LISA
Science & Ground Segment

Antoine Petiteau

(APC - Université de Paris)

IPHU conference on Gravitational Waves

Remote - 6th July 2021

THE GRAVITATIONAL WAVE SPECTRUM

SOURCES

quantum fluctuations in the very early Universe

binary supermassive black holes in galactic nuclei

phase transitions in the early universe

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

binary stars in the galaxy

and beyond

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

fast pulsars with mountains

Wave Period

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

Frequency (Hz)

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

DETECTORS

INFLATION PROBE

polarization map of cosmic microwave background

precision timing of millisecond pulsars

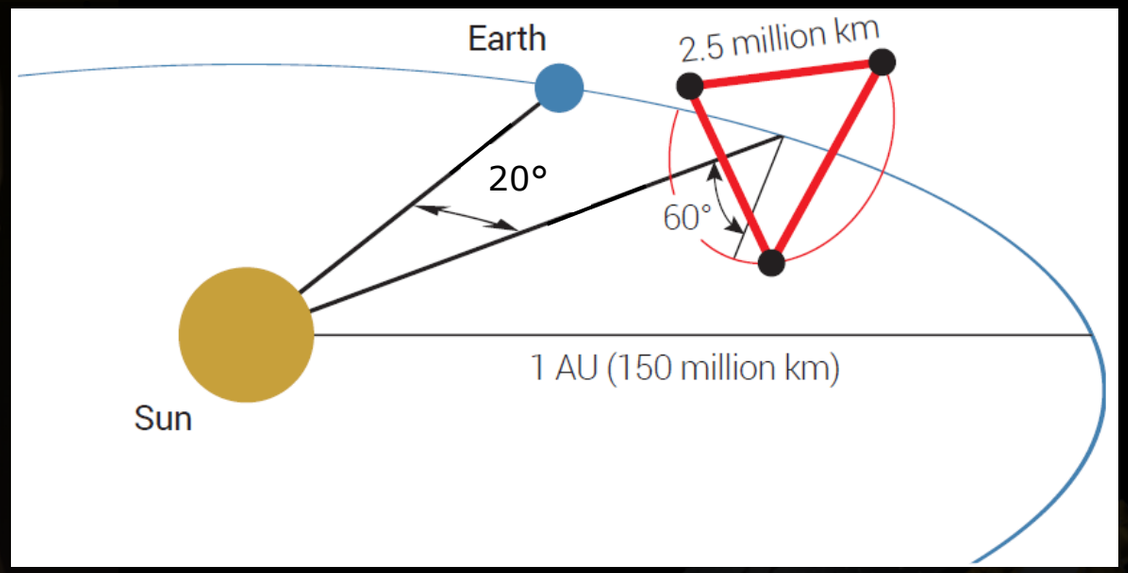
LISA

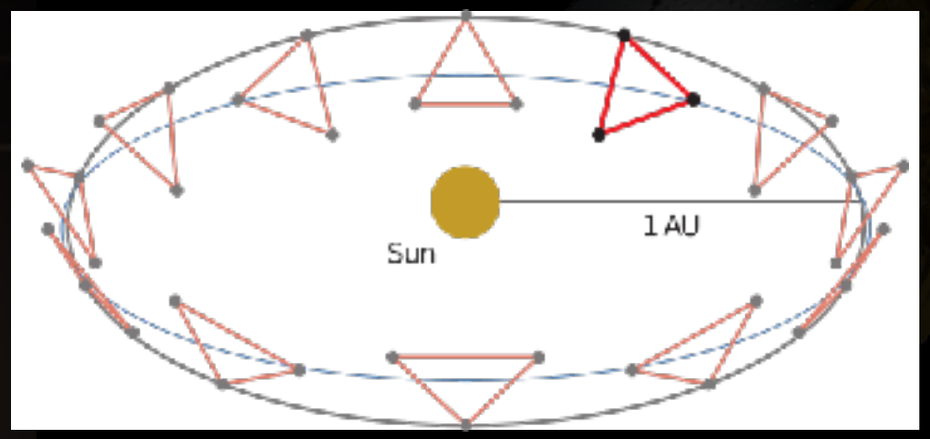
BIG BANG OBS

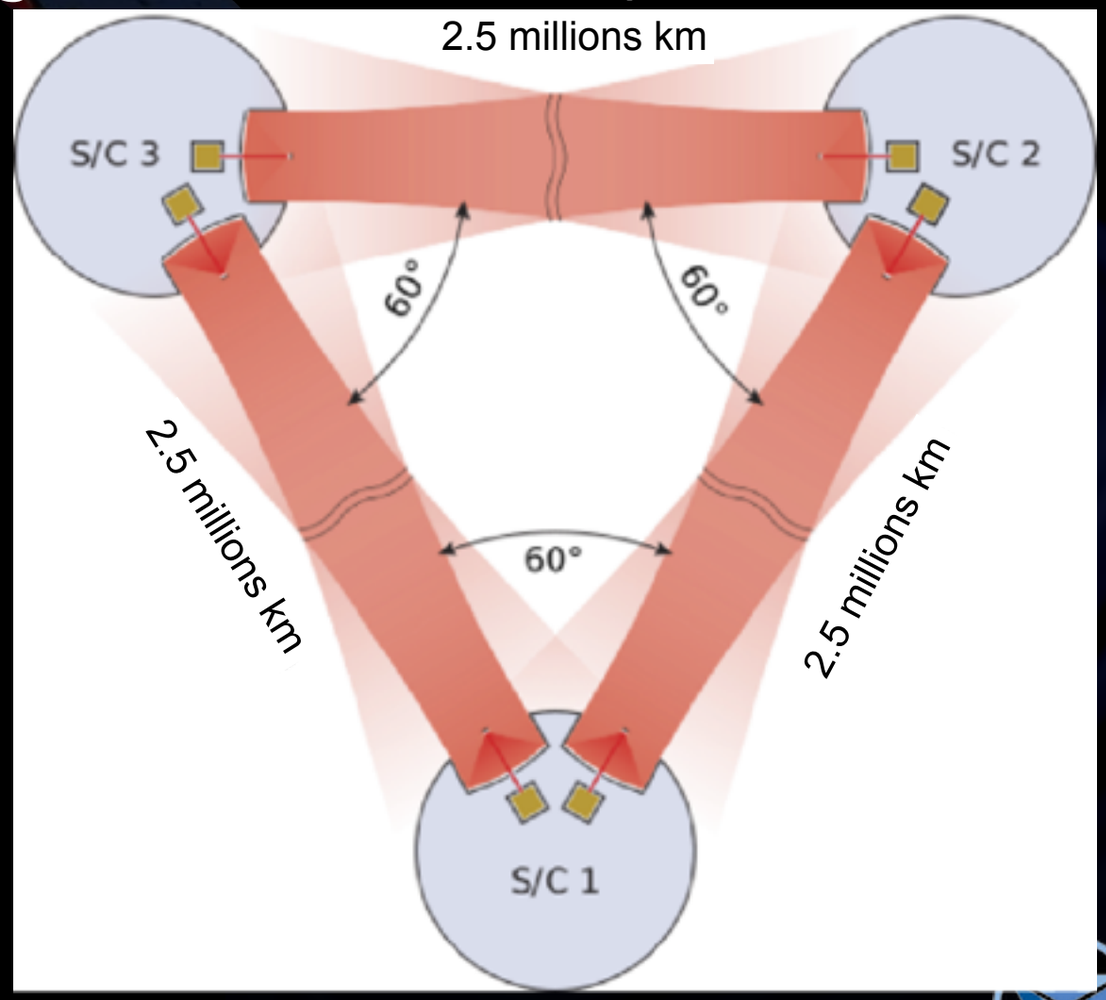
GEO, LIGO, VIRGO, TAMA

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

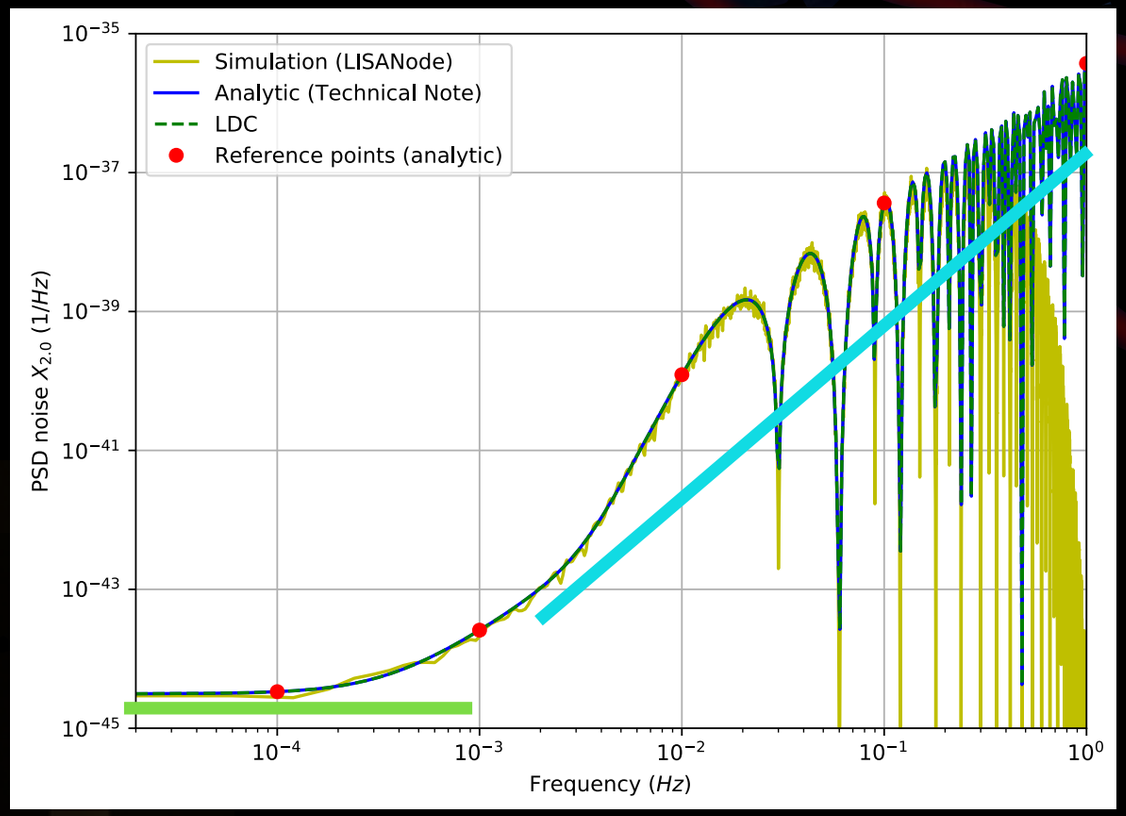




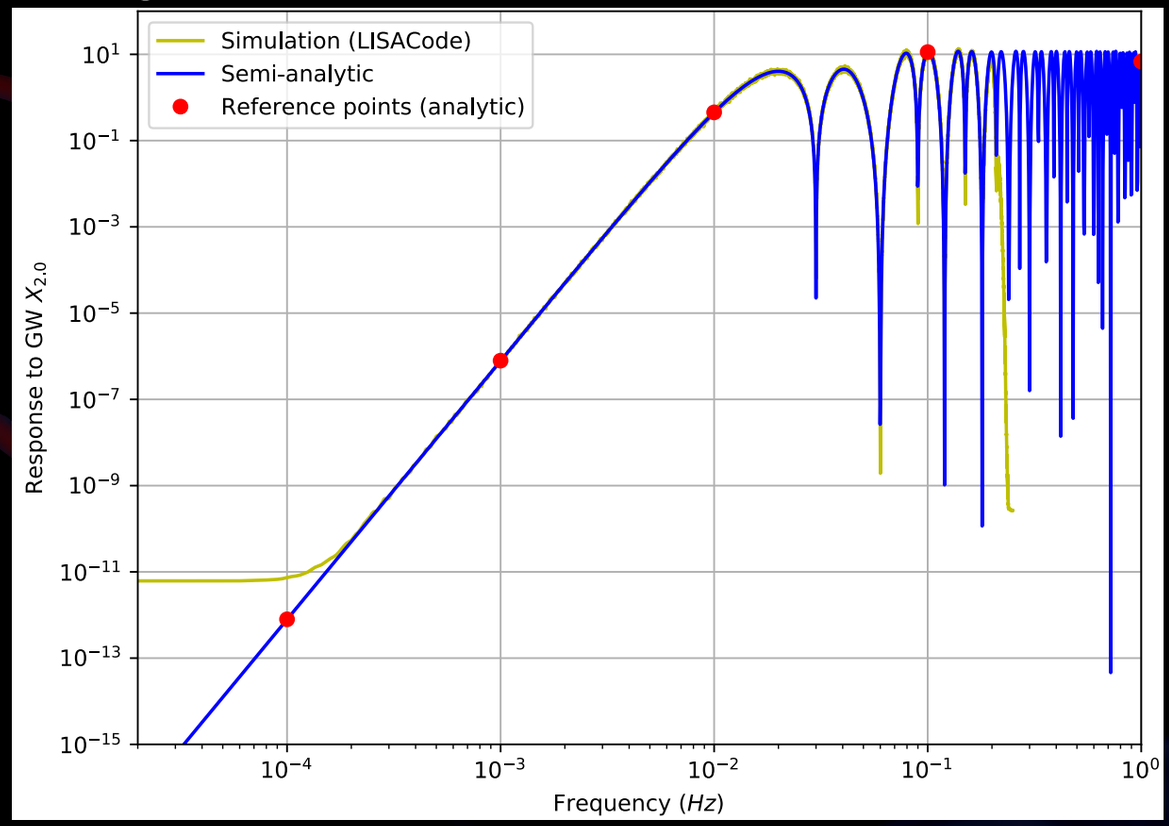


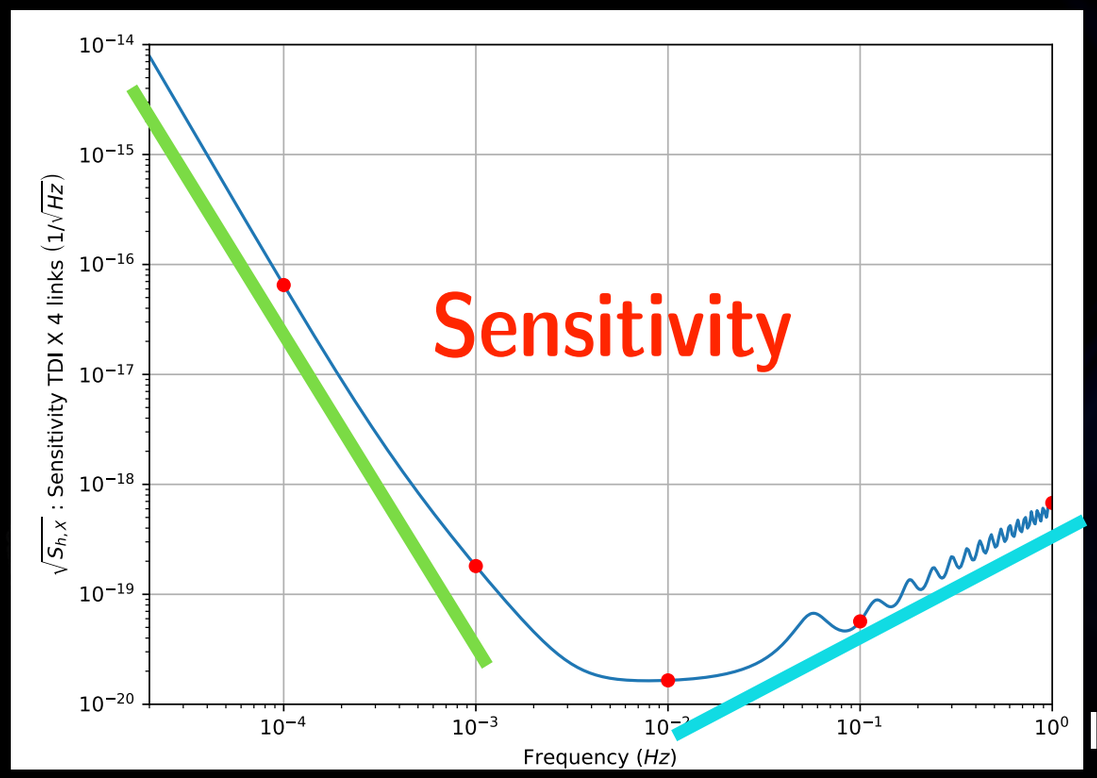
Sensitivity

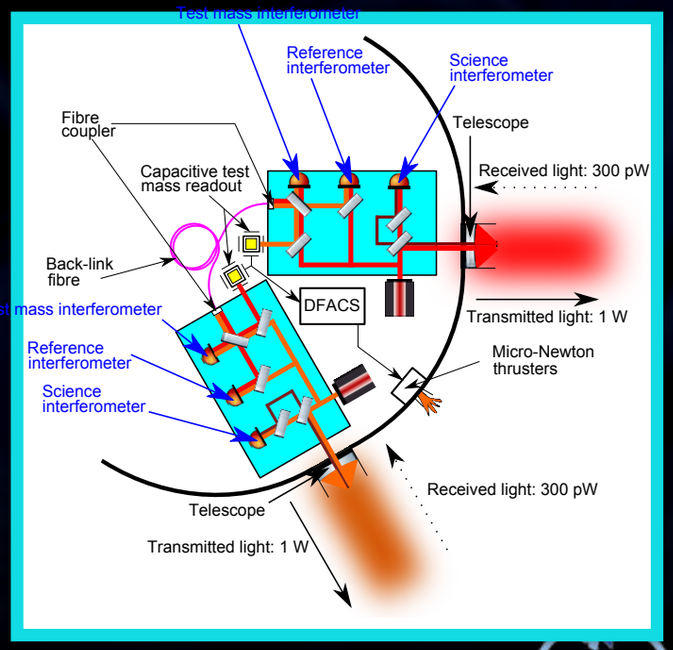
Noises



Response of the detector to GWs



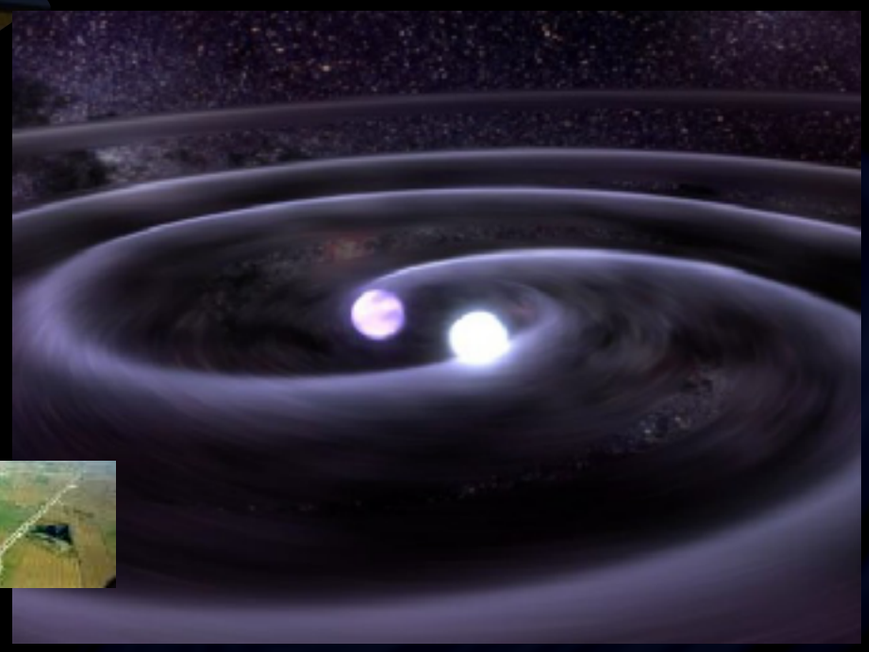




Compact solar mass binaries

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

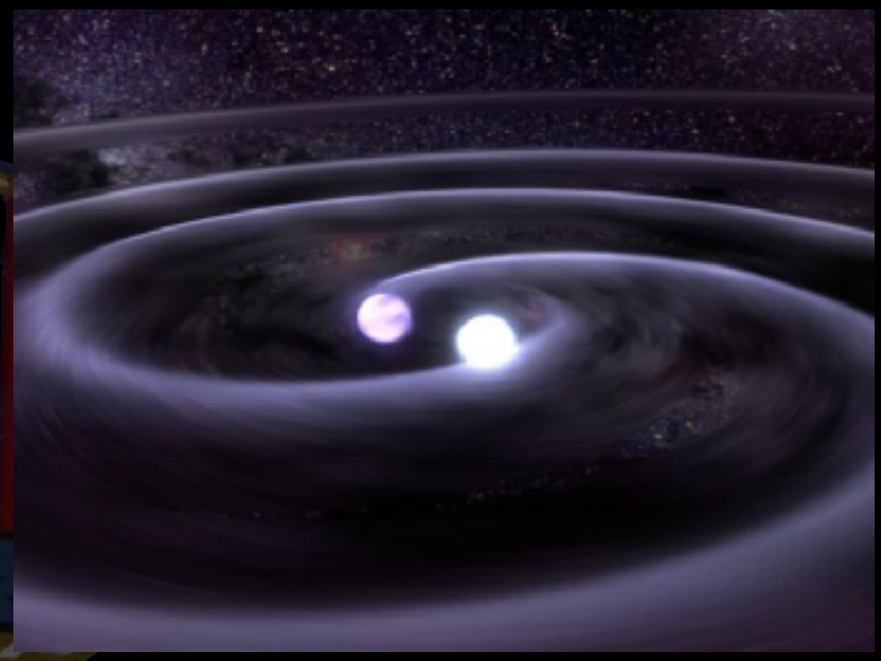
  $\Rightarrow$ existence of WD-WD, NS-WD and NS-NS binaries
- Estimation for the Galaxy: 60 millions.
- Gravitational waves:
  - most part in the slow inspiral regime (quasi-monochromatic): GW at mHz
  - few are coalescing: GW event of few seconds at f $>$ 10 Hz (LIGO/Virgo)



- Several known system emitting around the mHz

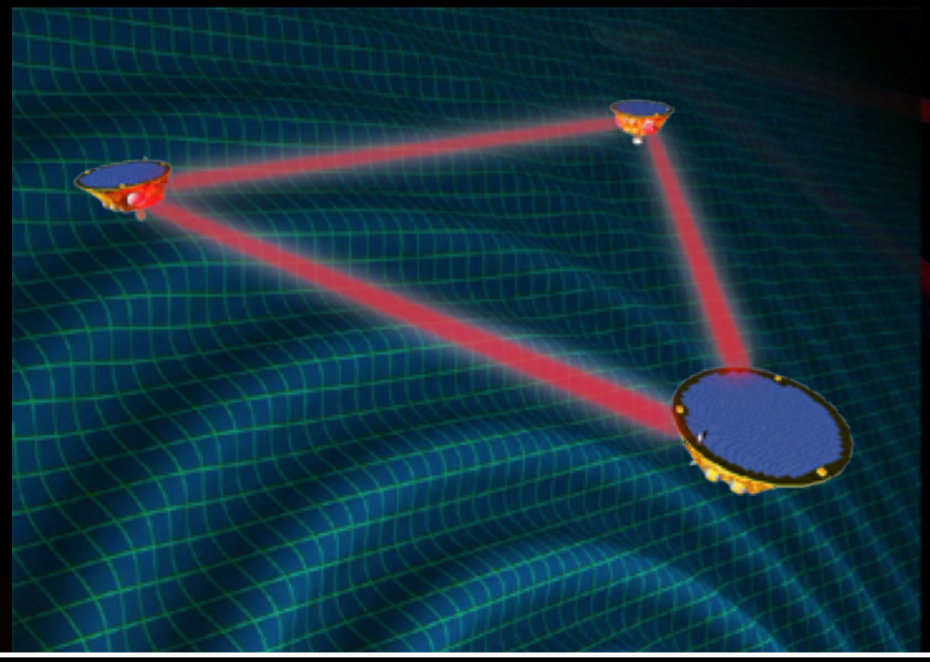
  $\Rightarrow$ guaranteed sources

Galactic binaries



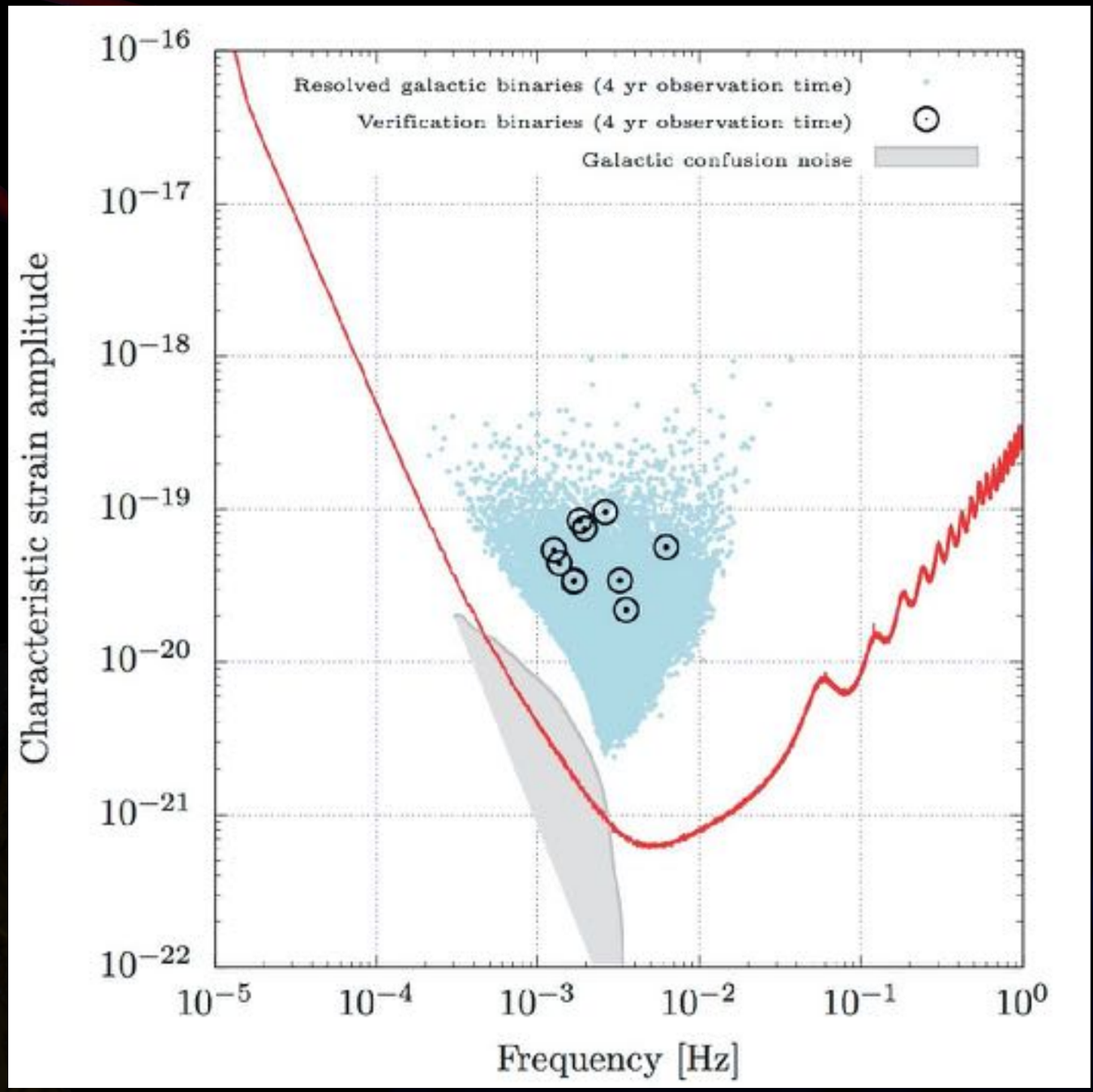
- Gravitational wave:
  - quasi monochromatic
- Duration: permanent
- Signal to noise ratio:
  - detected sources: 7 - 1000
  - confusion noise from non-detected sources
- Event rate:
  - 25 000 detected sources (over 30 millions sources)
  - more than 10 guarantied sources (verification binaries)

Galactic binaries



GW sources

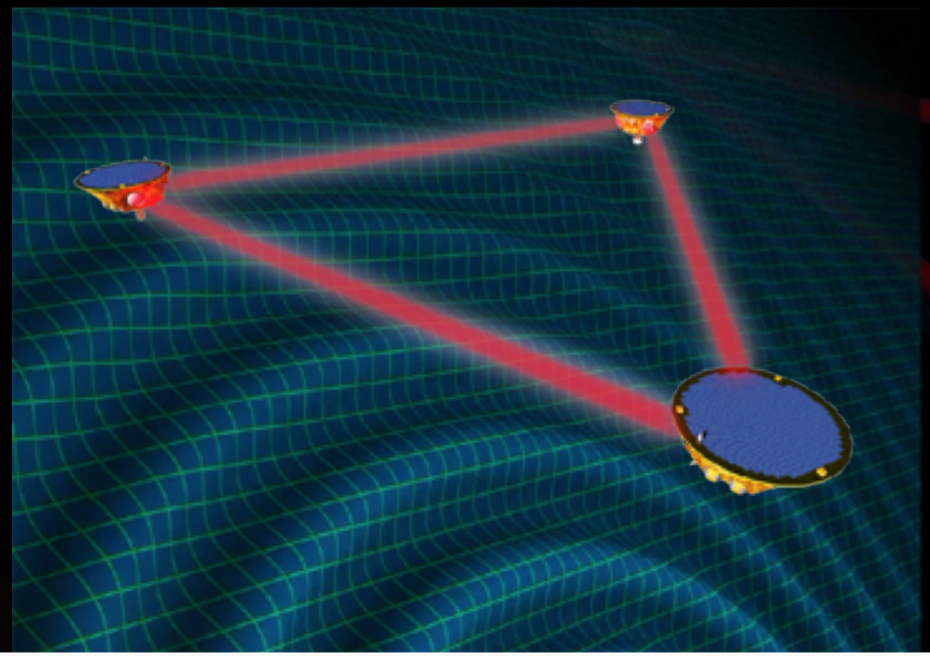
- 6 x10^7 galactic binaries



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



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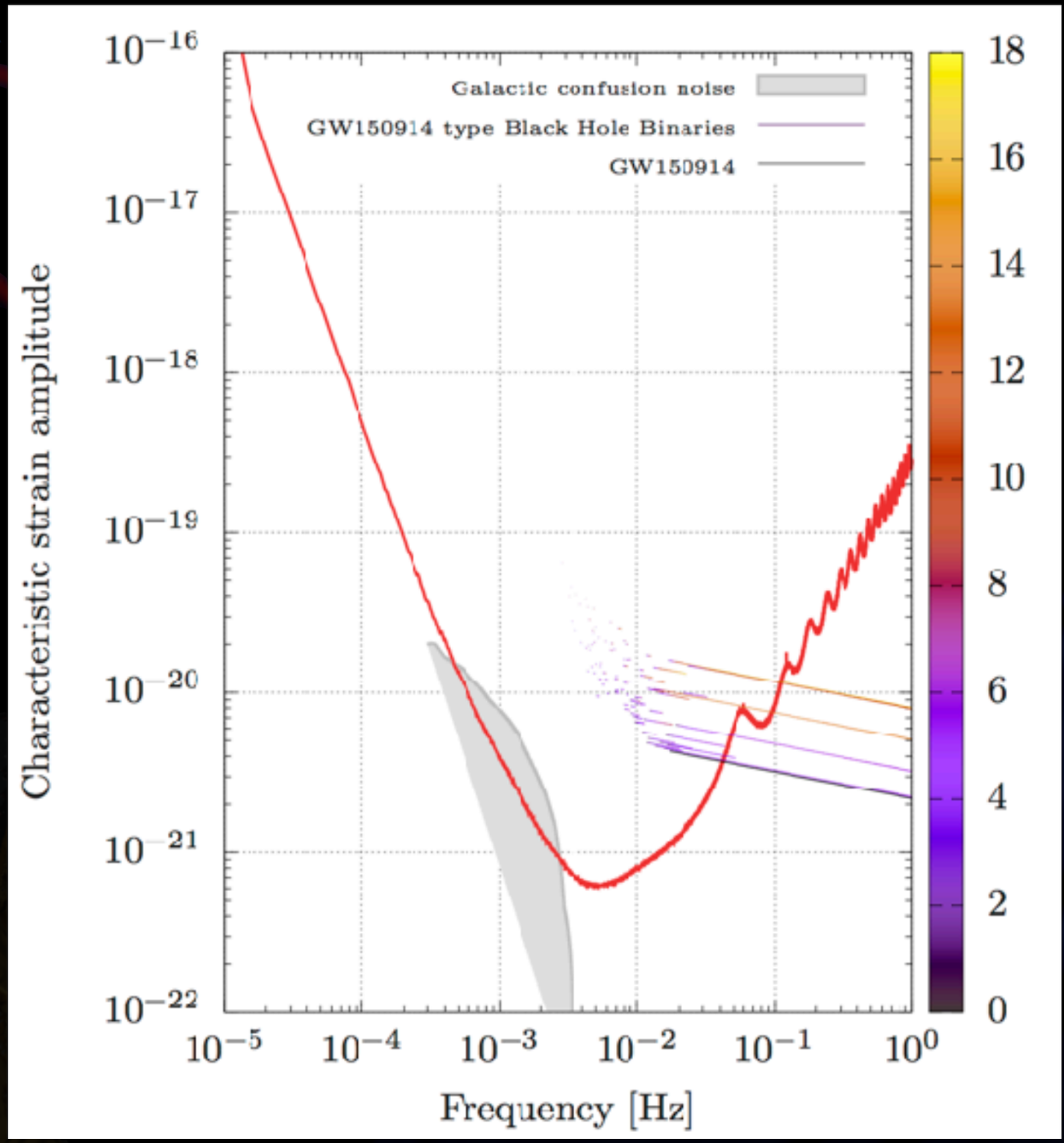
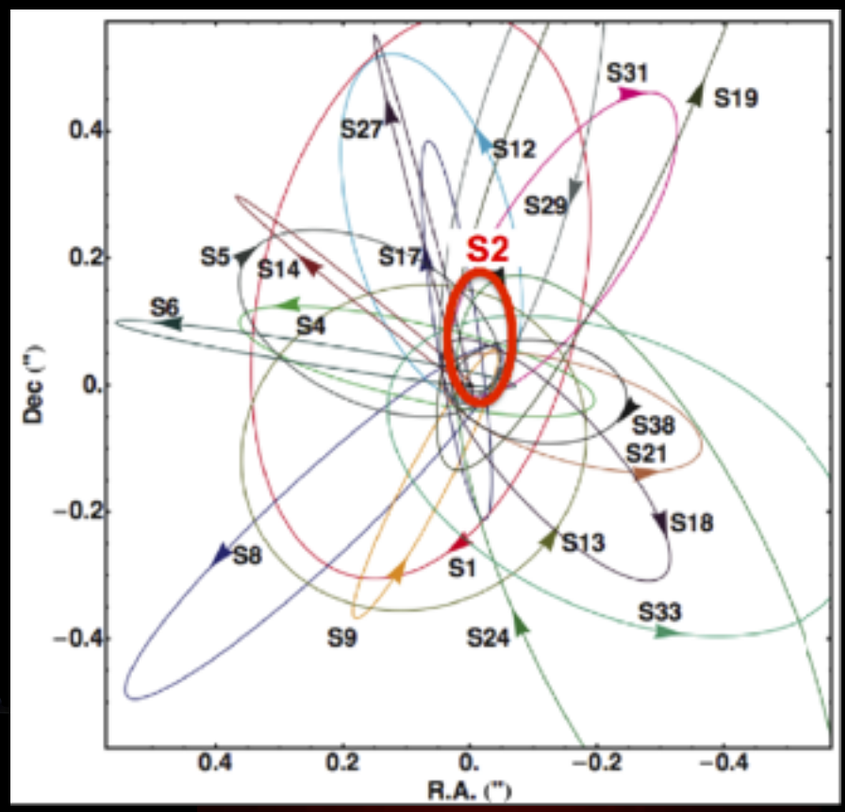


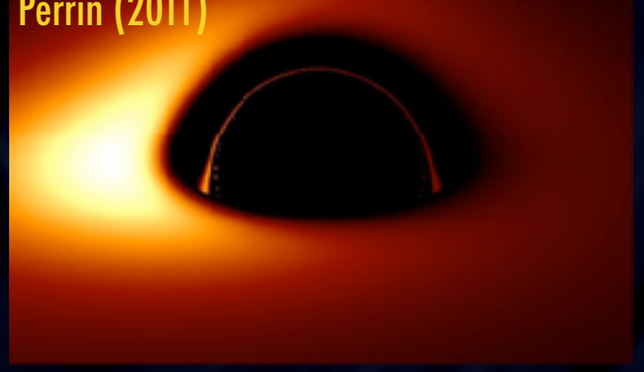
Supermassive Black Holes

- 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 =>

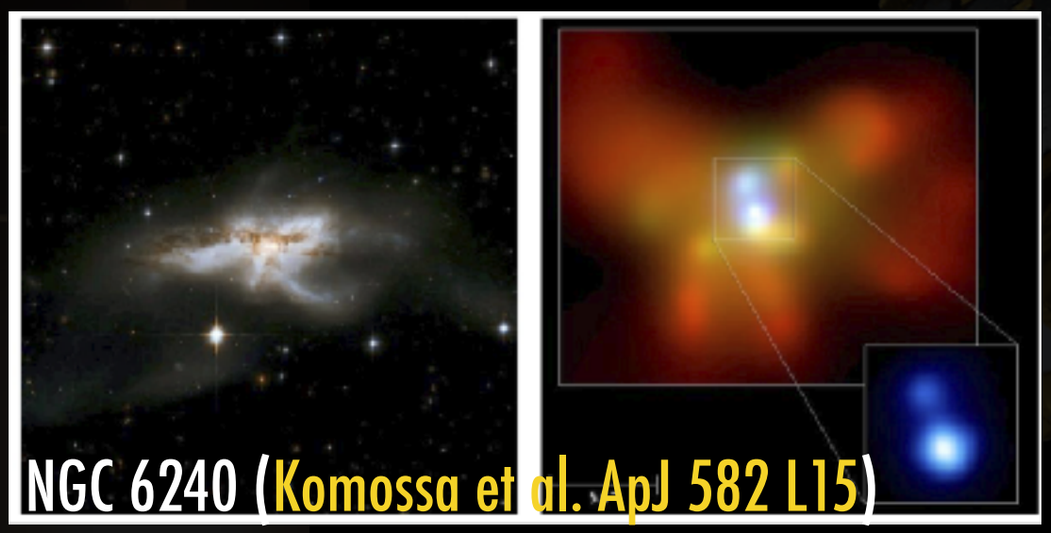
  => SuperMassive BH Binaries (SMBHB) should exist.



© Vincent, Paumard, Gourgoulhon, Perrin (2011)



© EHT (2019)

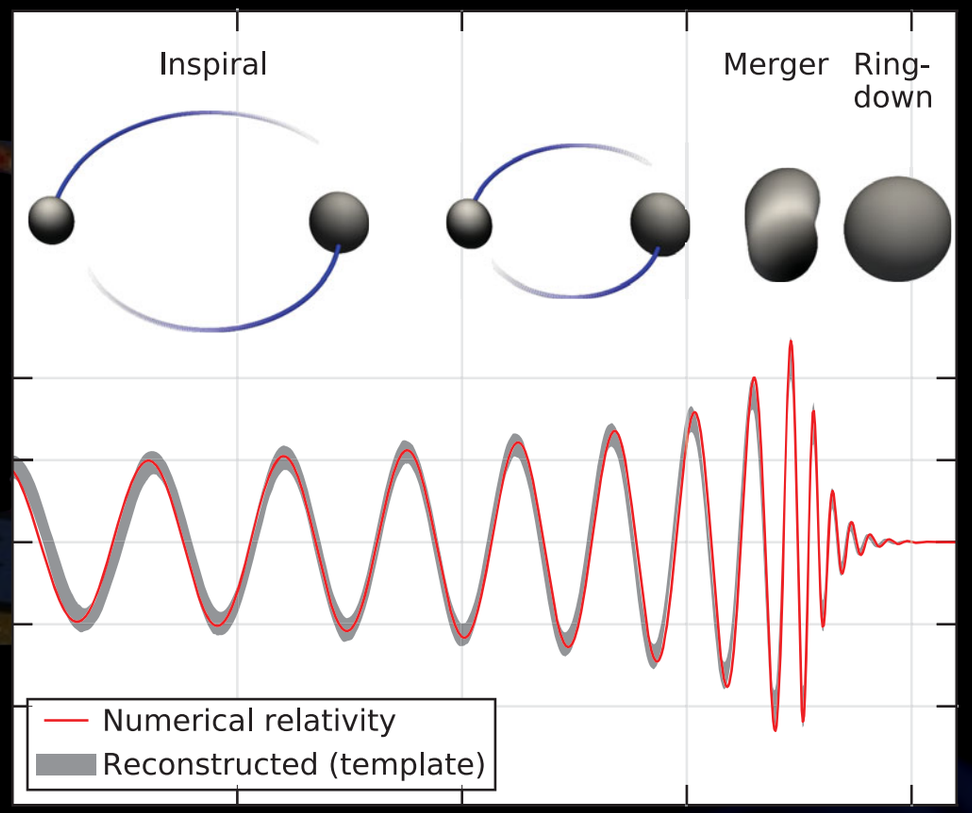


NGC 6240 (Komossa et al. ApJ 582 L15)

Antennae galaxies

Super Massive Black Hole Binaries

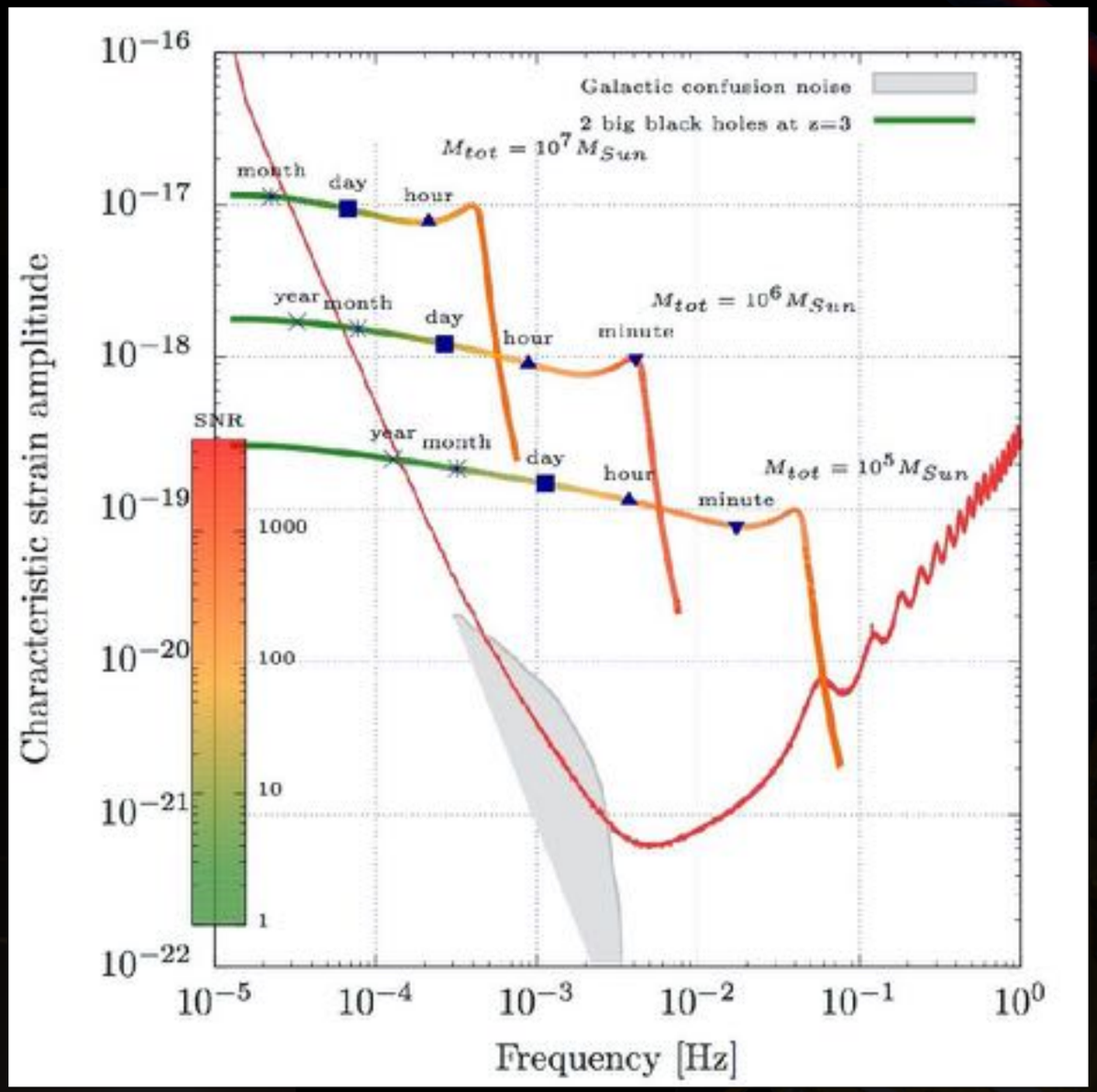
- Gravitational wave:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.

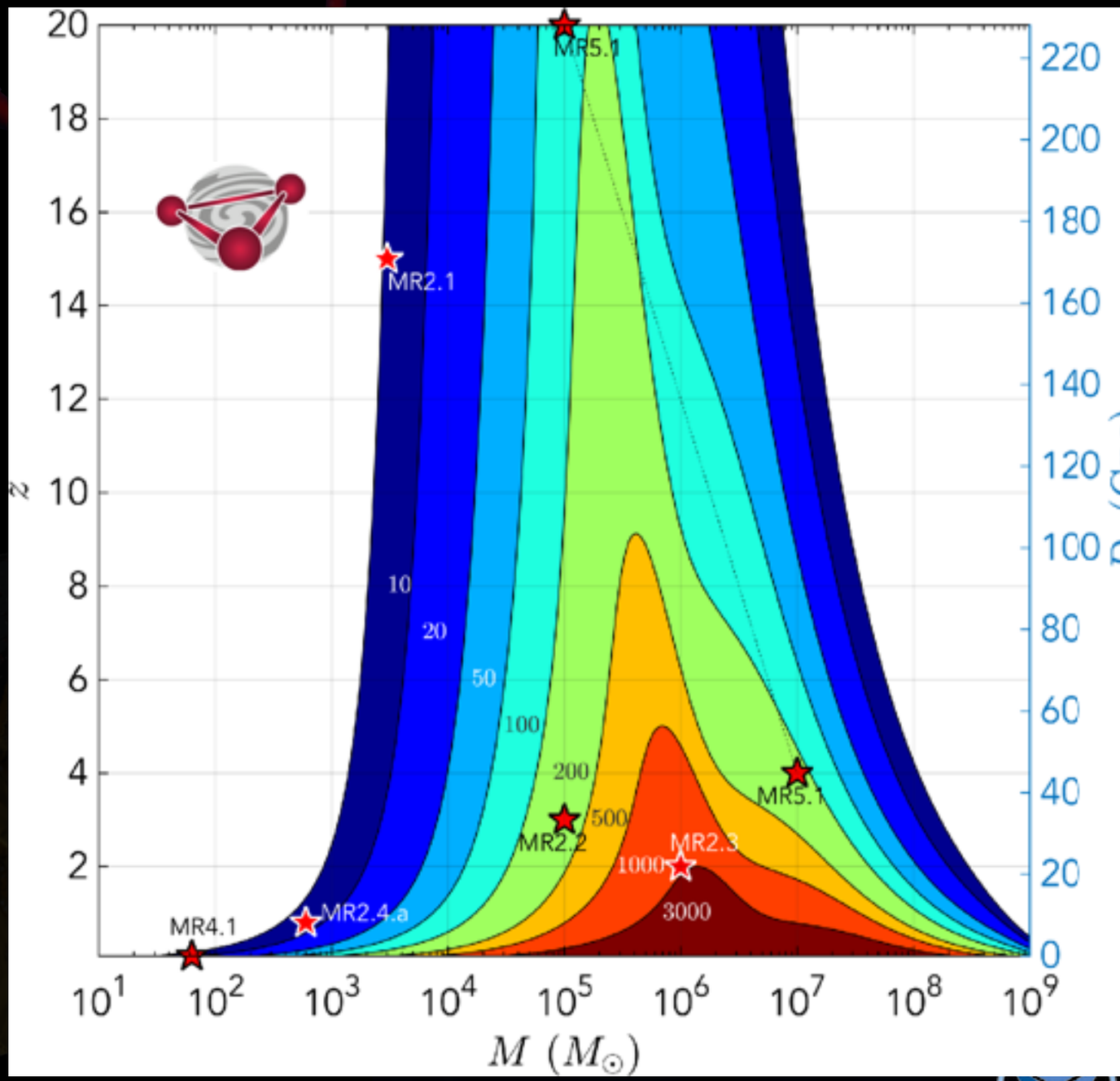


- Duration: between few hours and several months
- Signal to noise ratio: until few thousands
- Event rate: 10-100/year

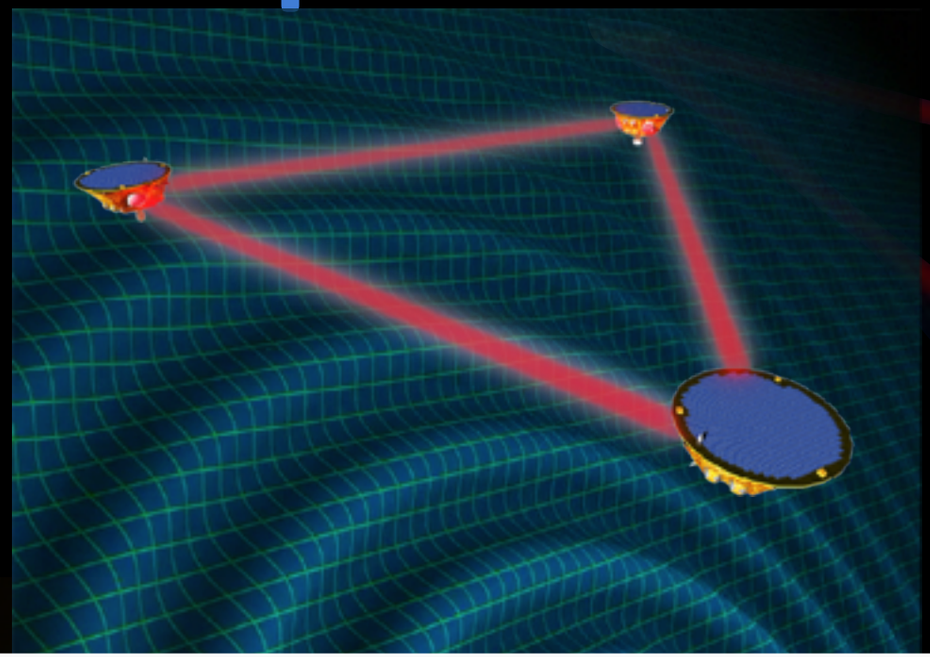
Super Massive Black Hole Binaries

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



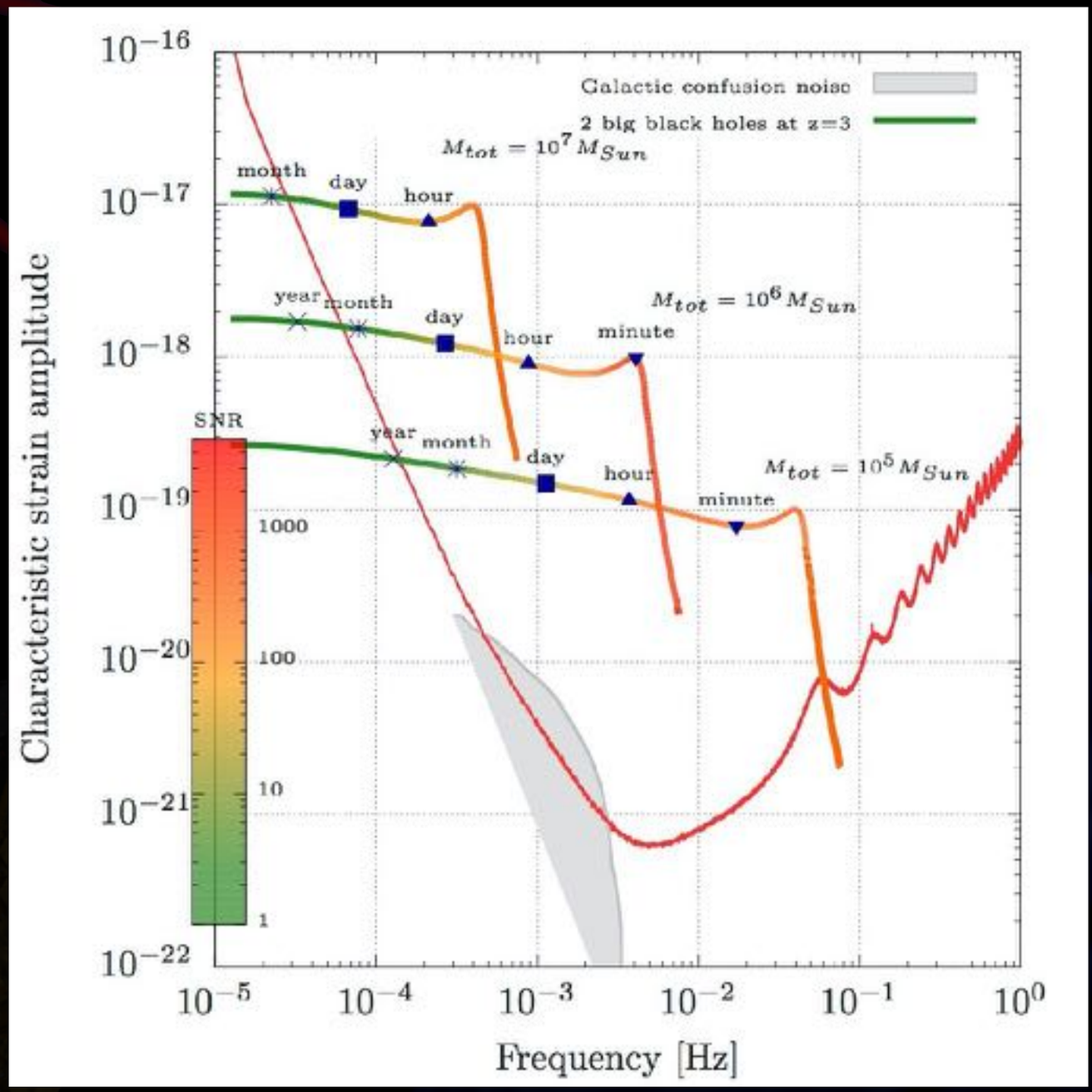


Super Massive Black Hole Binaries



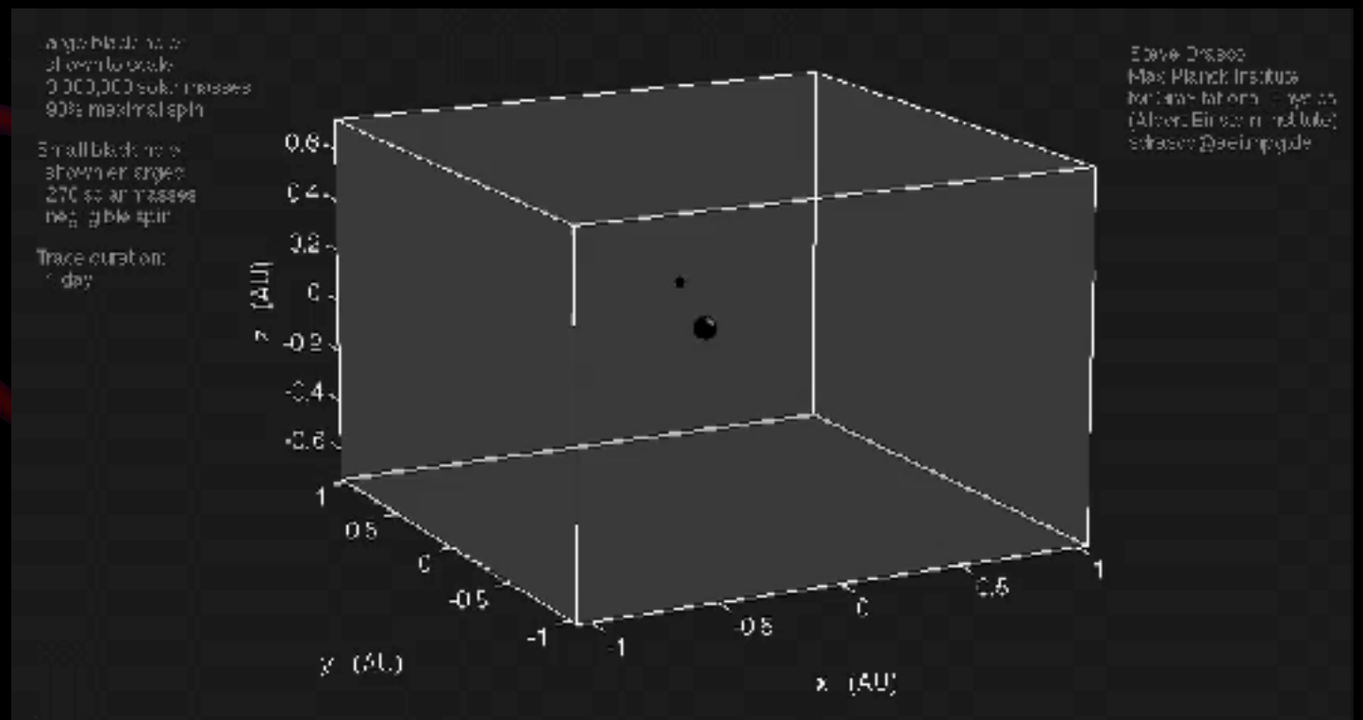
GW sources

- 6 x10^7 galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs

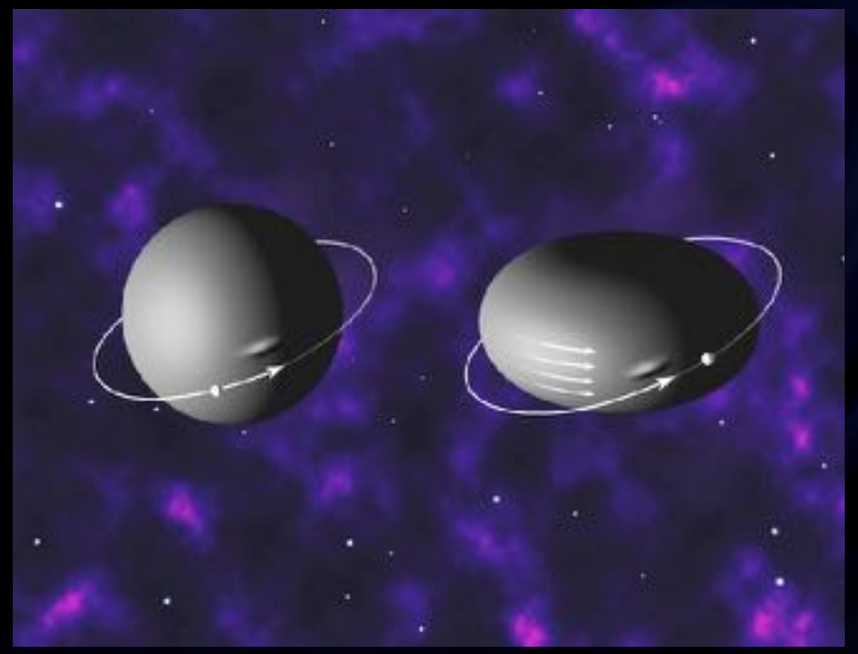


EMRIs

- 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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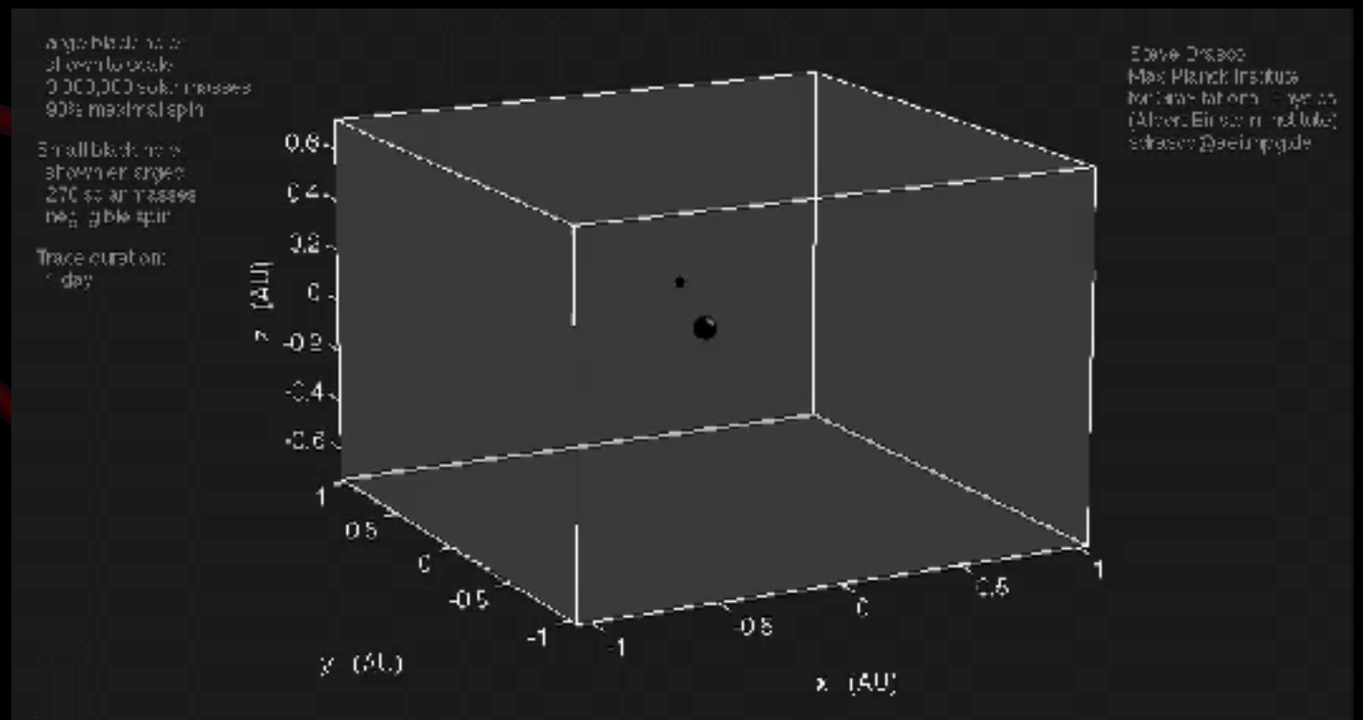

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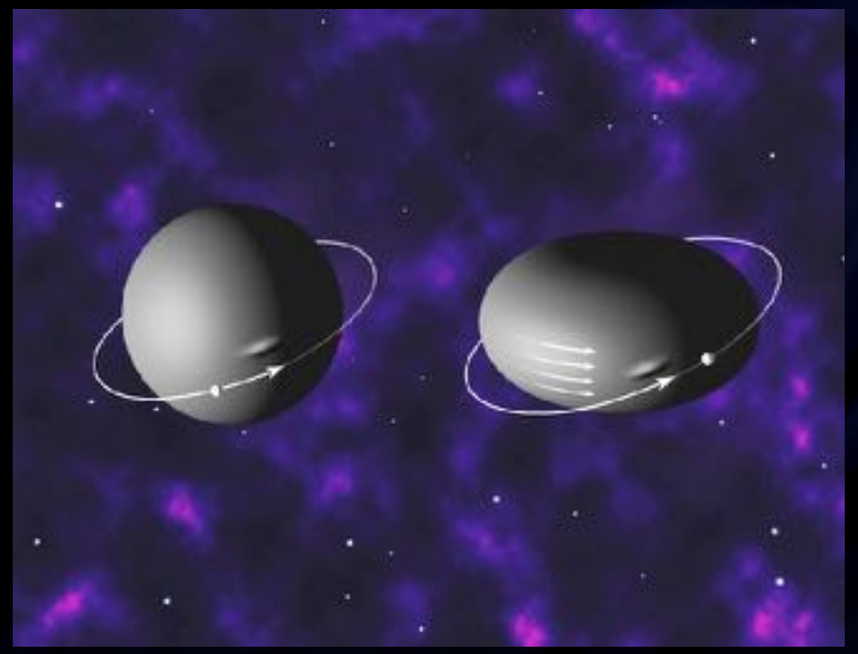
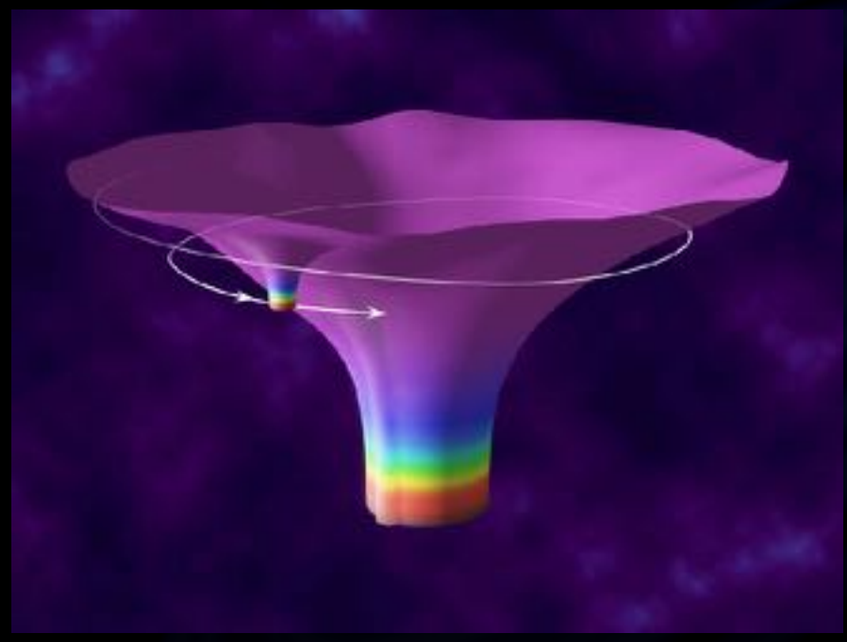


EMRIs

- 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



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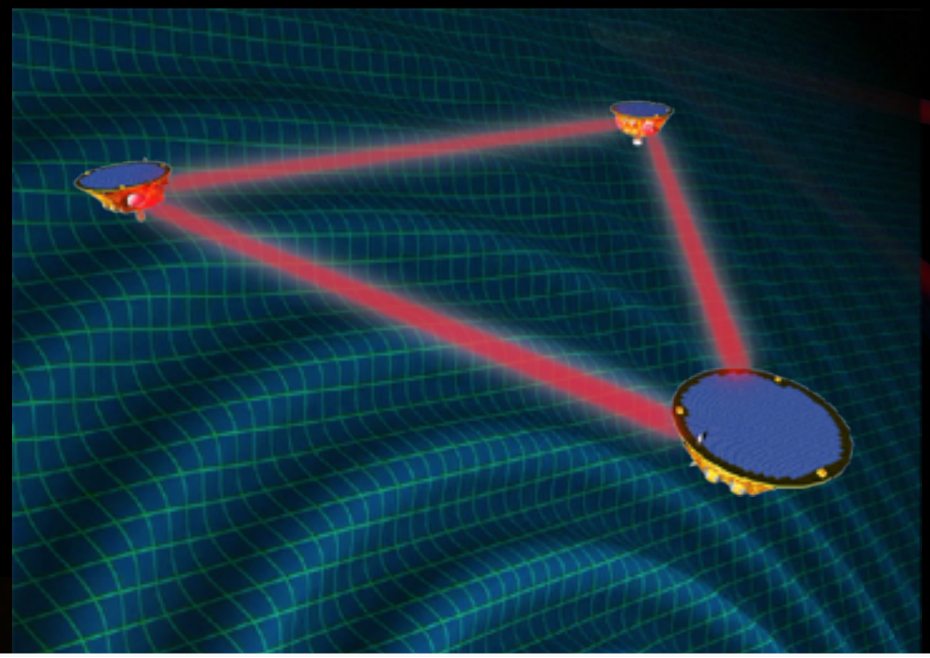

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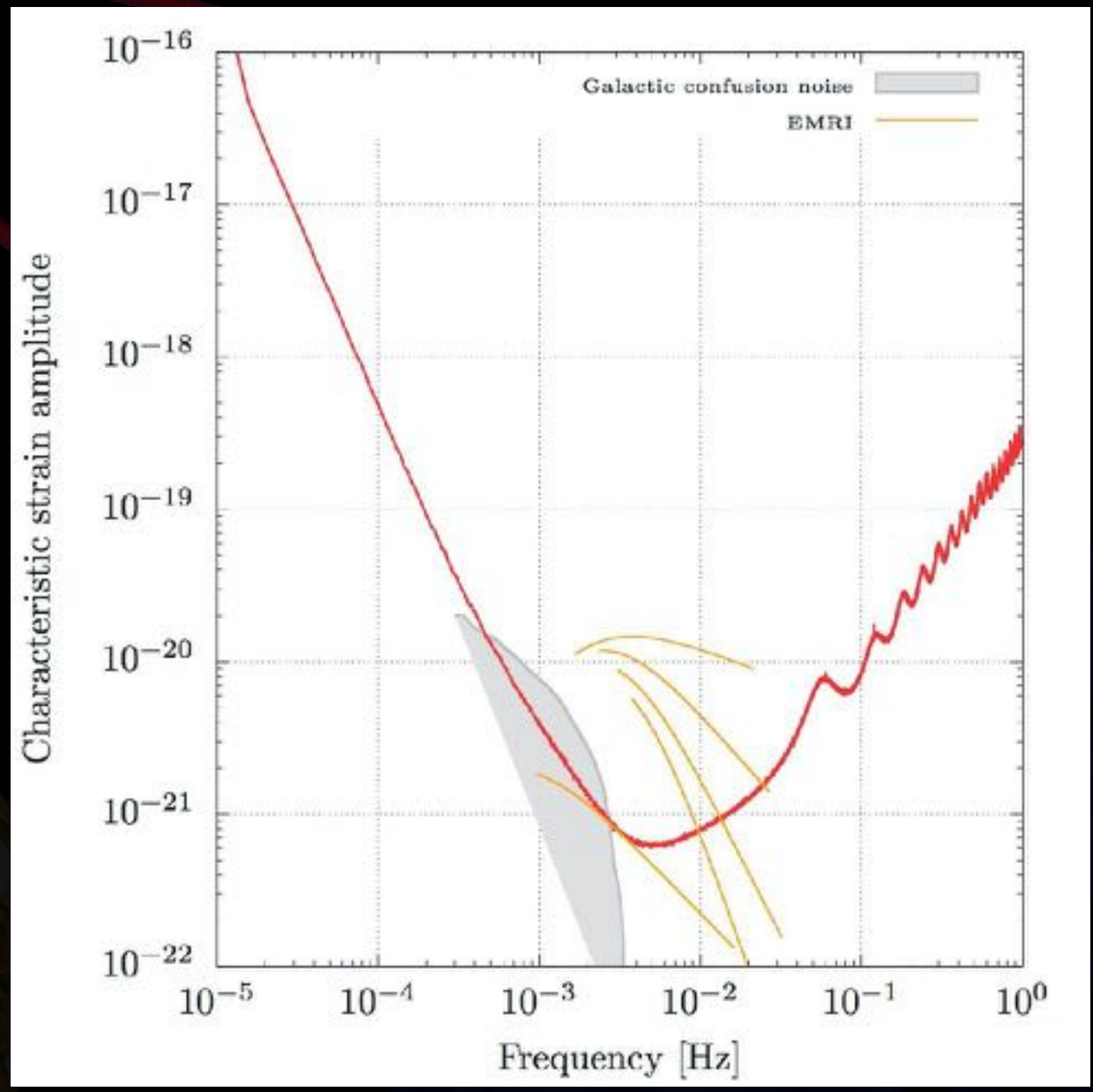
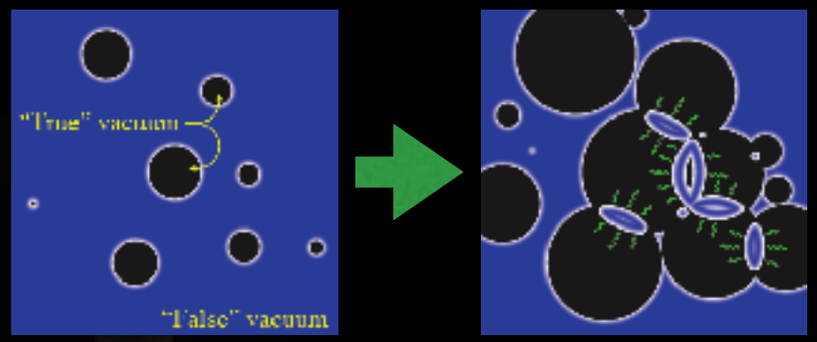
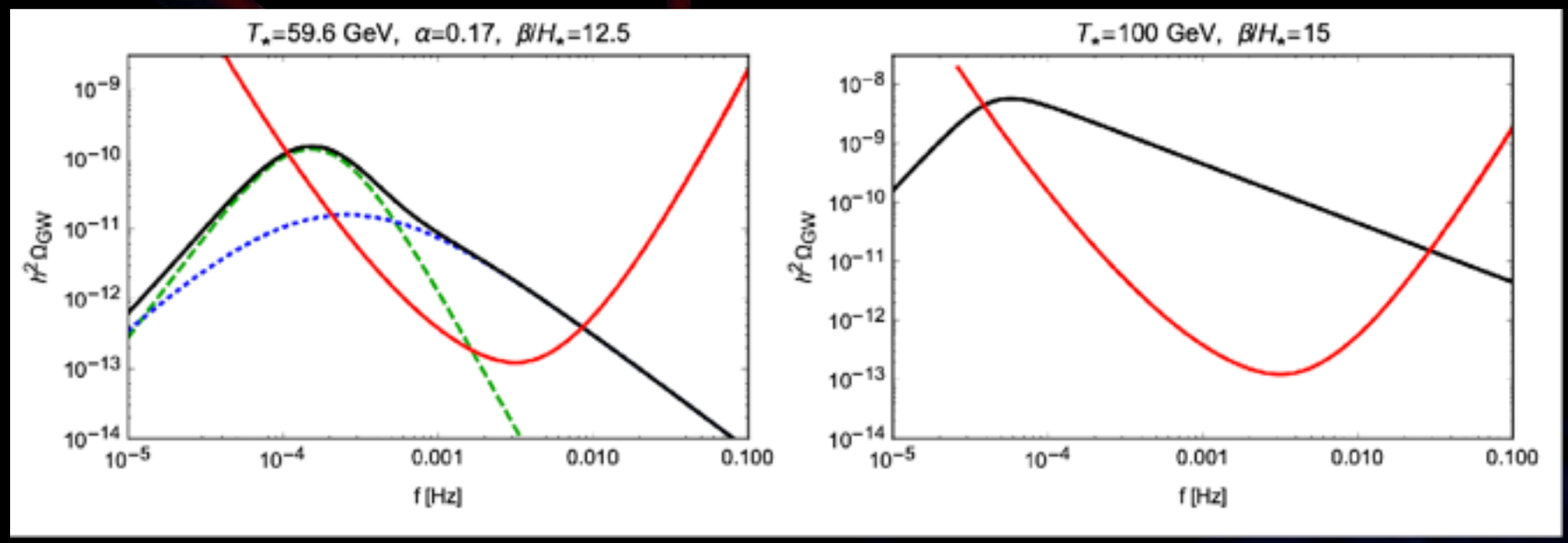


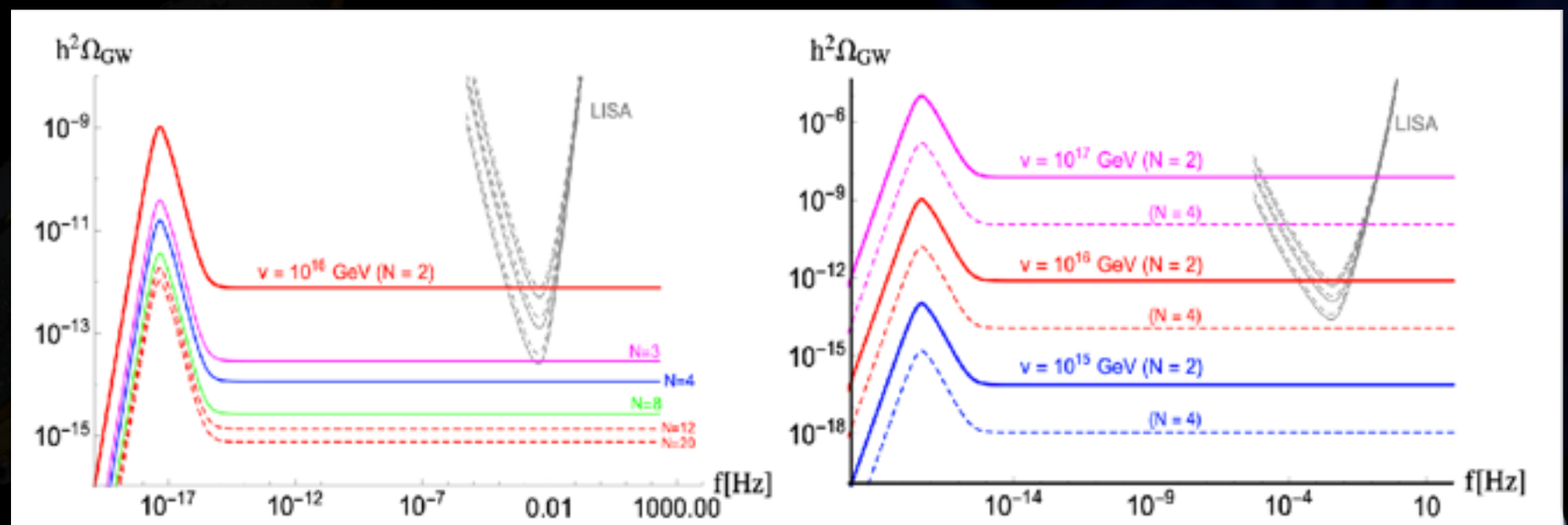
Cosmological backgrounds

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



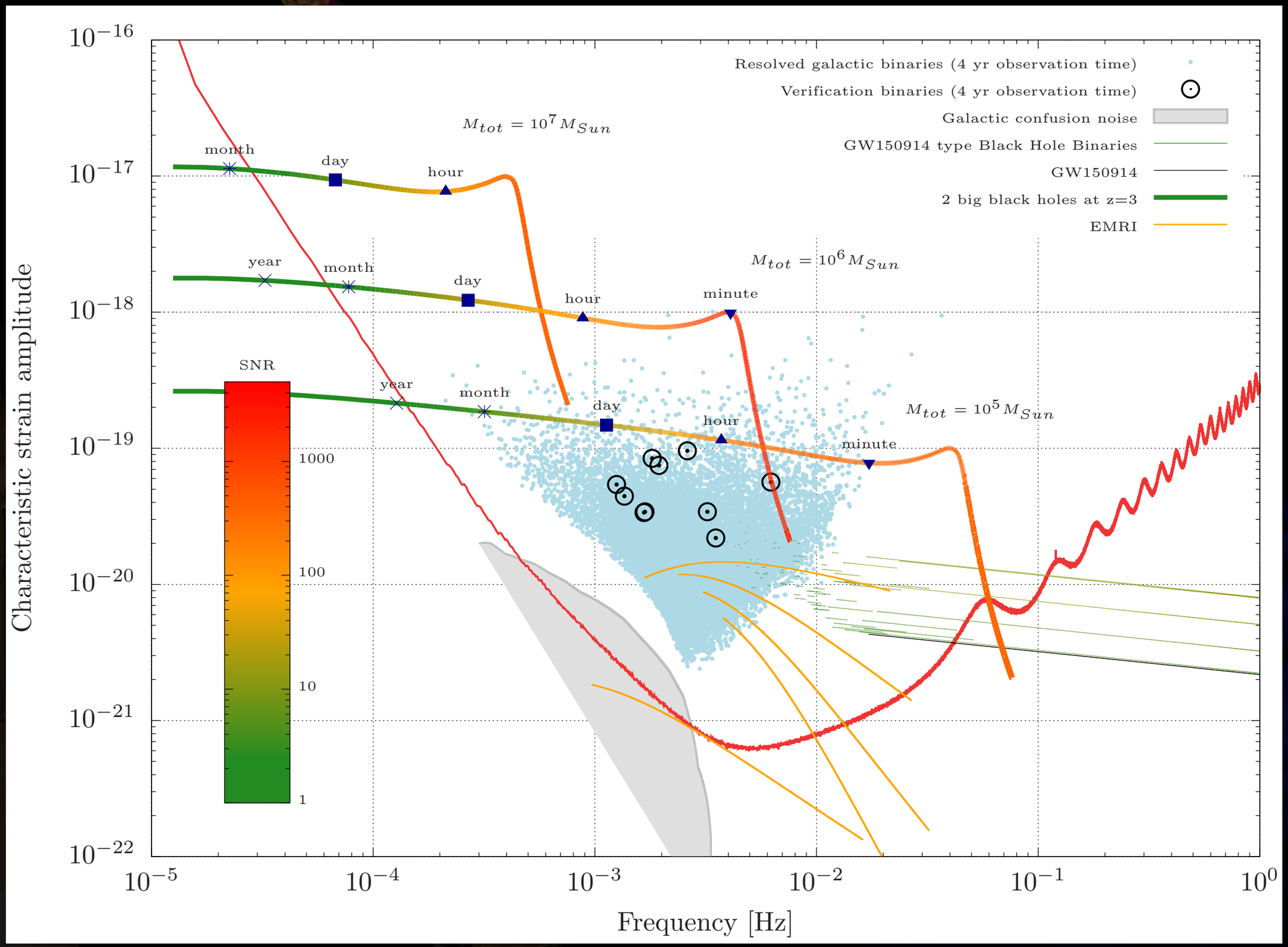


Caprini & Figueroa 2018, CQG 35,163001



- Cosmic strings network
- …

GW sources


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

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- 6 x10^7 galactic binaries
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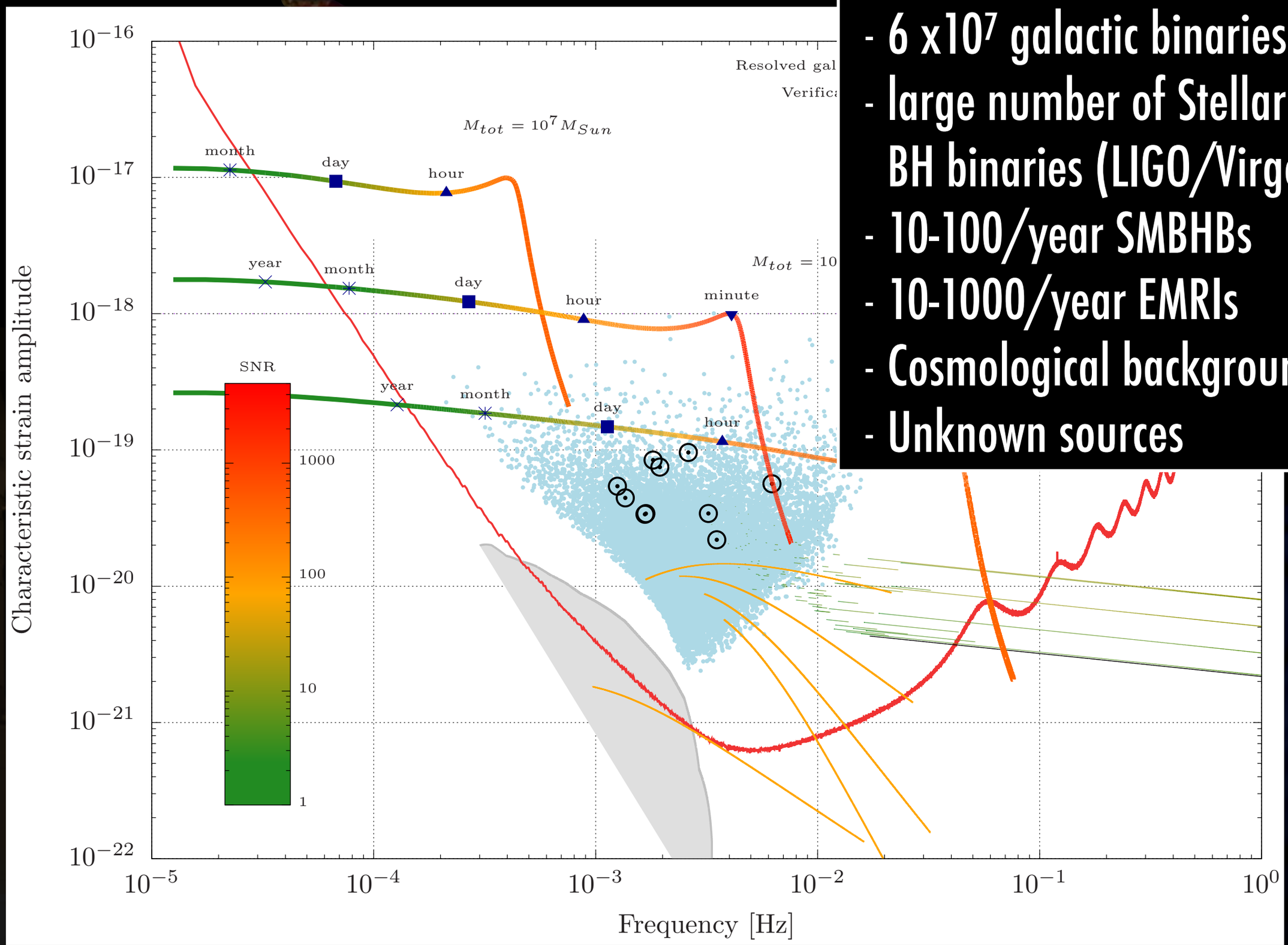
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources



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 data

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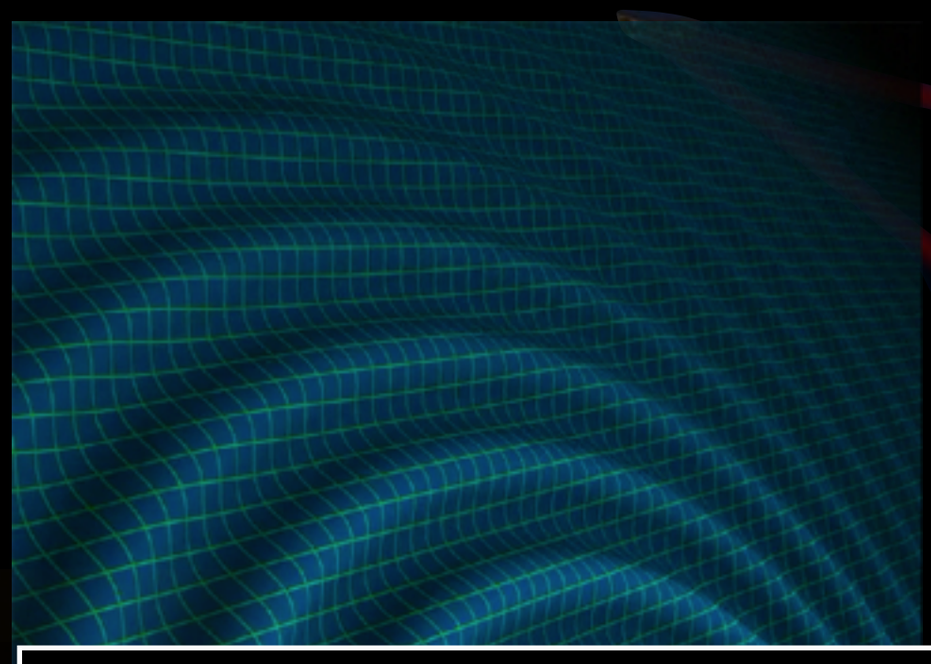

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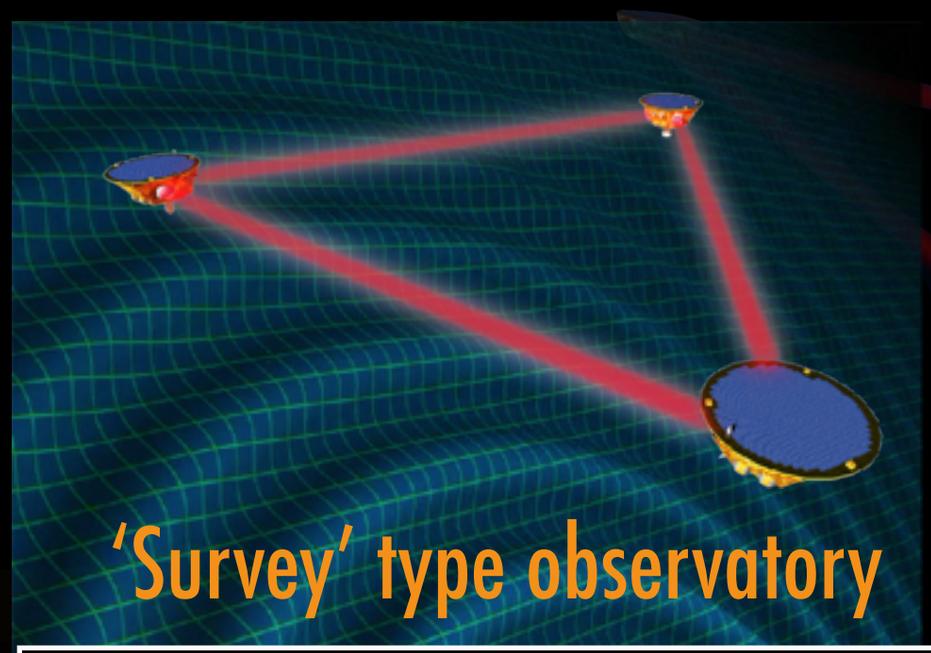

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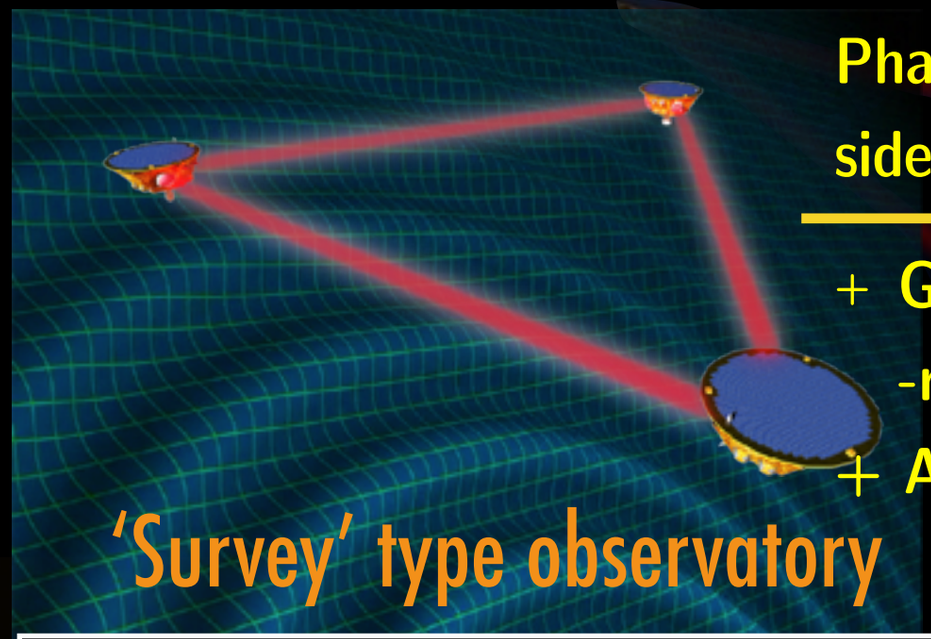

Phasemeters (carrier, sidebands, distance)

+ Gravitational Refe--rence Sensor
+ Auxiliary channels

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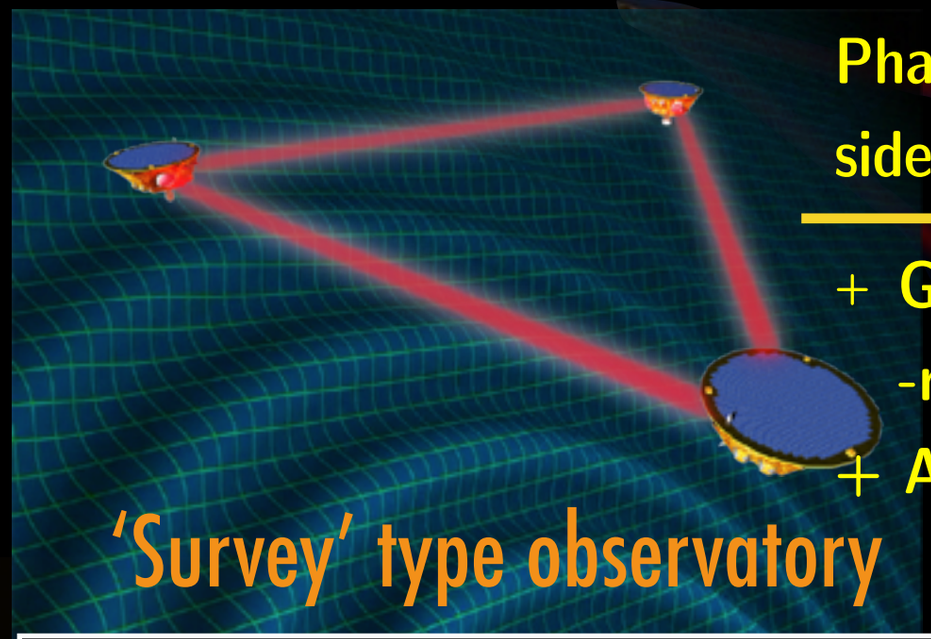

'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

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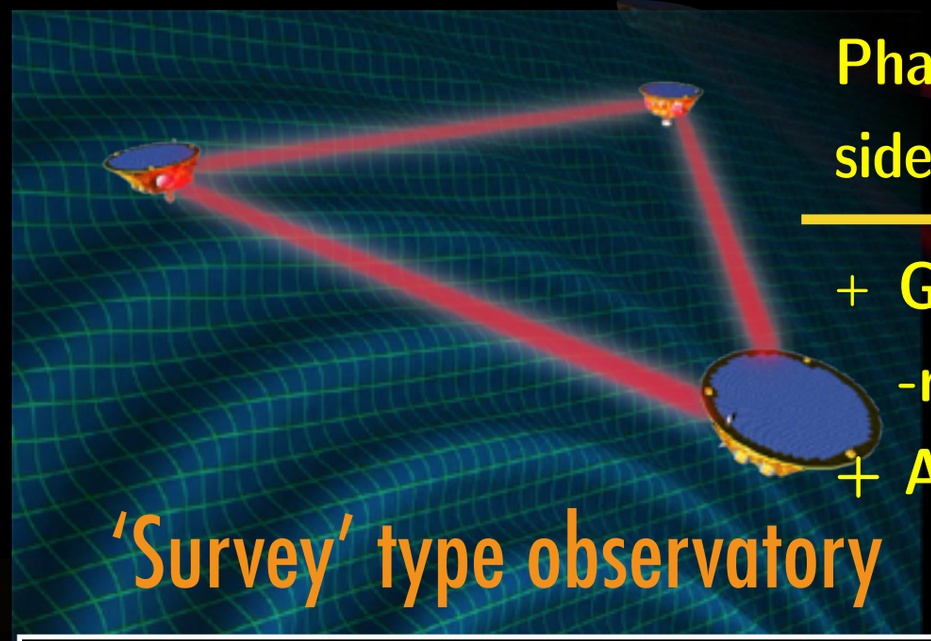

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Phasemeters (carrier, sidebands, distance)

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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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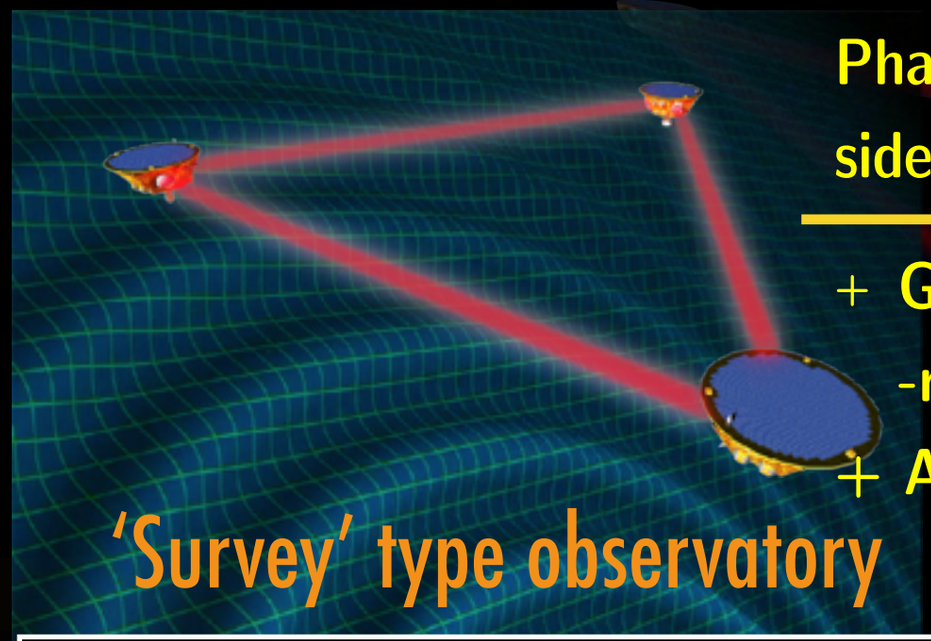

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Data Analysis of GWs

Catalogs of GWs sources
with their waveform

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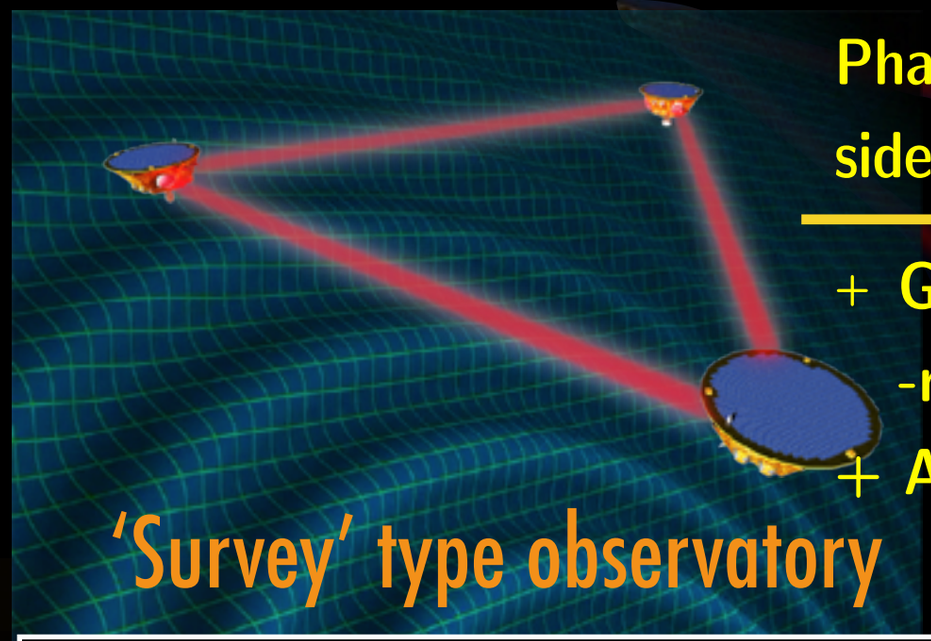

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L0

Calibrations corrections

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L1 — 3 TDI channels with 2 "~independents"

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

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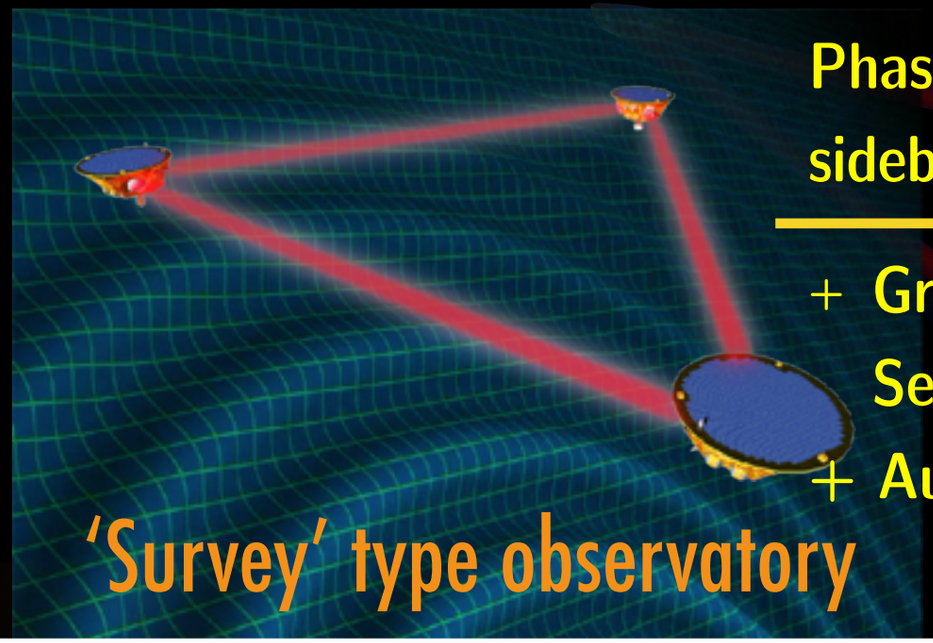
LISA data flow



'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ Gravitational Reference Sensor
+ Auxiliary channels

L0 — Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry
reduction of laser noise

L1 — 3 TDI channels with 2 "~independents"

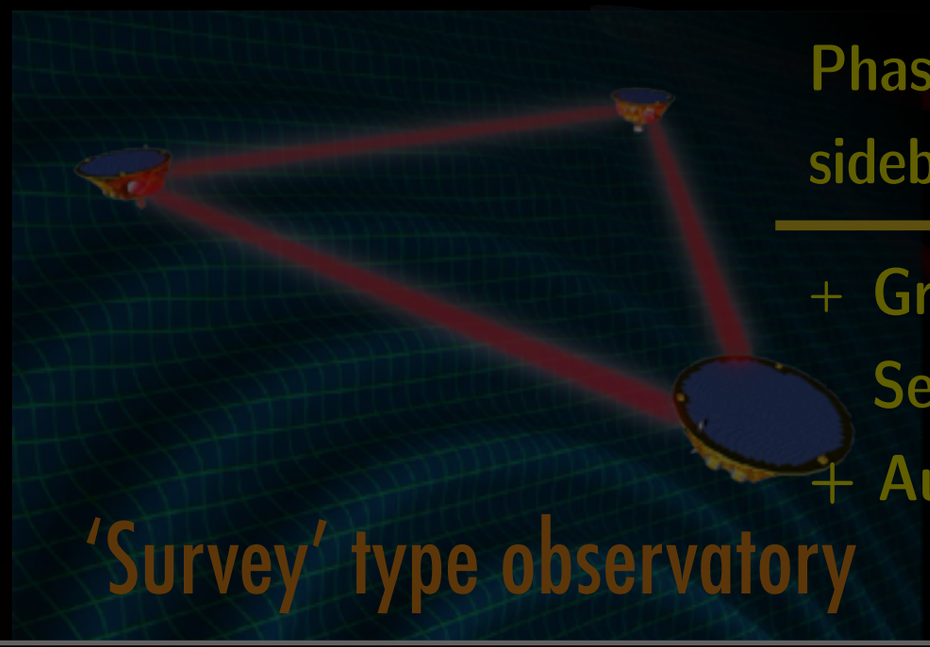
L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

GW sources

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

LISA data flow



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LISA data flow

Mission Operation Centre

Phasemeters (carrier, stance)

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+ Auxiliary channels

'Survey' type observatory

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Resynchronisation (clock)

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L2

Data Analysis of GWs

L3

Catalogs of GWs sources
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- 6 x10^7 galactic binaries
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- Unknown sources

LISA data flow

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'Survey' type observatory

L0

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Time-Delay Interferometry
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L1 — 3 TDI channels with 2 "~independents"

Science Operation Centre

- 6 x10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Origin

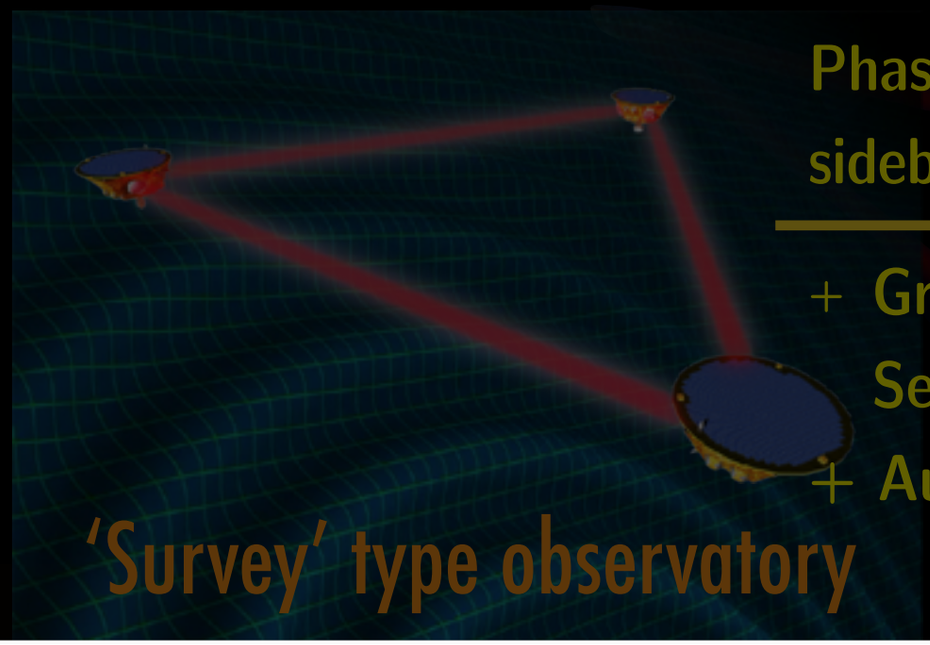
Distributed Data Processing Centre

- Unknown sources

L2 — Data Analysis of GWs

L3 — Catalogs of GWs sources with their waveform

LISA data flow



'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

+ Gravitational Reference Sensor
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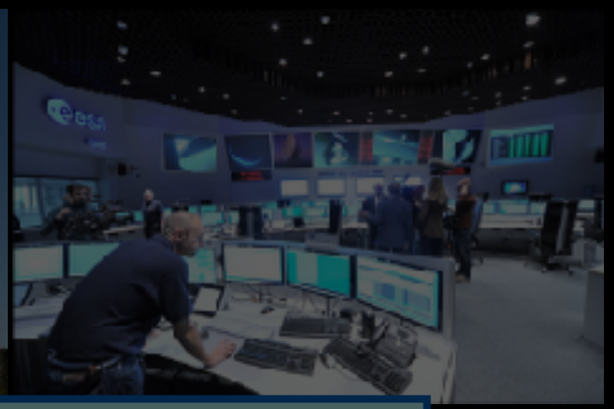

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Time-Delay Interferometry
reduction of laser noise

L1

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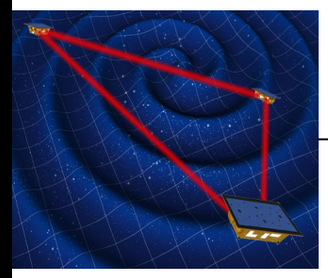
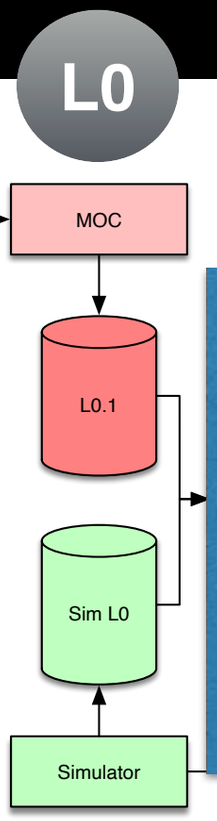
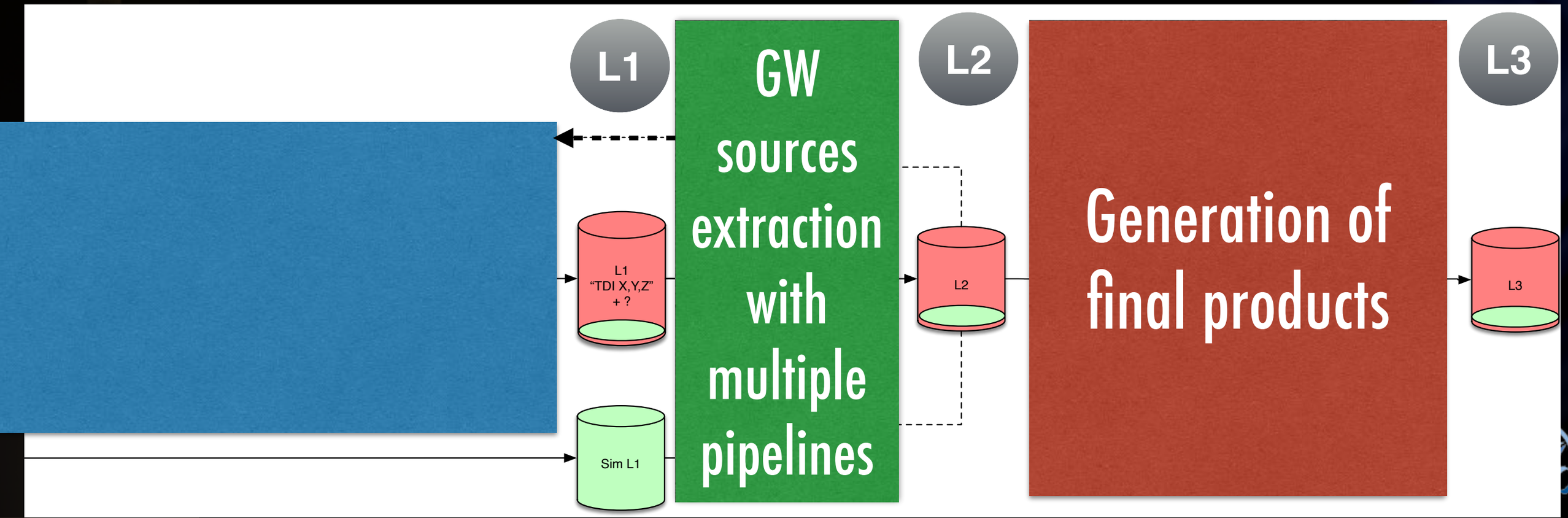
Segment sol LISA



Telemetry:
+ Phasemeter
+ DFACS
+ GRS FEE
+ CGT
+ CMS
+ SciDiag
+ Housekeeping



Initial Noise Reduction pipeline (TDI, etc)



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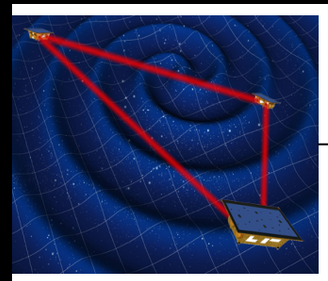

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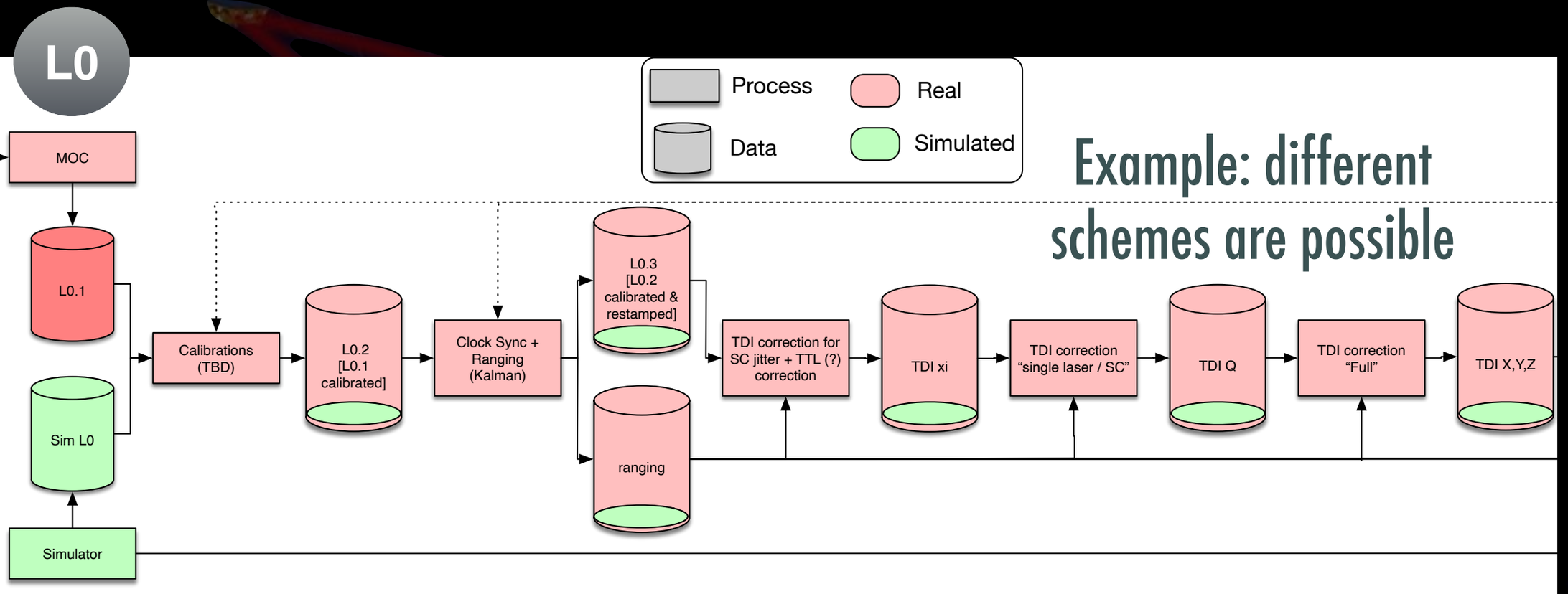
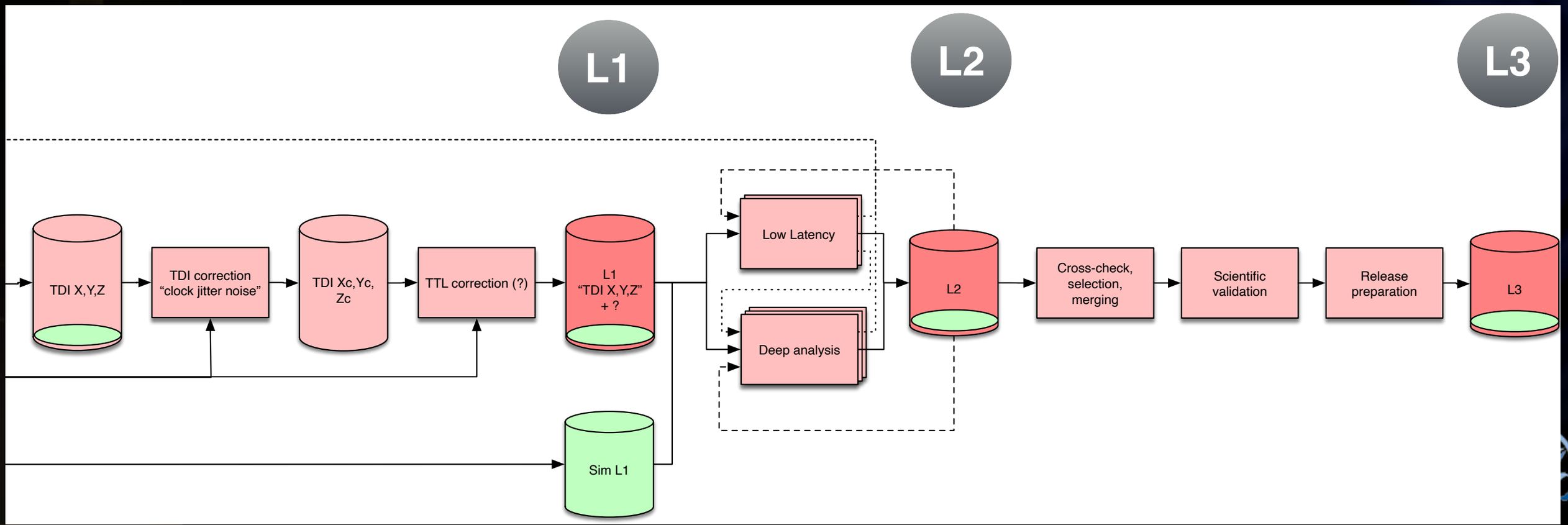
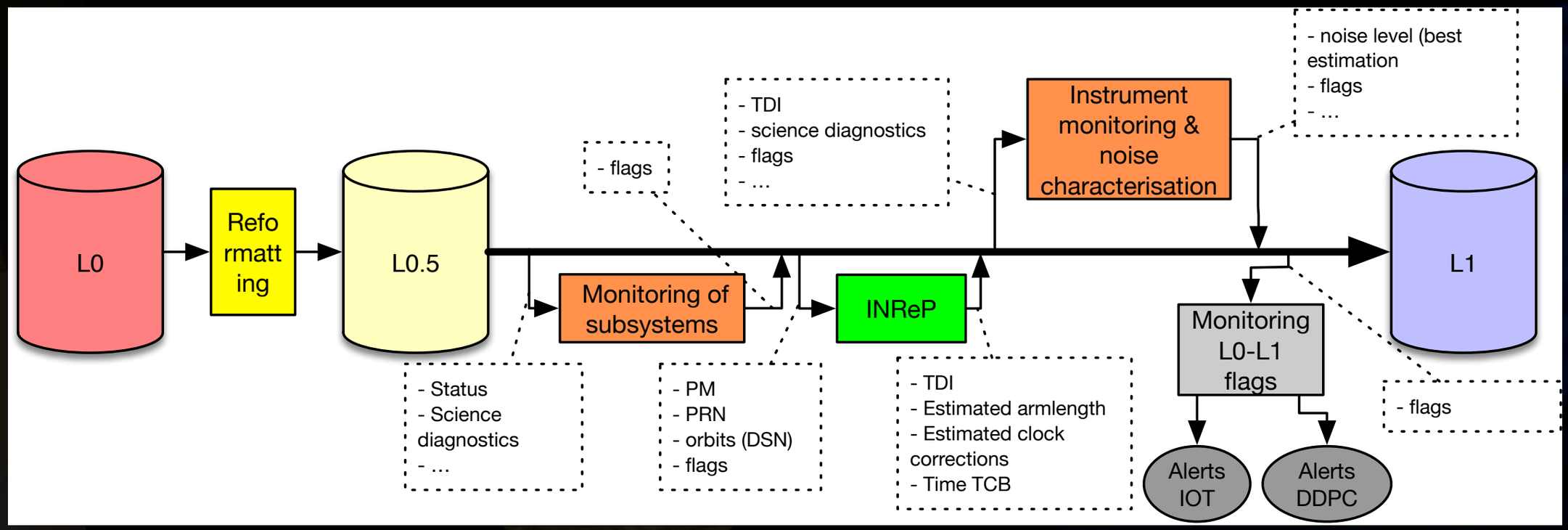




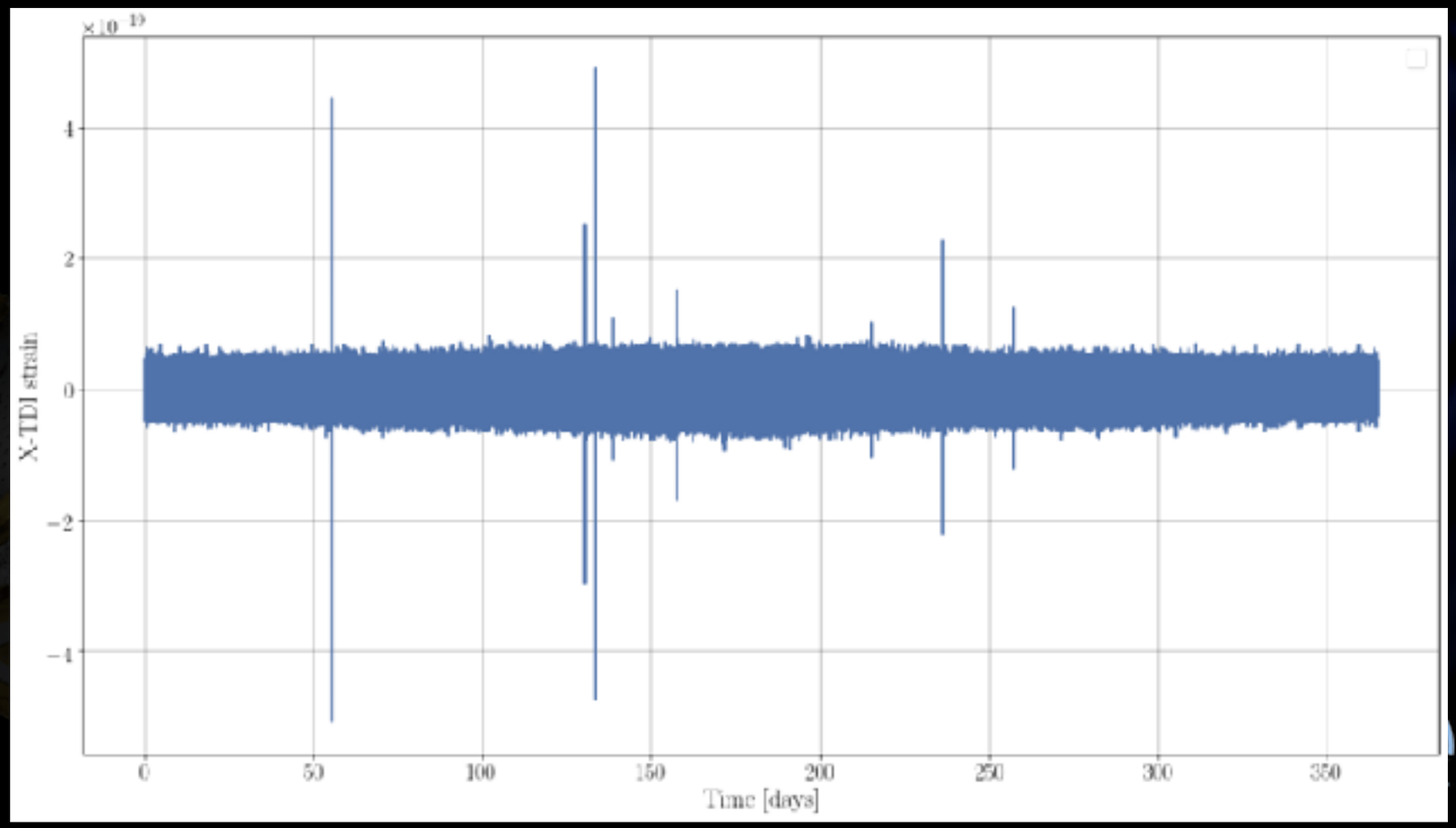
Noise reduction

- 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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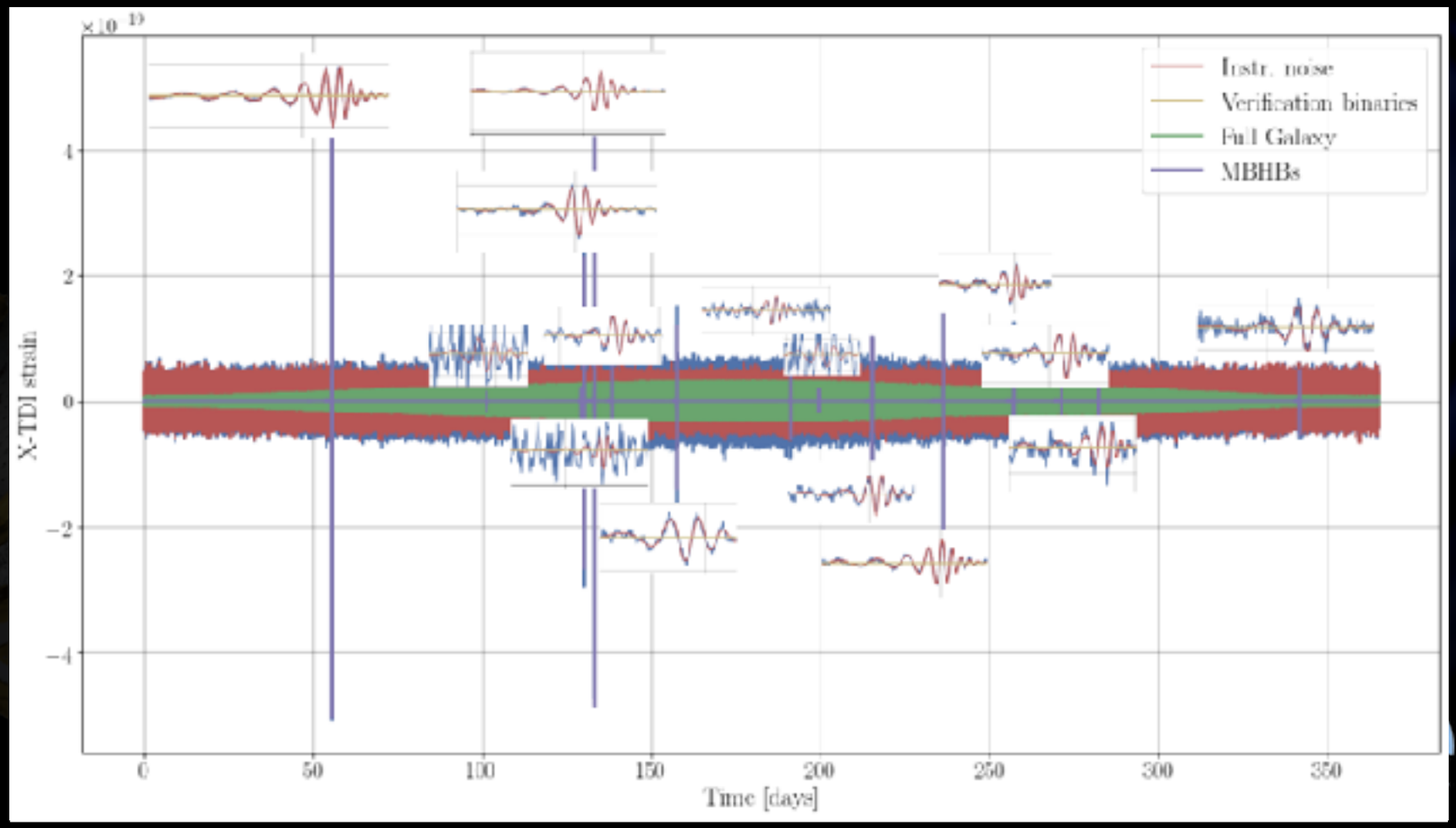
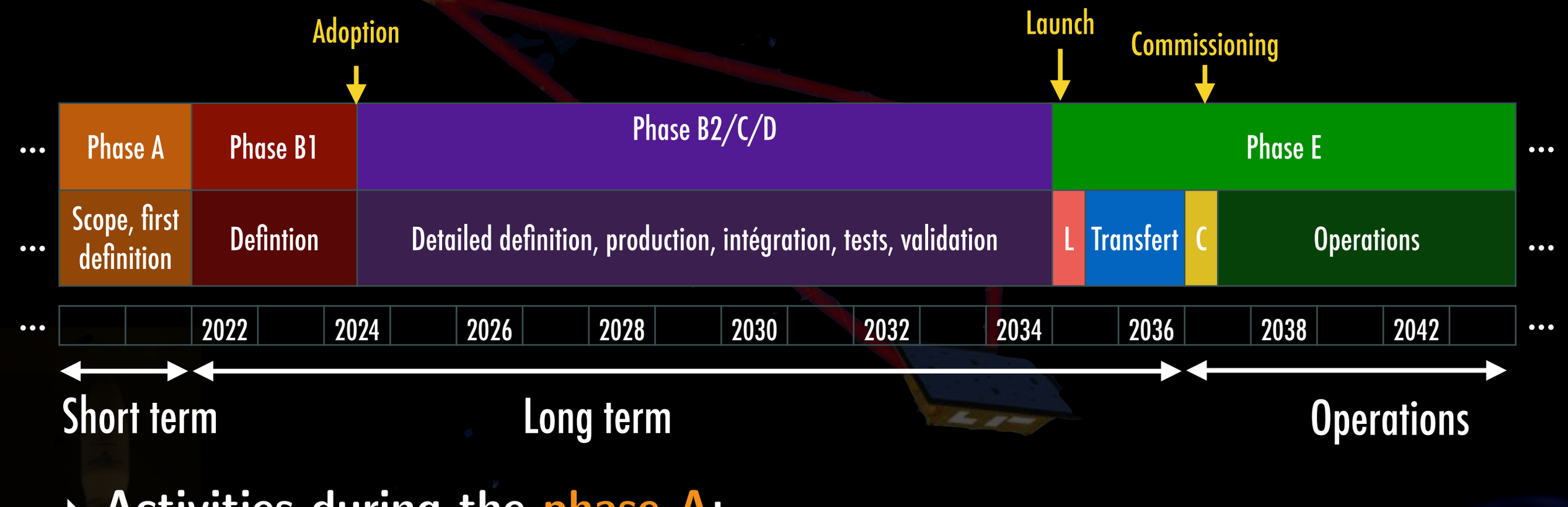


LISA at ESA

- 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

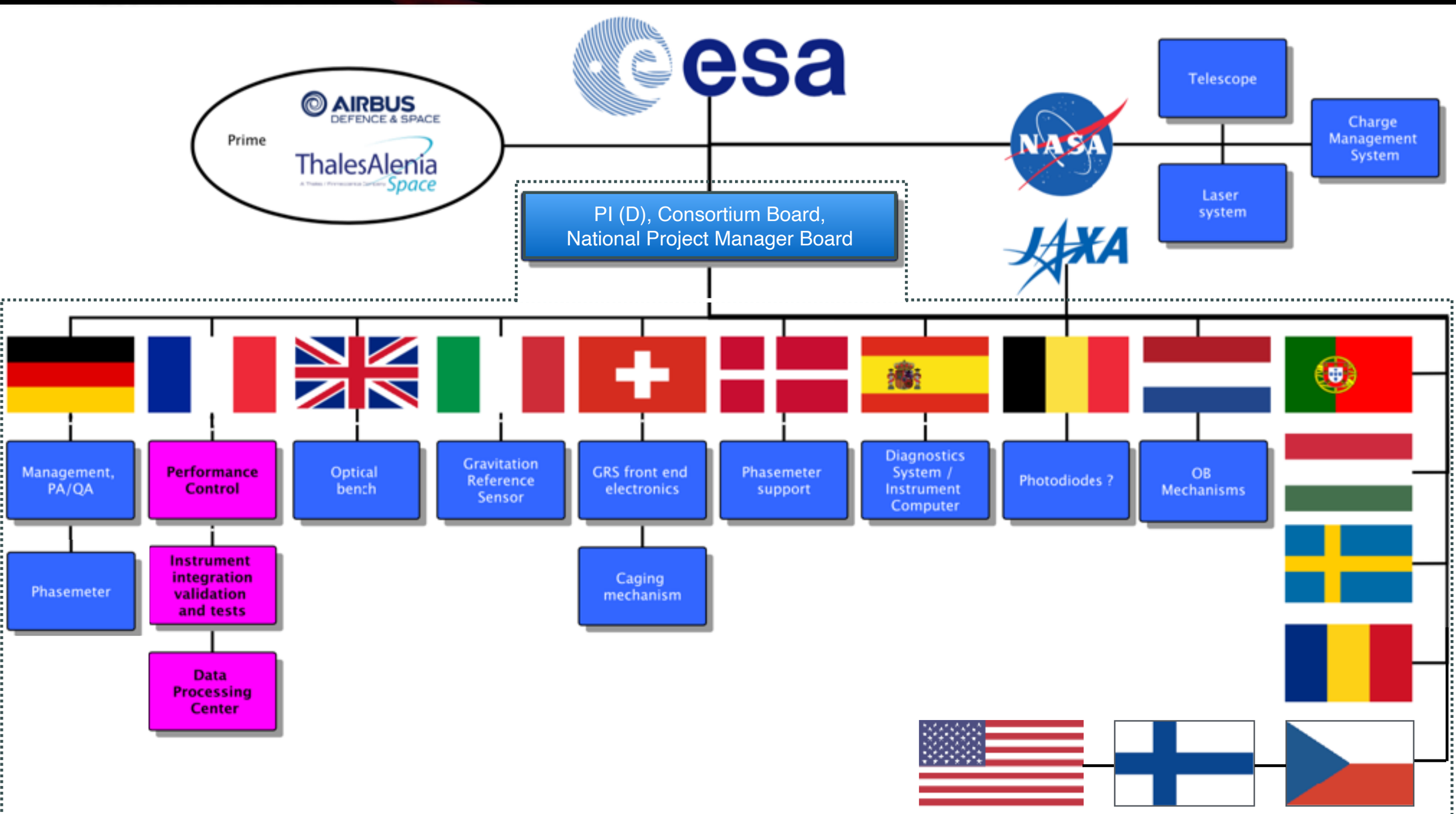
GW observations!

LISA timeline



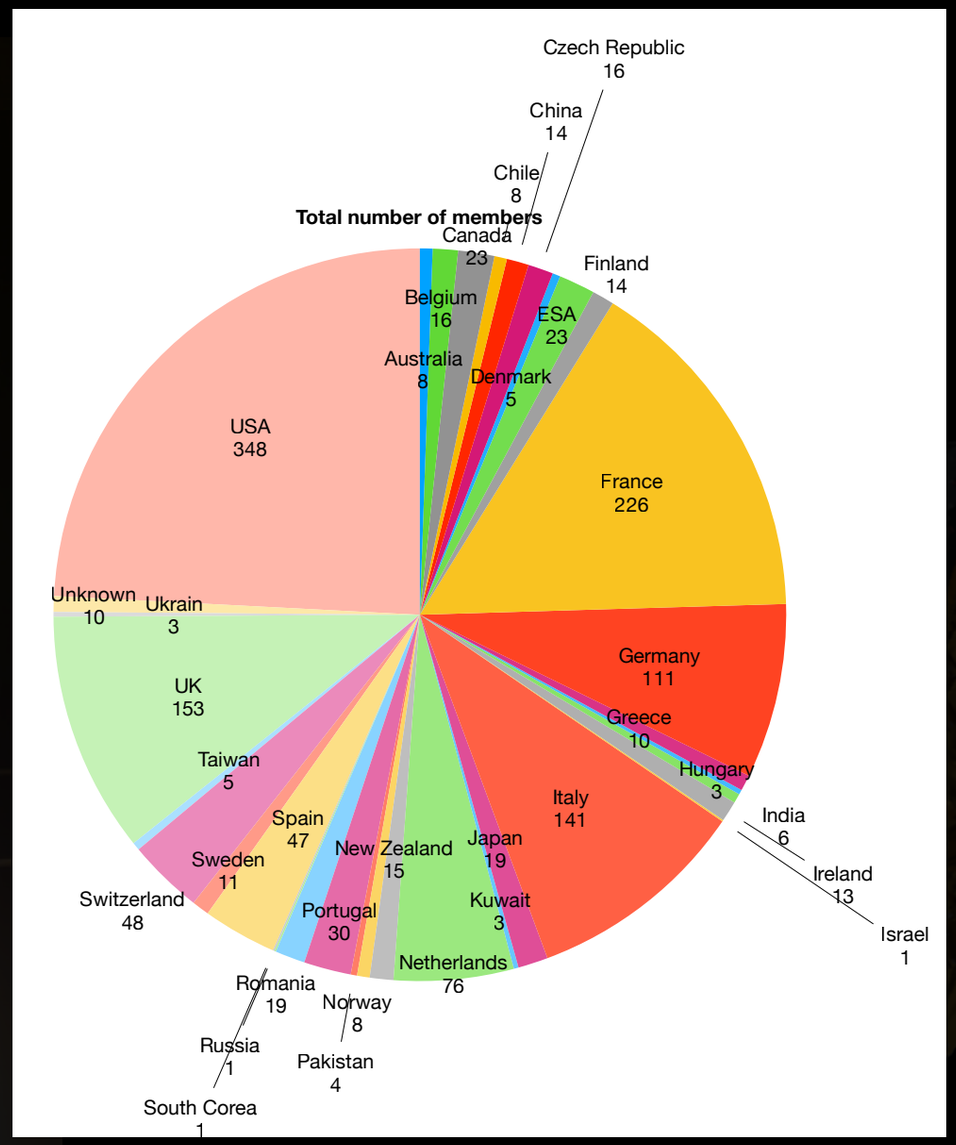
- Activities during the phase A:
  - Scope, first definitions, organisation, performances, ...
  - For the ground segment:
    - first mission of this kind + large number of overlapping sources: challenge for data analysis => development and prototyping started very early
    - Support & contribution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

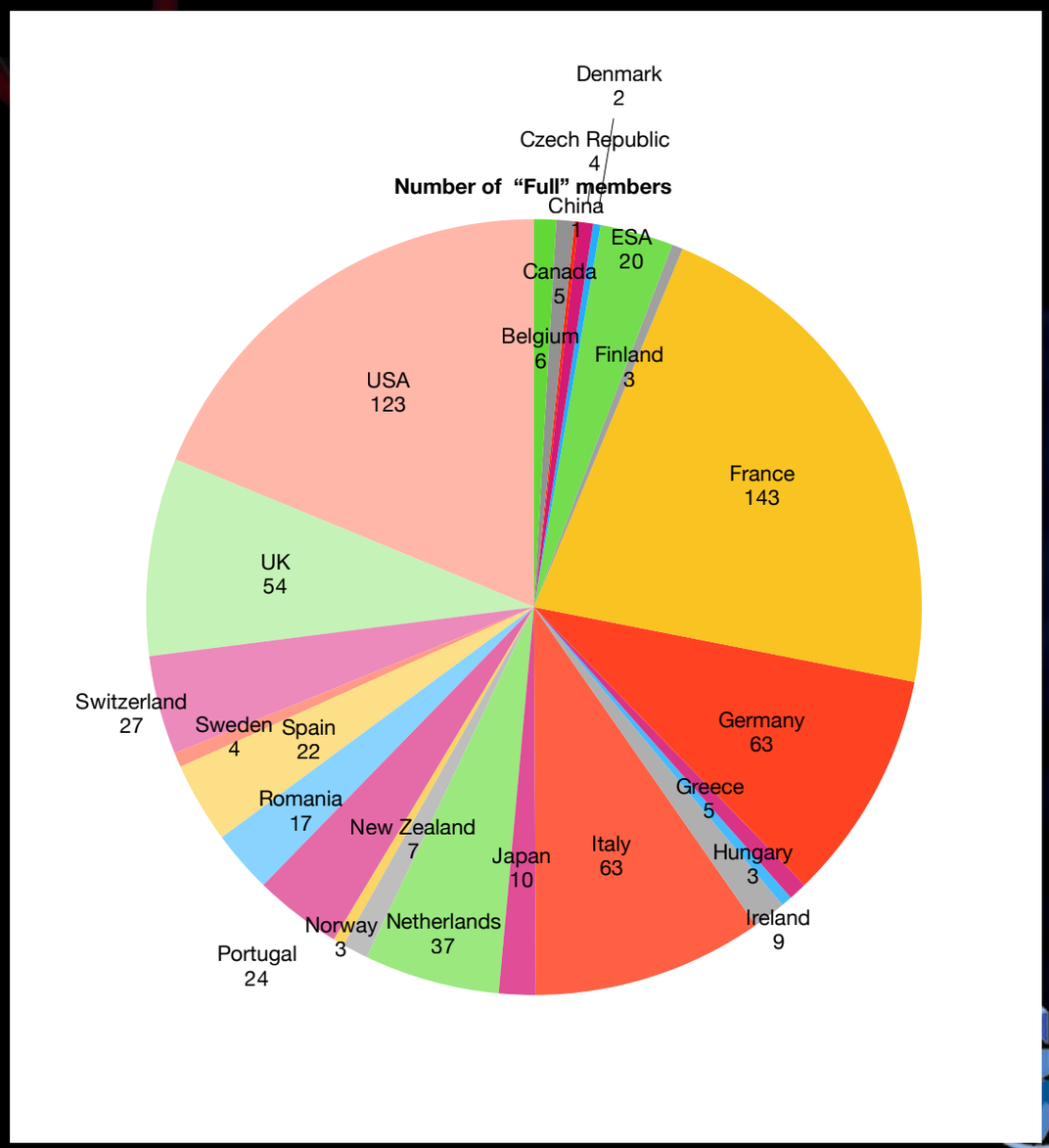
LISA Consortium



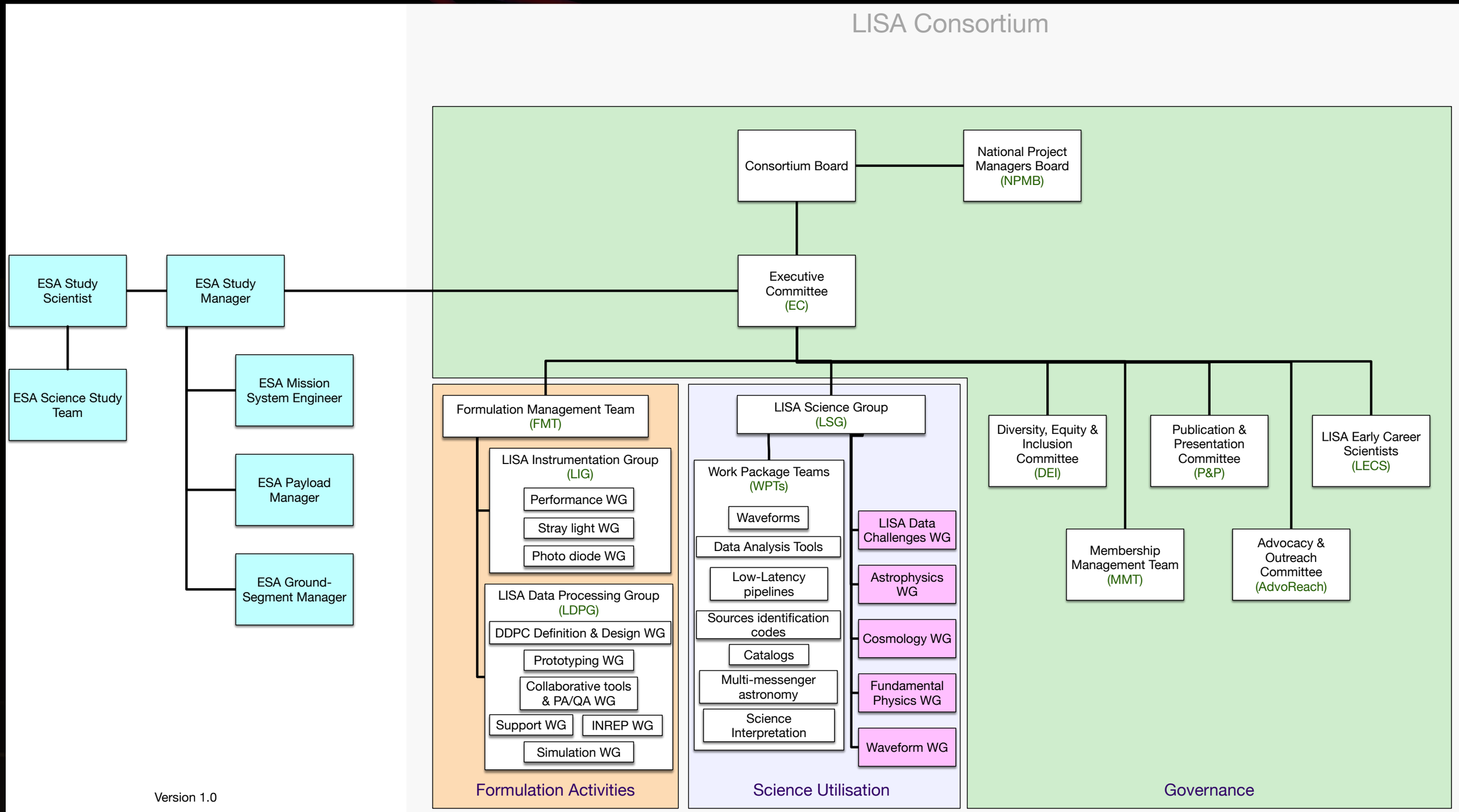
LISA Consortium

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





Consortium Organisation



Thank you