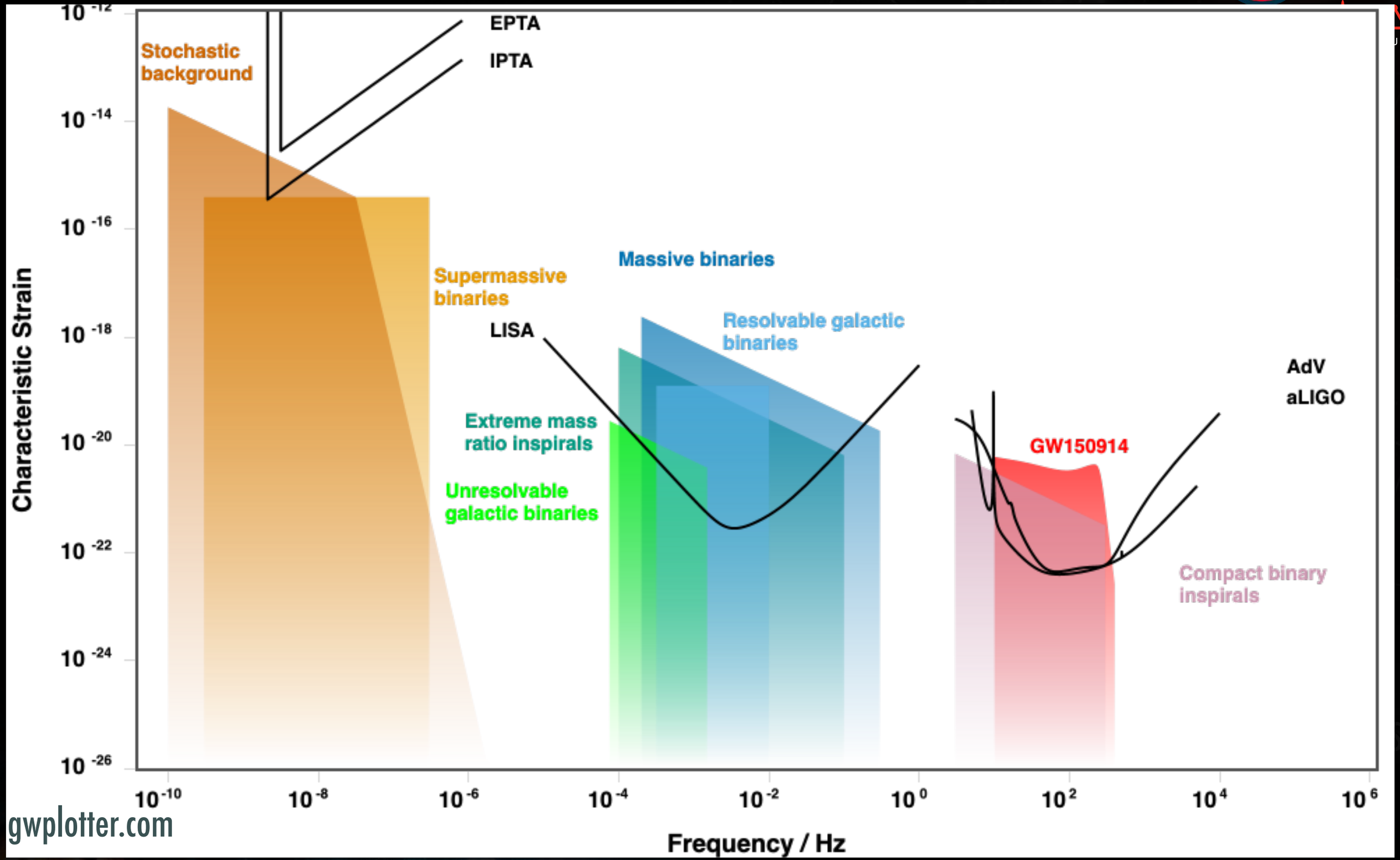
Space based/moon based and PTA gravitational wave observatories

Antoine Petiteau (CEA/IRFU/DPhP)

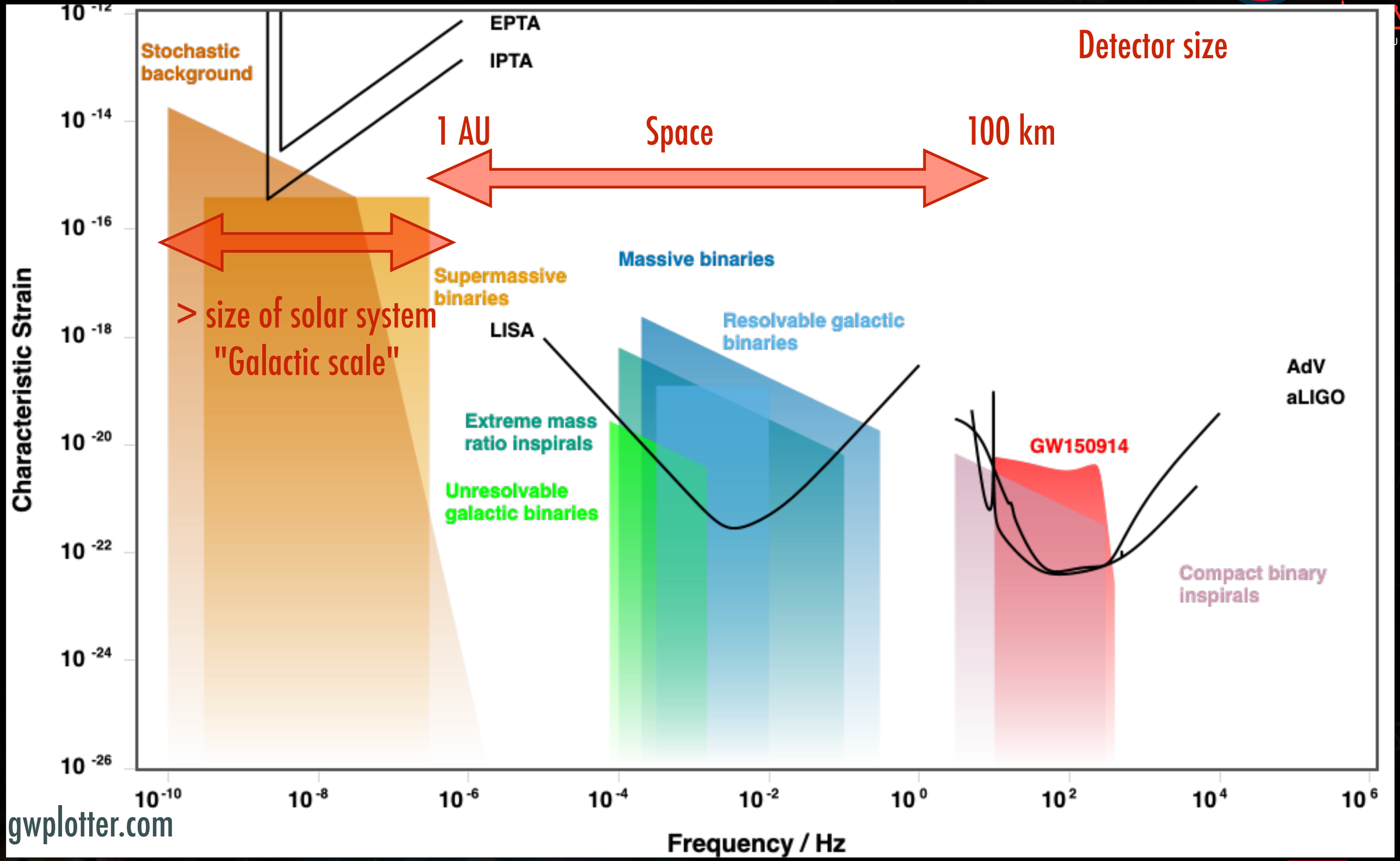
Workshop ACME

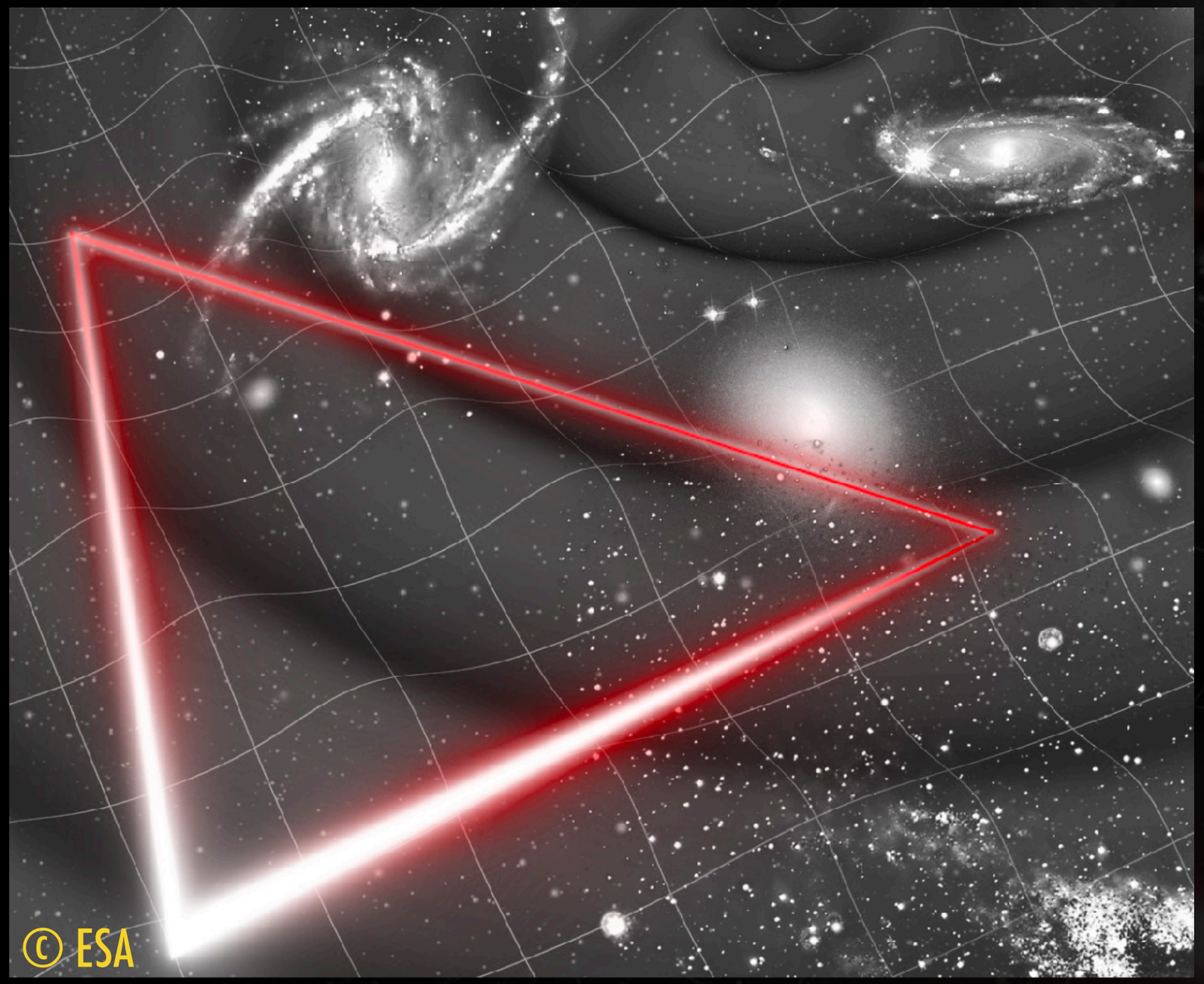
7th April 2025 - Toulouse

GW spectrum


Stochastic background
EPTA
IPTA
Supermassive binaries
Massive binaries
LISA
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
AdV
aLIGO
GW150914
Compact binary inspirals
Characteristic Strain
Frequency / Hz
gwplotter.com

GW spectrum

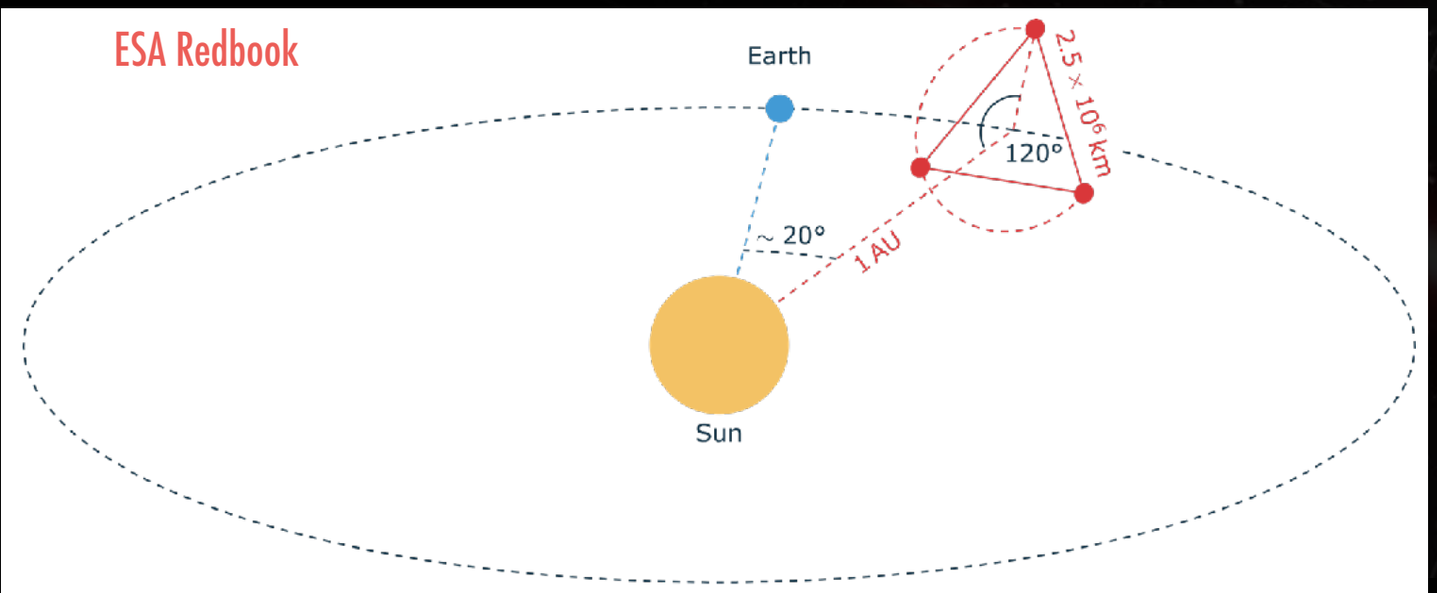

Characteristic Strain
Frequency / Hz
Stochastic background
EPTA
IPTA
Detector size
1 AU
Space
100 km
> size of solar system
"Galactic scale"
Supermassive binaries
Massive binaries
LISA
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
AdV
aLIGO
GW150914
Compact binary inspirals
gwplotter.com

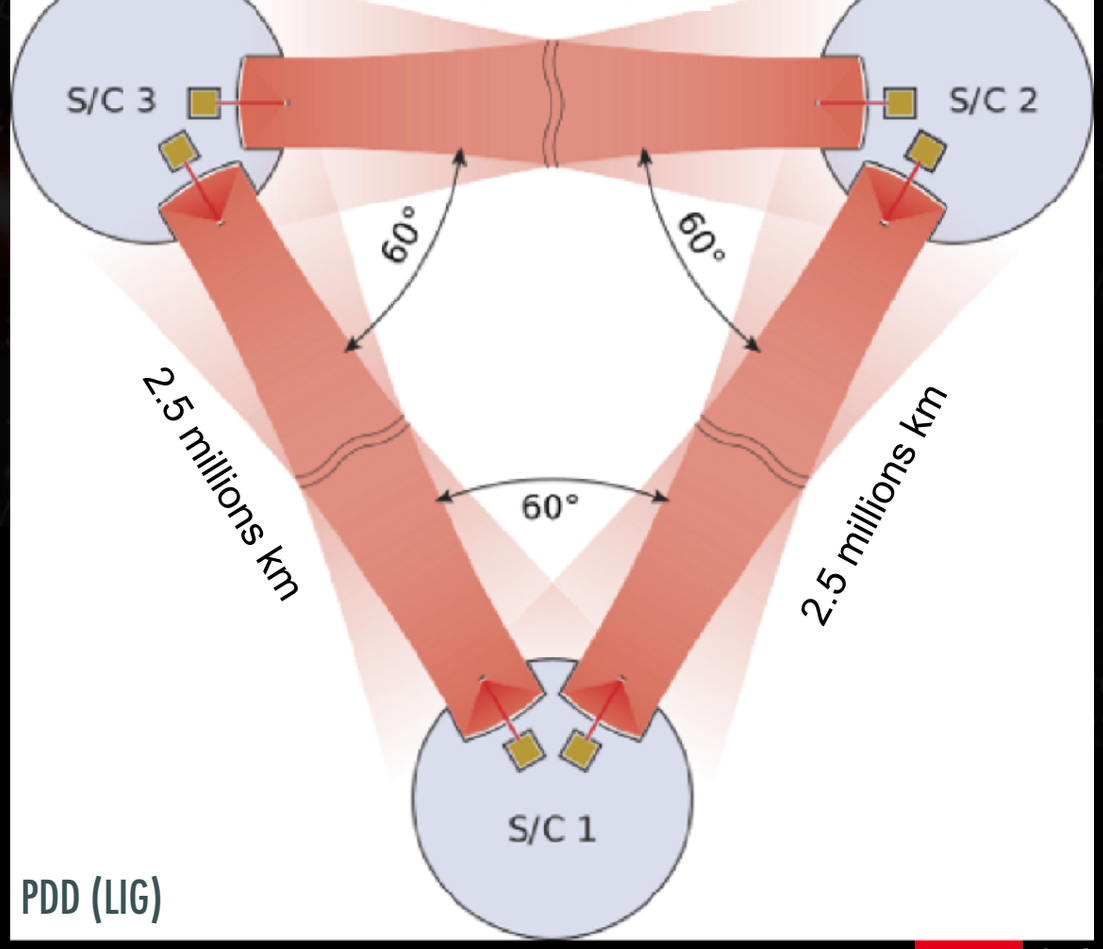


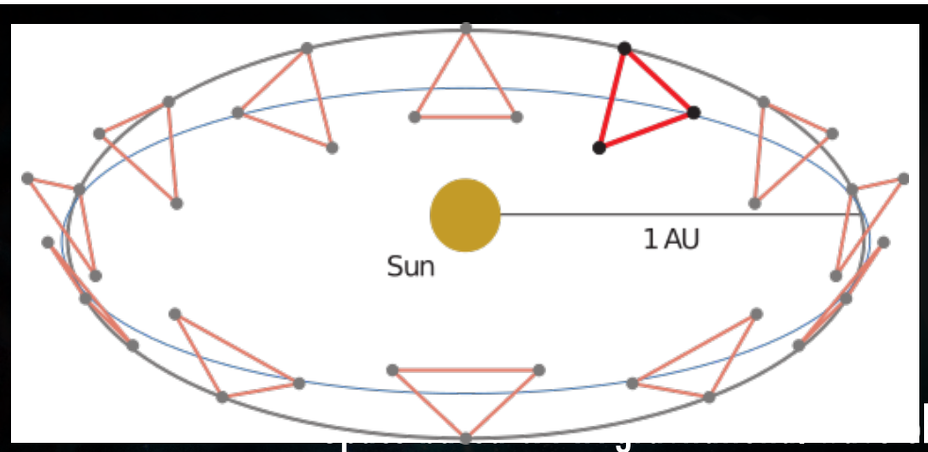
LISA

Mission design

- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits separated by 2.5 millions km
- Goal: detect strains of 10^{-21} by monitoring arm length changes at the few picometre level



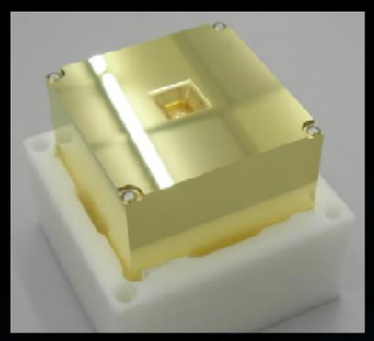


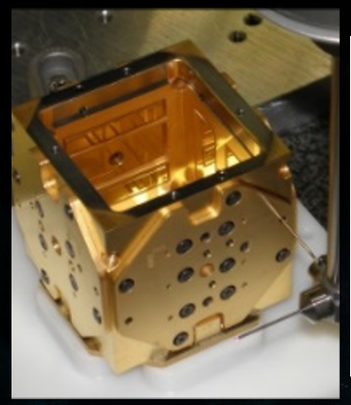


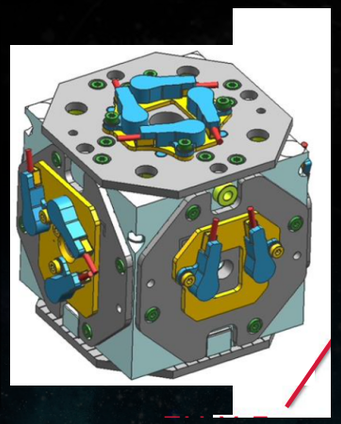
L3 proposal (LISA Consortium)

Mission design

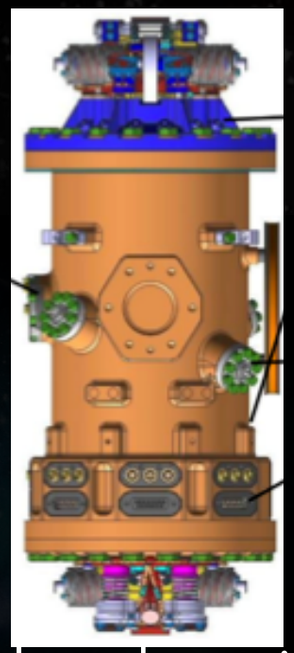
- Measurement points must be shielded from fluctuating non-gravitational influences:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing

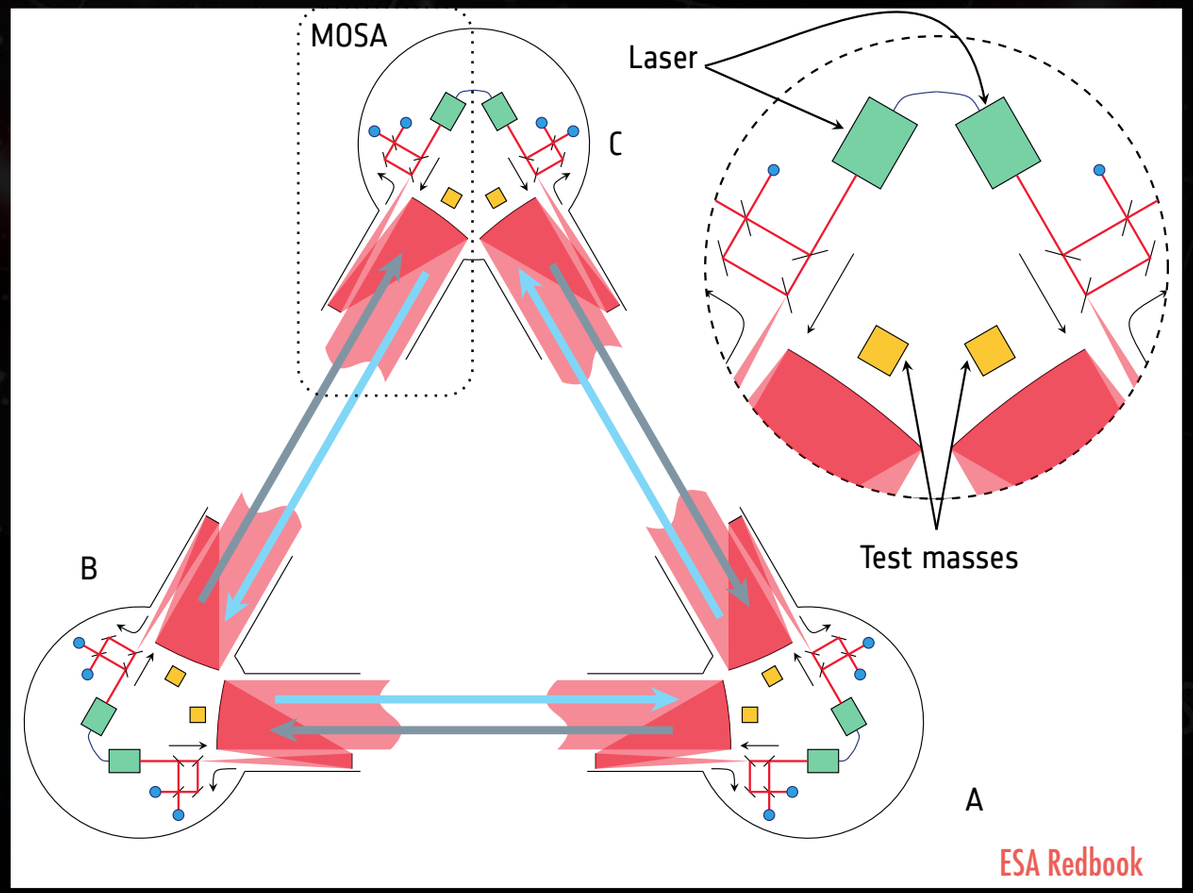






ESA Redbook - OHB Italia

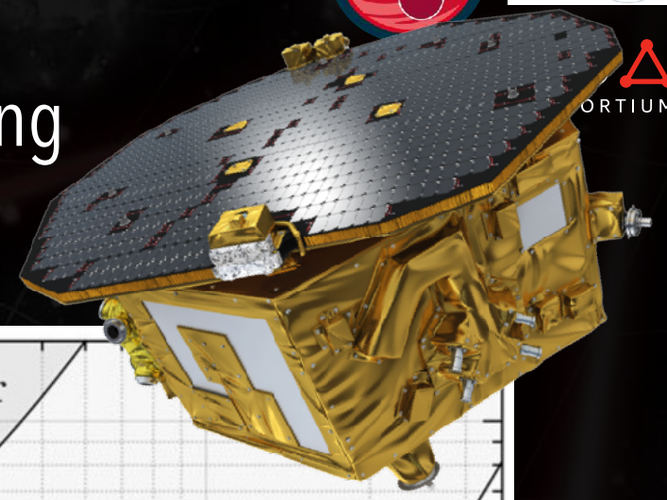


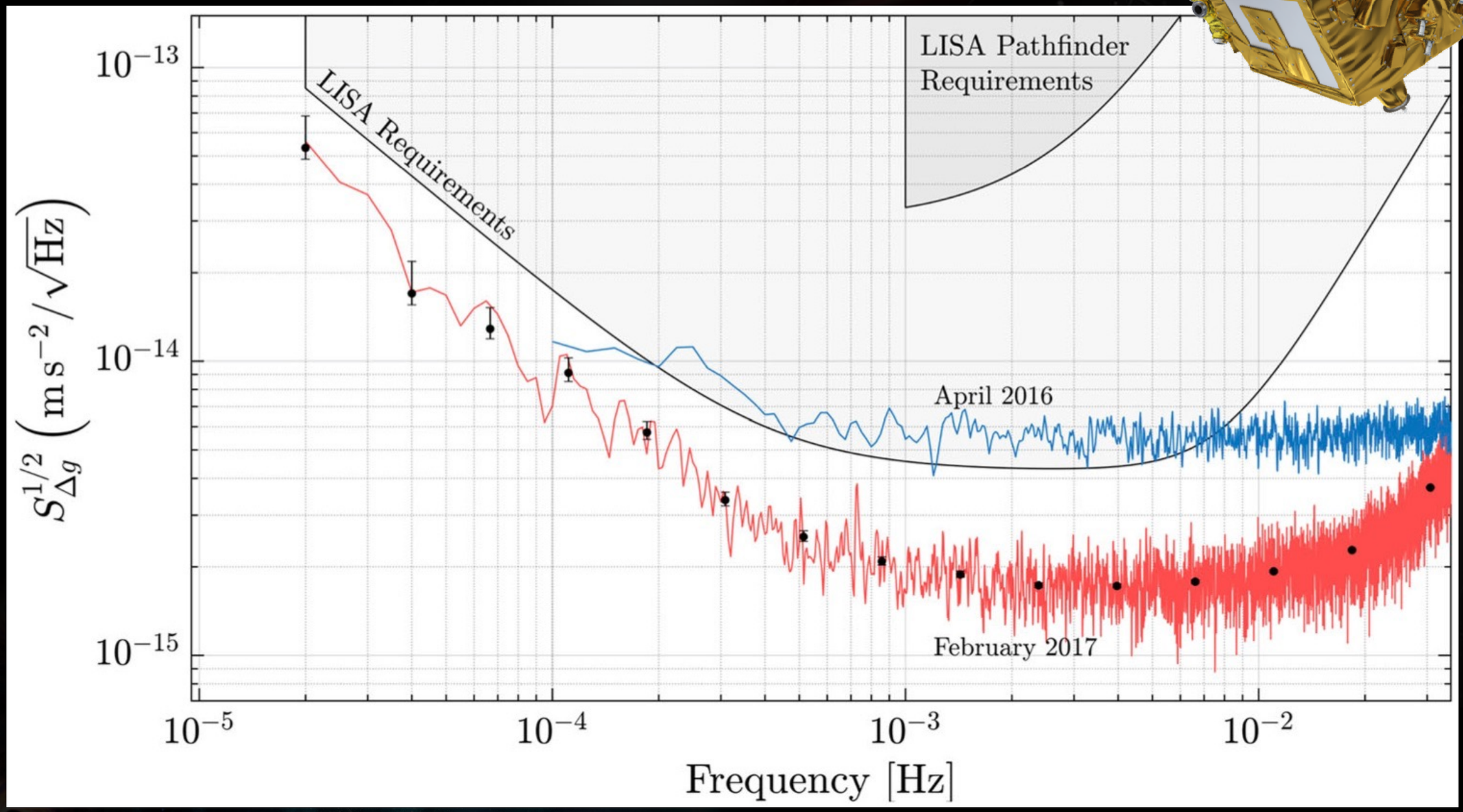


ESA Redbook

LISAPathfinder final main results

- Successful demonstration of the ability to shield from fluctuating non-gravitational influences

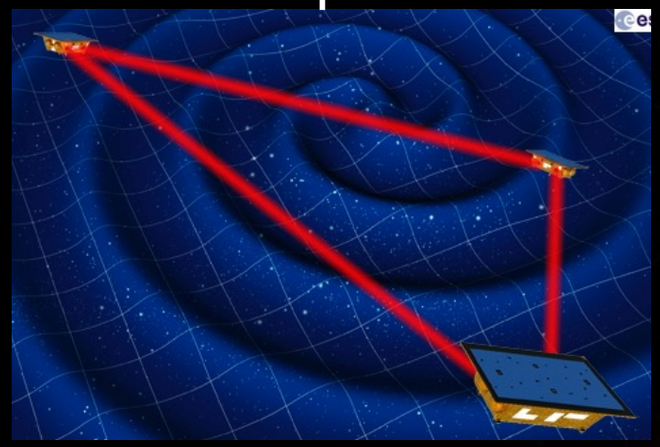




M. Armano et al. PRL 120, 061101 (2018)

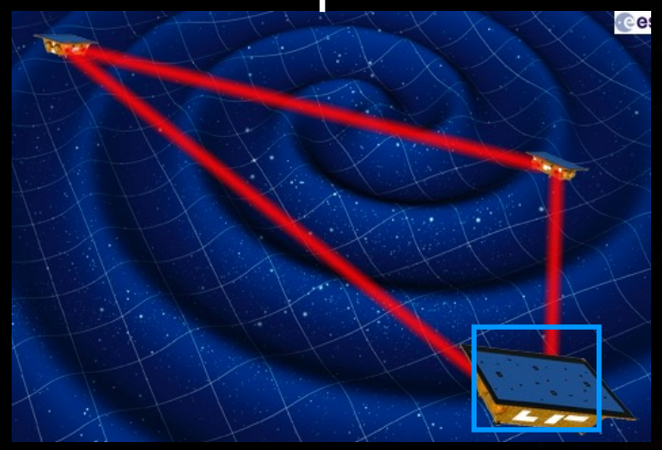
Mission design

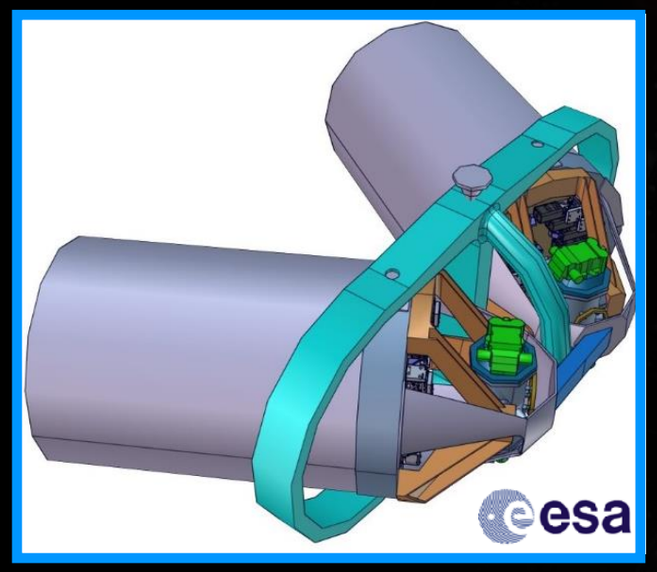
- Several steps towards the required precision of measurement



Mission design

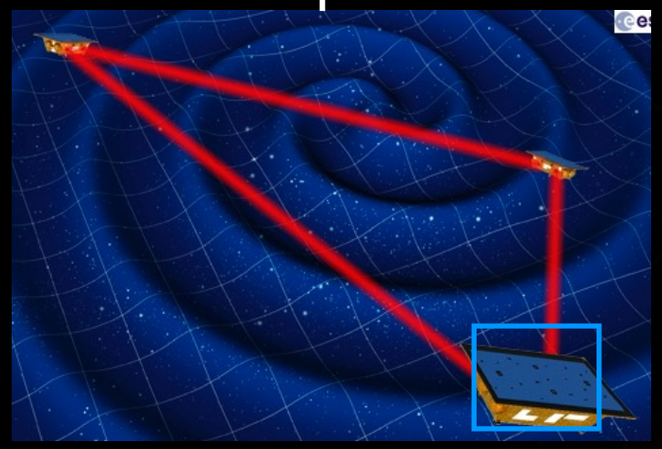
- Several steps towards the required precision of measurement

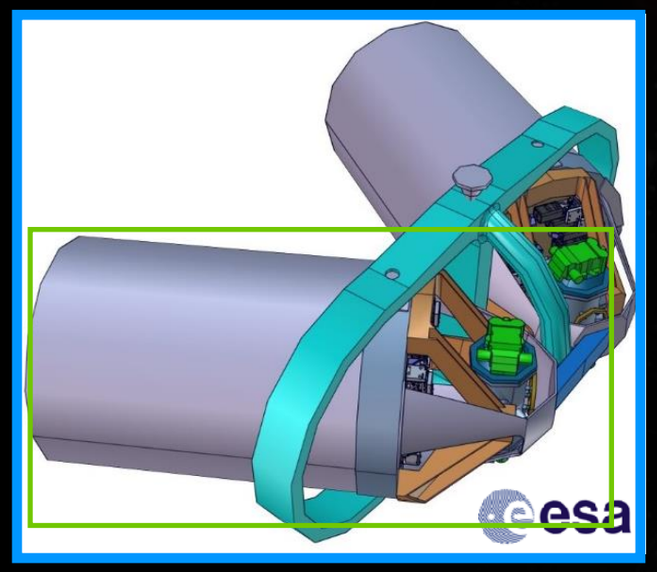


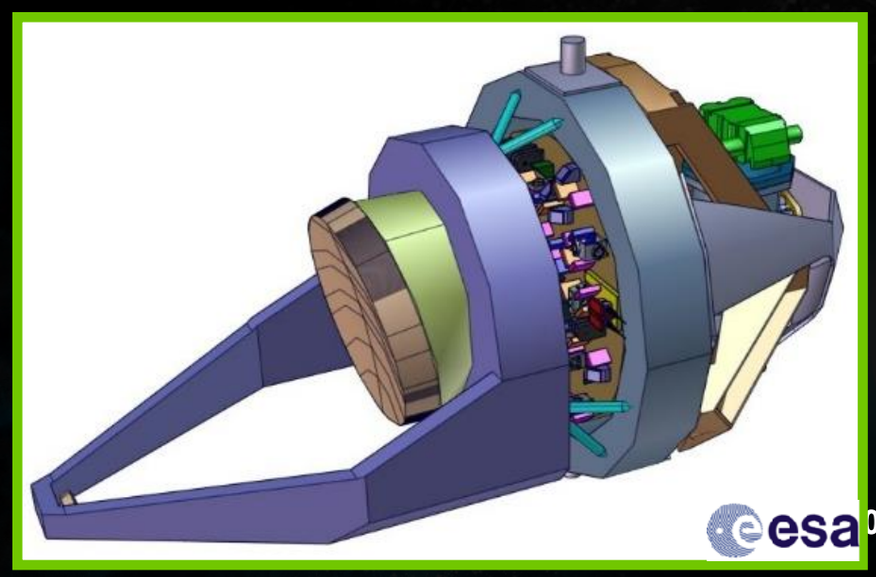


Mission design

- Several steps towards the required precision of measurement

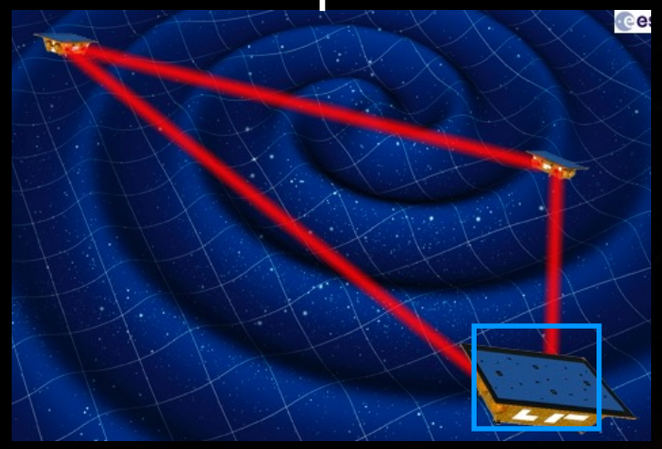


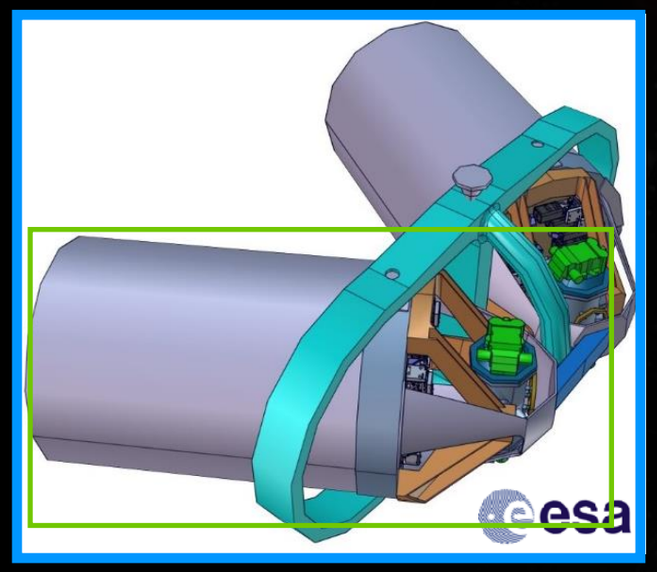


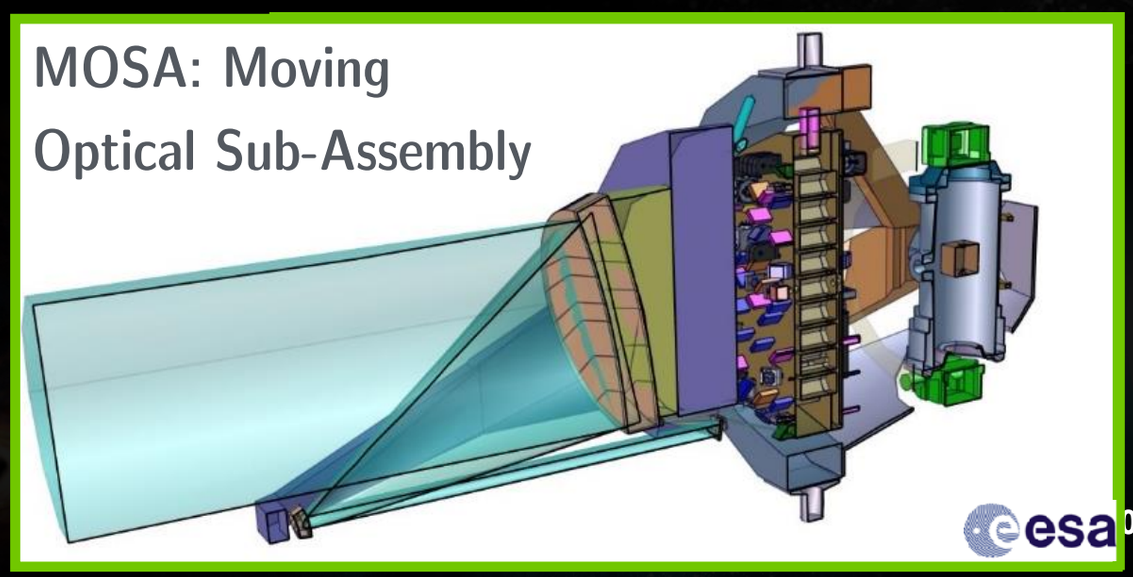


Mission design

- Several steps towards the required precision of measurement

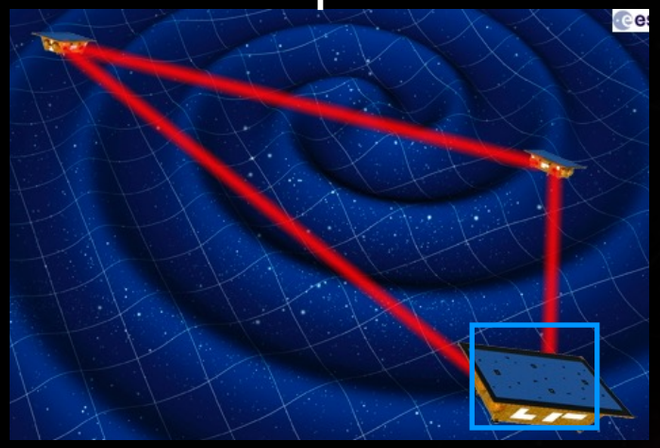


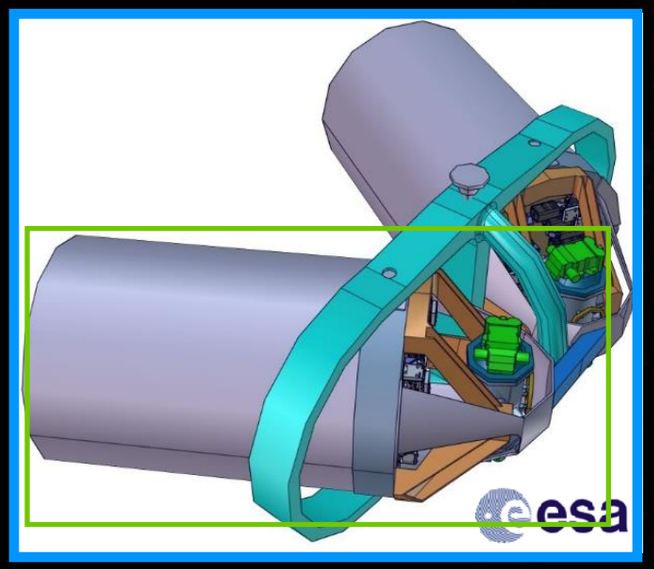


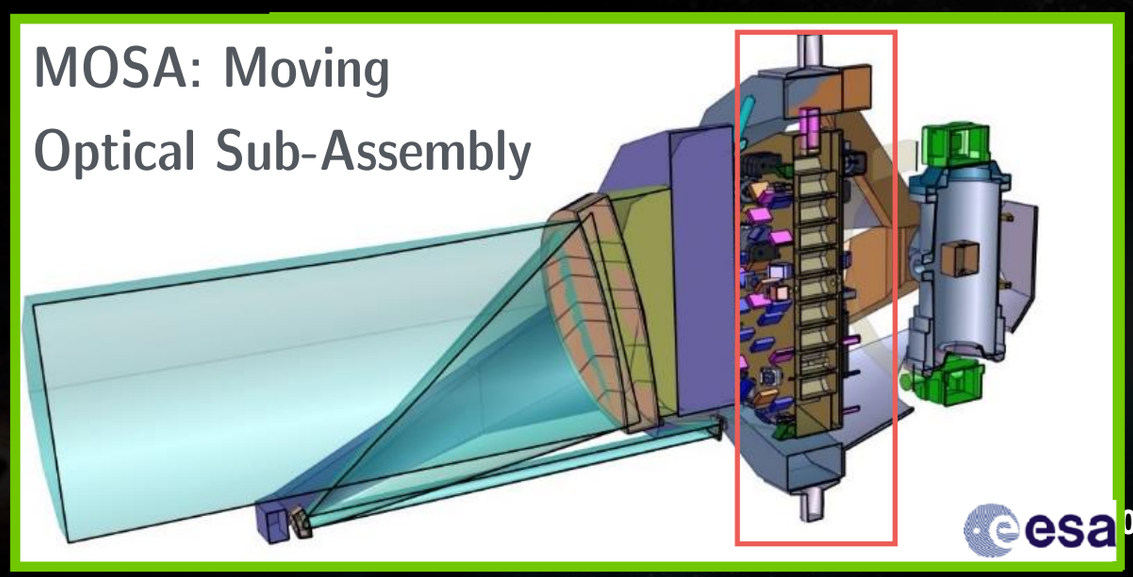


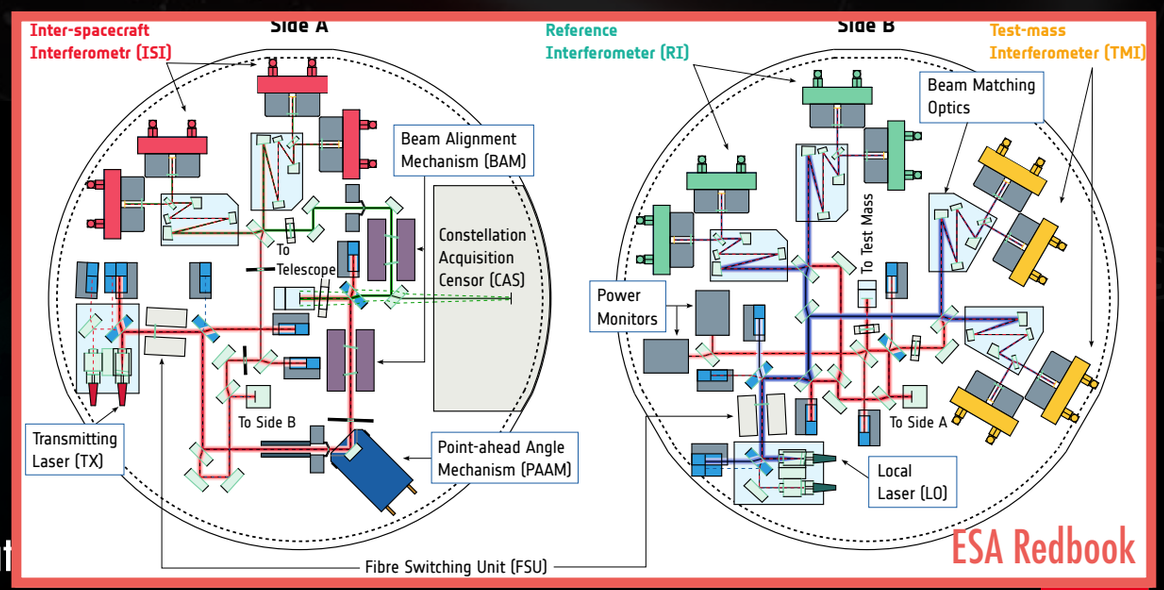
Mission design

- Several steps towards the required precision of measurement





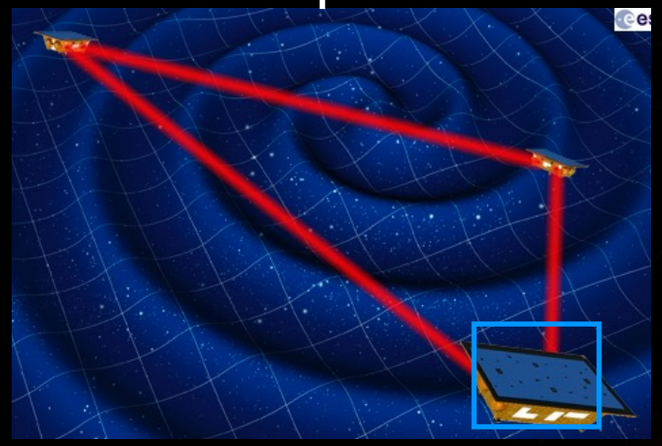




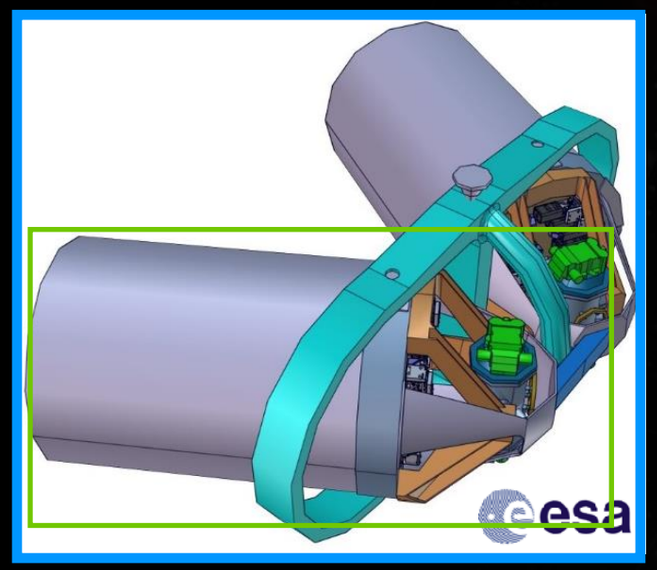
ESA Redbook

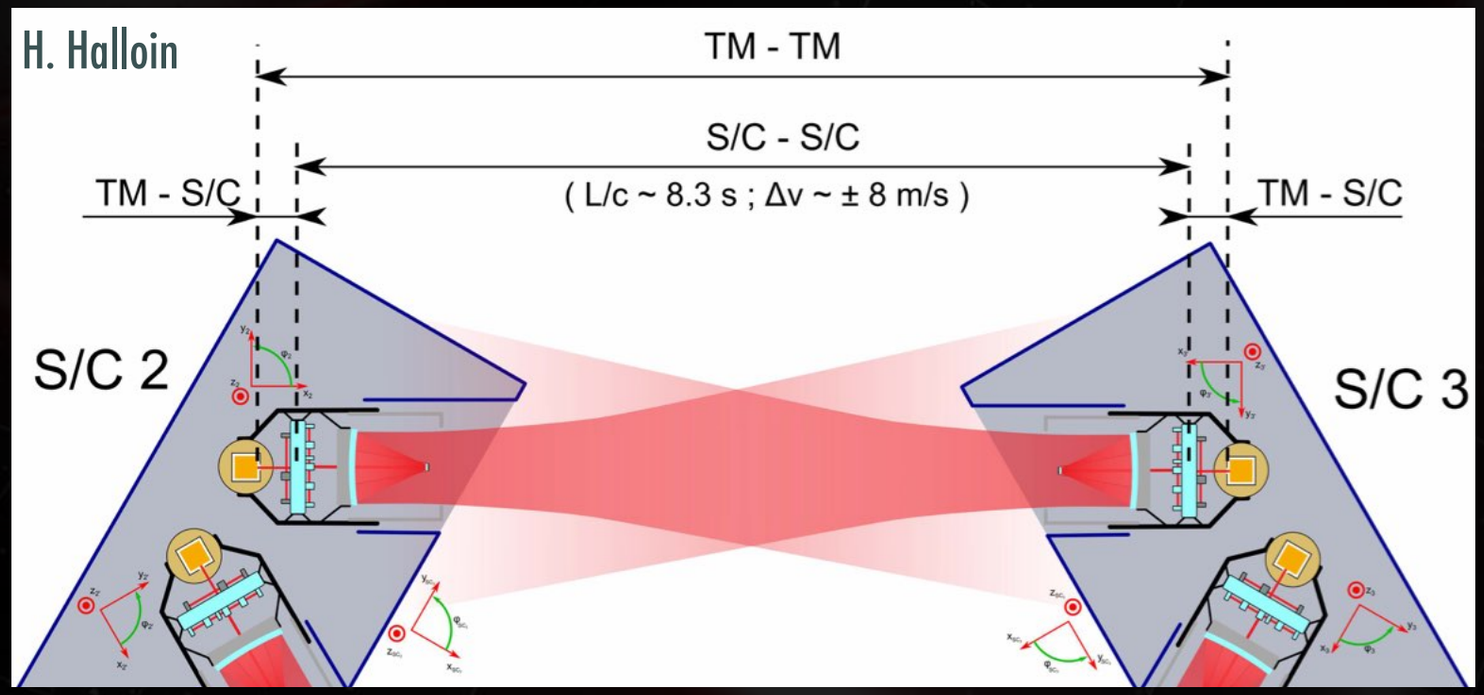
Mission design

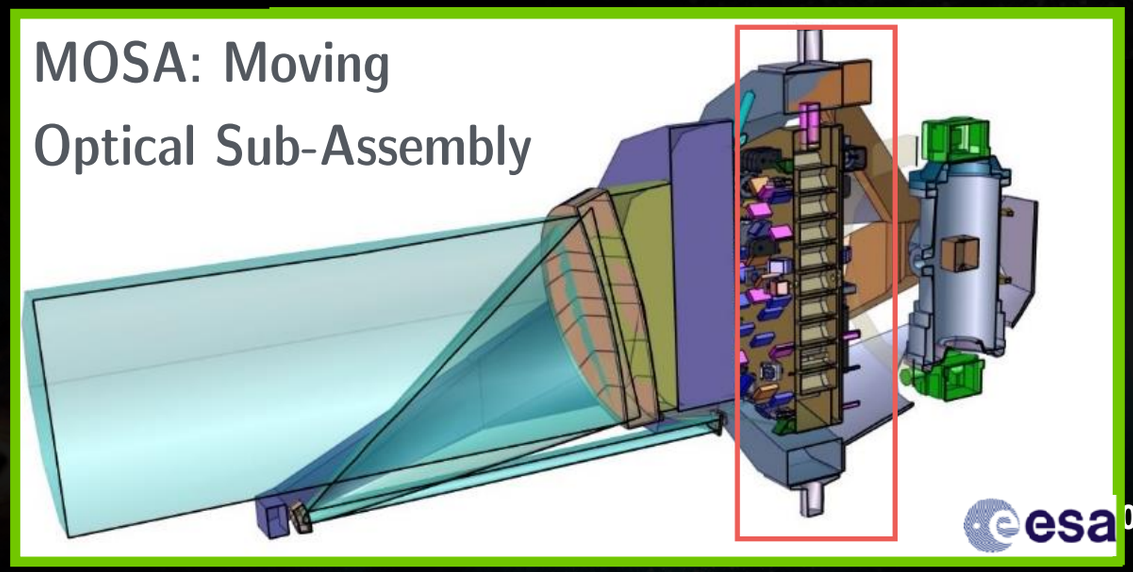
- Several steps towards the required precision of measurement

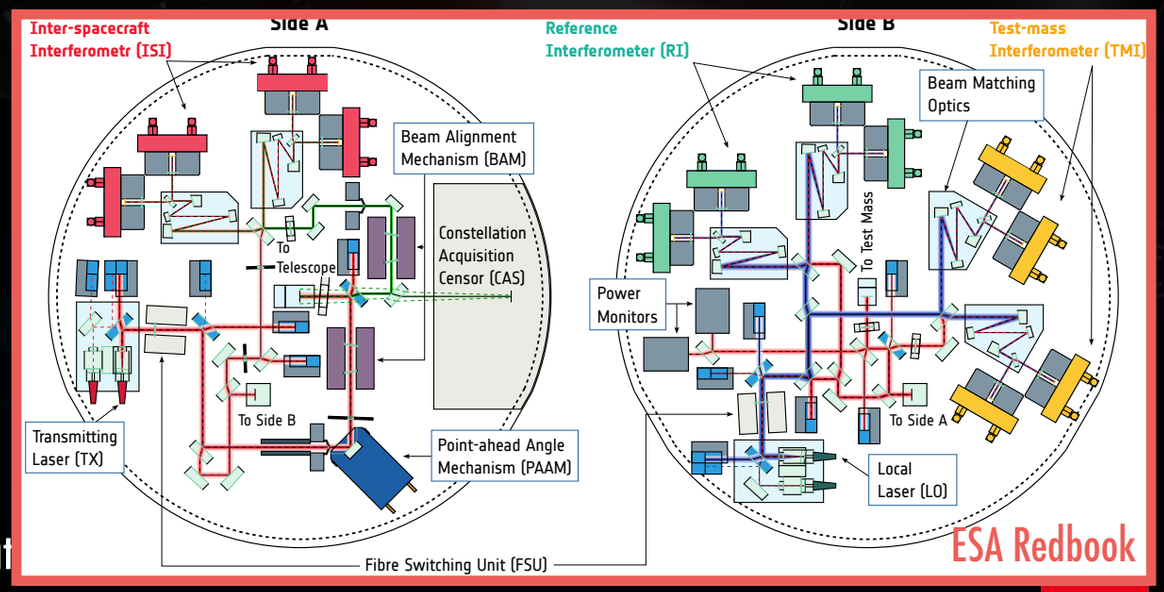


(TM2→SC2) + (SC2→SC3) + (SC3→TM3)





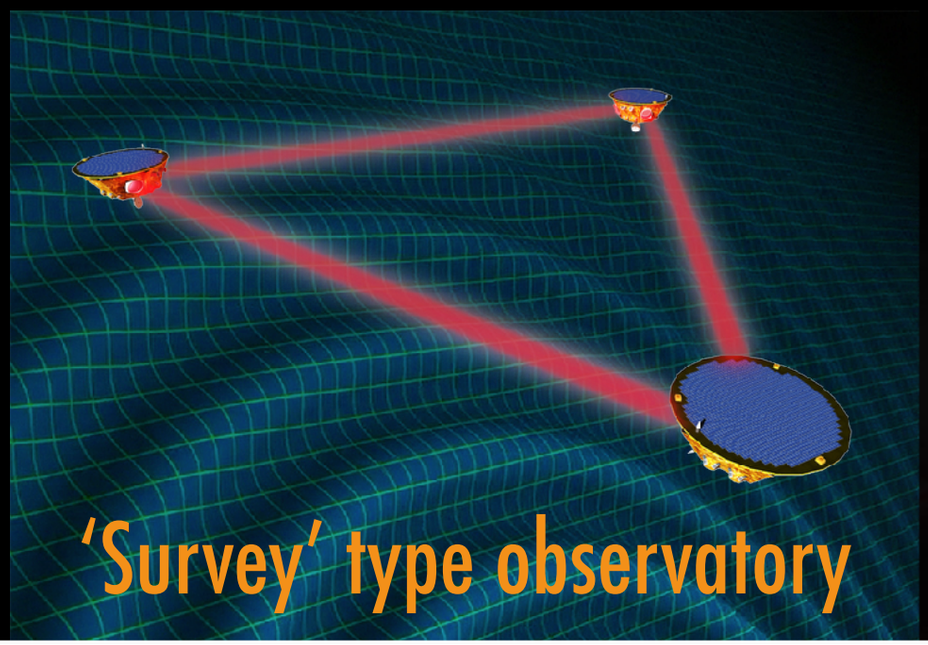




Data

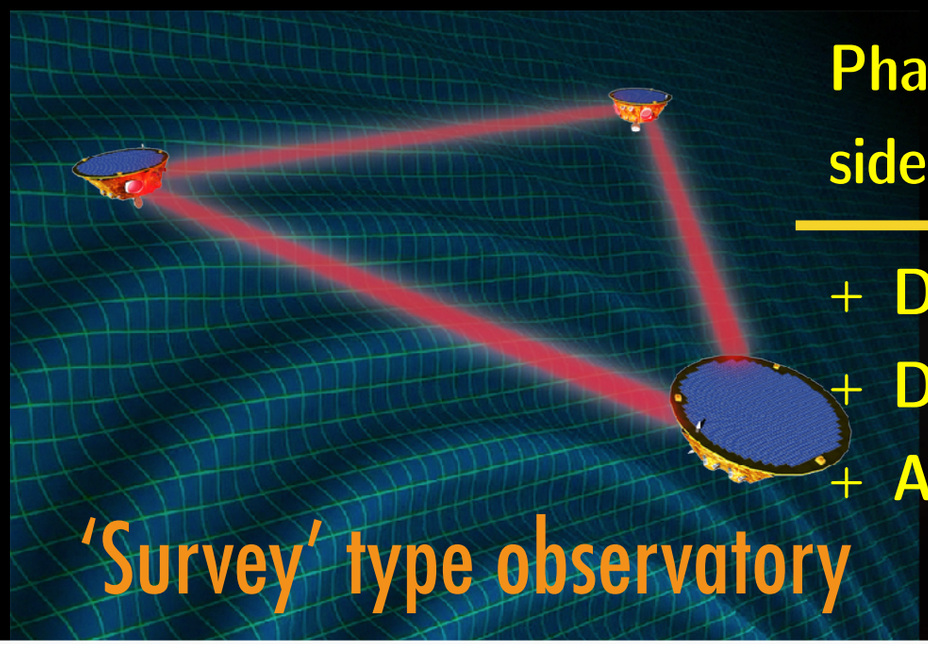
Gravitational wave sources emitting between 0.02mHz and 1 Hz

Data



Gravitational wave sources emitting between 0.02mHz and 1 Hz

Data



Phasemeters (carrier, sidebands, distance)

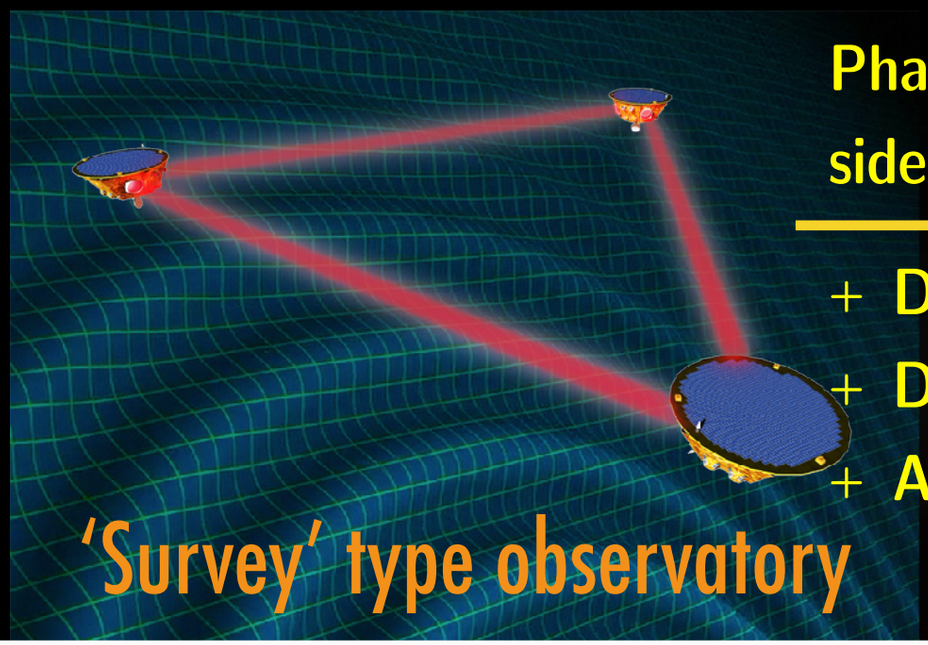
+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

Data



Phasemeters (carrier, sidebands, distance)

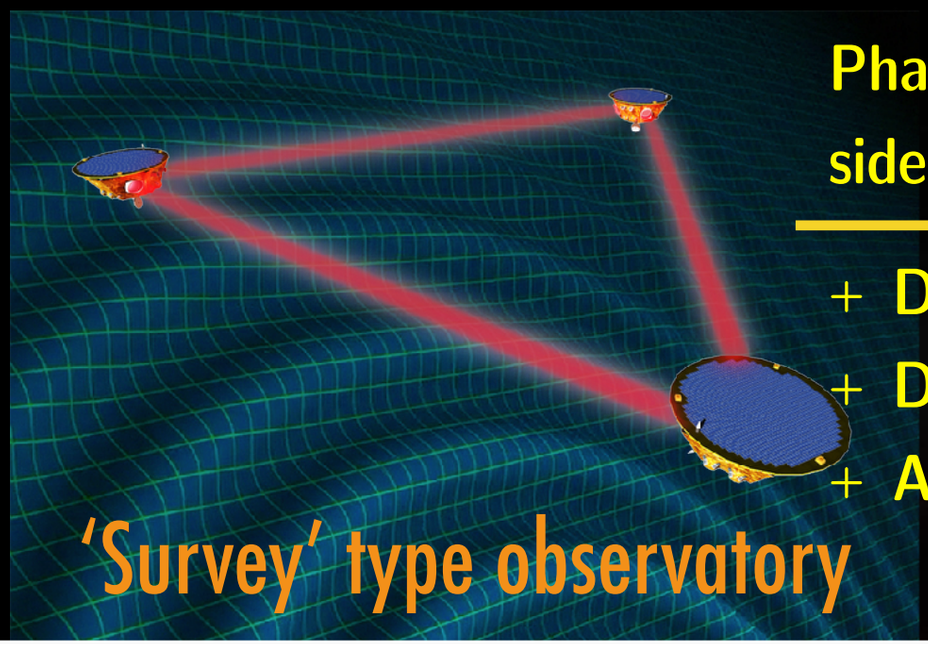
+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

Data



Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry
reduction of laser noise

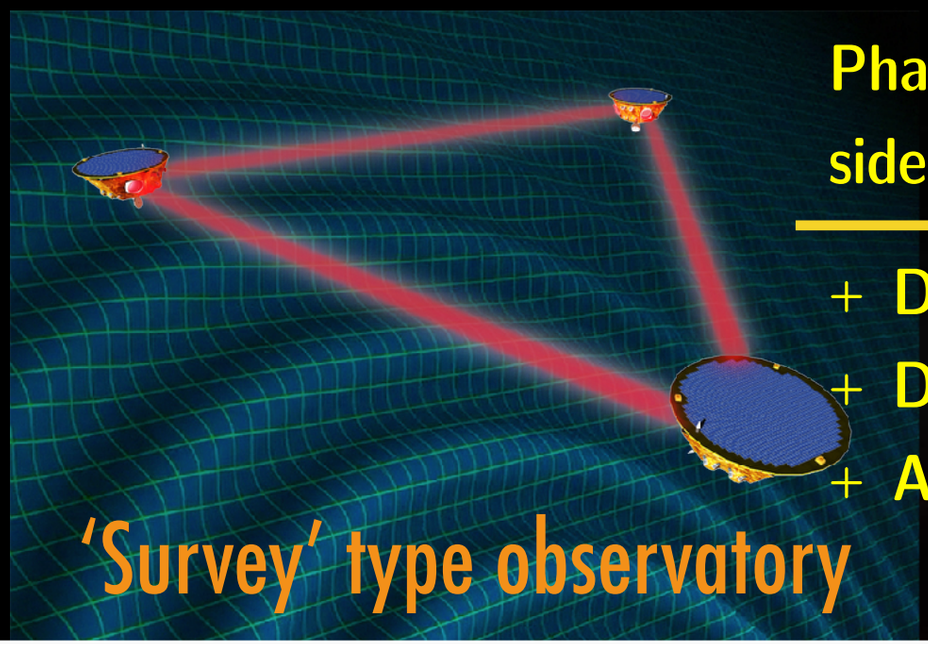
3 TDI channels with 2 "~independents"

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

Data



Phasemeters (carrier, sidebands, distance)

\+ DFACS* & CMD**

\+ Diagnostics

\+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry
reduction of laser noise

3 TDI channels with 2 "~independents"

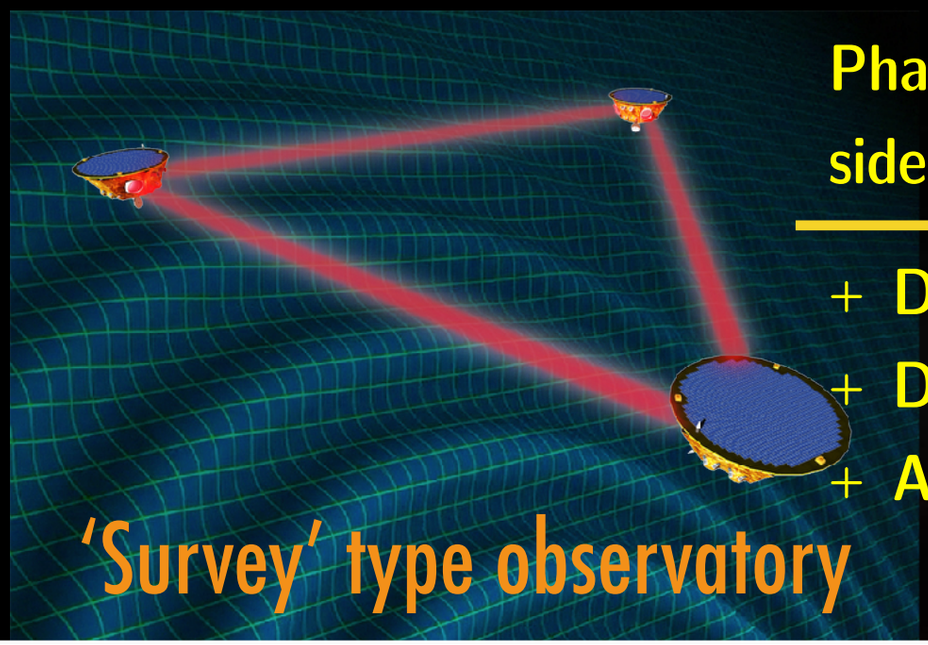
Data Analysis of GWs

Catalogs of GWs sources with their waveform

* Drag-Free Attitude Control System

** Charge Management Device

Data



Phasemeters (carrier, sidebands, distance)

L0

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

L0.5

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

* Drag-Free Attitude Control System

** Charge Management Device

Data

Phasemeters (carrier,

ds, distance)

CS* & CMD**

+ Diagnostics

+ Auxiliary channels

Mission Operation Center (ESA)

'Survey' type observatory

Science Operation Center (ESA)

Gravitational wave sources

emitting between 0.02mHz

z

DDPC: Distributed Data Processing Center (ESA Member States)

NASA Ground Segment

L0

L0.5

Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry
reduction of laser noise

L1

3 TDI channels with 2 "~independents"

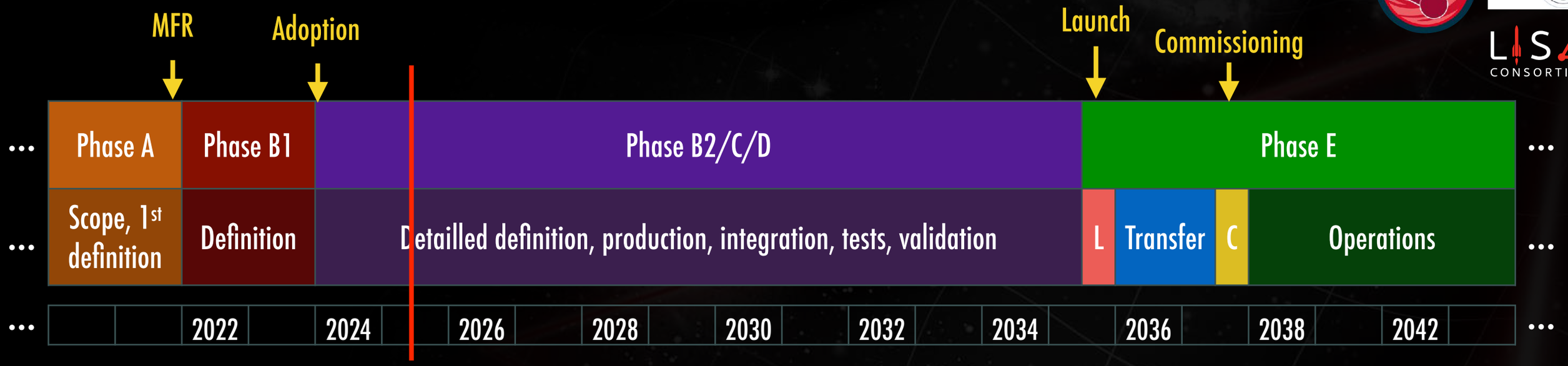
L2

Data Analysis of GWs

L3

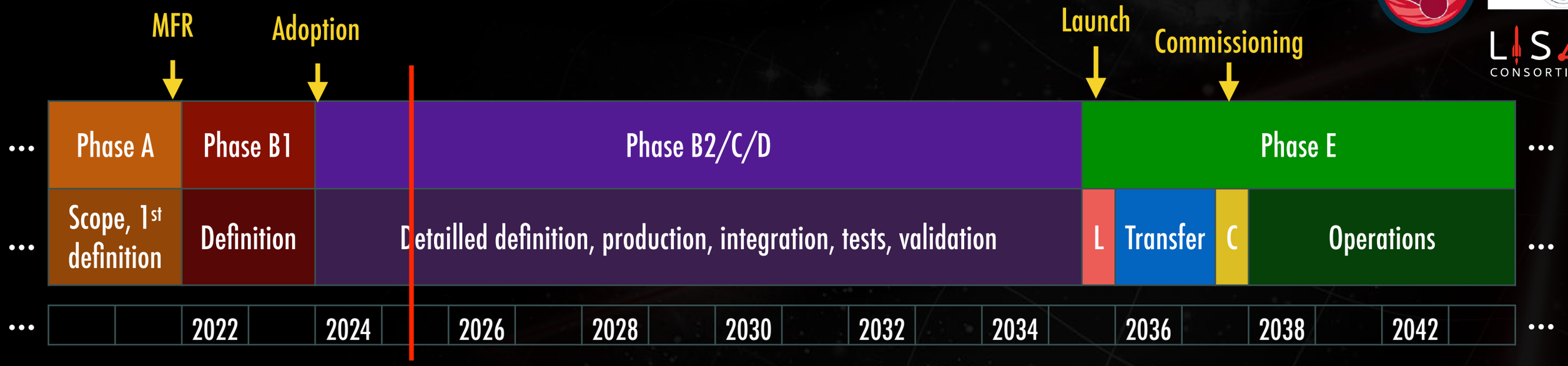
Catalogs of GWs sources with their waveform

Timeline and status



- 1993: first proposal ESA/NASA
- 20/06/2017: LISA mission approved by ESA Science Program Committee (SPC) after the success of LISAPathfinder and GW detection by LIGO-Virgo.
- 25/01/2024: success of the Mission Adoption Review and adoption by the SPC: design is fully validated and we have the ressource to build the instrument
- End 2024: industrial prime chosen; on-going co-engineering phase → official signature in June
- 2025 - 2035: building phase: multiple MOSAs (6 flight models + test models) + 3 spacecrafts
- Launch 2035
- 1.5 years of transfer, 4.5 years nominal mission, 6.5 years extension

Timeline and status

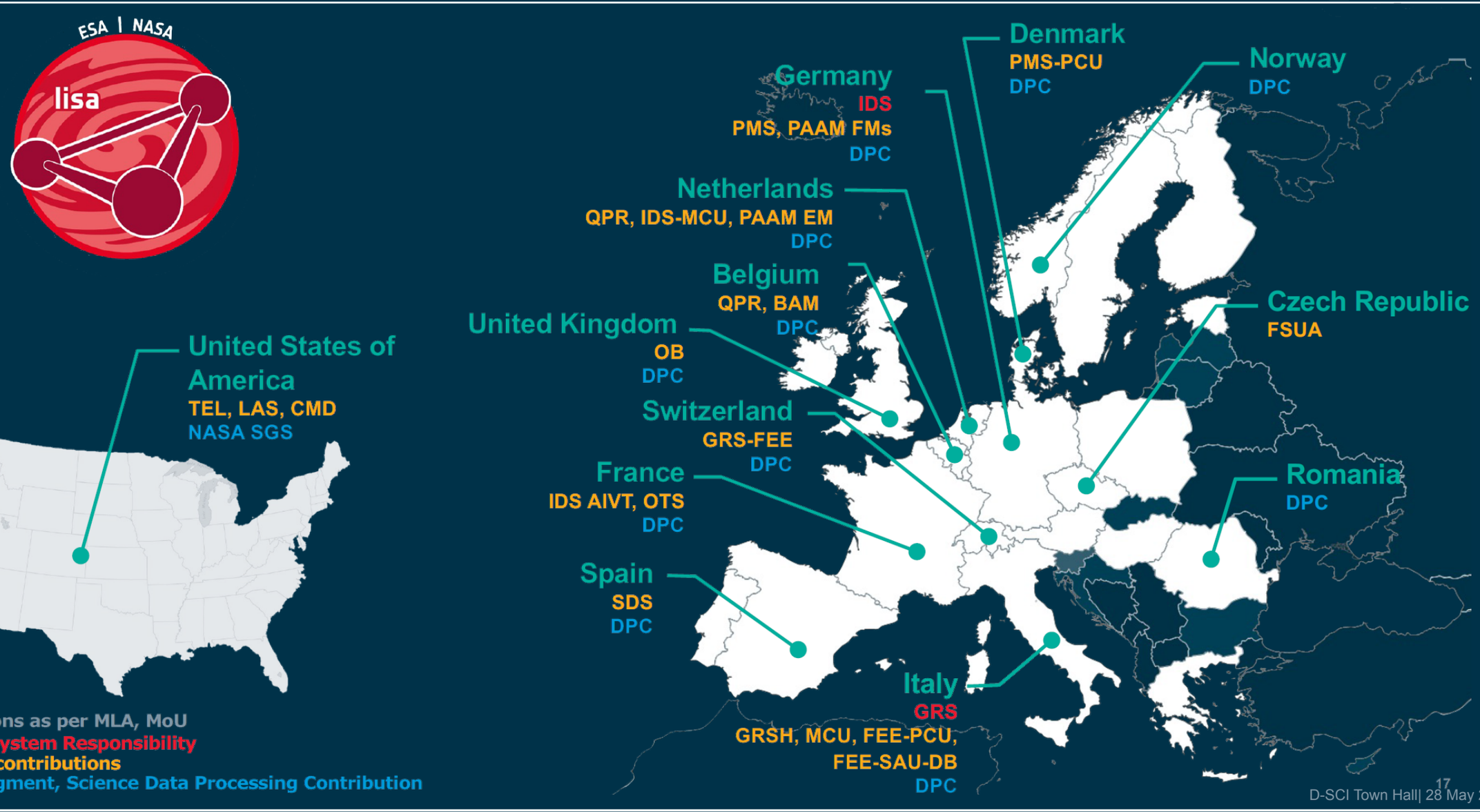


- 1993: first proposal ESA/NASA
- 20/06/2017: LISA mission approved by ESA Science Program Committee (SPC) after the success of LISAPathfinder and GW detection by LIGO-Virgo.
- 25/01/2024: success of the Mission Adoption Review and adoption by the SPC: design is fully validated and we have the ressource to build the instrument
- End 2024: industrial prime chosen; on-going co-engineering phase → official signature in June
- 2025 - 2035: building phase: multiple MOSAs (6 flight models + test models) + 3 spacecrafts
- Launch 2035
- 1.5 years of transfer, 4.5 years nominal mission, 6.5 years extension

LISA collaboration

- Contributions to the instrument and ground segment (data analysis)

LISA - An international mission led by ESA

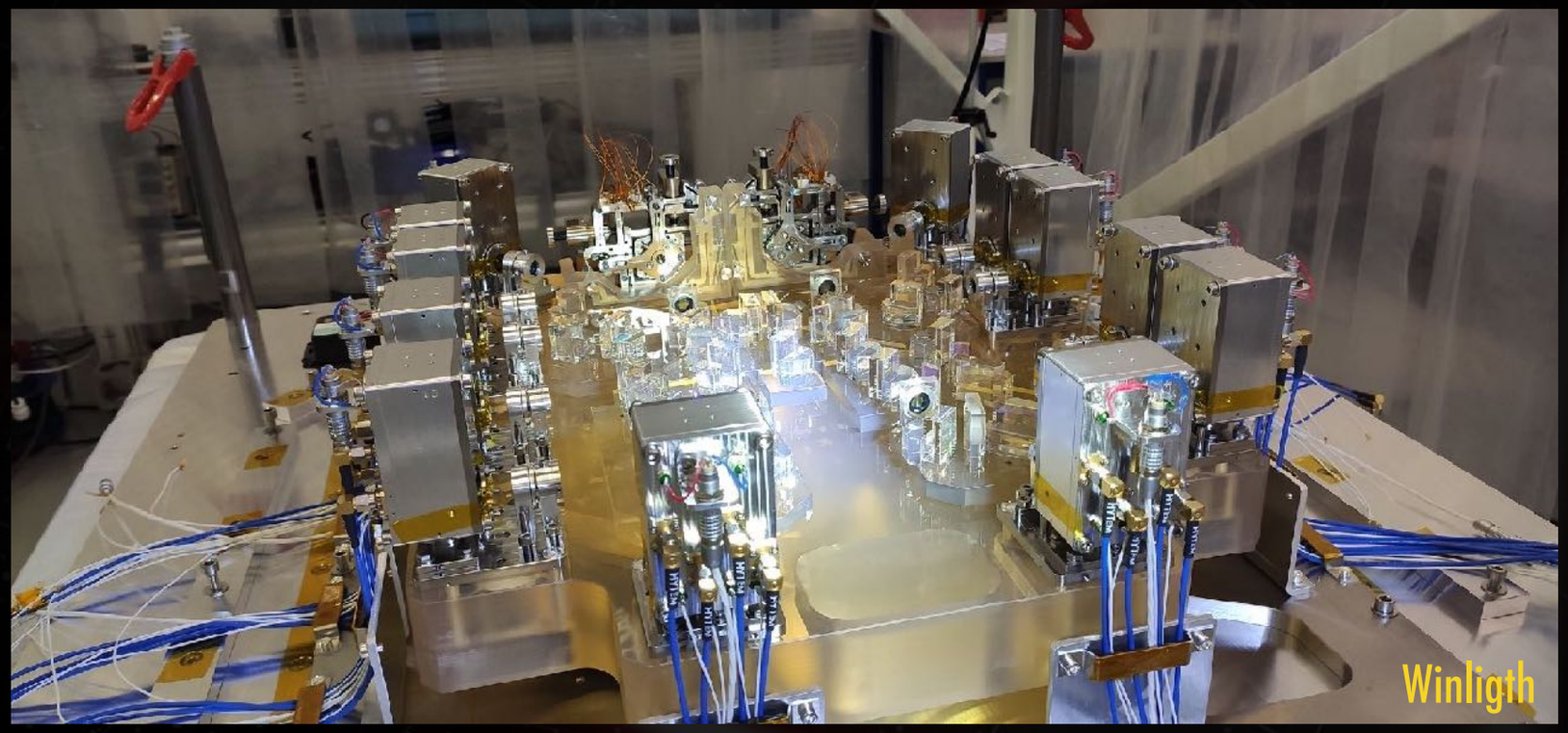


Contributions as per MLA, MoU
IDS/GRS System Responsibility
Hardware contributions
Ground Segment, Science Data Processing Contribution

Timeline and status

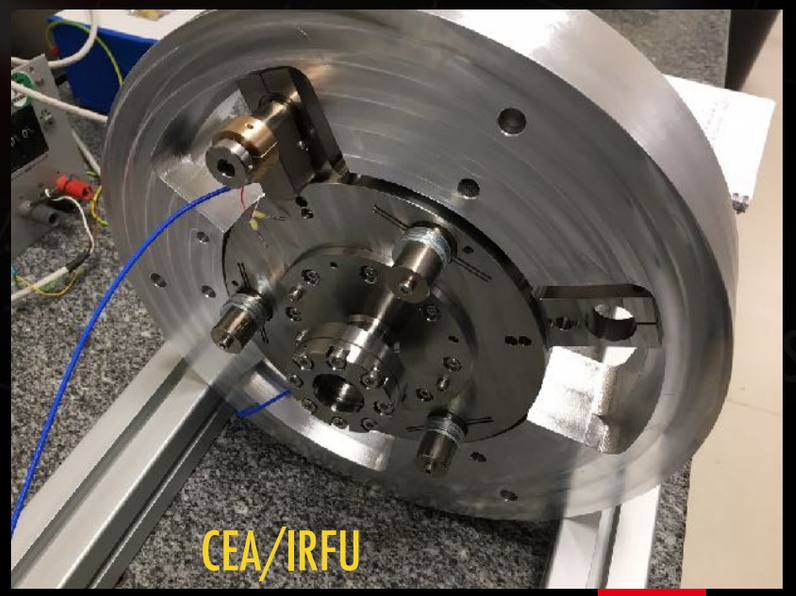
Building already started …

ZIFO (demonstration bench for high stability interferometry)



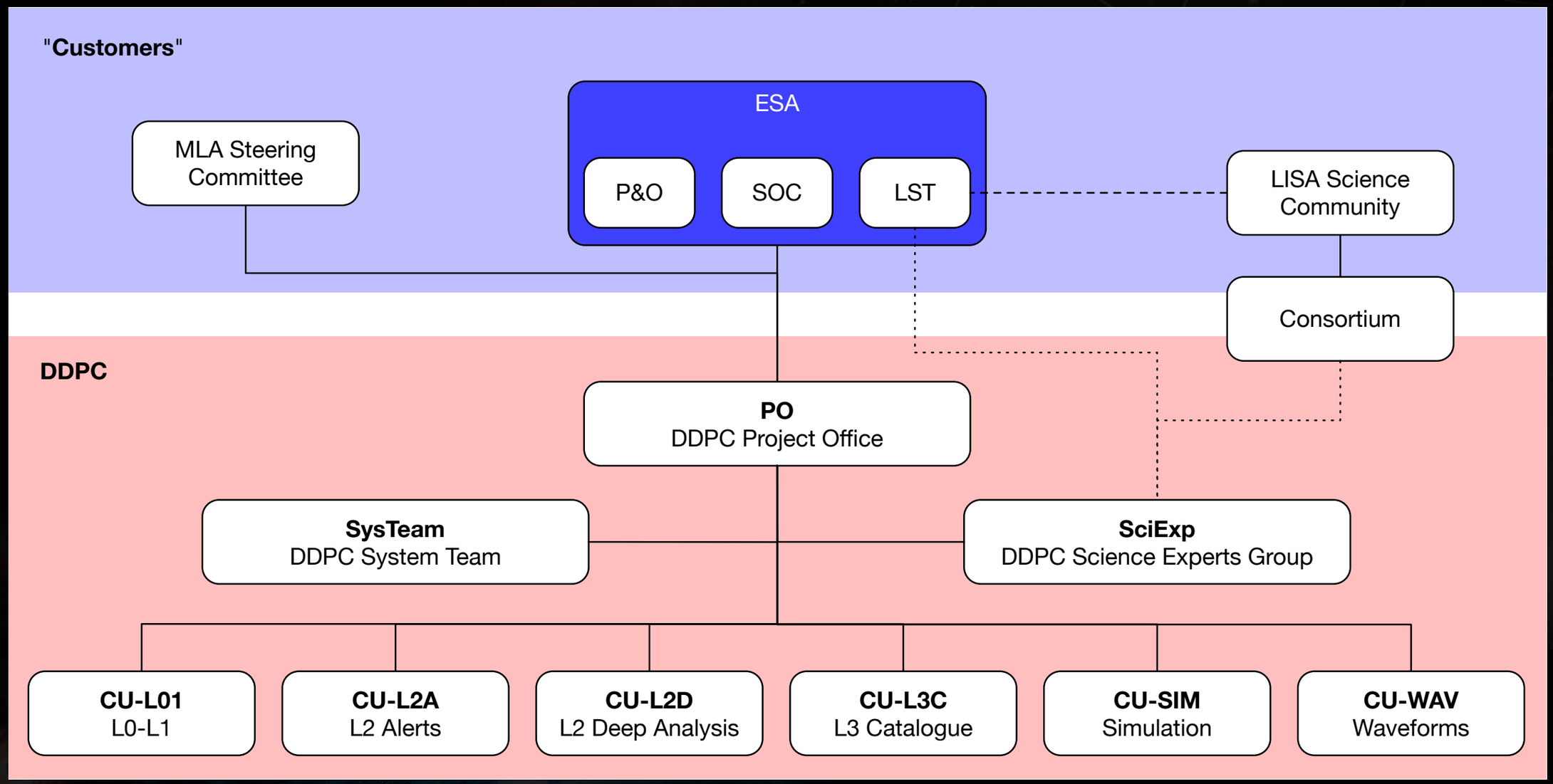
Telescope

Test-Mass Simulator



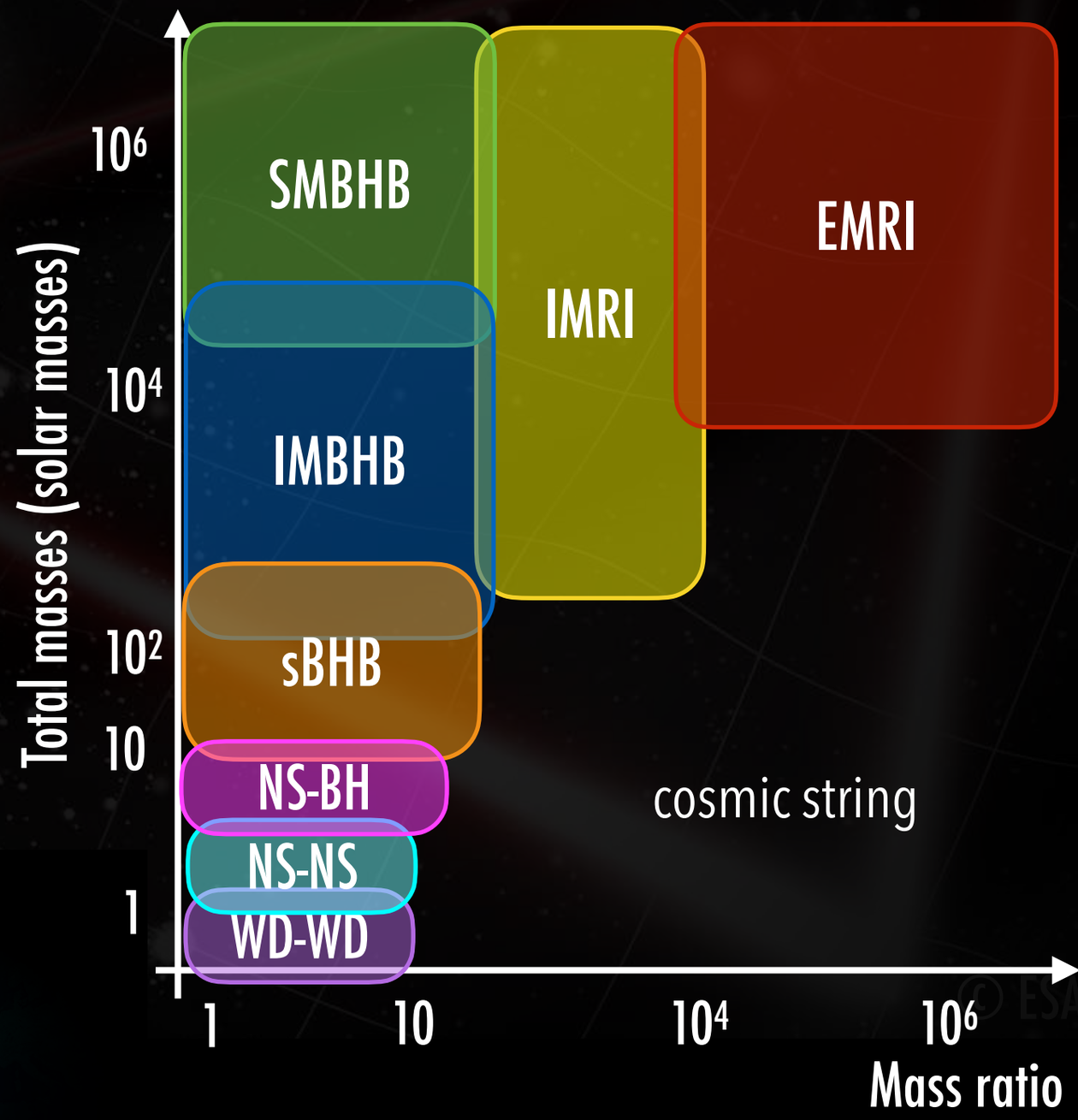
Timeline and status

- DDPC in place and active
- Release of the first common dataset in December 2025
- ~ 200 members



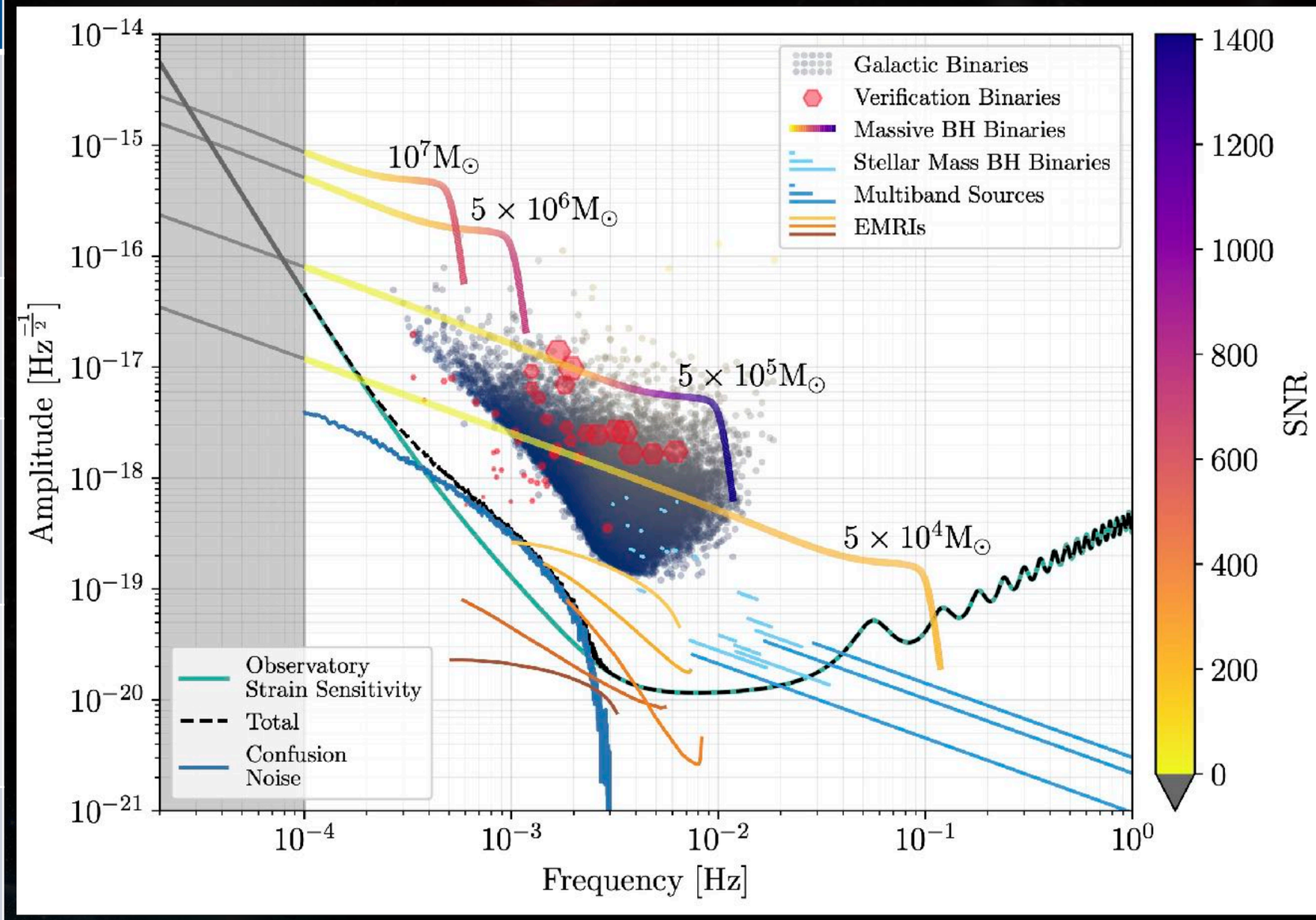
GW sources in the mHz band

- Binaries: large range of masses and mass ratios:
  - SuperMassive BH Binaries (SMBHB)
  - Extreme Mass Ratio Inspiral (EMRI)
  - Stellar mass BH Binaries (sBHB)
  - Double White Dwarfs (WD-WD)
  - Double Neutron Stars (NS-NS)
  - Intermediate Mass Ratio Inspiral (IMRI)
  - Intermediate Mass BH Binaries (IMBHB)
- Stochastic backgrounds:
  - First order phase transitions, networks, …
- Bursts: cosmic strings, …
- Unknown?



Binaries observed by LISA

Sources	SNR	Duration	Event rate
Galactic binaries	10 – 500	permanent	10000 – 30000 detectables + background
Verification binaries	7 - 100	permanent	20 (today)
Stellar mass black hole binaries	7 - 30	1 à 10 years	1 to 20
Extreme Mass Ratio Inspirals	7 - 60	1 year	1 to 2000 / year
Massive Black Hole binaries	10 - 3000	Hours - months	10 to 100 / year



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 properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs.
- 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.

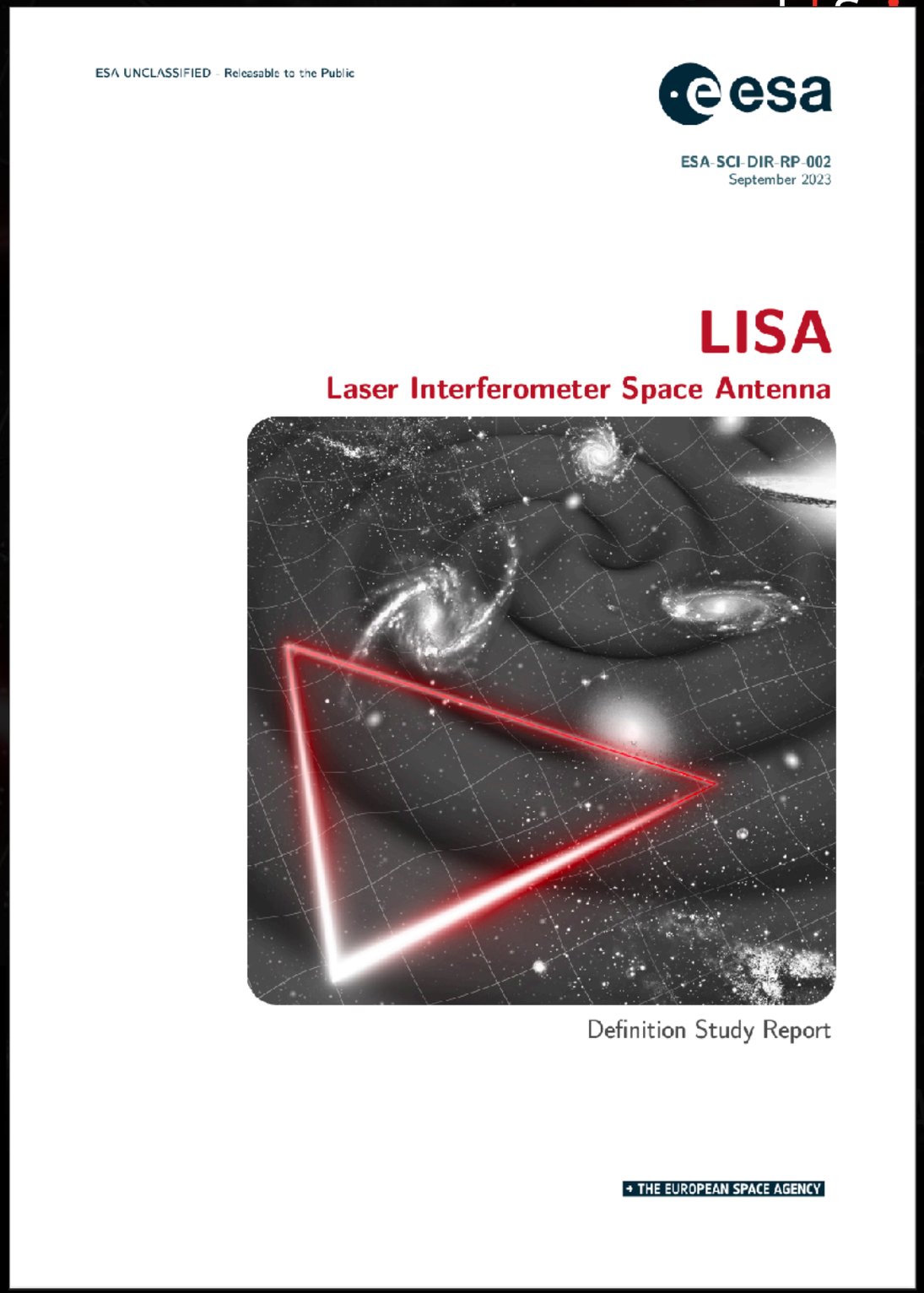
Astrophysics

Fundamental physics

Cosmology

LISA RedBook

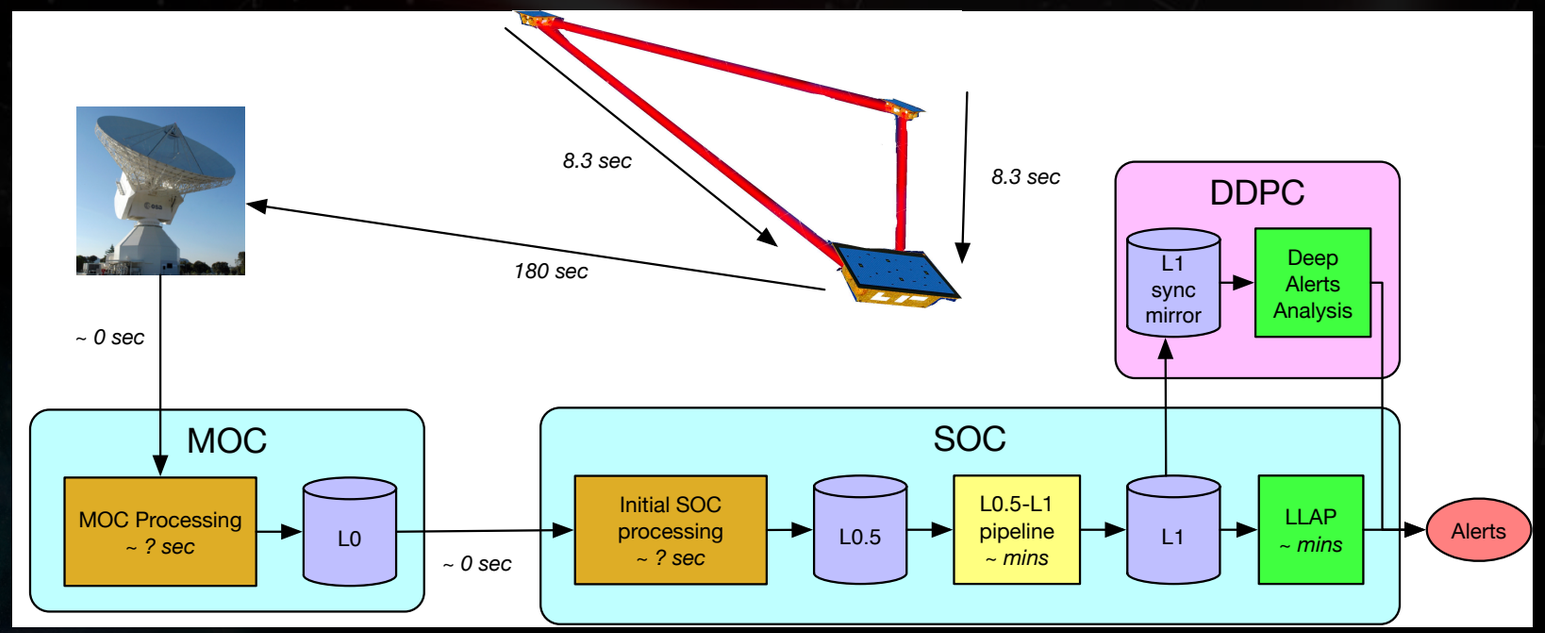
- LISA Definition Study Report (Redbook):
  - written by the LISA Science Study Team with the support of the LISA Consortium
  - submitted and validated at adoption
- Content:
  - Science of LISA
  - Instrument
  - Data processing
  - Organisation
- Available at :
  - arXiv:2402.07571
  - www.cosmos.esa.int/web/lisa/lisa-redbook



Multimessenger with LISA

- Main sources for multimessenger:
  - Continuous: galactic interacting binaries
  - Transient:
    - Massive Black Hole Binaries
    - Bursts (cosmic string, tidal disruption?, …)
    - Unknown

- Low Latency Alerts Pipeline: automatic near-real time analysis during the 8h/day of communication, to release an alert in <1 h:
  - New events
  - Update parameters (sky position) of detected events



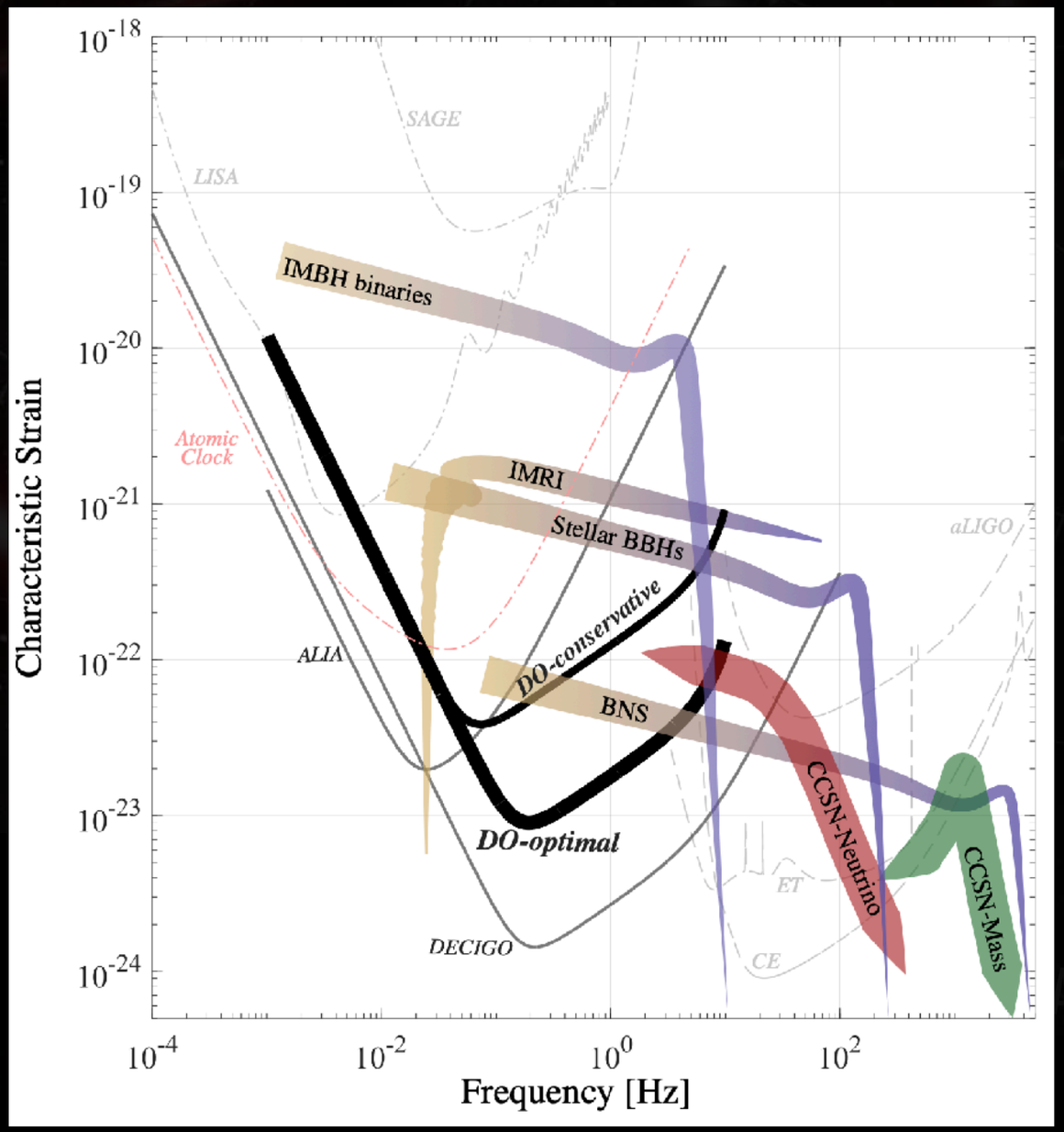
© Sesana et al., μARES white paper, Voyage2050

Other space based ideas

DeciHertz observatory

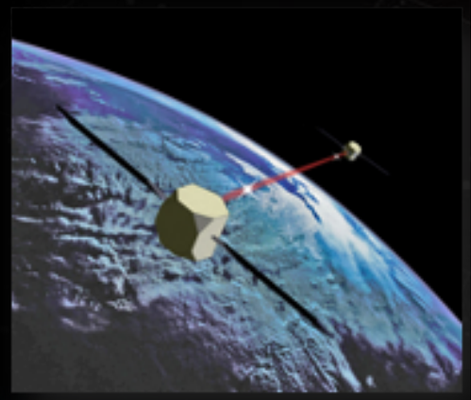
- Proposal submitted at Voyage2050 (ESA call for science themes for L4, L5 & L6, 2040-2060):
- 0.01-10 Hz ⟶ decihertz band:
  - IMBH, IMRI, stellar BBHs
  - BNS early-warning
- On-going study in the LISA Consortium:
  - Science
  - Technical feasibility
  - …

Sedda et al. 2020, gr-qc:1908.11375v3



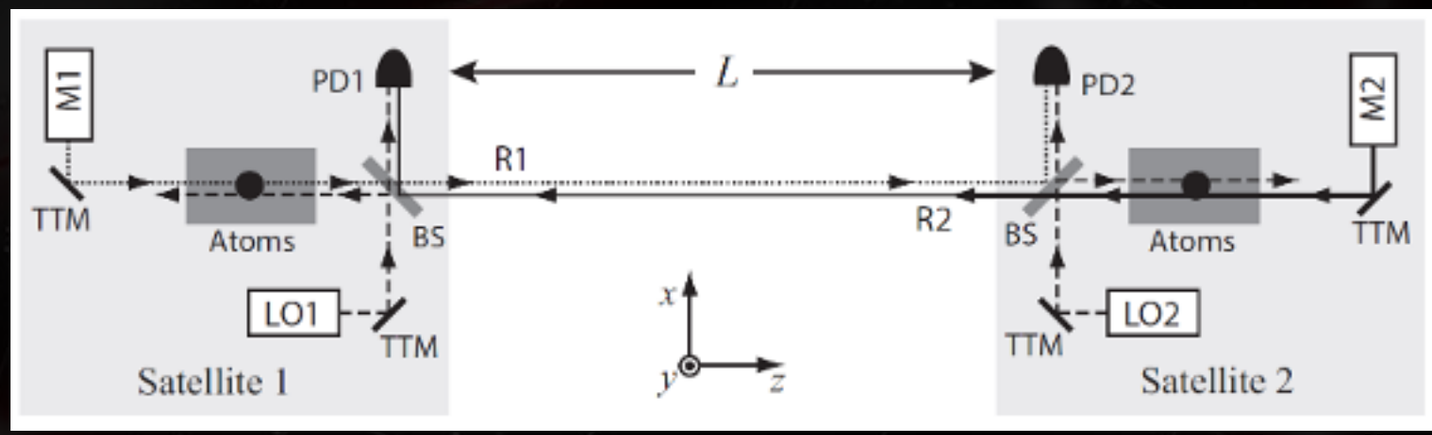
AEDGE

- Atomic Experiment for Dark Matter and Gravity Exploration
  - Pair of satellites in medium Earth orbit
  - Separation 4400 km

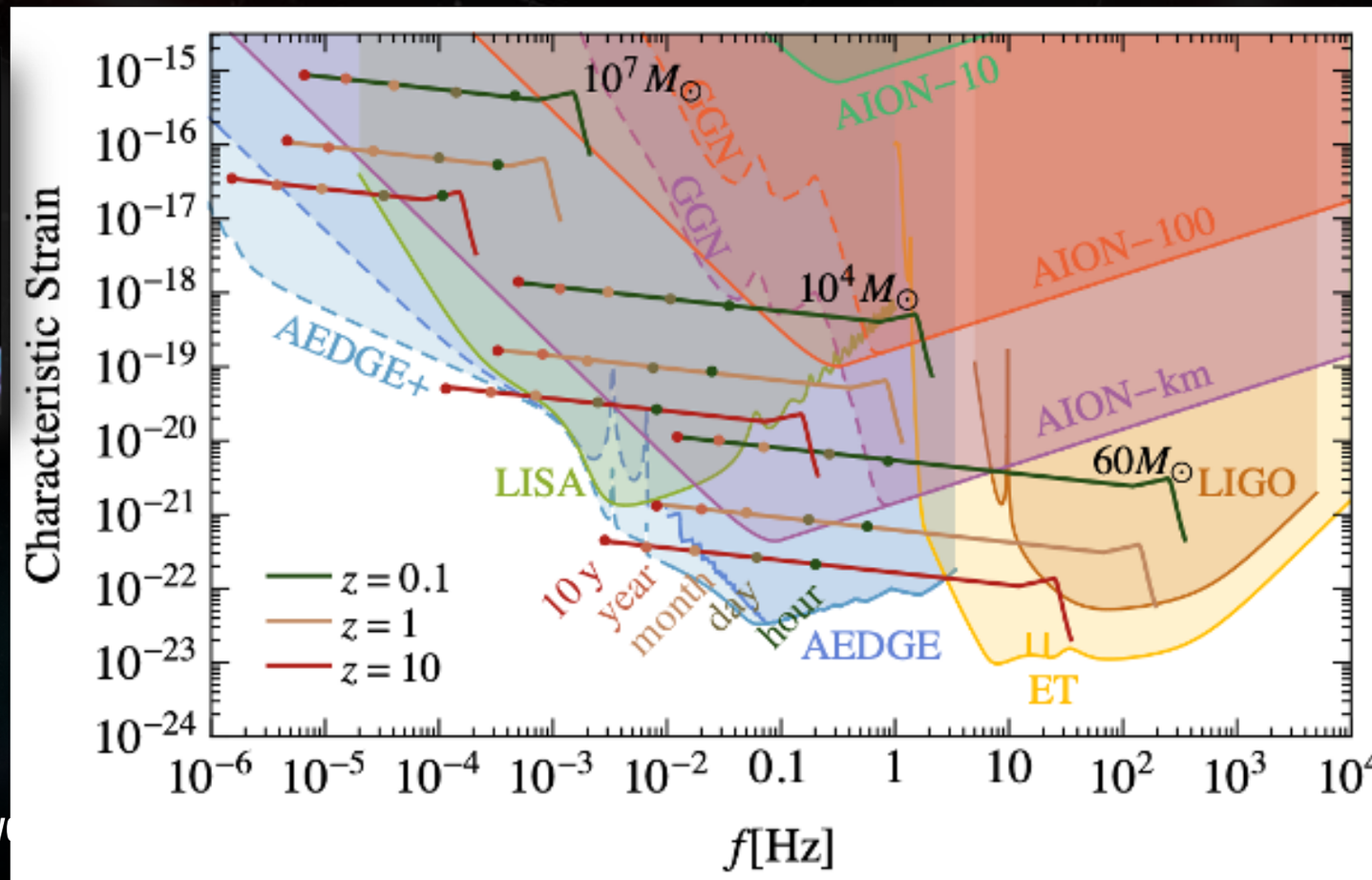


- Development on ground:
  - AION-100 : 100m
  - AION-km : 1km

Abou El-Neaj et al. 2029, gr-qc:1908.00802

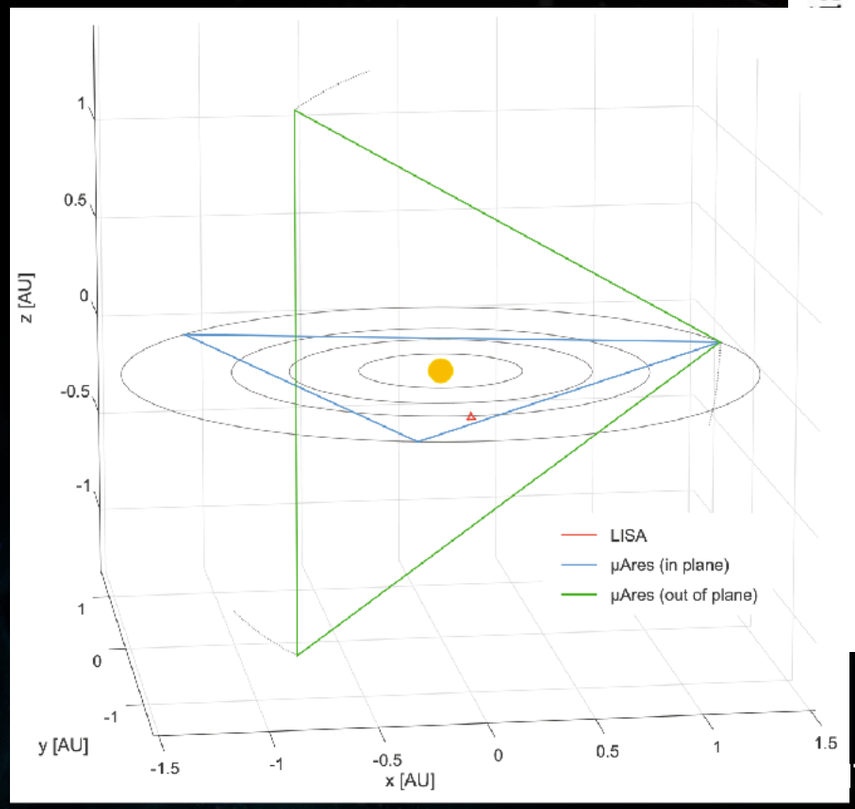


© Buchmueller

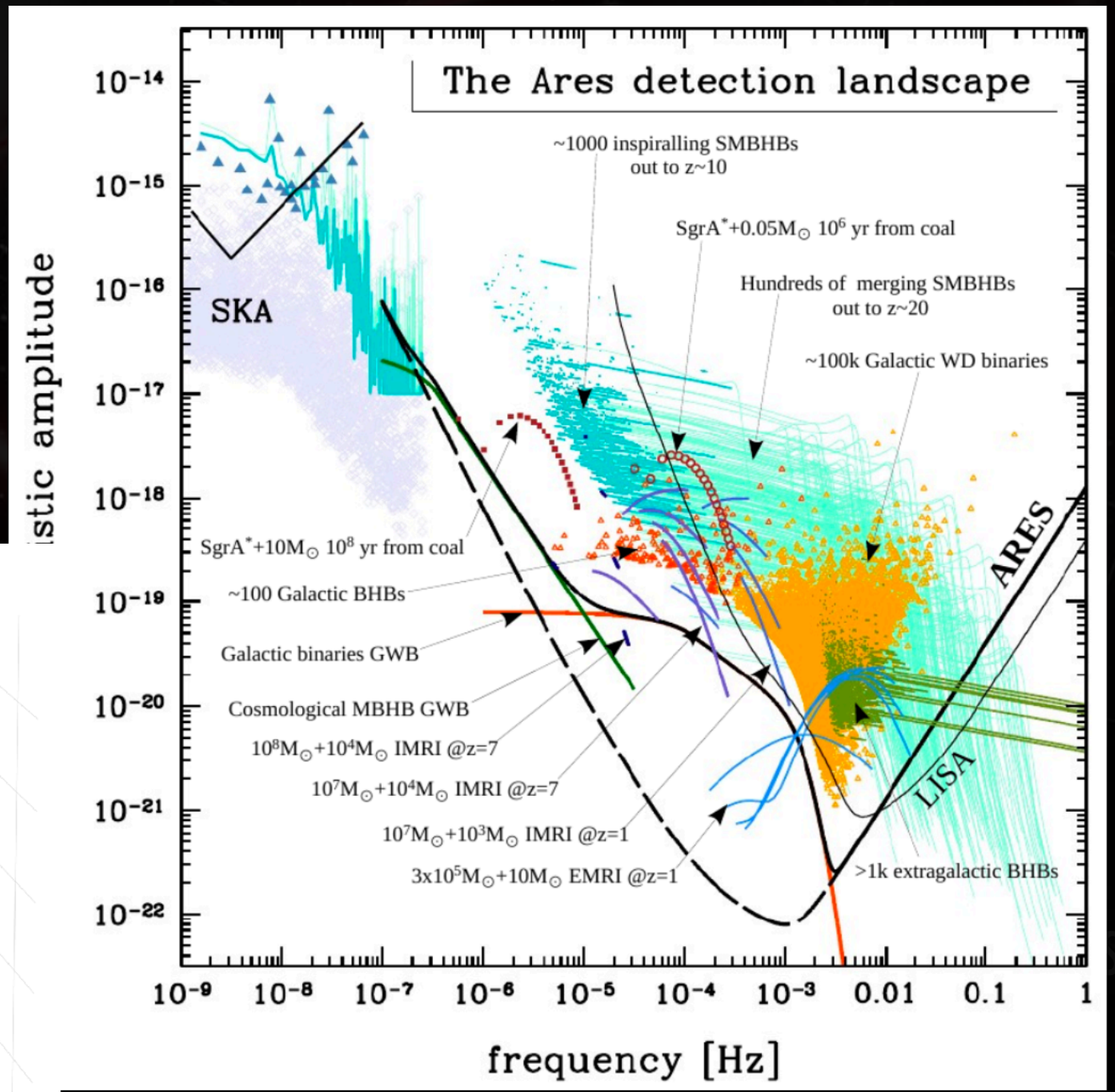


μARES

- Proposal submitted at Voyage2050 (ESA call for science themes for L4, L5 & L6, 2040-2060):
- 10^{-6} – 10^{-2} Hz $\longrightarrow$ μHz band
- On-going study in the LISA Consortium:
  - Science
  - Technical feasibility
  - …
- Arm of 1 AU

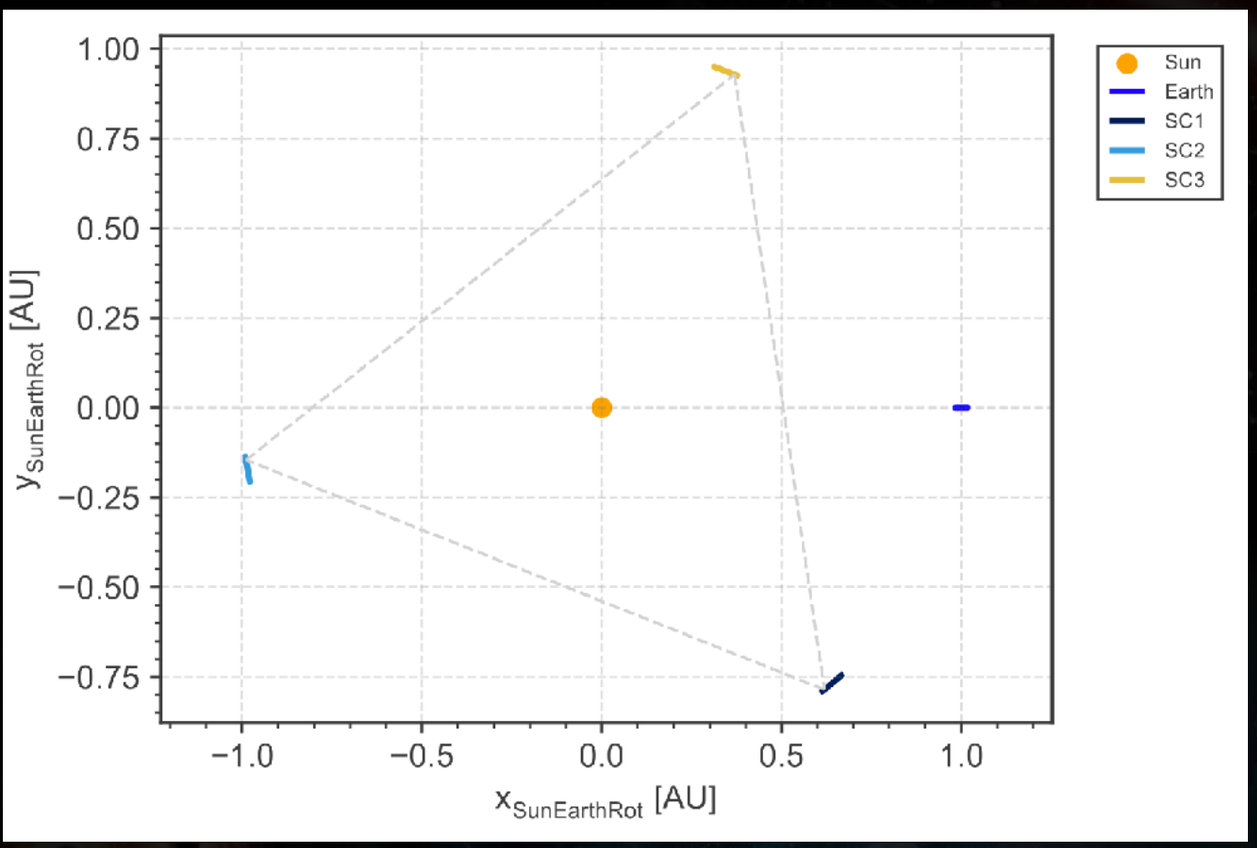


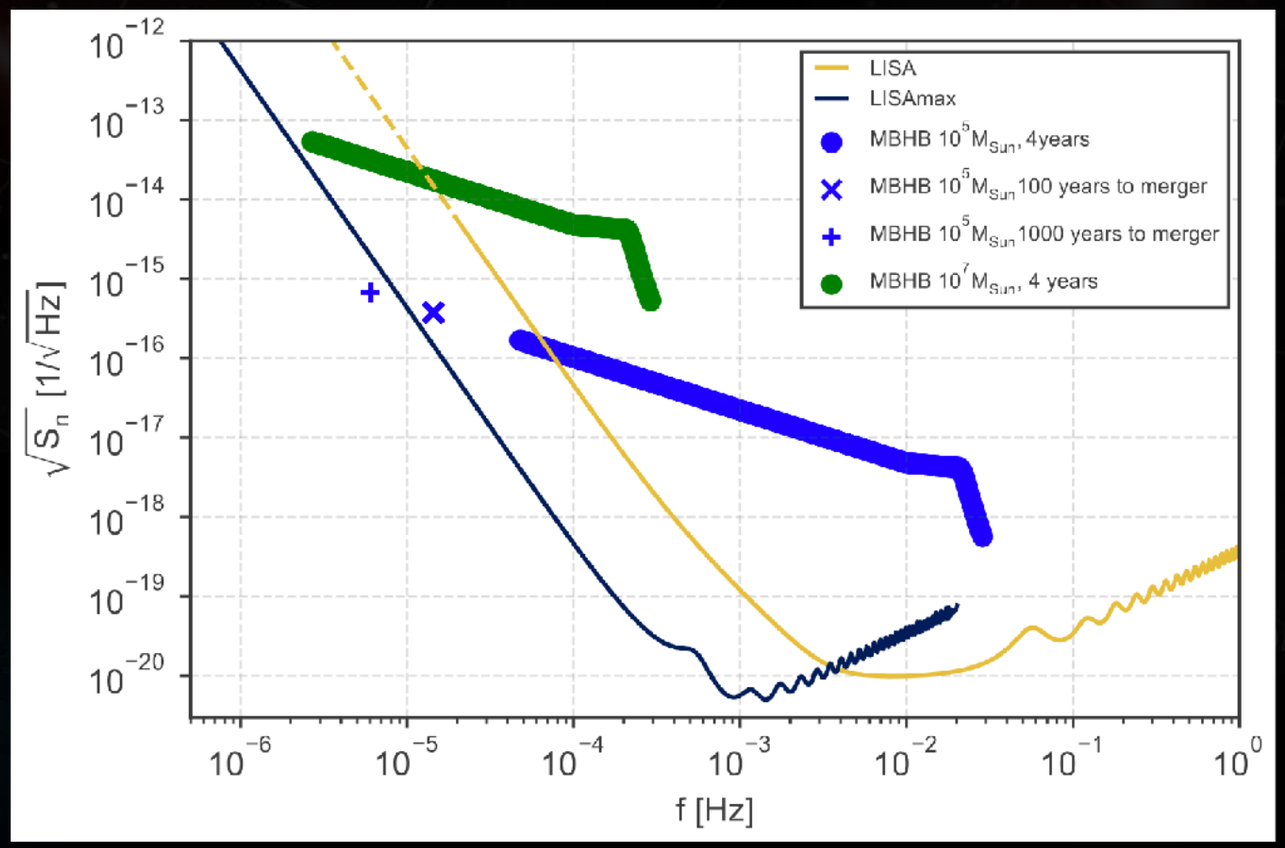
Sesana et al. 2021, Exp. Astro. 51:1333–1383



LISAMax

- LISA of 1 AU in the earth orbital plane
- Study for the orbits of the 3 spacecrafts:
  Martens, Khan & Bayle 2023, gr-qc:2304.08287v2
- Ongoing study of the scientific performances and feasibility (again in the context of Voyage2050)

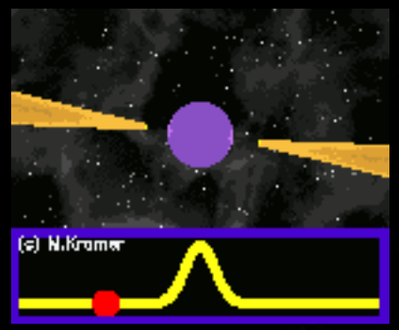




Pulsar Timing Array

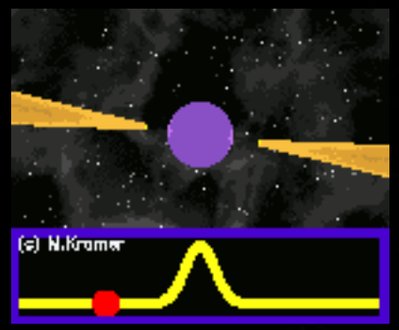
Pulsar timing

- Precise timing of arrival time of pulses => Time Of Arrival (TOA)



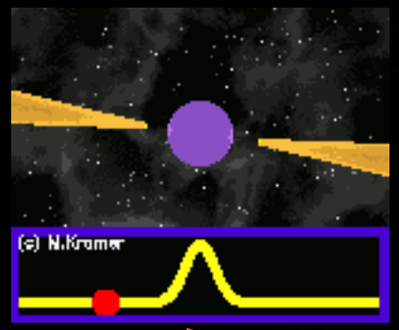
Pulsar timing

- Precise timing of arrival time of pulses => Time Of Arrival (TOA)



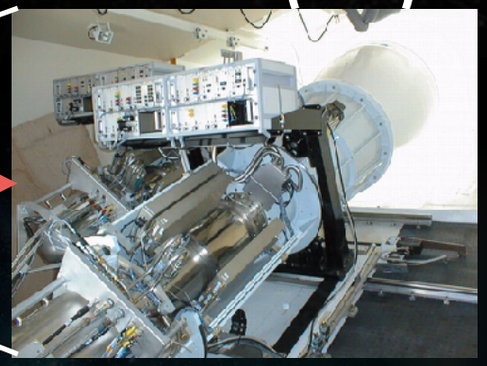
Pulsar timing

- Precise timing of arrival time of pulses => Time Of Arrival (TOA)



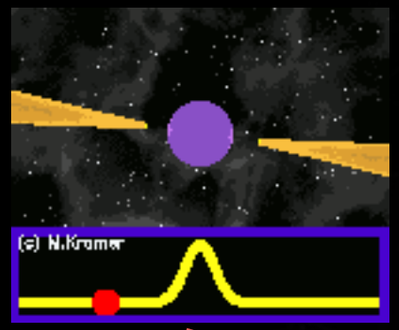
Radiotelescope

Receiver (GHz)



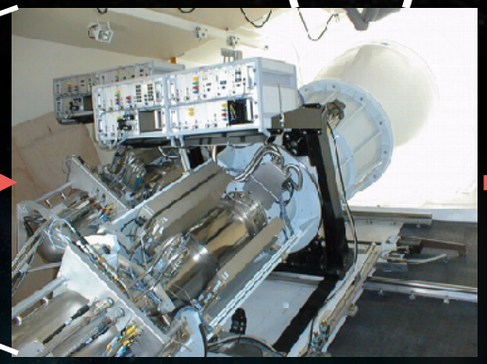
Pulsar timing

- Precise timing of arrival time of pulses => Time Of Arrival (TOA)

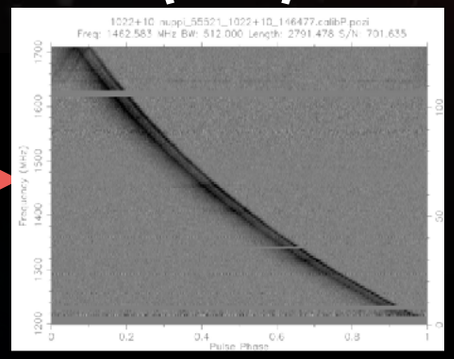


Radiotelescope

Receiver (GHz)

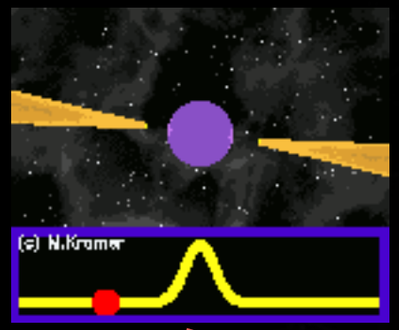


Coherent dedispersion (GPU)



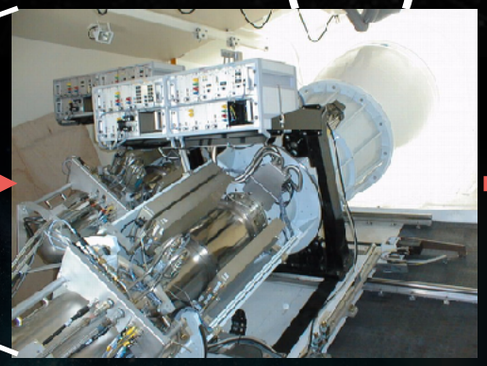
Pulsar timing

- Precise timing of arrival time of pulses => Time Of Arrival (TOA)

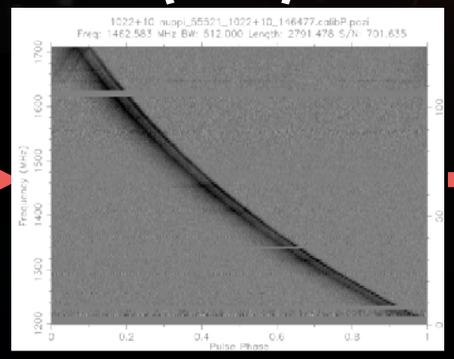


Radiotelescope

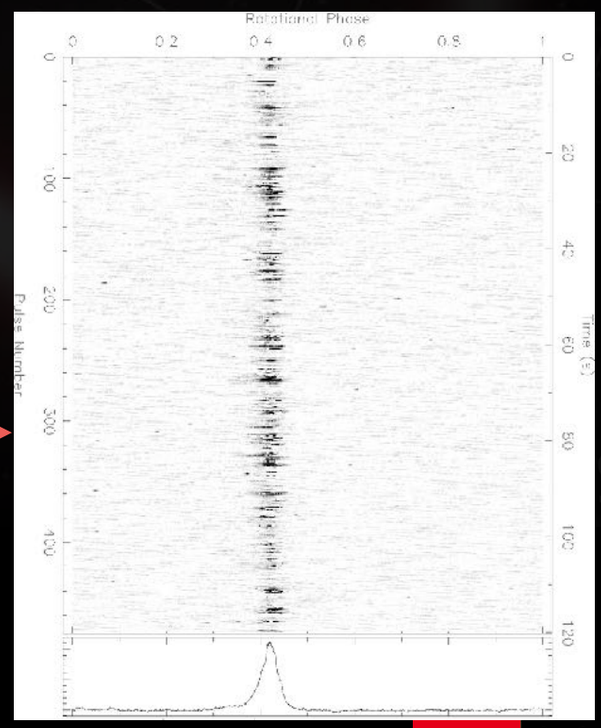
Receiver (GHz)



Coherent dedispersion (GPU)



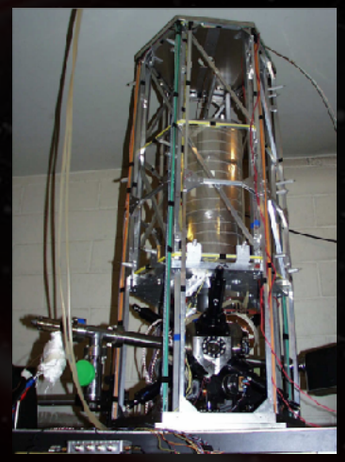
Folding



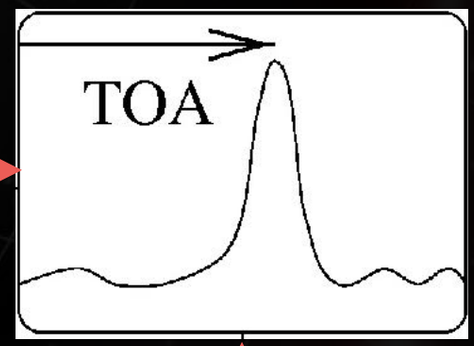
Pulsar timing

- Precise timing of arrival time of pulses => Time Of Arrival (TOA)

Reference clock



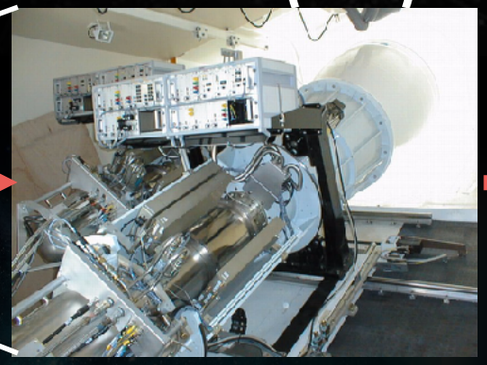
Integrated pulse



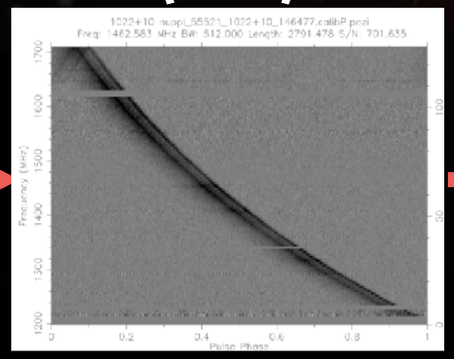
Folding

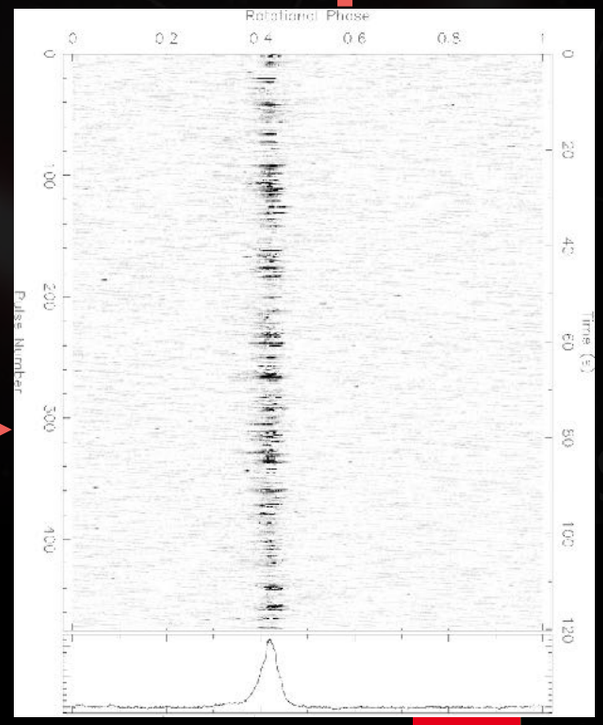
Radiotelescope

Receiver (GHz)



Coherent dedispersion (GPU)





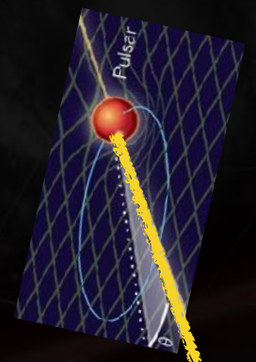
Pulsar timing

Pulsar timing

- TOAs are not perfectly regular due to many effects:

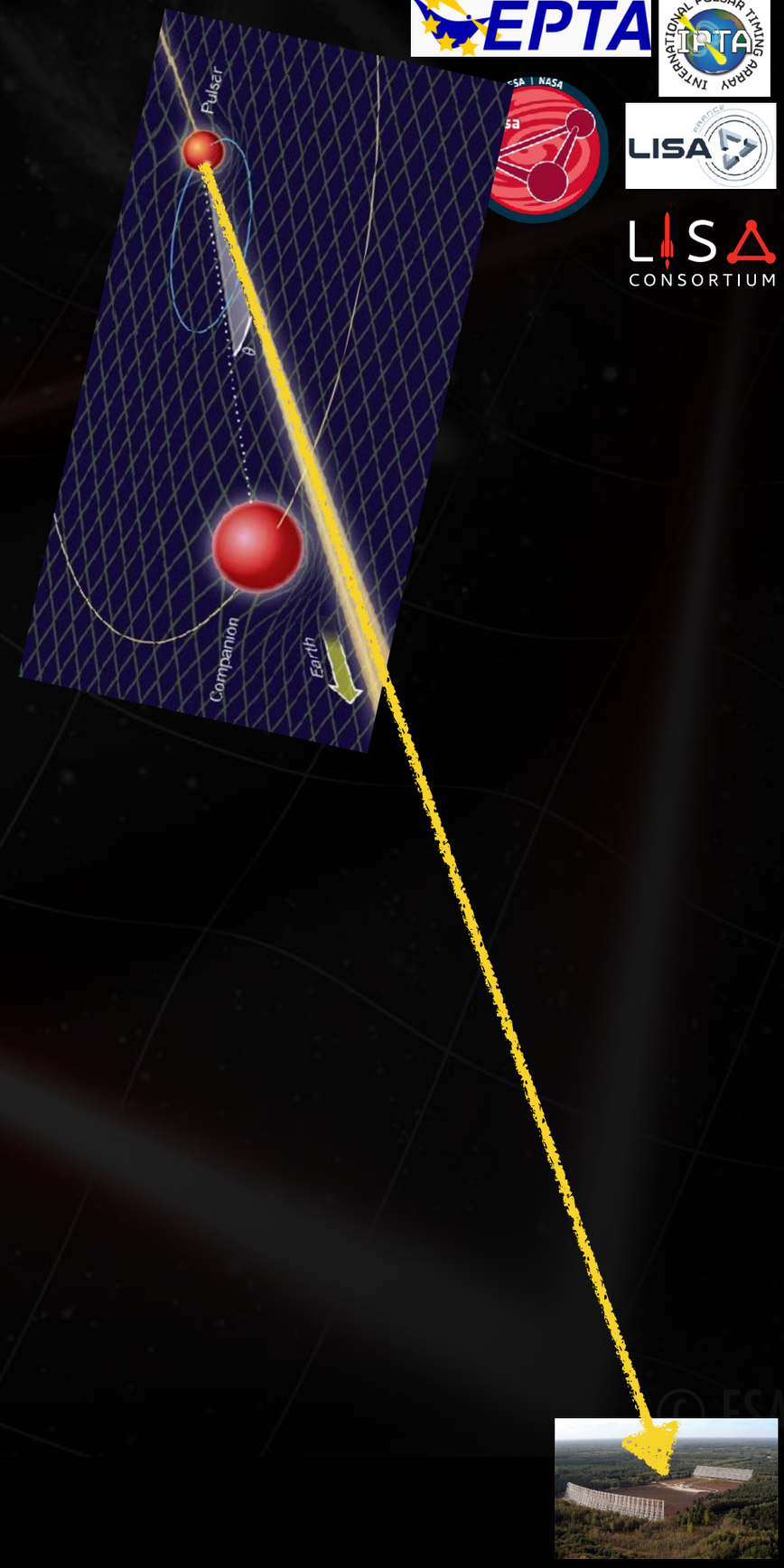
Pulsar timing

- TOAs are not perfectly regular due to many effects:
  - Pulsar itself:
    - period,
    - evolution of the period,
    - sky position



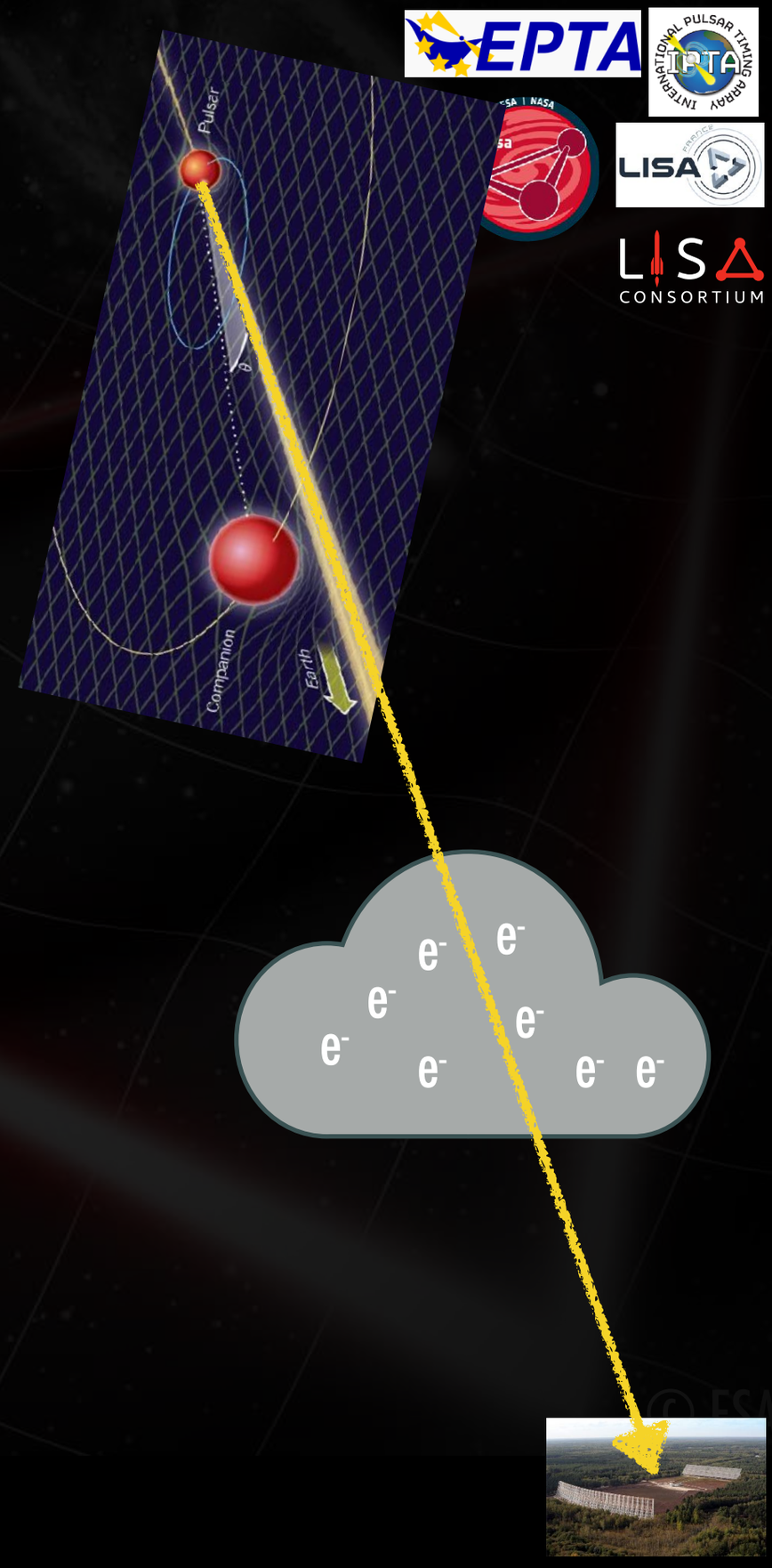
Pulsar timing

- TOAs are not perfectly regular due to many effects:
  - Pulsar itself:
    - period,
    - evolution of the period,
    - sky position
  - Pulsar environnement:
    - binary system,
    - proper motion



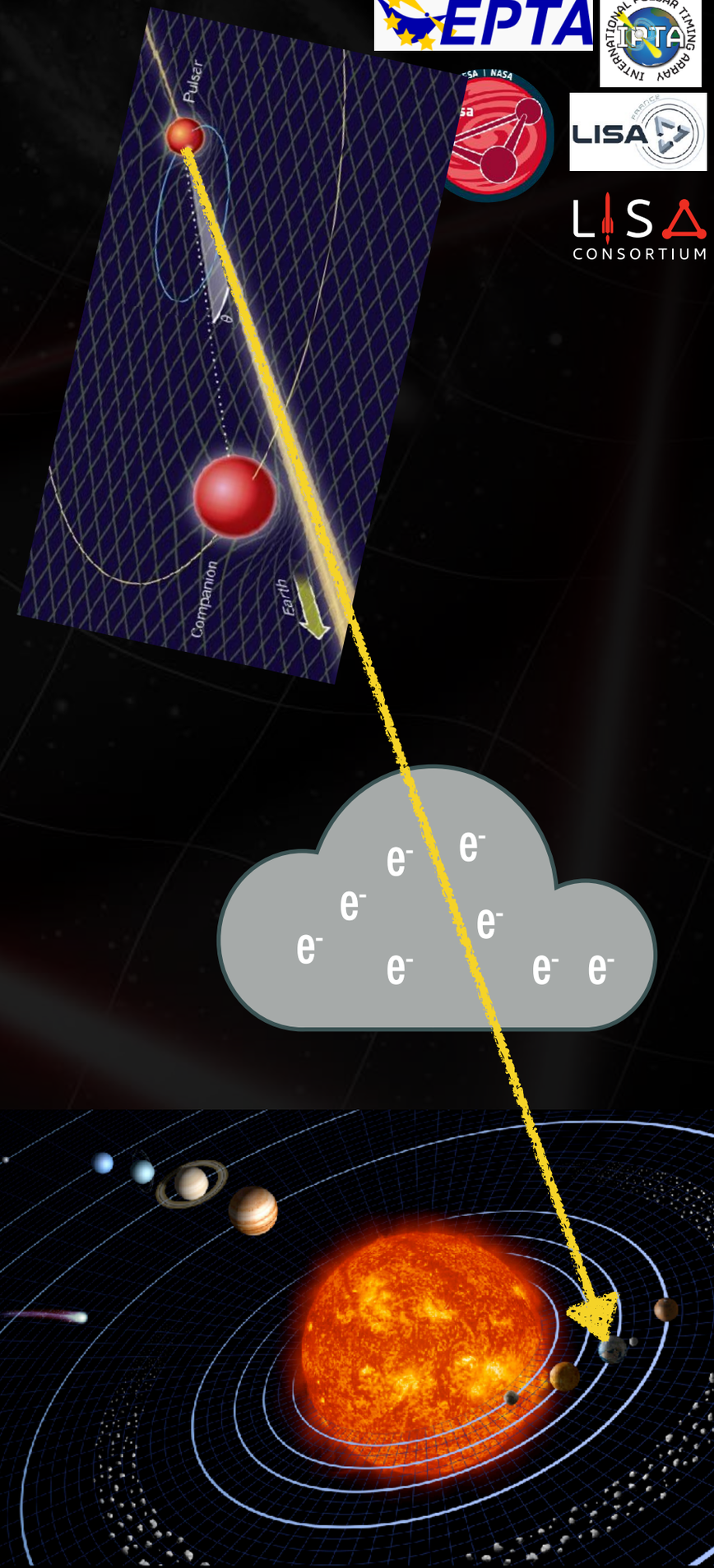
Pulsar timing

- TOAs are not perfectly regular due to many effects:
  - Pulsar itself:
    - period,
    - evolution of the period,
    - sky position
  - Pulsar environnement:
    - binary system,
    - proper motion
  - Beam propagation: interstellar medium



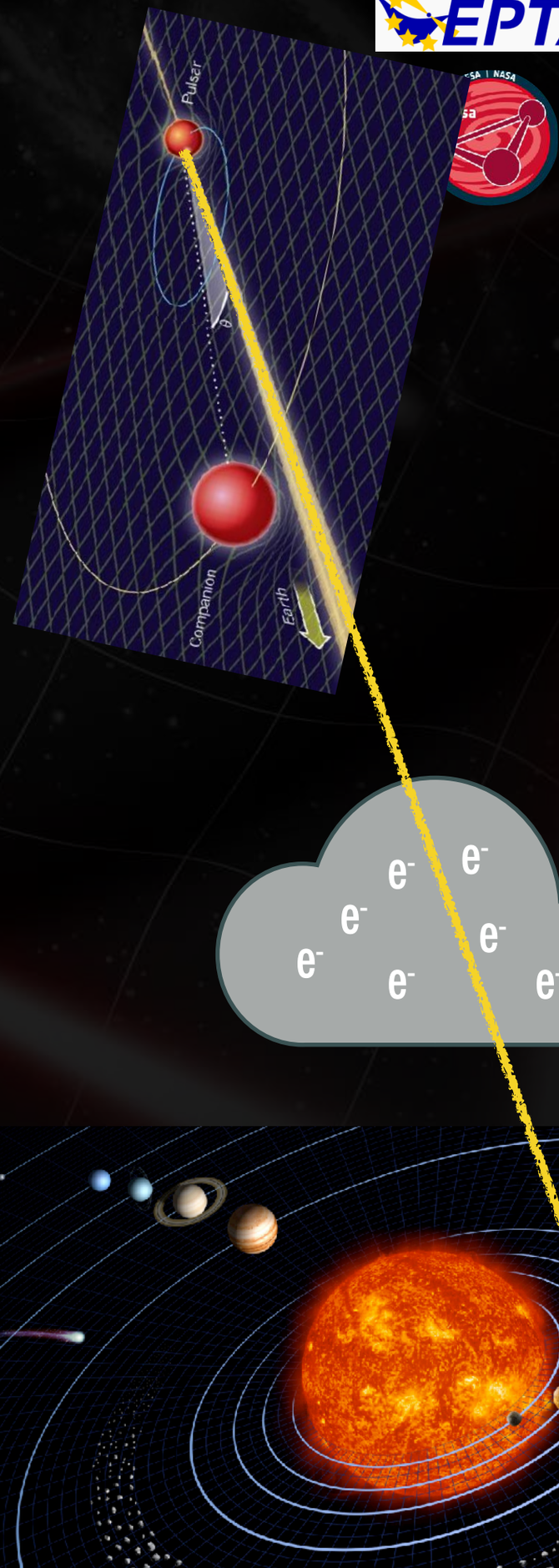
Pulsar timing

- TOAs are not perfectly regular due to many effects:
  - Pulsar itself:
    - period,
    - evolution of the period,
    - sky position
  - Pulsar environnement:
    - binary system,
    - proper motion
  - Beam propagation: interstellar medium
  - Earth position (ephemerides of the Solar System)



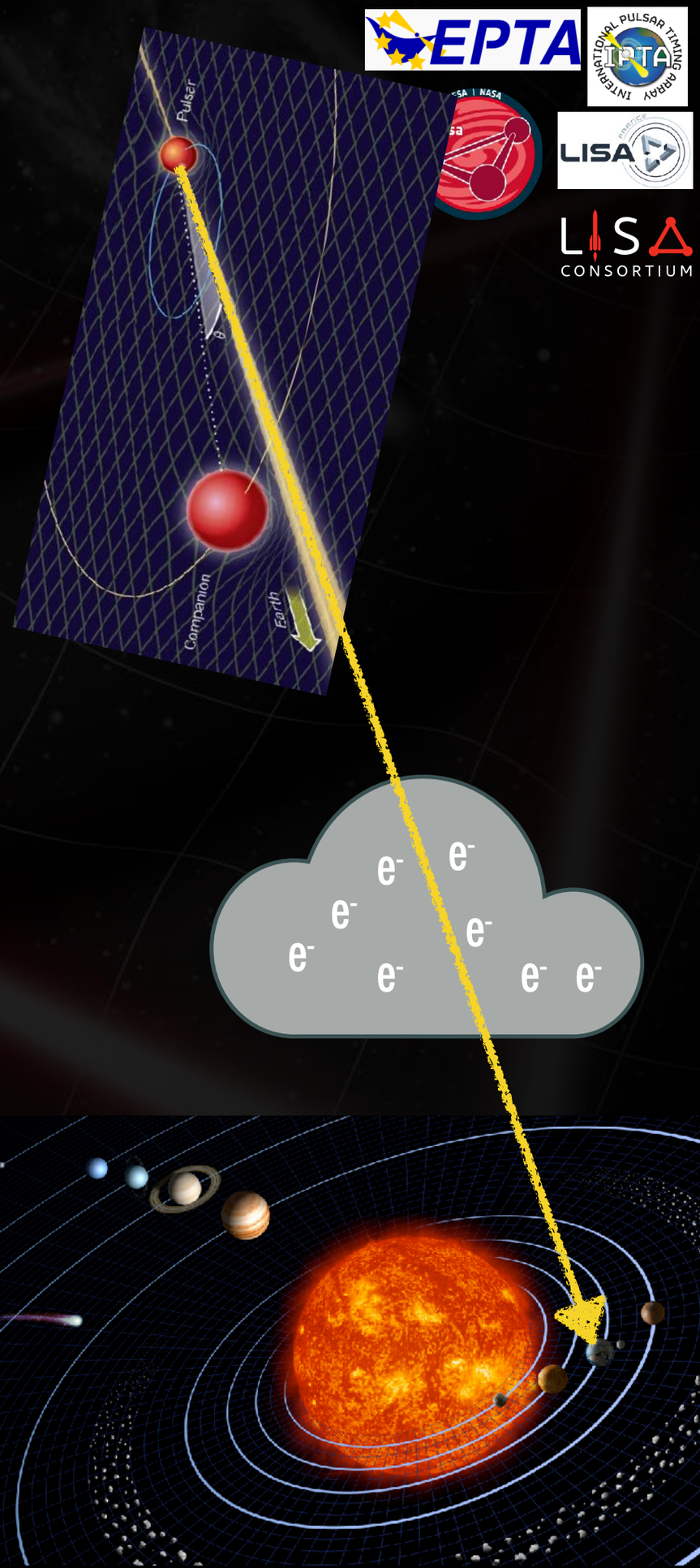
Pulsar timing

- TOAs are not perfectly regular due to many effects:
  - Pulsar itself:
    - period,
    - evolution of the period,
    - sky position
  - Pulsar environnement:
    - binary system,
    - proper motion
  - Beam propagation: interstellar medium
  - Earth position (ephemerides of the Solar System)
  - Gravitational waves …



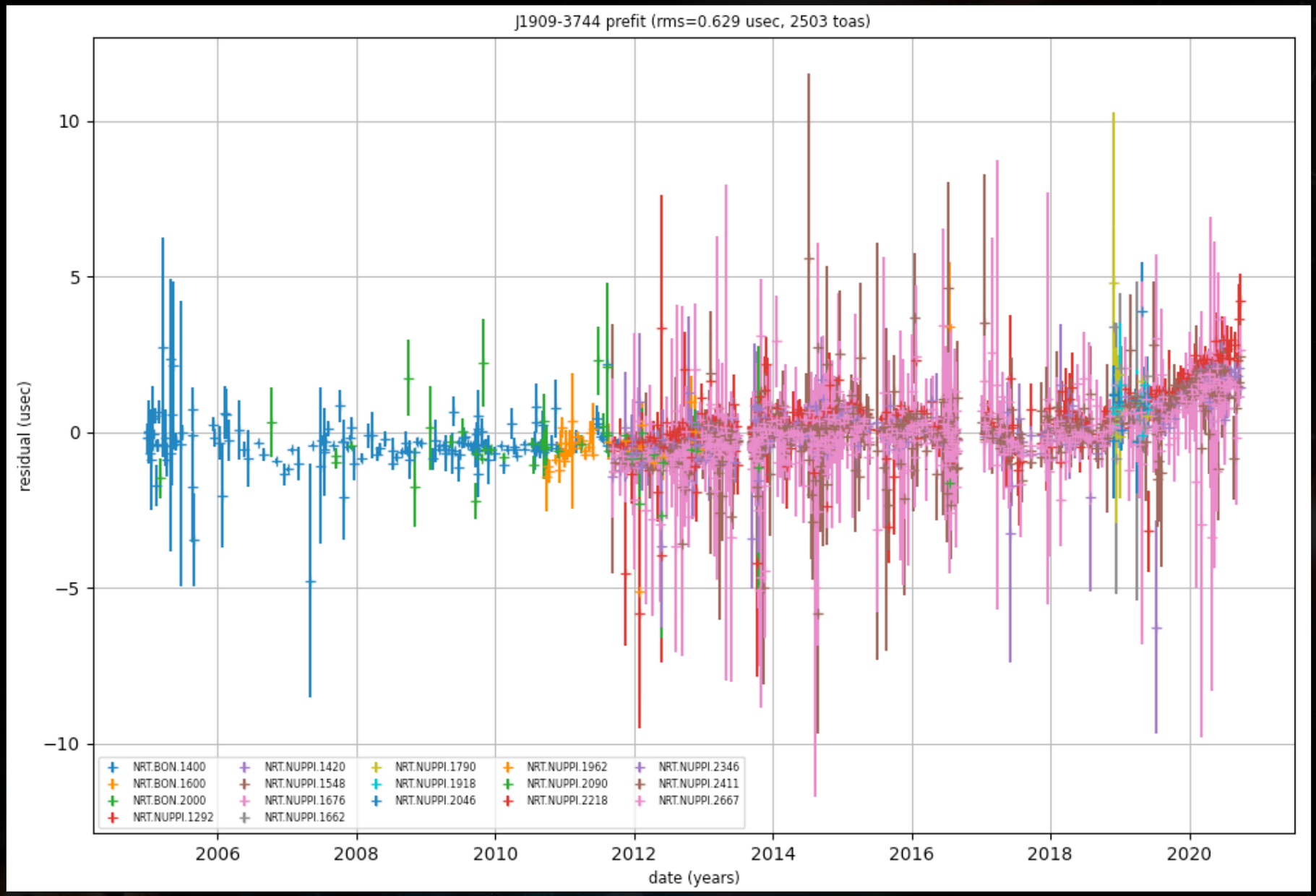
Pulsar timing

- TOAs are not perfectly regular due to many effects:
  - Pulsar itself:
    - period,
    - evolution of the period,
    - sky position
  - Pulsar environnement:
    - binary system,
    - proper motion
  - Beam propagation: interstellar medium
  - Earth position (ephemerides of the Solar System)
  - Gravitational waves …
- Modelling of each pulsars



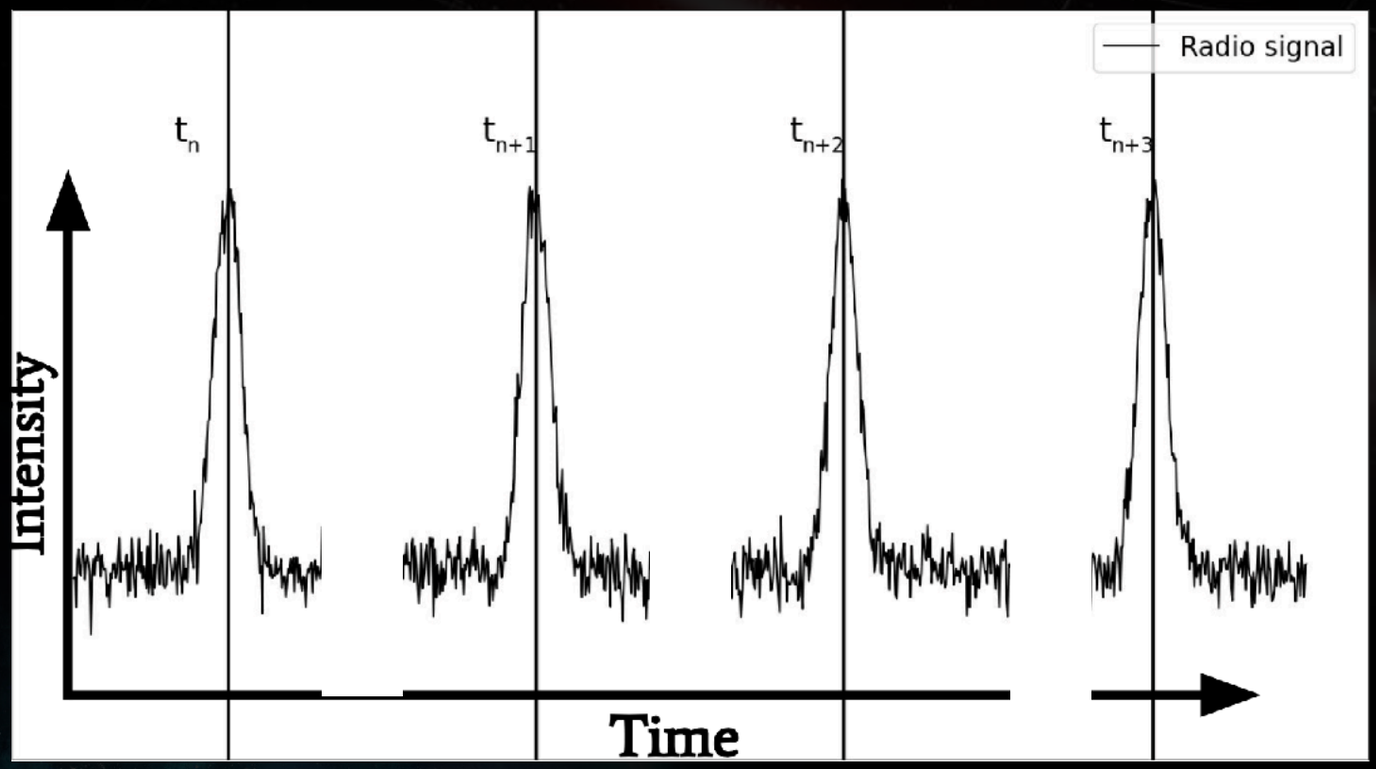
Pulsar timing

- Examples:
  - J1909-3744:



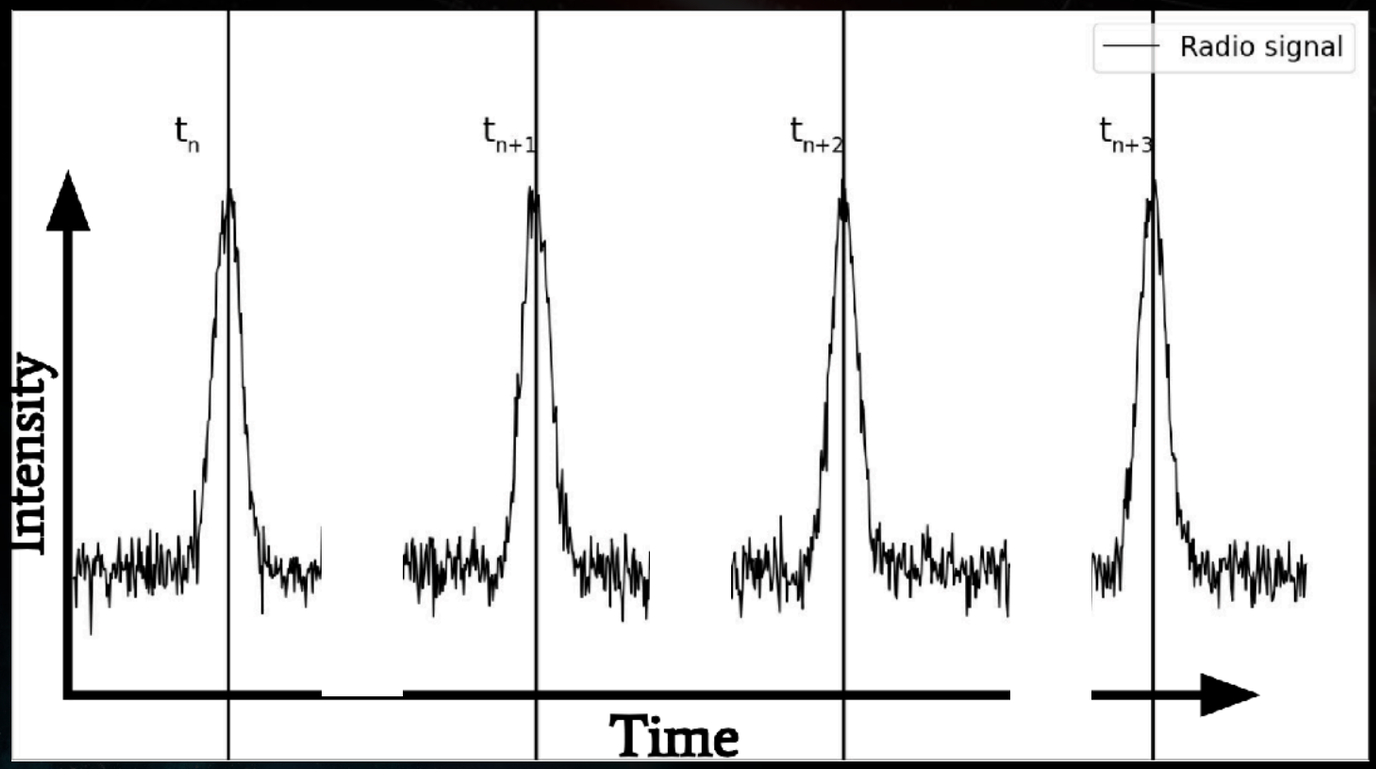
Name	fit	prefit
RAJ	yes	5.01691 +/- 5.01691
DECJ	yes	-0.658641 +/- -0.658641
F0	yes	339.316 +/- 339.316
F1	yes	-1.6148e-15 +/- -1.6148e-15
DM	yes	10.3906 +/- 10.3906
DM1	yes	-0.000250904 +/- -0.000250904
DM2	yes	1.48176e-05 +/- 1.48176e-05
PMRA	yes	-9.52683 +/- -9.52683
PMDEC	yes	-35.8098 +/- -35.8098
PX	yes	1.0623 +/- 1.0623
SINI	yes	0.997779 +/- 0.997779
PB	yes	1.53345 +/- 1.53345
A1	yes	1.89799 +/- 1.89799
PBDOT	yes	5.1216e-13 +/- 5.1216e-13
XDOT	yes	-1.17023e-15 +/- -1.17023e-15
TASC	yes	53114 +/- 53114
EPS1	yes	4.93407e-09 +/- 4.93407e-09
EPS2	yes	-1.37334e-07 +/- -1.37334e-07
M2	yes	0.218395 +/- 0.218395
JUMP1	yes	-8.5495e-05 +/- -8.5495e-05
JUMP2	yes	-8.49454e-05 +/- -8.49454e-05
JUMP3	yes	-8.34176e-05 +/- -8.34176e-05
JUMP4	yes	-7.4828e-07 +/- -7.4828e-07
JUMP6	yes	2.58546e-07 +/- 2.58546e-07

Pulsar timing and GWs



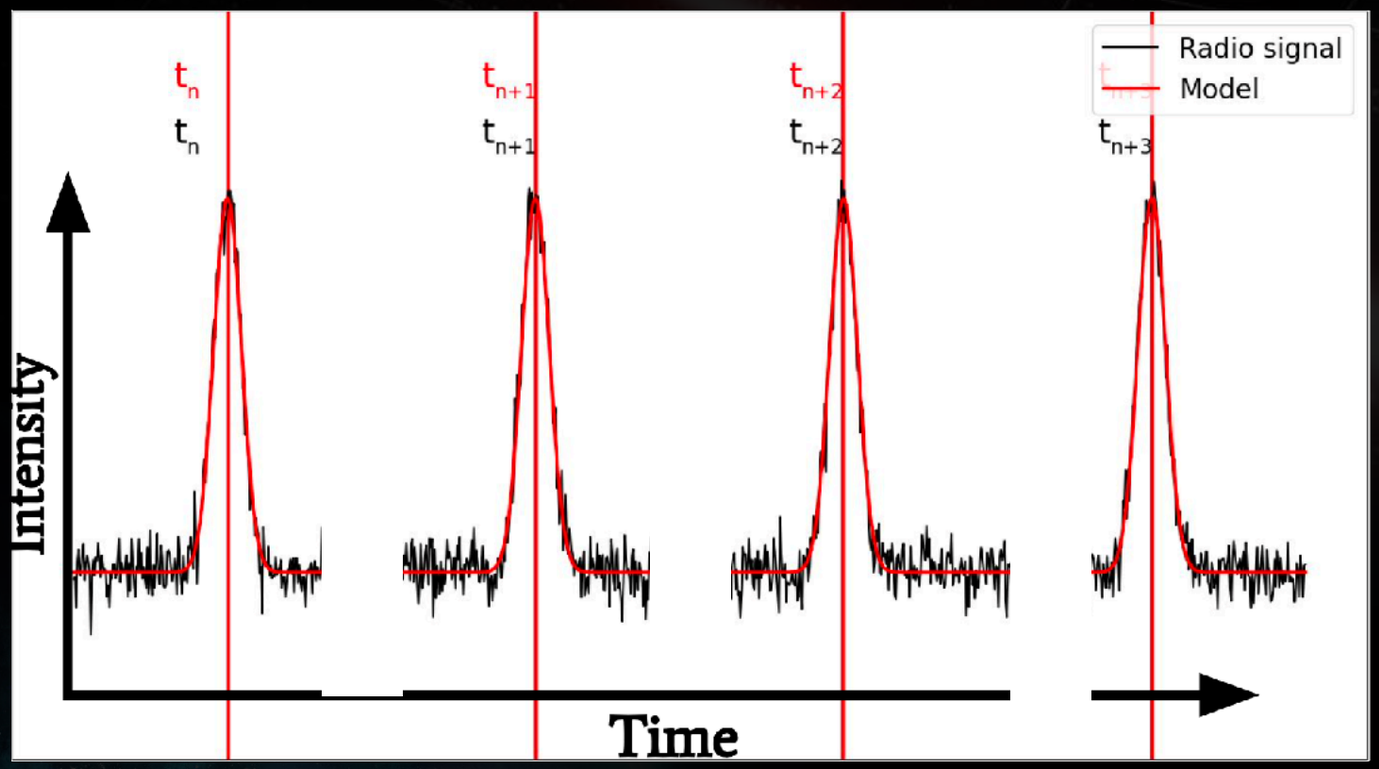
Pulsar timing and GWs

- When gravitational waves (GWs) are passing between pulsar and Earth, they will slightly modified the arrival time of pulses, i.e. the TOA



Pulsar timing and GWs

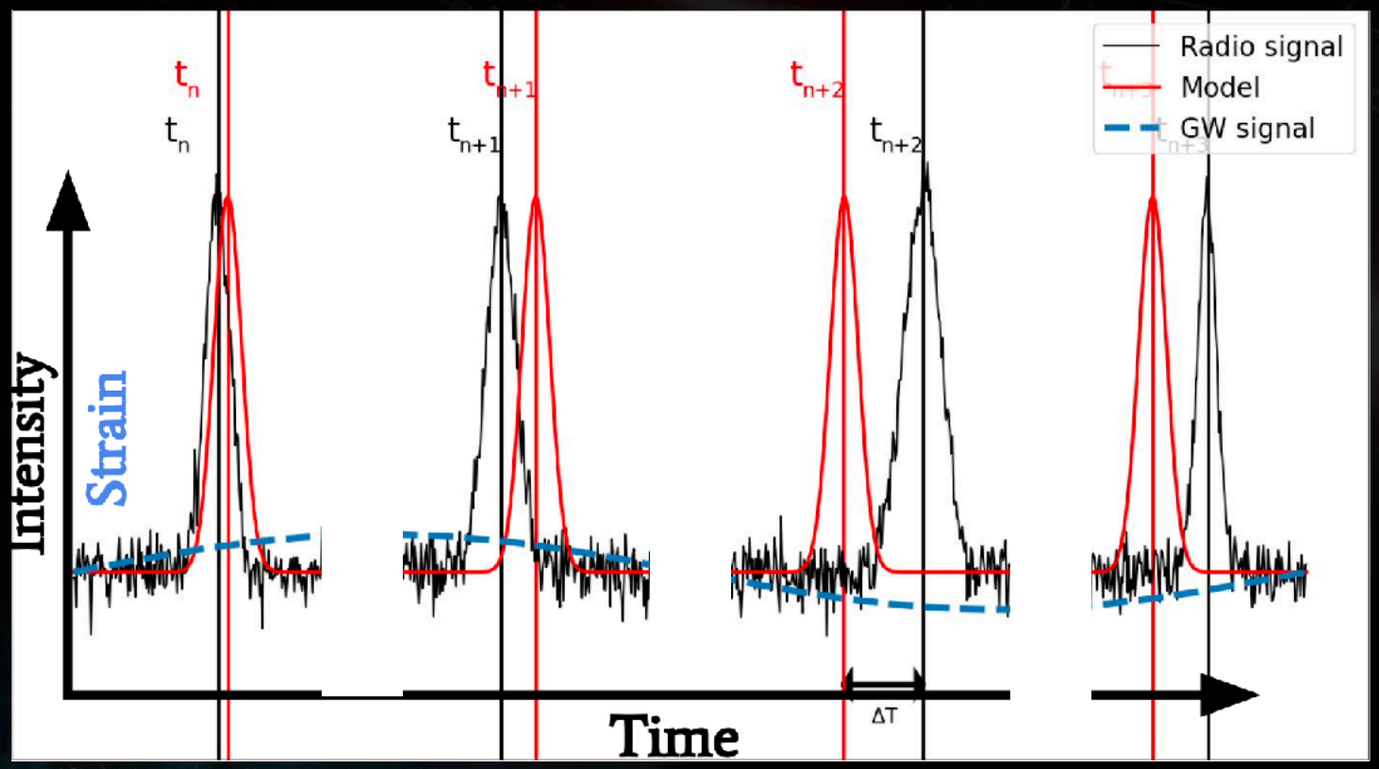
- When gravitational waves (GWs) are passing between pulsar and Earth, they will slightly modified the arrival time of pulses, i.e. the TOA
- We have a model for the TOA



Pulsar timing and GWs

- When gravitational waves (GWs) are passing between pulsar and Earth, they will slightly modified the arrival time of pulses, i.e. the TOA
- We have a model for the TOA
- If GWs => deviation from the model

  => GWs observed in the residuals = data - model



Pulsar timing and GWs

- GWs => correlated fluctuations in TOAs of multiple pulsars

Observed & emitted pulsar spin frequency

$$\delta t_{GW}(t_a) = \int_{t_e}^{t_a} \frac{\nu(t') - \nu_0}{\nu_0} dt' = \int_{t_e}^{t_a} \frac{\delta\nu(t')}{\nu_0} dt'$$

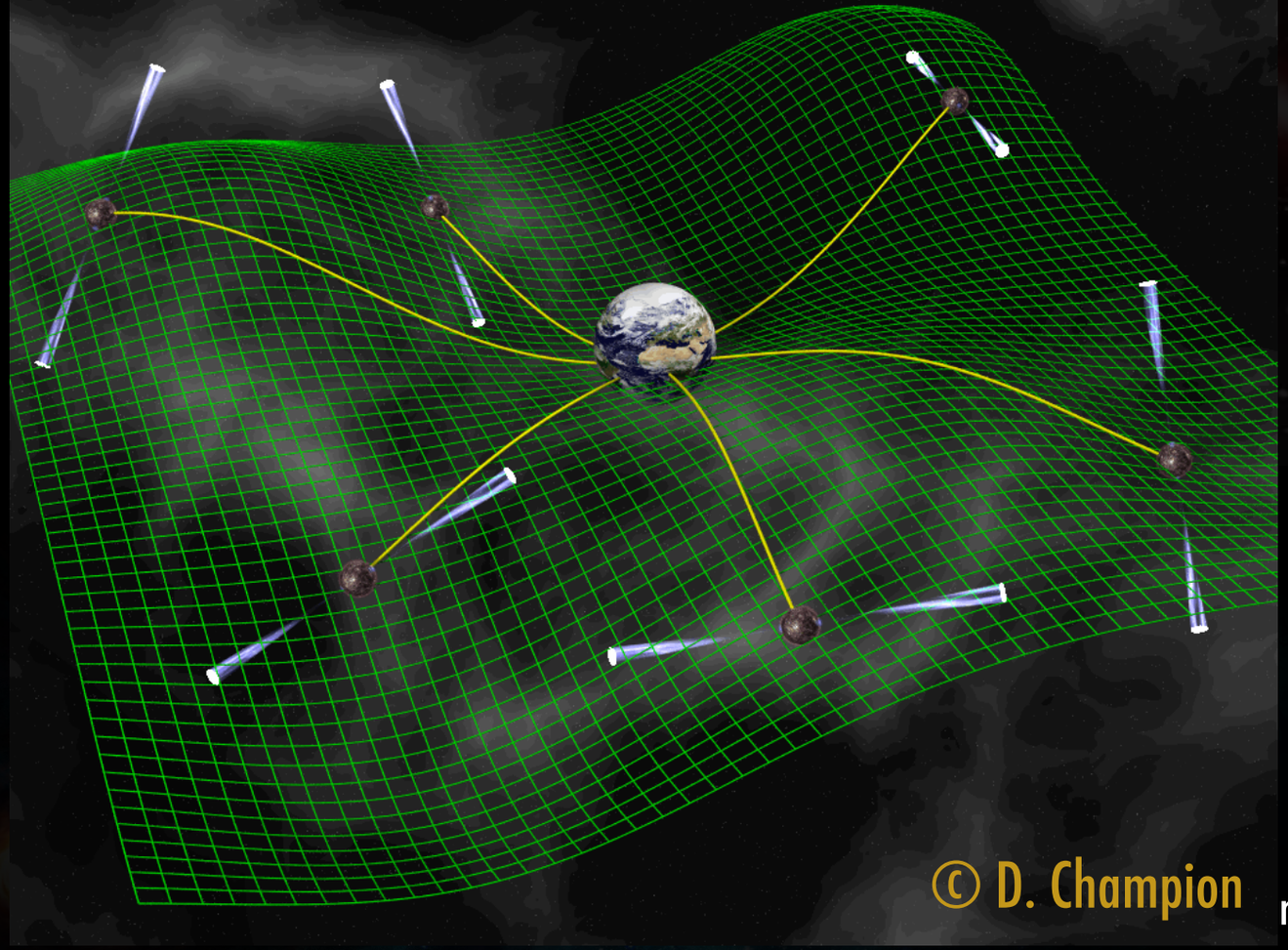
Emission & reception times of pulses

$$\frac{\delta\nu(t')}{\nu_0} = \frac{\hat{n}^i_\alpha \, \hat{n}^j_\alpha}{2\left(1 + \hat{n}_\alpha . \hat{k}\right)} \Delta h_{ij}$$

Pulsar & GW source sky location

$$\Delta h_{ij} = h_{ij}(t_e) - h_{ij}(t_a)$$

GW characteristic strain

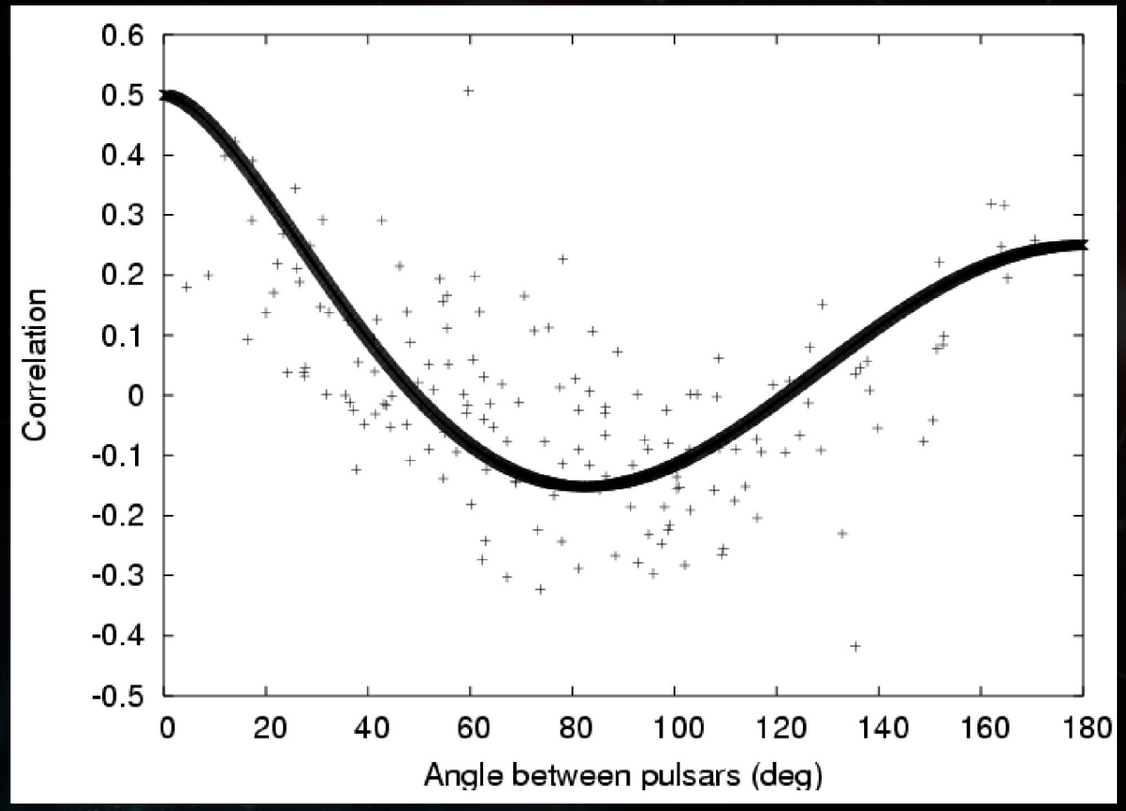


© D. Champion

Pulsar timing and GWs

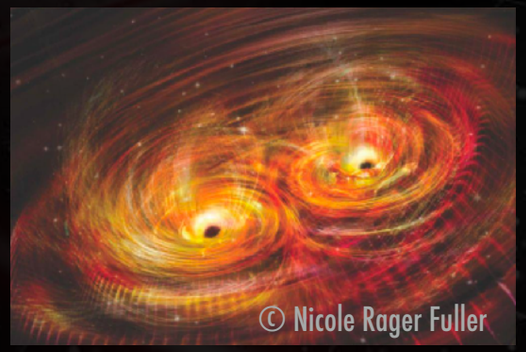
- For an isotropic GW background, characteristic spatial correlation: Hellings-Down curve: specific relation between correlation of 2 pulsar and their angular separation => signature of GW Background

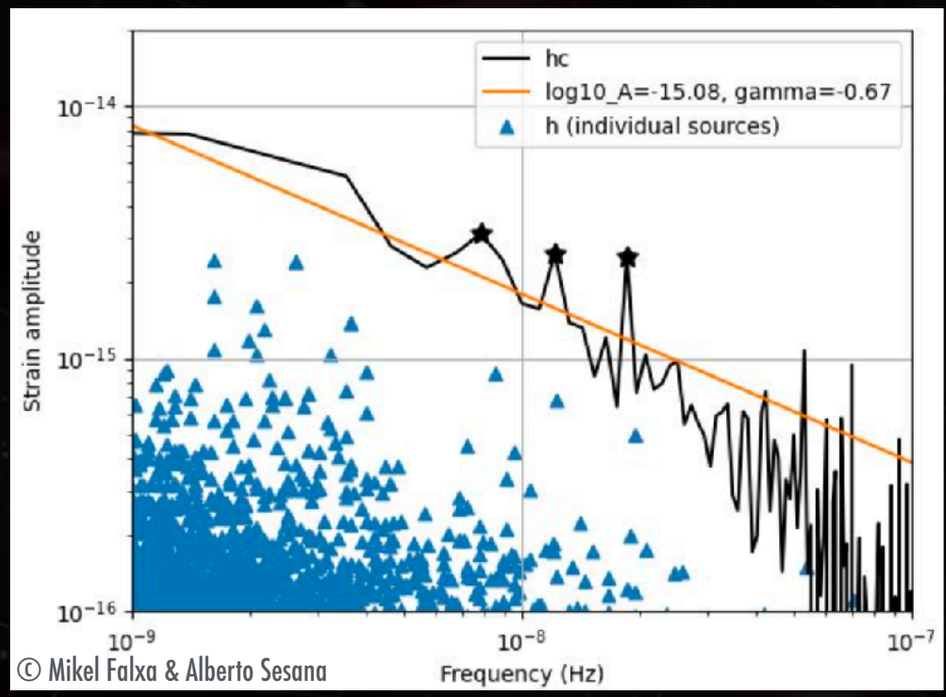
$$\Gamma_{\mathrm{GWB}}(\zeta_{IJ}) = \frac{3}{2} x_{IJ} \ln x_{IJ} - \frac{x_{IJ}}{4} + \frac{1}{2} + \frac{1}{2}\delta x_{IJ} \qquad \text{with} \quad x_{IJ} = [1 - \cos(\zeta_{IJ})]/2$$



GW sources in the nHz band

- Supermassive black hole binaries
  - Ex: chirp mass = 10^9 M_{Sun} , 1000 years before merger
  - Very massive: masses $> 10^7$ M_{Sun},
  - Close: distance z<2,
  - Quasi-monochromatic
  - Large number of sources:
    - Individual sources
    - "Stochastic" background built from large number of non-resolved sources

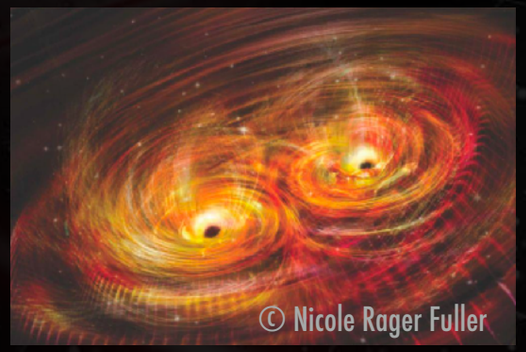


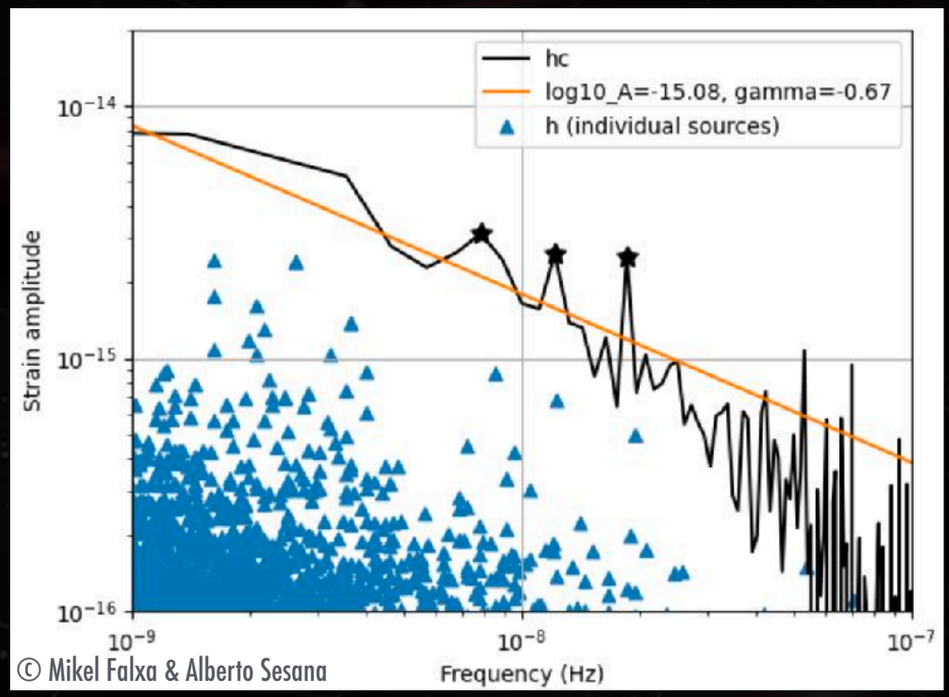


© Binétruy et al.

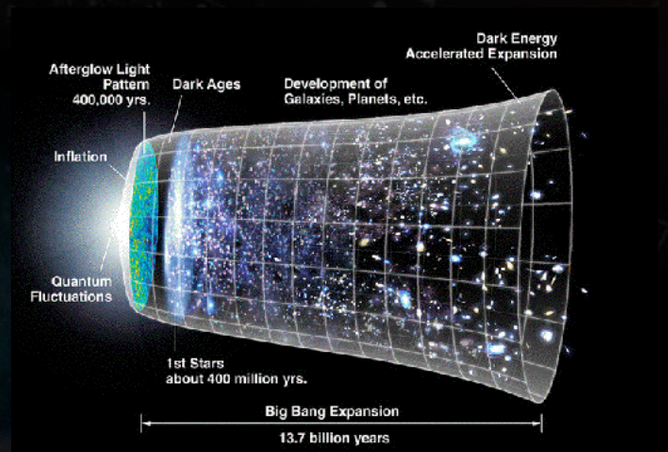
GW sources in the nHz band

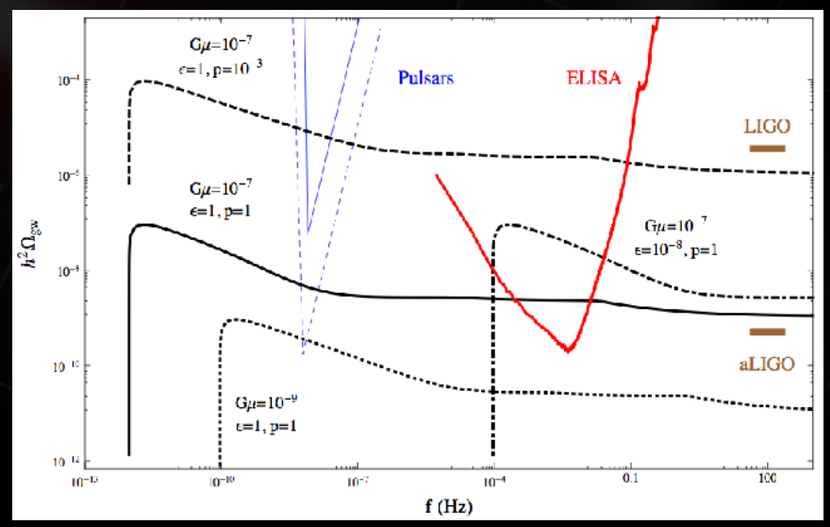
- Supermassive black hole binaries
  - Ex: chirp mass = 10^9 M_{Sun} , 1000 years before merger
  - Very massive: masses $> 10^7$ M_{Sun},
  - Close: distance z<2,
  - Quasi-monochromatic
  - Large number of sources:
    - Individual sources
    - "Stochastic" background built from large number of non-resolved sources





- Stochastic background from cosmological origin:
  - First order phase transition
  - Cosmic strings
  - Primordial GWs
  - …

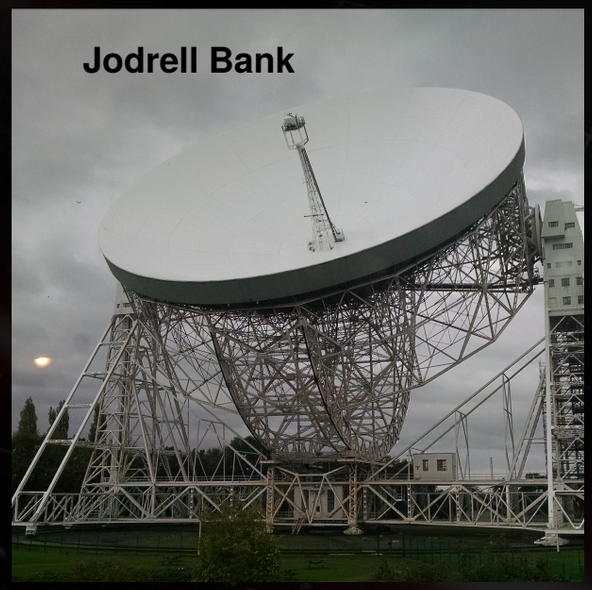




© Binétruy et al.

EPTA

- European collaboration:
  - Nancay RT (FR),
  - Effelsberg RT (G),
  - Jodrell Bank Obs. (UK),
  - Westerbork Synthesis RT(NL),
  - Sardinia RT (I).



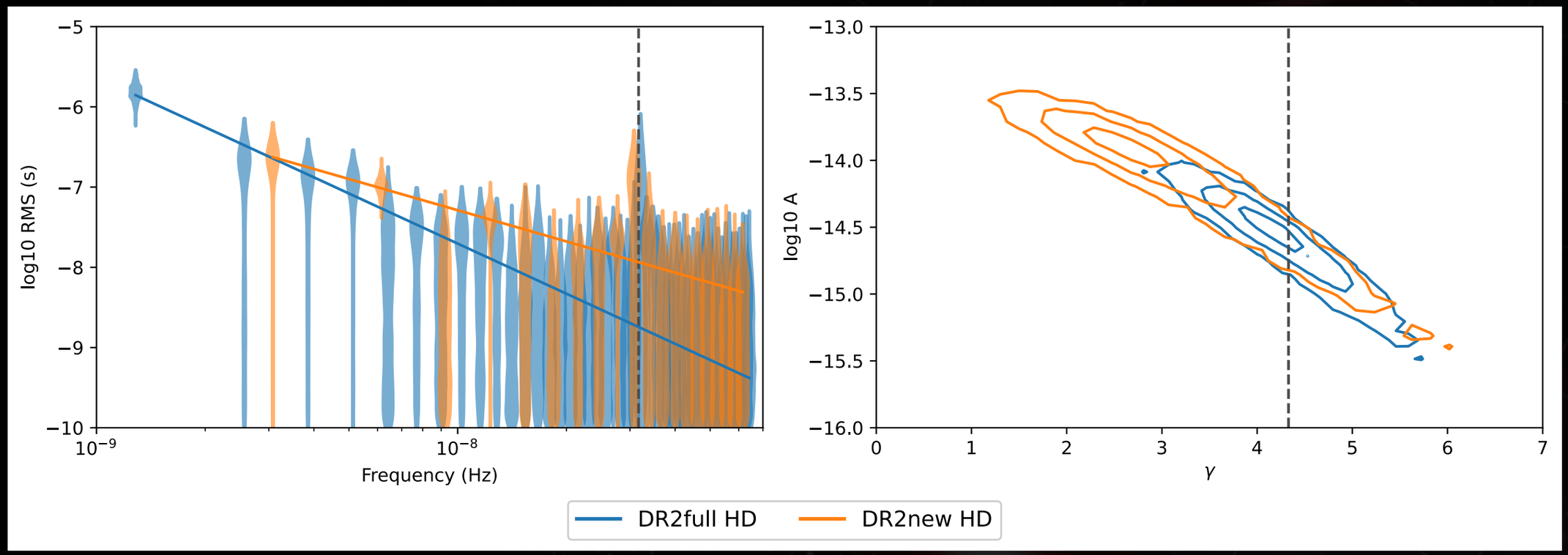
IPTA

- Two others "historical" collaborations
  - Parkes PTA (Australia)
    - Parkes radiotelescope
  - NANOGrav (USA):
    - ~~Arecibo~~
    - Green Bank
    - CHIME
- Recent collaborations:
  - InPTA: GMRT, ORT (Inde)
  - CPTA: FAST, … (Chine)
  - APT (African Pulsar Timing): MeerKAT
- Worldwide collaboration: International PTA

EPTA results: evidence for GWs

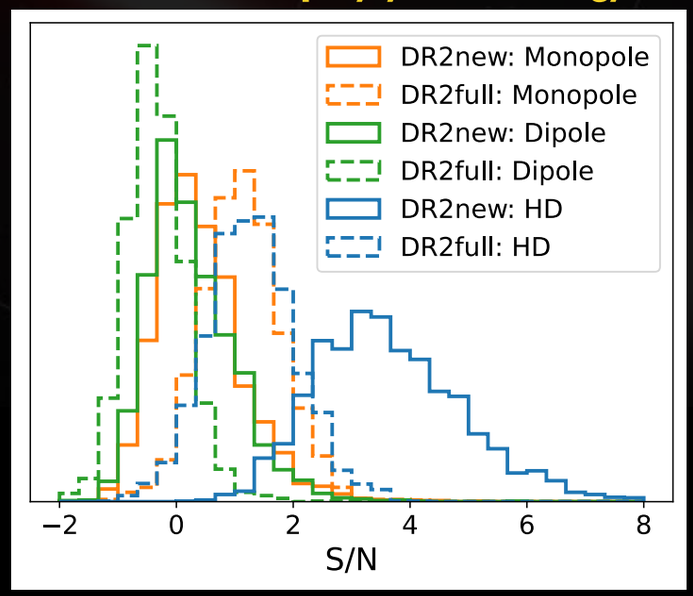
- Free spectrum

Posterior for GWB parameters



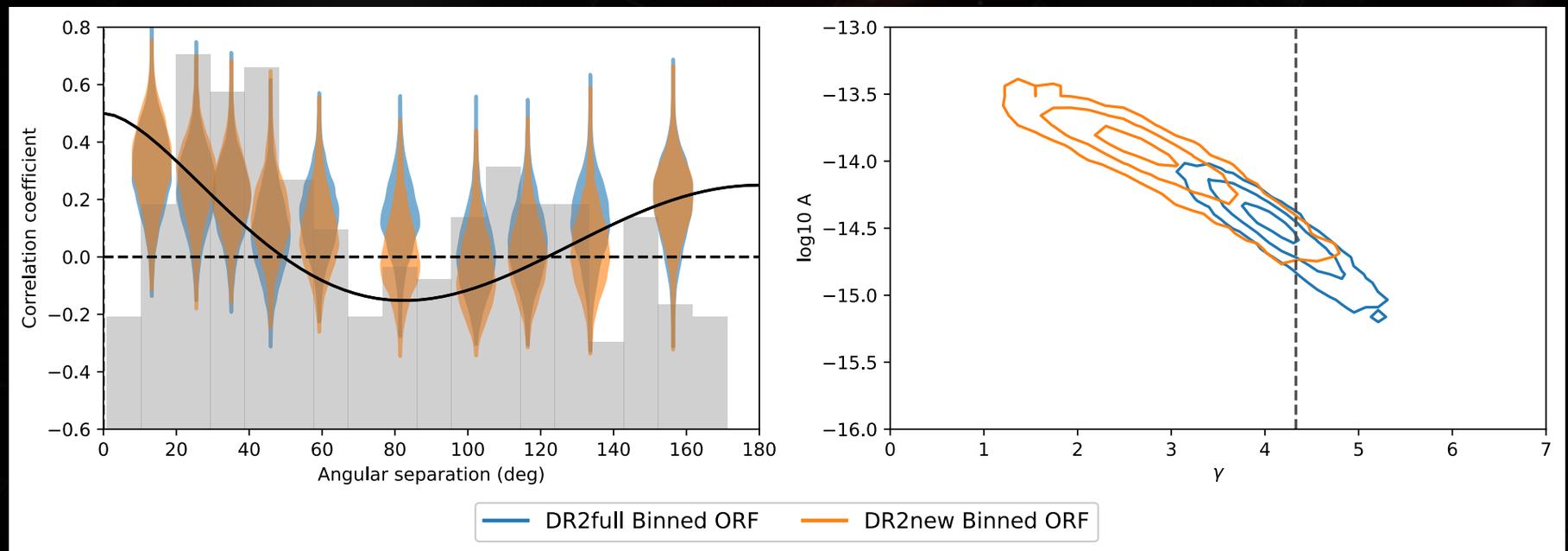
https://arxiv.org/abs/2306.16214

- GWB parameters (DR2new):
  - logarithmic amplitude: $\log_{10} A = -13.94^{+0.23}_{-0.48}$
  - spectral index: $\gamma = 2.71^{+1.18}_{-0.73}$
- No dipole and no monopole

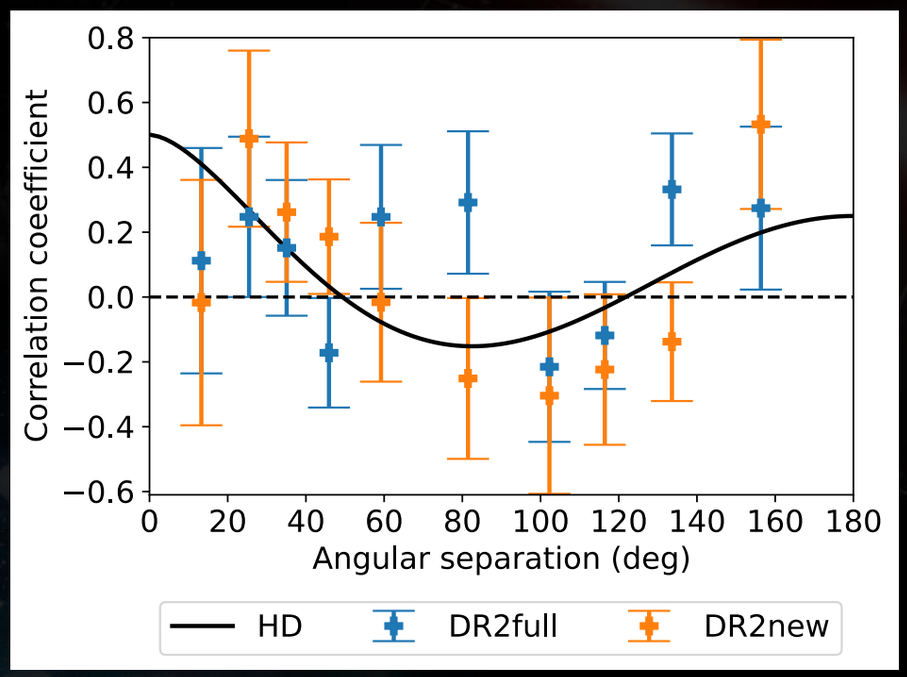


EPTA results: evidence for GWs

- Spatial correlation: overlap reduction function
  - Binned



- Optimal statistic

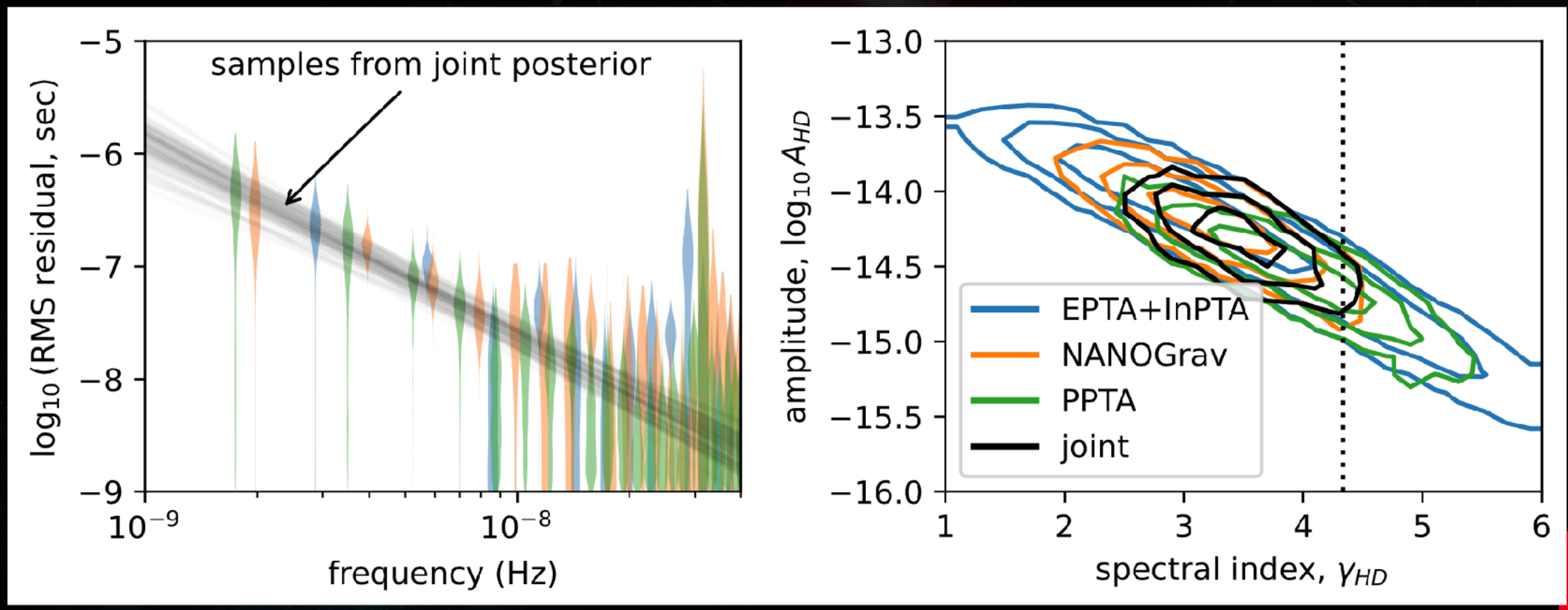


https://arxiv.org/abs/2306.16214

IPTA results

- Similar results from other PTA collaborations
- The origin of the signal is still to be understood.
- IPTA is working on a joined analysis :
  - All TOAs together
  - We should be able to confirm the detection and have a better characterisation soon …
  - But complex analysis

https://arxiv.org/abs/2309.00693



PTA near future

- IPTA:
  - 121 combined pulsars will be available very soon
  - Data analysis complex and heavy
  - Goal: confirm and characterise the detection
- SKA:
  - > 100 pulsars with very high timing precision
  - First science data of SKA in 2028
  - Large improvement in sensitivity:
    - If SMBHBs, understand the population (seed, evolution, merger history, …) – synergy with LISA
    - If cosmological origins, measure the spectrum in details to understand "physics"
    - If individual sources, measure the waveform
      => test GR? understand environment of SMBHB, …

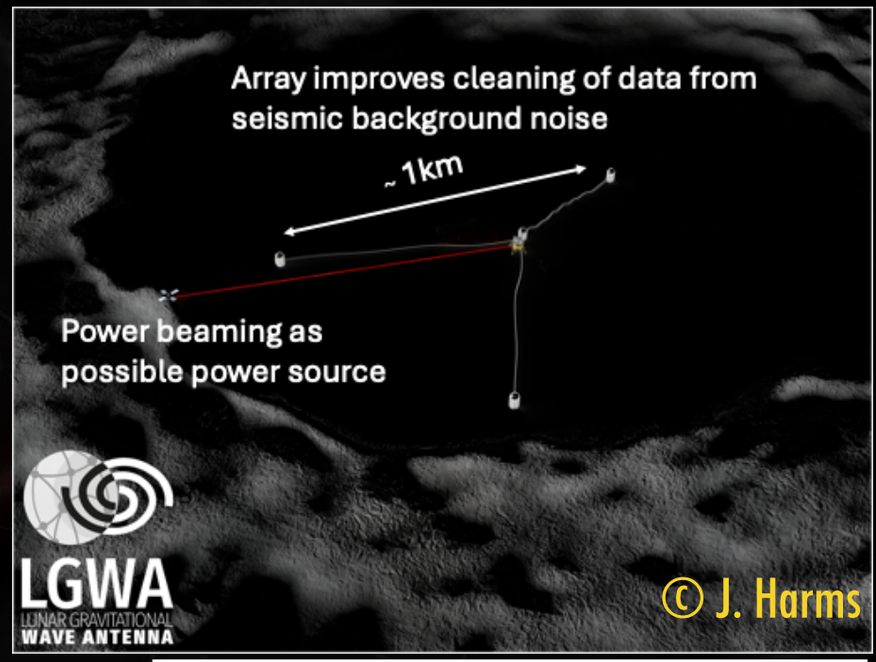
Multimessenger with PTA

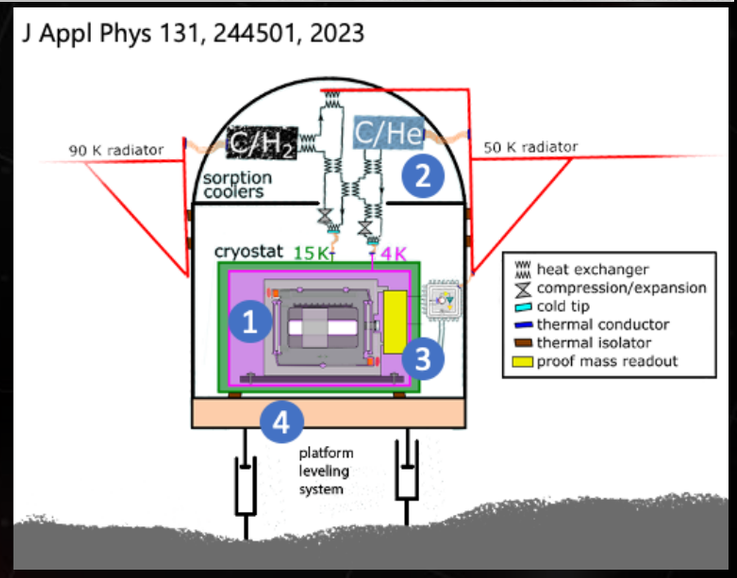
- Observations of individual SMBHB:
  - Close and heavy => very good candidate for identifying an electromagnetic counterpart
  - Targeting search using catalogs of potential binaries as for example:
    - Catalina Real-time Transient survey
    - Zwicky Transient Facility

Moon based GW observatories

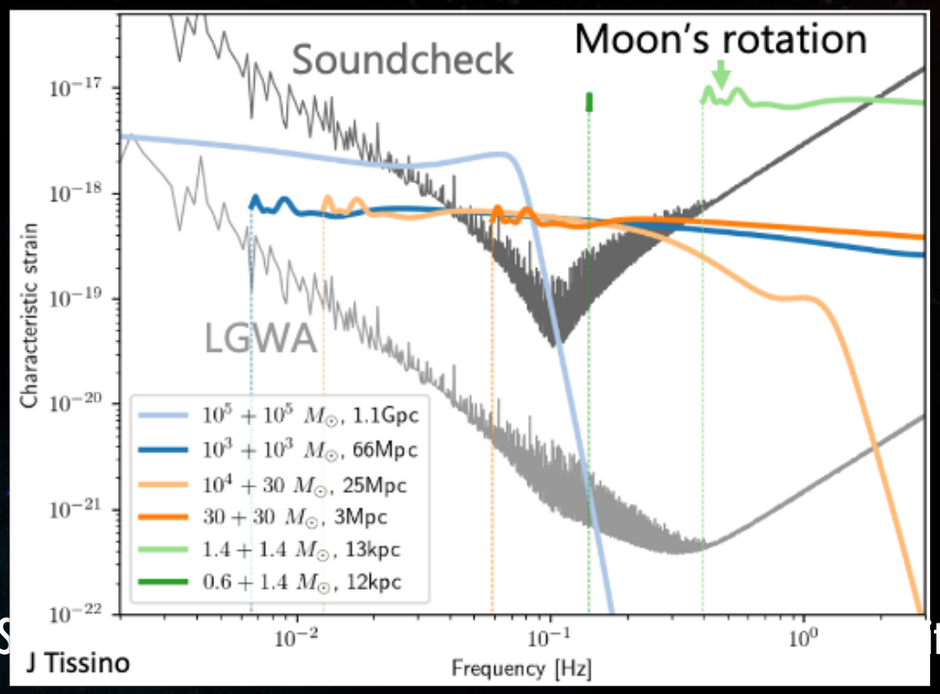
LGWA

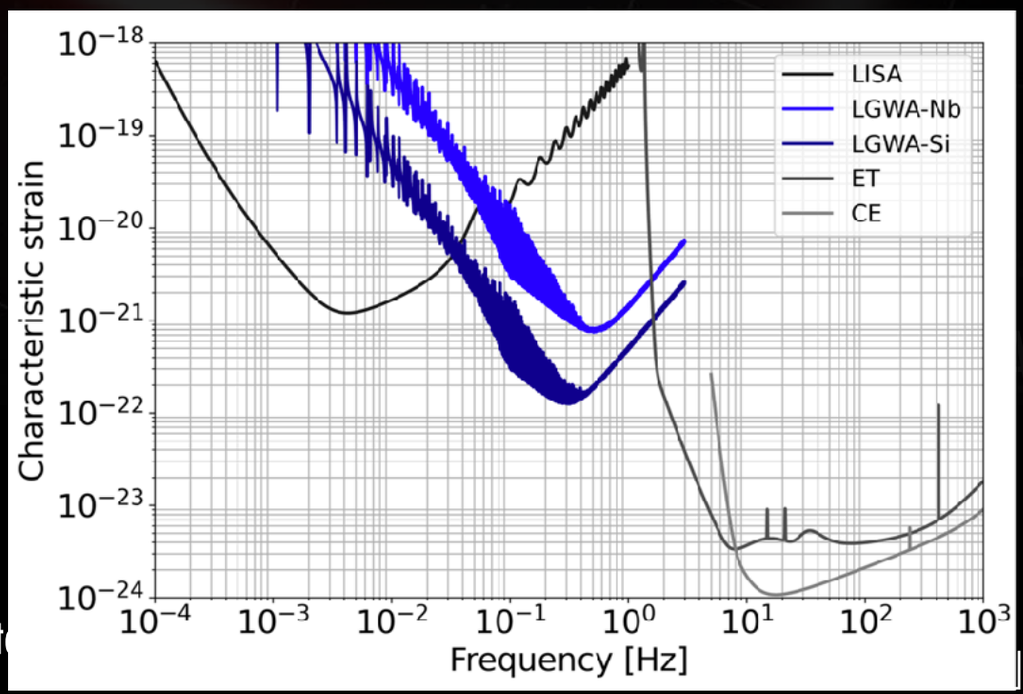
- Lunar Gravitational Wave Antenna
  - Array of seismometers on the Moon using the Moon as a resonant bar ("Weber" bar)
- Science case: GW and multi-messenger observations
  - Studying astrophysical explosions
  - Exploring black-hole populations and their role for structure formation in our Universe
  - Hubble constant measurement
  - Enabling the next level of high-precision waveform measurements





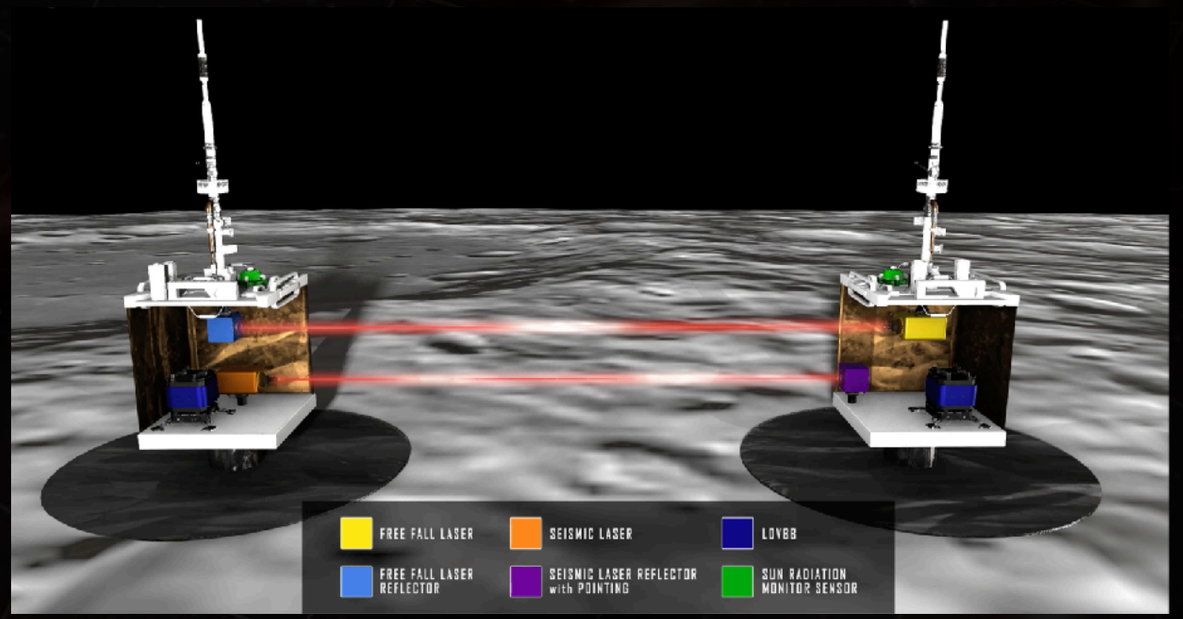
LGWA Workshop https://indico.ict.inaf.it/event/2782/



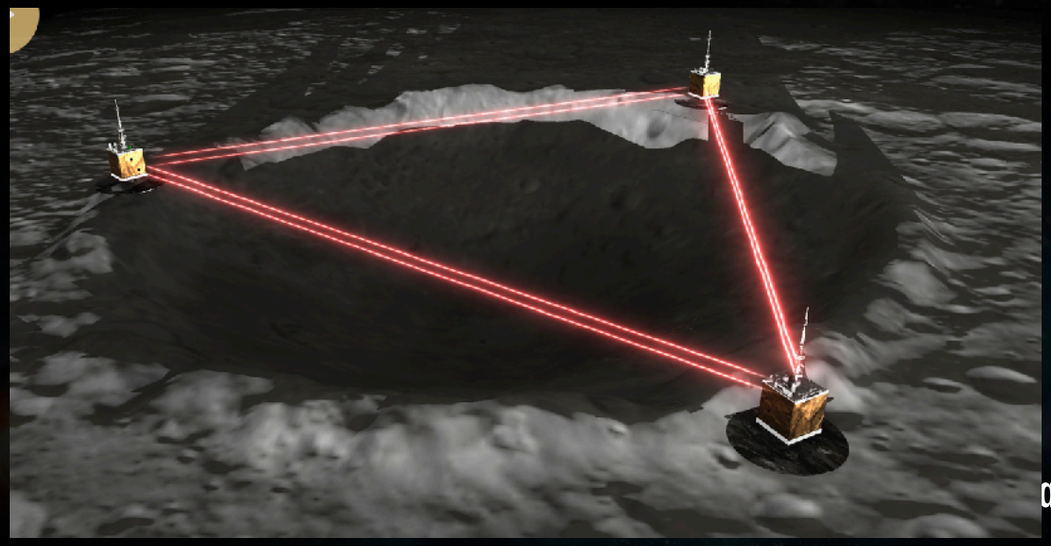


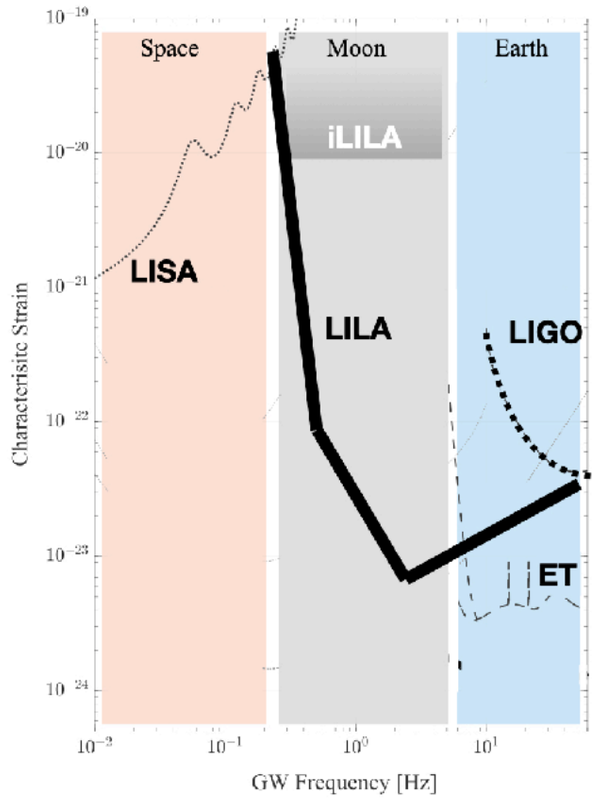
LILA

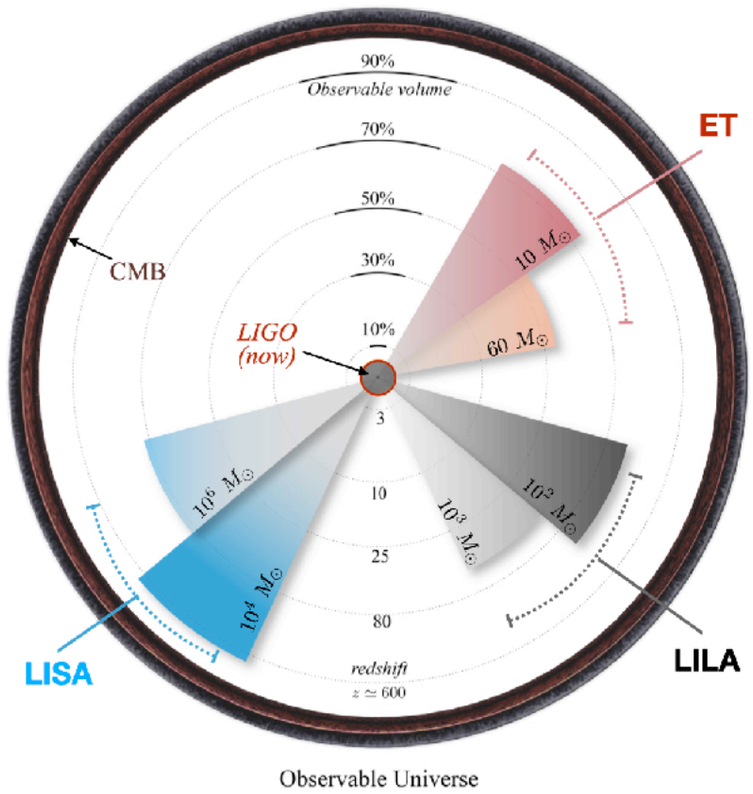
- Laser Interferometer Lunar Antenna
  - 3 landers placed in triangular shape (few km)
  - Payload: mirrors, lasers, seismic isolation
- 2 different ways to detect GW:
  - Space-time induced between free falling masses
  - Vibration of the Moon induced by passing GW
- Sub-Hertz frequencies
- GW sources:
  - Weeks-ahead early-warning system for observing binary neutron star mergers,
  - Type Ia supernovae progenitors,
  - Survey of intermediate-mass BHs to Dark Ages



LILA meeting https://www.vanderbilt.edu/lunarlabs/lila/







Conclusion

- GW observations in the millihertz and decihertz bands:
  space based or Moon based instruments:
  - LISA:
    - Adopted mission in development/implementation phases for a launch in 2035,
    - Large science case for astrophysics, fundamental physics and cosmology
  - Many others ideas either in space or on the Moon: early study phase

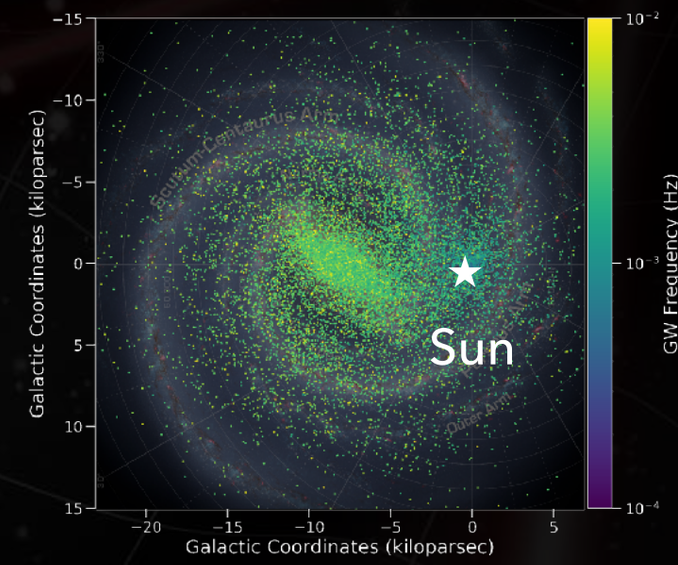
- GW observations in the nanohertz band: galactic scale detector:
  Pulsar Timing Array:
  - Strong evidence for GW detection obtained by EPTA, NanoGRAV and PPTA
  - Confirmation and characterisation will come soon with IPTA (including MeerKAT, CHIME, FAST and LEAP) then SKA

Thank you

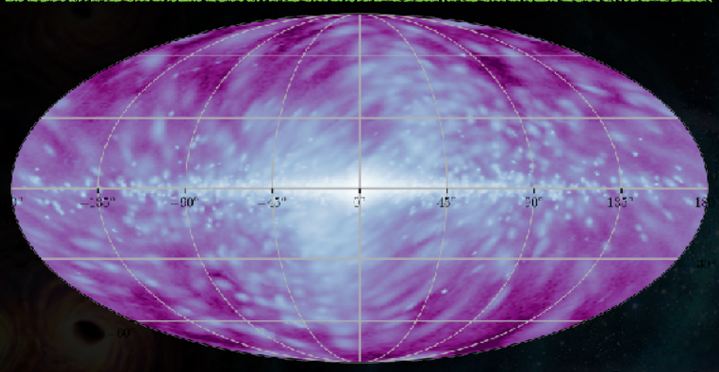
© ESA

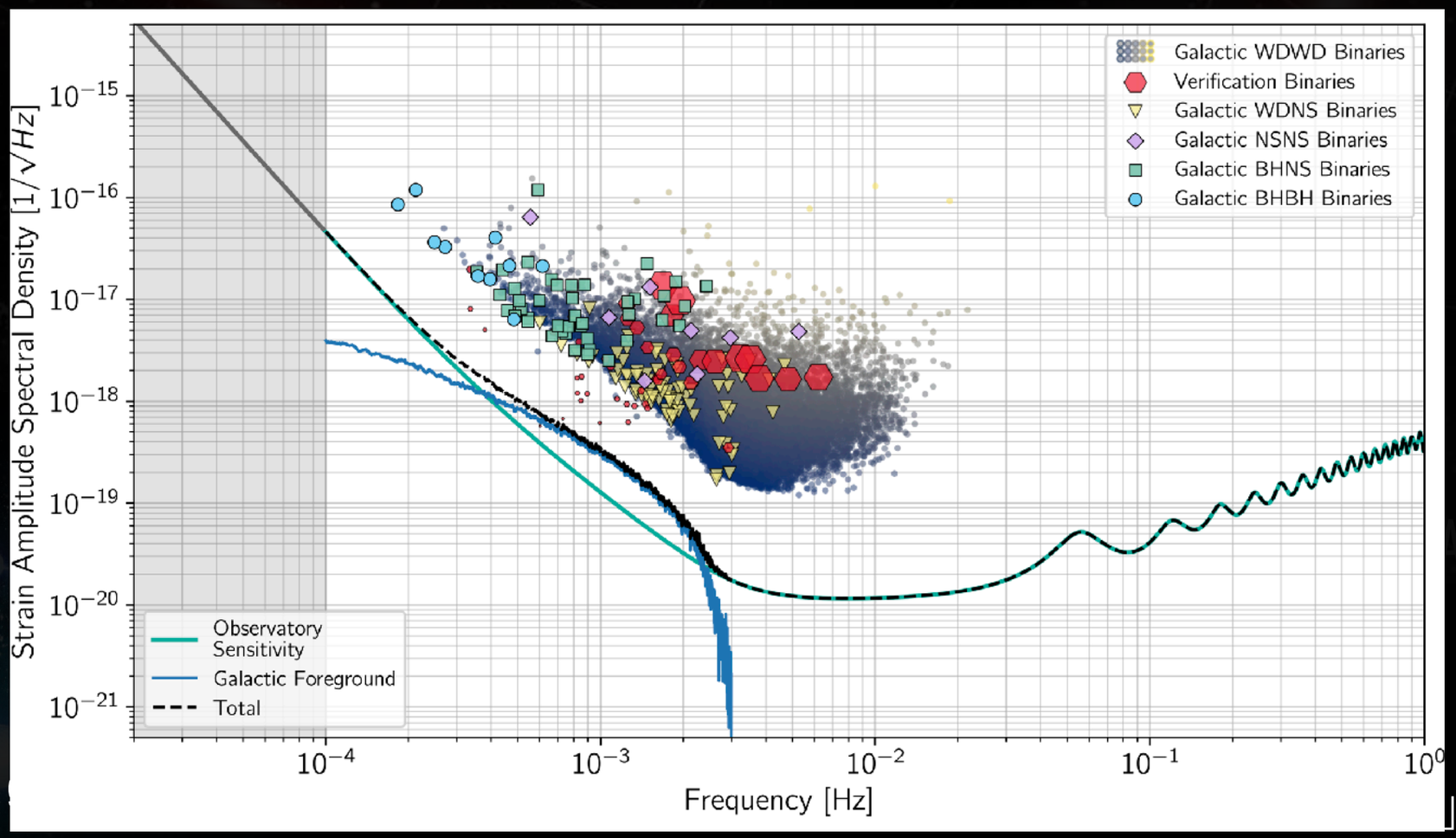
LISA Science

- SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy:
  - Formation and evolution pathways of dark compact in the Milky Way and in neighbouring galaxies;
  - The Milky Way mass distribution;
  - The interplay between gravitational waves and tidal dissipation.



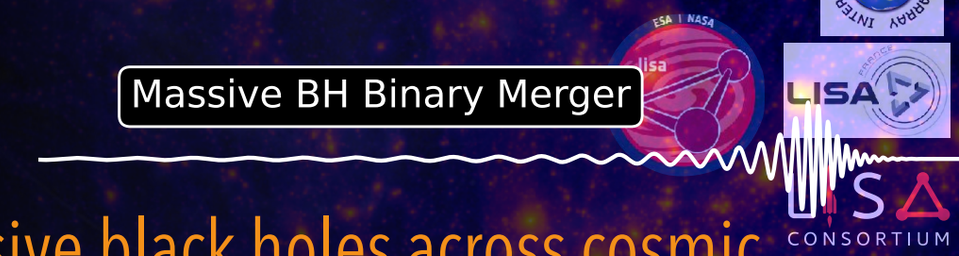
Precision:
- Distance: ~ 30% - 1%
- Chirp mass: ~10% - 0.0001%
- Sky position: ~few deg²



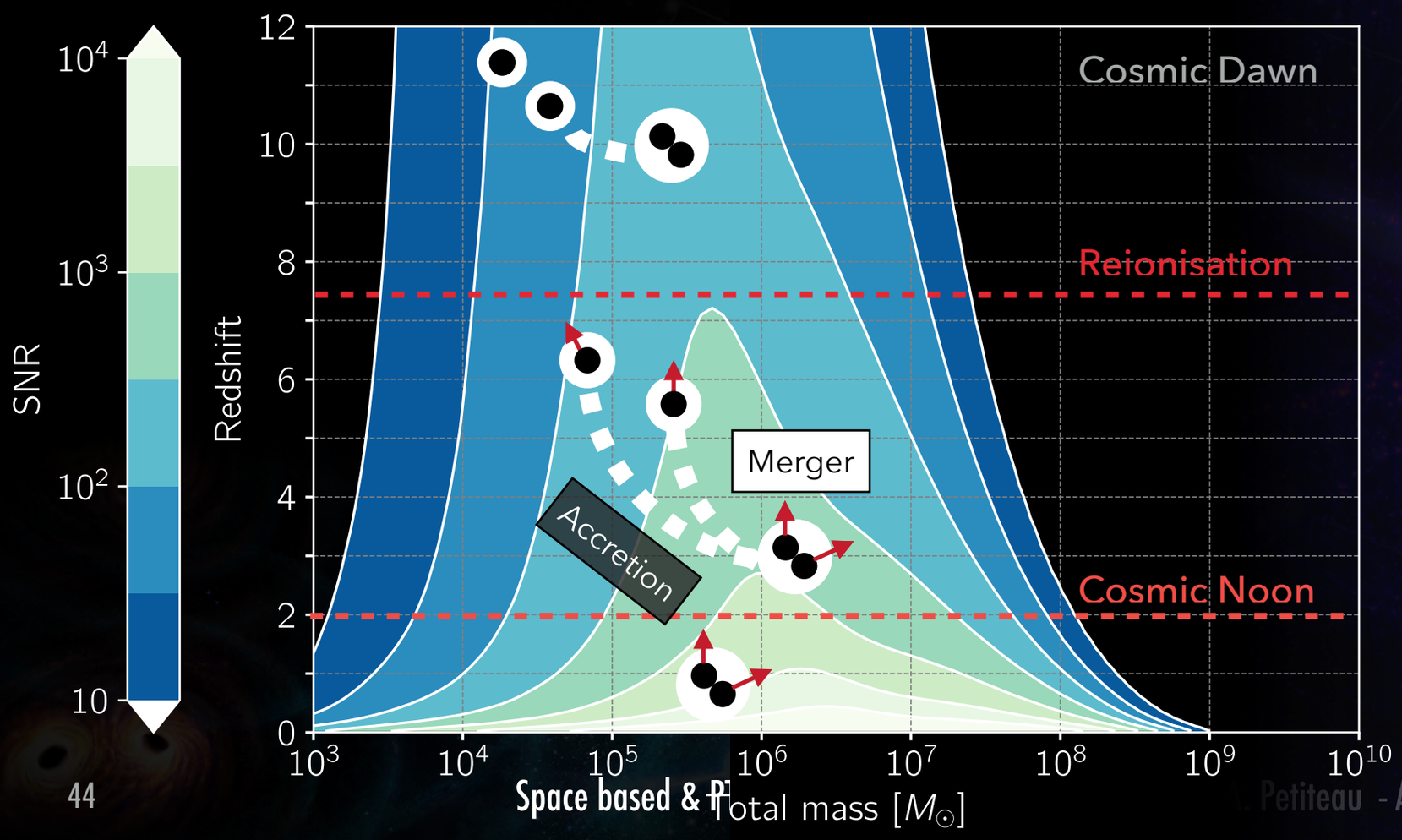


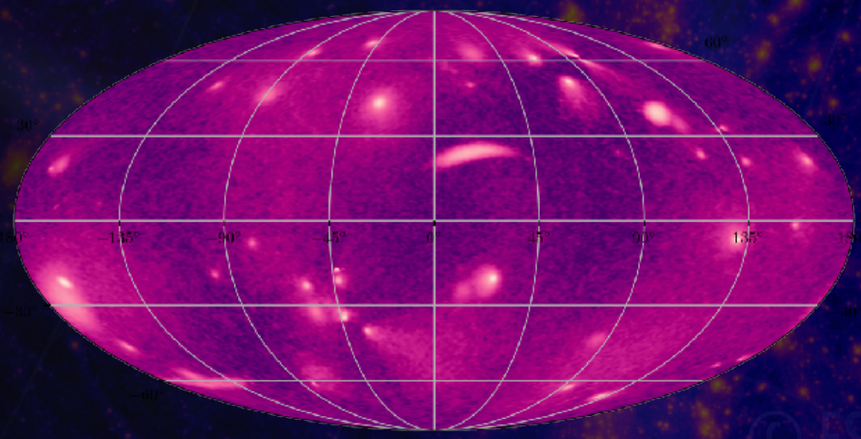
Space based & PTA

LISA Science



- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages:
  - Discover seed black holes at cosmic dawn;
  - Study the growth mechanism and merger history of massive black holes from the epoch of the earliest quasars;
  - …

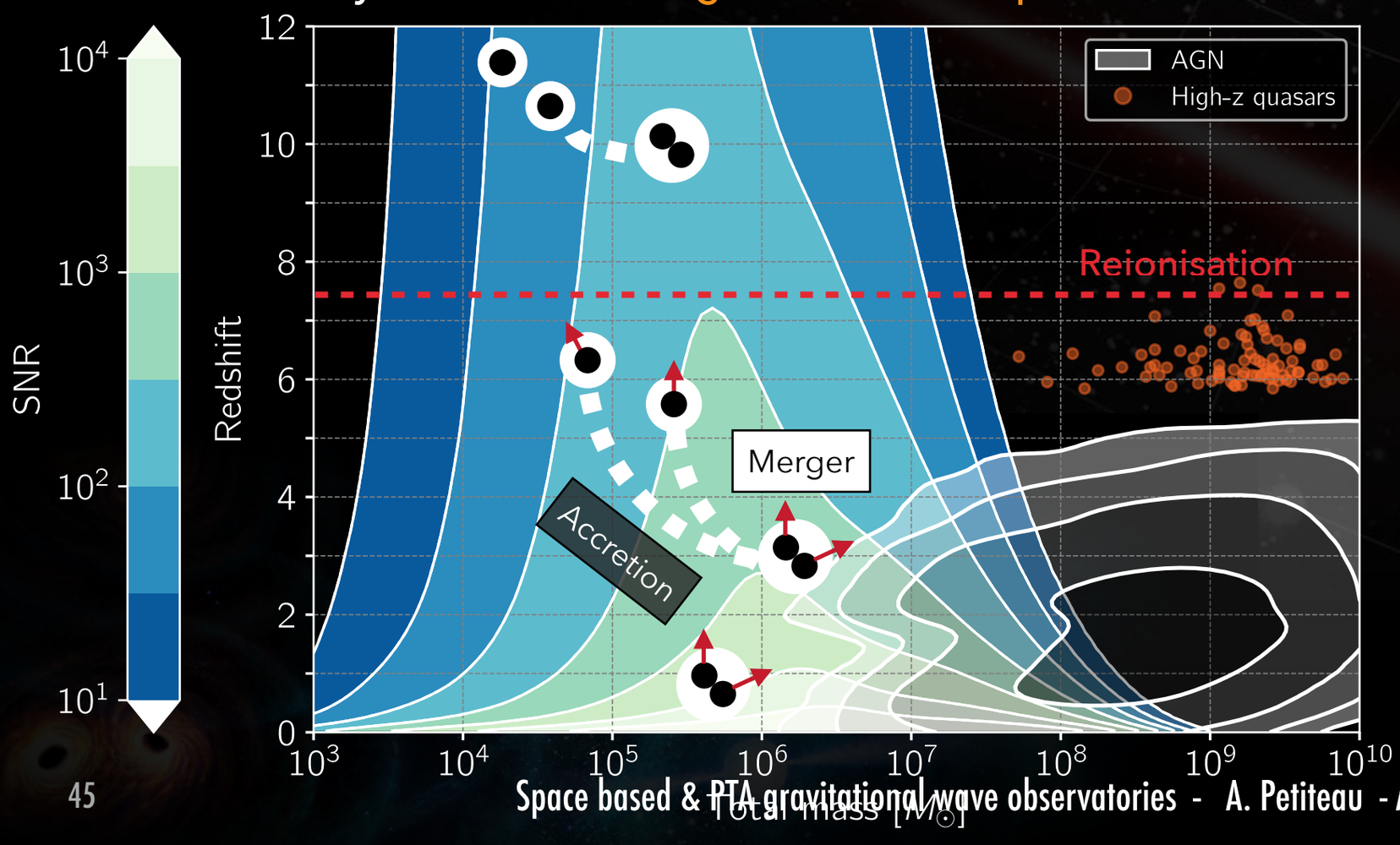




LISA Science

Massive BH Binary Merger

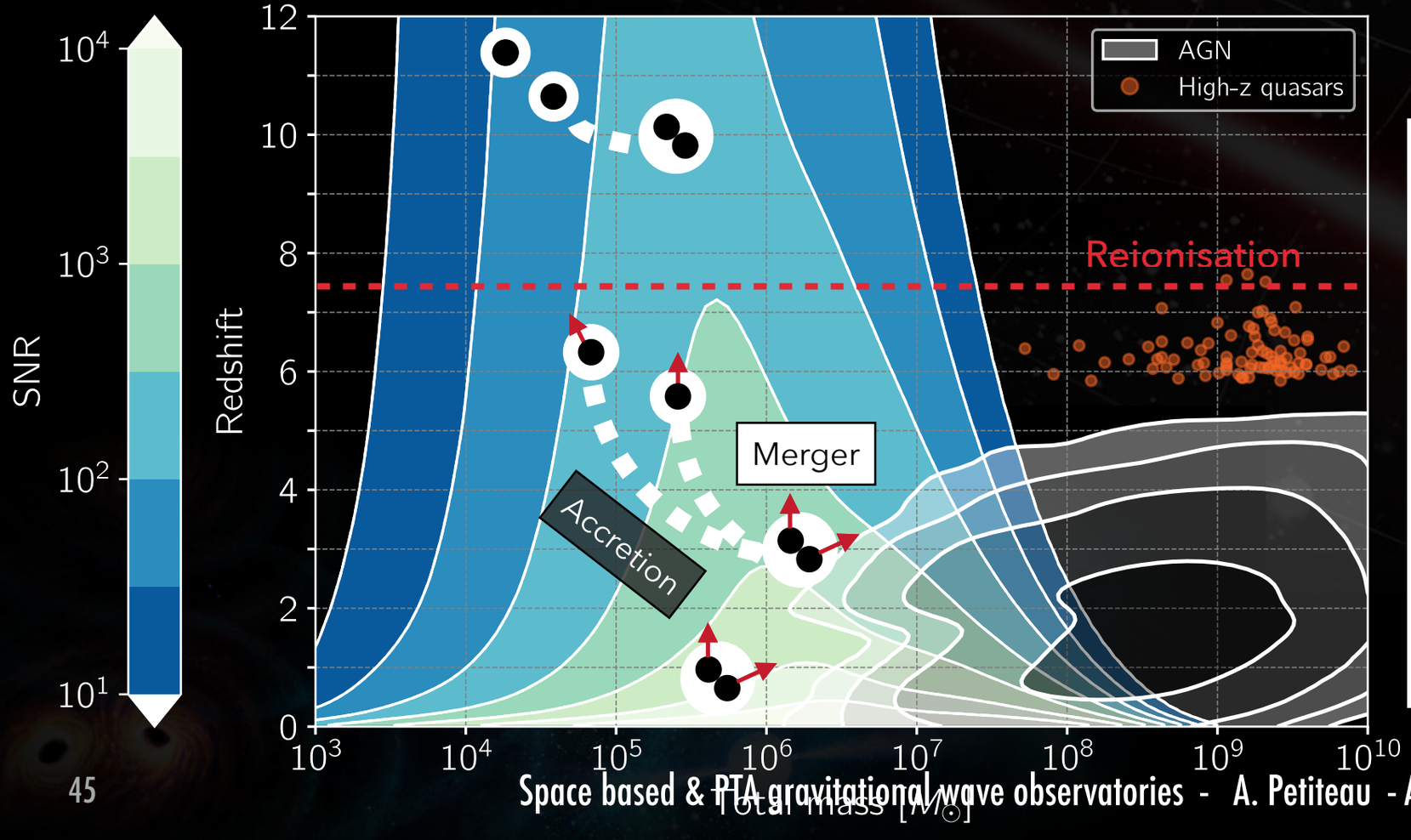
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages:
  - …
  - …
  - Identify the electromagnetic counterparts of massive black hole binary coalescences.

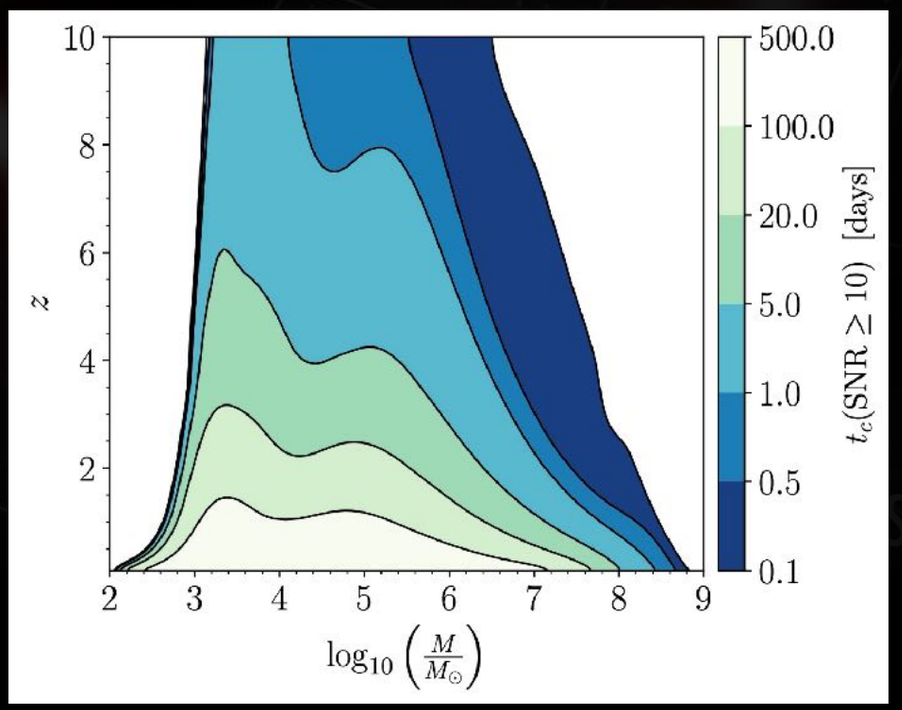


LISA Science

Massive BH Binary Merger

- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages:
  - …
  - …
  - Identify the electromagnetic counterparts of massive black hole binary coalescences.

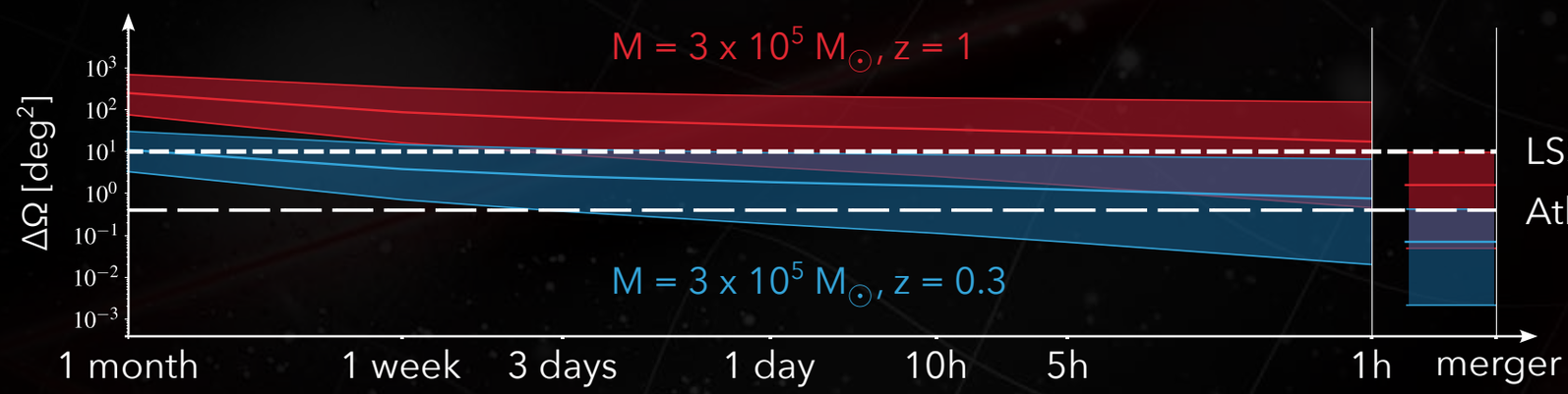


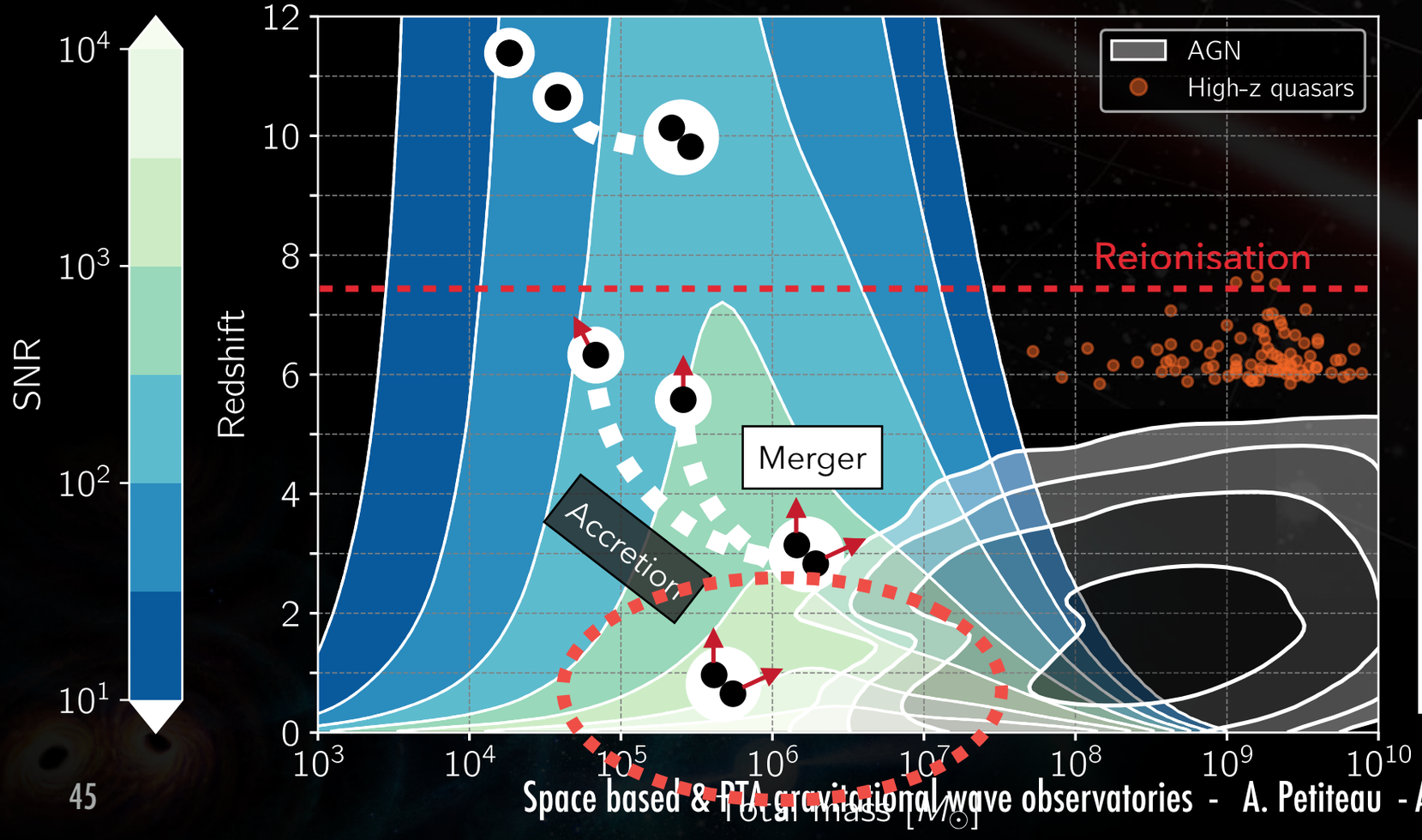


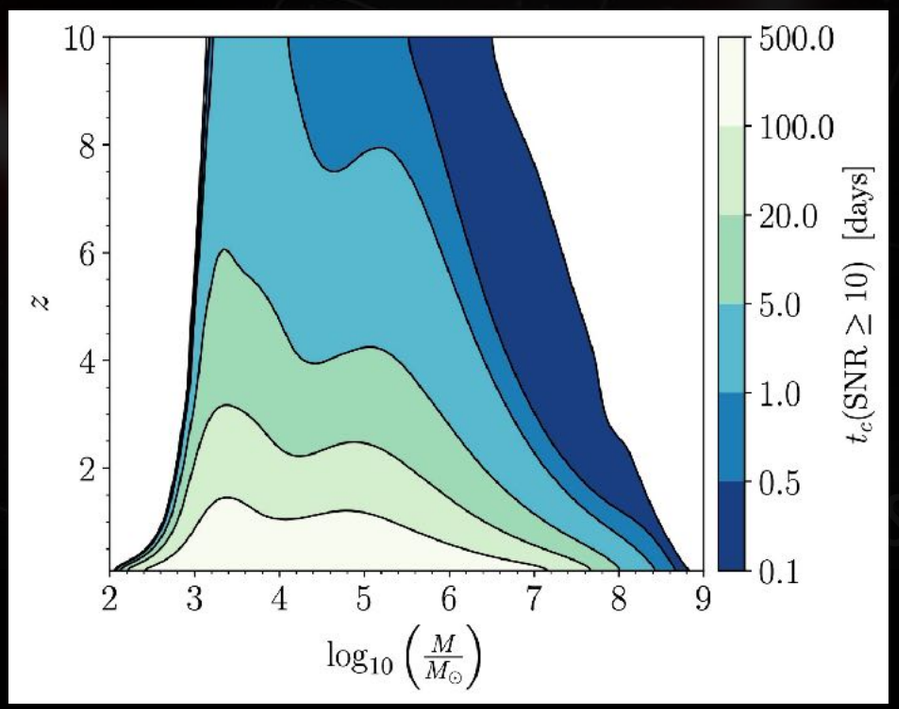
LISA Science

Massive BH Binary Merger

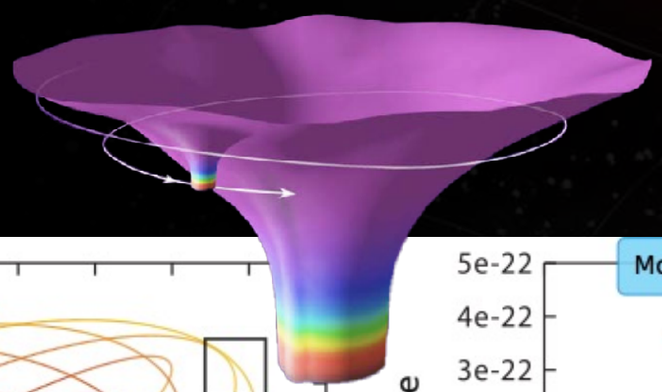
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages:
  - …
  - …
  - Identify the electromagnetic counterparts of massive black hole binary coalescences.



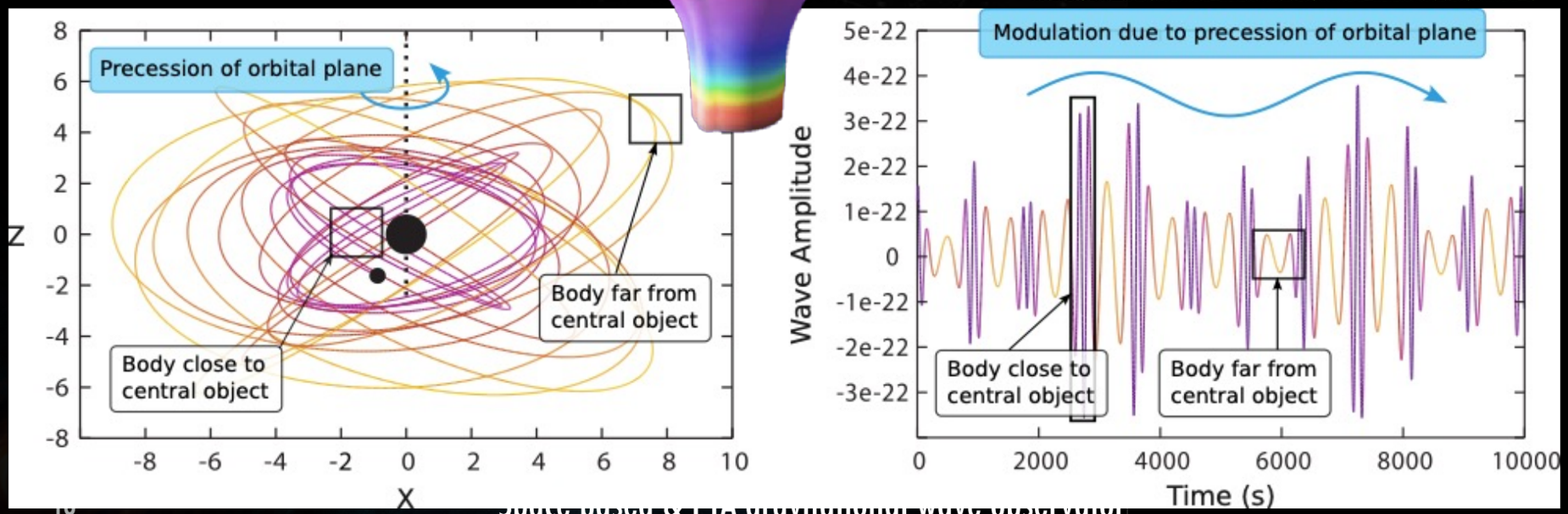




LISA Science



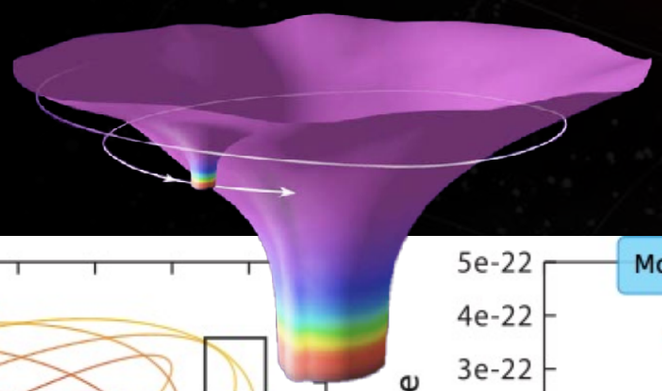
Precision:
- Mass & spin at 0.0001%



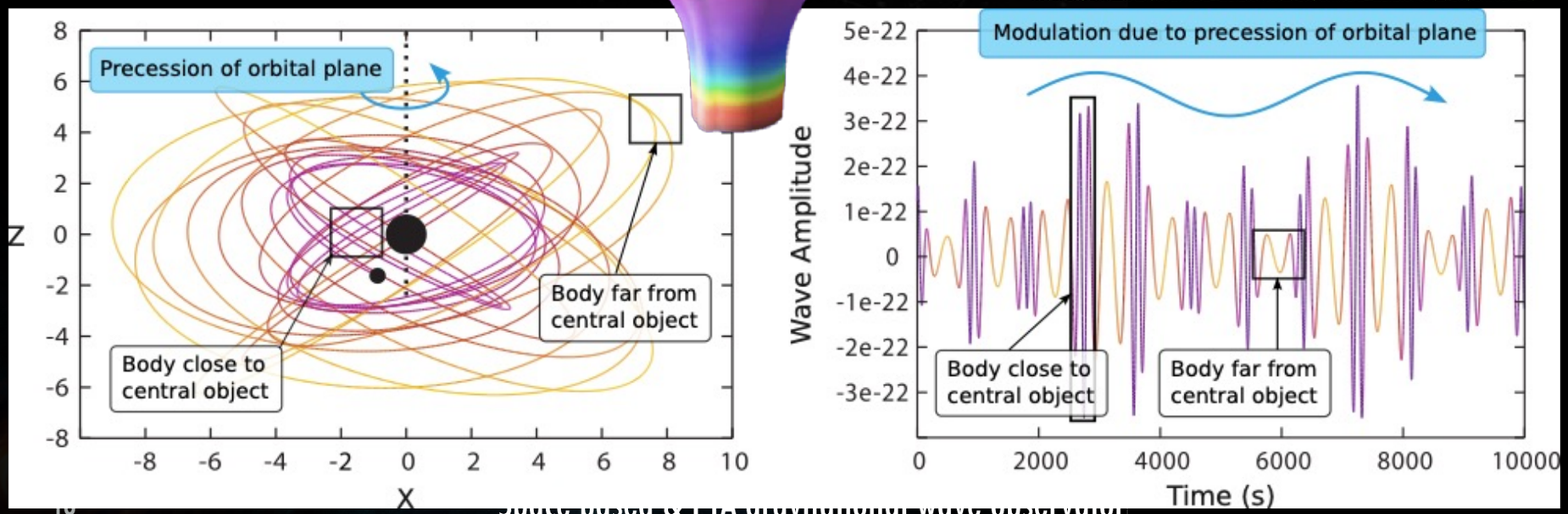
Space-based & PTA gravitational wave observatories

LISA Science

- SO3: Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs:

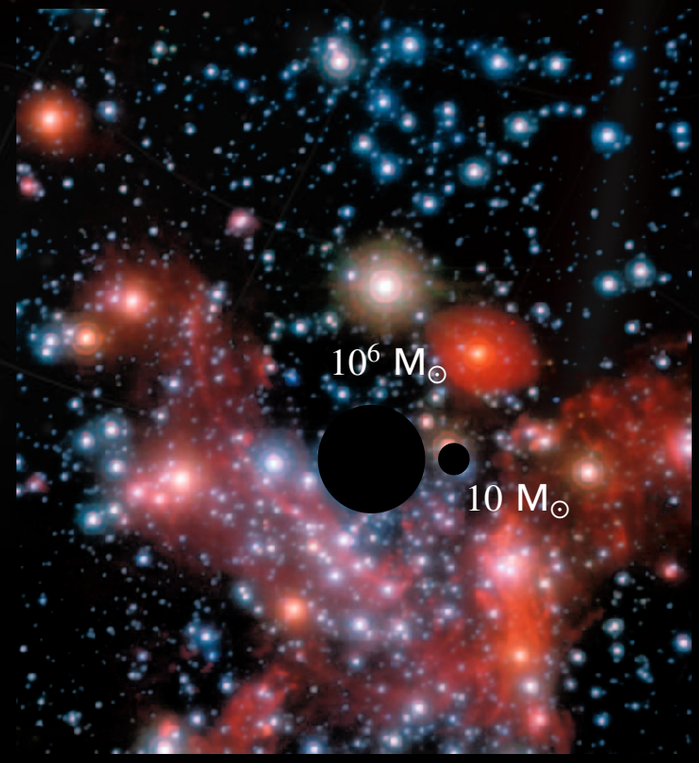


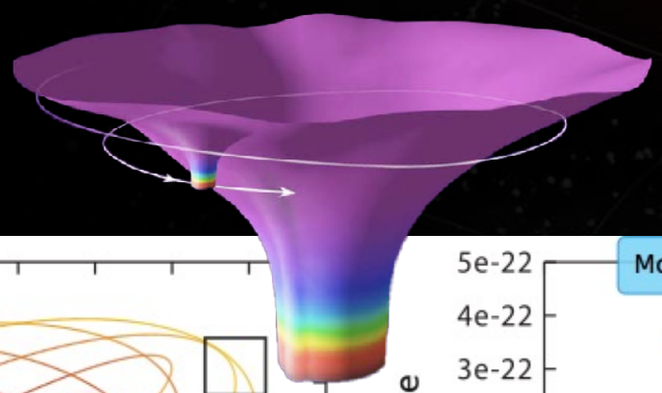
Precision:
- Mass & spin at 0.0001%



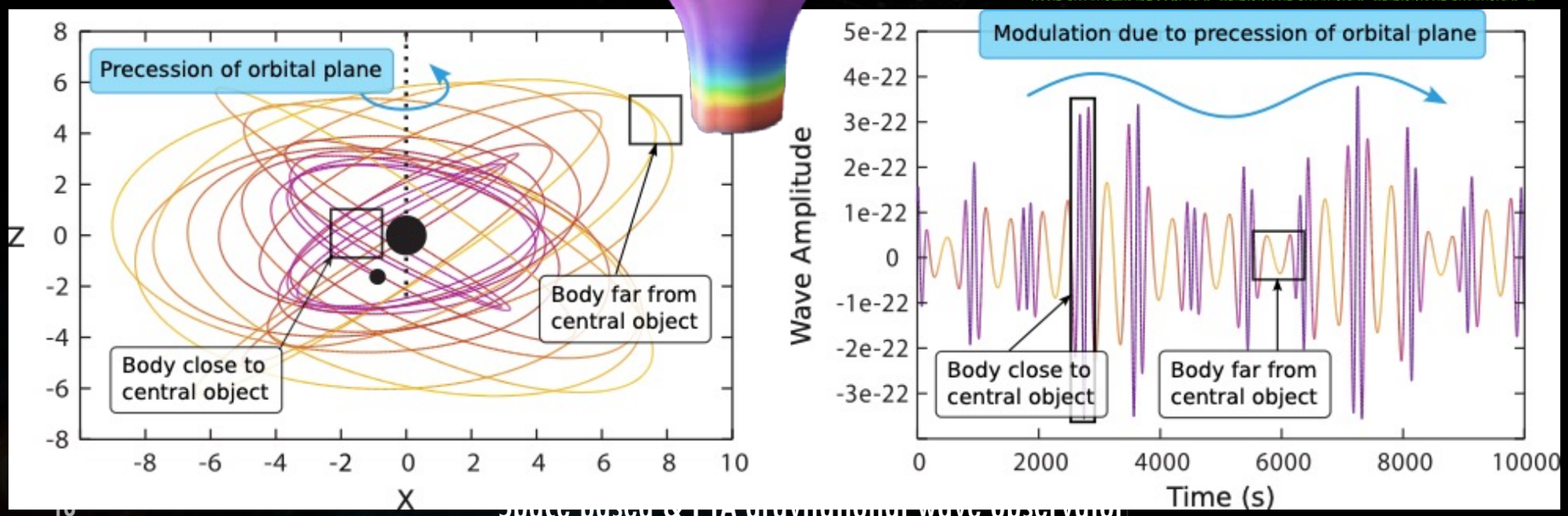
LISA Science

- <u>SO3:</u> Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs:
  - Study the properties and immediate environment of Milky Way-like MBHs using EMRIs;



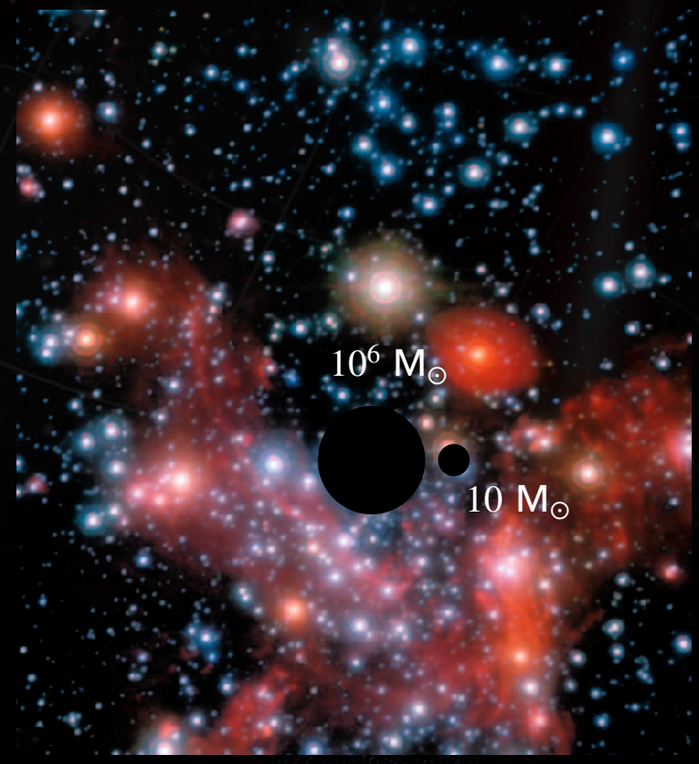


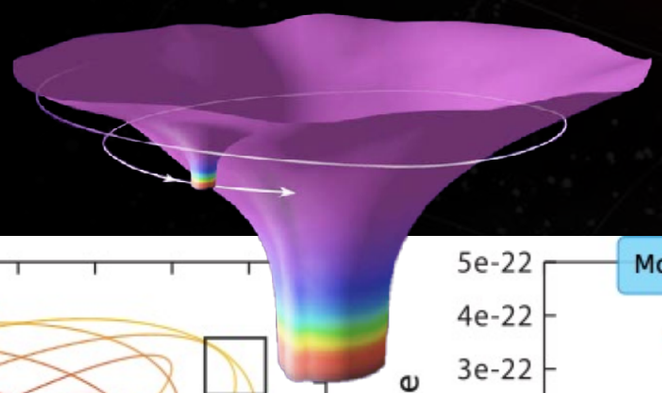
Precision:
- Mass & spin at 0.0001%



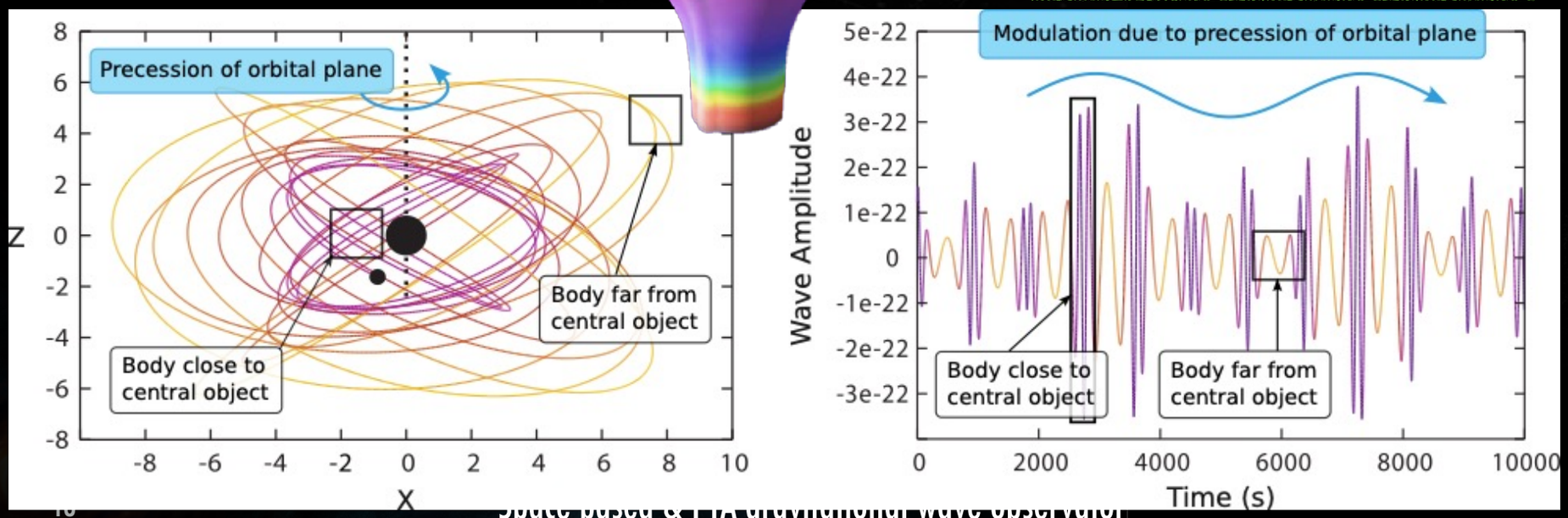
LISA Science

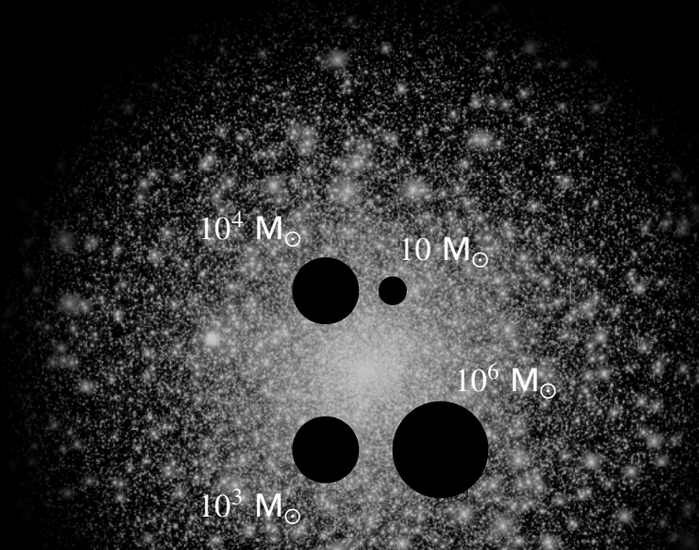
- SO3: Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs:
  - Study the properties and immediate environment of Milky Way-like MBHs using EMRIs;
  - Study the IMBH population using IMRI.





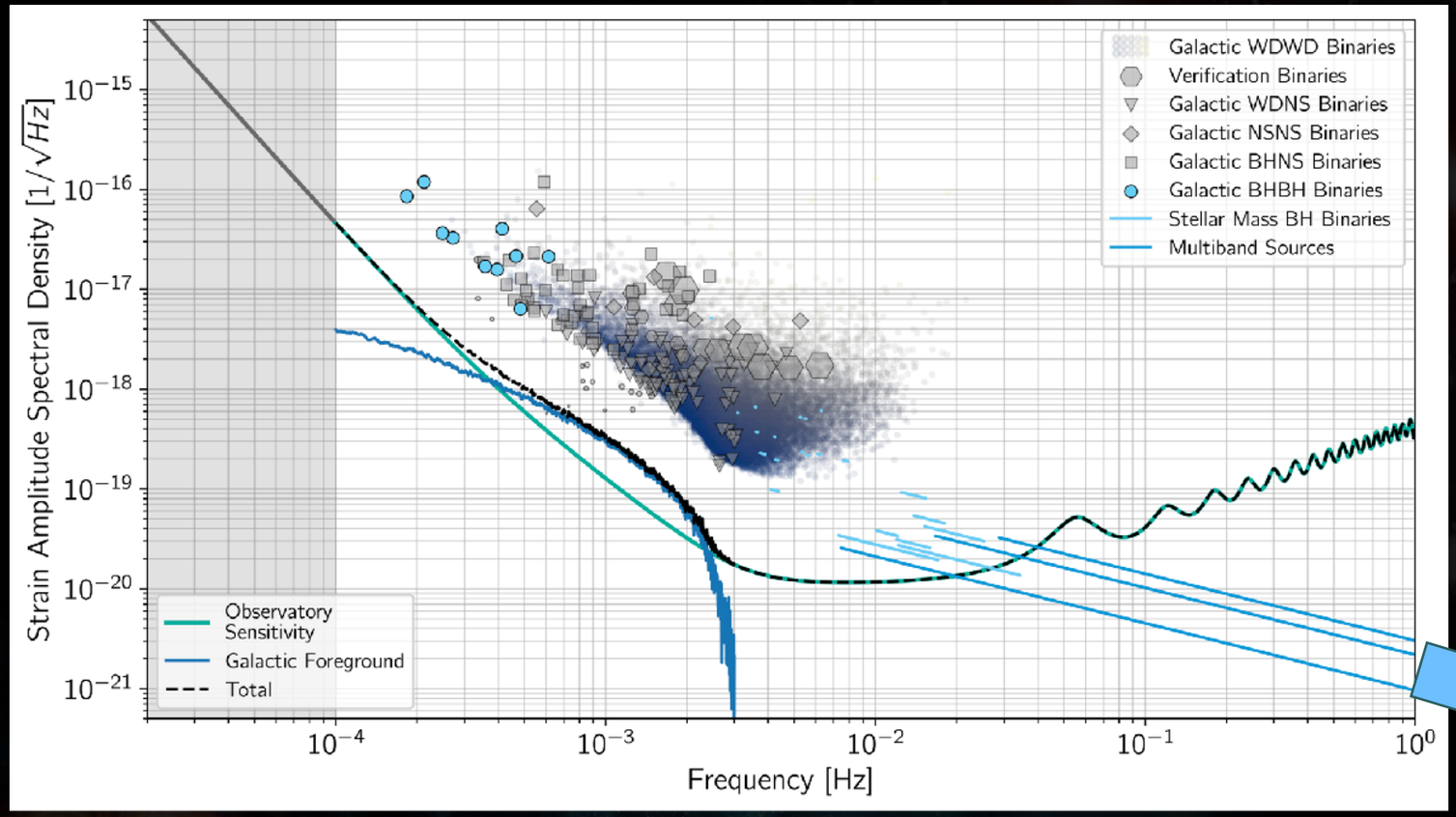
Precision:
- Mass & spin at 0.0001%





LISA Science

- SO4: Understand the astrophysics of stellar origin black holes :
  - Study the statistical properties of sBHs far from merger;
  - Detecting high mass sBHBs and probing their environment;
  - Enabling multiband and multimessenger observations at the time of coalescence.



Precision:
- Eccentricity at 0.01%

Towards the band of ground based observatory

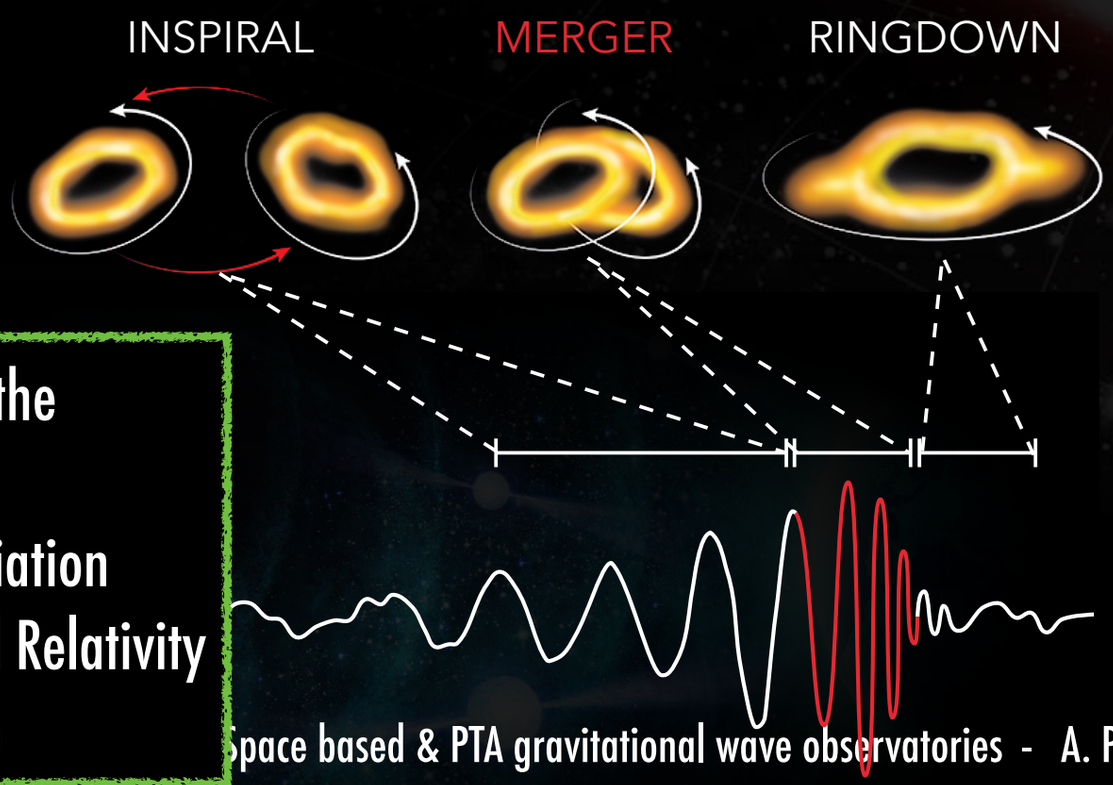
LISA Science

LISA Science

- SO5: Explore the fundamental nature of gravity and black holes :

LISA Science

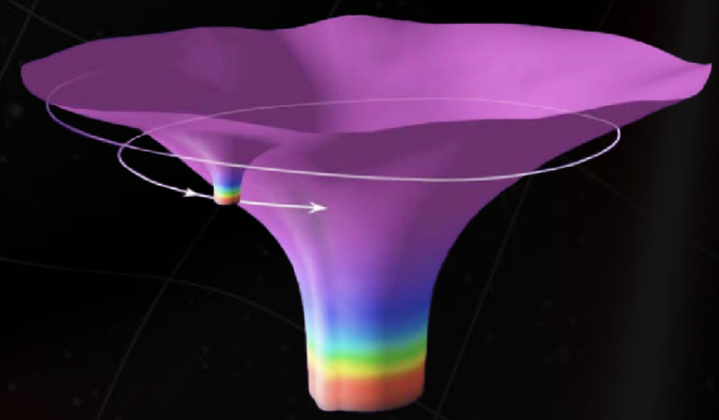
- SO5: Explore the fundamental nature of gravity and black holes :
  - Use ringdown characteristics observed in MBHB coalescences to test whether the post-merger objects are the MBHs predicted by GR;

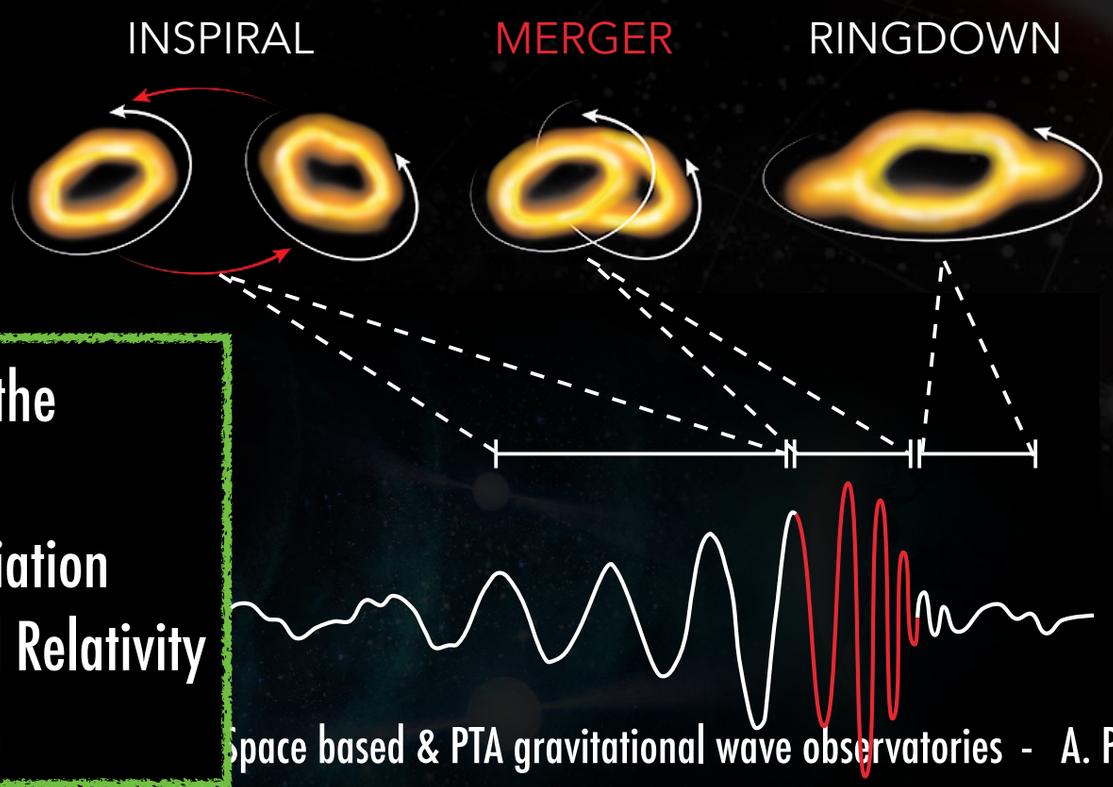


Precision from the ringdown:
- Measure deviation from General Relativity at 10% to 1%

LISA Science

- SO5: Explore the fundamental nature of gravity and black holes :
  - Use ringdown characteristics observed in MBHB coalescences to test whether the post-merger objects are the MBHs predicted by GR;
  - Use EMRIs to explore the multipolar structure of MBHs and search for the presence of new light fields;



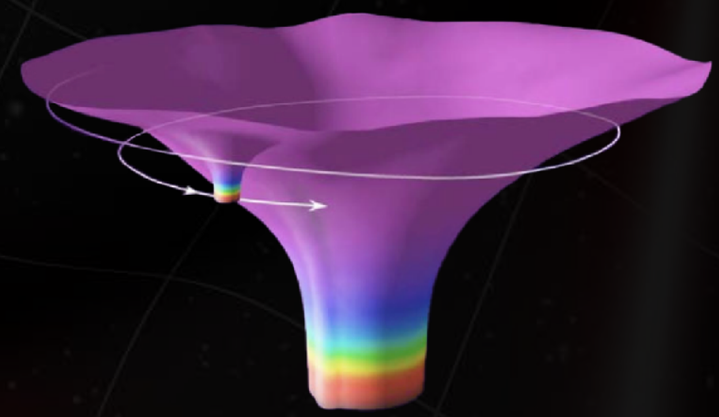


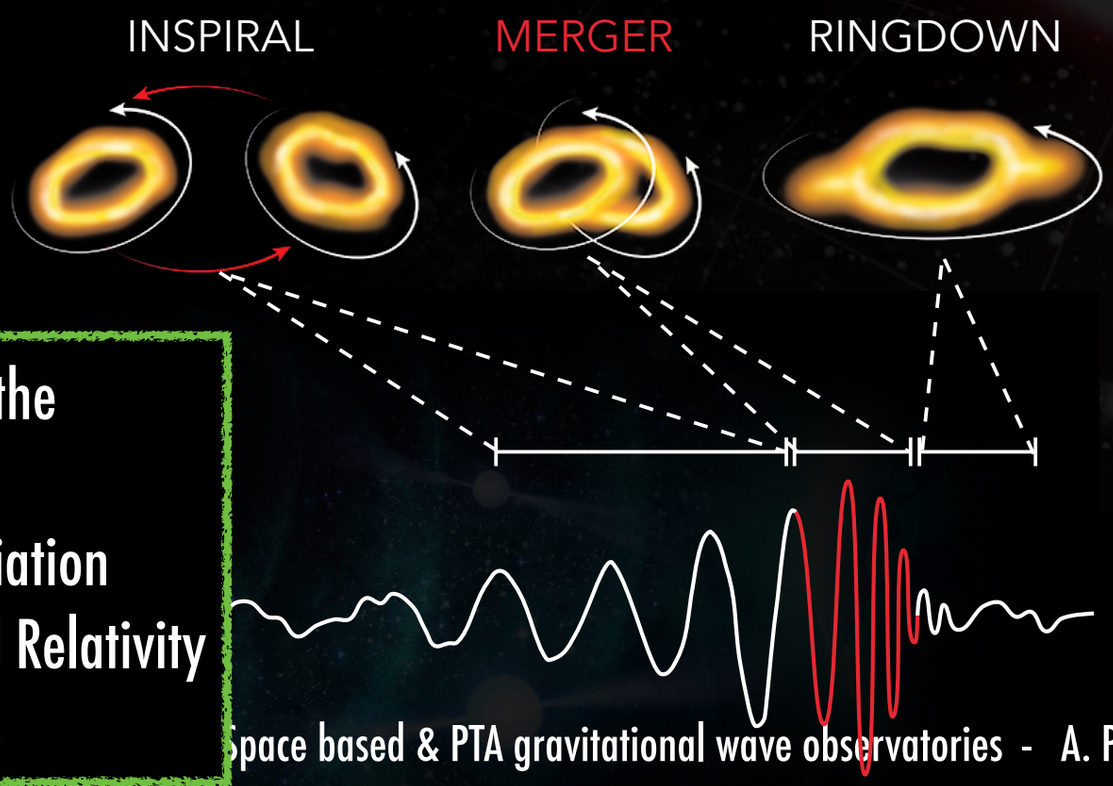
Precision from the ringdown:
- Measure deviation from General Relativity at 10% to 1%

Precision for the "golden" EMRI :
- Mass of the big black hole at $\sim$ 0.001%
- Spin of the big black hole 10^{-5} (absolute)
- Quadrupolar moment 10^{-3} %

LISA Science

- SO5: Explore the fundamental nature of gravity and black holes :
  - Use ringdown characteristics observed in MBHB coalescences to test whether the post-merger objects are the MBHs predicted by GR;
  - Use EMRIs to explore the multipolar structure of MBHs and search for the presence of new light fields;
  - Test the presence of beyond-GR emission channels;
  - Test the propagation properties of GW.



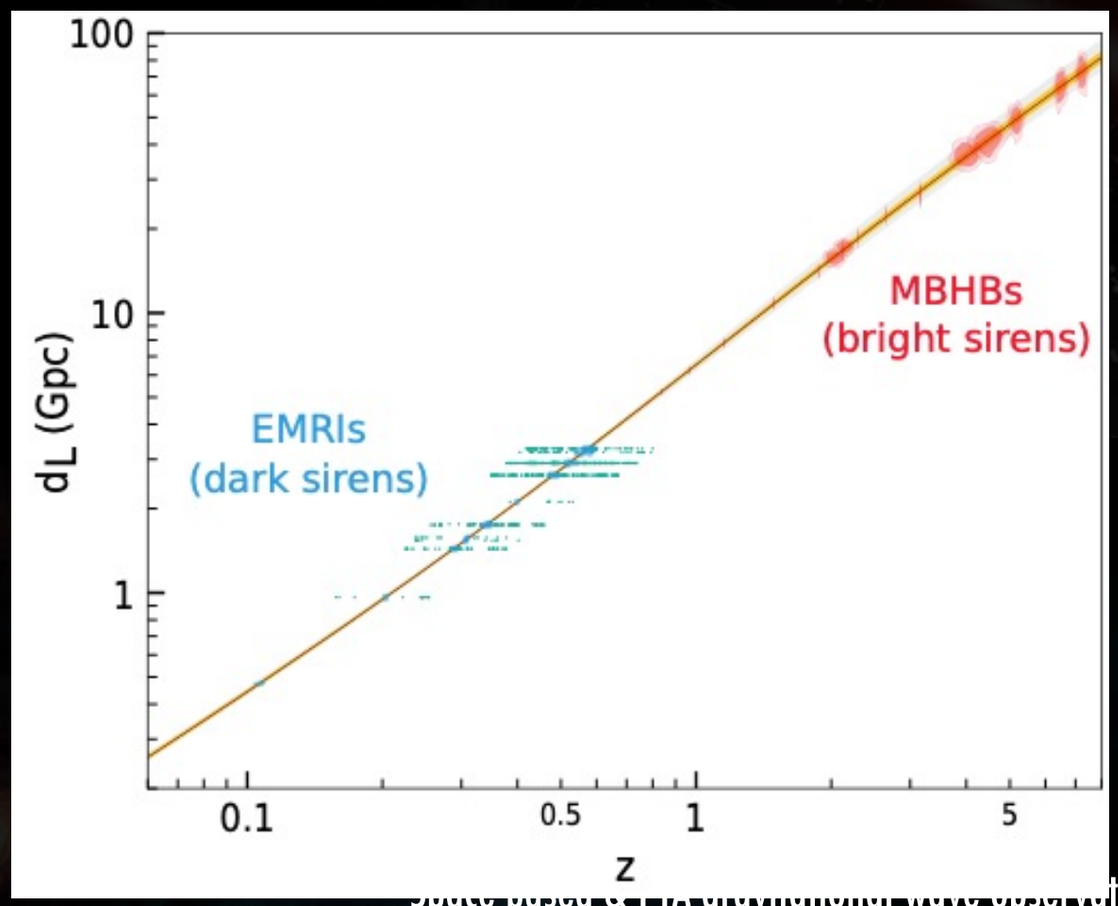


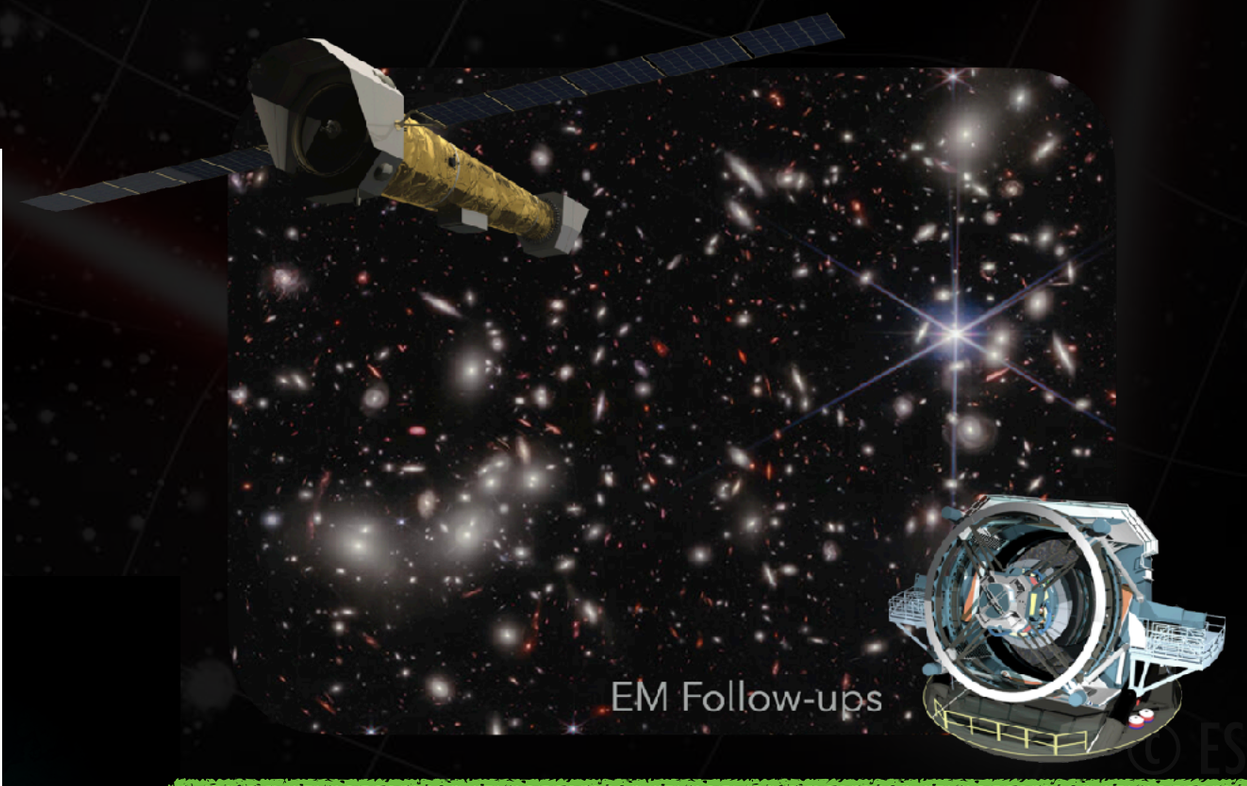
Precision from the ringdown:
- Measure deviation from General Relativity at 10% to 1%

Precision for the "golden" EMRI :
- Mass of the big black hole at $\sim$ 0.001%
- Spin of the big black hole 10^{-5} (absolute)
- Quadrupolar moment 10^{-3} %

LISA Science

- SO6: Probe the rate of expansion of the Universe :
  - Cosmology from bright sirens: massive black hole binaries;
  - Cosmology from dark sirens: extreme mass ratio inspirals and stellar-origin black hole binaries;
  - Cosmology at all redshift: combining local and high-redshift LISA standard sirens measurements.



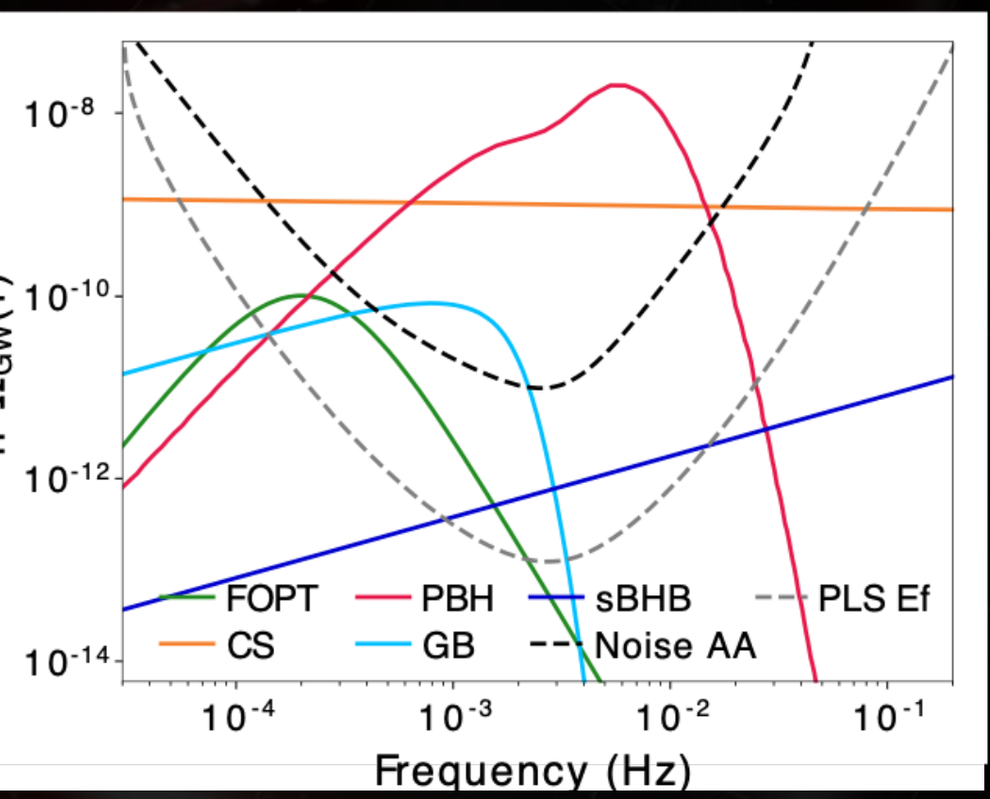


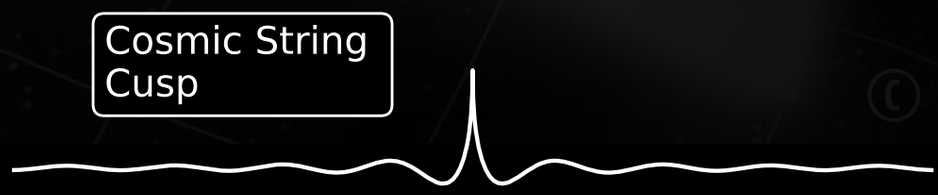
Constraint on the geometry of the Universe:
- No calibration needed
- H_0 to a few % with observations up to $z \sim 3$

LISA Science

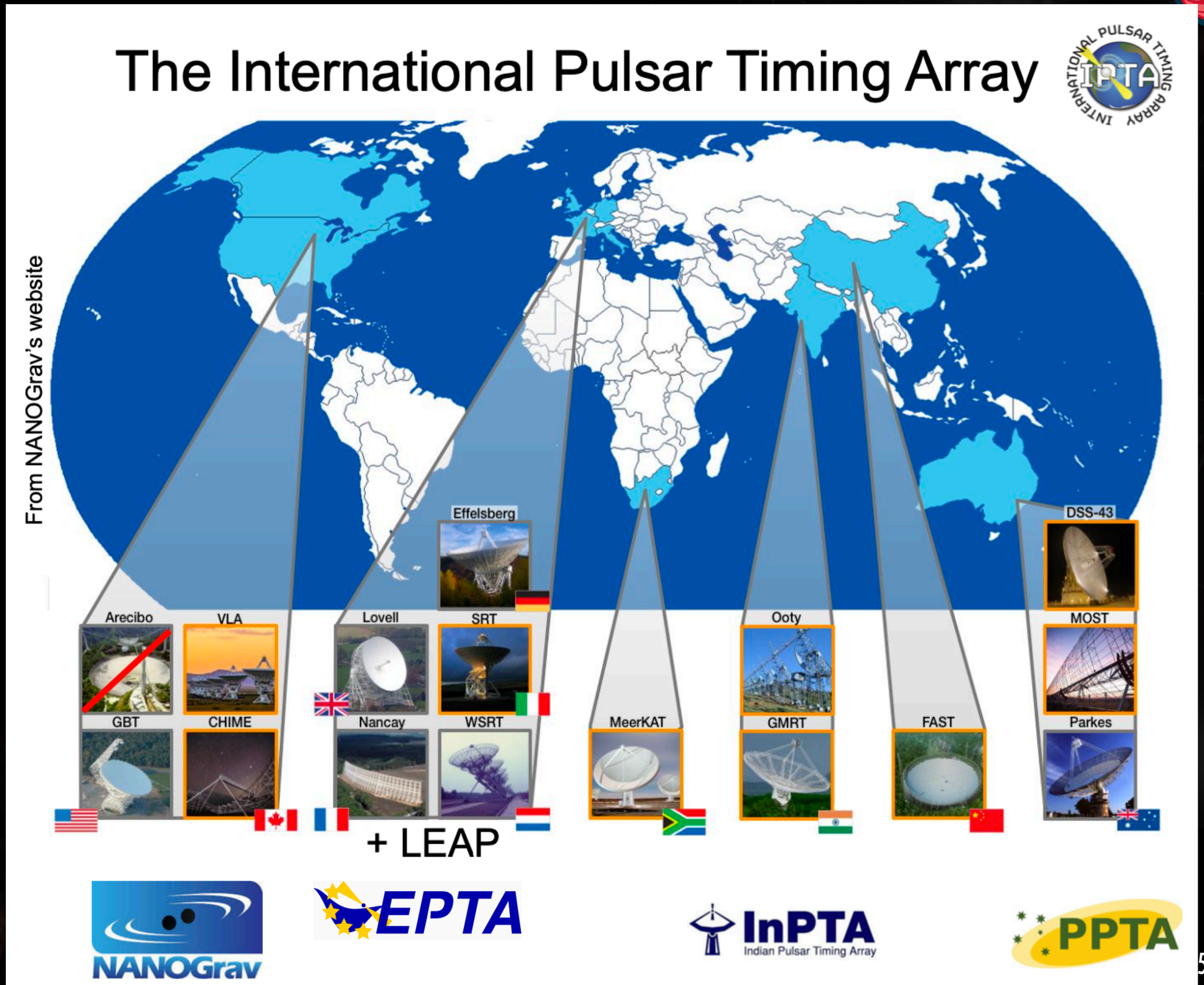
- SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics:
  - Characterise the astrophysical SGWB;
  - Measure, or set upper limits on, the spectral shape of the cosmological SGWB;
  - Characterise the large-scale anisotropy of the SGWB.

- SO8: Search for GW bursts and unforeseen sources :
  - Search for cusps and kinks of cosmic strings;
  - Search for unmodelled sources.





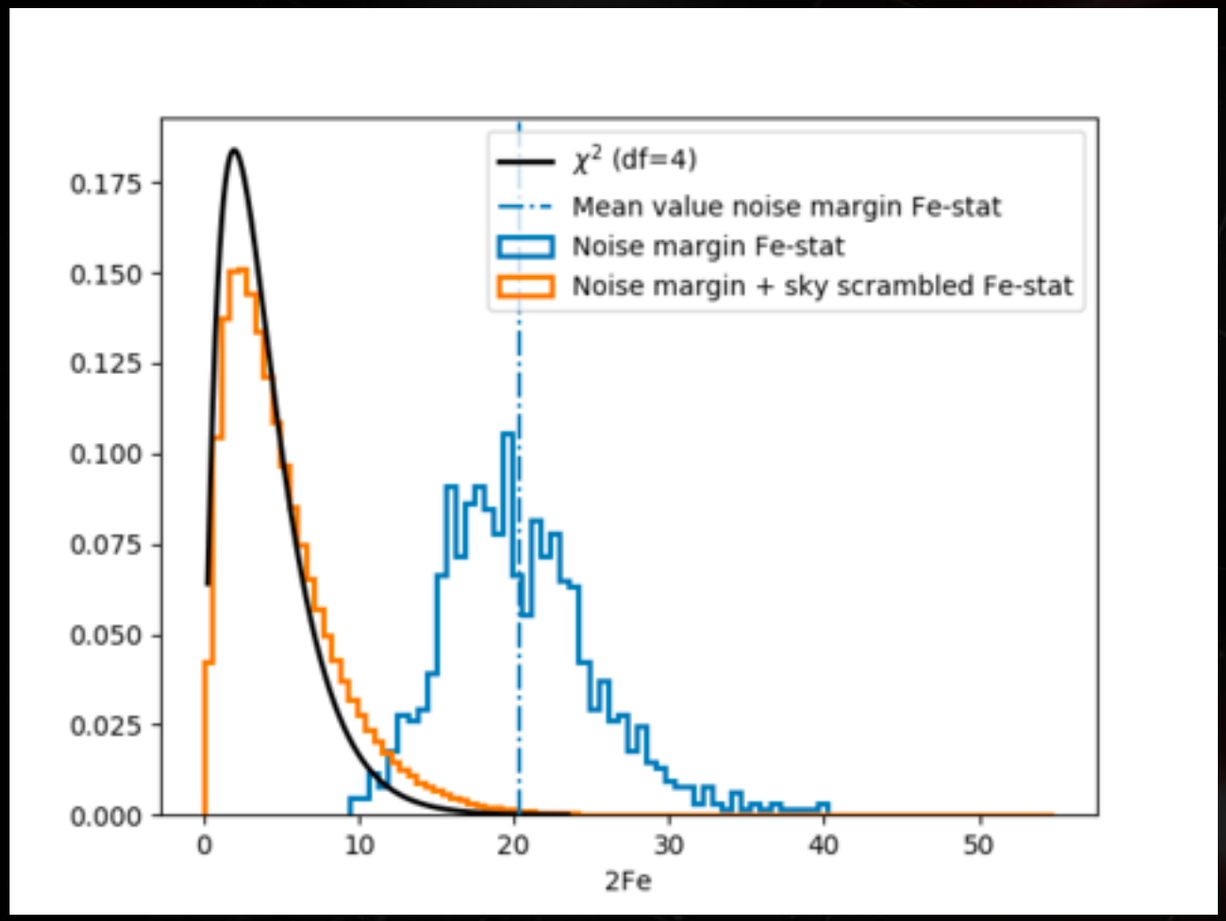
PTA collaborations



EPTA results: GWB

https://arxiv.org/abs/2306.16214

- Scrambling the sky position of pulsar, destroy the signal



- Many other tests see https://arxiv.org/abs/2306.16214

EPTA results: individual sources

https://arxiv.org/abs/2306.16226

- Continuous GW search = Super Massive Black Hole Binary
- GW described by $8 + 2 \times N_{PSR}$ parameters:
  - Amplitude, frequency, chirp mass, sky position, inclination, polarisation, initial phase, phase at pulsar, pulsar distance
- Frequentist analysis:
  - Maximum F-statistic (equivalent to likelihood) at 4.6 nHz