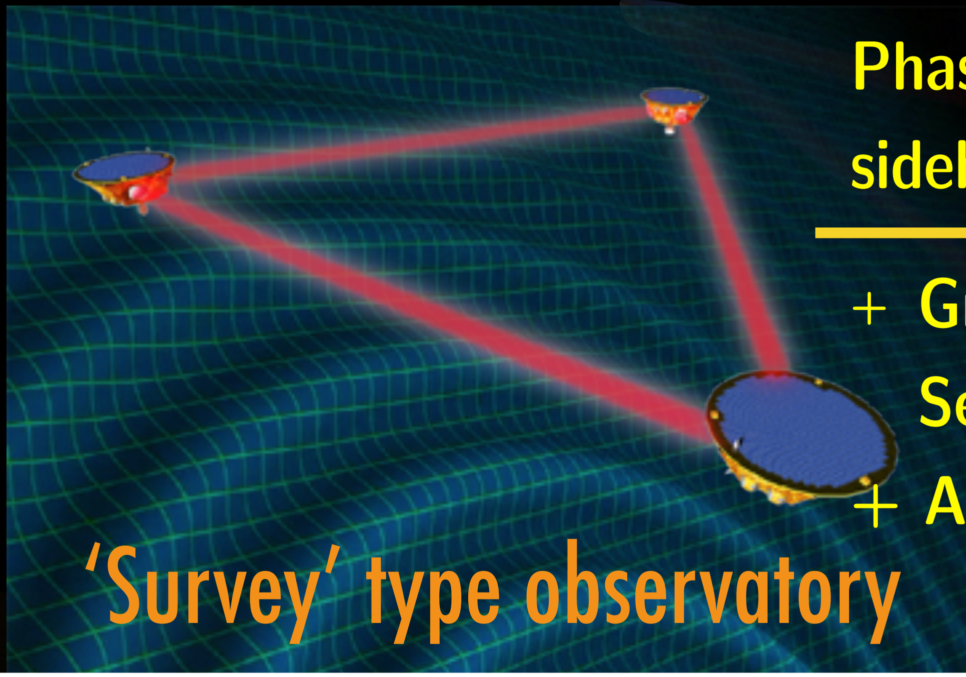

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Resynchronisation (clock)

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

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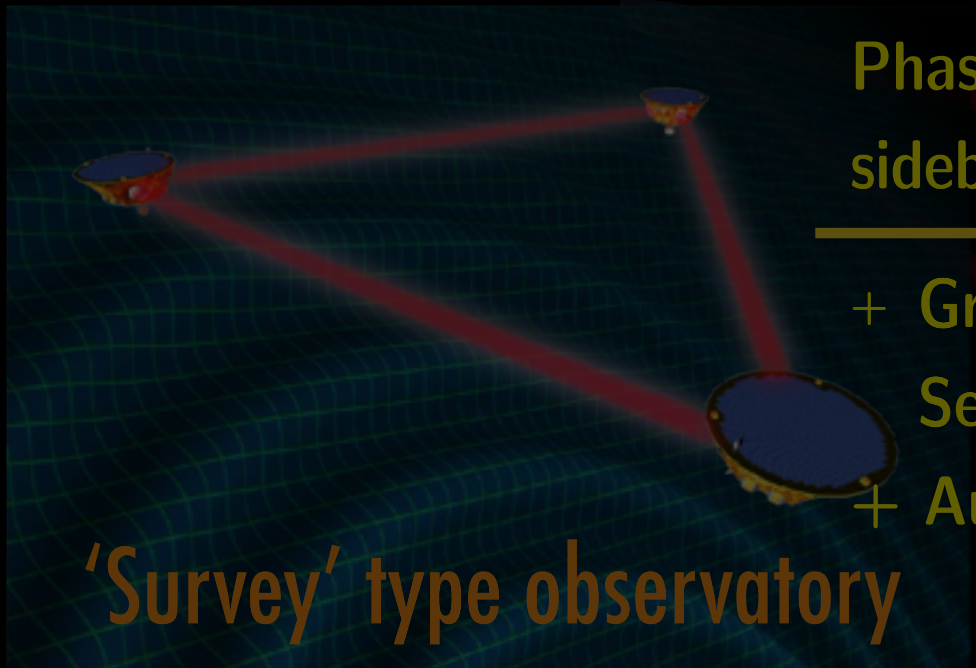
LISA data flow



GW sources

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

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

LISA data flow

Mission Operation Centre

(carrier,
stance)

+ Gravitational Reference Sensor
+ Auxiliary channels

'Survey' type observatory

L0

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Science Operation Centre

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LISA data flow

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(carrier,
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+ Gravitational Reference Sensor
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Distributed Data Processing Centre

- Unknown sources

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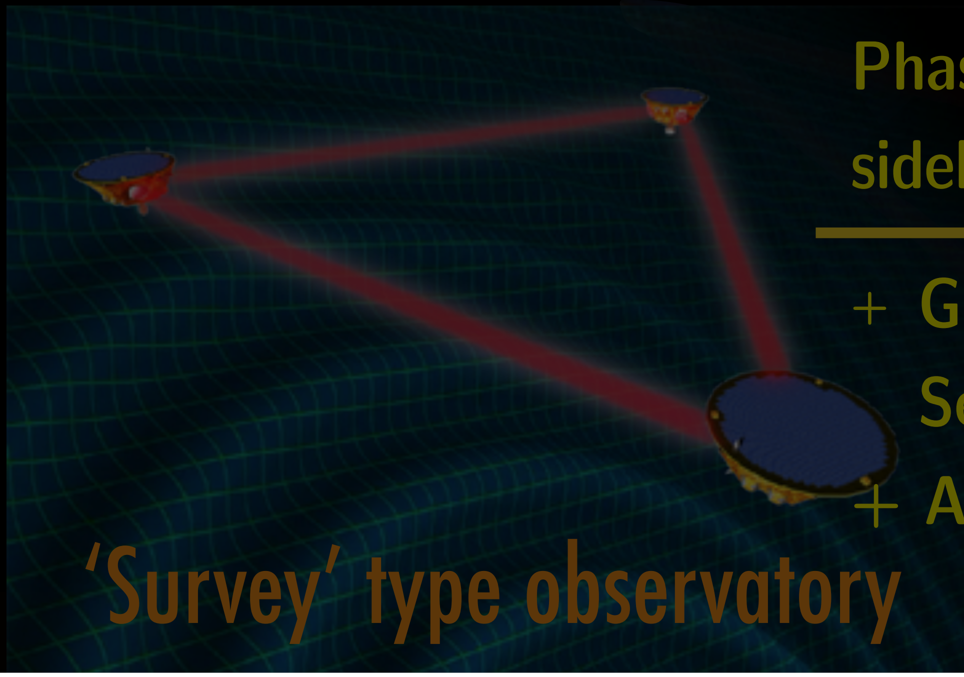

'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

\+ Gravitational Reference Sensor

\+ Auxiliary channels

L0

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

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Data Analysis of GWs

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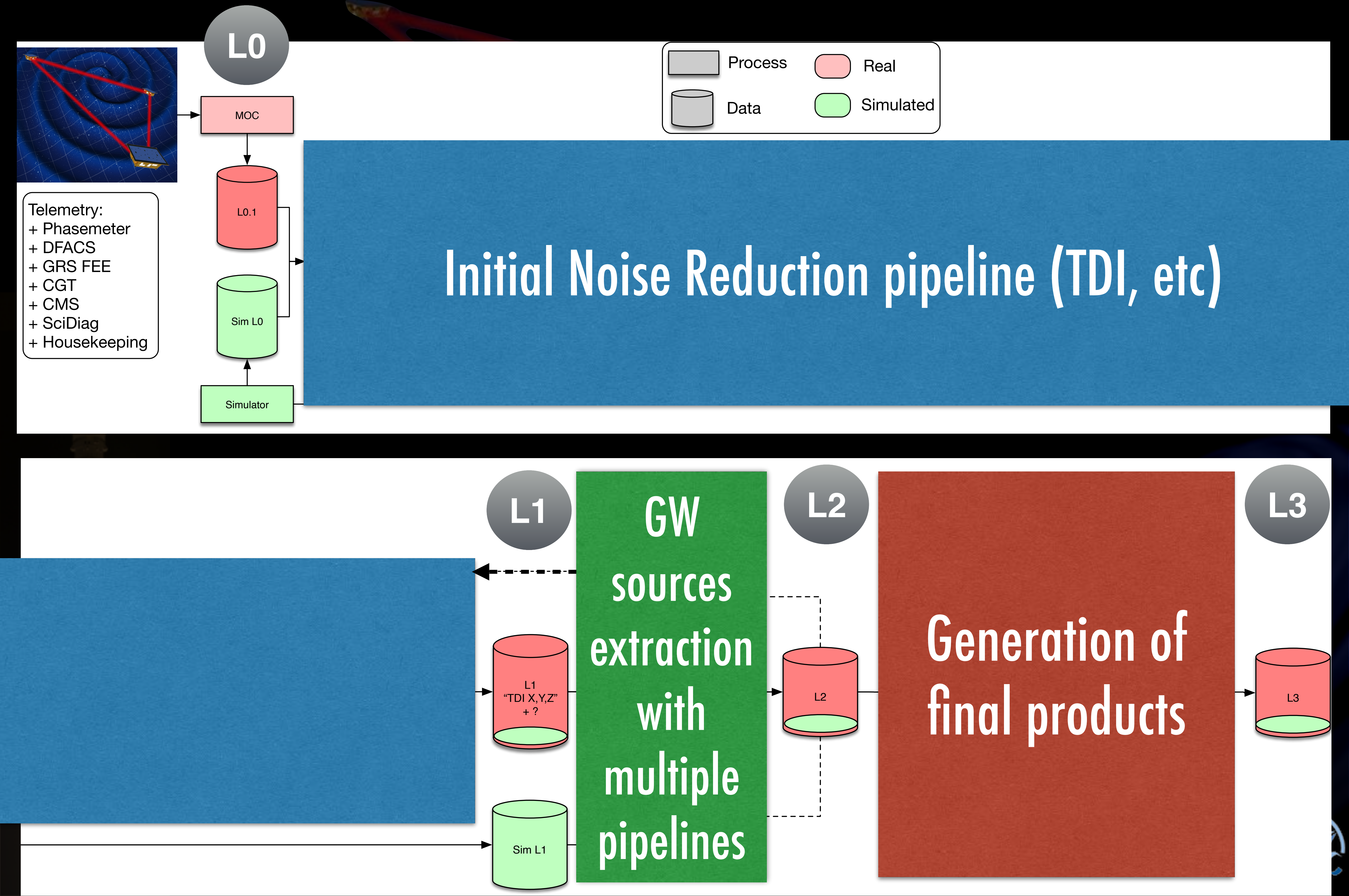
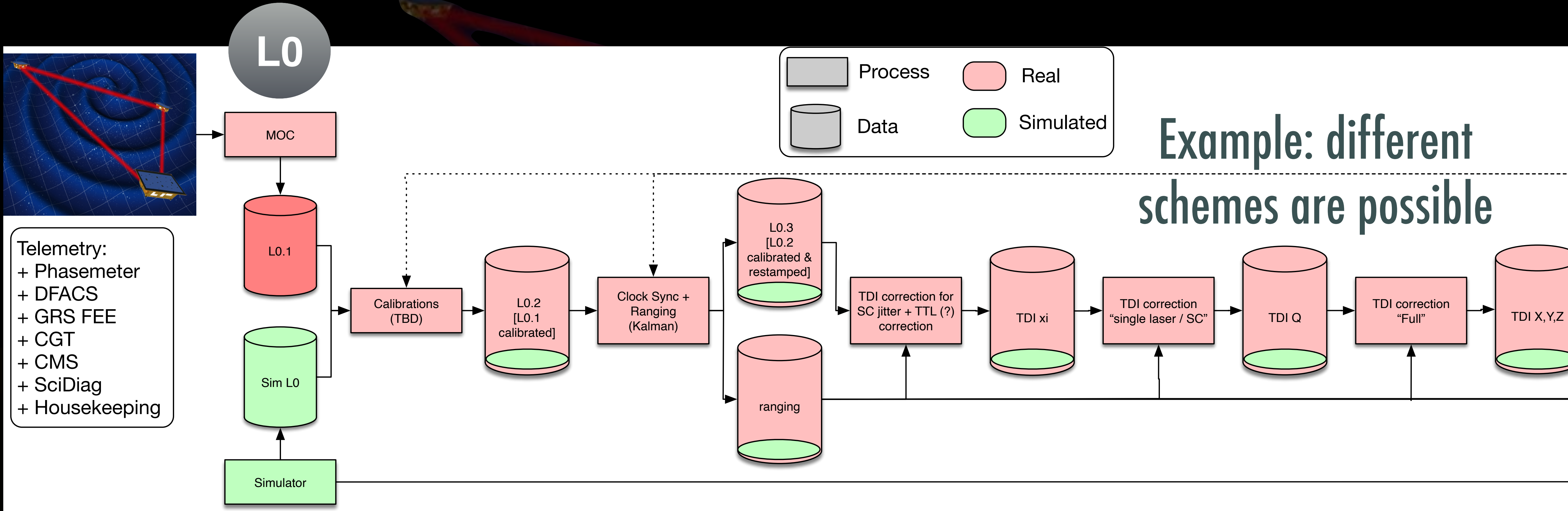
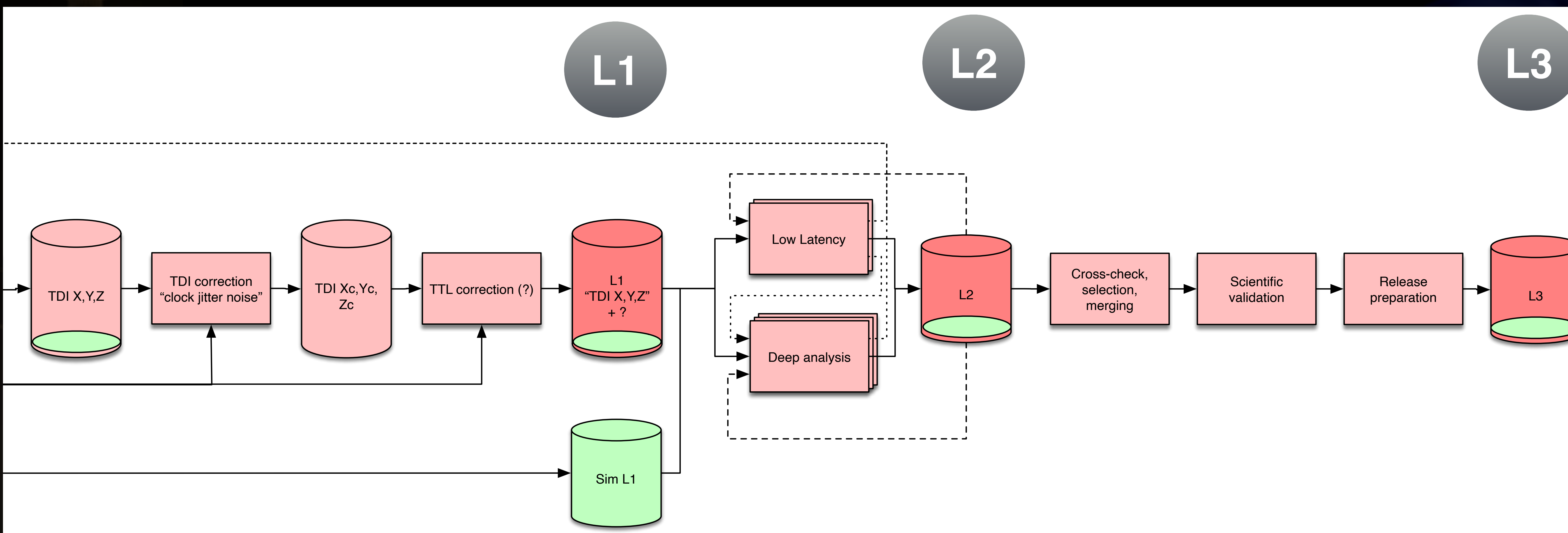
Segment sol LISA



Segment sol LISA

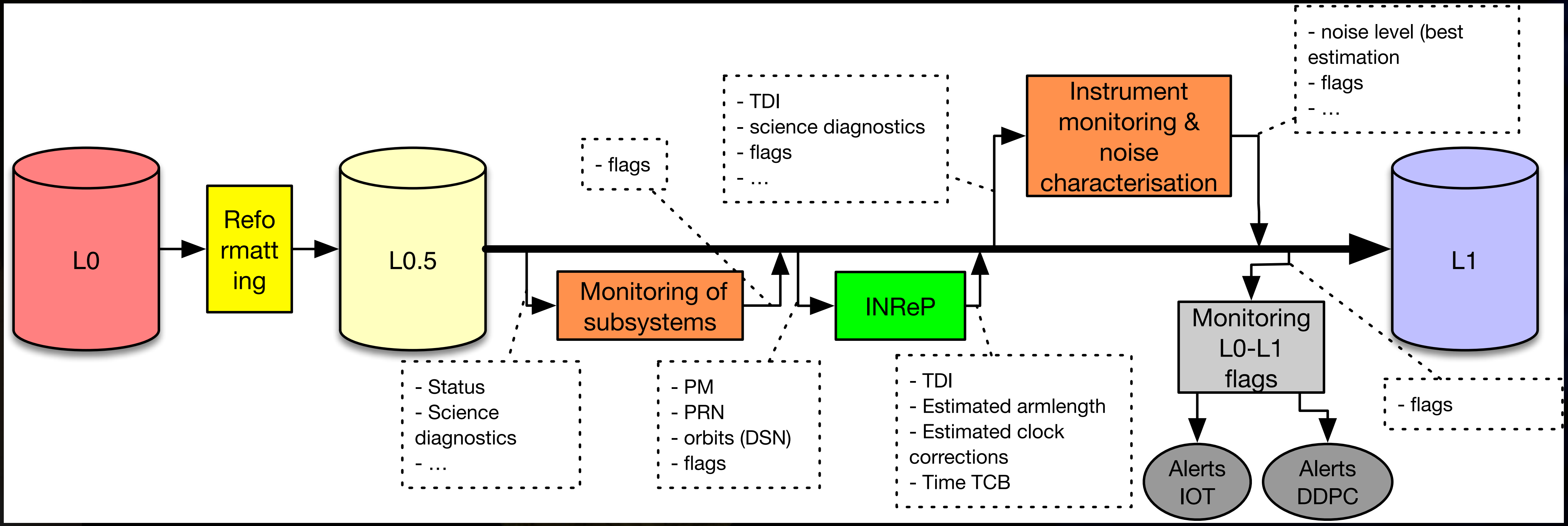


Example: different schemes are possible



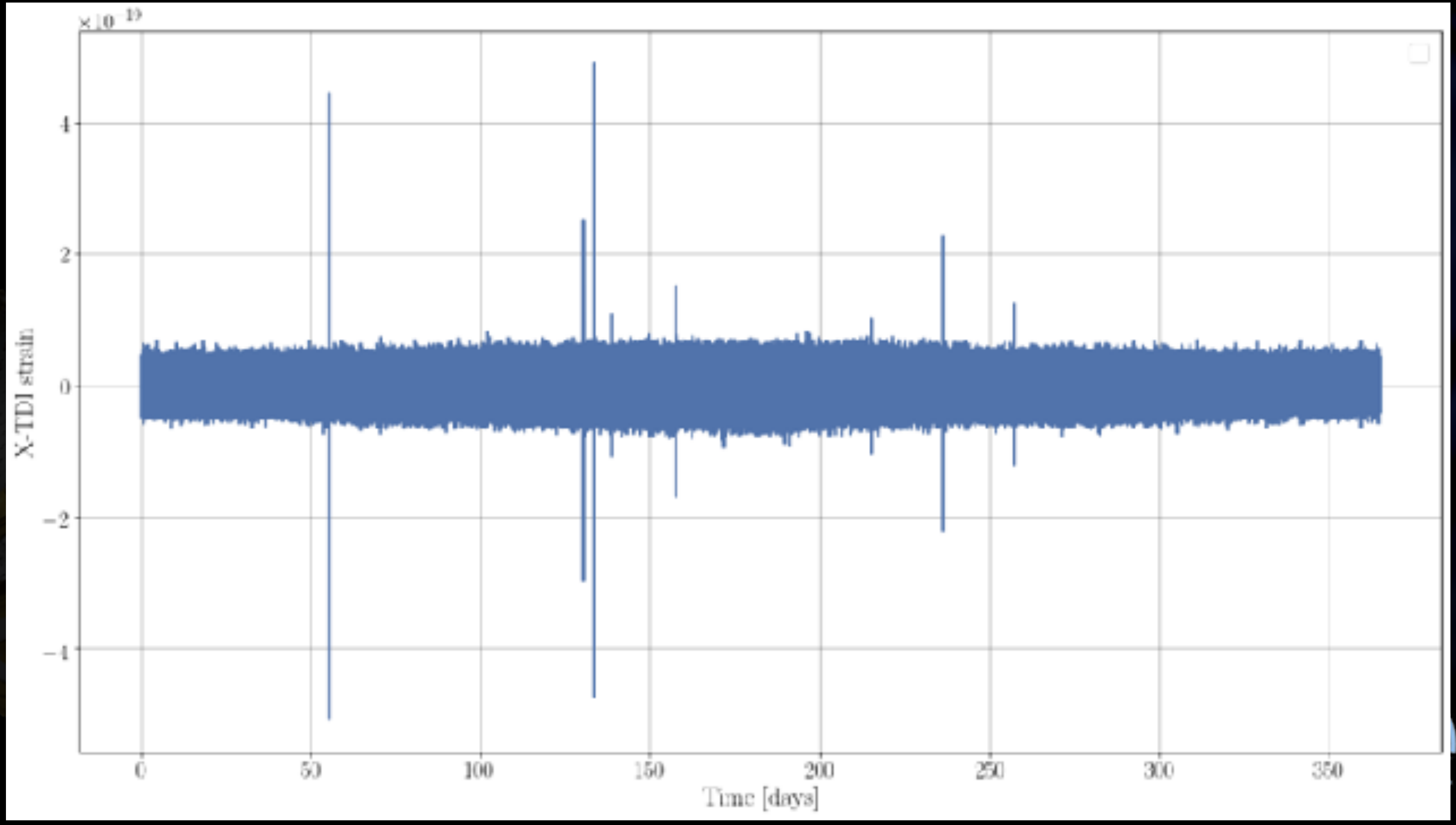
Noise reduction

- From L0 (raw data) to L1 (TDI: data used to extract GWs)
  - Initial Noise Reduction Pipeline (INReP)
    - Synchronisation of time reference
    - Estimation of armlength
    - Time Delay Interferometry
  - Monitoring of instrument



Extracting GWs

- From L1 (TDI) to L2/L3 (science products: GW catalogue, etc)
- Complex: large number of sources + artefacts (gaps, glitches, ...)
- LISA Data Challenge
  - Generate datasets provided to the community
  - Organise development of data analysis
  - Increase complexity of datasets
  - Example: Sangria dataset



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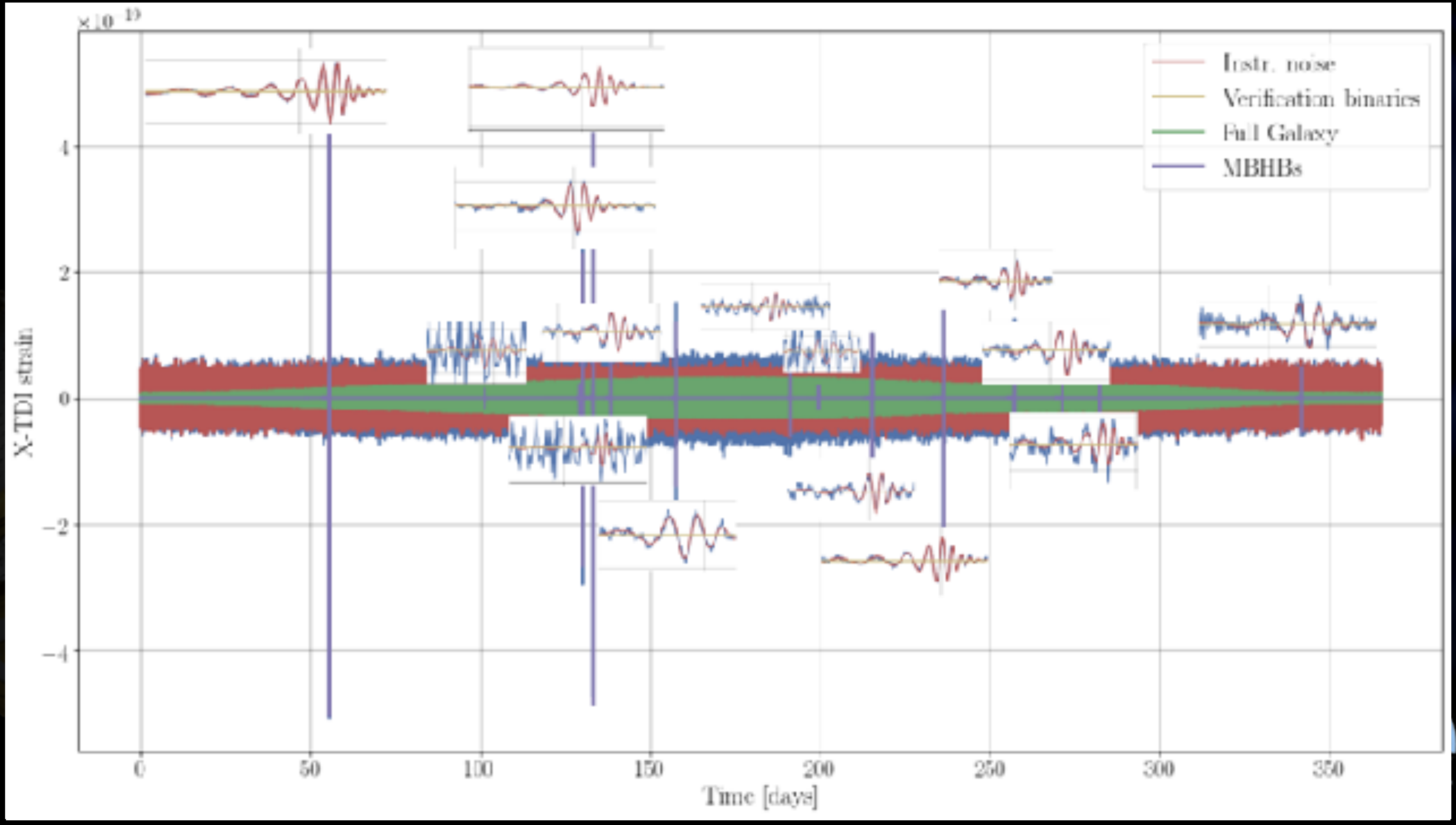
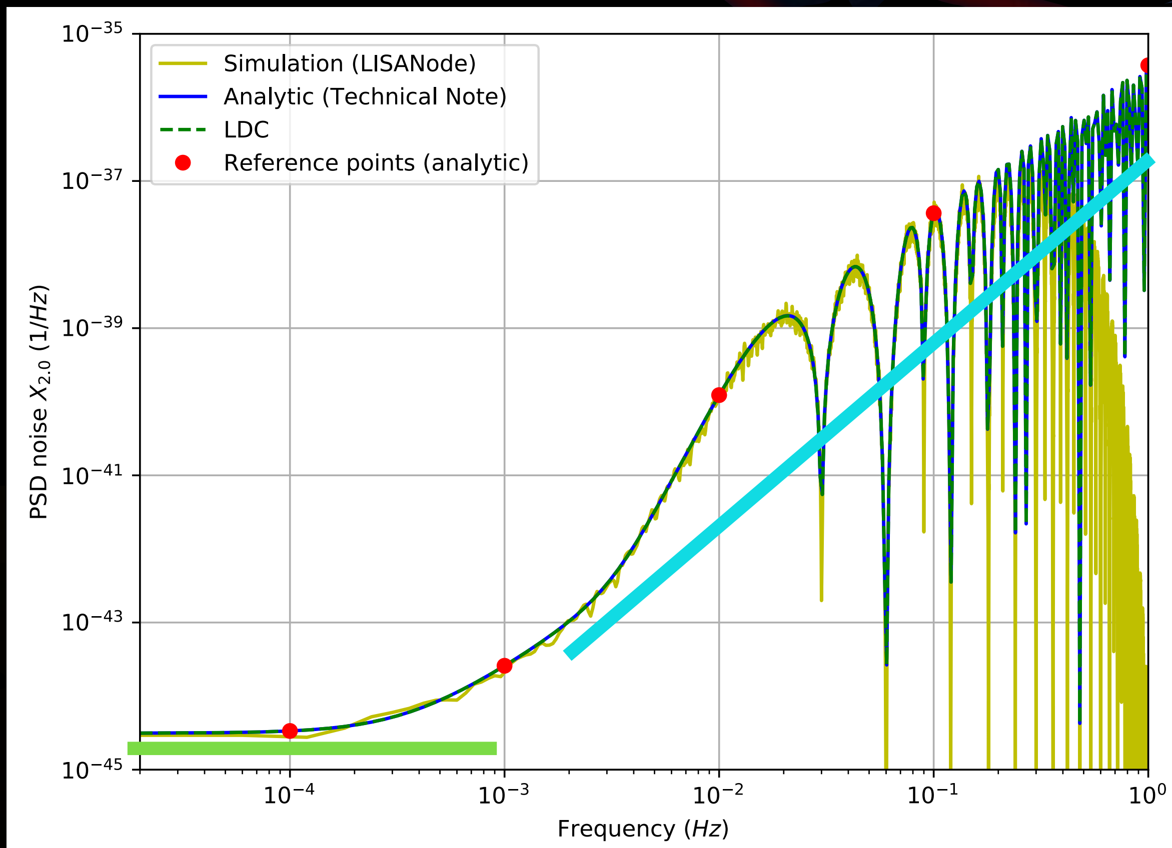
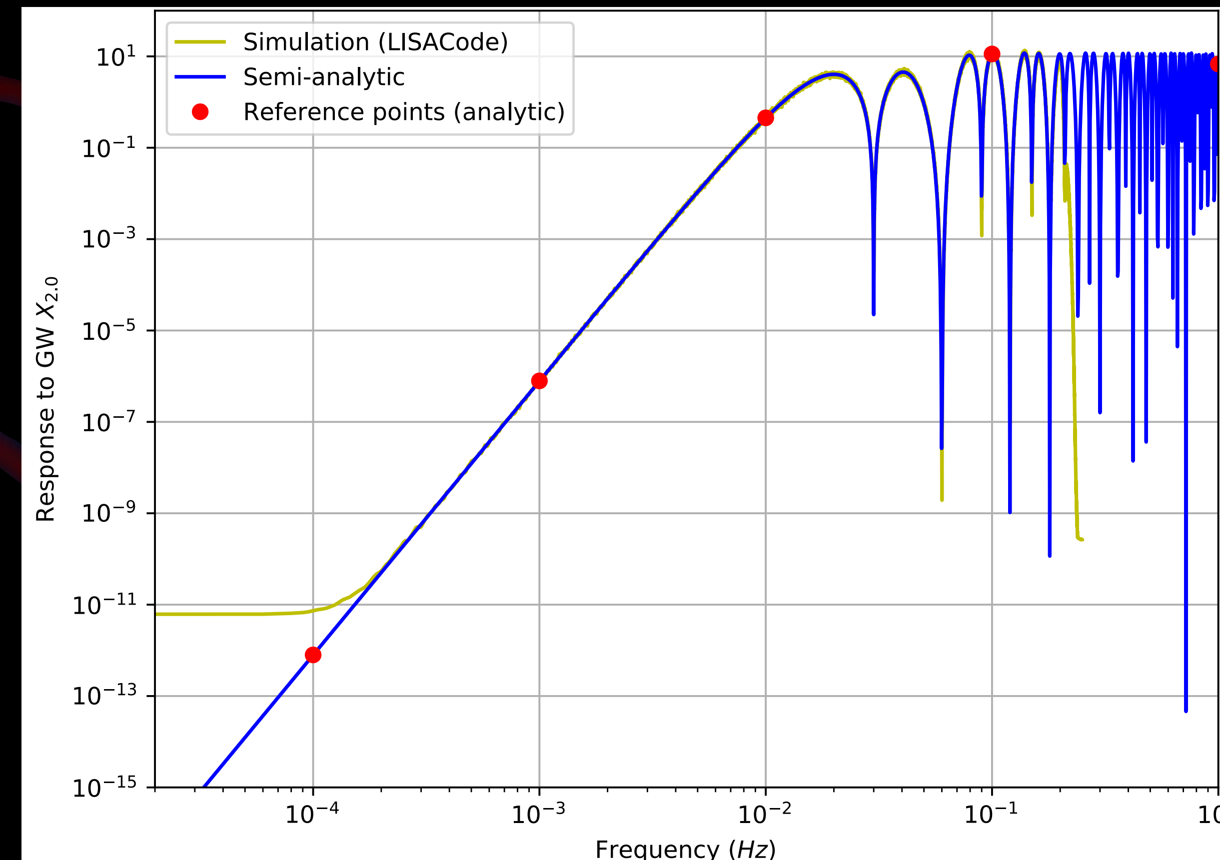


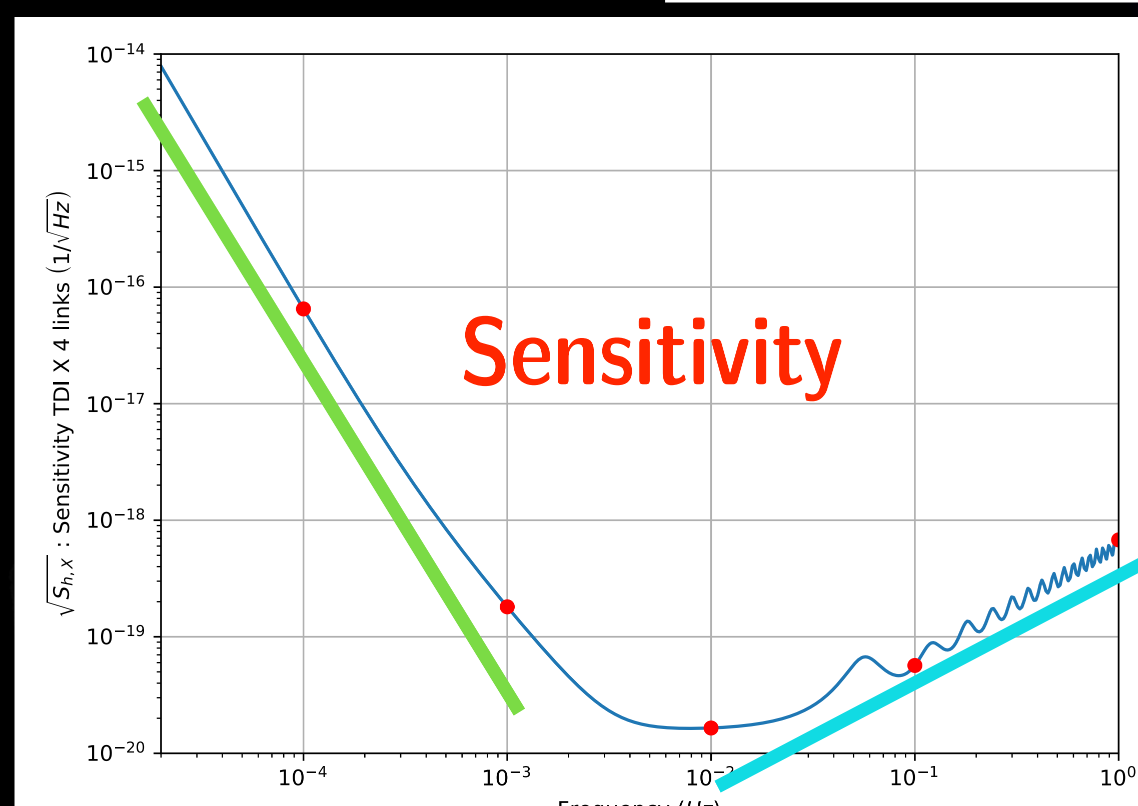
Sensitivity

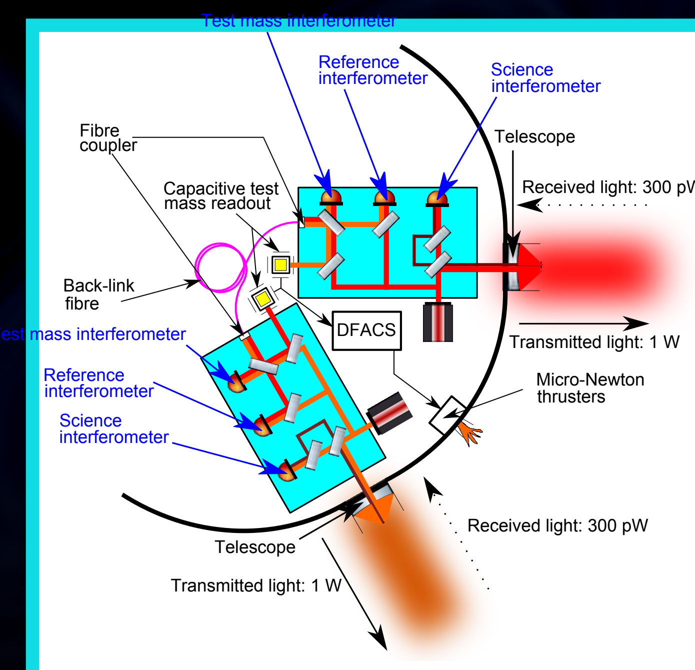
Noises



Response of the detector to GWs



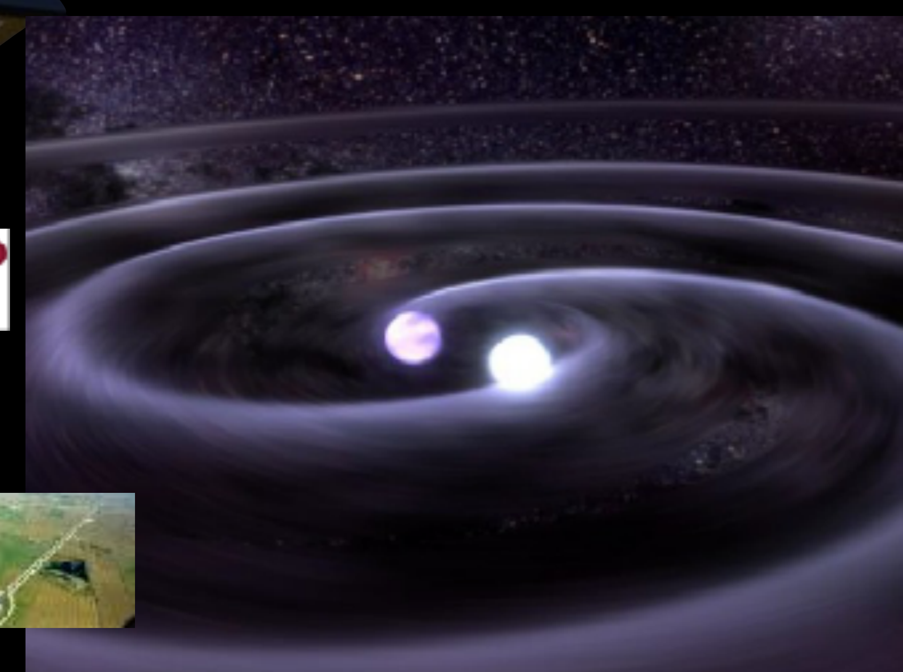




Compact solar mass binaries

- Large number of stars are in binary system.
- Evolution in white dwarf (WD) and neutron stars (NS).

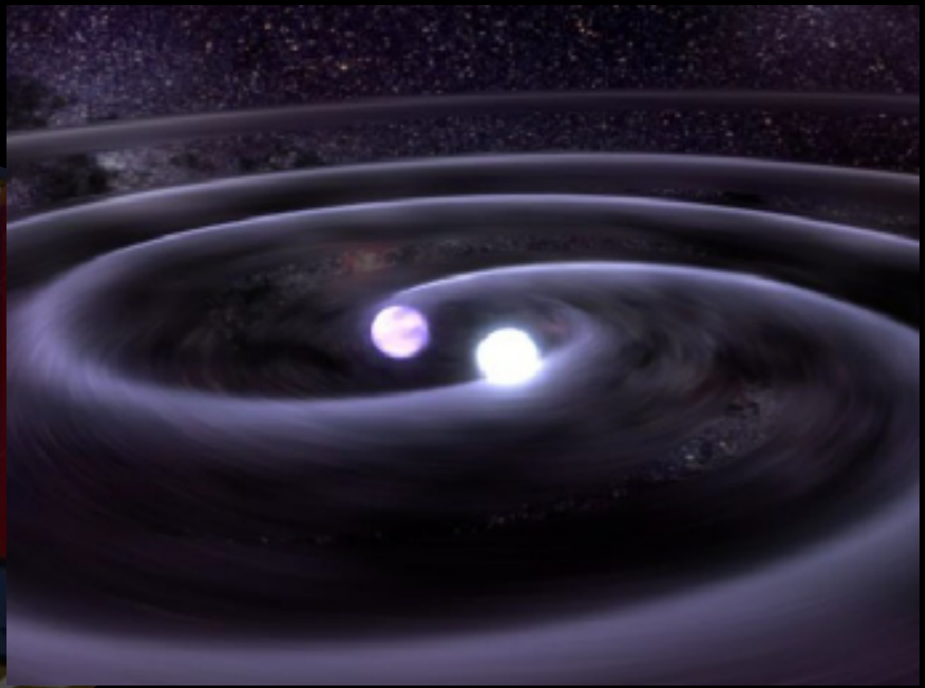
  => existence of WD-WD, NS-WD and NS-NS binaries
- Estimation for the Galaxy: 60 millions.
- Gravitational waves:
  - most part in the slow inspiral regime (quasi-monochromatic): GW at mHz
  - few are coalescing: GW event of few seconds at f > 10 Hz (LIGO/Virgo)



- Several known system emitting around the mHz

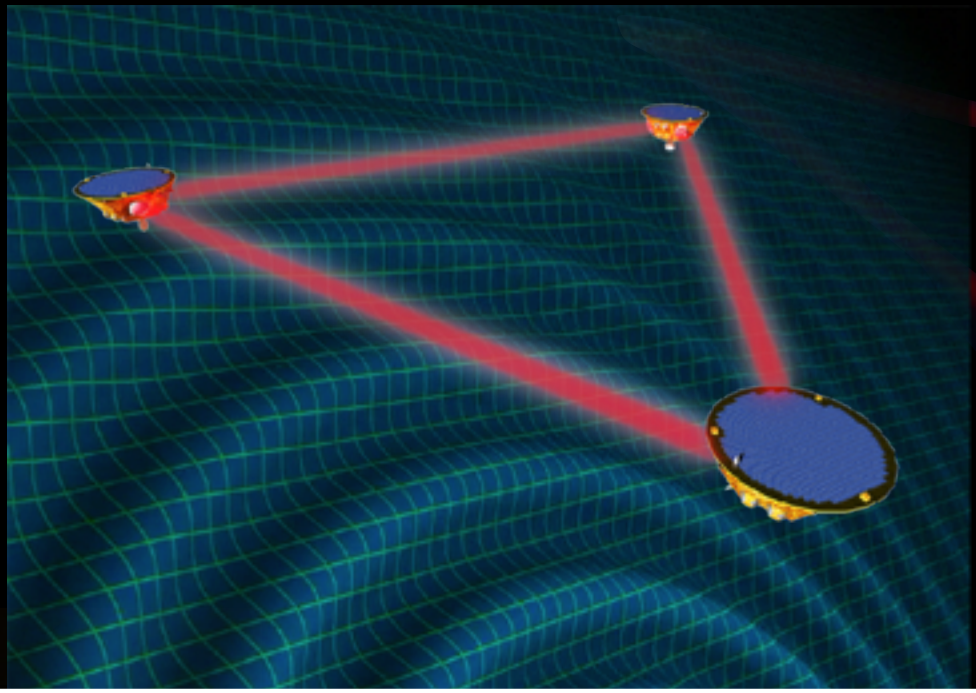
  => guaranteed sources

Galactic binaries



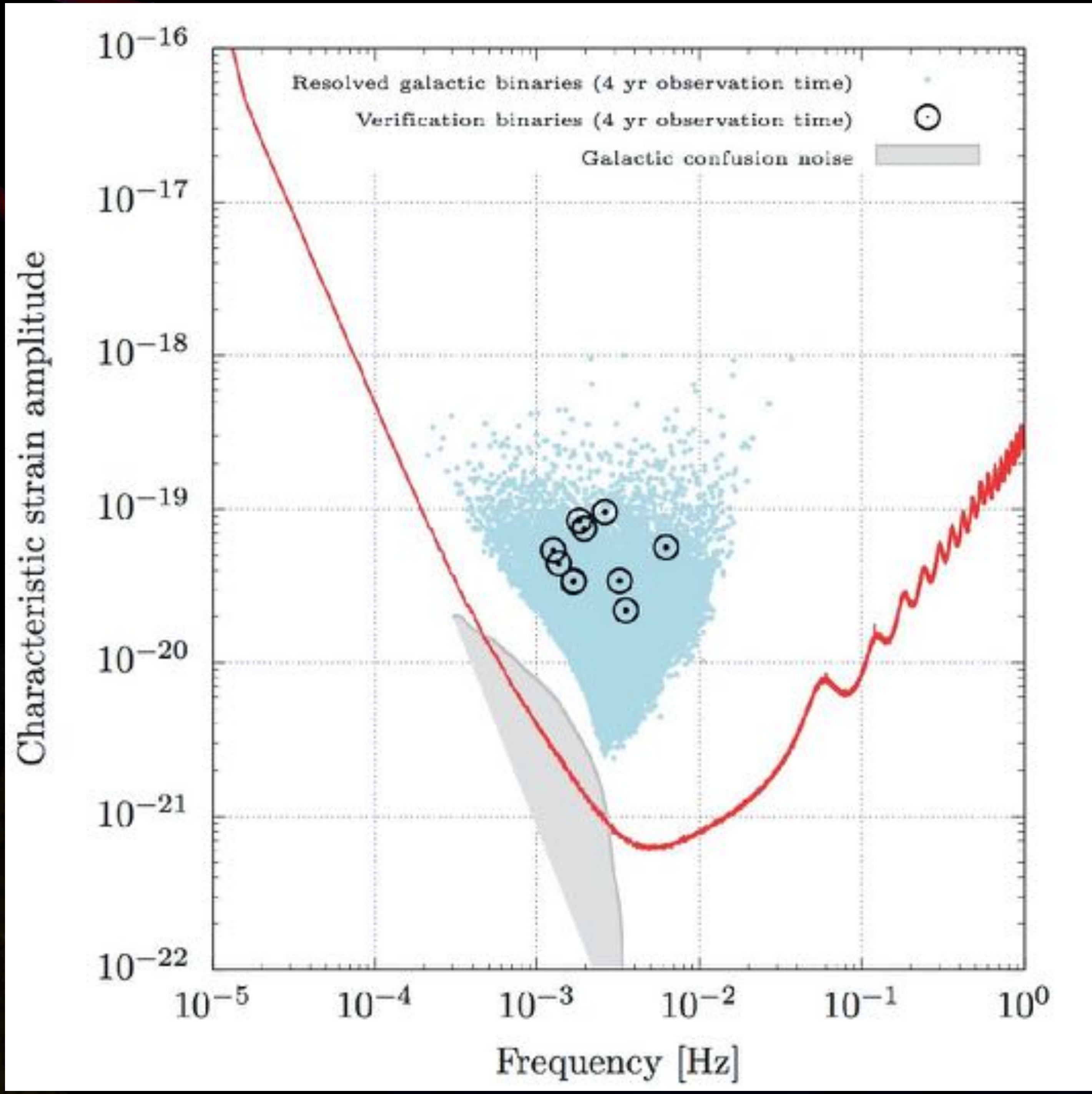
- Gravitational wave:
  - quasi **monochromatic**
- Duration: **permanent**
- Signal to noise ratio:
  - detected sources: 7 - 1000
  - confusion noise from non-detected sources
- Event rate:
  - **25 000 detected sources** (over 30 millions sources)
  - more than **10 guarantied** sources (verification binaries)

Galactic binaries



GW sources

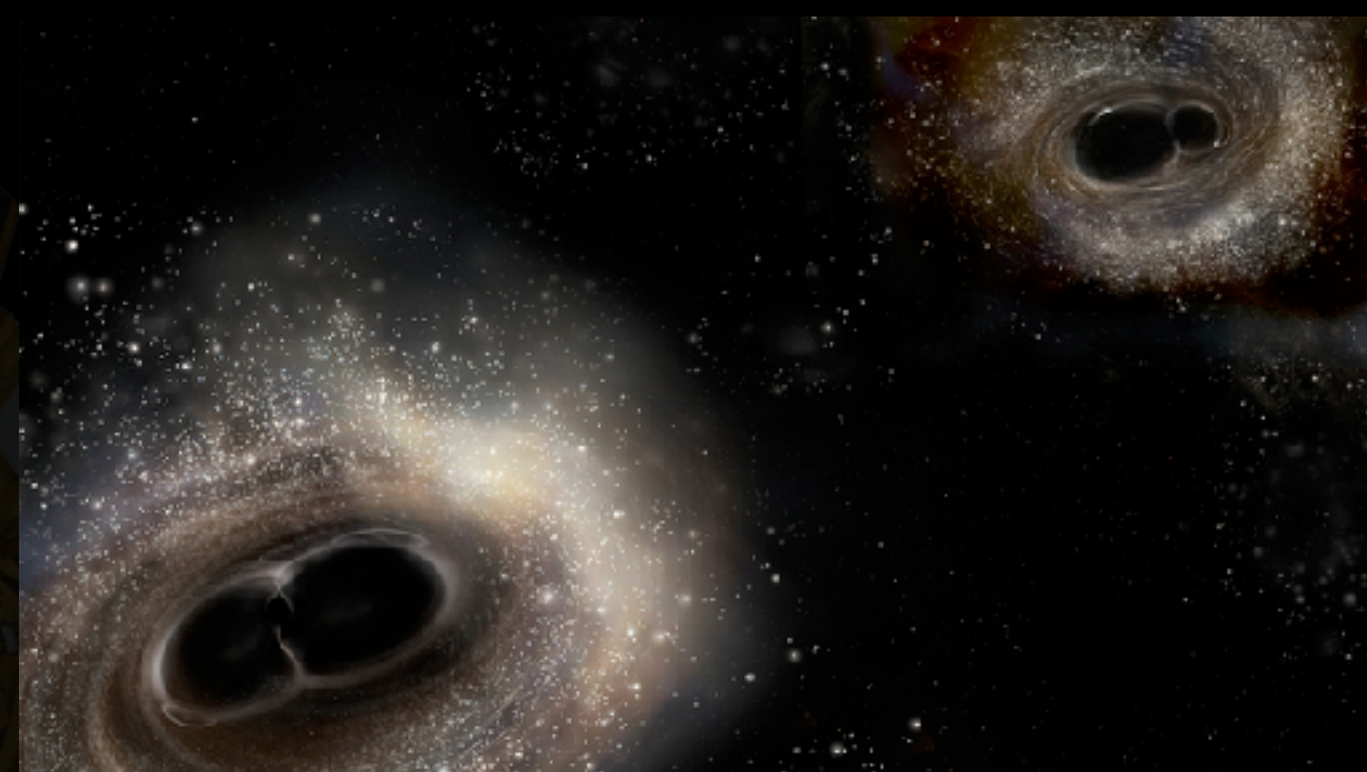
- 6 x10^7 galactic binaries



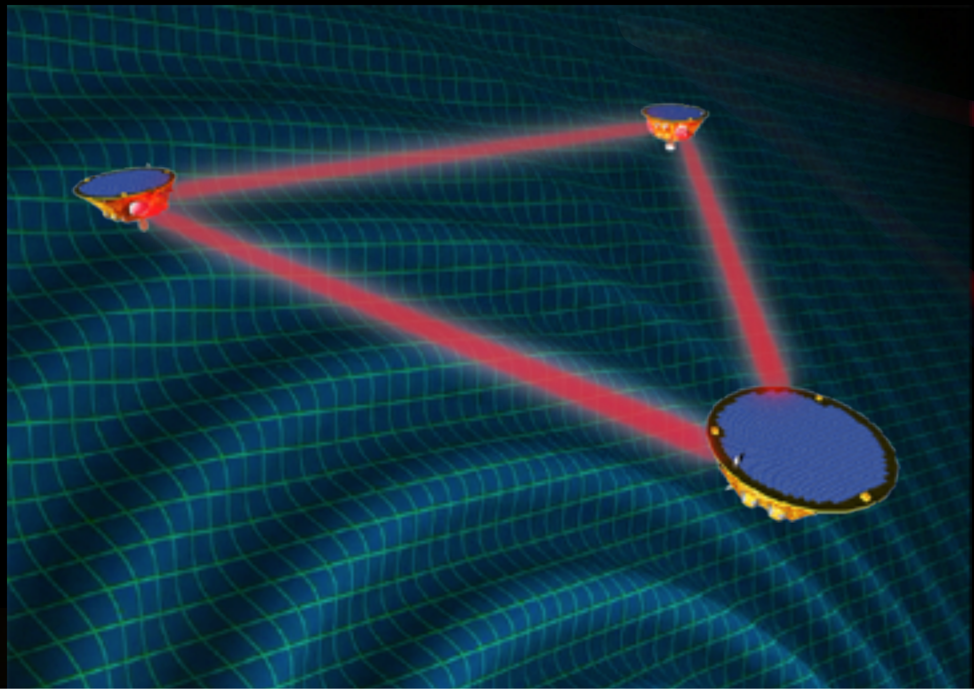
Stellar mass BH binaries

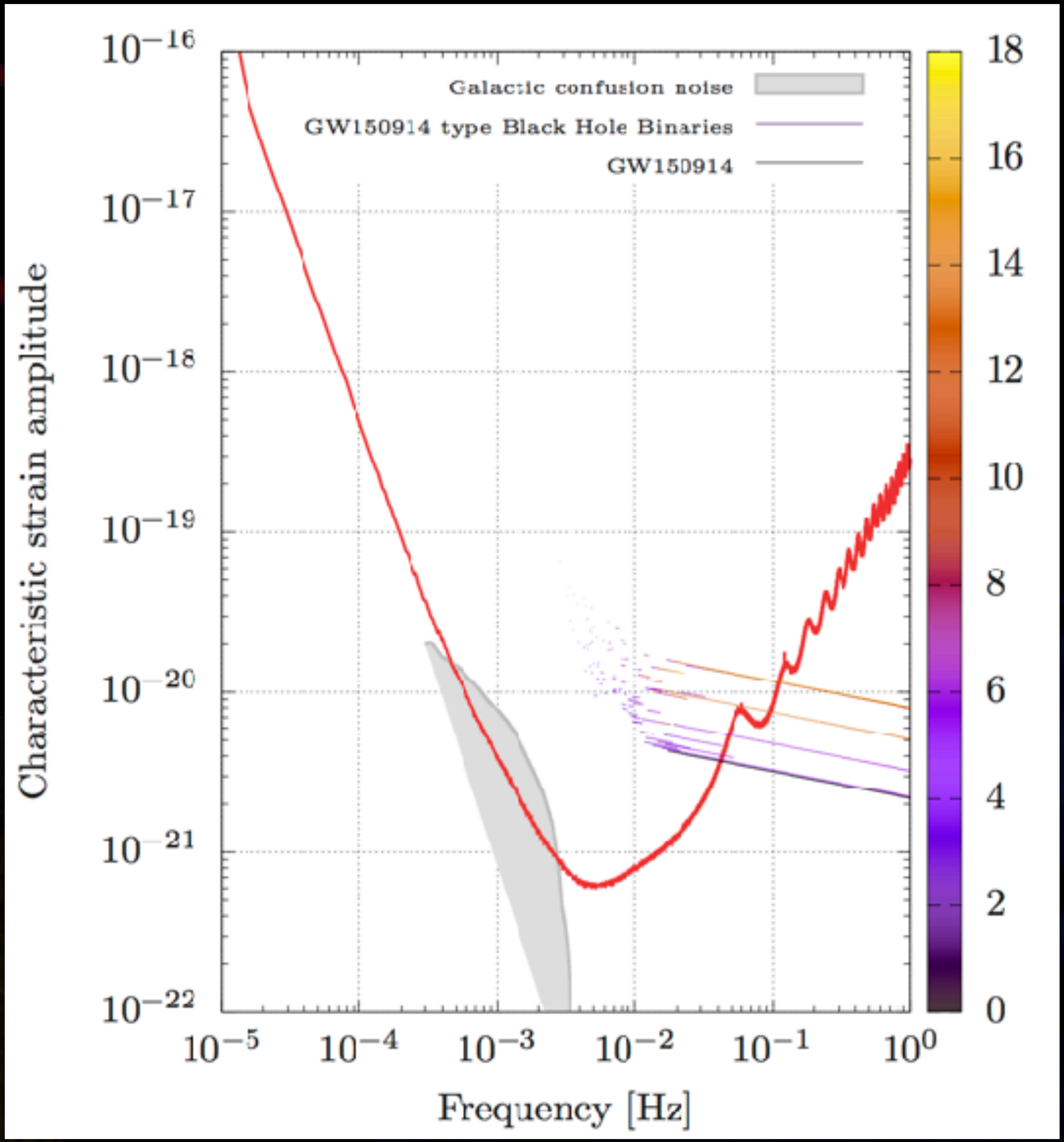
- Binaries with 2 black holes of masses between few M_{Sun} and 100 M_{Sun} , so called “Stellar mass BH Binaries”
- Inspiral: emission in the mHz band
- Merger: powerful emission around few tens Hz
  => many sources already observed

- Fast evolution: few years
  from tens mHz to tens Hz
  => multi-observatories
  observations



Stellar mass BH binaries





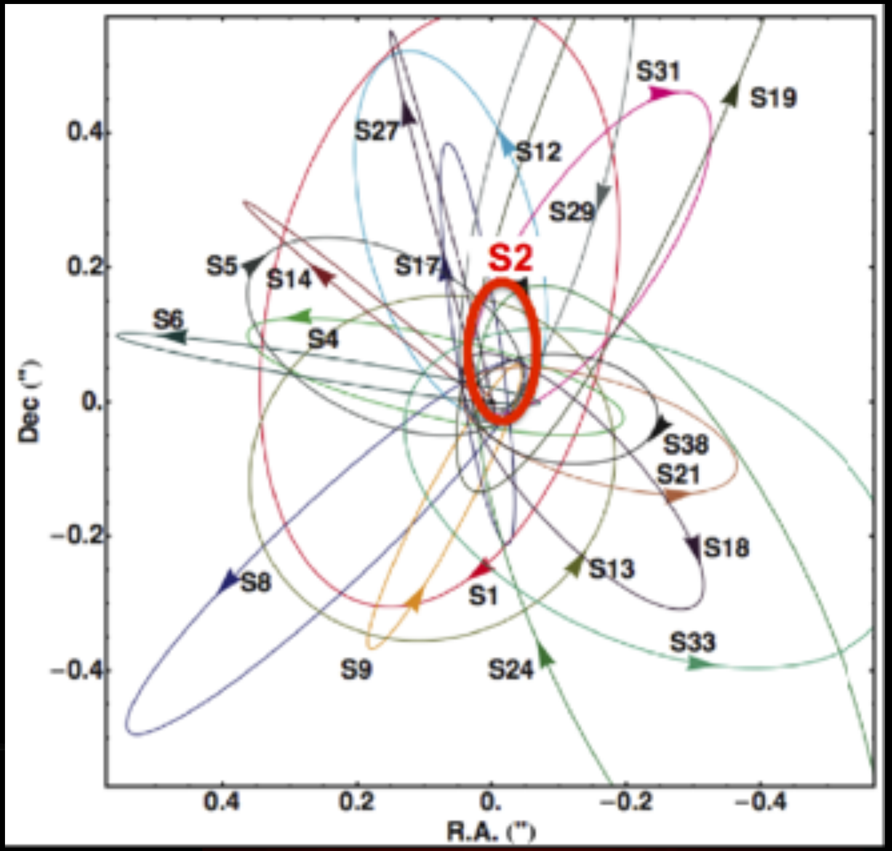
GW sources

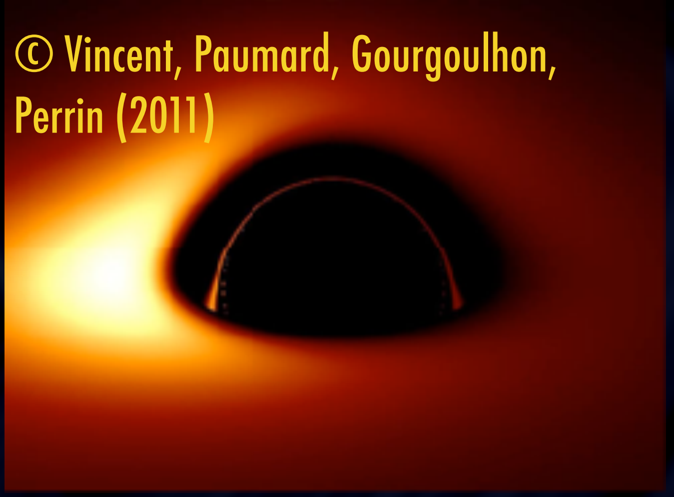
- 6×10^7 galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)

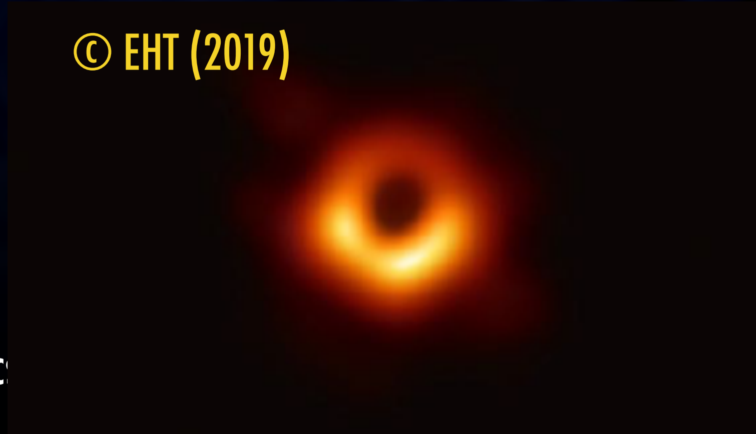
Supermassive Black Holes

- Observations:
  - Sgr A* : 4.5x10^6 M$_{Sun}$ at the center of the Milky Way (VLT - Gravity)
  - M87: 6.5x10^9 M$_{Sun}$ (picture EHT)
- Supermassive Black Hole are indirectly observed in the centre of a large number of galaxies (Active Galactic Nuclei).
- Observations of galaxy mergers =>

  => SuperMassive BH Binaries (SMBHB) should exist.




© Vincent, Paumard, Gourgoulhon, Perrin (2011)

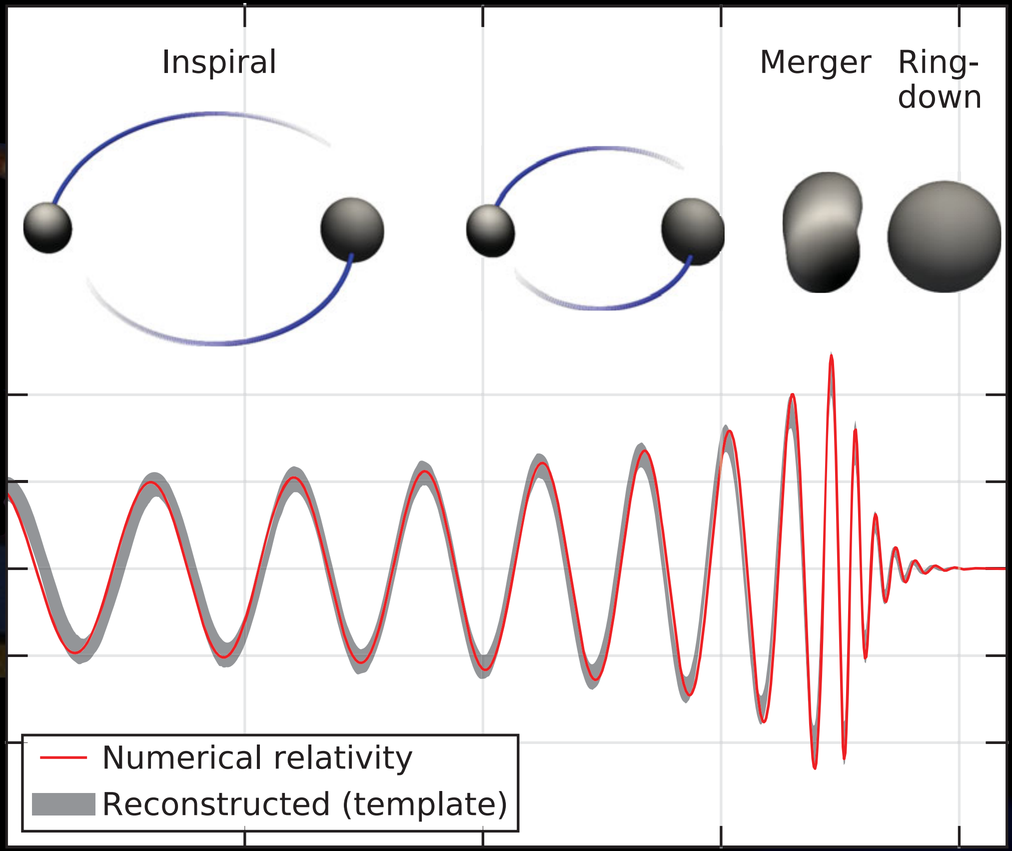

© EHT (2019)


NGC 6240 (Komossa et al. ApJ 582 L15)


Antennae galaxies

Super Massive Black Hole Binaries

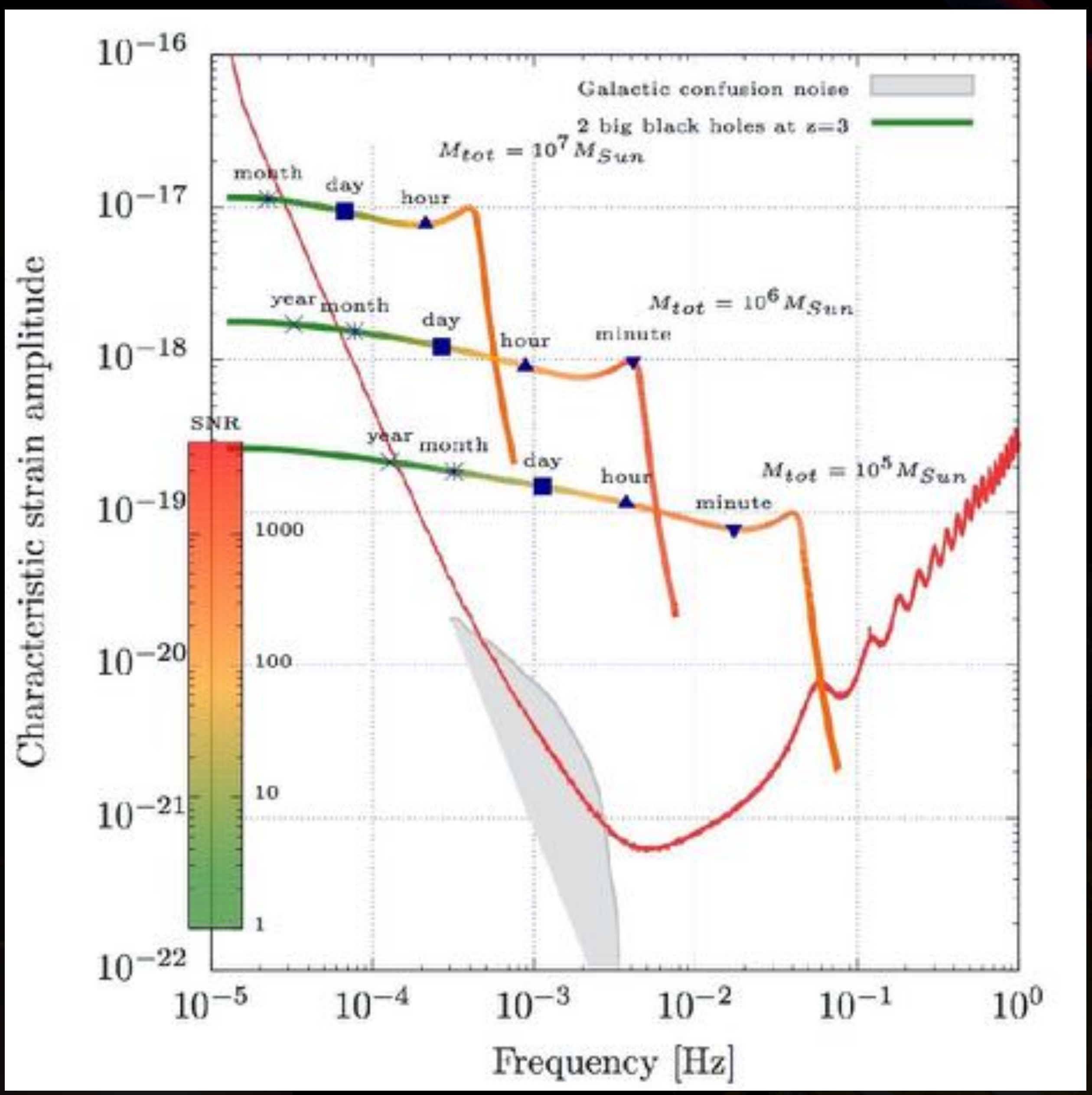
- Gravitational wave:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.

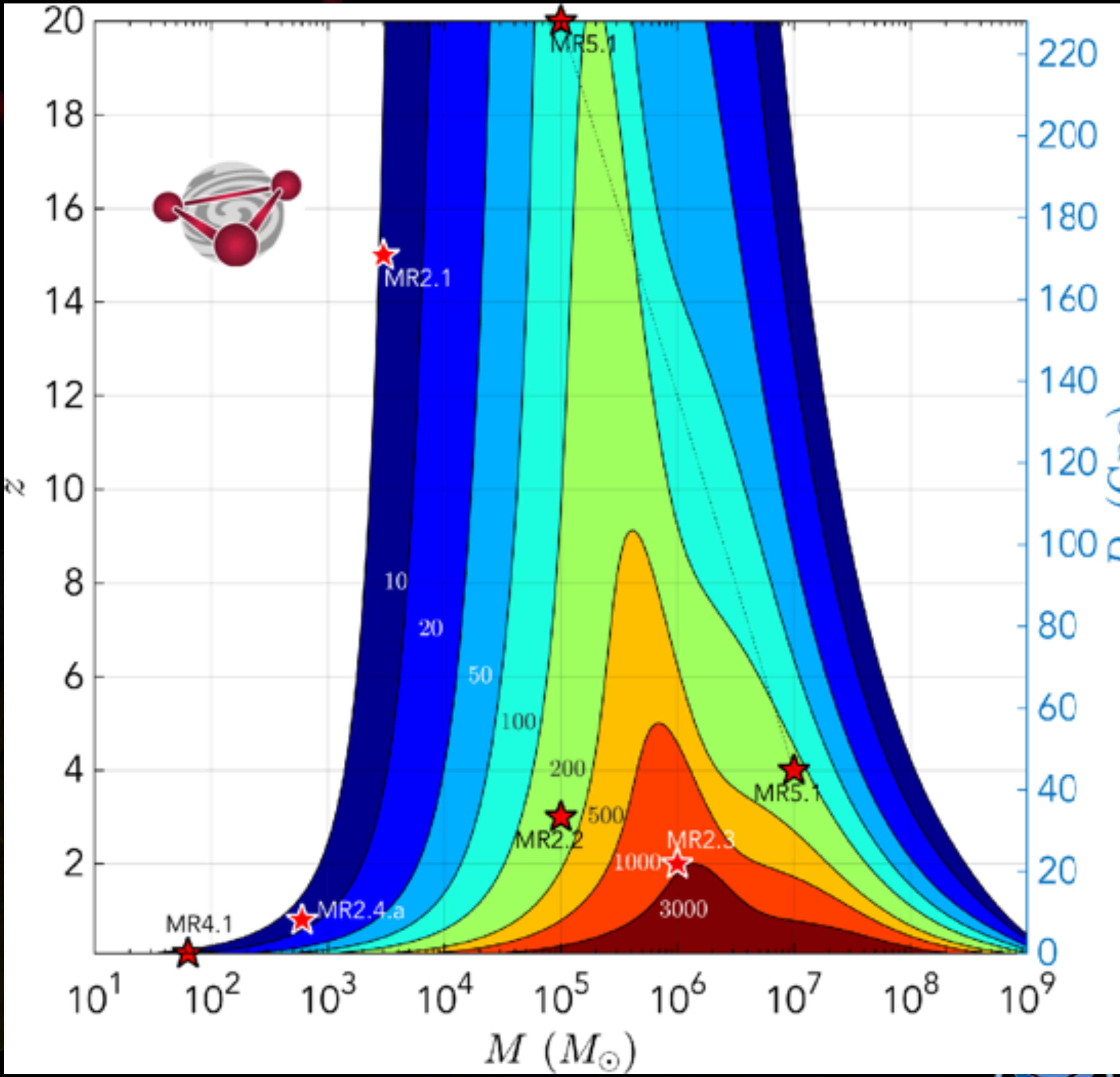


- Duration: between few hours and several months
- Signal to noise ratio: until few thousands
- Event rate: 10-100/year

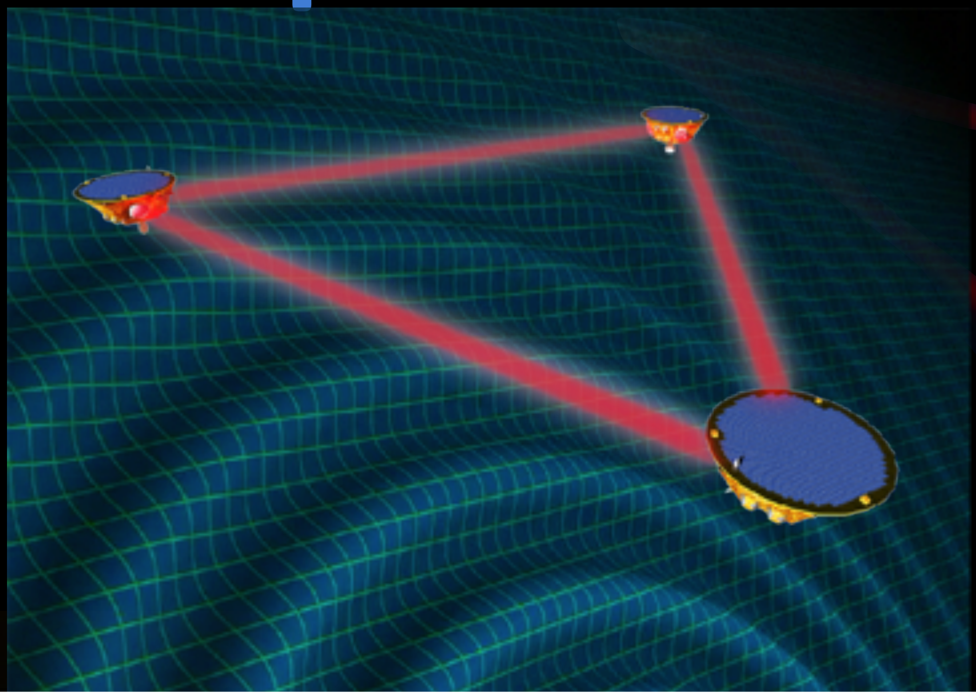
Super Massive Black Hole Binaries

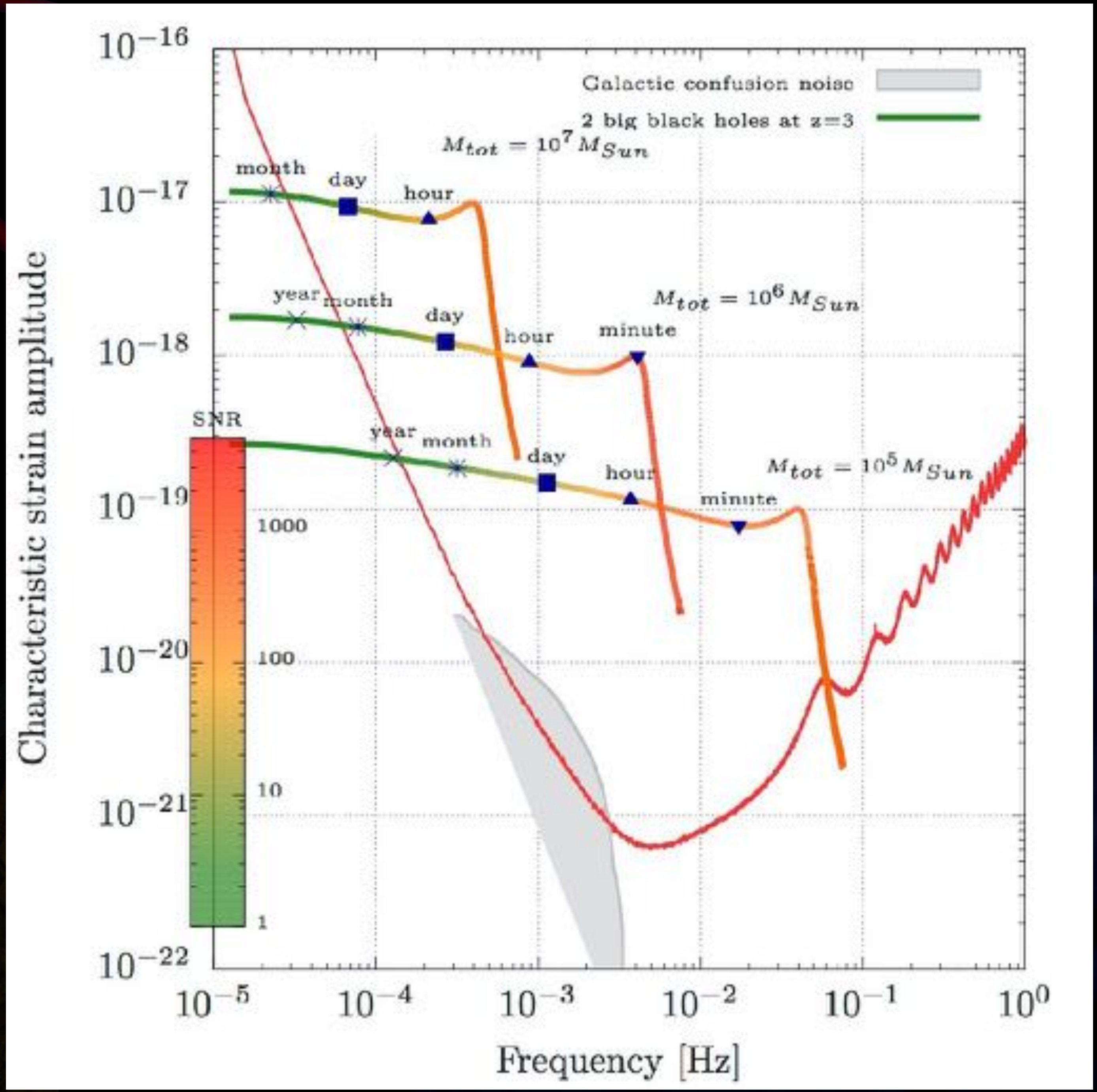
- LISA: SMBHB from 10^4 à 10^7 solar masses in "all" Univers





Super Massive Black Hole Binaries



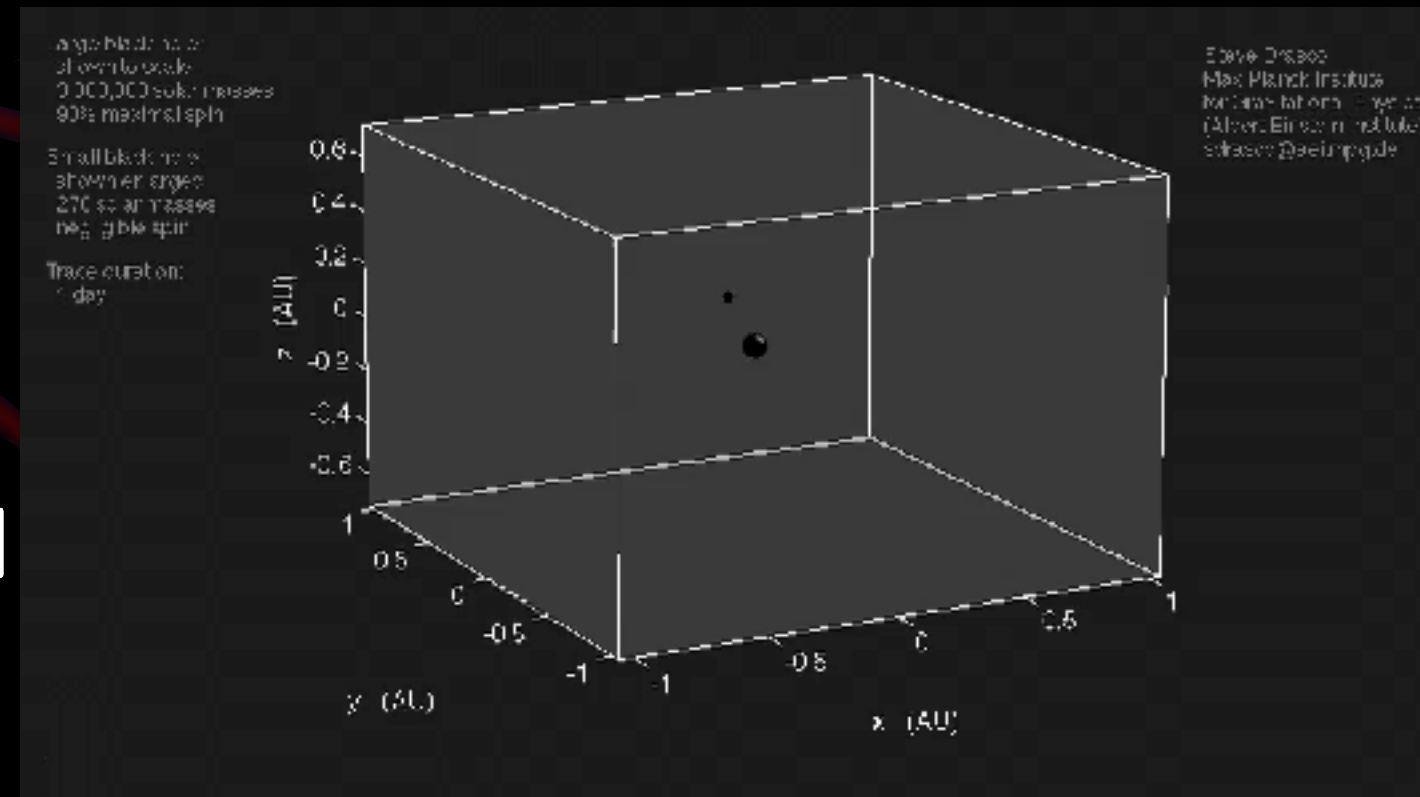


GW sources

- 6×10^7 galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs

EMRIs

- Capture of a “small” object by massive black hole ($10 – 10^6\ M_{Sun}$): Extreme Mass Ratio Inspiral
  - 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



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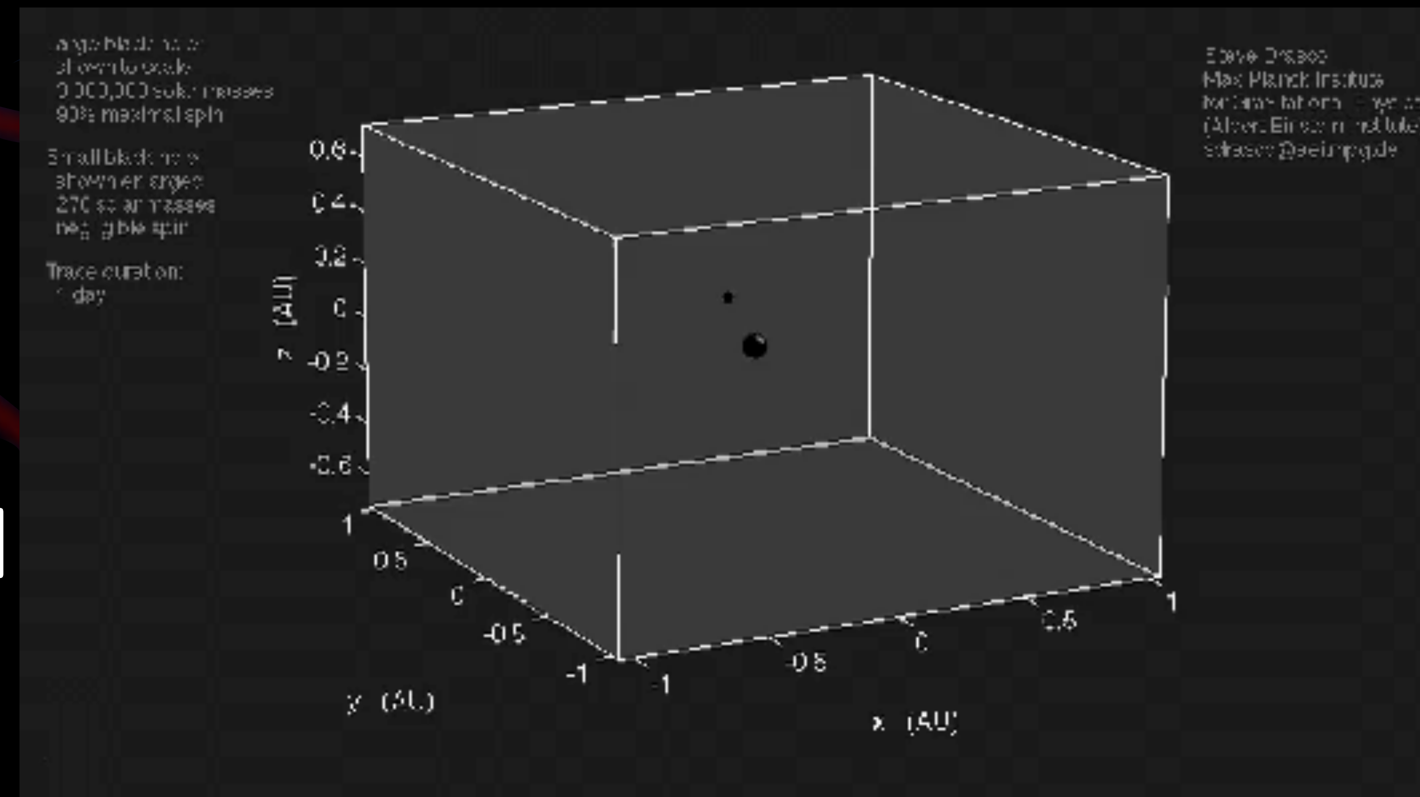
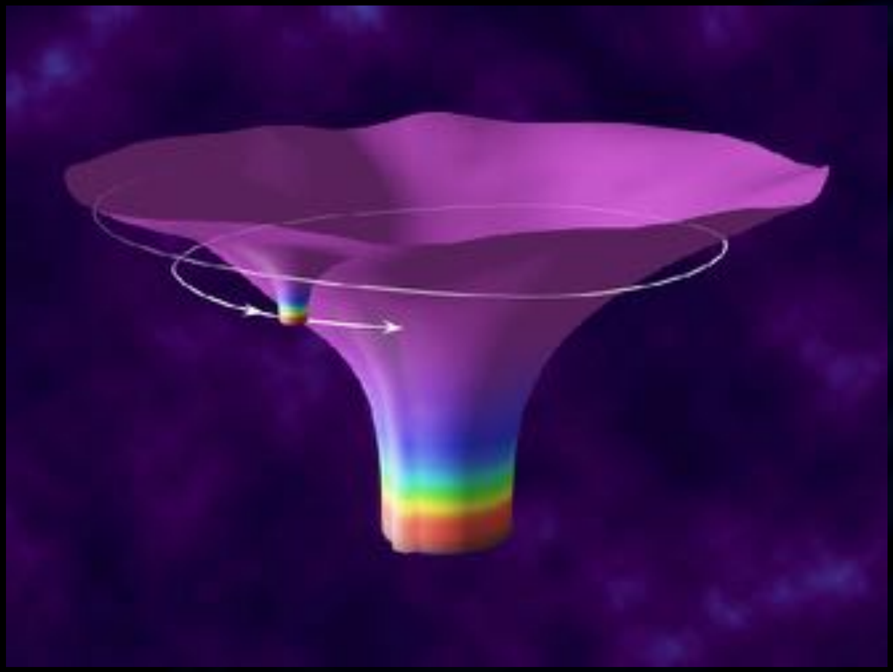
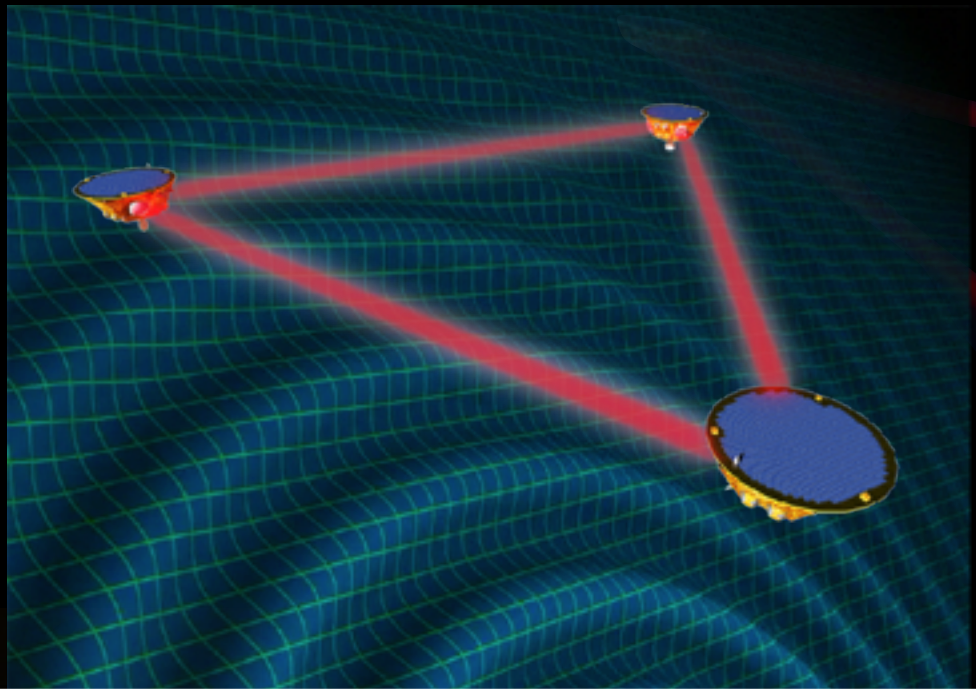


EMRIs

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



EMRIs



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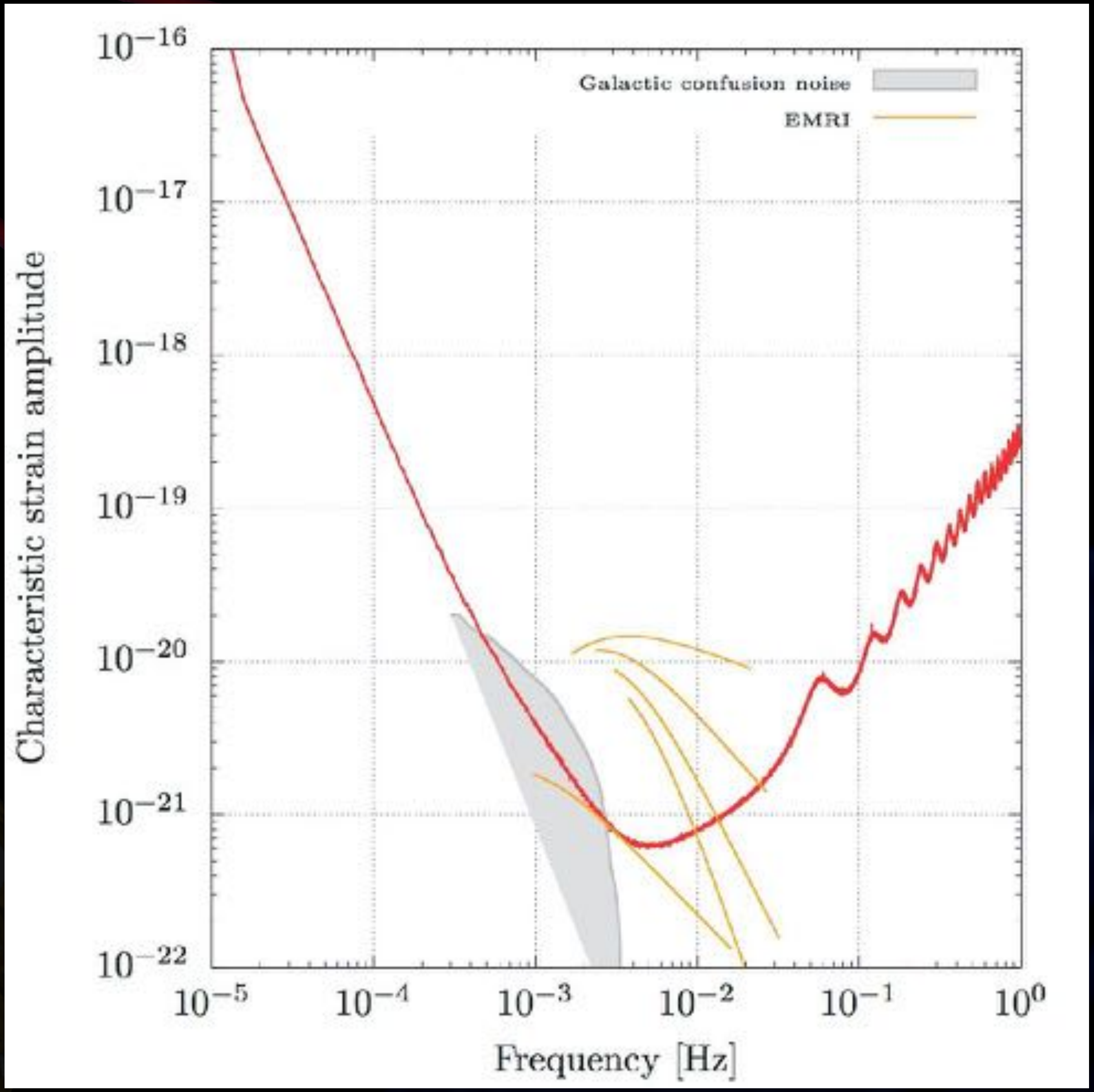
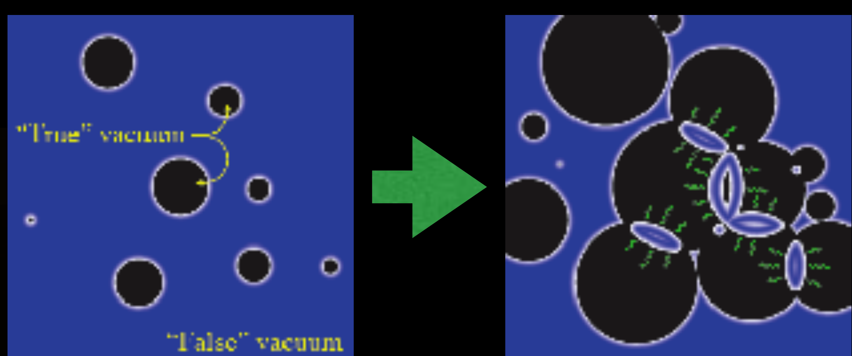
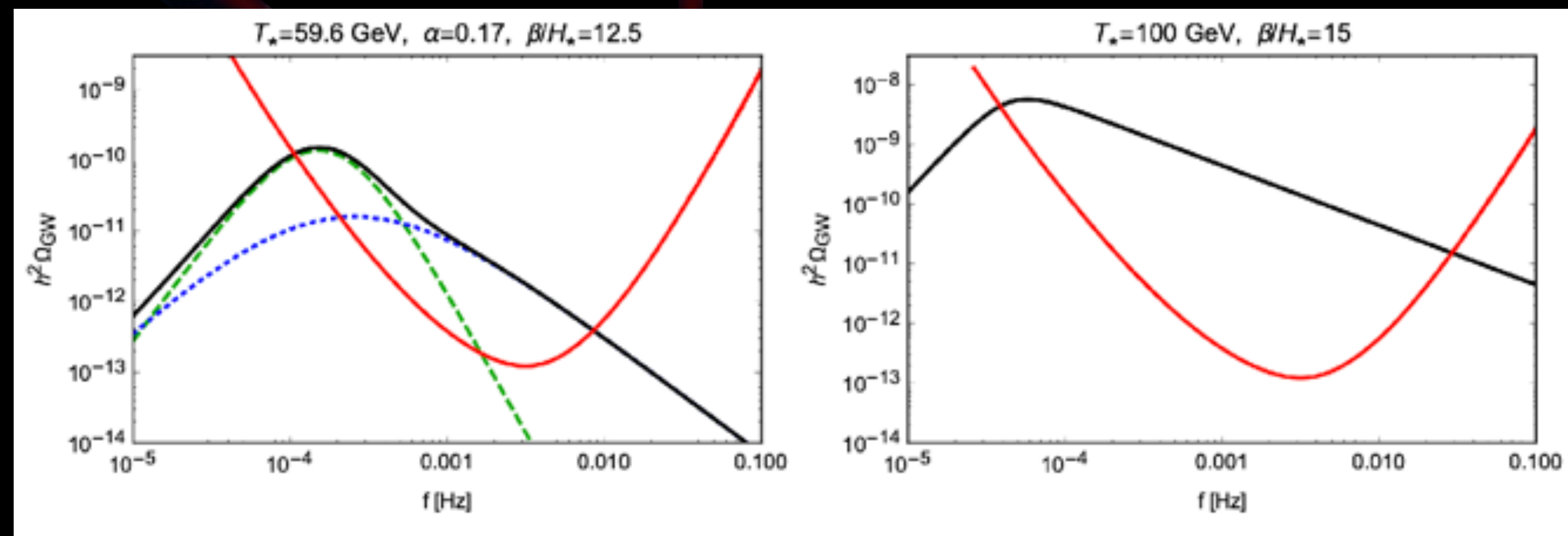


Cosmological backgrounds

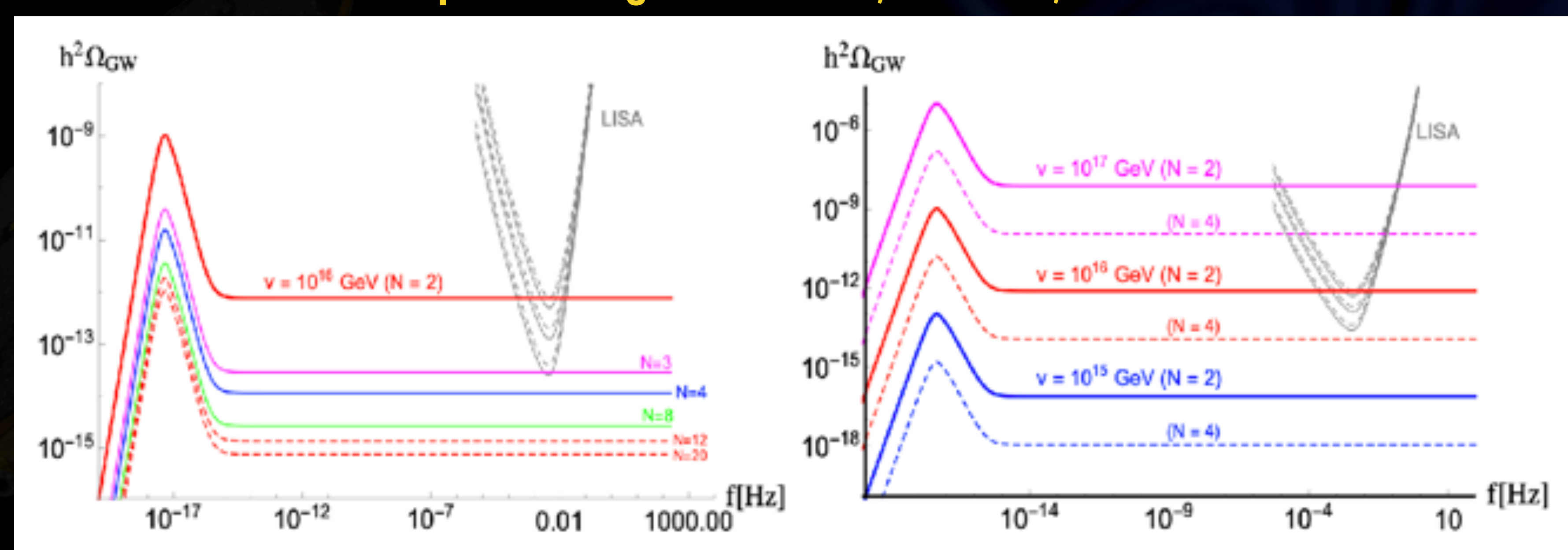
- Potential detection of cosmological background from:
  - First order phase transition in the very earlyUniverse





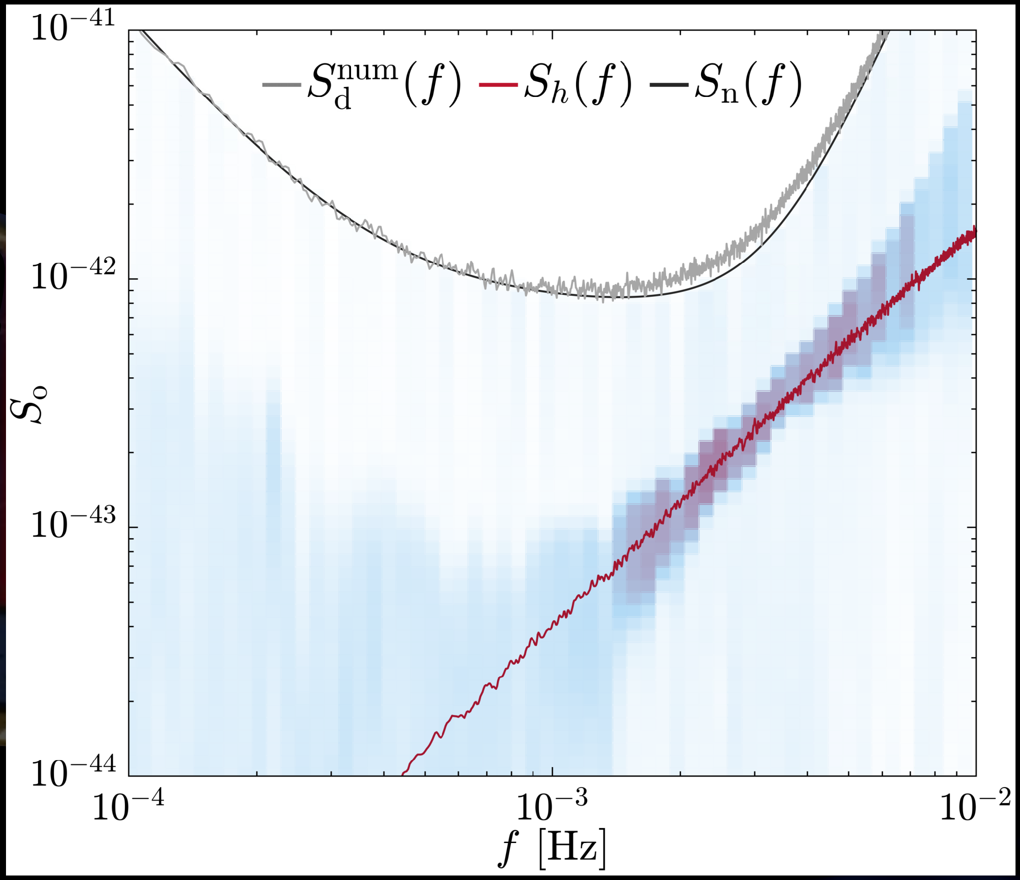
Caprini & Figueroa 2018, CQG 35,163001

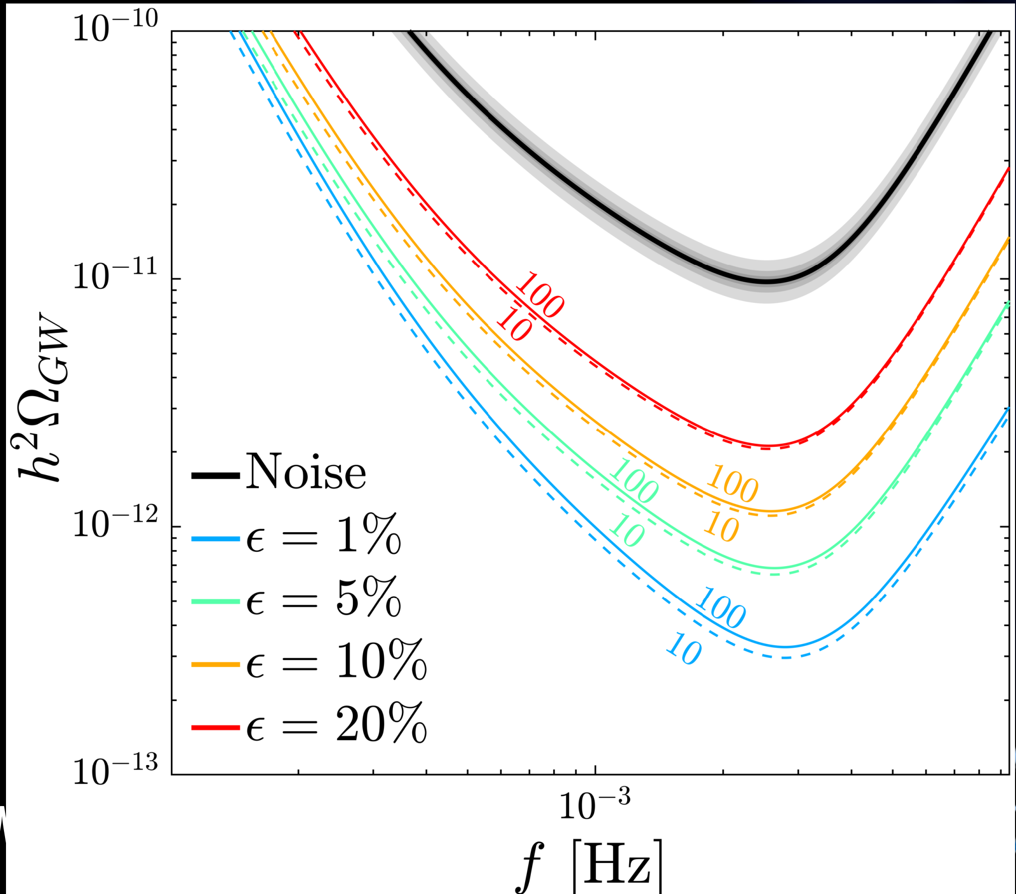
- Cosmic strings network
- ...



Cosmological backgrounds

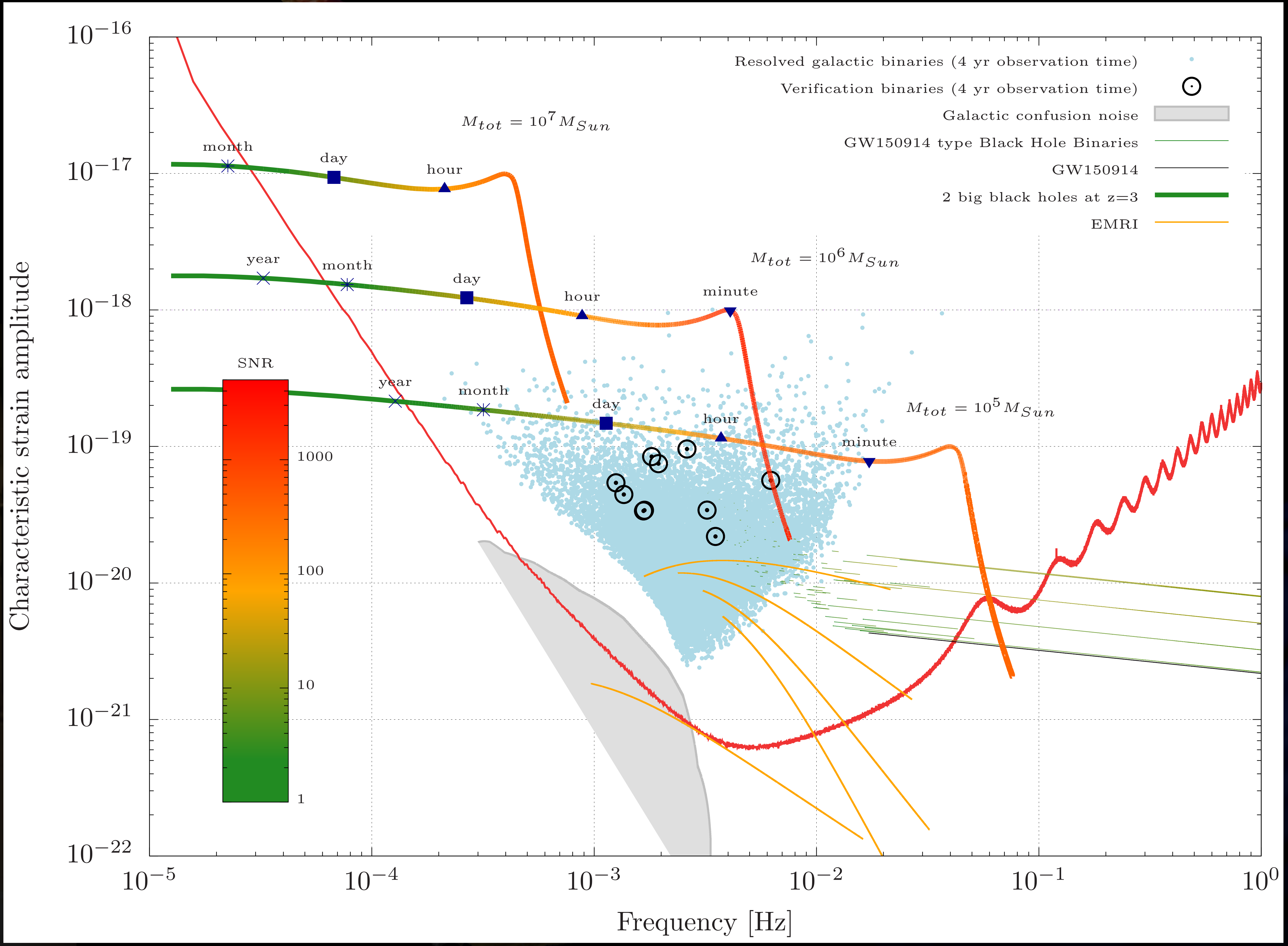
- Detectability and characterisation: challenging!
  - Separation of the SGWB and instrument noises
    - Noise knowledge? Study of possible calibrations
    - Use of TDI possibilities?
  - Separation from foreground from other sources and residual after the "subtraction" of other sources
  - Data analysis possibility to be deeply investigated





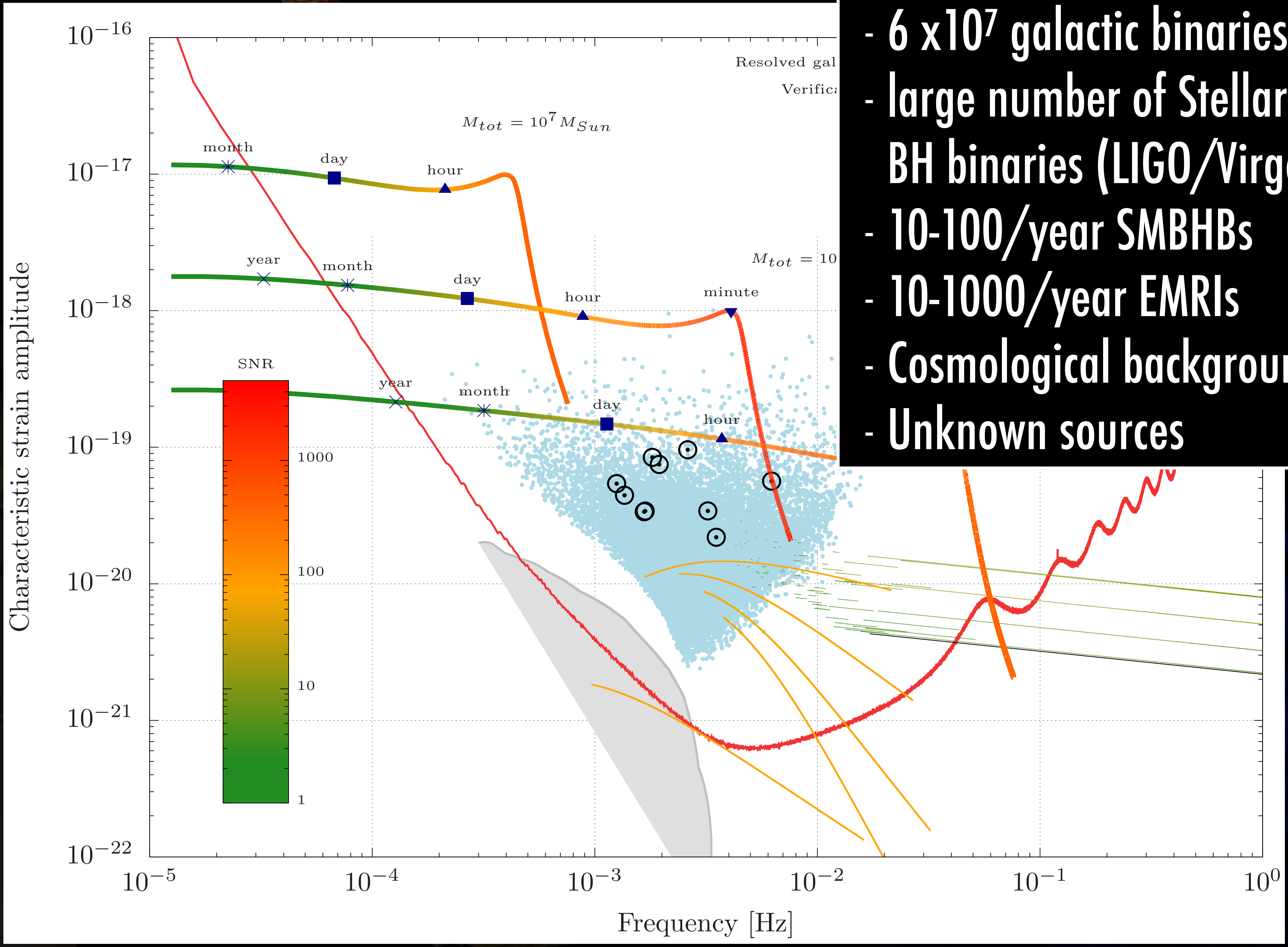
N. Karnesis et al. (2020)

GW sources



Characteristic strain amplitude
Frequency [Hz]
Resolved galactic binaries (4 yr observation time)
Verification binaries (4 yr observation time)
Galactic confusion noise
GW150914 type Black Hole Binaries
GW150914
2 big black holes at z=3
EMRI
SNR
1000
100
10
1
$M_{tot} = 10^7 M_{Sun}$
$M_{tot} = 10^6 M_{Sun}$
$M_{tot} = 10^5 M_{Sun}$
month
day
hour
year
minute
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
- large number of Stellar Mass BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources

LISA science objectives

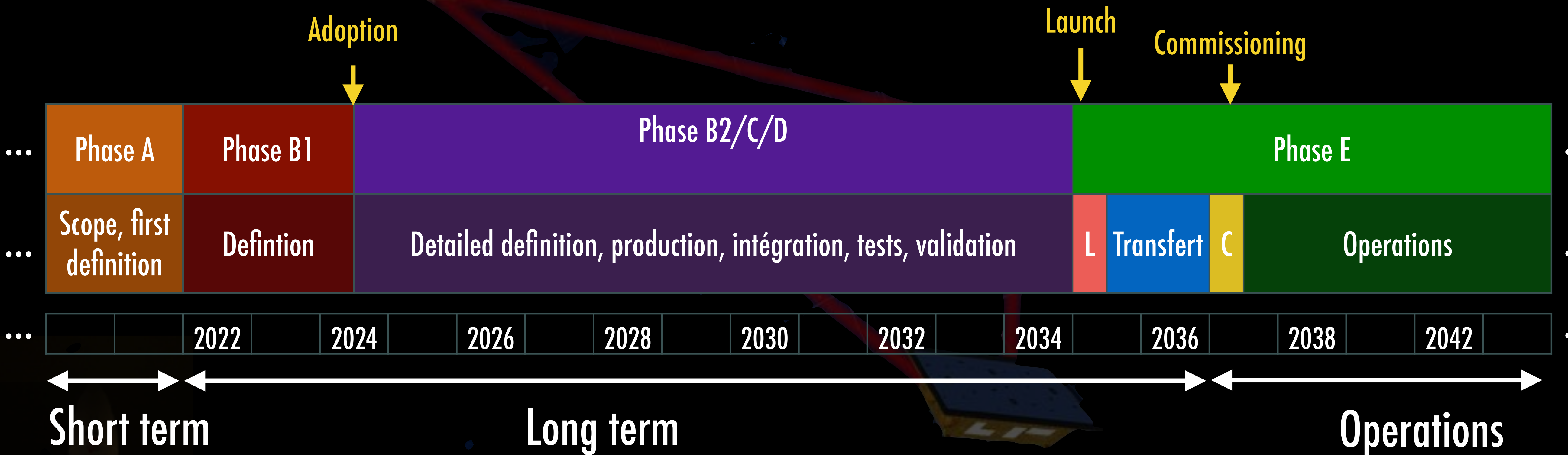
- SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages
- SO3: Probe the dynamics of dense nuclear clusters using EMRIs
- SO4: Understand the astrophysics of stellar origin black holes
- SO5: Explore the fundamental nature of gravity and black holes
- SO6: Probe the rate of expansion of the Universe
- 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 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→2021 : phase A: payload study + competitive studies for 2 primes
- 2021→2023 : phase B1
- 2024 : mission adoption
- During about 10 years : production: challenge (3 S/Cs with 2 MOSAs)
- 2034 : launch Ariane 6.4
- 1.5 years for transfert
- 6 - 12 months for commissioning
- 4-6 years of nominal mission (75% duty cycle)
- Possible extension to 10 years

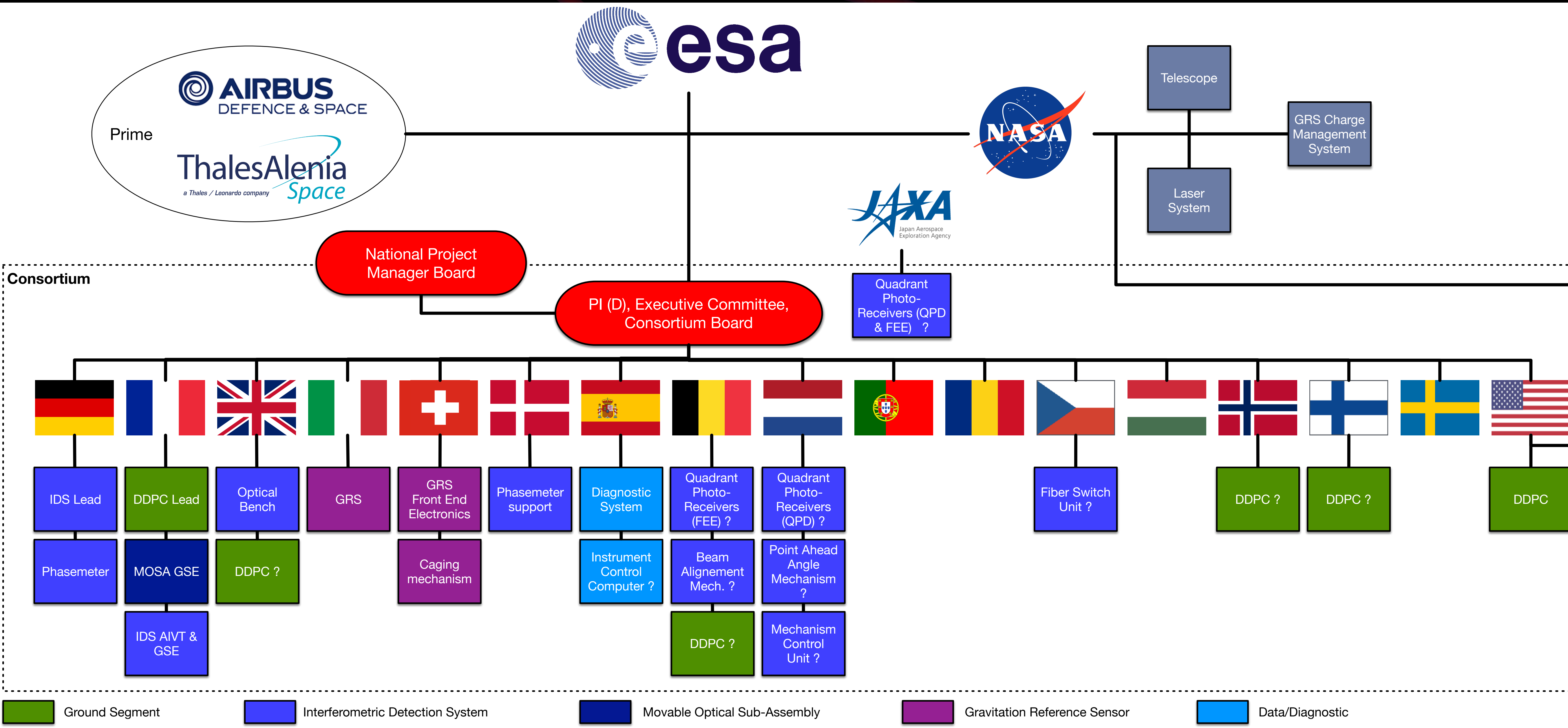
GW observations!

LISA timeline



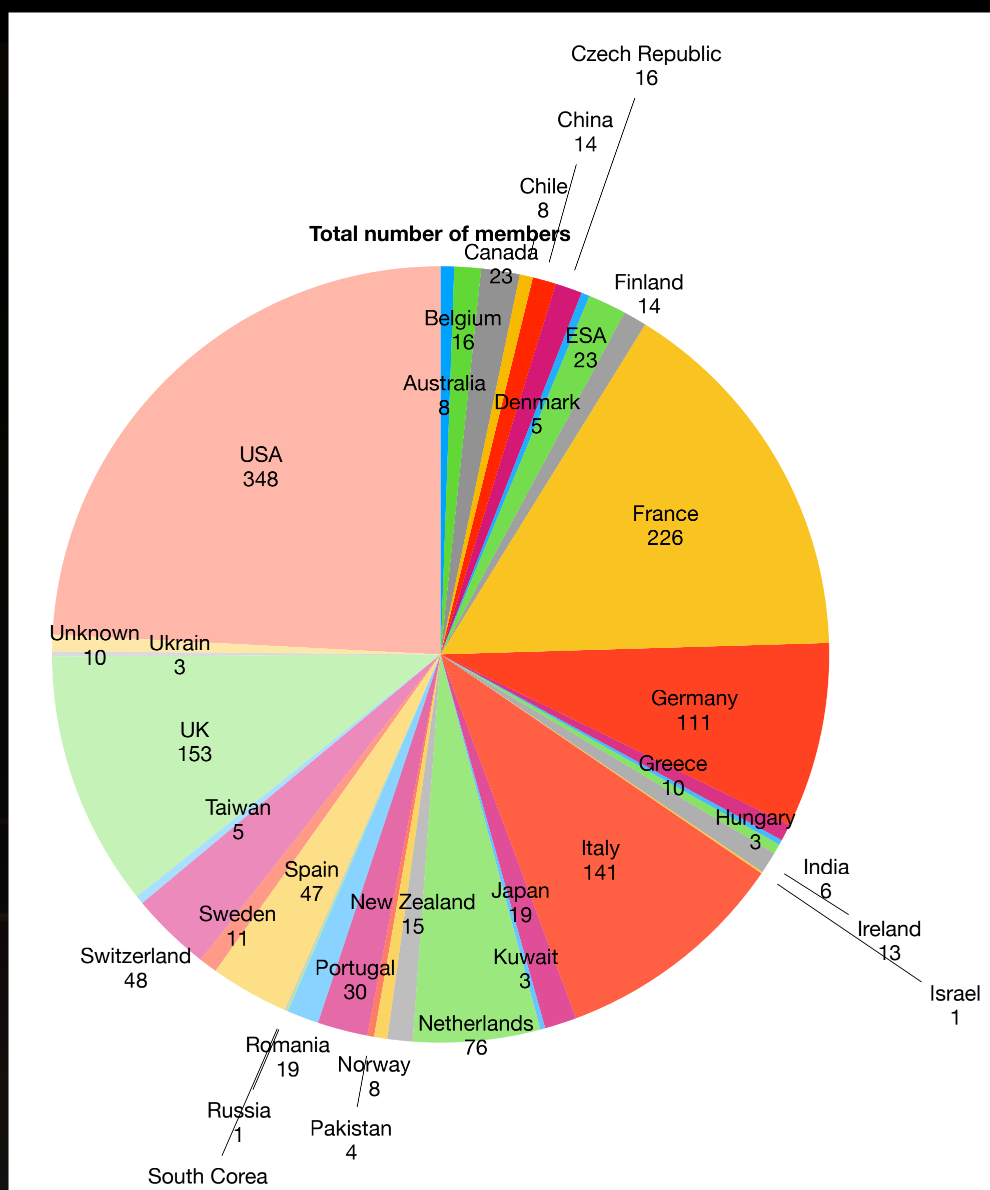
- Activities during the phase A:
  - Scope, first definitions, organisation, performances, ...
  - For the ground segment:
    - first mission of this kind + large number of overlapping sources: challenge for data analysis => development and prototyping started very early
    - Support & contribution to Consortium activities: figure of merits, performance model, simulations, ...

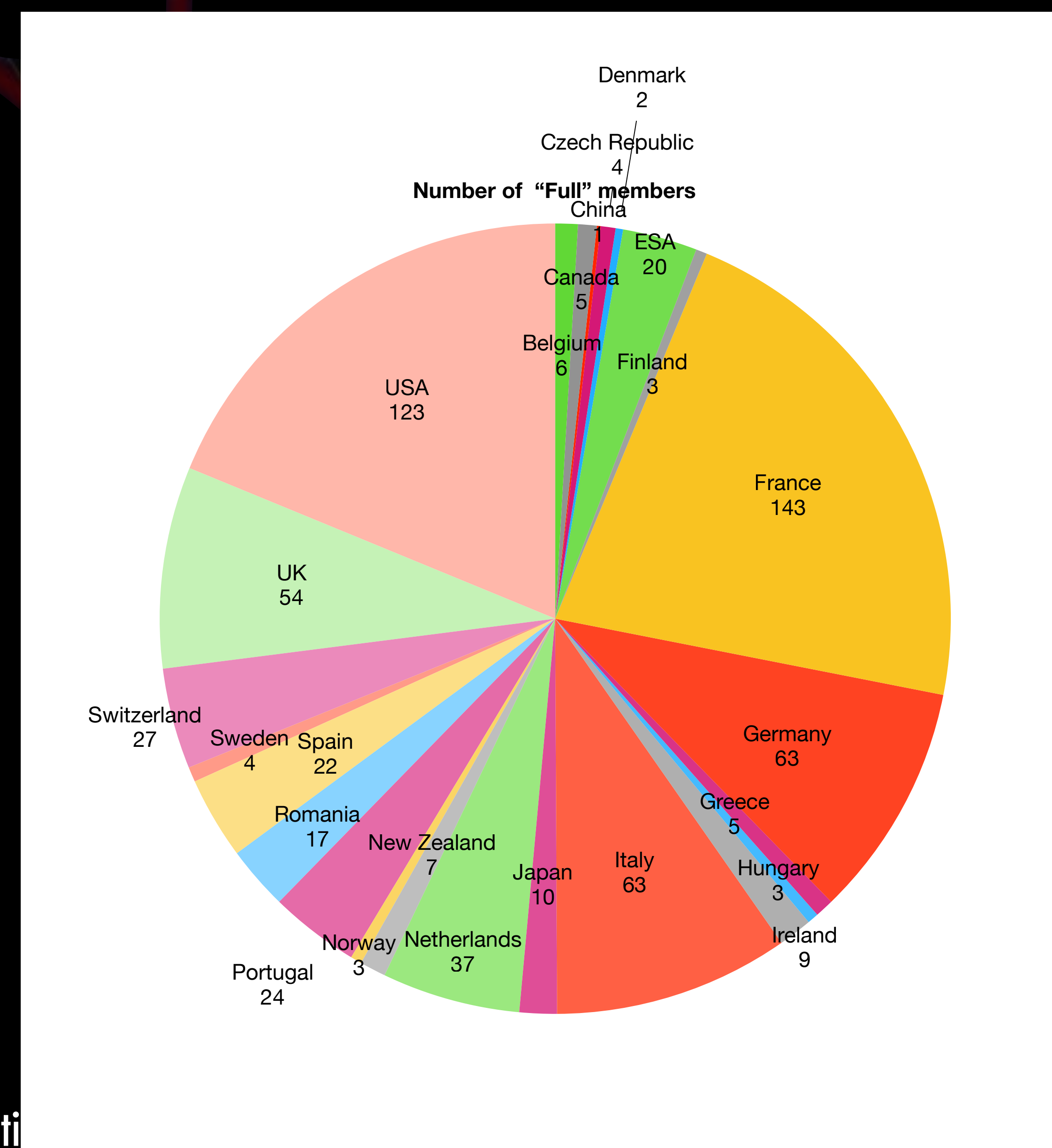
Organisation of LISA



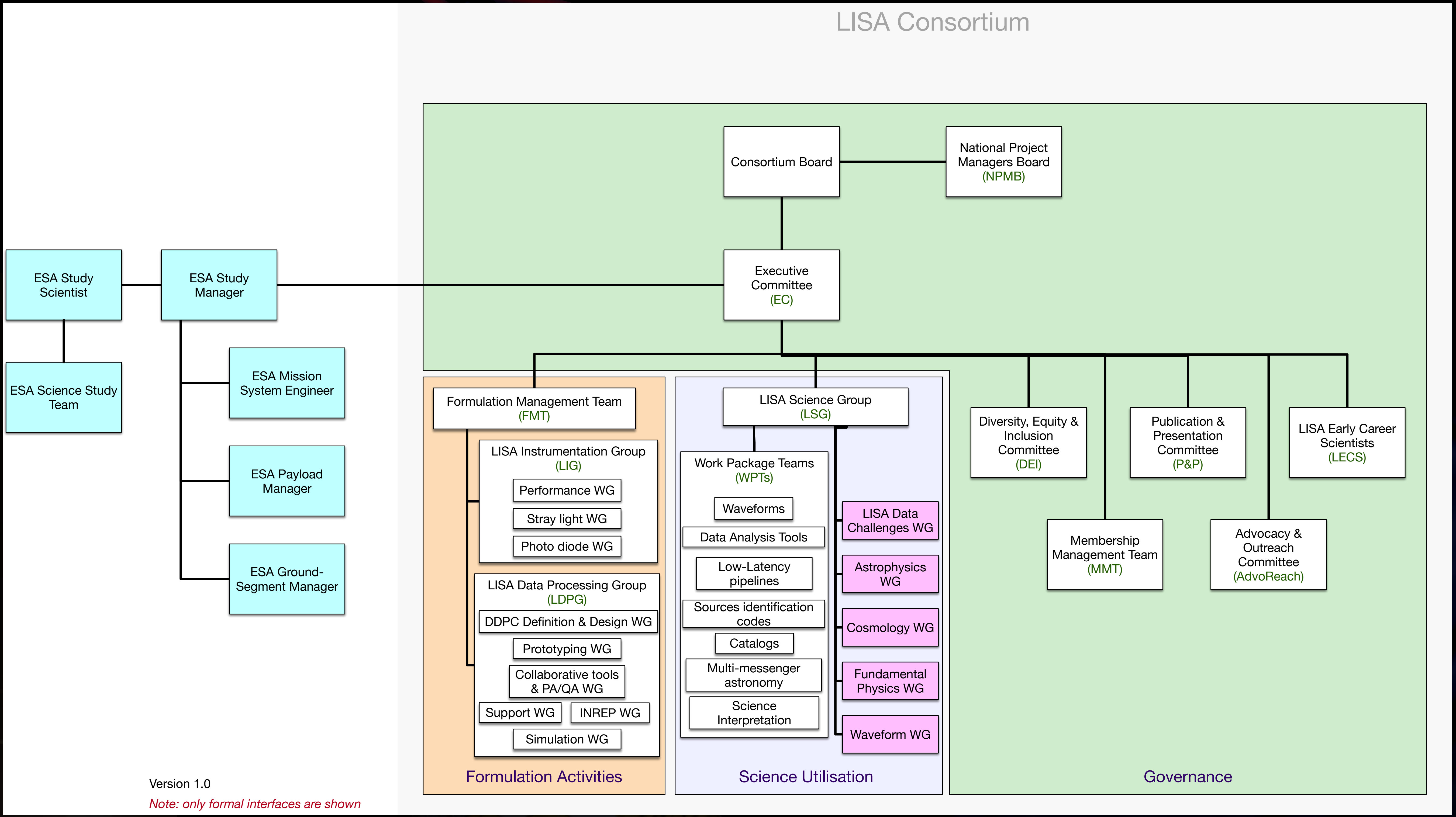
LISA Consortium

- Currently 1439 members
  - 655 full members committing time to LISA Consortium activities
  - 774 associates





Consortium Organisation



LISA Working Groups

- Large number of members :
  - Astrophysics: 502
  - Cosmology: 330
  - Fundamental Physics: 354
  - Waveforms: 212
  - LISA Data Challenge: 237
- And active:
  - Regular workshops
  - Producing white papers: state of the art of LISA Science
  - Multiple projects within groups

Conclusion

- LISA mission is in phase A and progressing well for a launch in 2034.
- No critical technology but complexity in the high level of integration.
- Instrument is the payloads + the spacecrafts + on ground processing to suppress dominant noise
- Complex processing to suppress noises and extract GW sources
- LISA will observe a large number and variety of GW sources in the frequency band 10^{-5} to 1 Hz
- Stochastic GW Background: LISA has a huge potential but extracting SGWB for LISA data is challenging.

Thank you