# Gravitational waves

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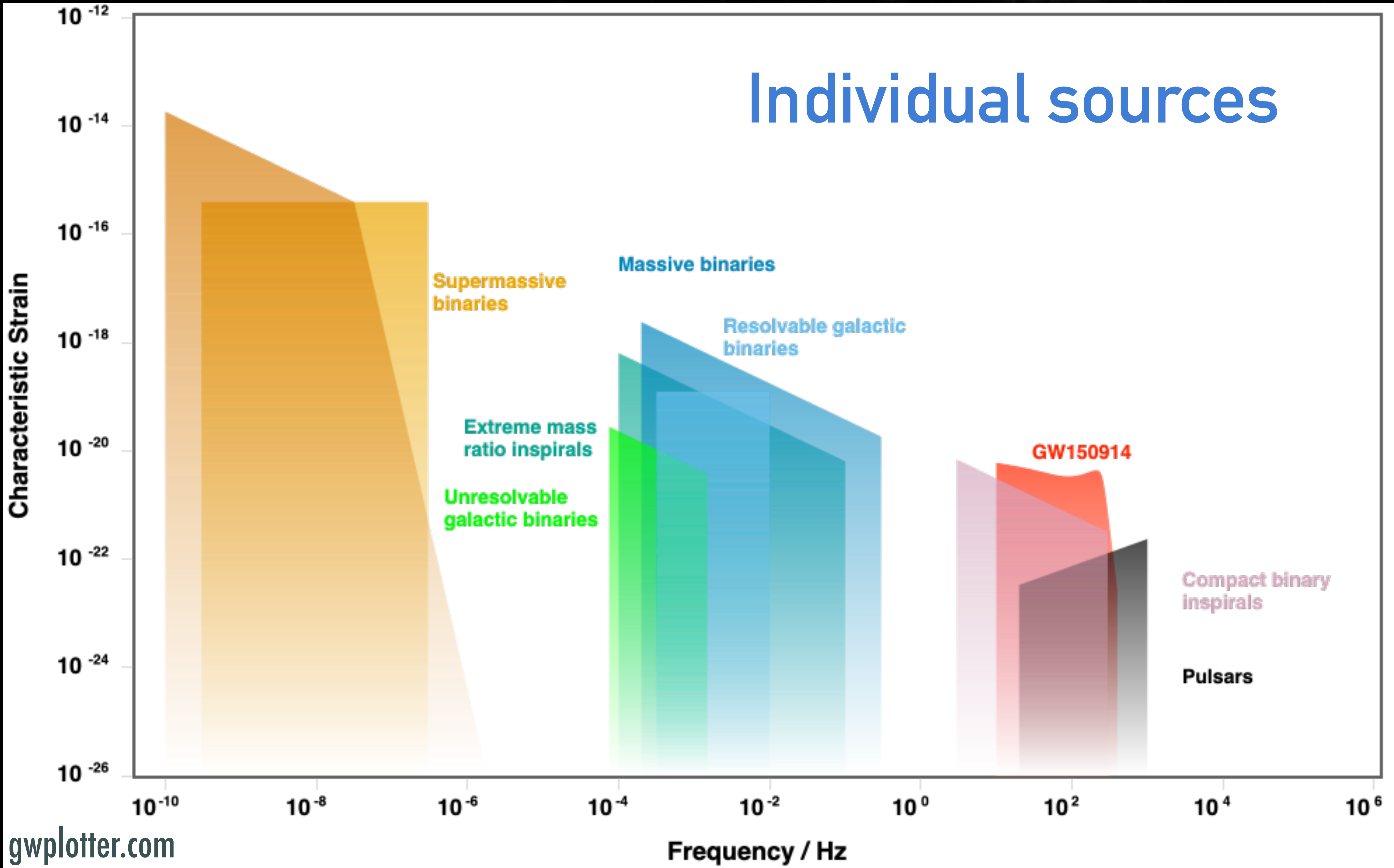
EPS - HEP

Marseille, 11th July 2025

# Outline

- Current observations:
  - LIGO, Virgo, KAGRA
  - Pulsar Timing Array
- Future observatories:
  - Pulsar Timing Array: IPTA, SKA
  - LISA
  - Einstein Telescope, Cosmic Explorer
- Others projects:
  - Space-based GW projects
  - Moon based GW projects
  - Atom Interferometry
  - High frequency

# GW spectrum

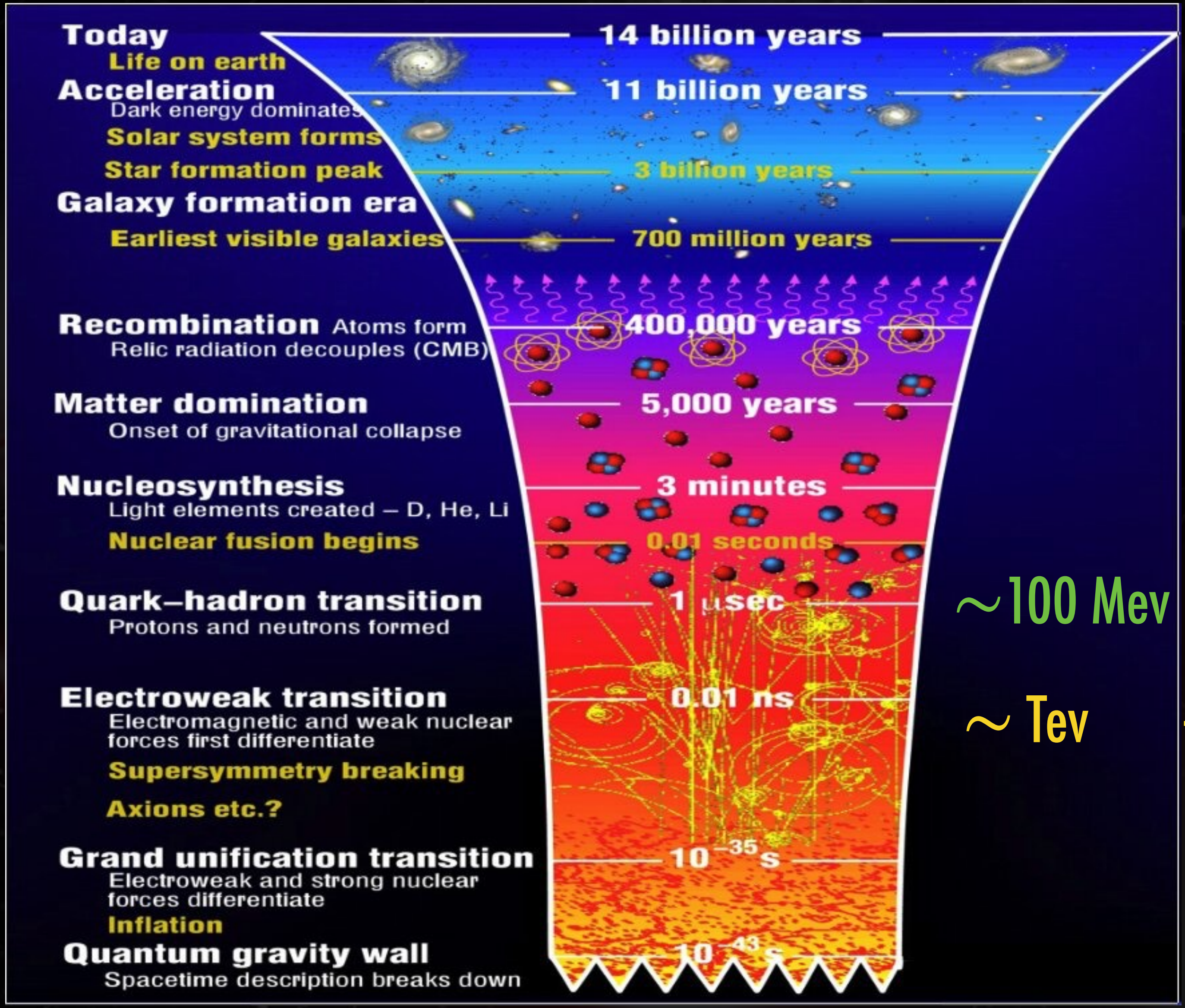



gwplotter.com

# GW spectrum

## Stochastic background(s)

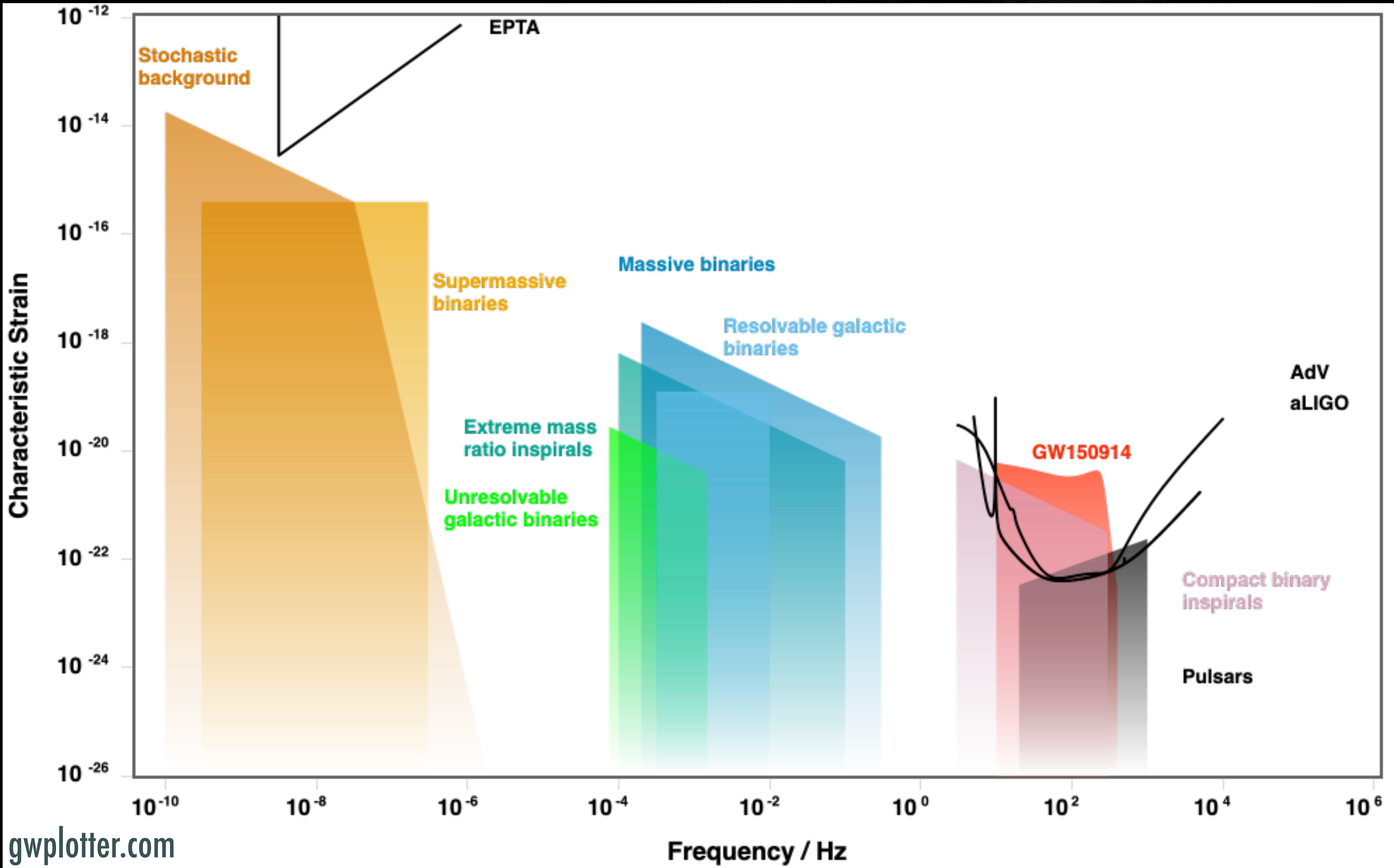
- Confusion of astrophysical sources
- 1st order transition from Early Universe:
  - "bubbles" collisions → GWs (wavelength depending on the size of the Universe at the time of the transition)
  - Main components in models :
    - Bubble collisions
    - Kinetic energy of the turbulent motions and magnetic fields sustained by the MHD turbulence.
  - Caprini et al. 2010, Robert Pol et al. 2022, …
- Cosmic strings
- …




~100 Mev → nHz

~ Tev → mHz

# GW spectrum: current

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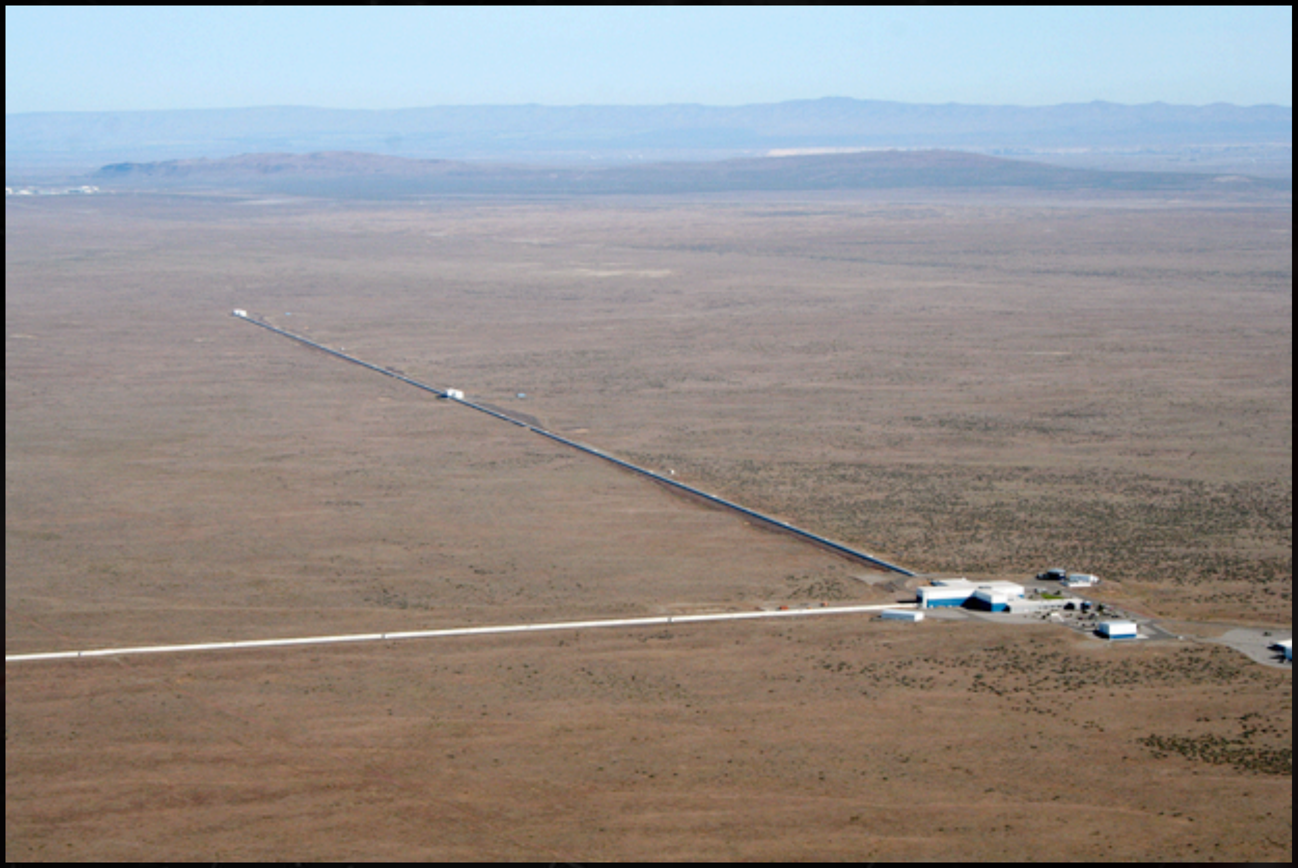
Credit: Virgo collaboration



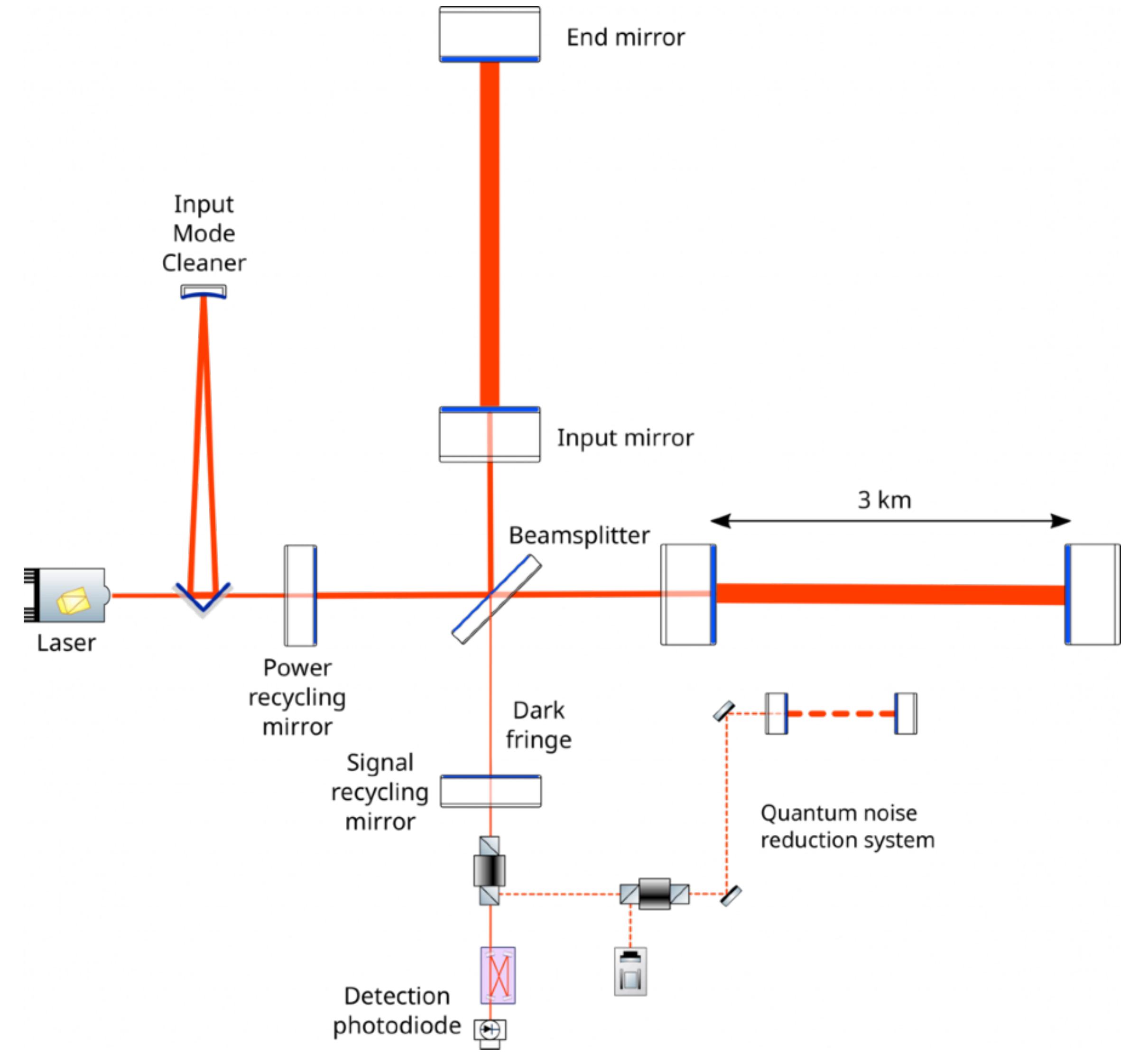
Credit: Caltech/MIT/LIGO Lab

# Ground based Observatories

## LIGO, Virgo, KAGRA

# On ground interferometers

- Improved Michelson interferometers:
  - Fabry-Perot cavities to increase the optical path
  - Recycling of the power
  - Signal recycling
  - Quantum noise reduction
- Other key technologies:
  - Vacuum (~10 000 m$^3$ at 10$^{-9}$mbar)
  - Isolation
  - Mirrors (surface accurate within 5 atoms)
- Where?
  - 2 LIGOs in US
  - Virgo in Italy
  - Kagra in Japan

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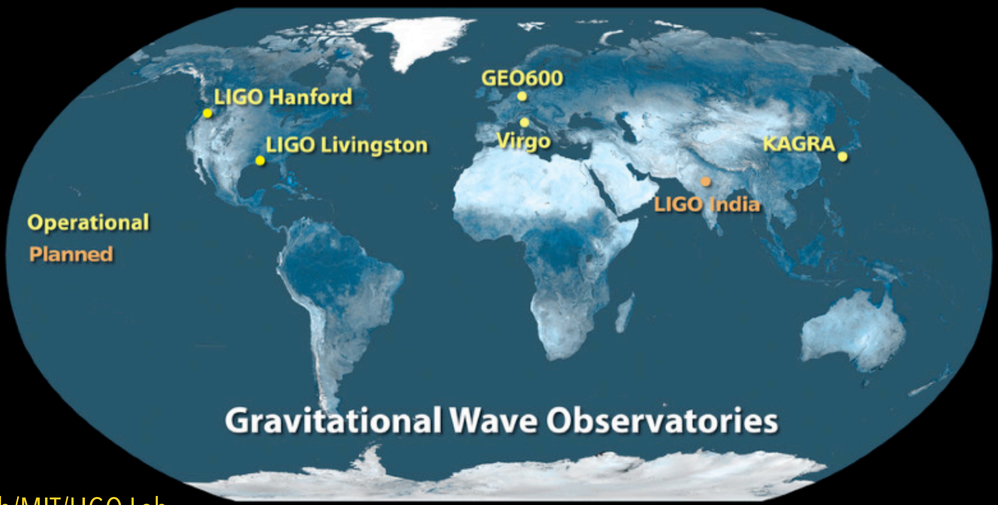
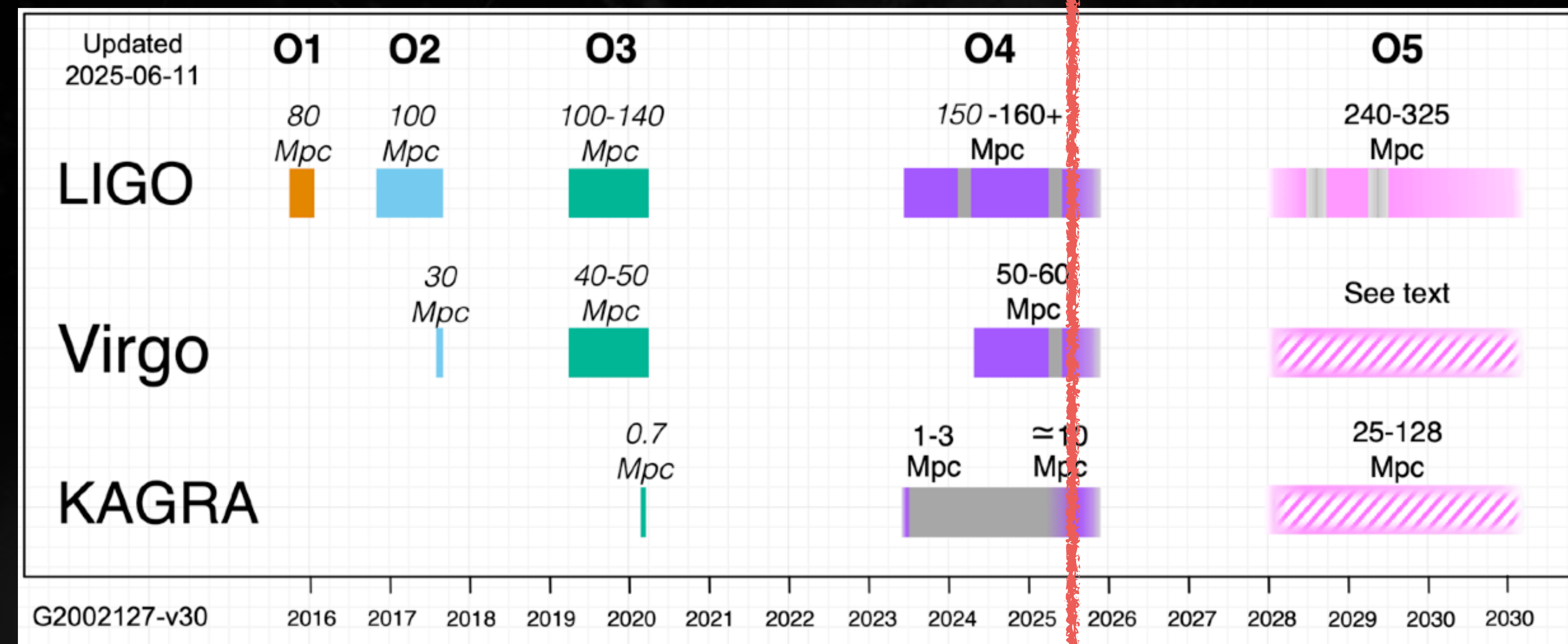
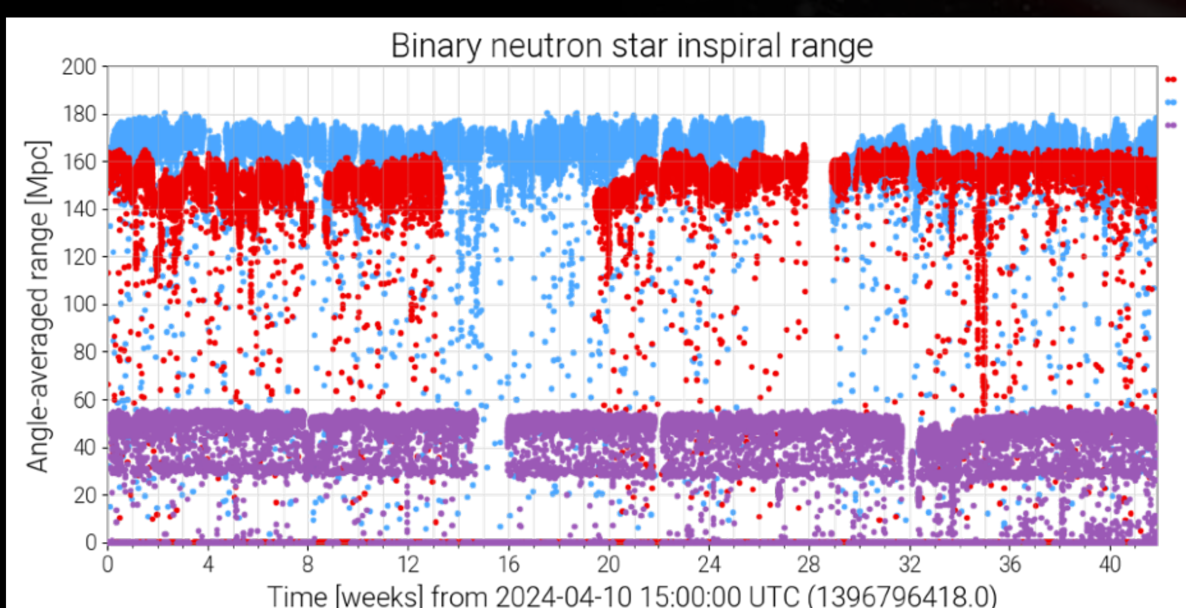


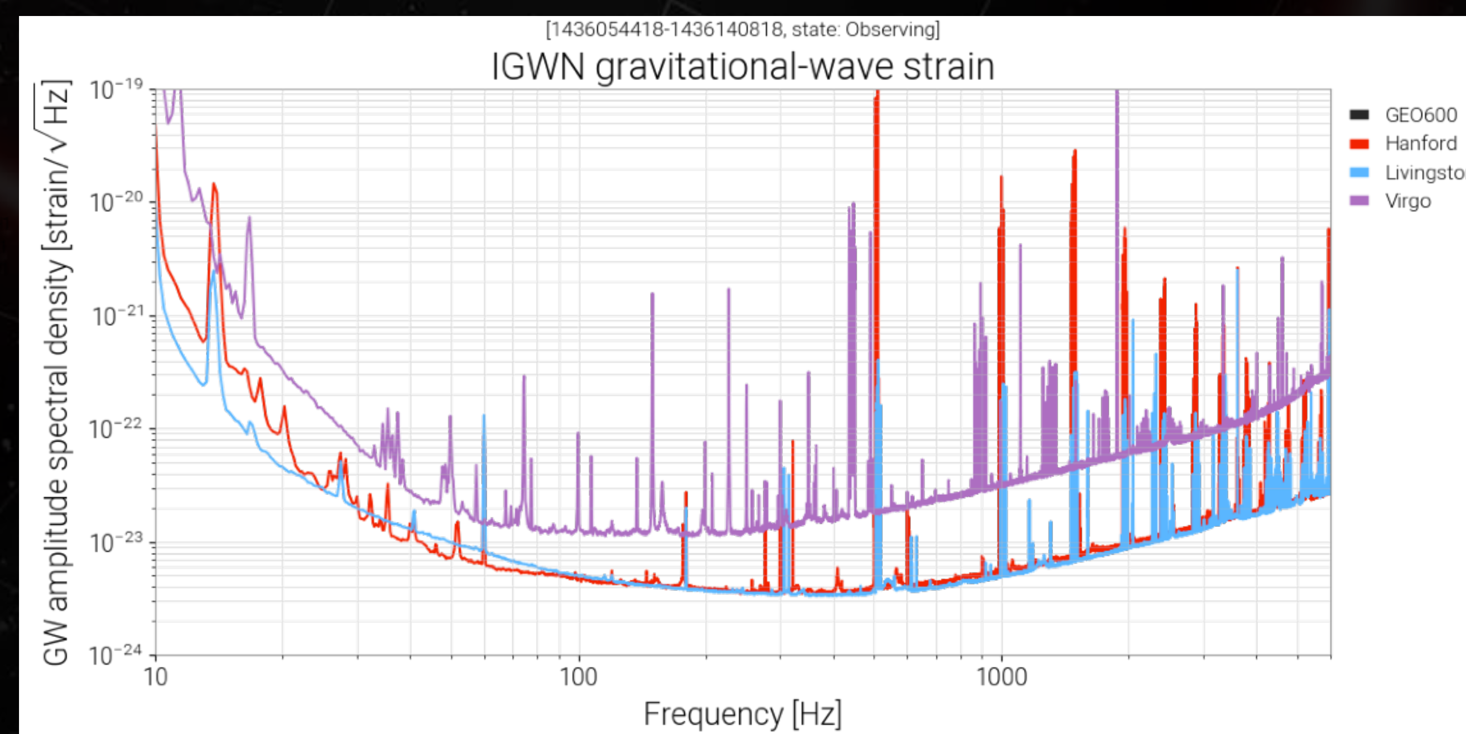

Credit: Caltech/MIT/LIGO Lab

# Sensitivities

- LIGO and Virgo restarted in June
- Sensitivity (horizon for an NS binary):
  - Livingston: 140-160 Mpc
  - Handford: 150 Mpc
  - Virgo: 50 Mpc

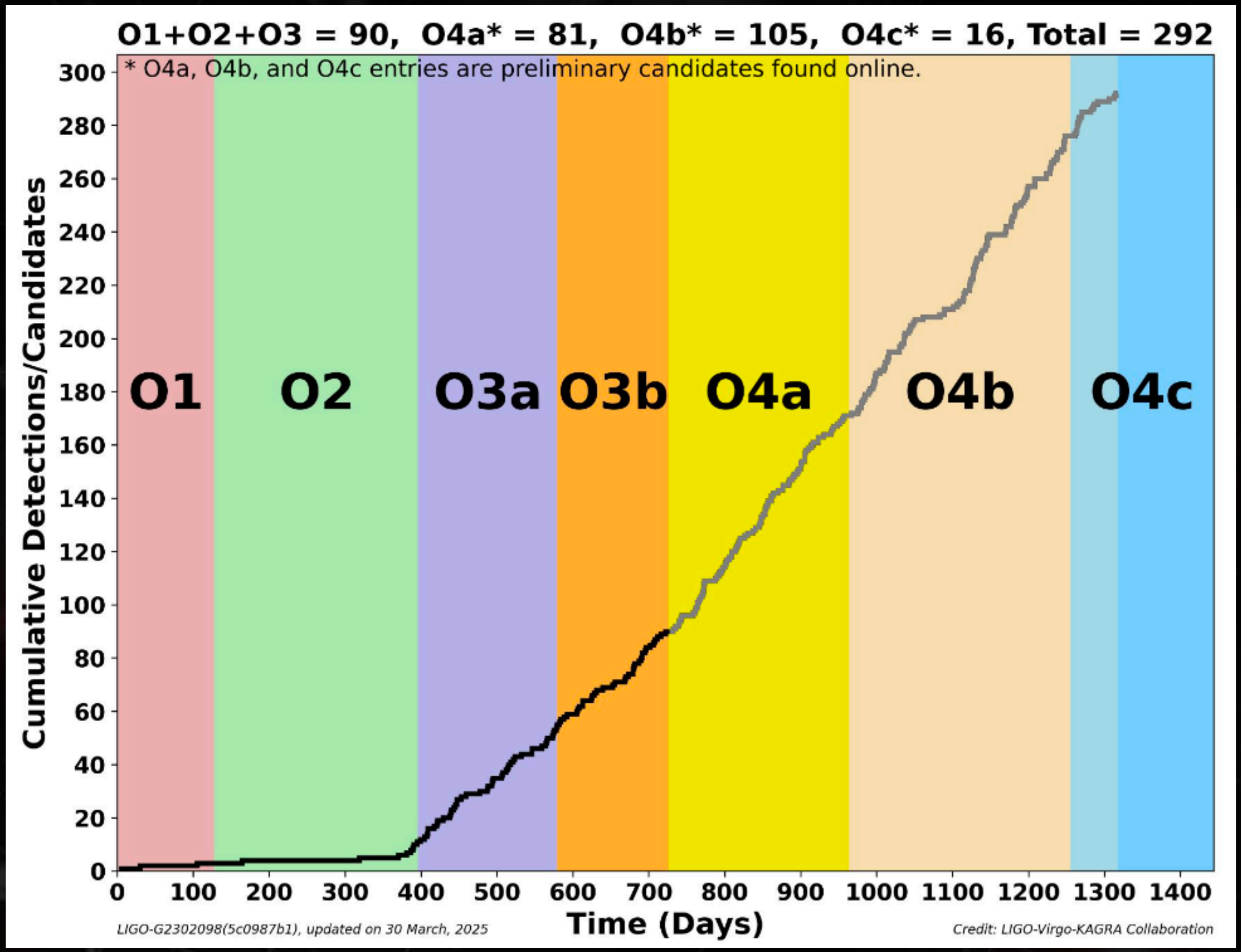


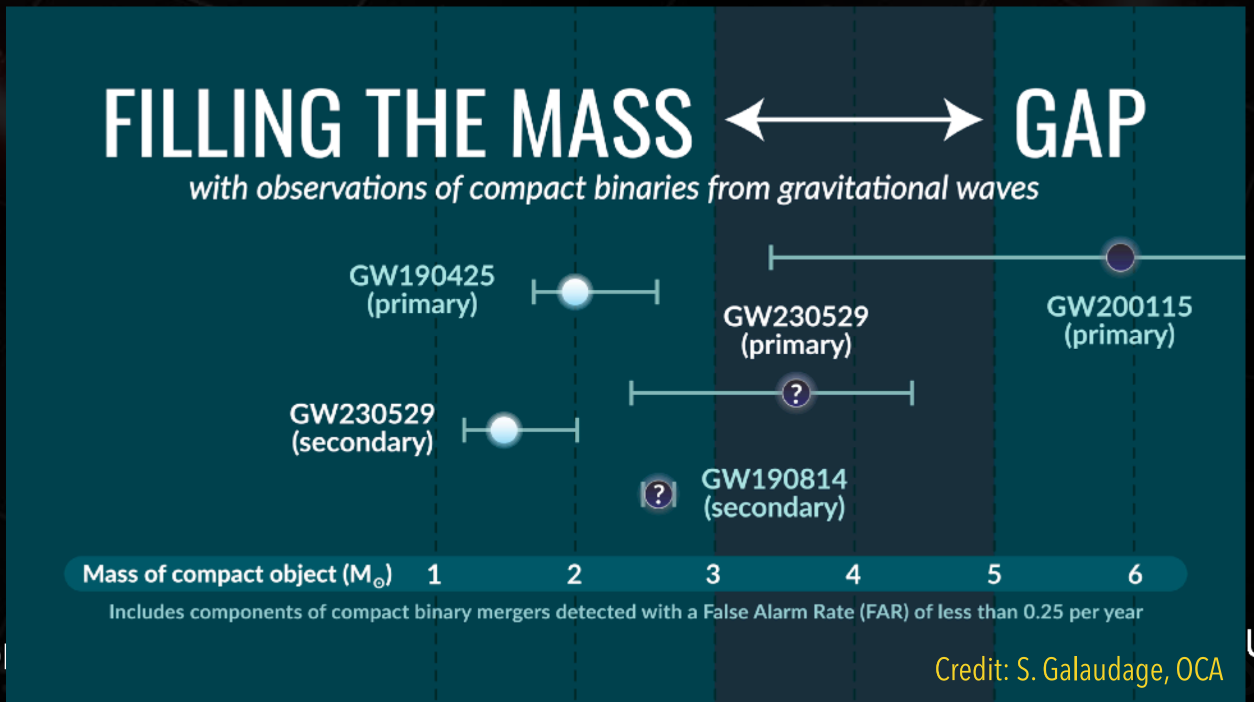



# Results

Credit: LVK collaboration




- Detection:
  - O1+O2: 11 events
  - O3a: 55 events
  - O3b: 98 events
  - O4a: 81 (92 Total - 11 Retracted)
  - O4b : 105 (114 Total - 9 Retracted)
  - O4c: 19 (14 Total - 5 Retracted)
- Type of sources:
  - Mainly stellar mass BH binaries
  - Few neutron star (NS) binaries and NS-BH
- Outstanding detections:
  - First BBH: GW150914
  - First NS-NS (multimessenger): GW170817
  - Highest mass (> 100 $M_\odot$): GW190426
  - First NS-BH: GW200105
- Last public result: GW230529 with a component in the mass gap?




Credit: S. Galaudage, OCA

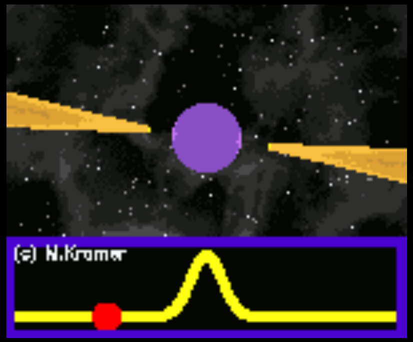
Crédit: MPIfR

# Pulsar Timing Array

## EPTA, NANOGrav, PPTA, CPTA

# Pulsar timing

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



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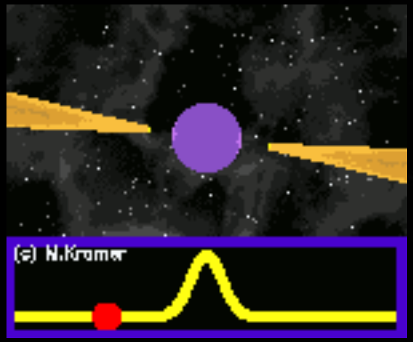

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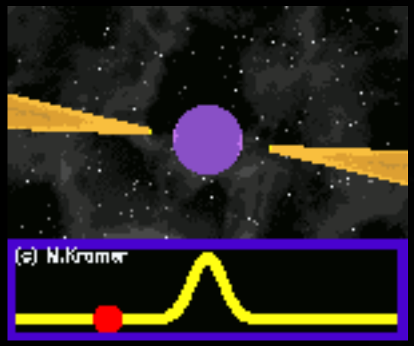
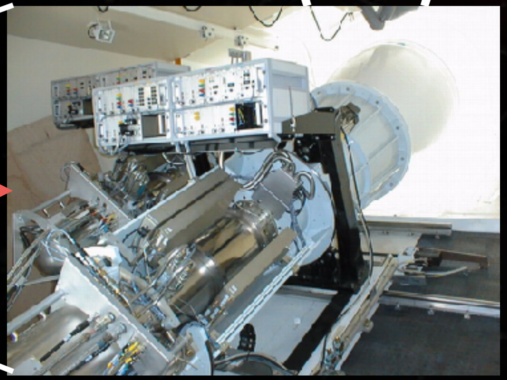



Radiotelescope

Receiver (GHz)



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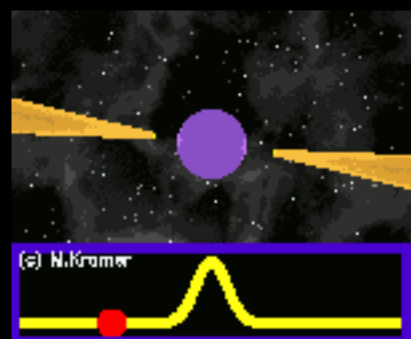


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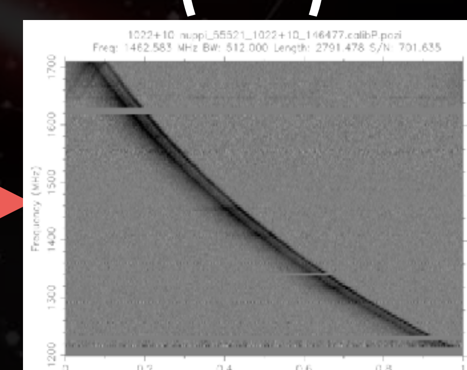
Receiver (GHz)

Coherent dedispersion (GPU)



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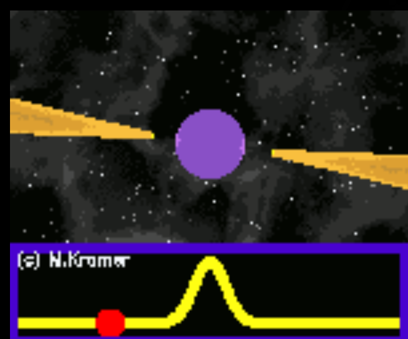


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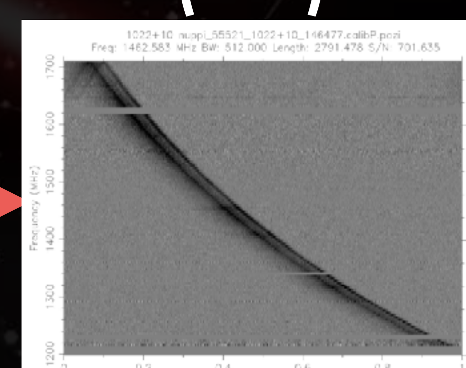
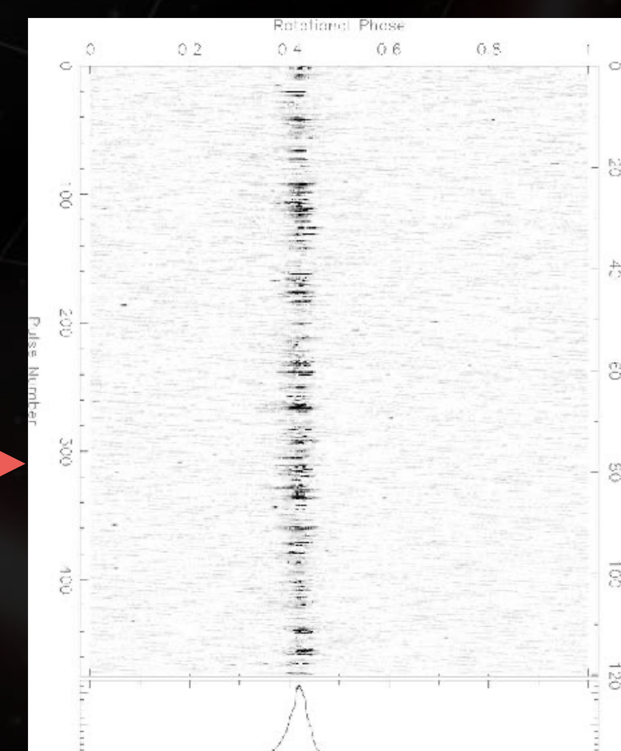


Folding



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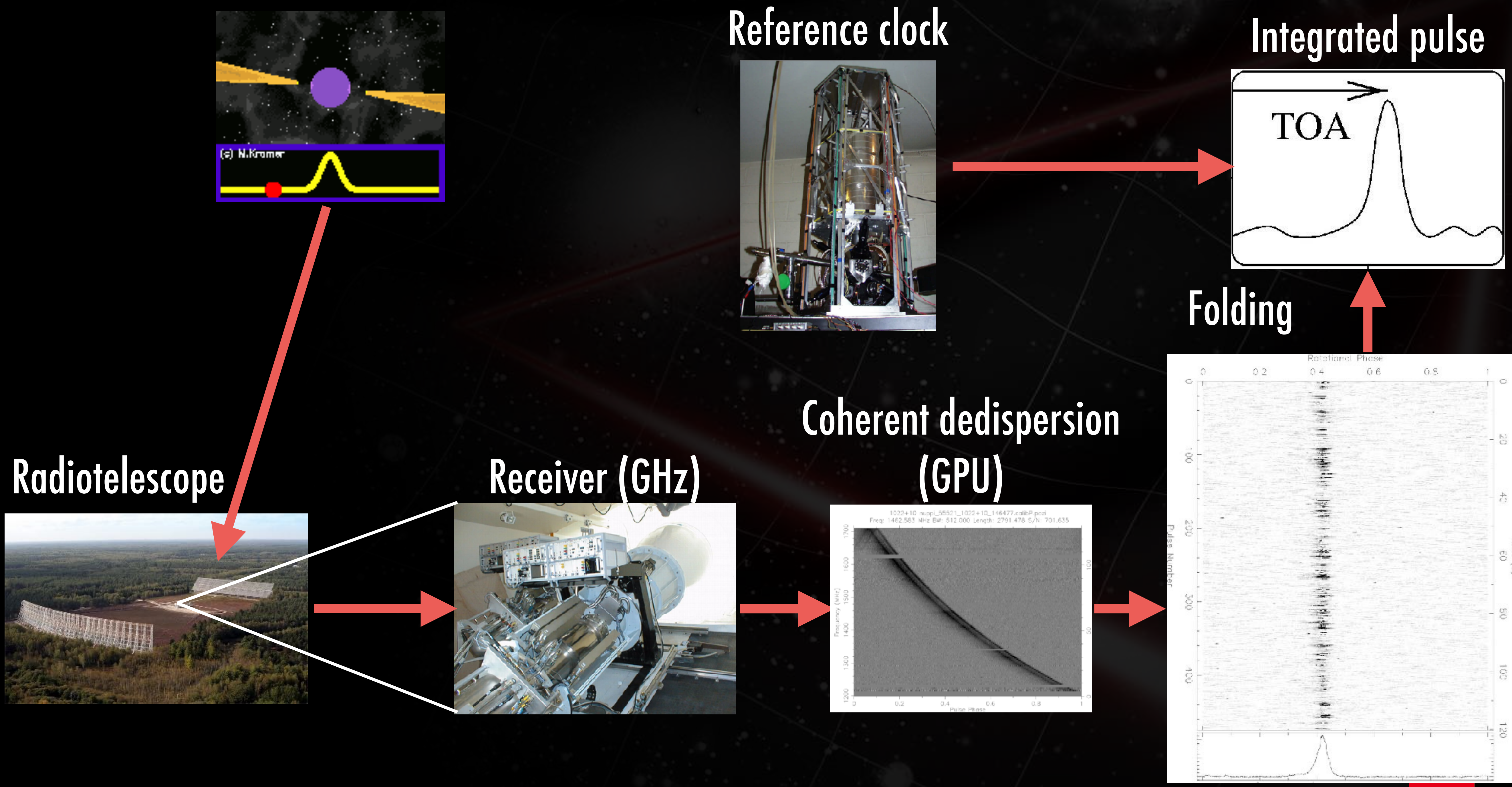

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    - period,
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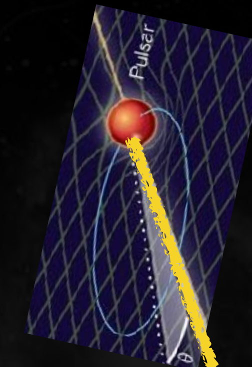


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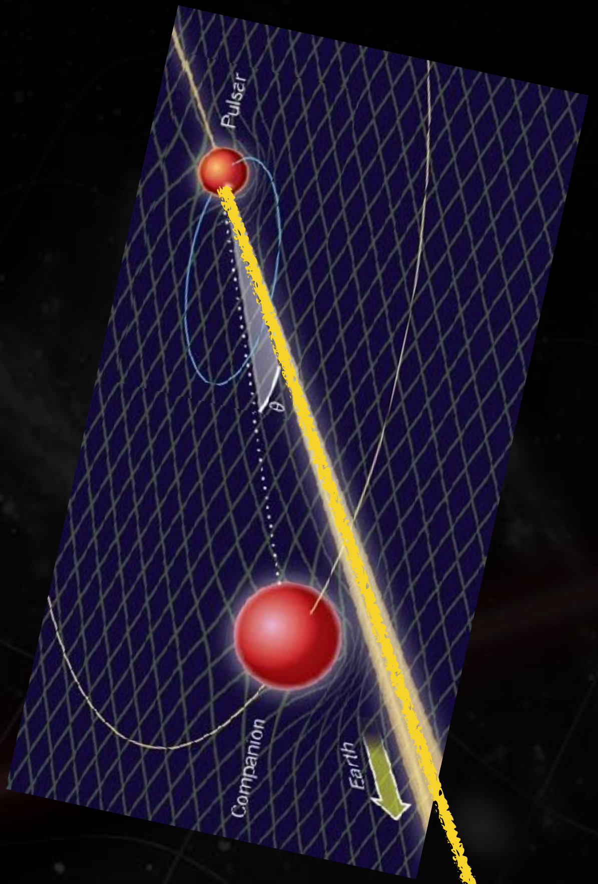


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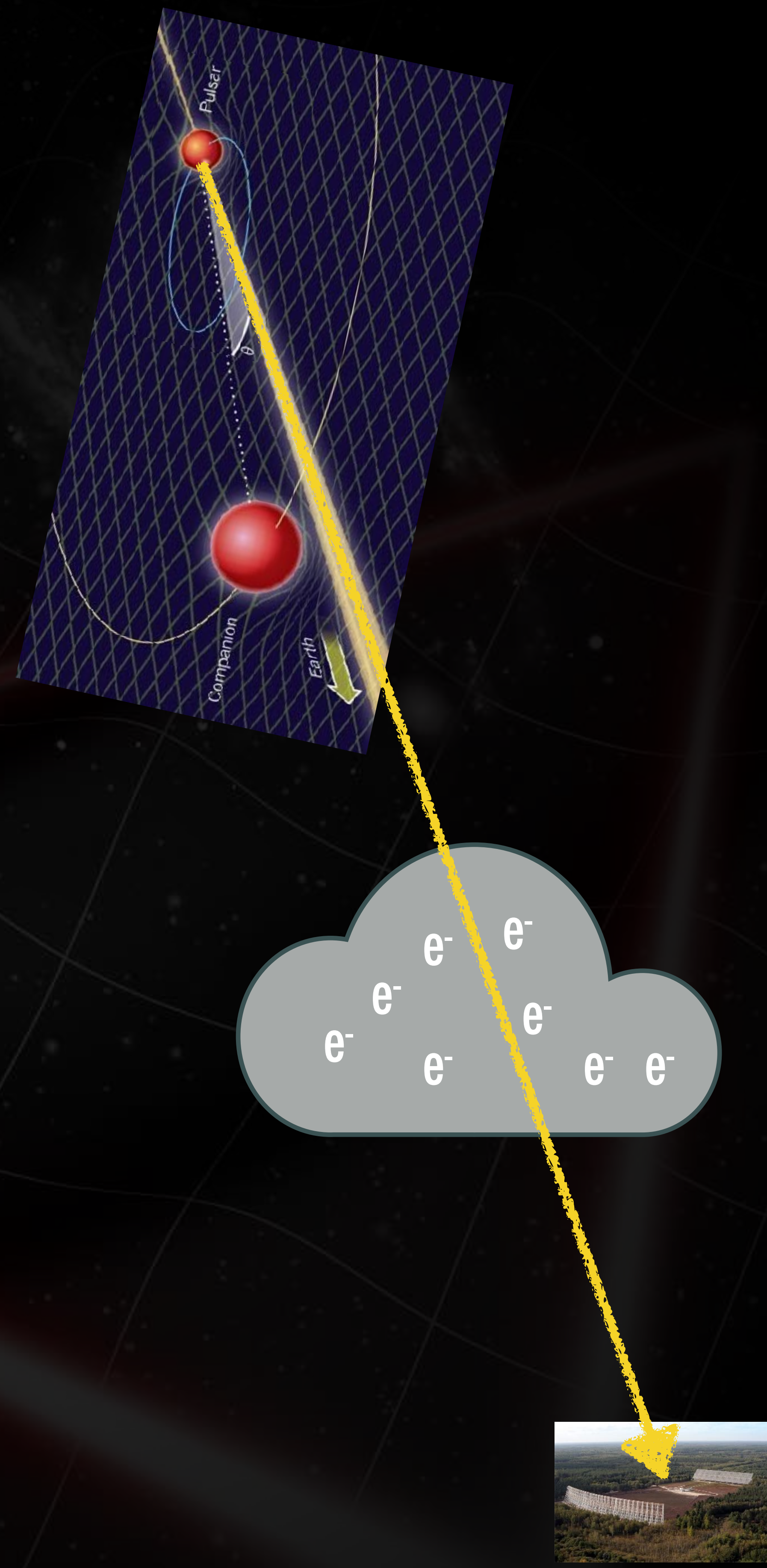

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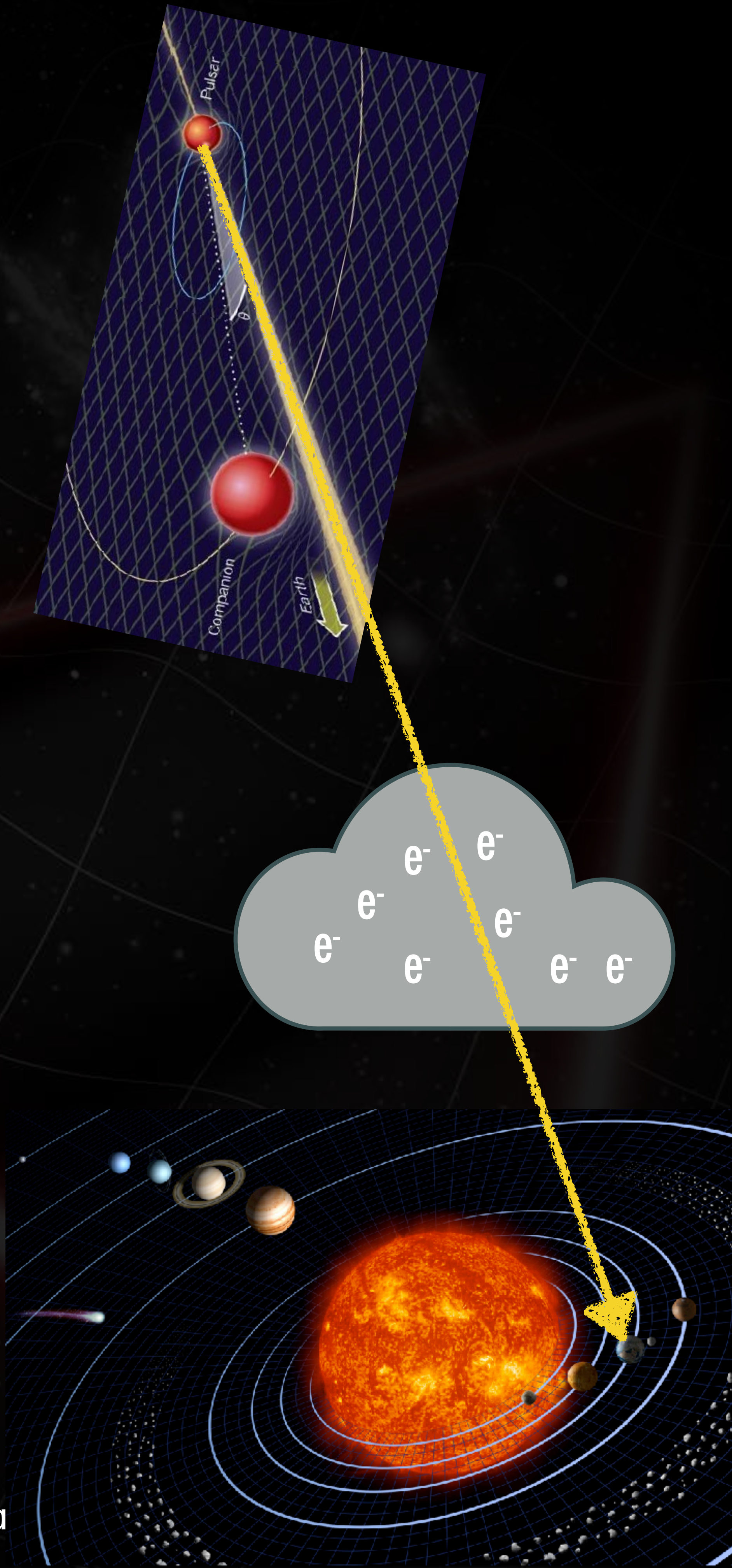

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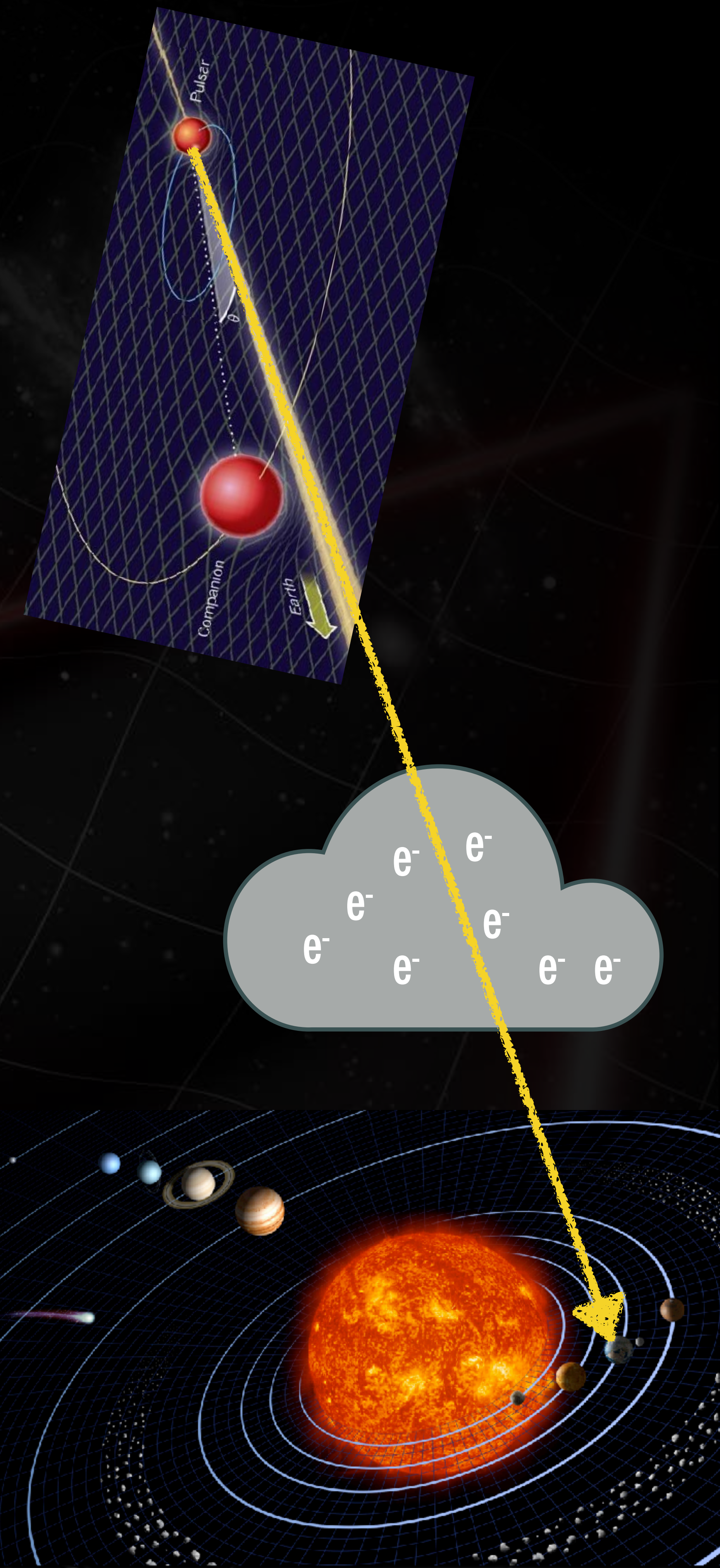

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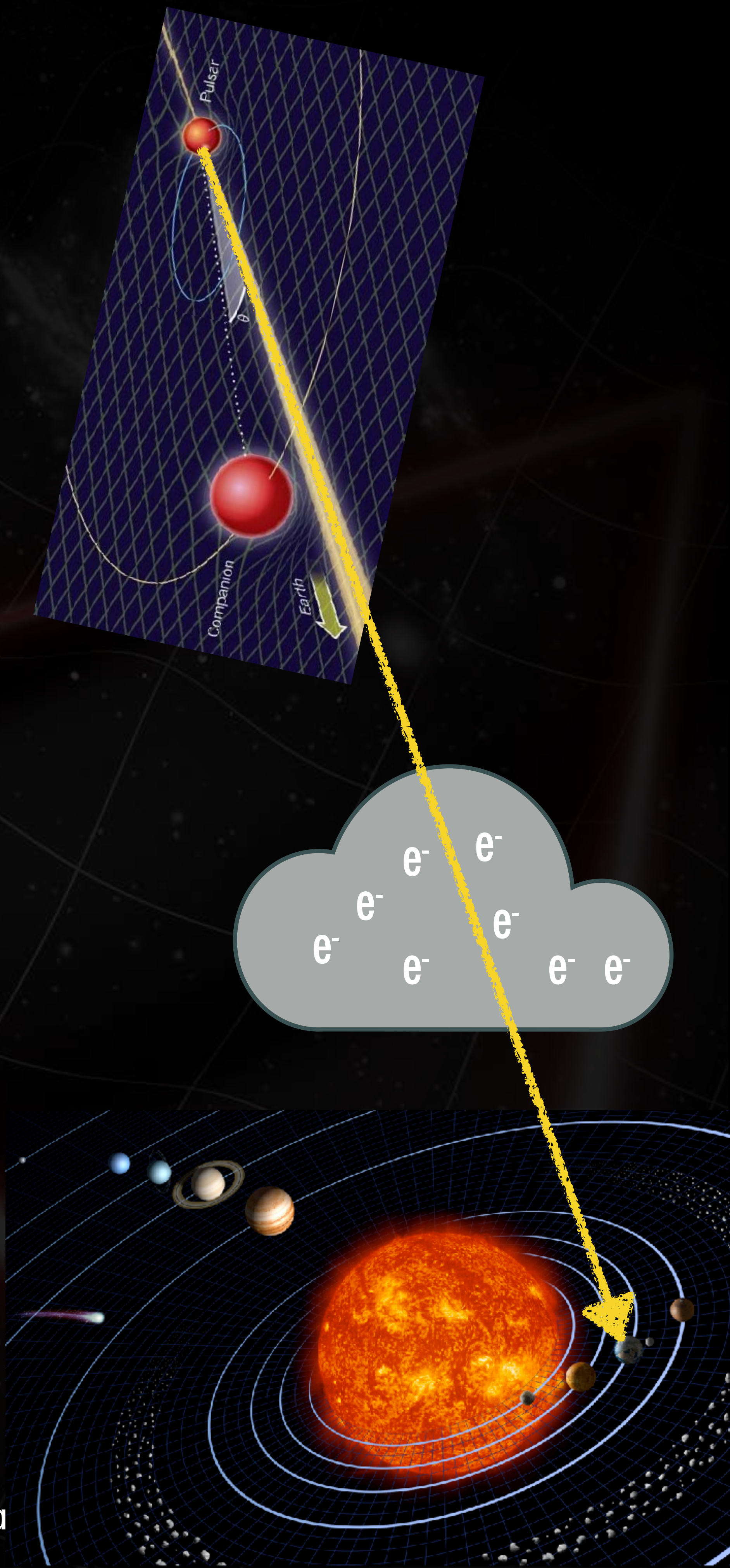
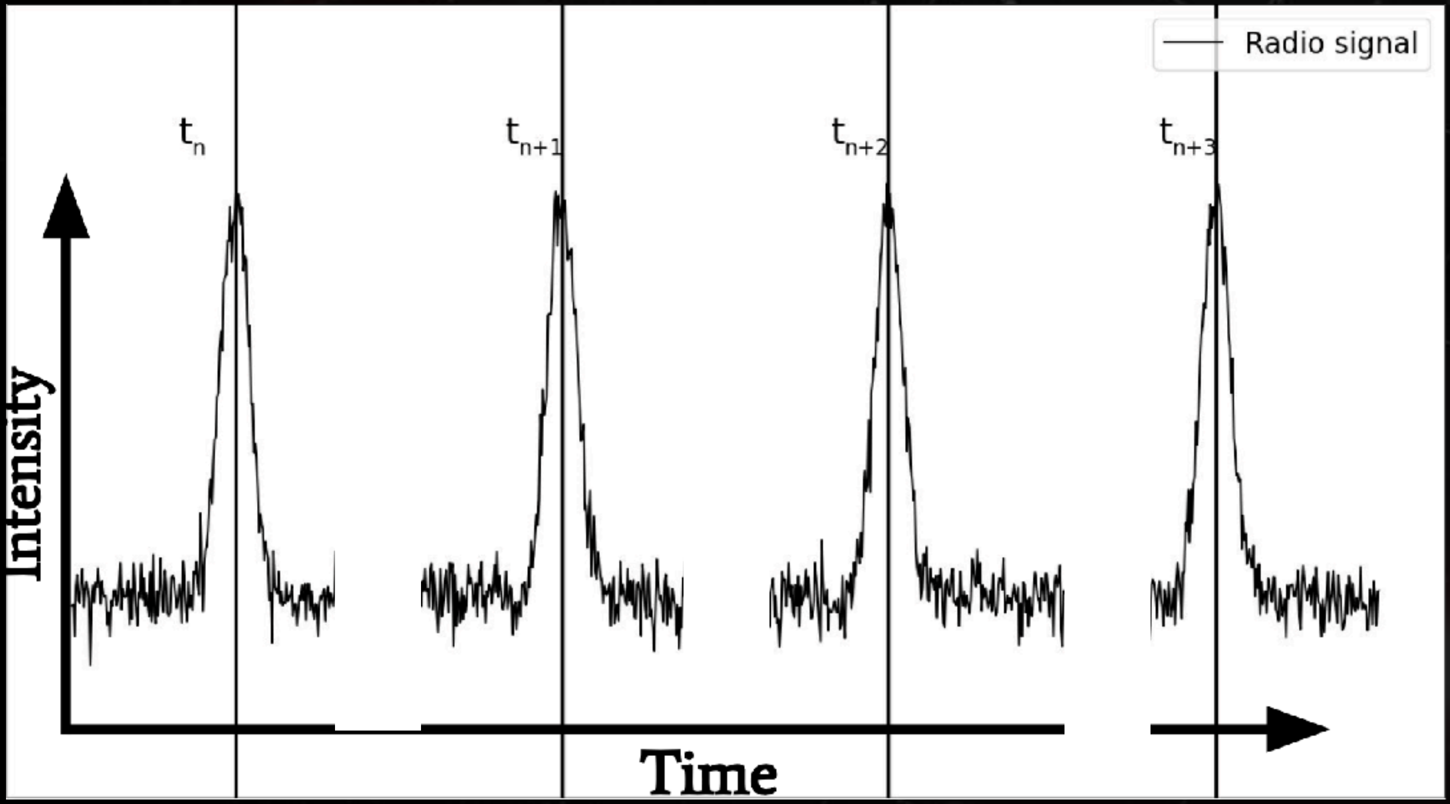
  - Beam propagation: interstellar medium
  - Earth position (ephemerides of the Solar System)
  - Gravitational waves …
- Modelling of each pulsars

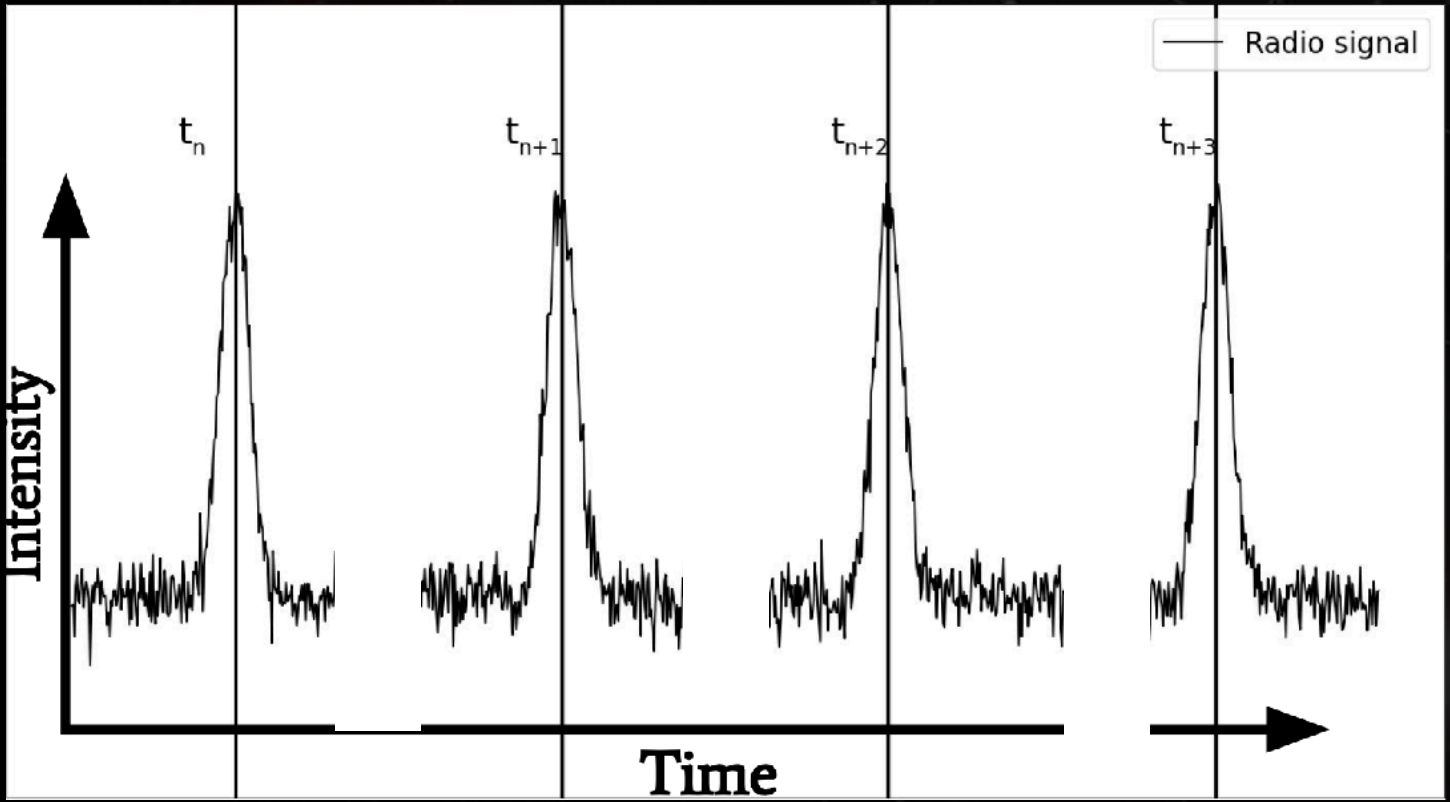


# Pulsar timing and GWs



# 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



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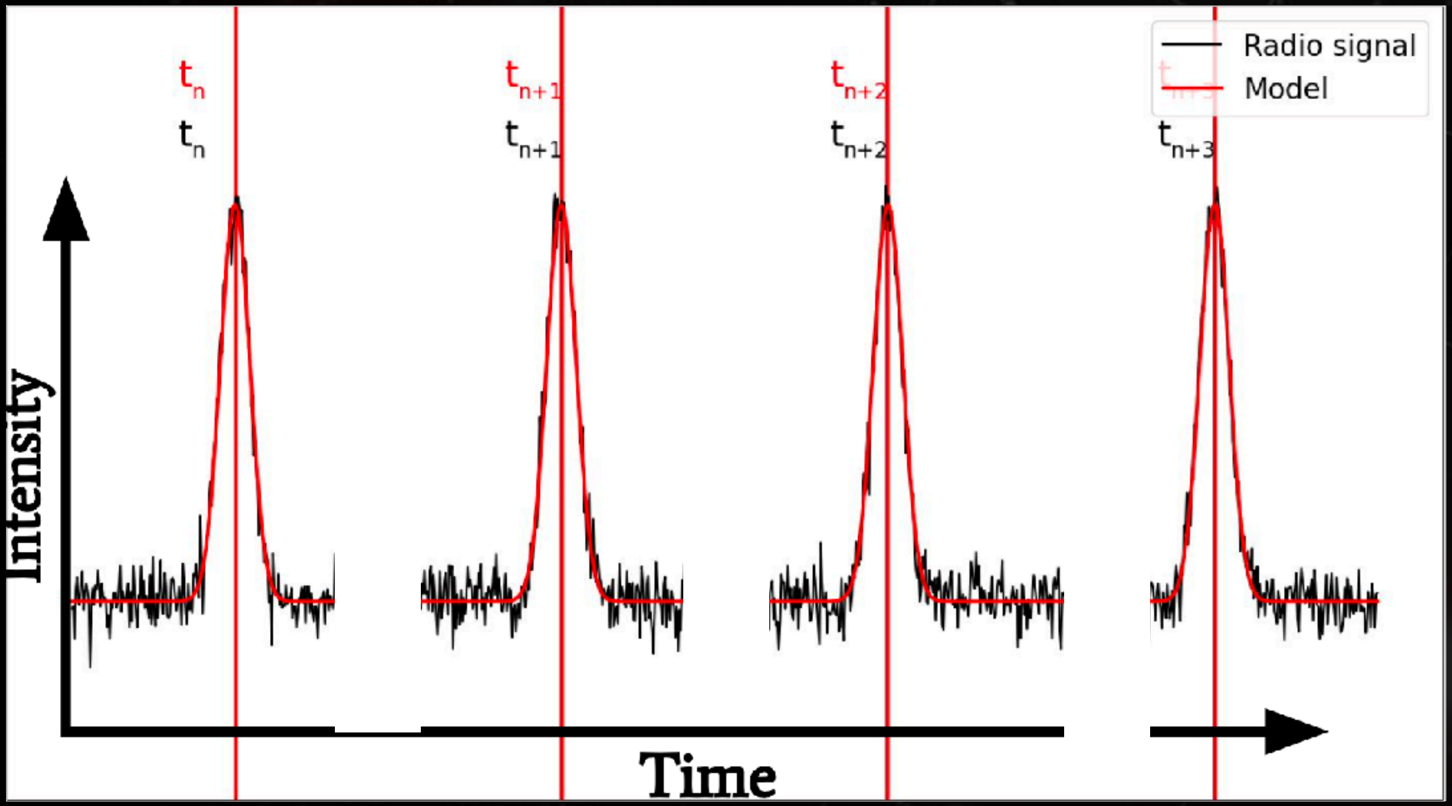
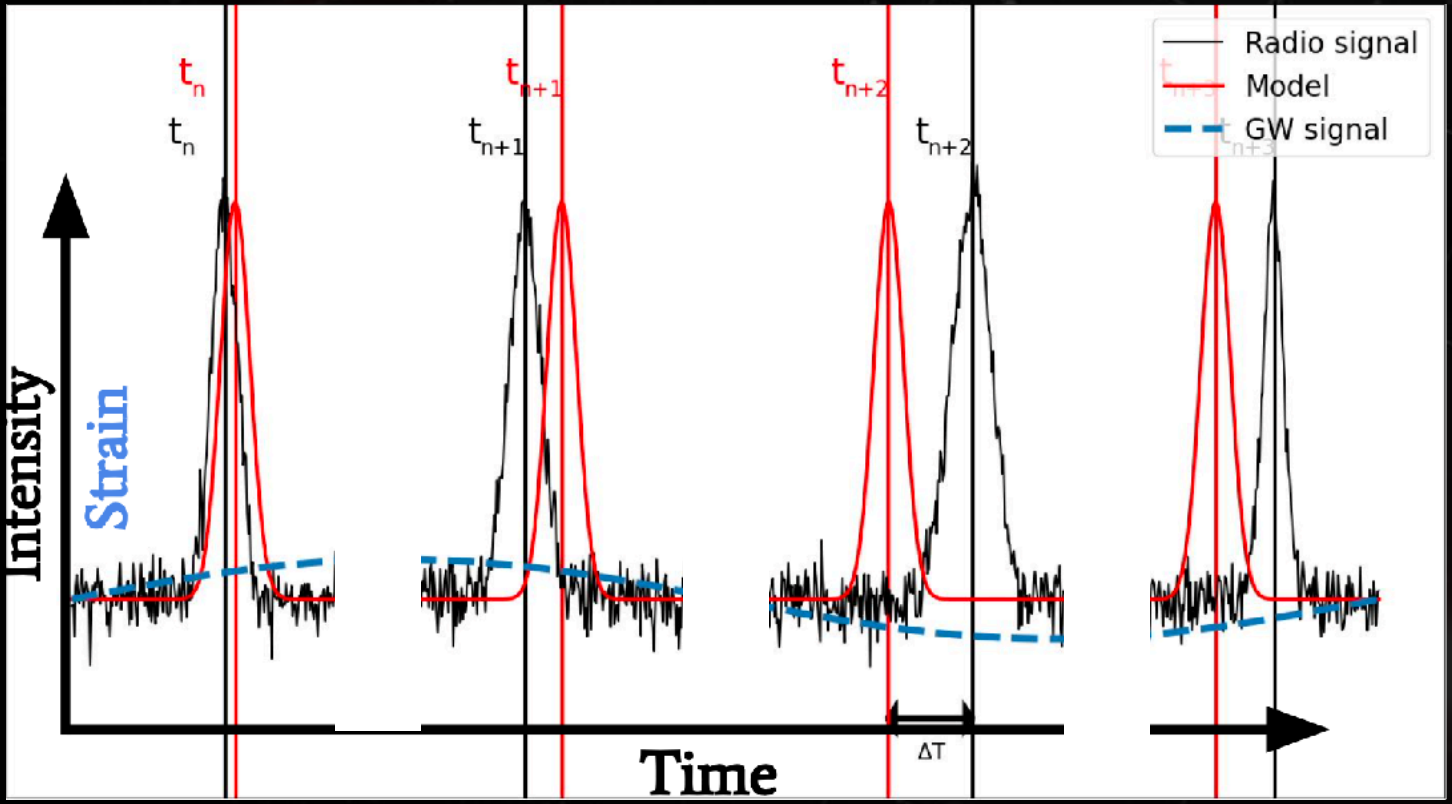


# Pulsar timing and GWs

- 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

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

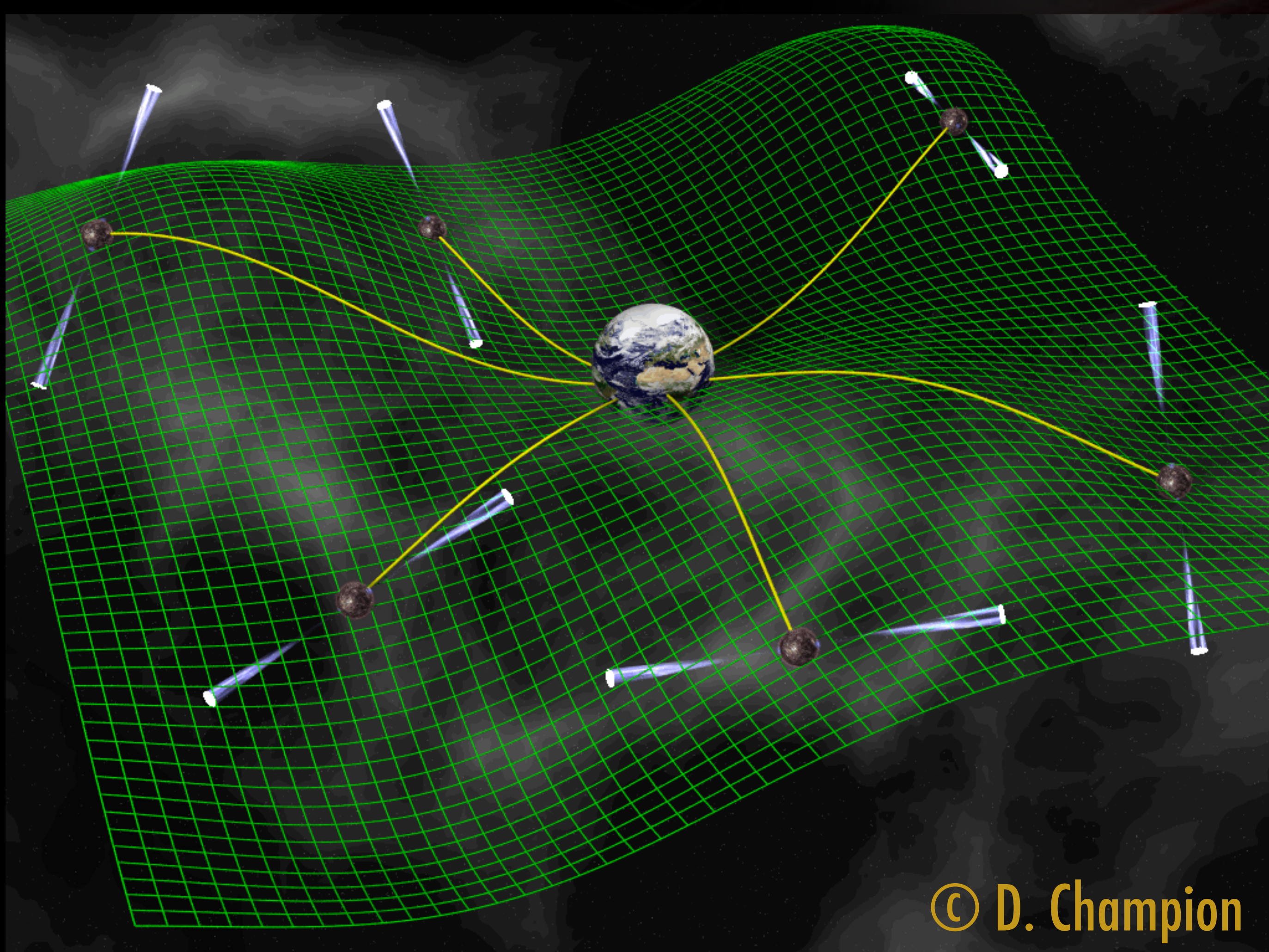
Emission & reception times of pulses

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

Pulsar & GW source sky location

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

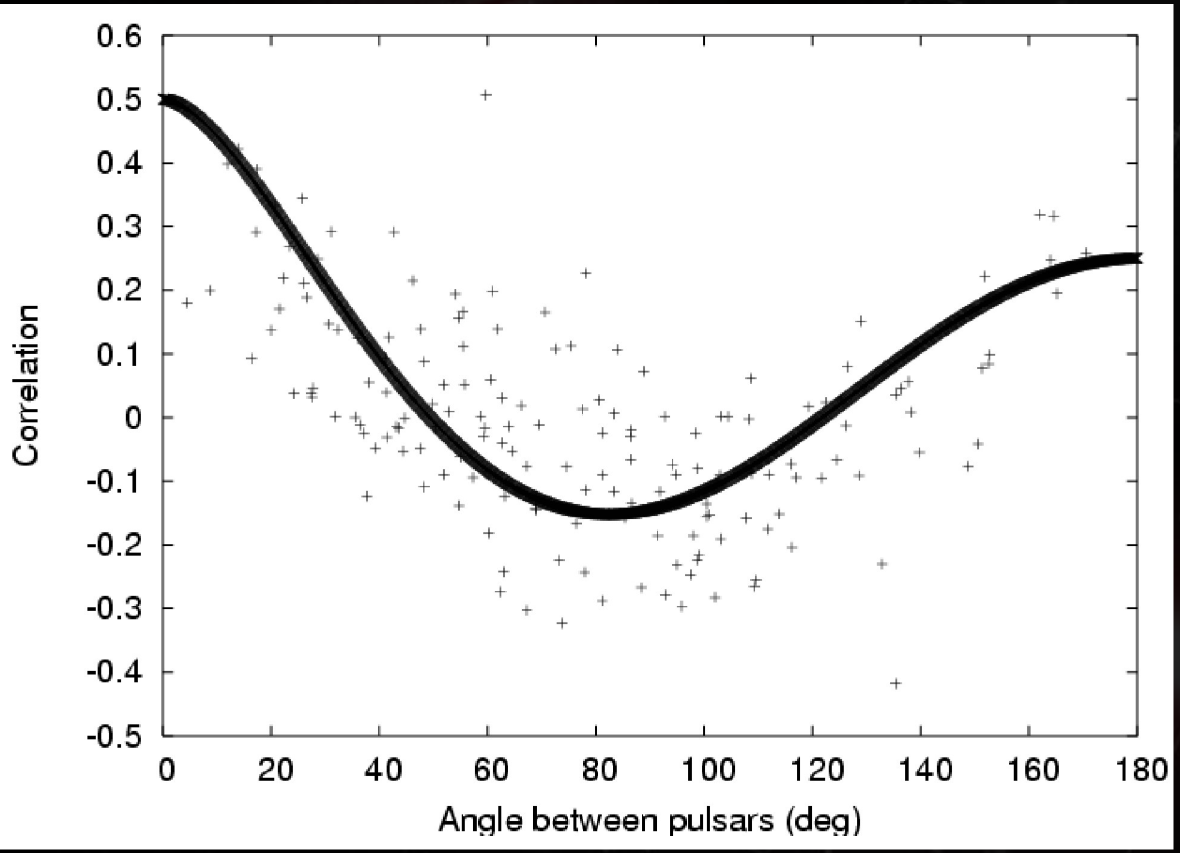
GW characteristic strain



# Pulsar timing and GWs

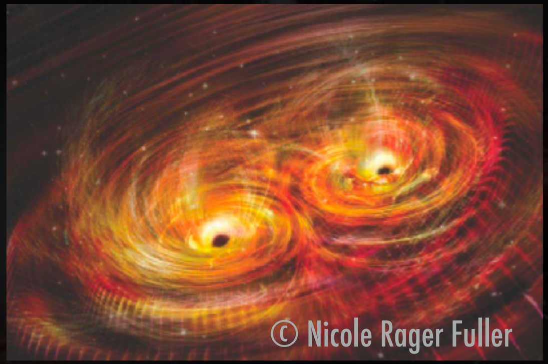
- For an isotropic GW background, characteristic spatial correlation: Hellings-Down curve: specific relation between correlation of 2 pulsar and their angular separation => signature of GW Background

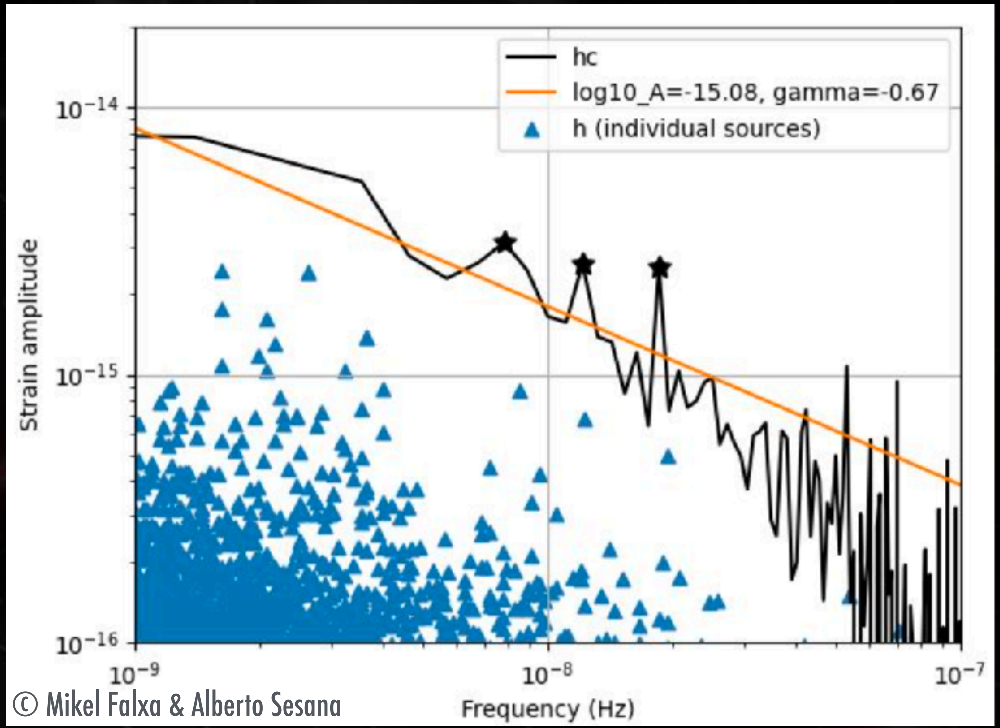
$$\Gamma_{\mathrm{GWB}}(\zeta_{IJ}) = \frac{3}{2}x_{IJ}\ln x_{IJ} - \frac{x_{IJ}}{4} + \frac{1}{2} + \frac{1}{2}\delta x_{IJ} \qquad \text{with} \qquad x_{IJ} = [1-\cos(\zeta_{IJ})]/2$$



# 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

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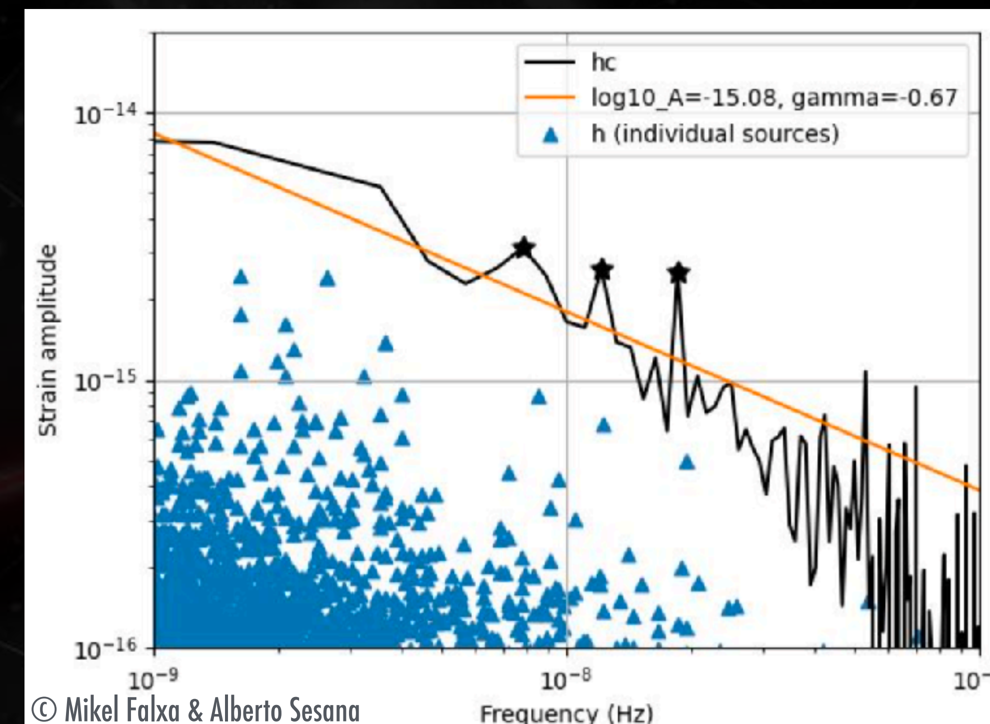
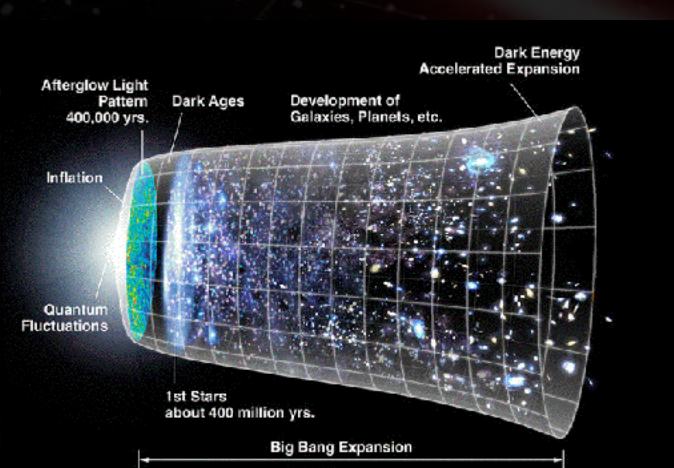



- Stochastic background from cosmological origin:
  - First order phase transition (QCD)
  - Cosmic strings
  - Primordial GWs
  - …

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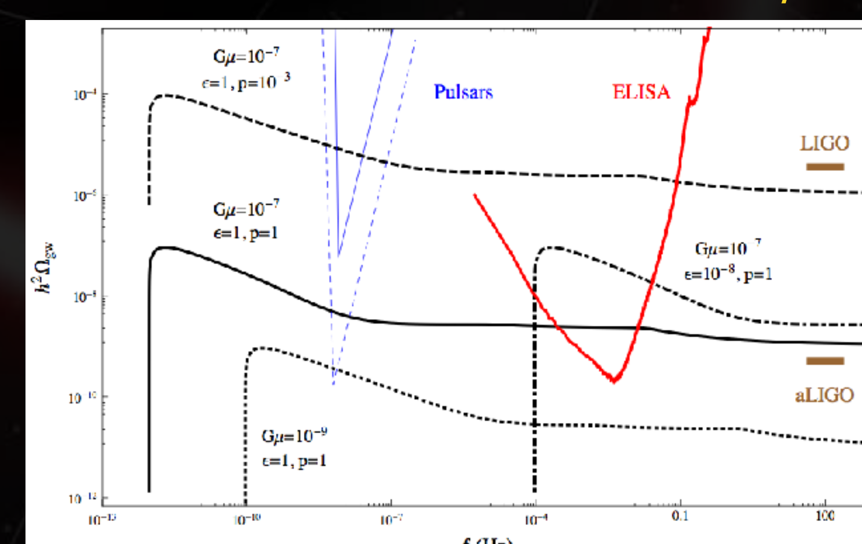
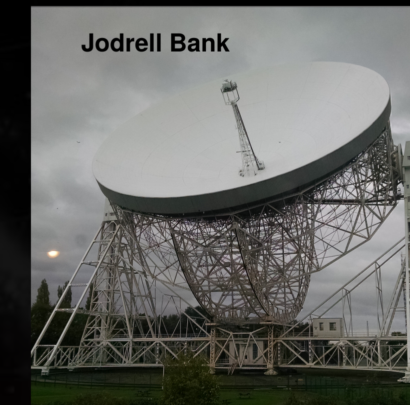


# PTA collaborations

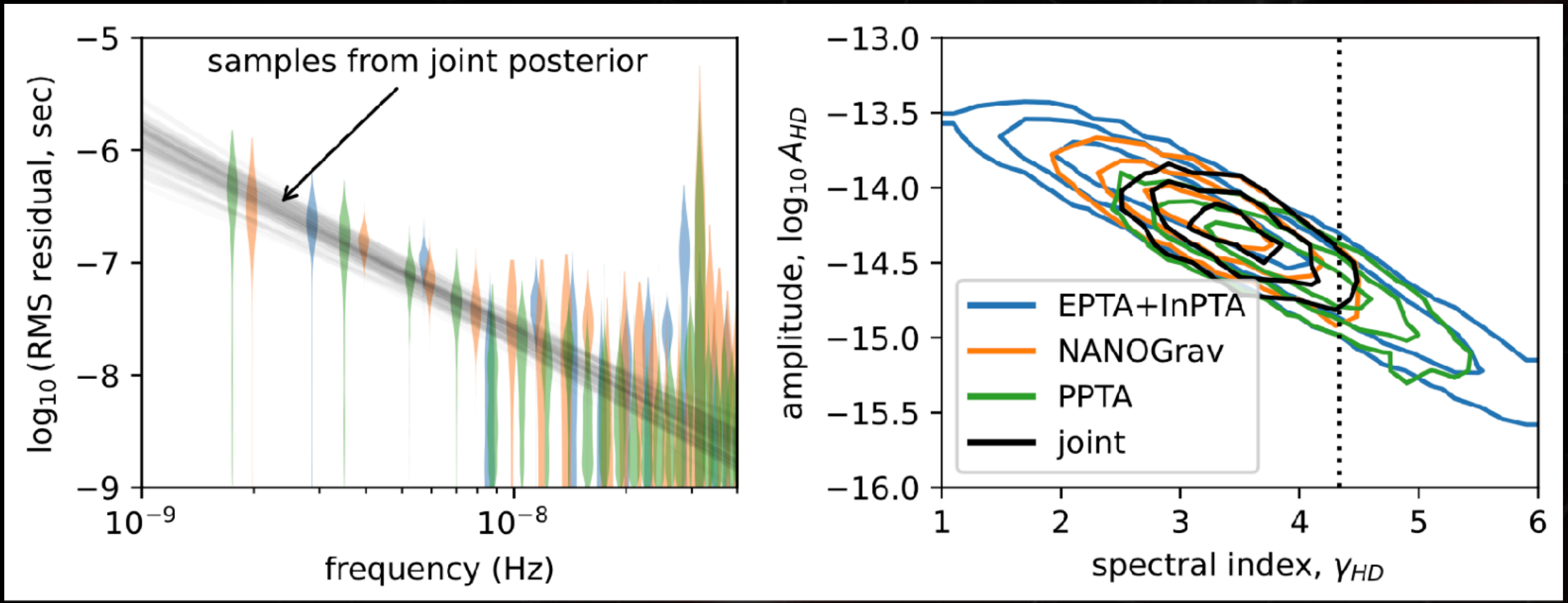
- 3 "historical" collaborations:
  - EPTA (Europe):
    - Nancay RT (FR),
    - Effelsberg RT (G),
    - Jodrell Bank Obs. (UK),
    - Westerbork Synthesis RT(NL),
    - Sardinia RT (I).
  - PPTA (Australia)
    - Parkes radiotelescope
  - NANOGrav (USA):
    - ~~Arecibo~~
    - Green Bank
    - CHIME
- Recent collaborations:
  - InPTA: GMRT, ORT (Inde)
  - CPTA: FAST, … (Chine)
  - APT (African Pulsar Timing): MeerKAT
- Worldwide collaboration: International PTA


# Results: strong evidence for GW signal

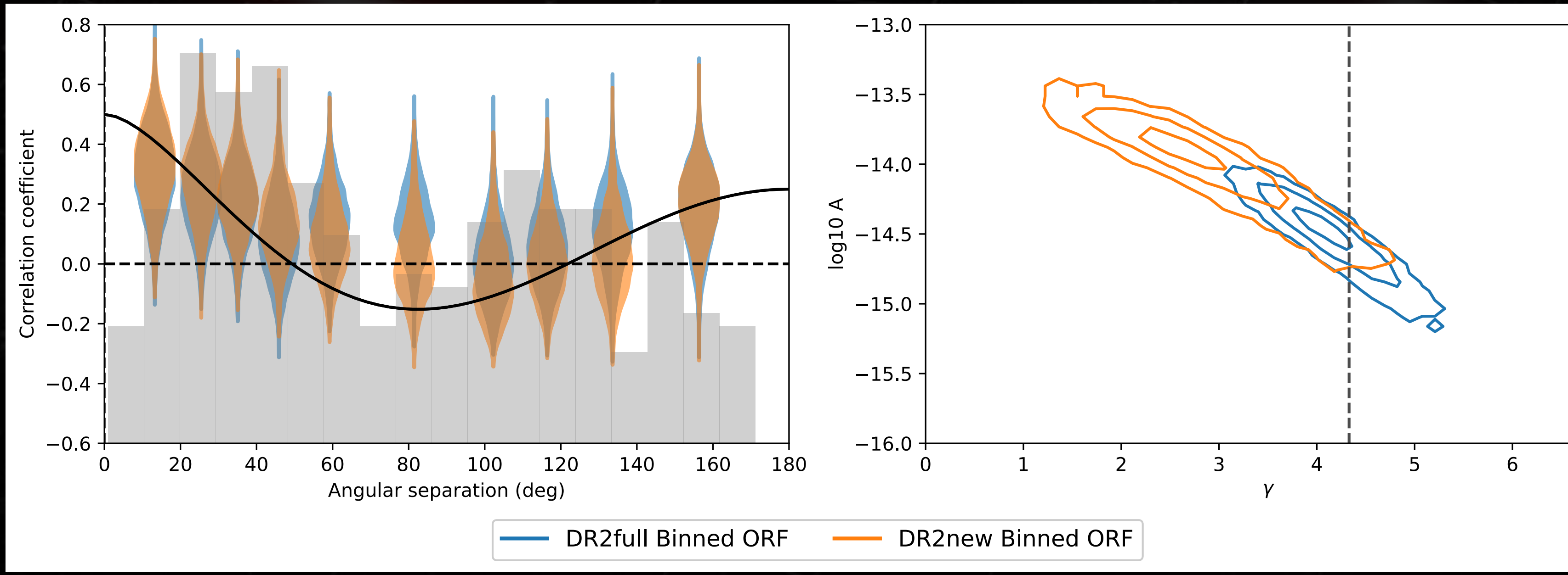
- Results from the 3 "historical" PTA collaborations
- The origin of the signal is still to be understood.

https://arxiv.org/abs/2309.00693

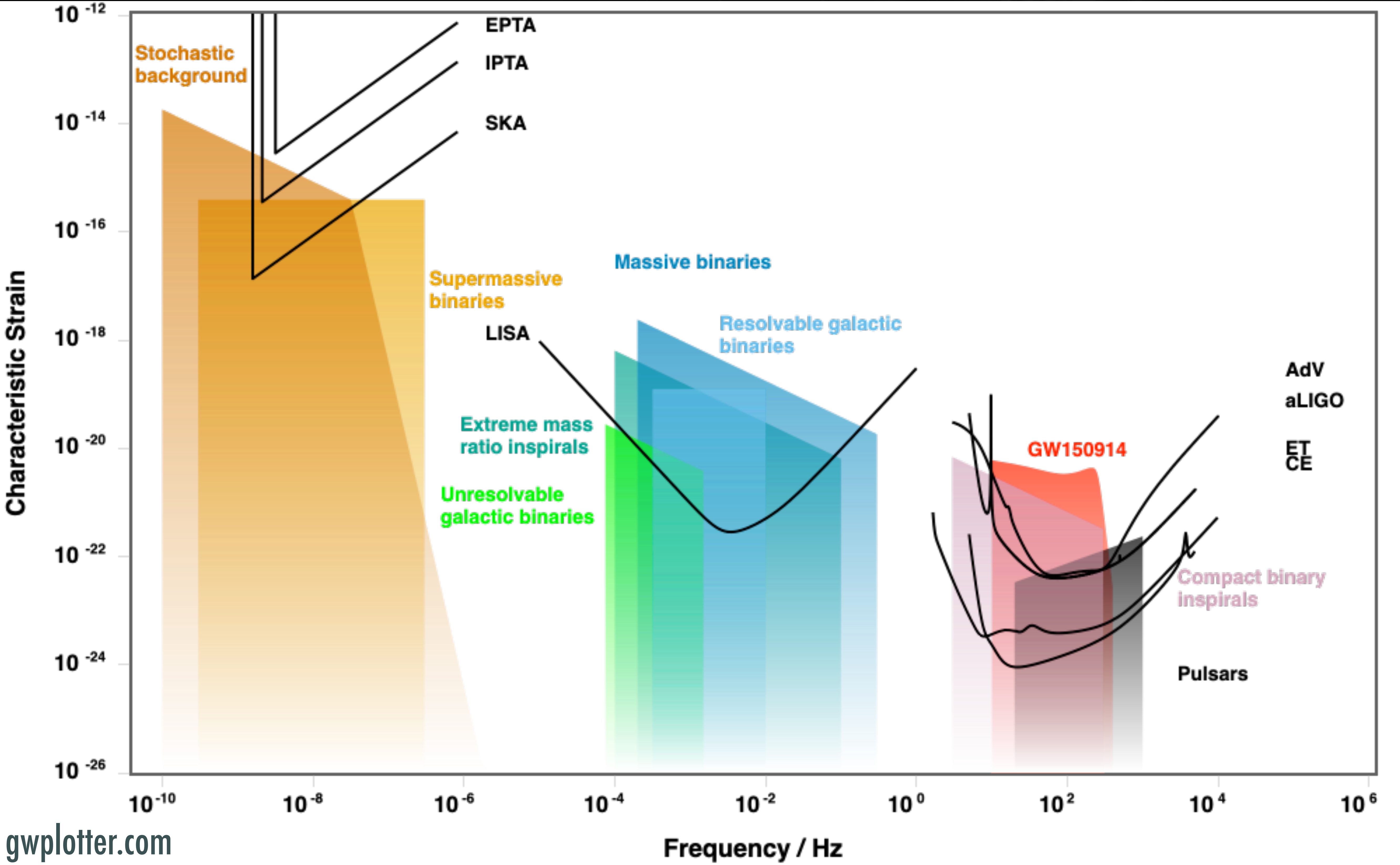



- EPTA spatial correlation

https://arxiv.org/abs/2306.16214



# GW spectrum: current + future




gwplotter.com

Crédit: MPIfR

# Pulsar Timing Array

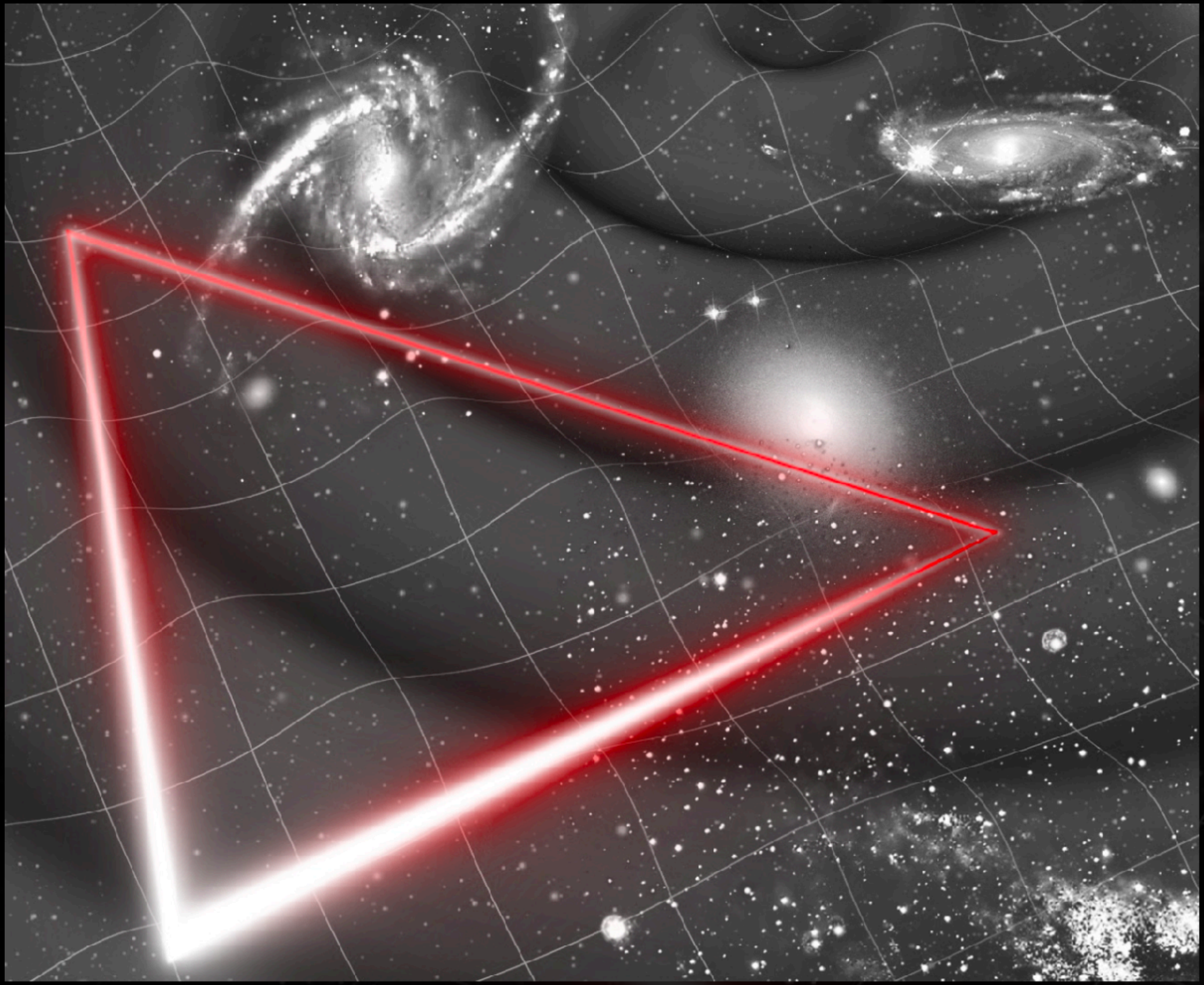
## IPTA, SKA

# IPTA

- 121 combined pulsars with a time span of ~ 25 years
- Data from
  - EPTA (DR2) EPTA LOW-F (LOFAR + NenuFar)
  - NANOGrav 15-Year
  - PPTA DR3;
  - InPTA DR1
  - MPTA DR2 (MeerKAT)
  - CHIME DR1
  - CPTA DR1?
- Status:
  - Combination almost done
  - Data analysis complex and heavy → results expected in 2026
- We should be able to confirm and characterise the detection

# PTA with SKA

- > 100 pulsars with very high timing precision
- First science data of SKA in 2028
- First SKA PTA results expected mid-2030s
- 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, …



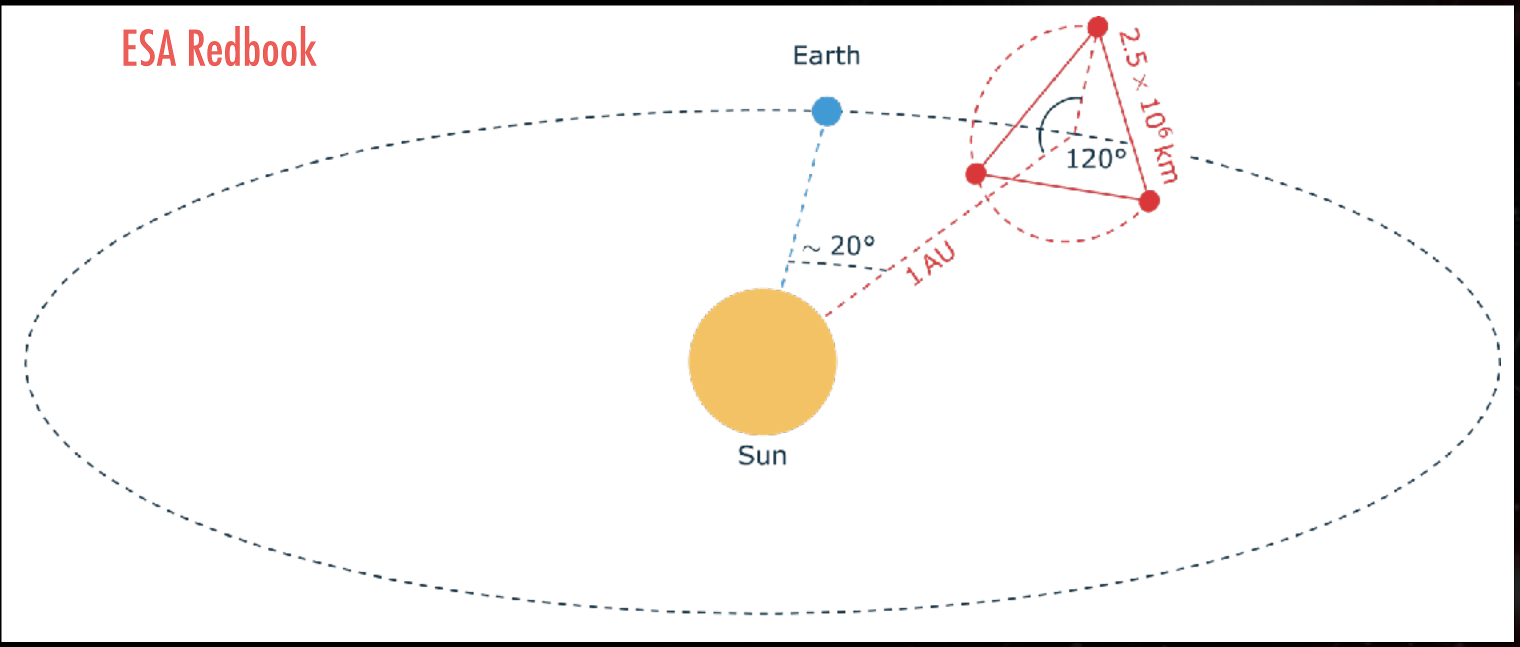
Crédit: ESA

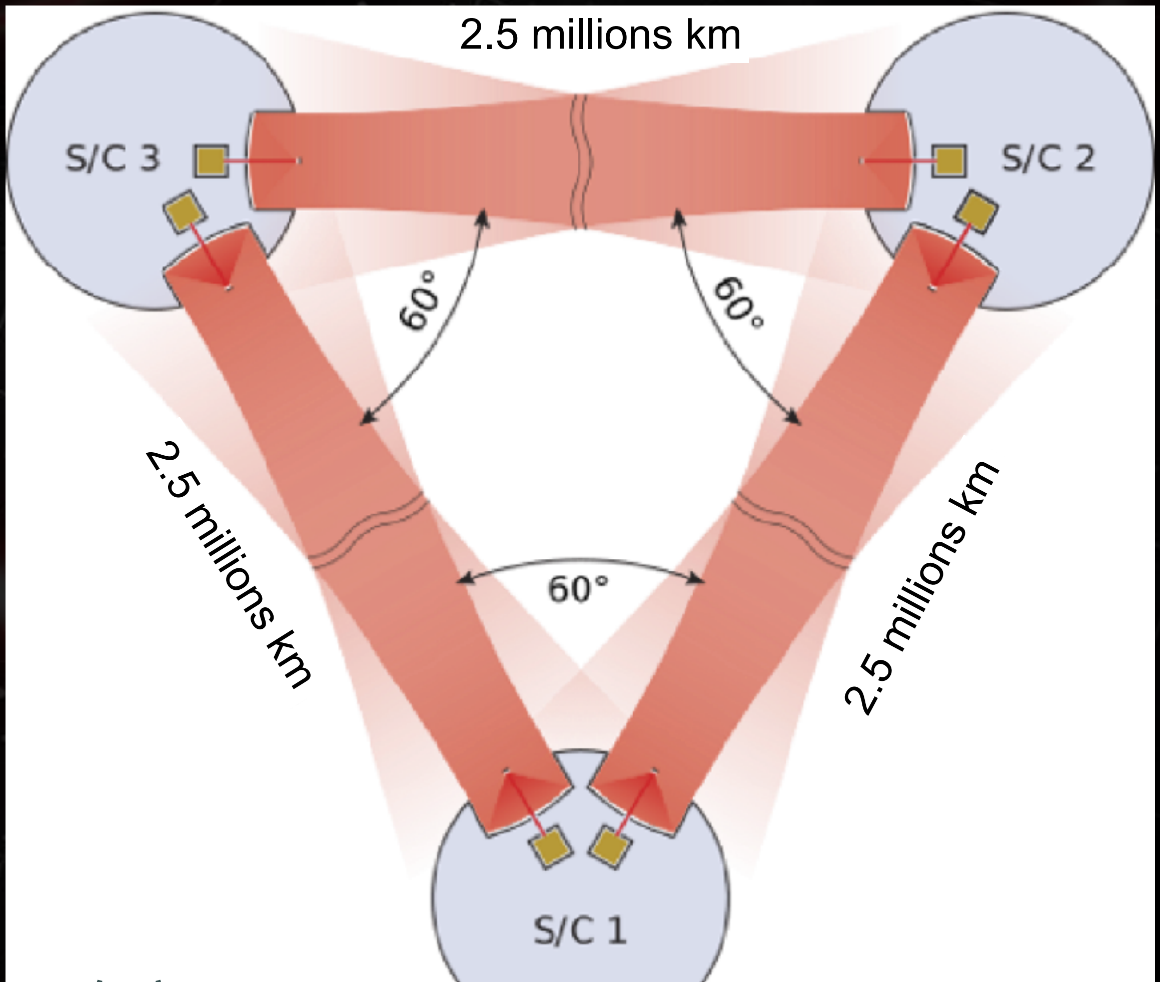
# LISA

# Mission design

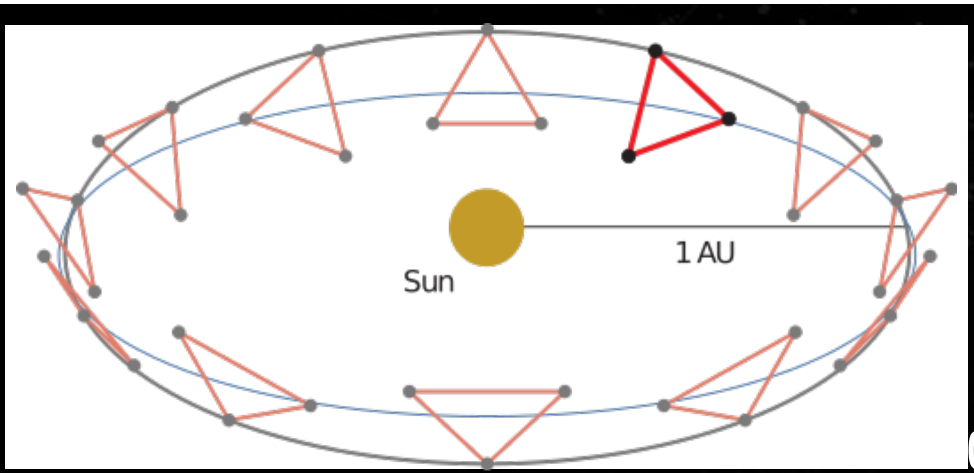
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits separated by 2.5 millions km
- Goal: detect strains of $10^{-21}$ by monitoring arm length changes at the few picometre level

ESA Redbook



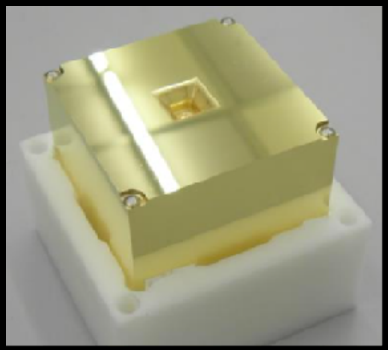

PDD (LIG)

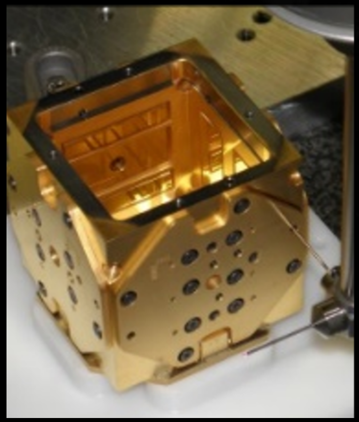


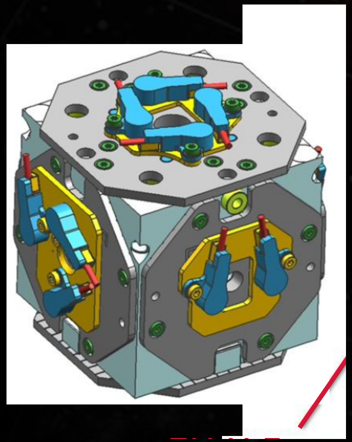

L3 proposal (LISA Consortium)

# Mission design

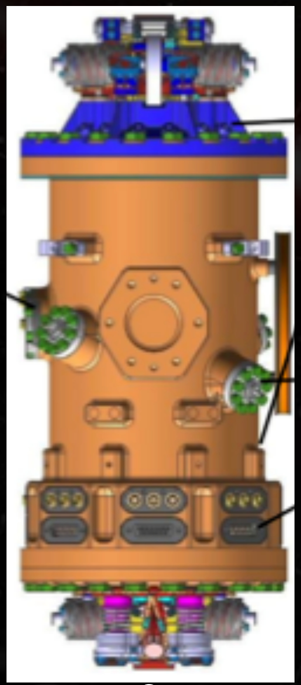
- Measurement points must be shielded from fluctuating non-gravitational influences:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing

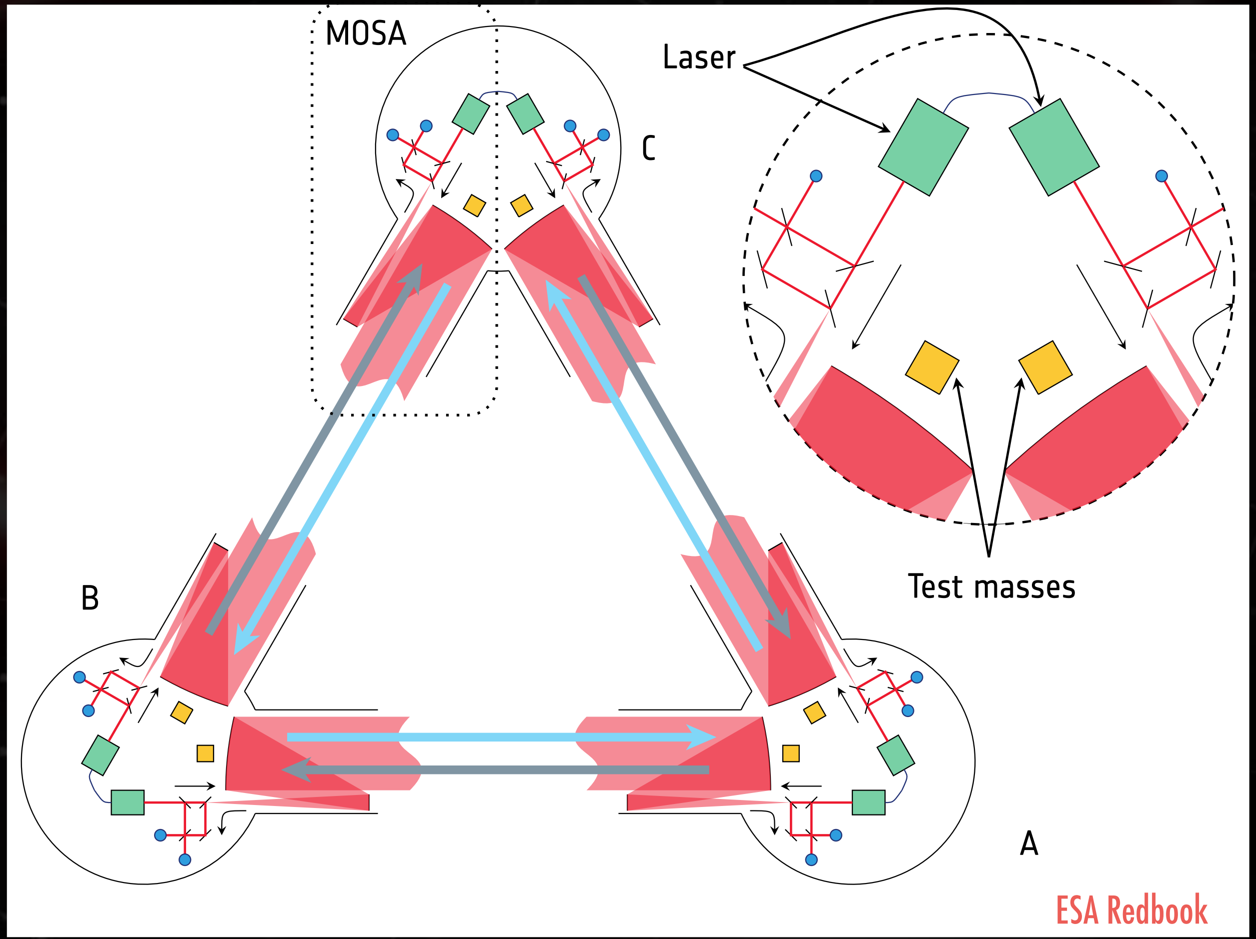






ESA Redbook - OHB Italia

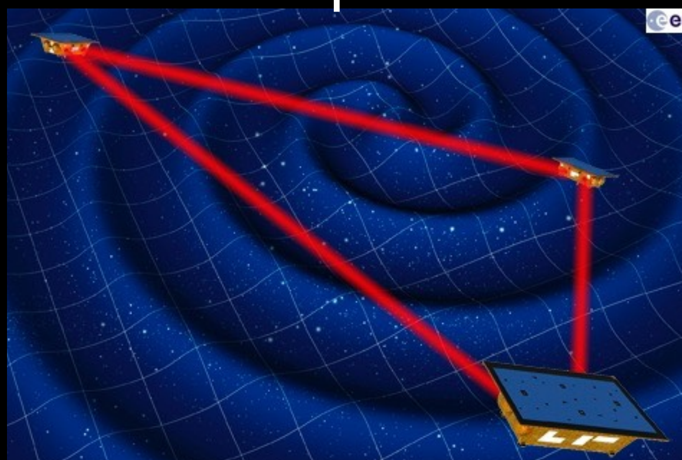





ESA Redbook

# Mission design

- Several steps towards the required precision of measurement



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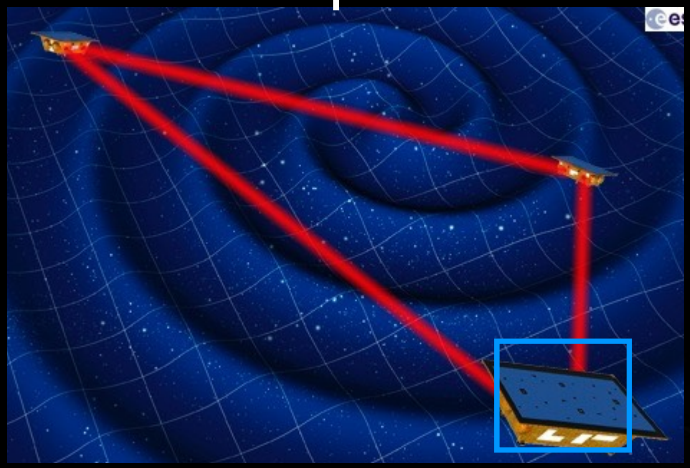

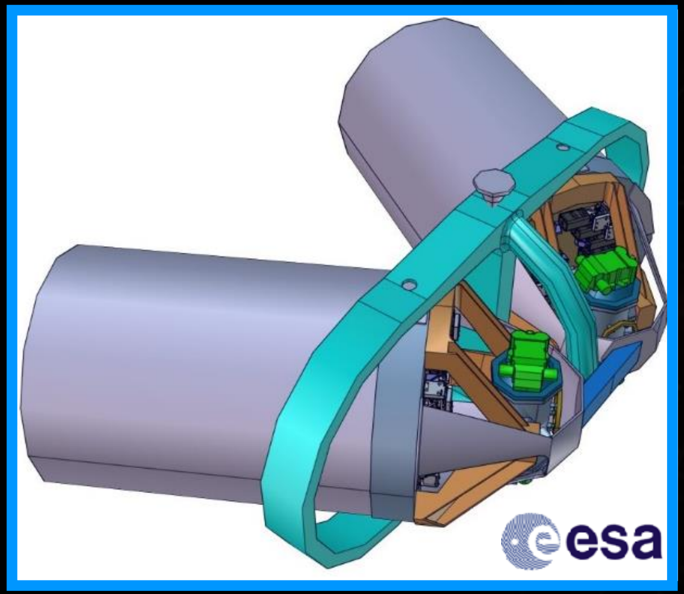

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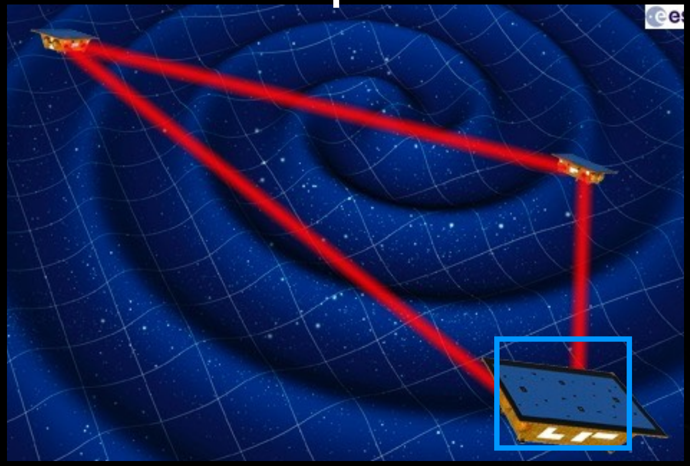

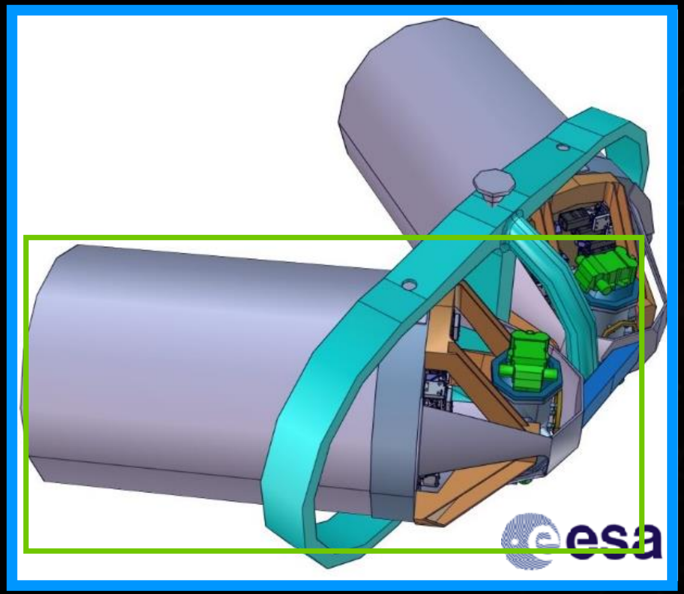

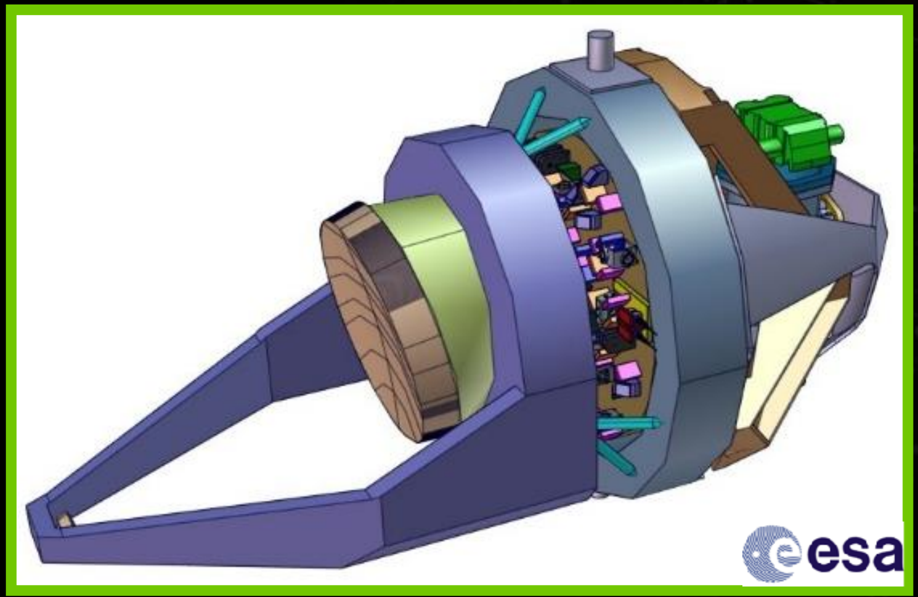

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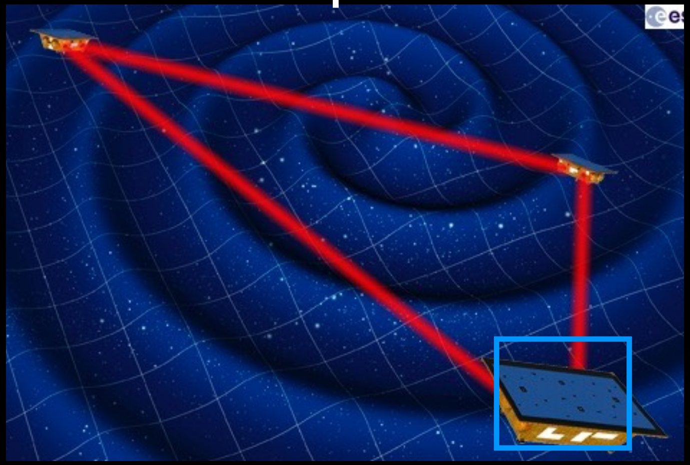

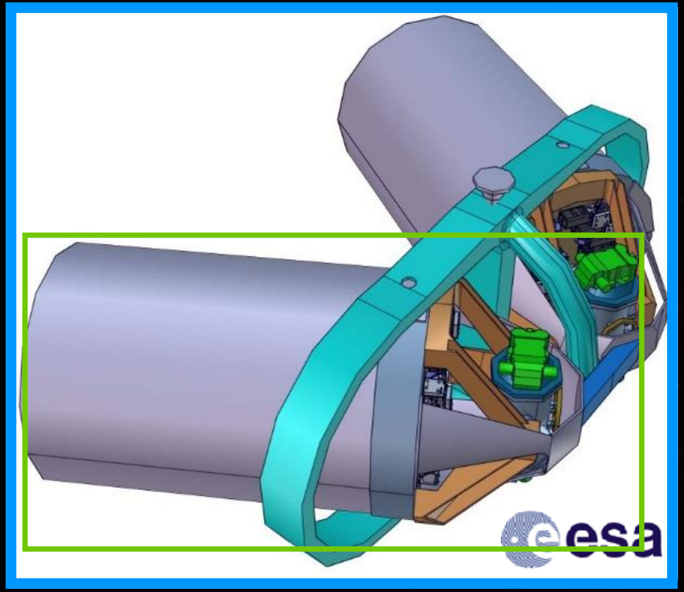


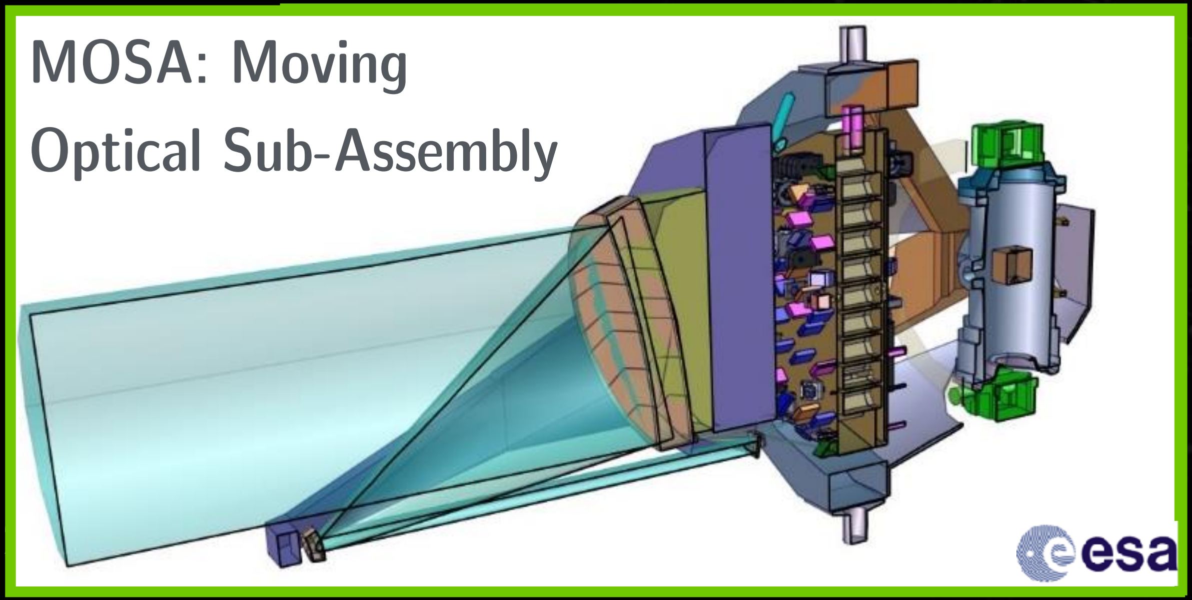

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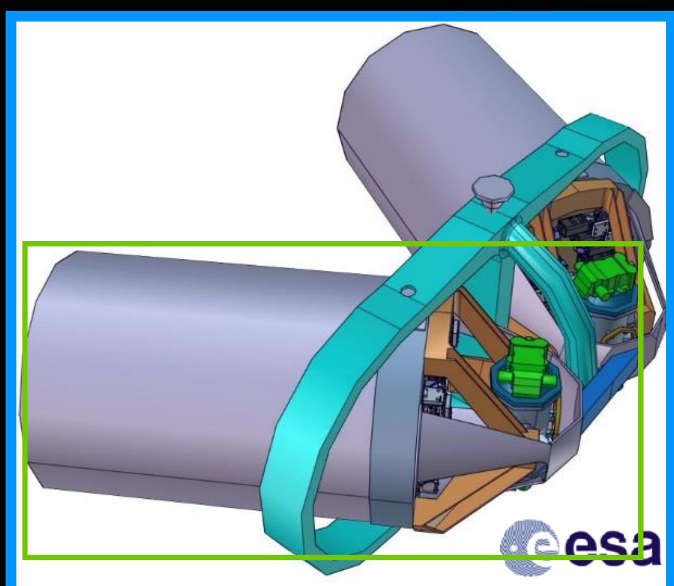
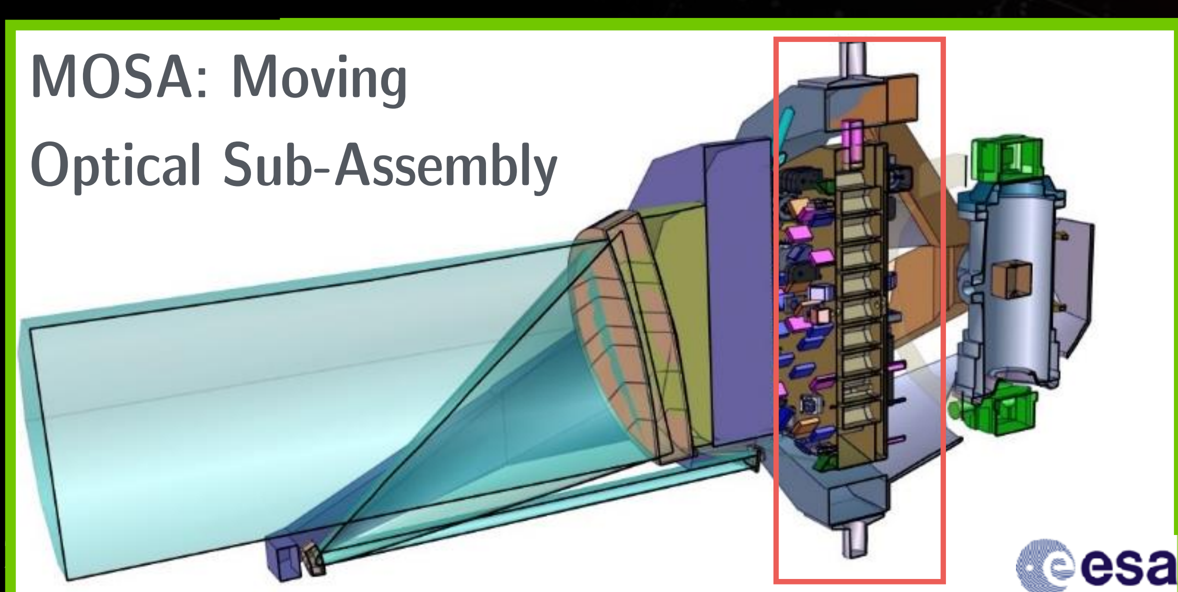
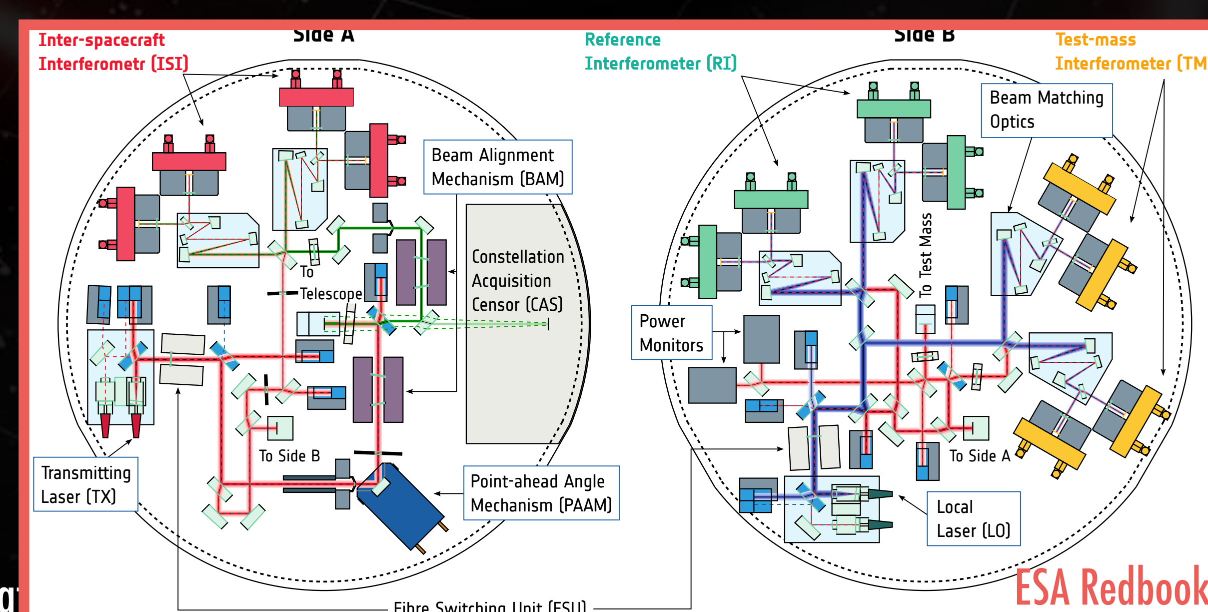


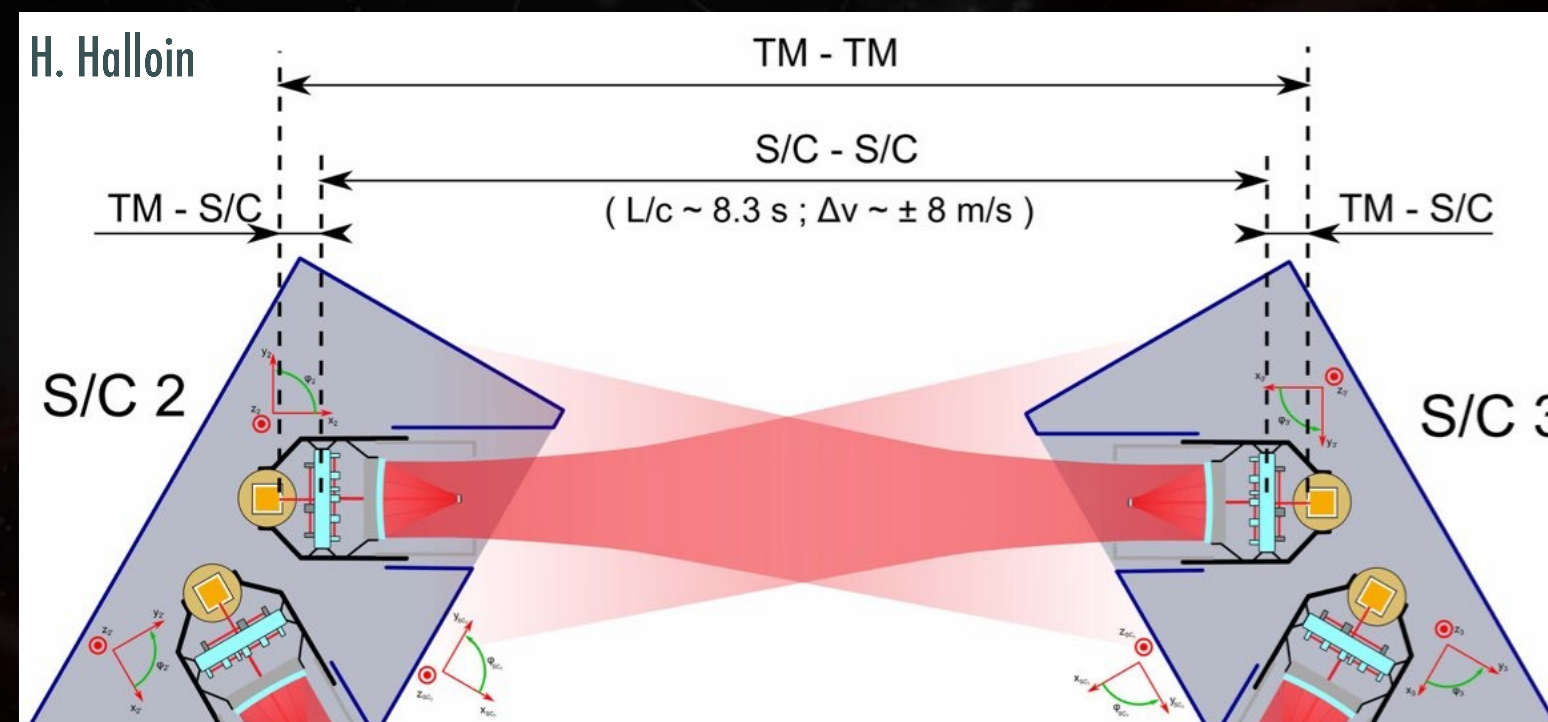


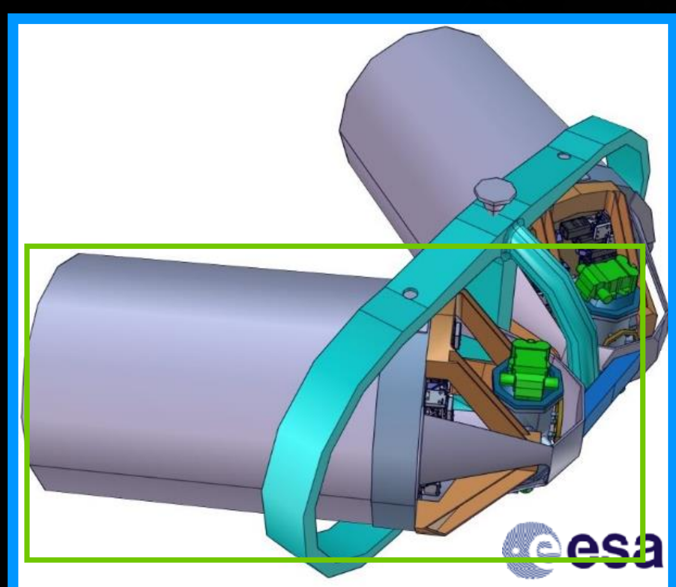



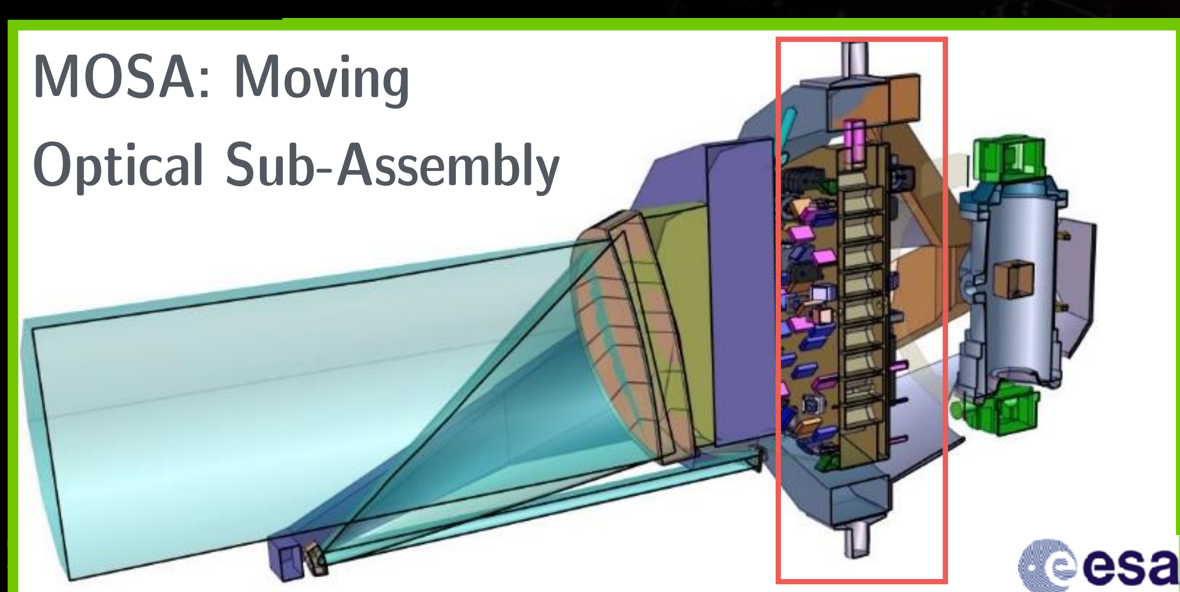
# Mission design

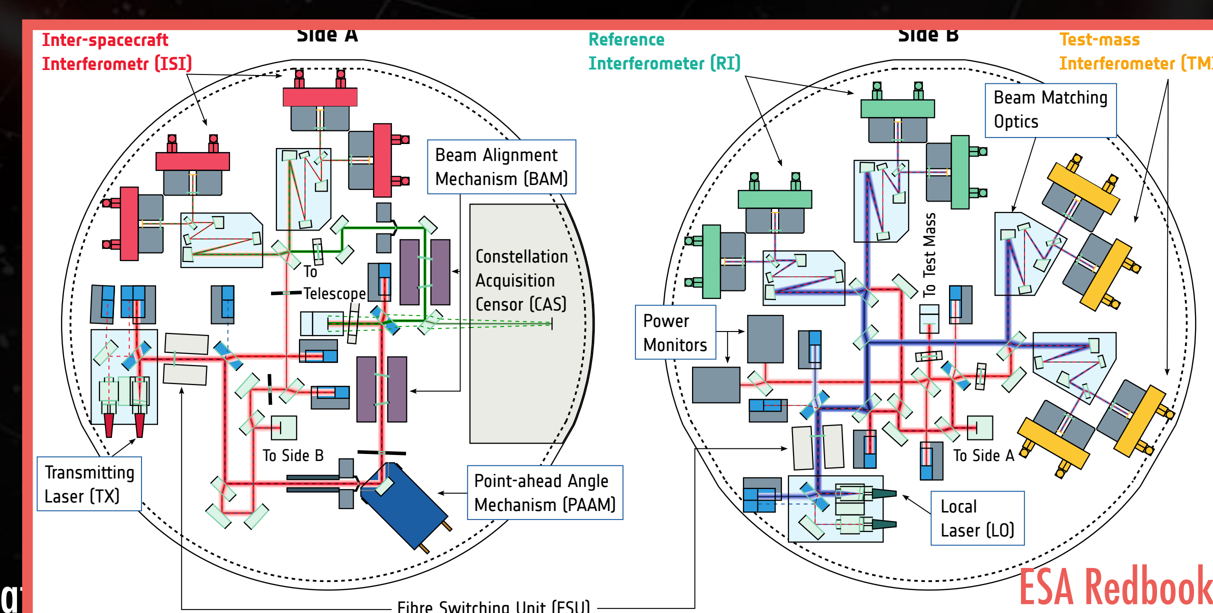
- Several steps towards the required precision of measurement

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



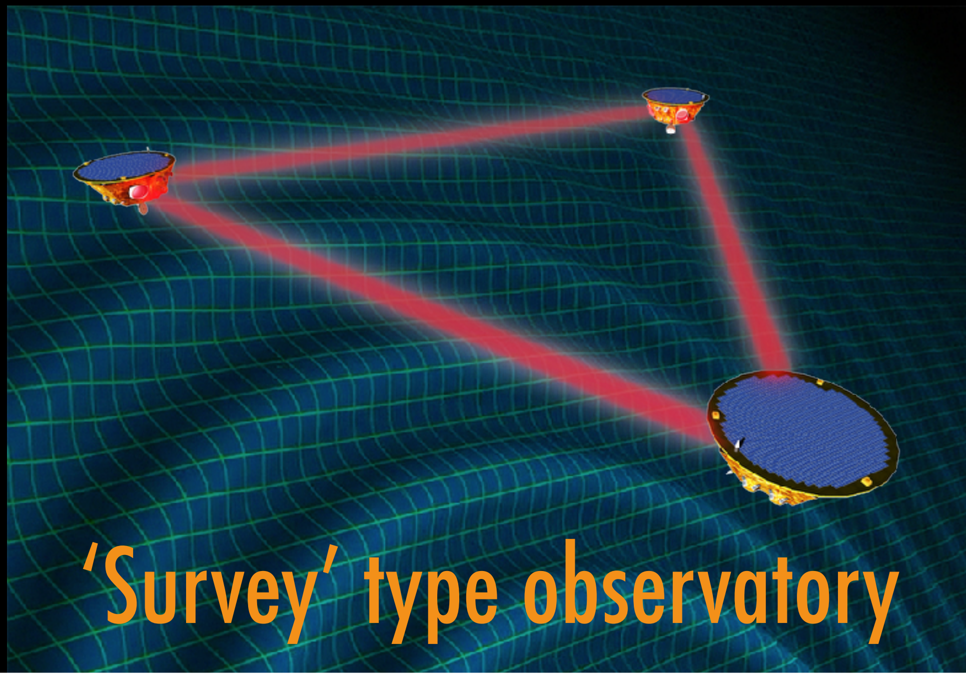


# Data

Gravitational wave sources emitting between 0.02mHz and 1 Hz

# Data

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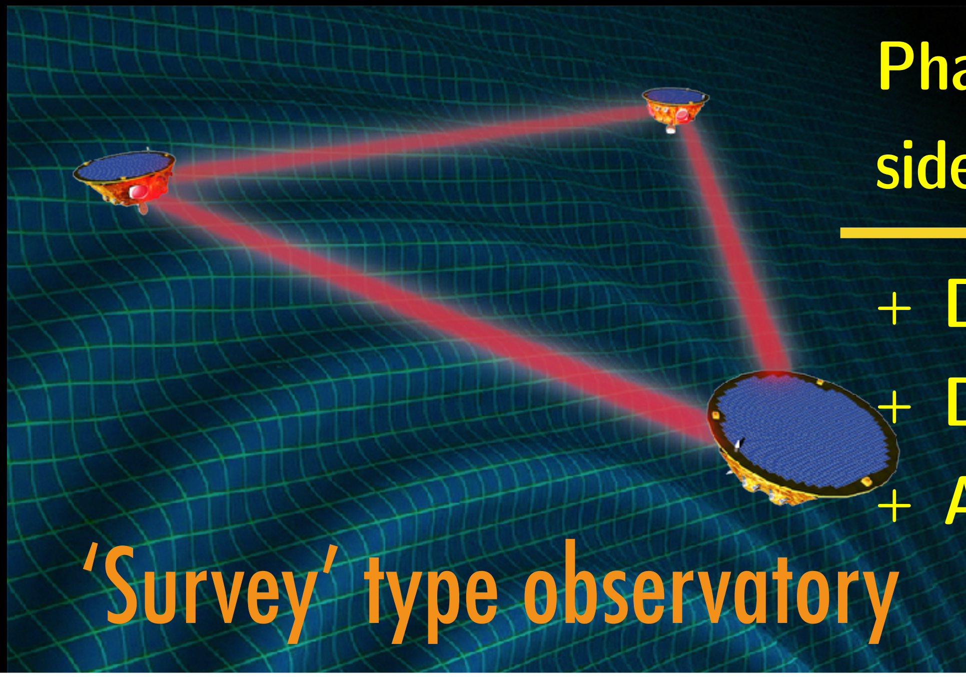



Phasemeters (carrier, sidebands, distance)

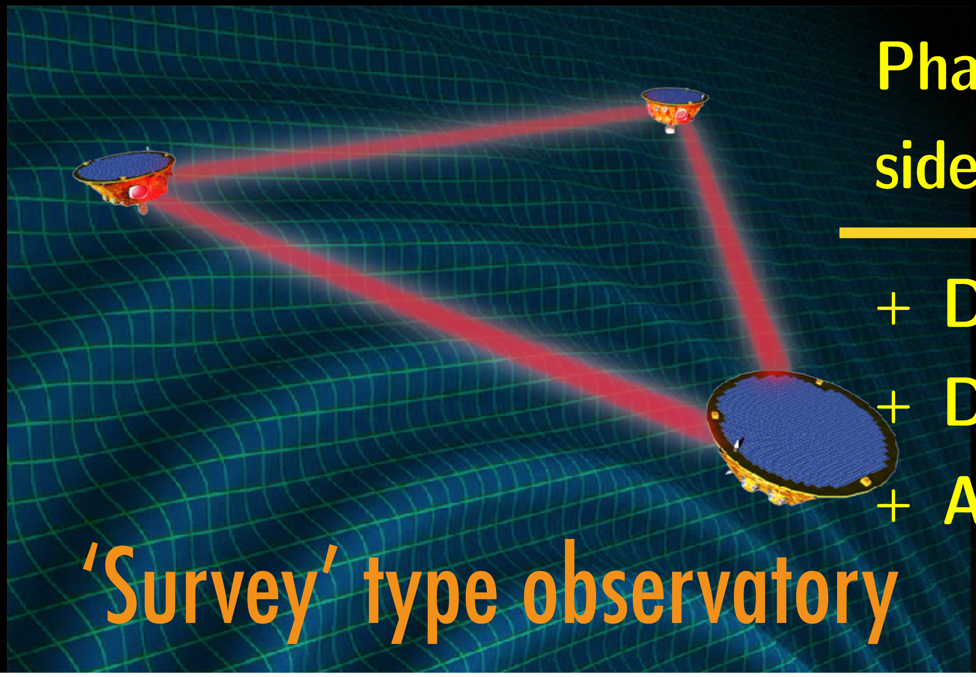
+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

**Gravitational wave sources emitting between 0.02mHz and 1 Hz**

* Drag-Free Attitude Control System

** Charge Management Device

# Data

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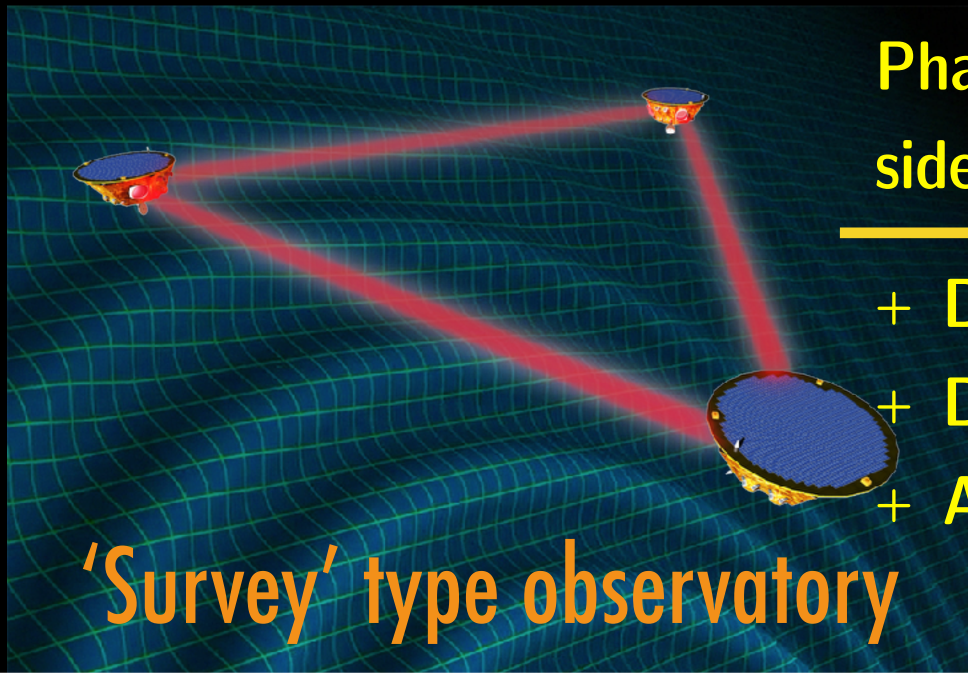


Phasemeters (carrier, sidebands, distance)

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

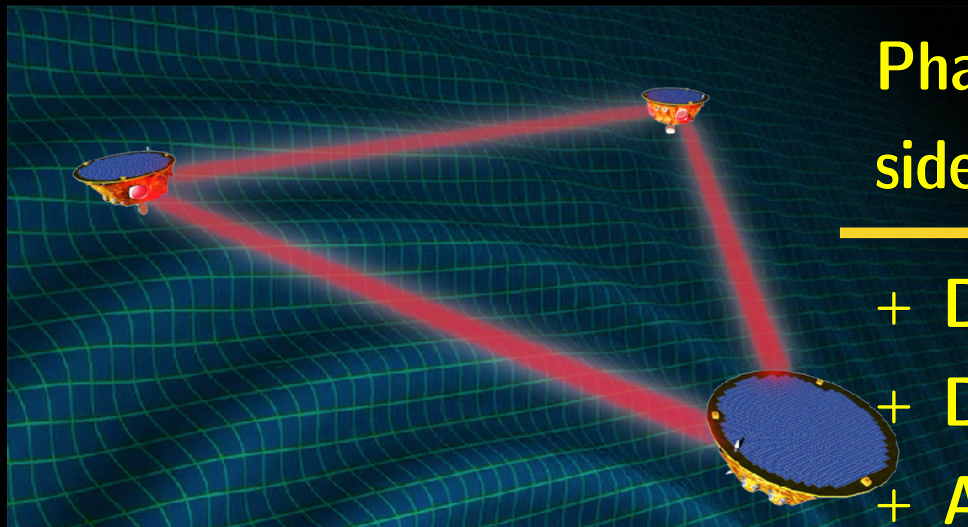
3 TDI channels with 2 "~independents"

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

# Data



'Survey' type observatory

Phasemeters (carrier, sidebands, distance)

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

Calibrations corrections
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3 TDI channels with 2 "~independents"

Data Analysis of GWs

Catalogs of GWs sources with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

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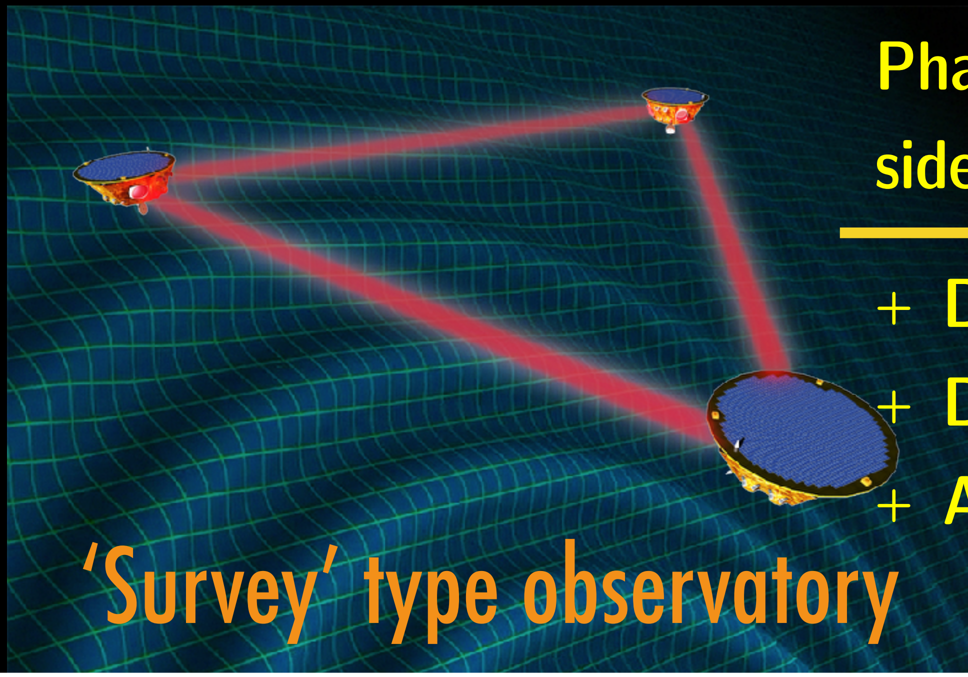
# Data




Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
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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

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device



cea irfu

# Data

Mission Operation Center (ESA)

Science Operation Center (ESA)

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"

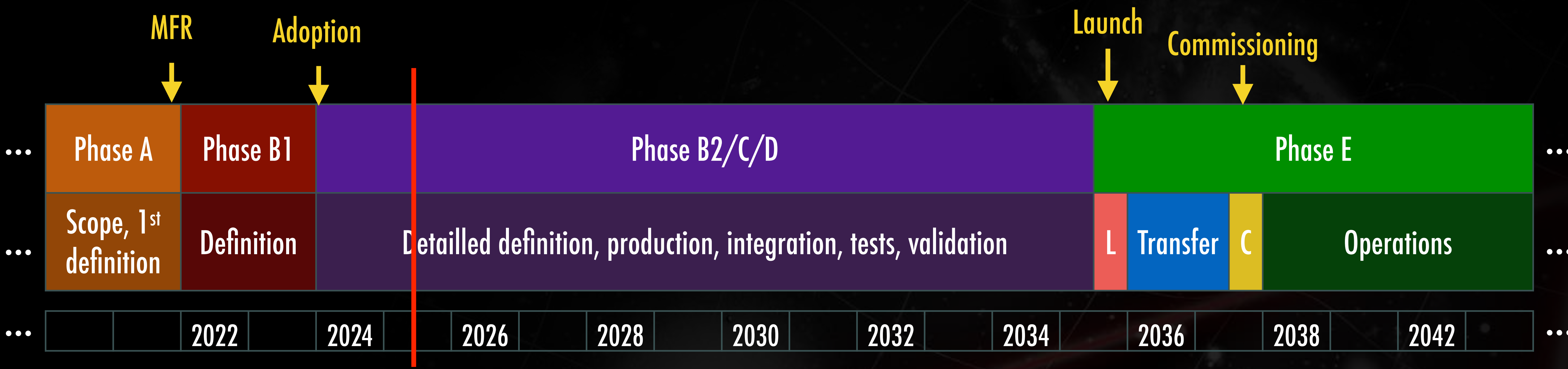
L2

Data Analysis of GWs

L3

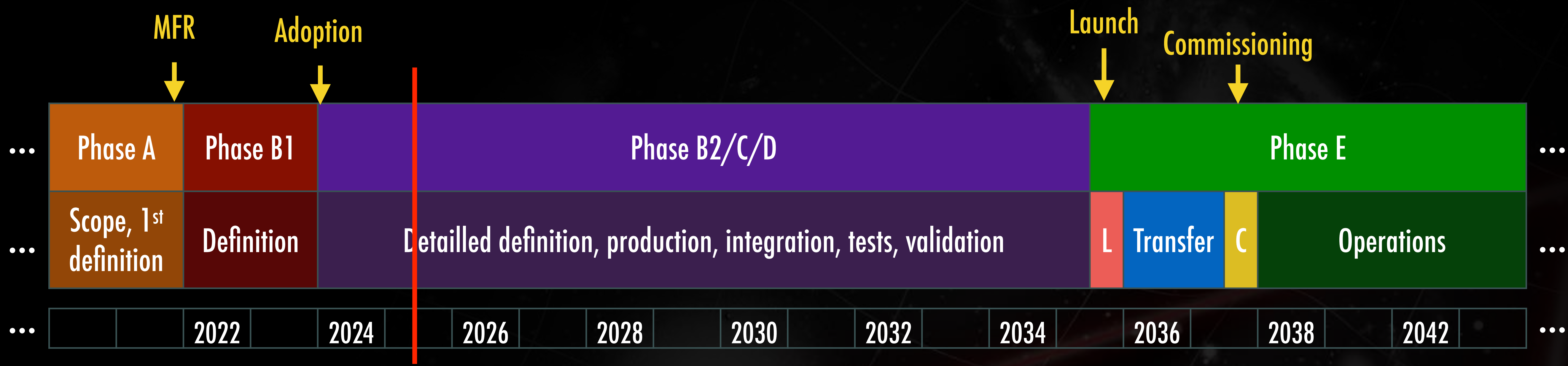
Catalogs of GWs sources with their waveform

# 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

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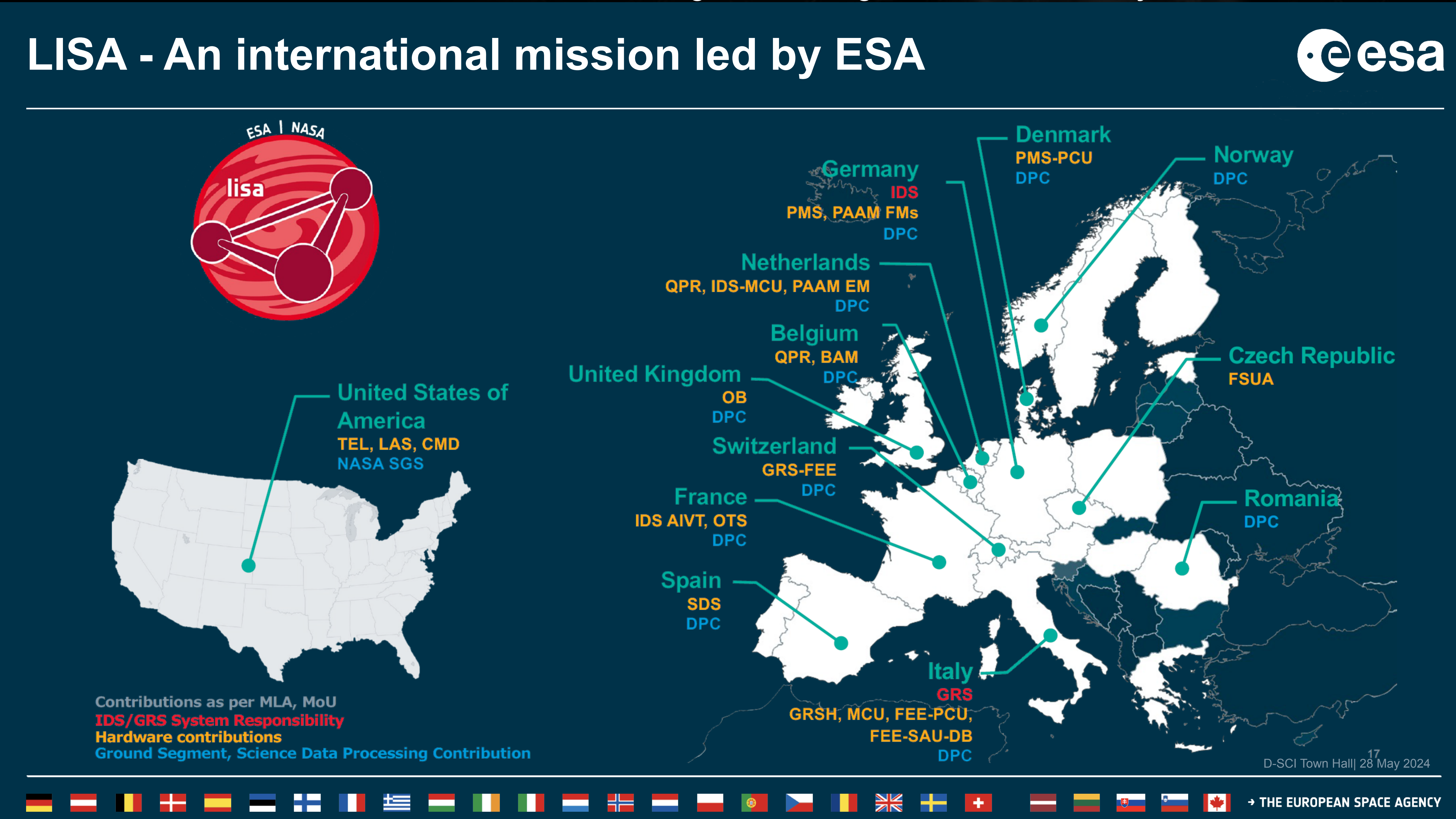
# LISA collaboration

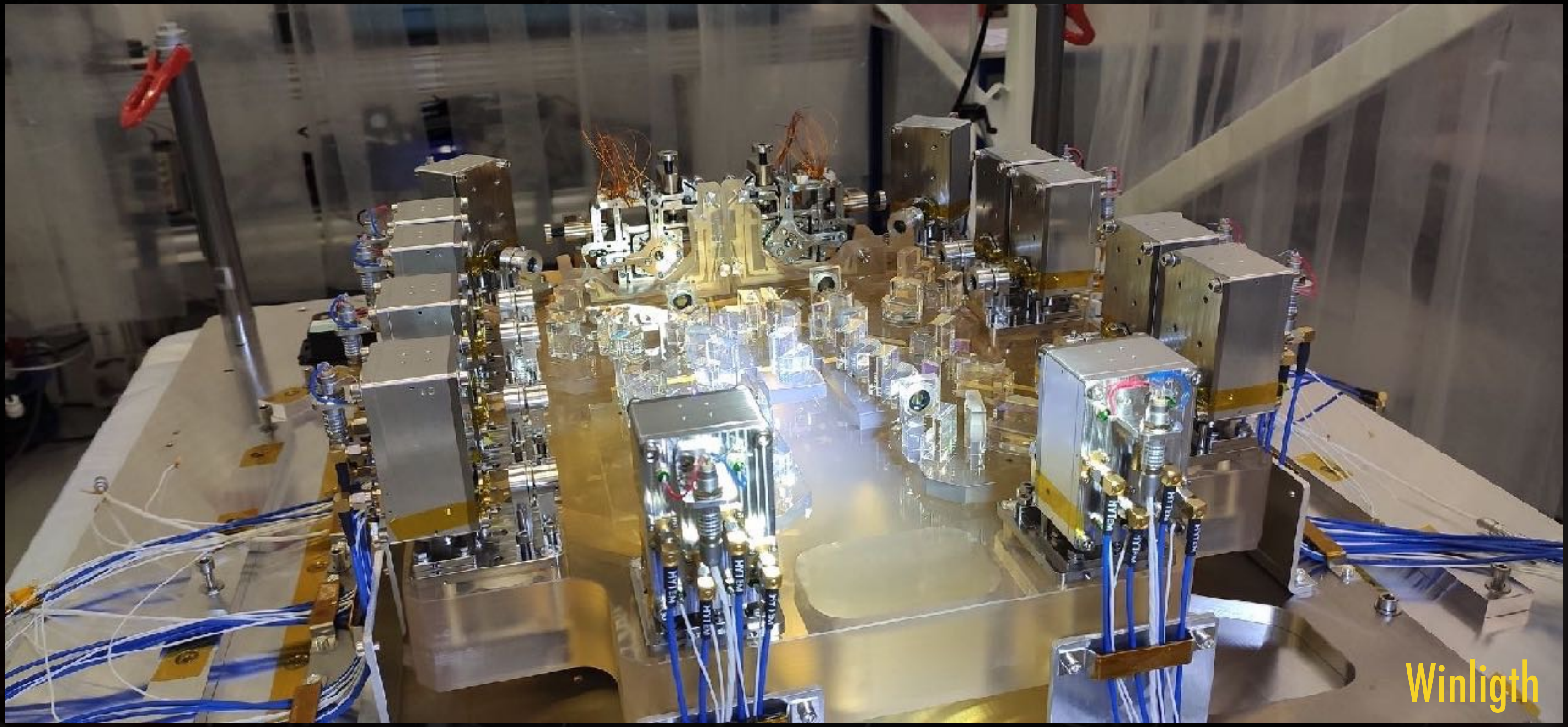
- Contributions to the instrument and ground segment (data analysis)



# Timeline and status

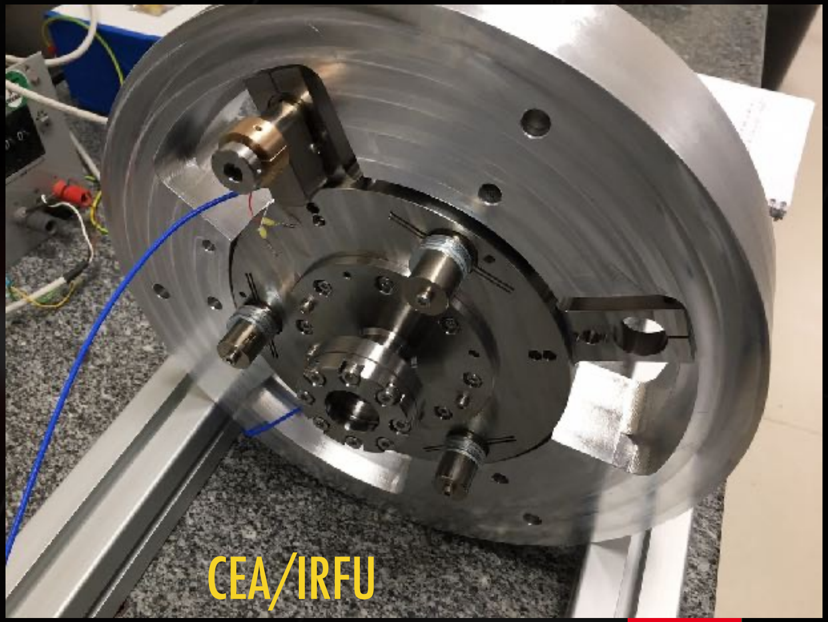
## Building already started …

ZIFO (demonstration bench for high stability interferometry)



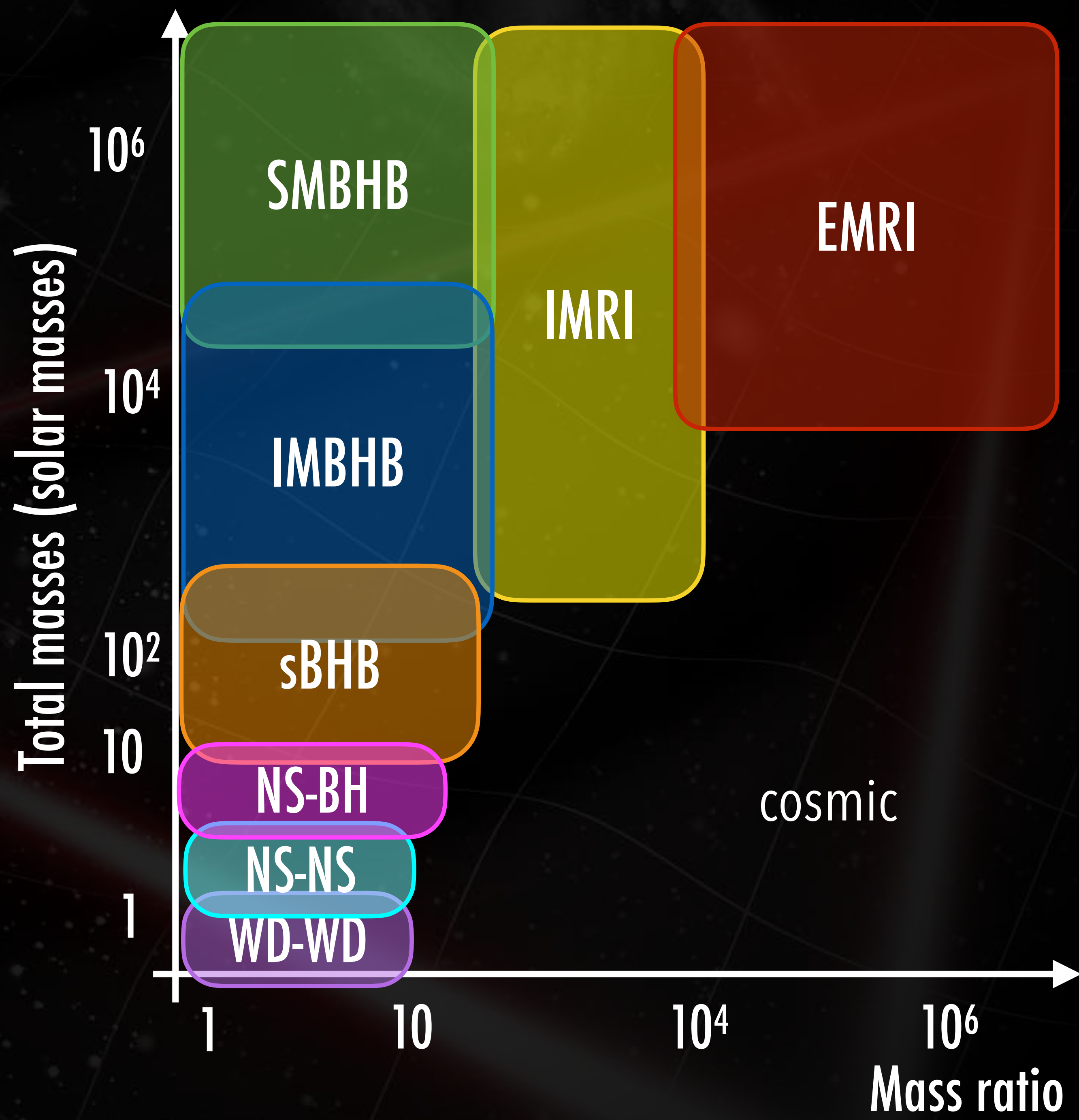

Telescope


Test-Mass Simulator



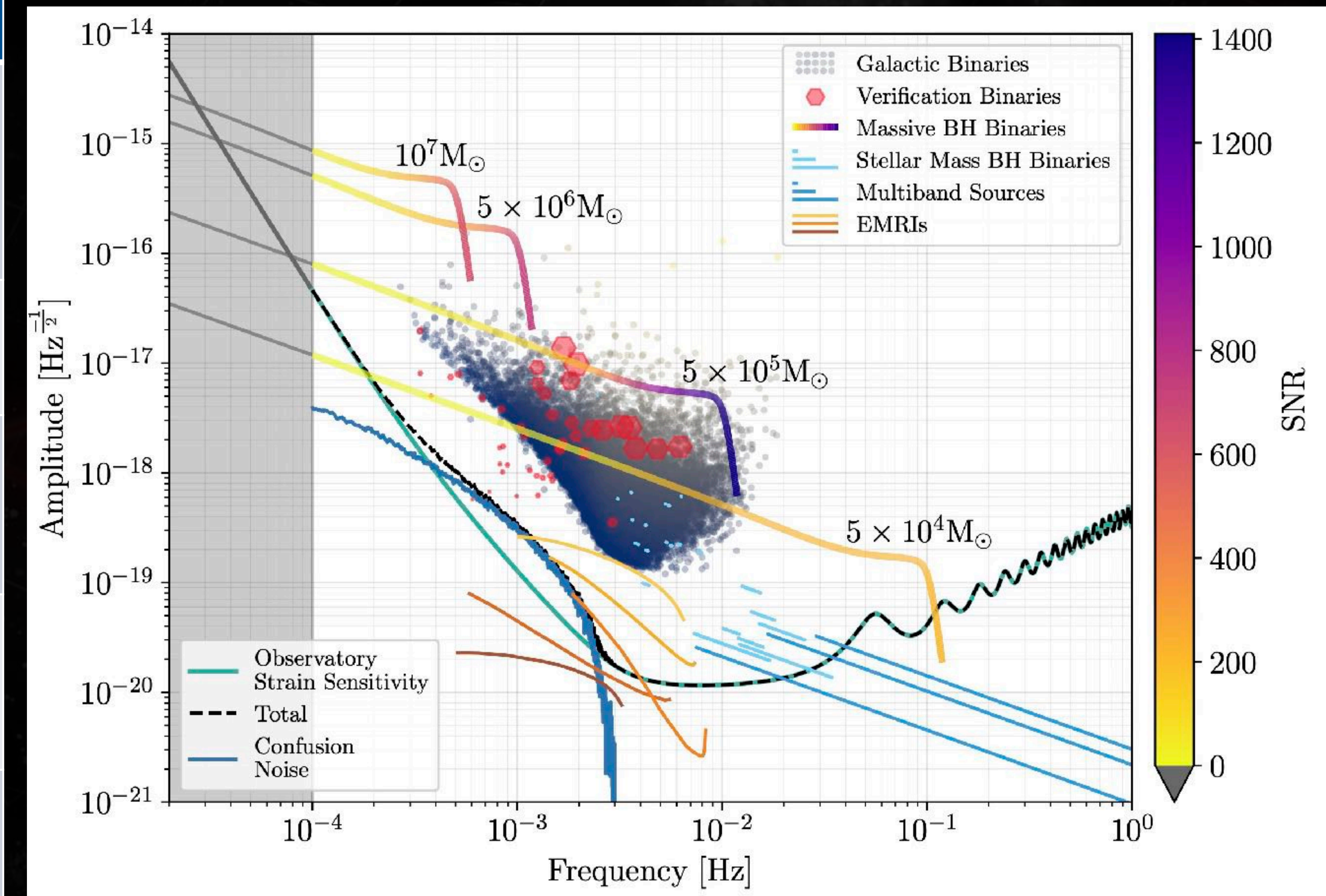
# GW sources in the mHz band

- 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 (EW), string networks, …
- Bursts: cosmic strings, …
- Unknown?



# Binaries observed by LISA

| Sources | SNR | Duration | Event rate |
|---|---|---|---|
| Galactic binaries | 10 – 500 | permane nt | 10000 – 30000 detectables + background |
| Verification binaries | 7 - 100 | permane nt | 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.

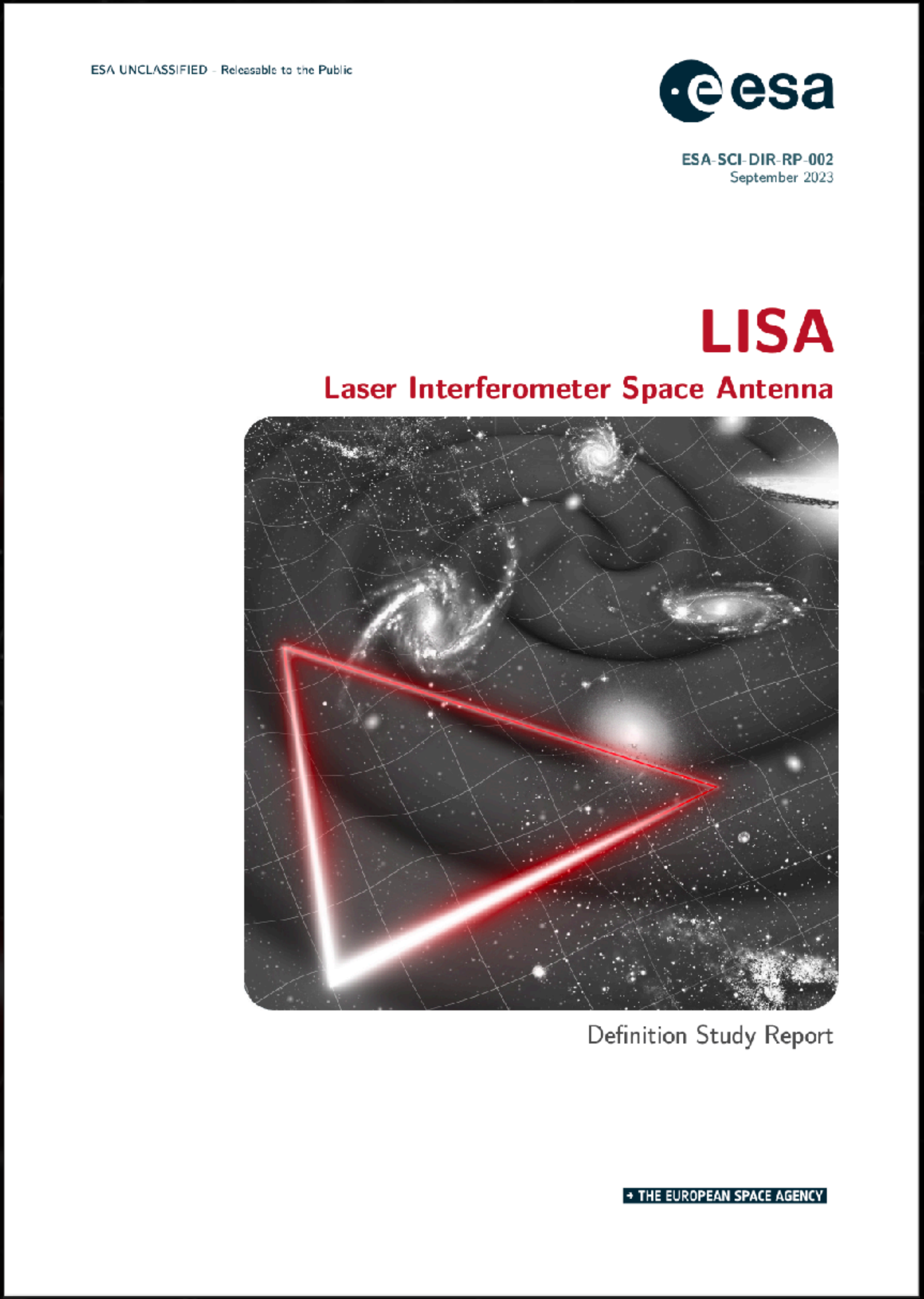
Astrophysics

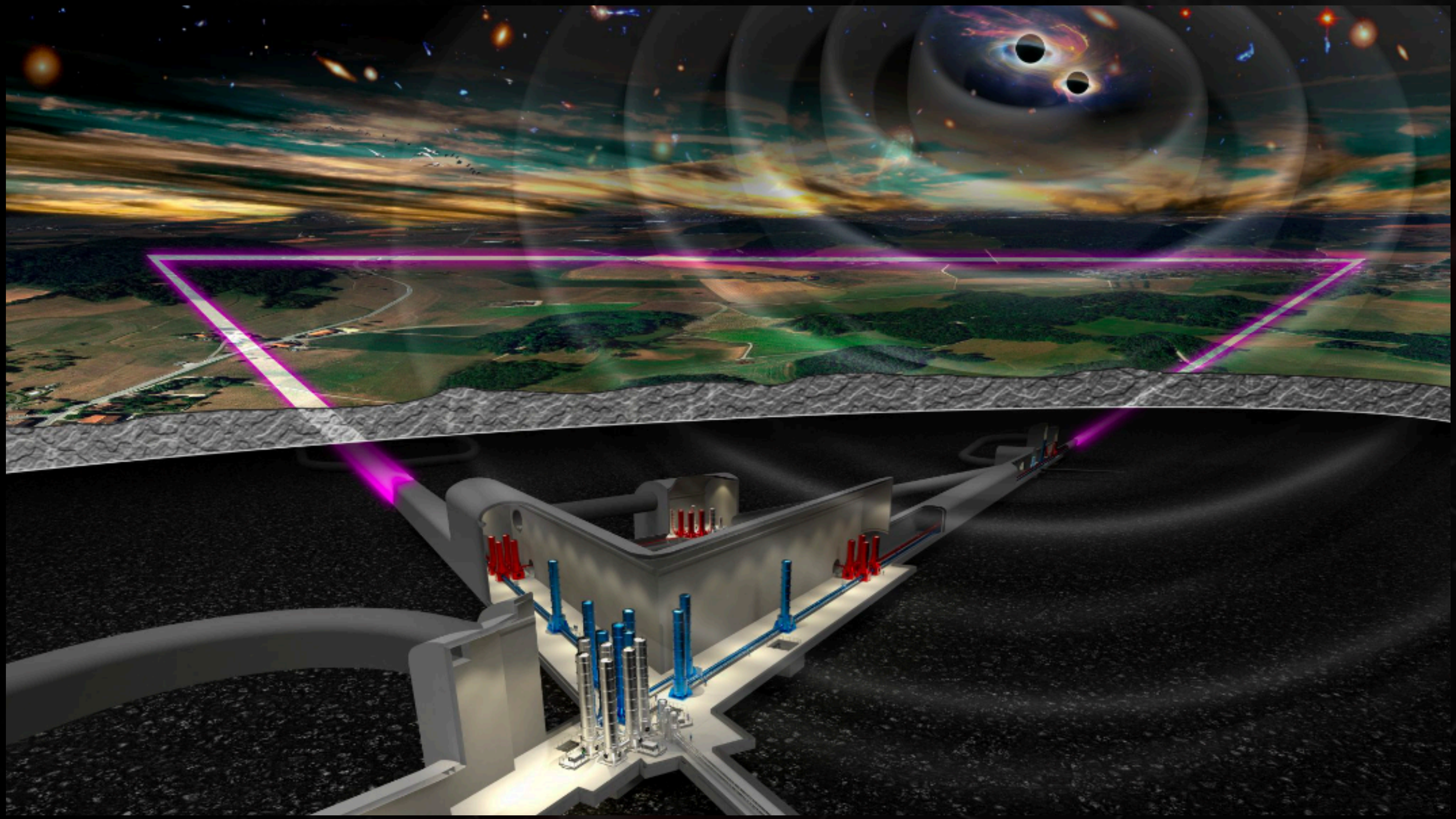
Fundamental physics

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



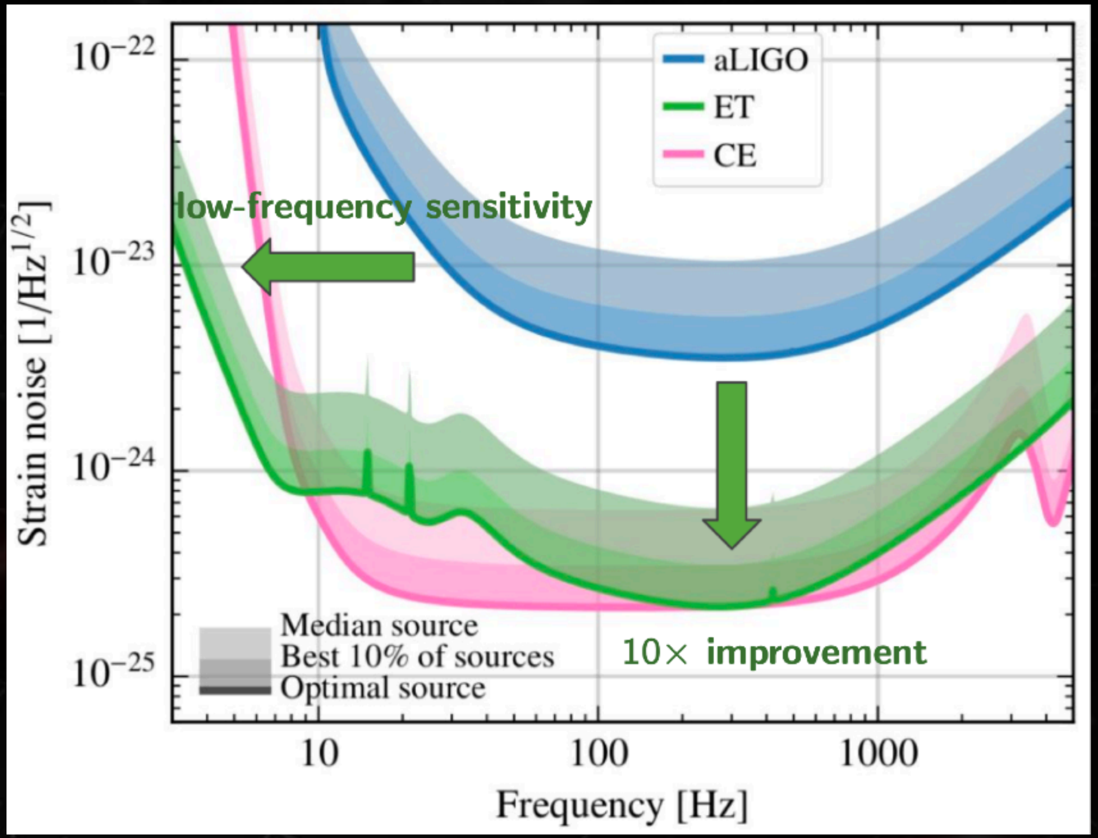


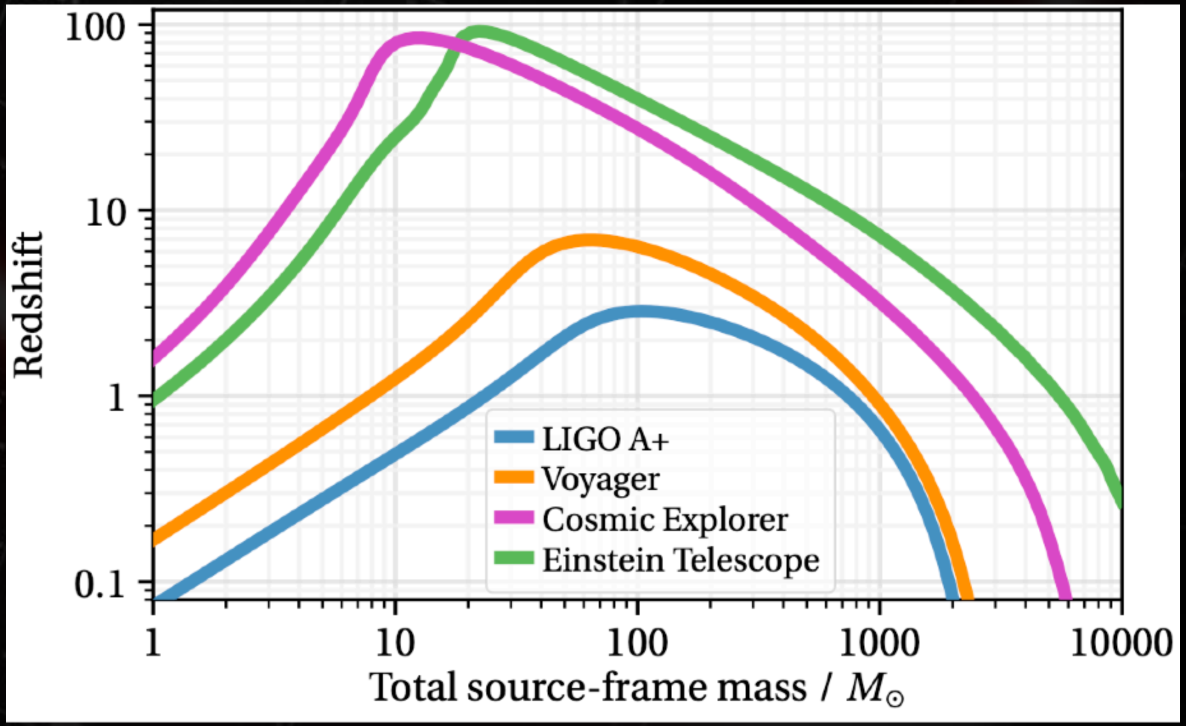
Crédit: Einstein Telescope

# $3^{rd}$ generation ground based observatories

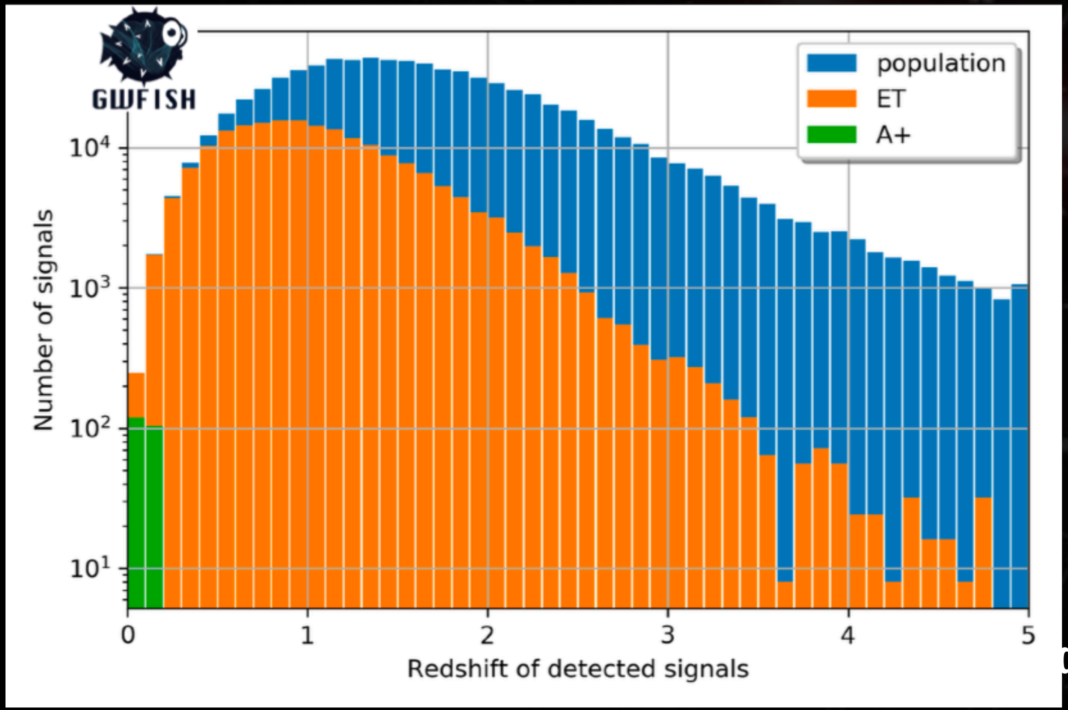
# 3rd generation ground based observatories

- Improve sensitivity in the band of ground based obs.
- Science:
  - Binary BH coalescences up to cosmological distances
  - Extend the region of Black Holes masses
  - Coalescence of Binary NS (early warning)
  - Accurate tests of General Relativity
  - New astrophysical sources (core collapse supernovae, isolated rotating NS, etc.)
  - Stochastic backgrounds from cosmological origin



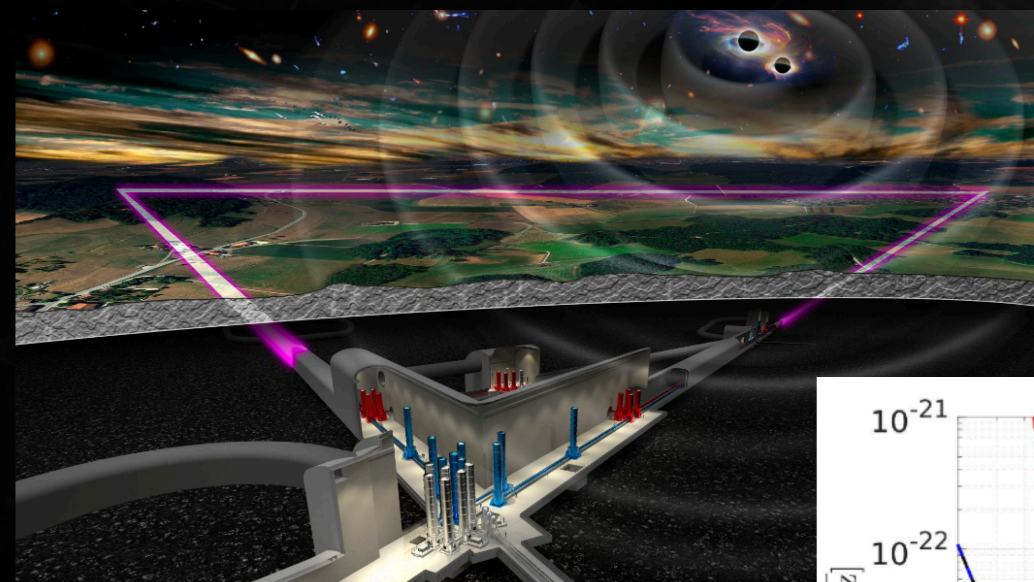



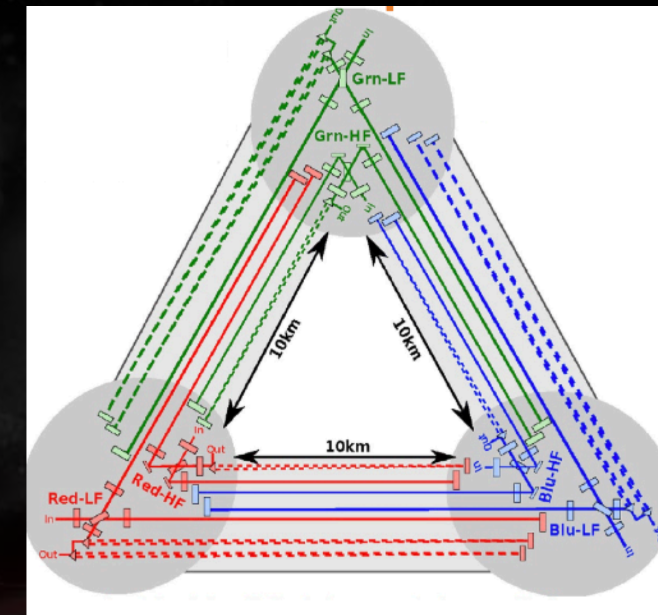

Binary Neutron Star Mergers

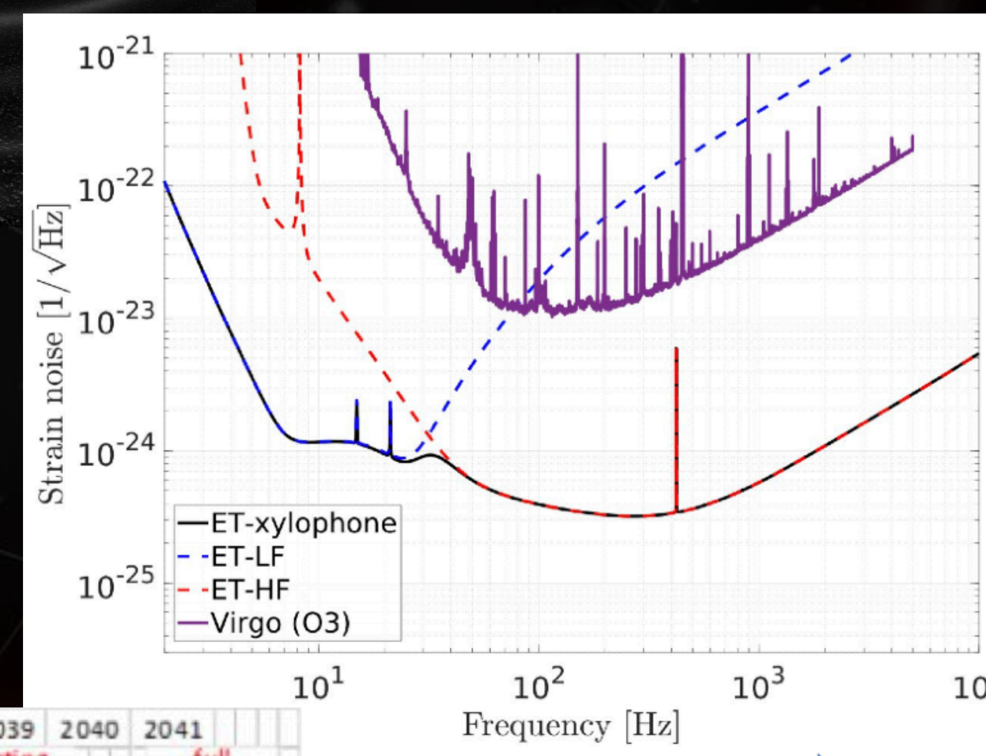


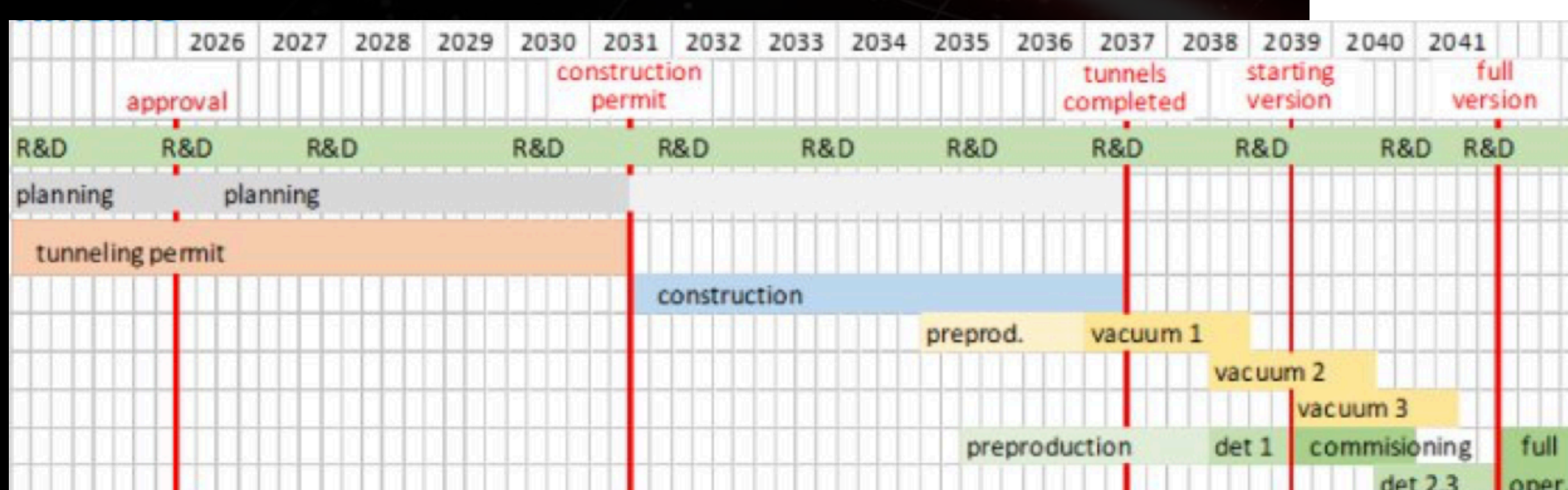
# Einstein Telescope

- Design:
  - Longer arms (≳ 10 km)
  - Underground
  - “Xylophone” (HF-LF)
  - Cryogenic
  - Quantum technology
  - High laser power in arms
  - …
- Still 2 big questions:
  - Which shape? Triangle or 2 L ?
  - Where? EMR, Sardinia, (+Lausitz)
- Timeline:





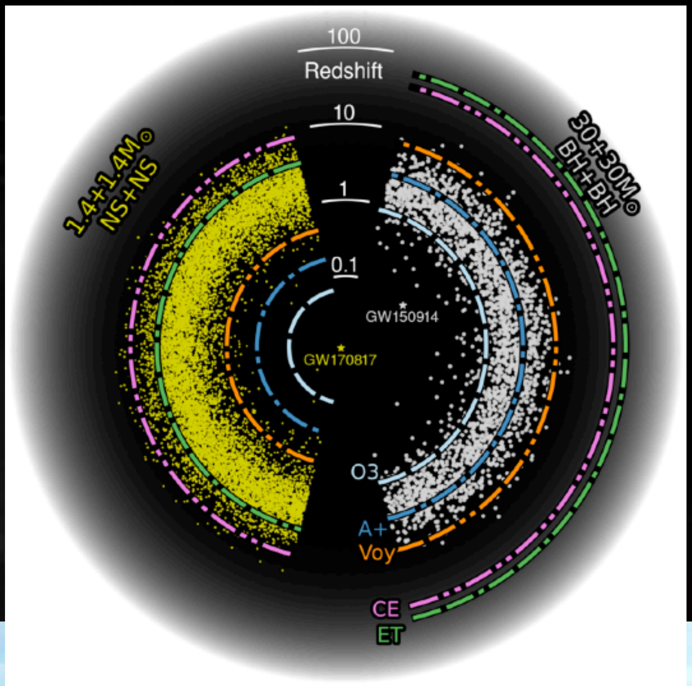



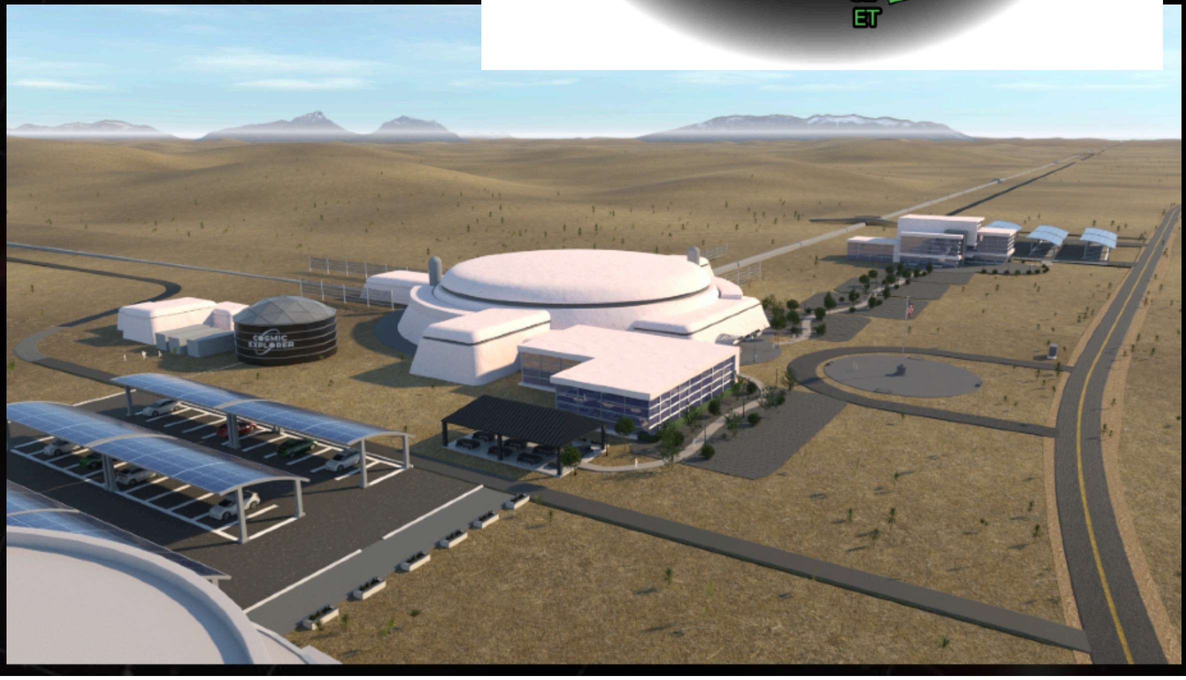

Crédit: Einstein Telescope

# Cosmic Explorer

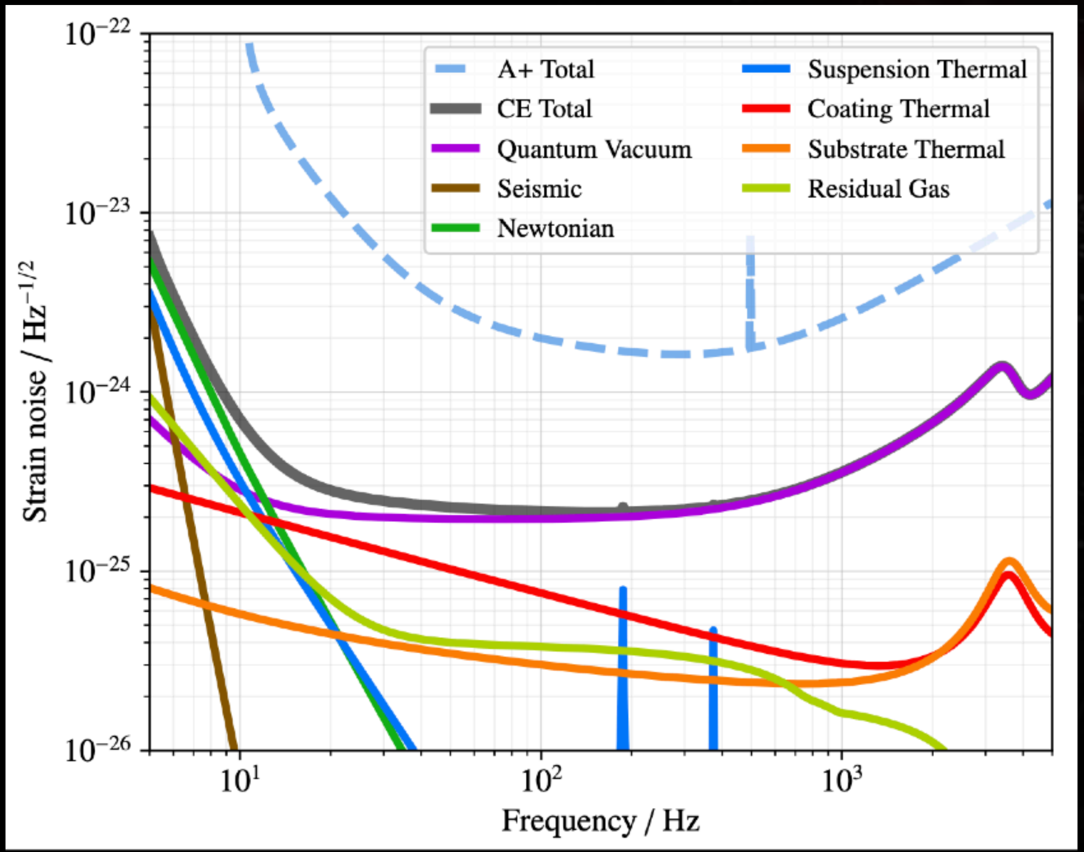
- Design:
  - 2 L-shape Interferometers:
    - 40km
    - 20 km
  - Same technology as Advanced LIGO

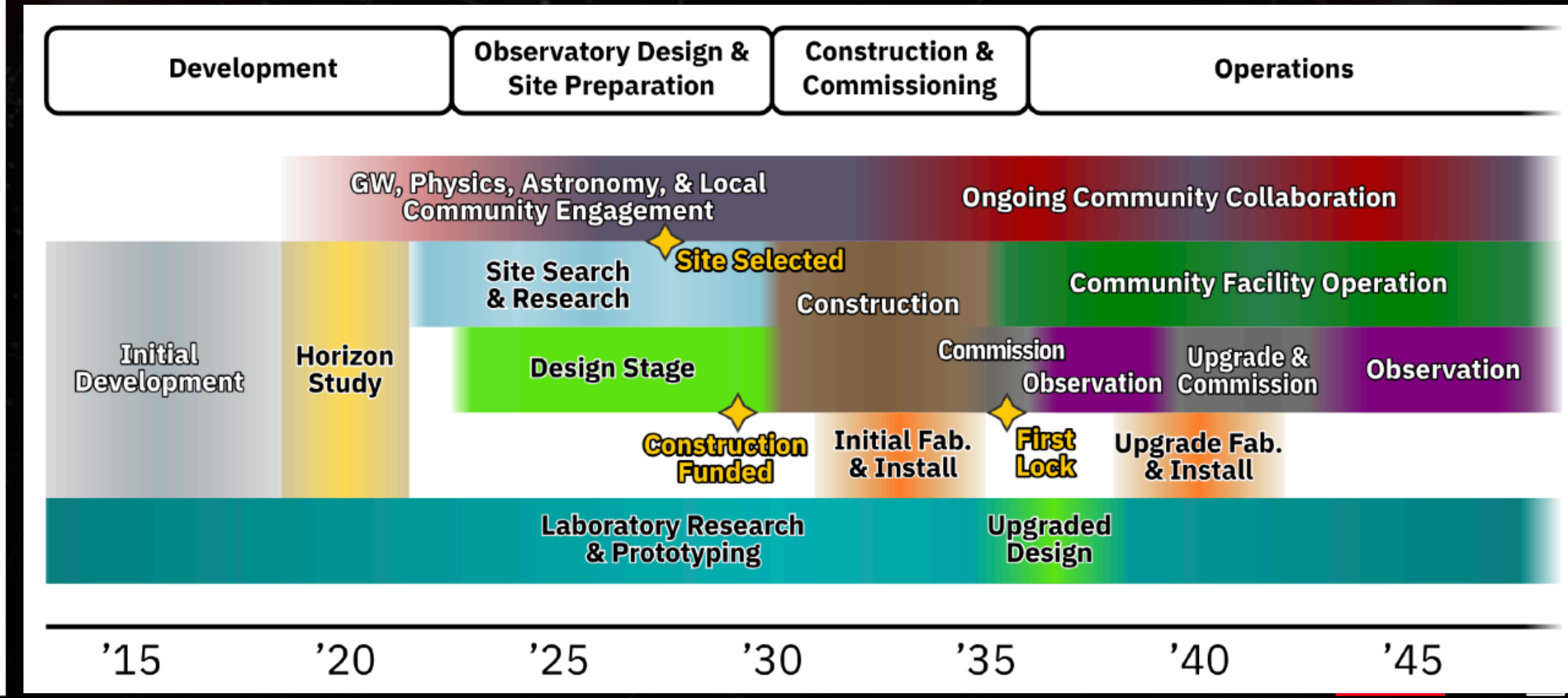



Crédit: Cosmic Explorer

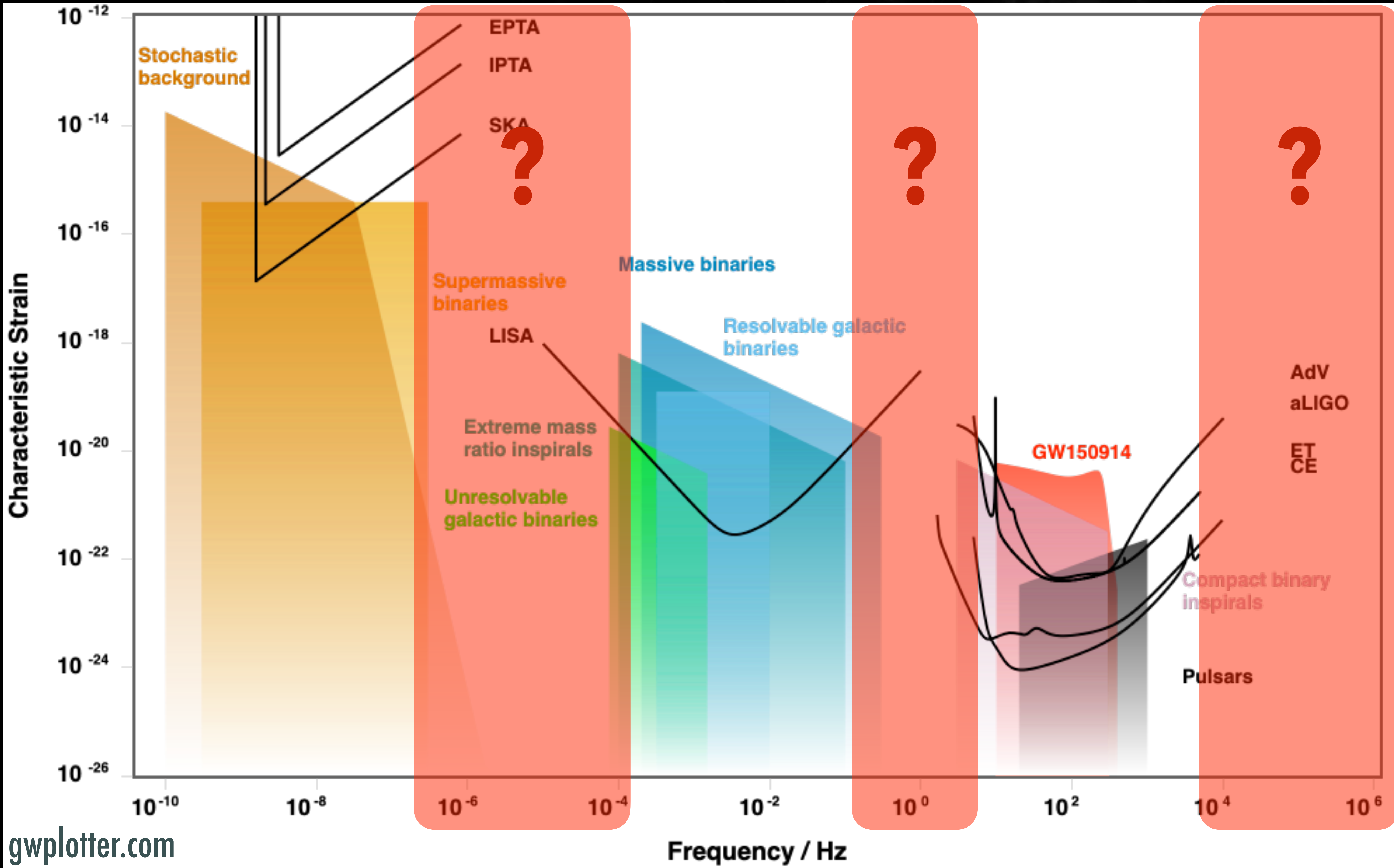


Horizon Study, Cosmic Explorer, 2021



# GW spectrum: current + future + ?



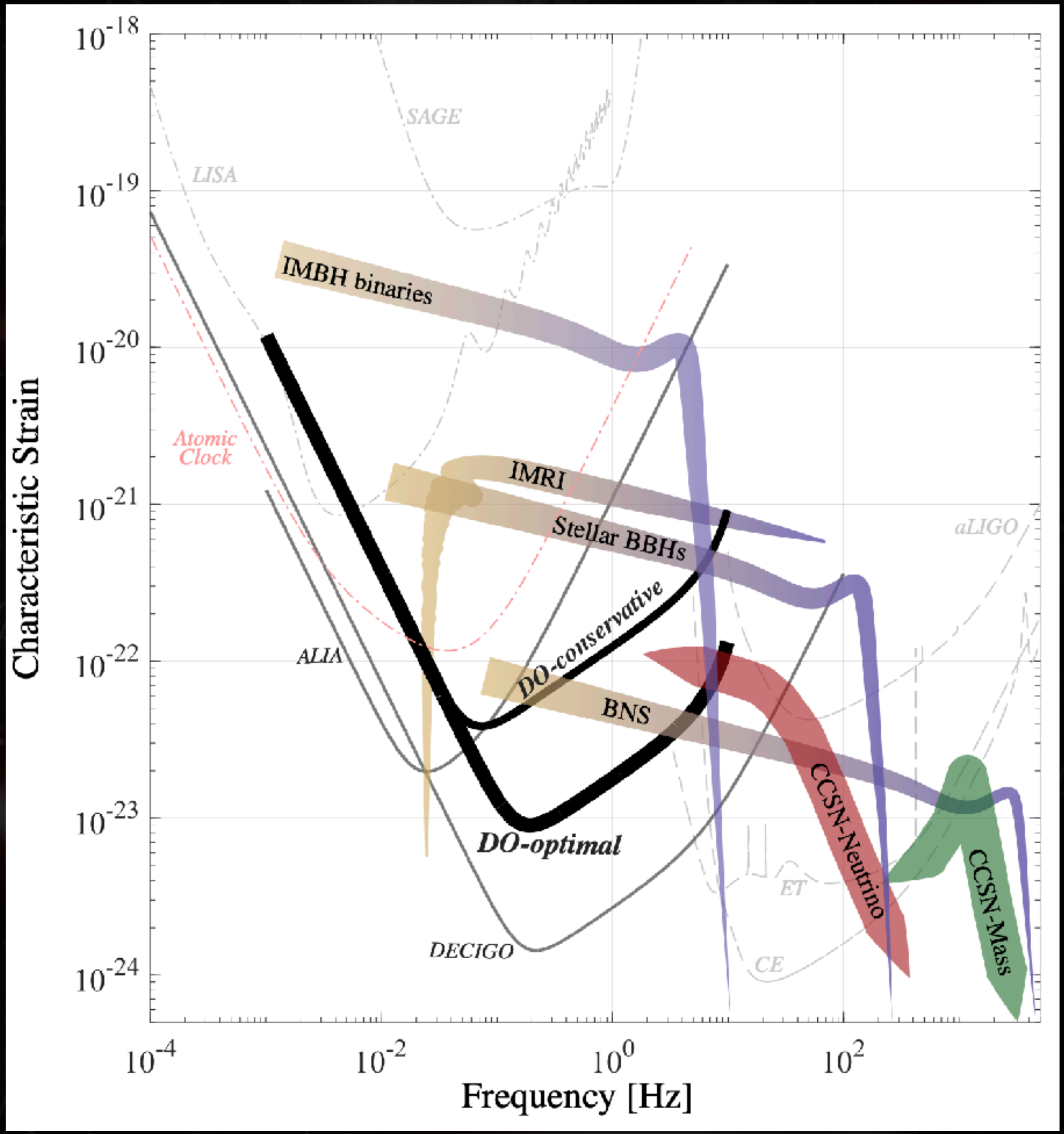

gwplotter.com


# Others space based GW projects

# 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 - Voyage 2050:
    - Science
    - Technical feasibility
    - …

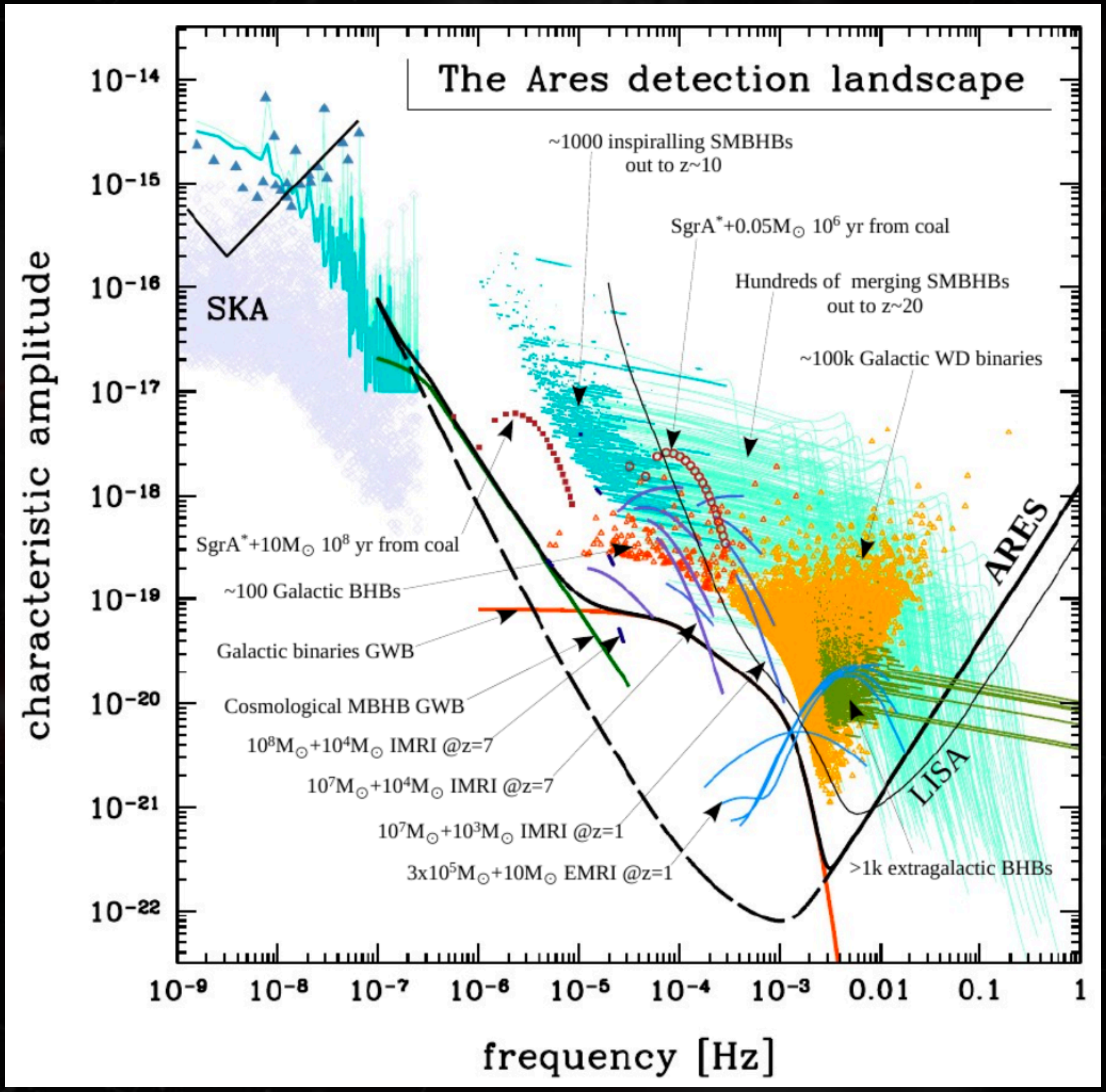
Sedda et al. 2020, gr-qc:1908.11375v3



# $\mu$ARES

- Proposal submitted at Voyage2050 (ESA call for science themes for L4, L5 & L6, 2040-2060):
- $10^{-6}$ – $10^{-2}$ Hz $\rightarrow \mu$Hz band
- On-going study in the LISA Consortium - Voyage 2050:
    - Science
    - Technical feasibility
    - …
- Arm of 1 AU

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



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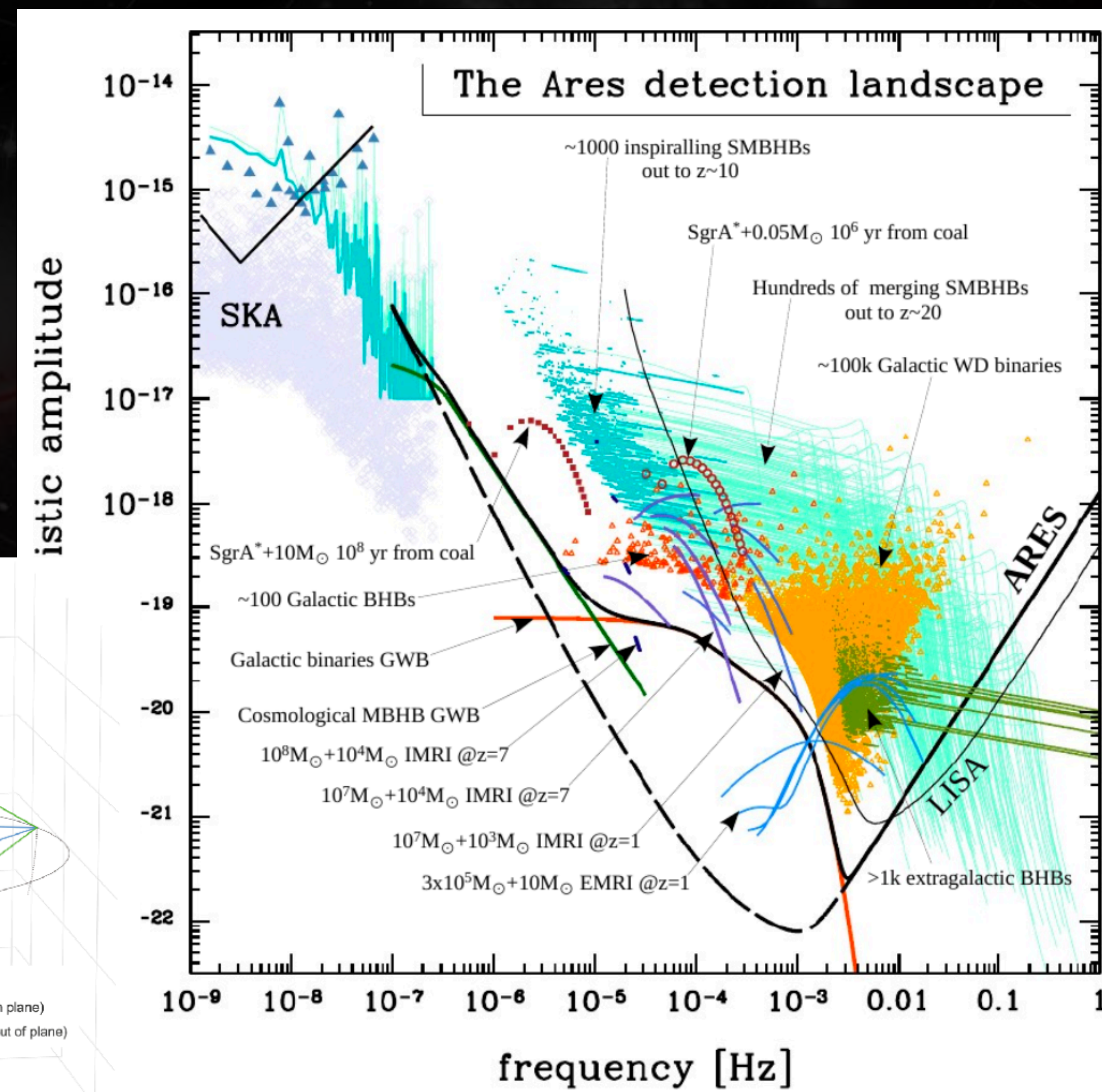
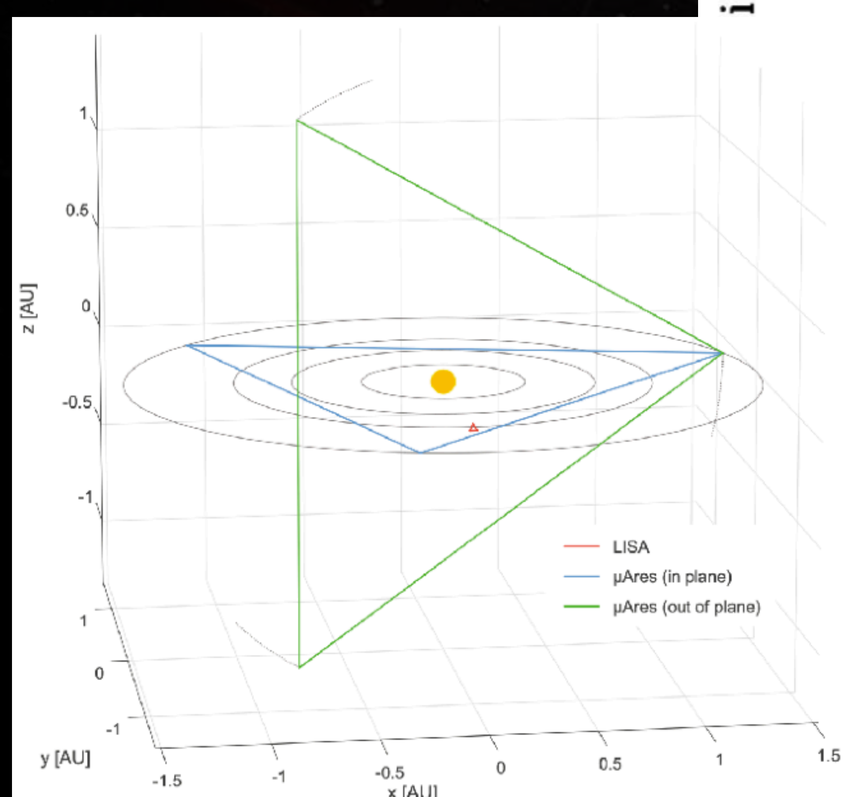
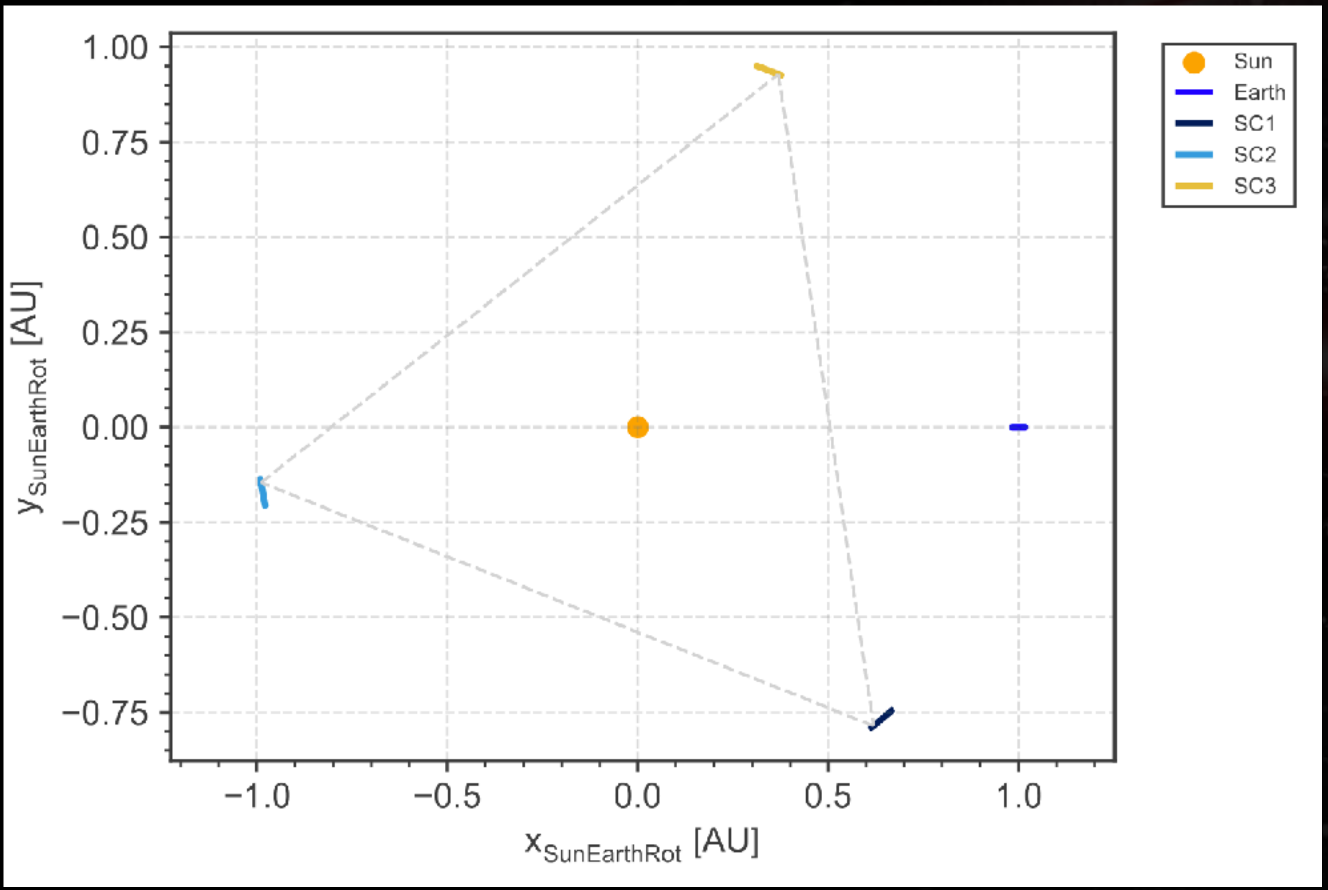
Sesana et al. 2021, Exp. Astro. 51:1333–1383

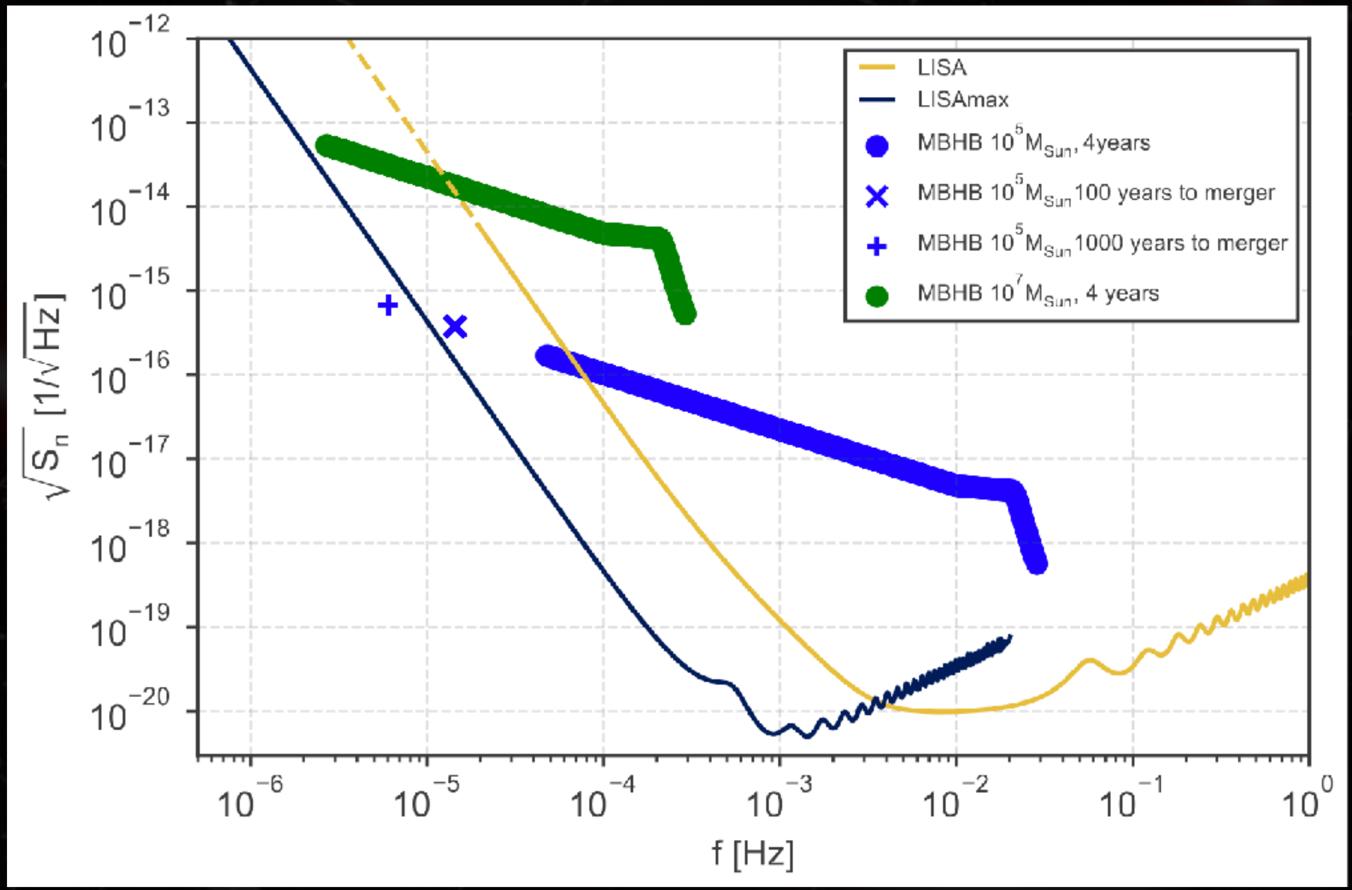


# LISAMax

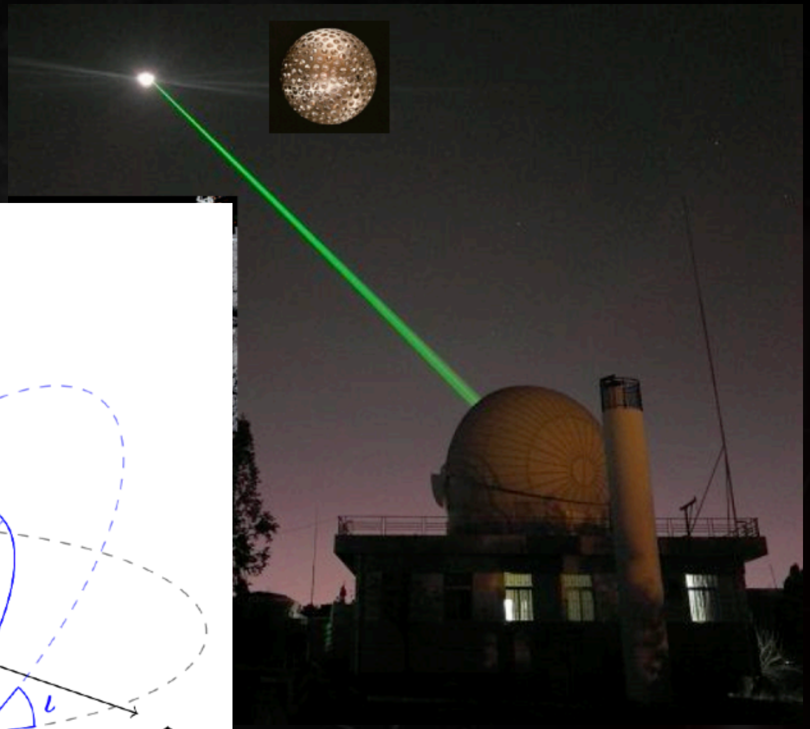
- LISA of 1 AU in the earth orbital plane
- Study for the orbits of the 3 spacecrafts: Martens, Khan & Bayle 2023, gr-qc:2304.08287v2
- Ongoing study of the scientific performances and feasibility (again in the context of Voyage2050)

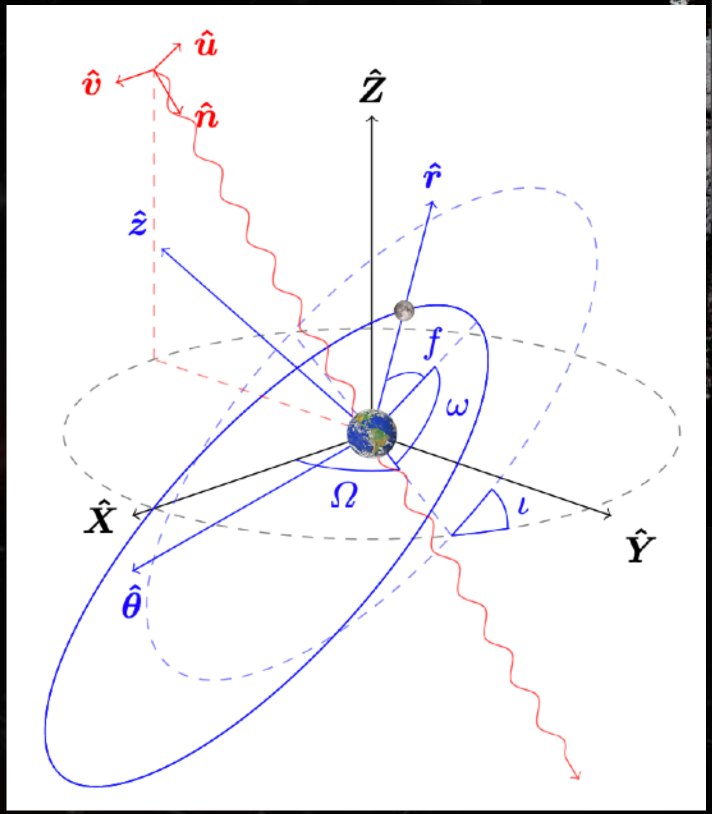


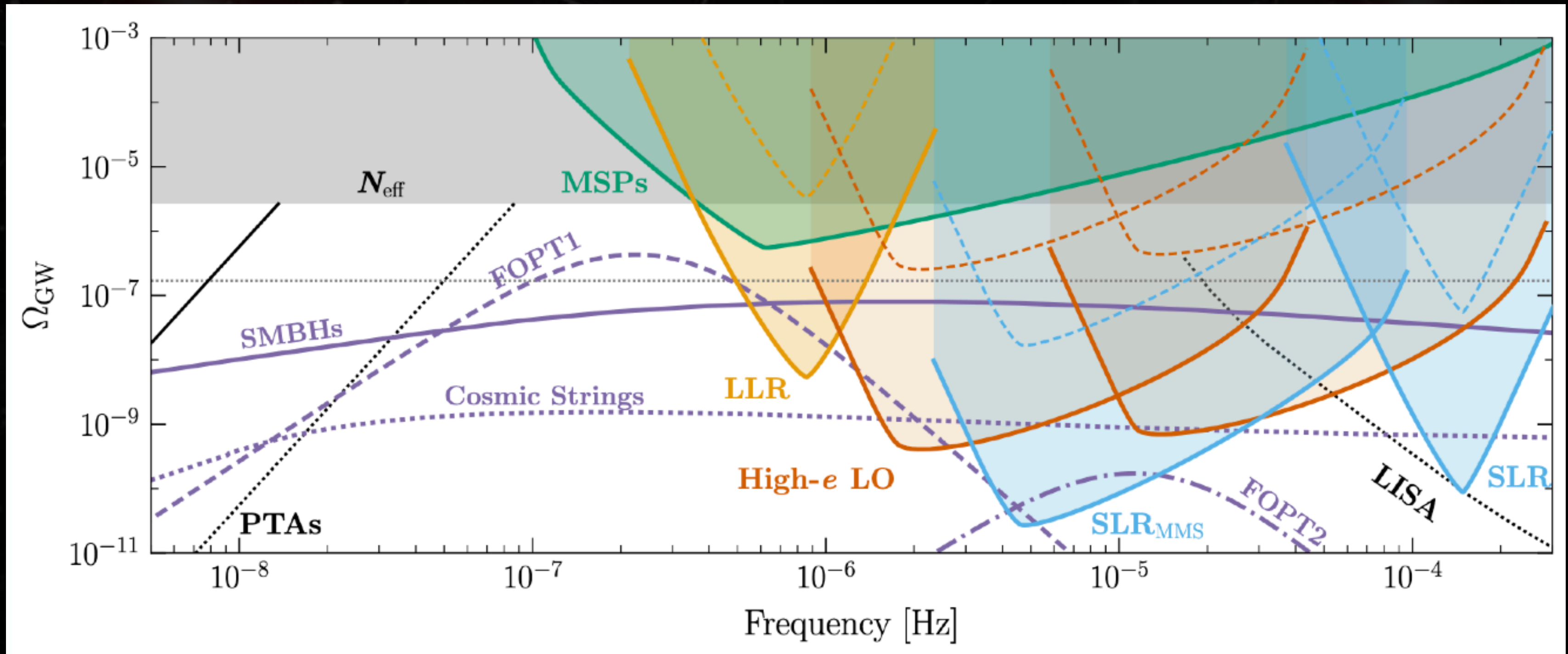



# Resonant absorption of GW in (artificial) binaries

- Principle:
  - Binary systems act as high-quality resonators
  - Efficient transfer of energy and momentum between the orbit and GW
  - Leading to potentially detectable orbital perturbations.
- Design:
  - Few passive spacecrafts in eccentric orbits around Earth
  - Precise spacecraft orbits measurements with Laser Ranging
- Science:
  - Gravitational waves in the $\mu$Hz regime
  - Ultra-light Dark Matter
- Status:
  - Project submitted to the on-going call for mission F3 at ESA
- References:
  - https://arxiv.org/abs/2504.16988
  - https://arxiv.org/abs/2504.15334
  - https://arxiv.org/abs/2506.11802



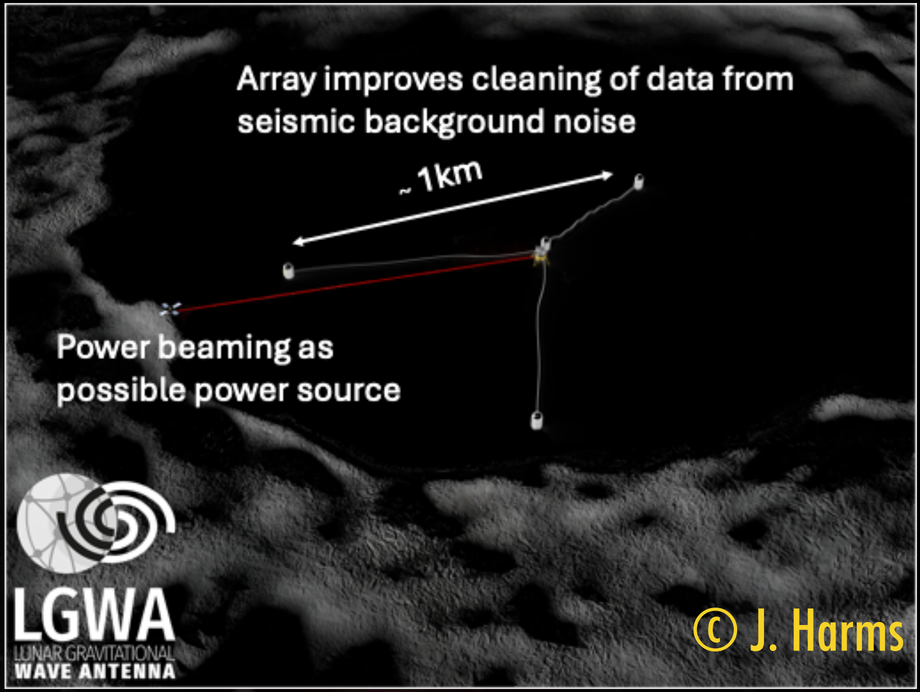


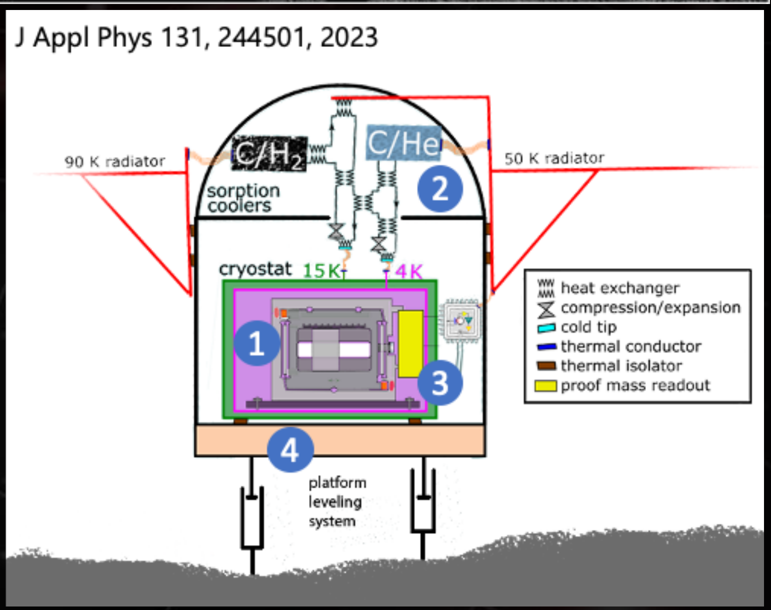



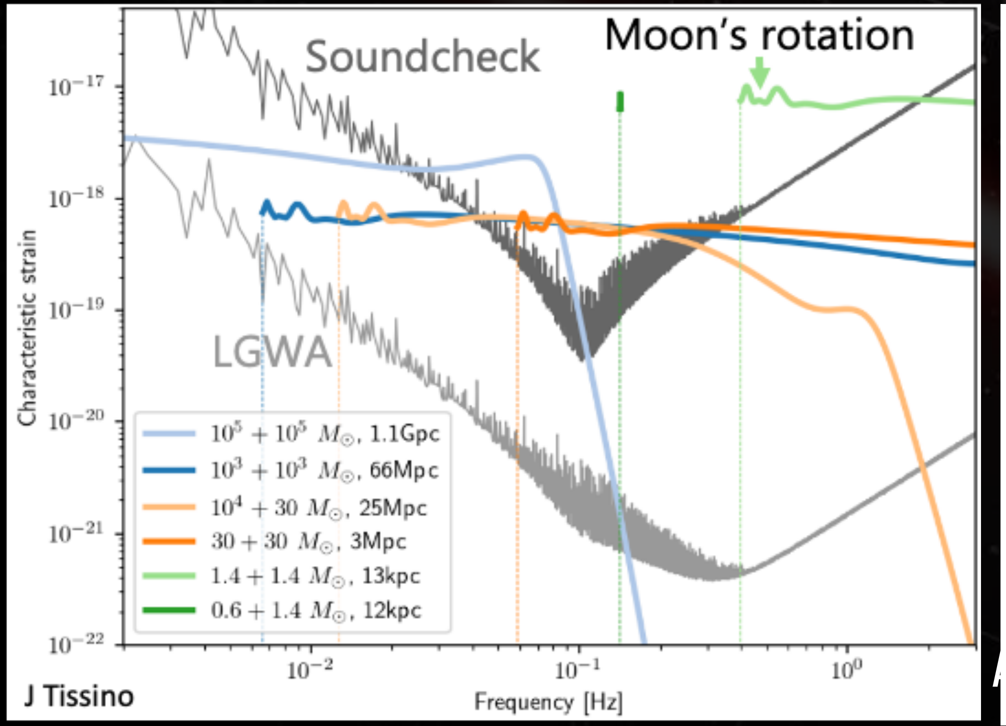

# Moon based GW projects

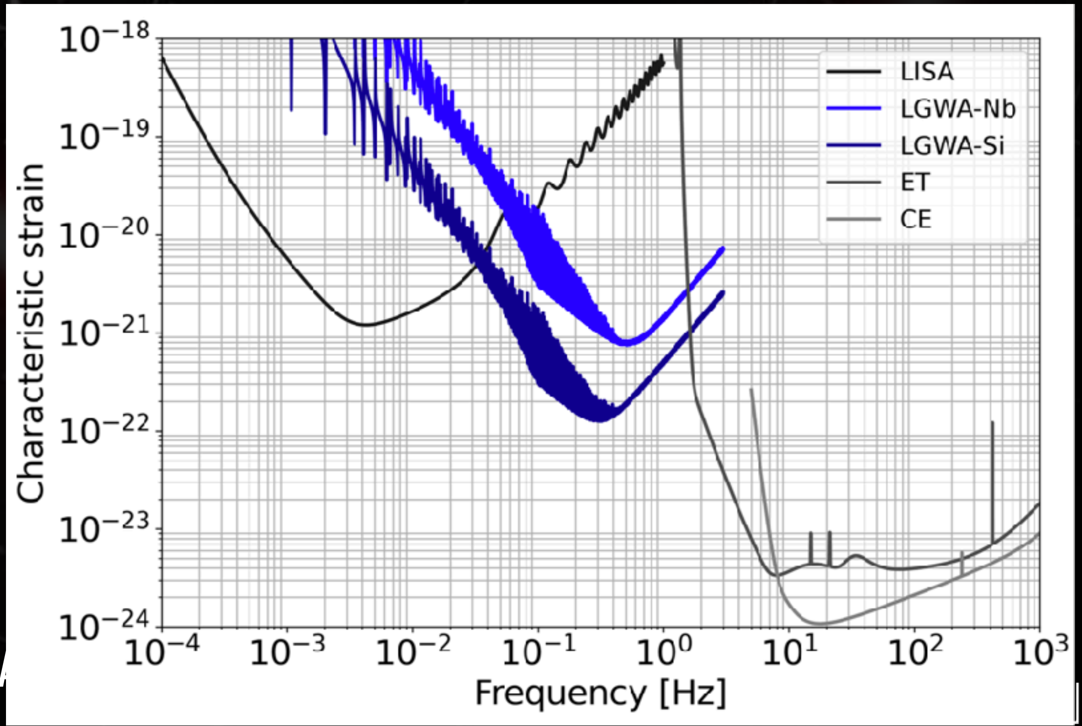
# LGWA

- 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



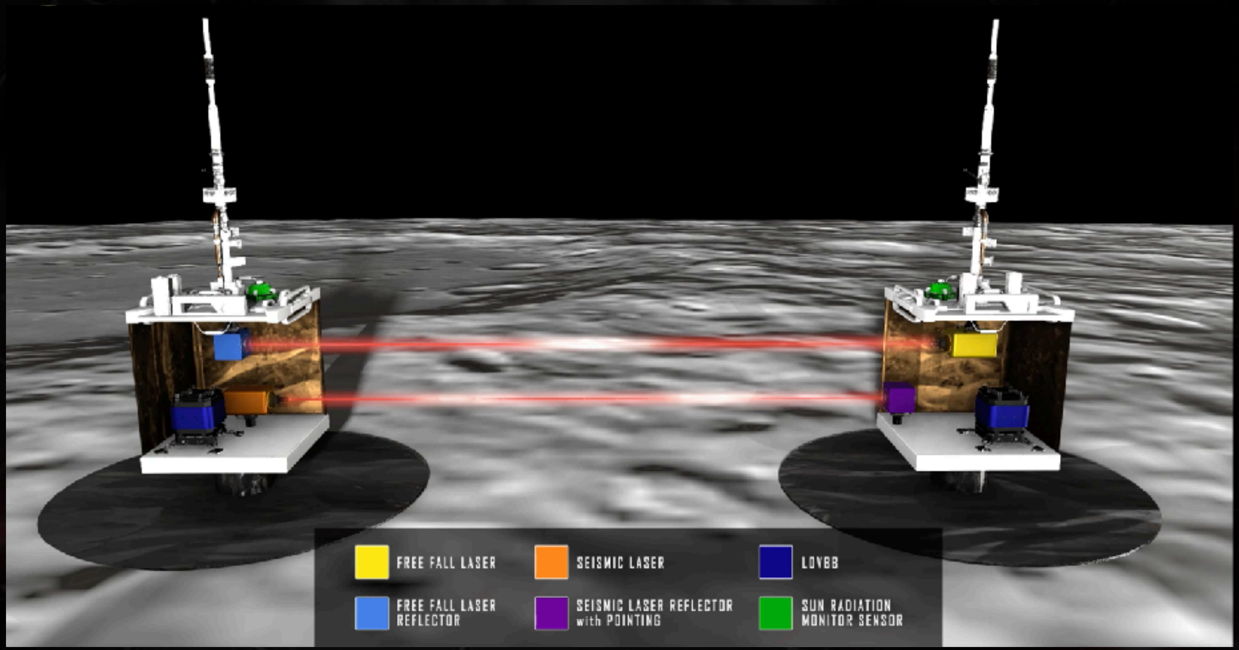



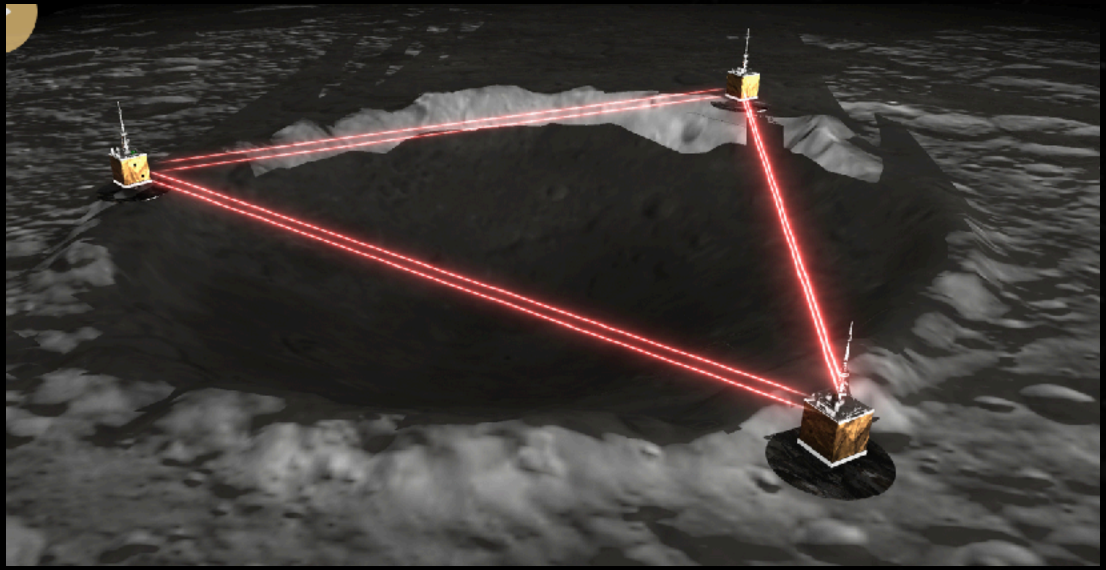

LGWA Workshop https://indico.ict.inaf.it/event/2782/

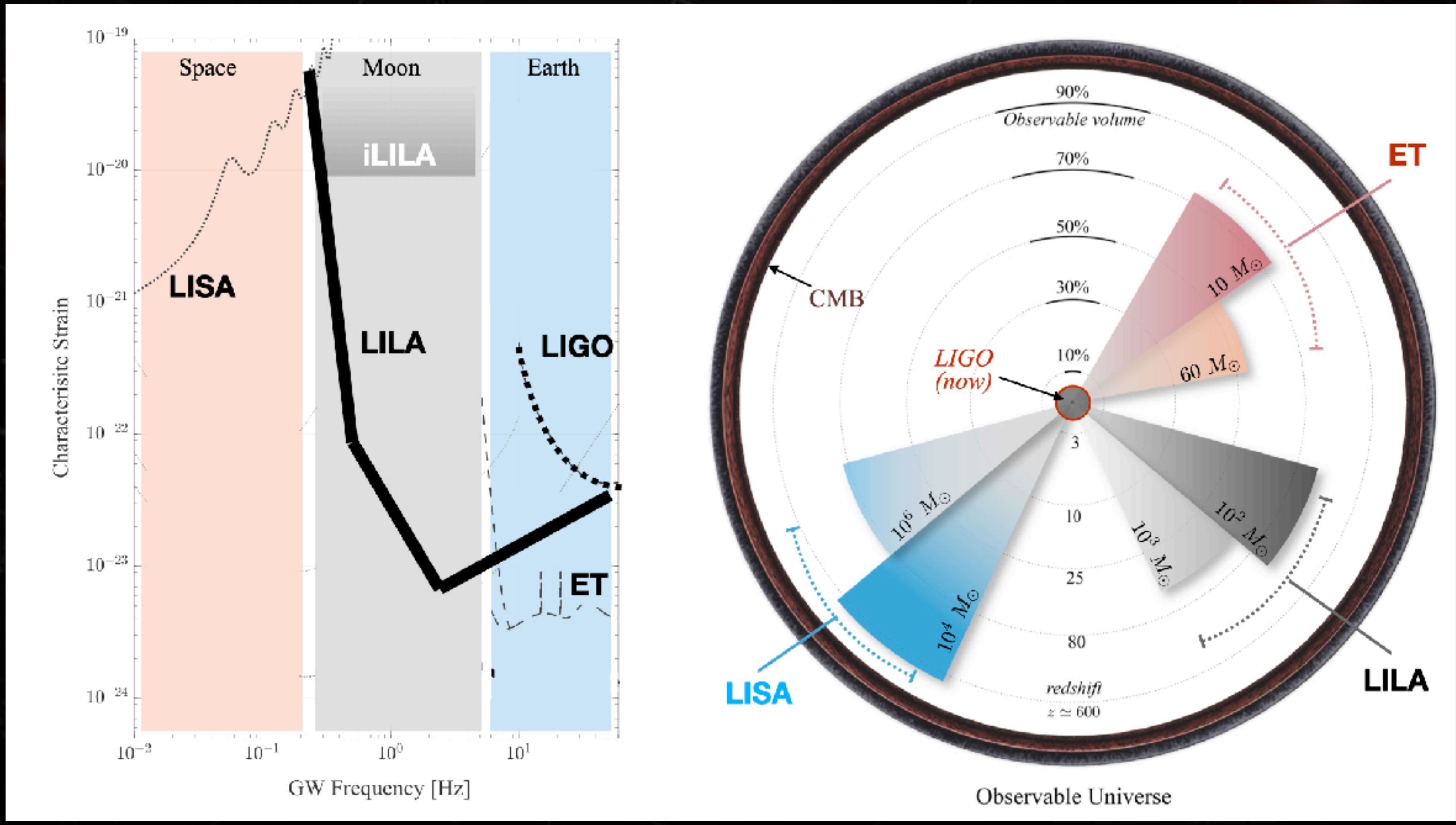
# LILA

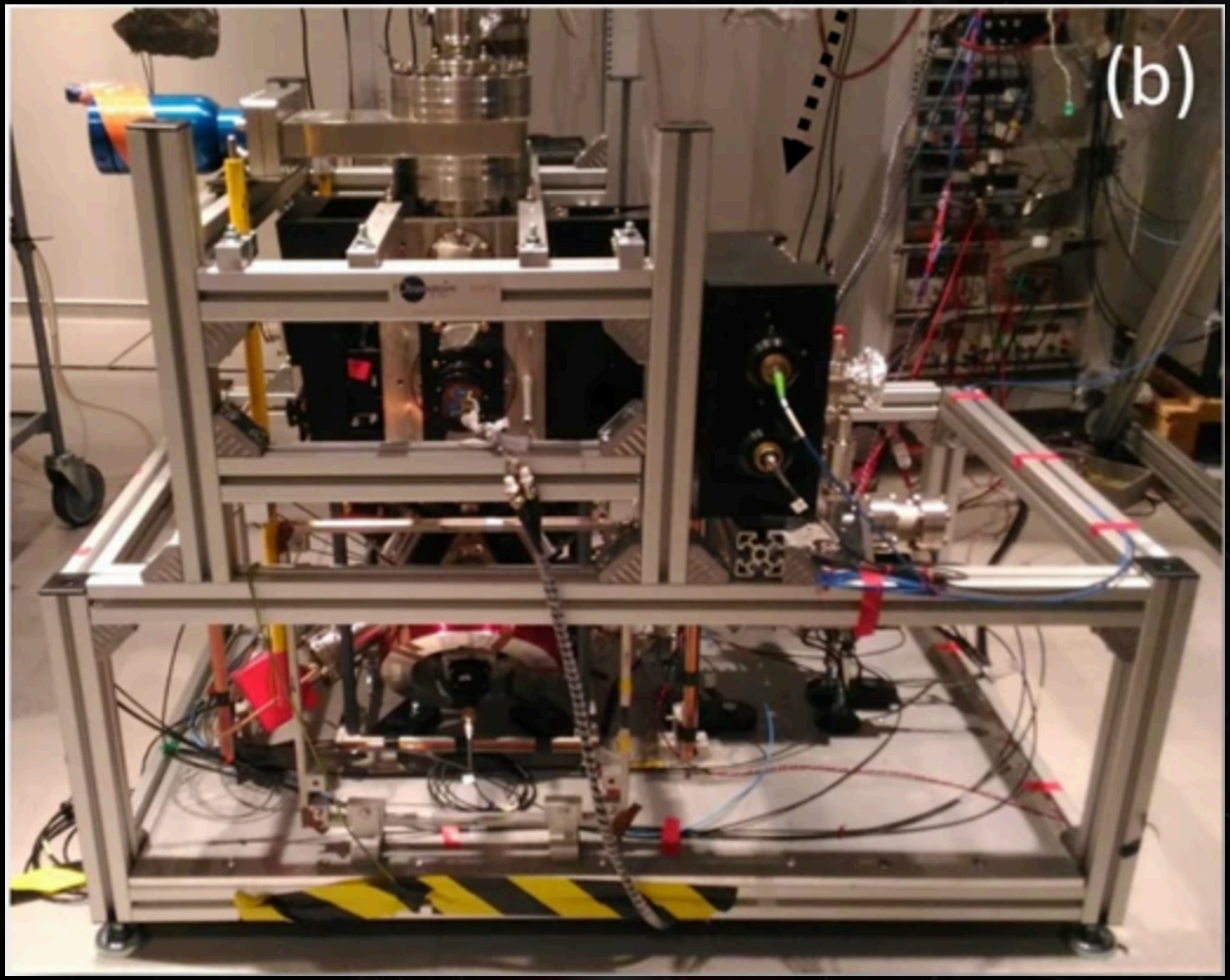
- Laser Interferometer Lunar Antenna
  - 3 landers placed in triangular shape (few km)
  - Payload: mirrors, lasers, seismic isolation
- 2 different ways to detect GW:
  - Space-time induced between free falling masses
  - Vibration of the Moon induced by passing GW
- Sub-Hertz frequencies
- GW sources:
  - 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/







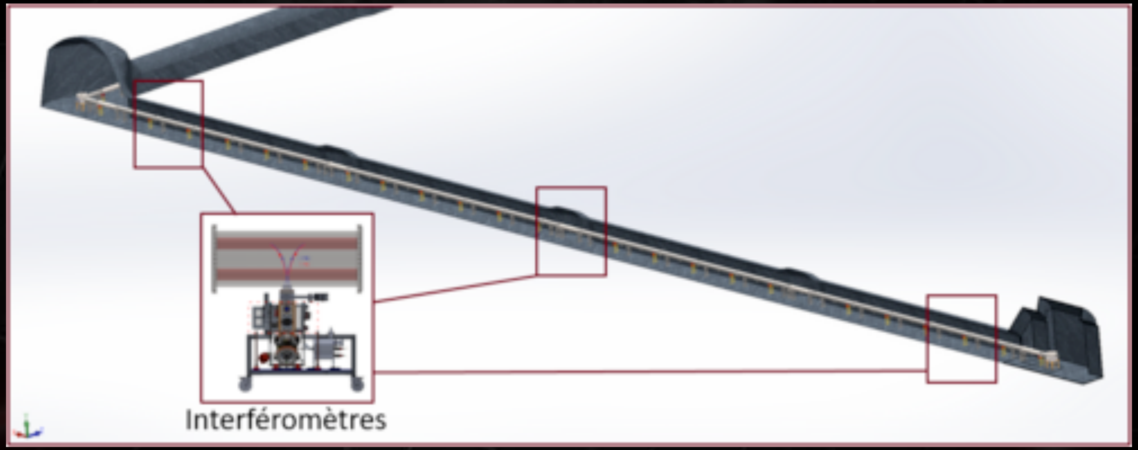
Credit: MIGA, Nature 14064 (2018)

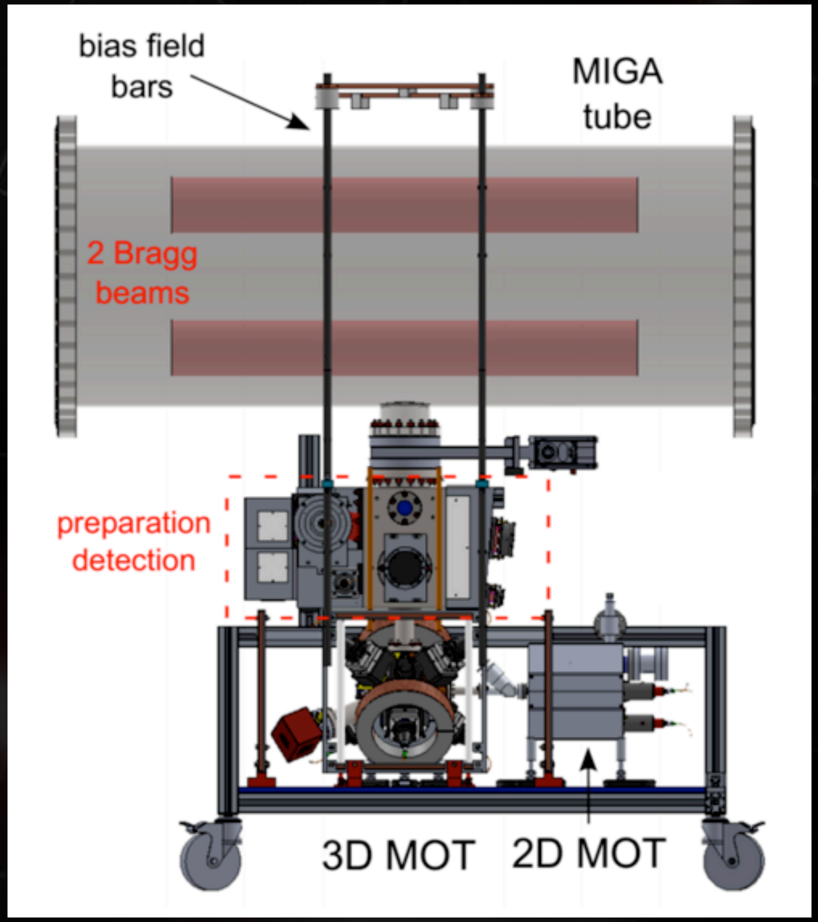
# Atom interferometry

# MIGA

- Principle:
  - Use cold atoms to measure the gravity gradient
  - 3 atom interferometers on 150m horizontal arms, each one measuring the local acceleration
    → difference = local gravity gradient
  - Reference laser beam in vacuum common to all interferometers
- Prototype with limited sensitivity
- Science:
  - Earth gravity field
  - Prototype for future GW observatories in the band 0.1 - 10 Hz
- Status:
  - On-going building in Laboratoire Souterrain Bas Bruit in Provence Alpes Côte d'Azur

Crédit: MIGA



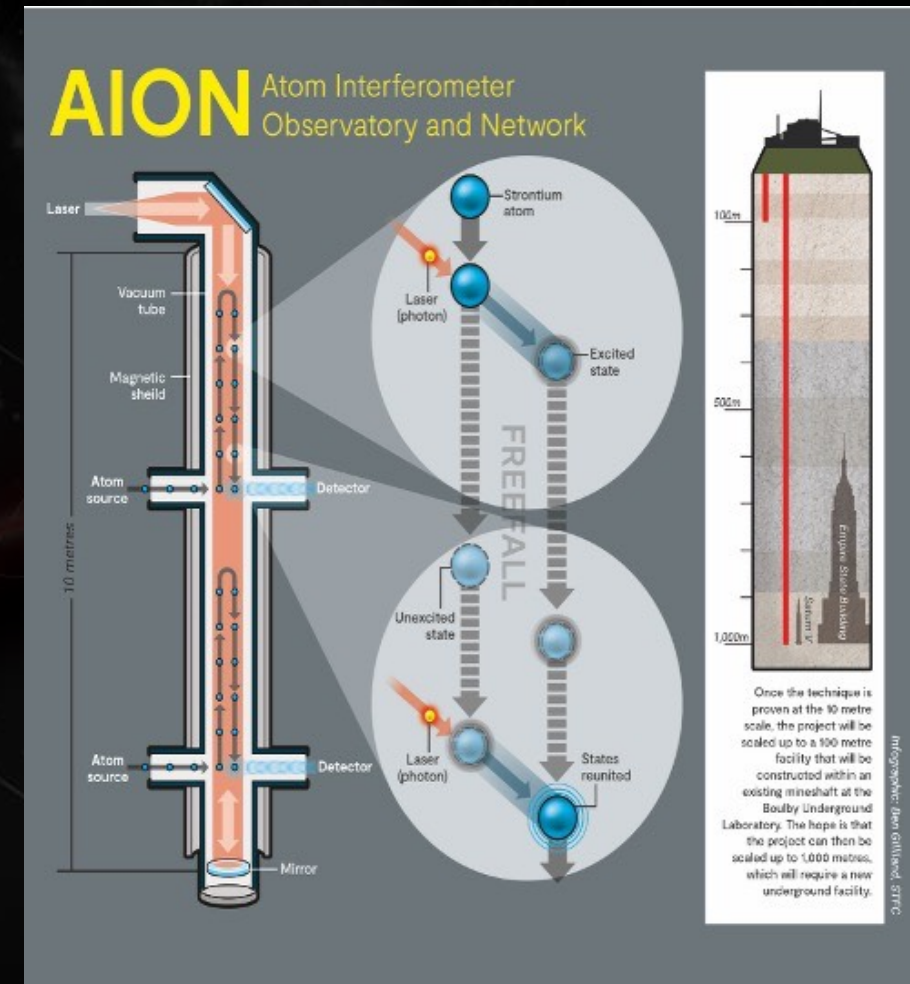



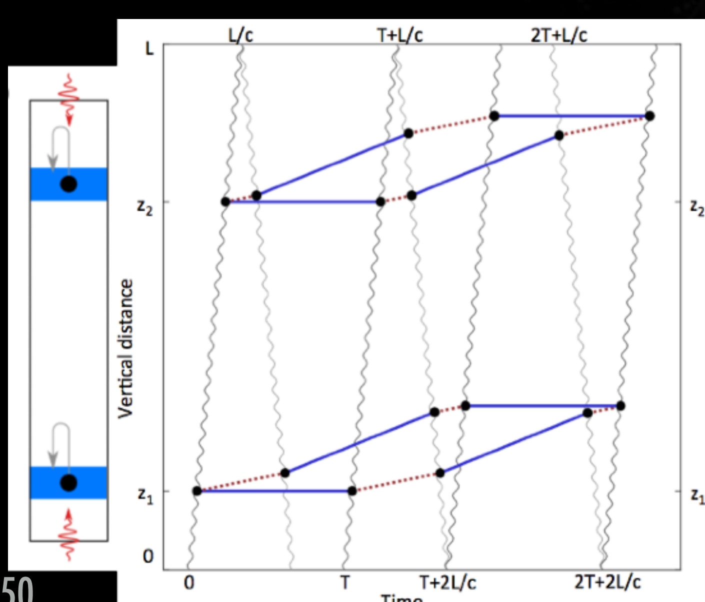
# AION

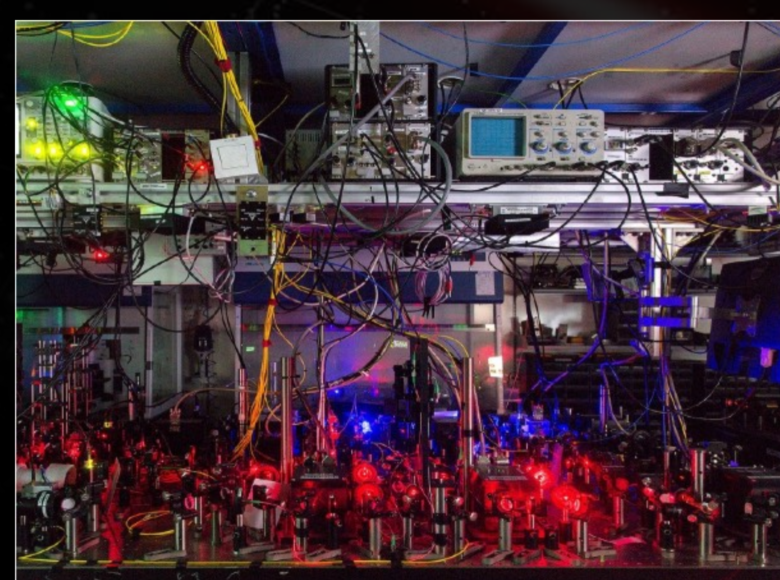
Crédit: O. Buchmueller

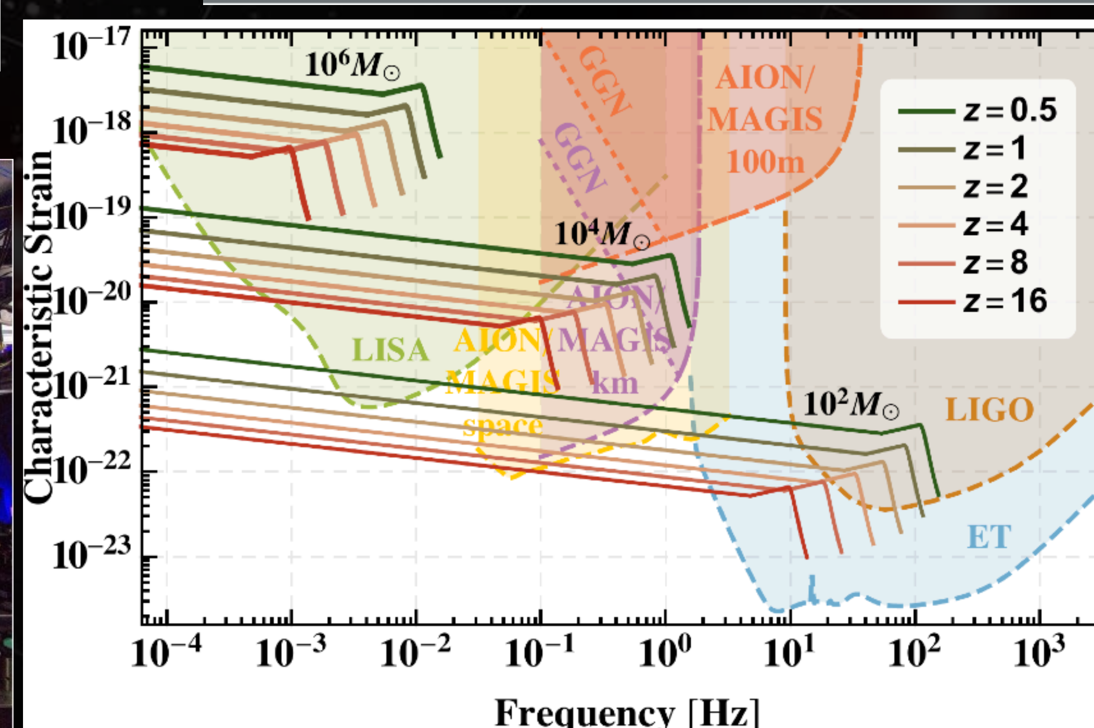
- "Interference between wave-packets of laser-cooled atoms to search for gravitational waves and dark matter"
- Vertical atom interferometer with several versions increasing in length developed in UK
- 10m prototype currently under construction at the University of Oxford

| Sensitivity Scenario | L [m] | $T_{int}$ [sec] | $\delta\phi_{\text{noise}}$ [$1/\sqrt{\text{Hz}}$] | LMT [number $n$] |
|---|---|---|---|---|
| AION-10 (initial) | 10 | 1.4 | $10^{-3}$ | 100 |
| AION-10 (goal) | 10 | 1.4 | $10^{-4}$ | 1000 |
| AION-100 (initial) | 100 | 1.4 | $10^{-4}$ | 1000 |
| AION-100 (goal) | 100 | 1.4 | $10^{-5}$ | 40000 |
| AION-km | 2000 | 5 | $0.3 \times 10^{-5}$ | 40000 |



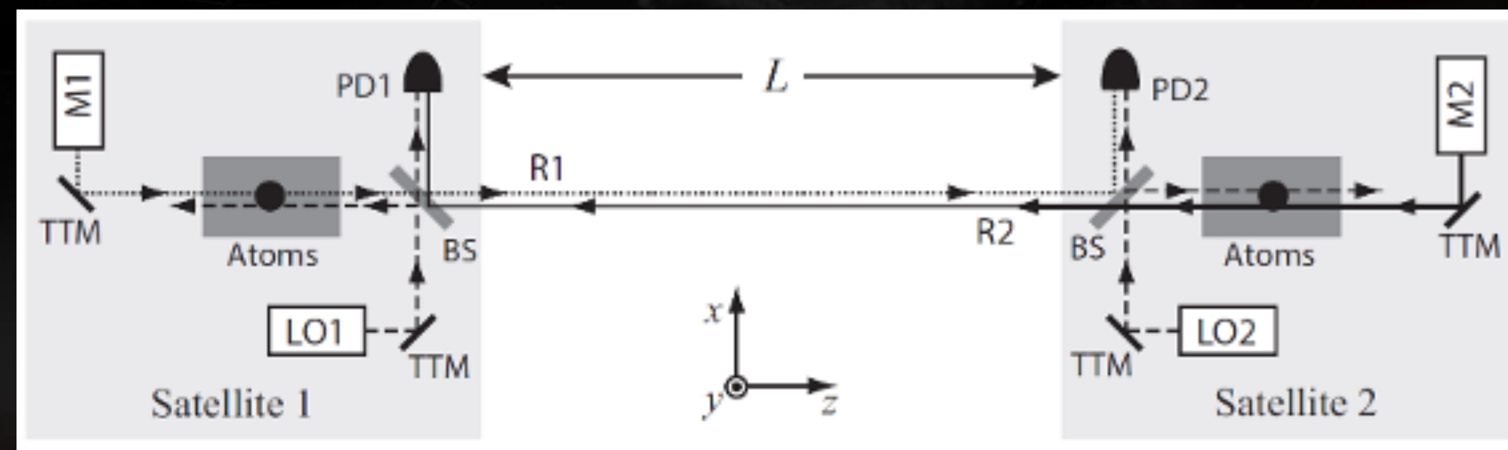



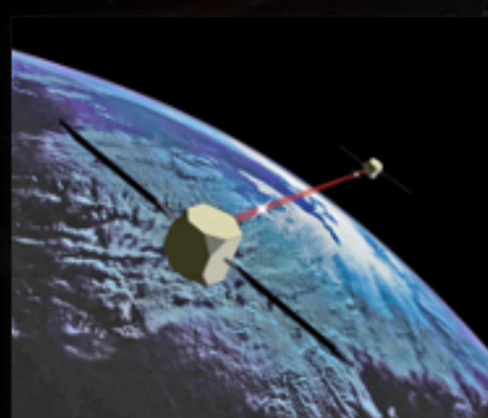


# AEDGE

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

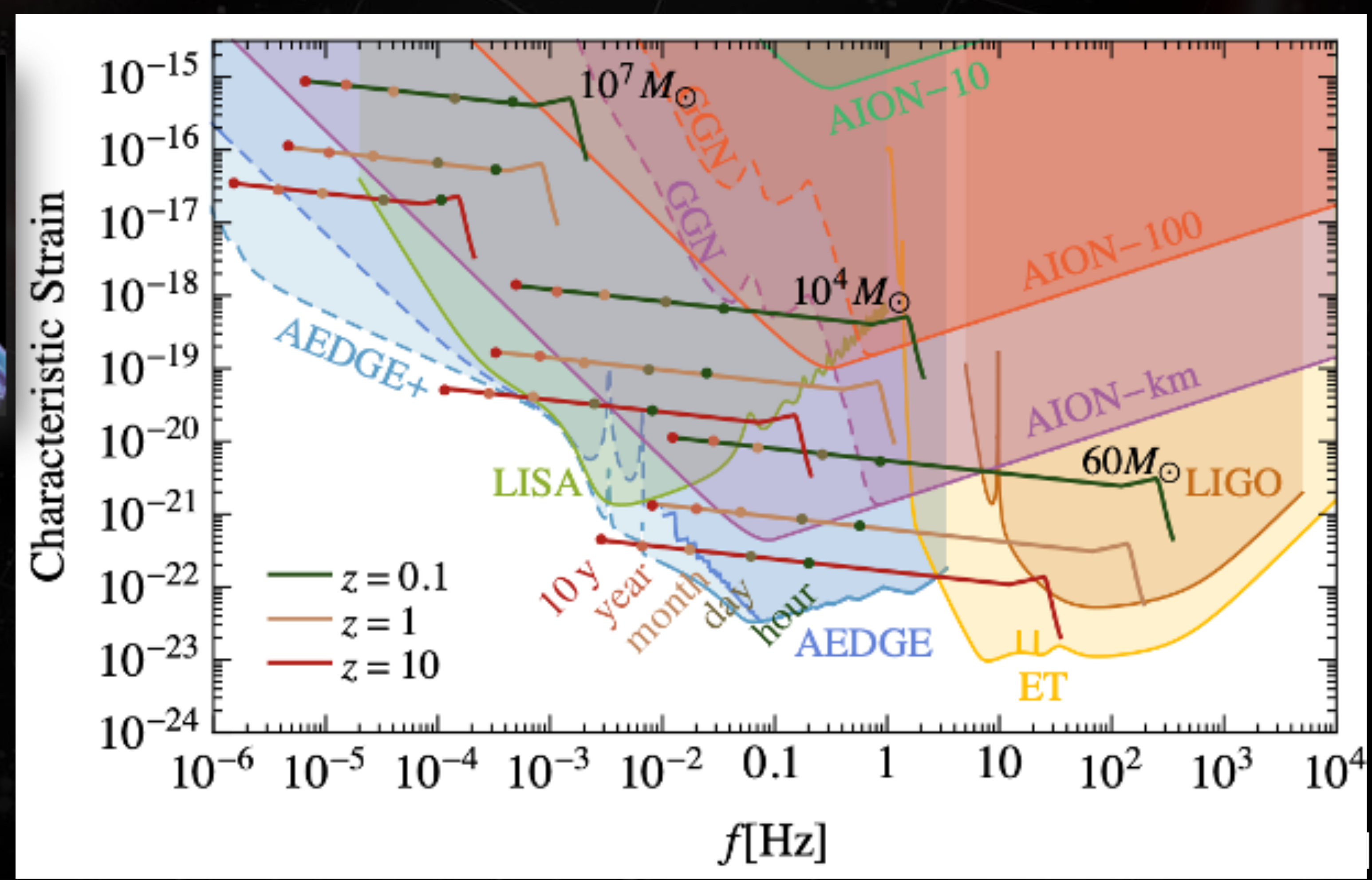
Abou El-Neaj et al. 2029, gr-qc:1908.00802



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

Crédit: O. Buchmueller



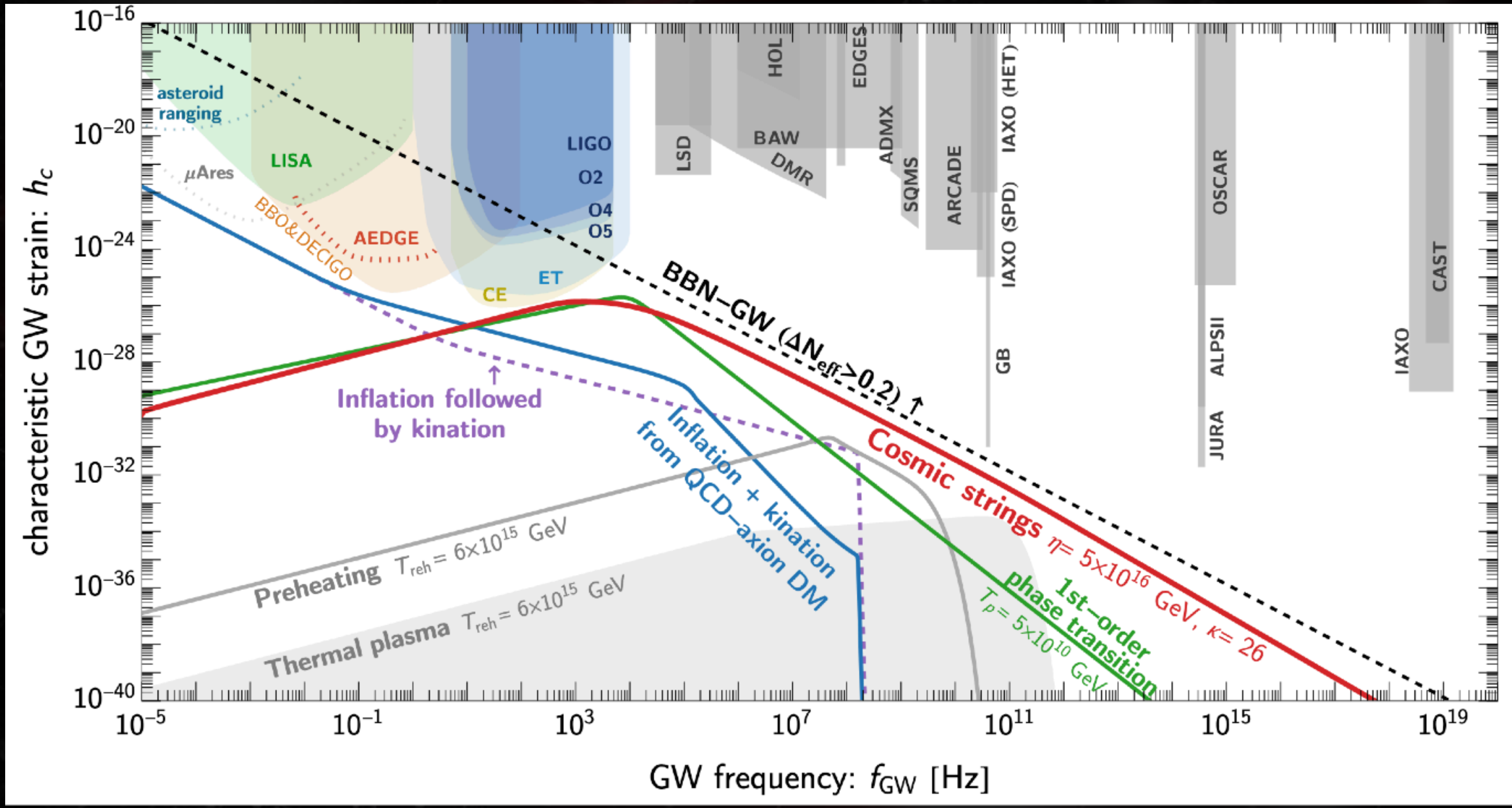
Credit: DESY

# Ultra-high frequency projects

# GW at ultra-high frequency

- GW at frequency > kHz ; instruments used to search for axions
- Ideas for detectors:
  - High-energy pulsed laser
  - Transverse static magnetic field
  - Resonant bars or magnets
  - …
- Hypothetical GW sources :
  - cosmic string,
  - First order phase transition at $10^{10}$ GeV,
  - Primordial BHs
  - …

Credit: Servant et al. 2023




- Workshop on the topic in 2023: https://indico.cern.ch/event/1257532/overview

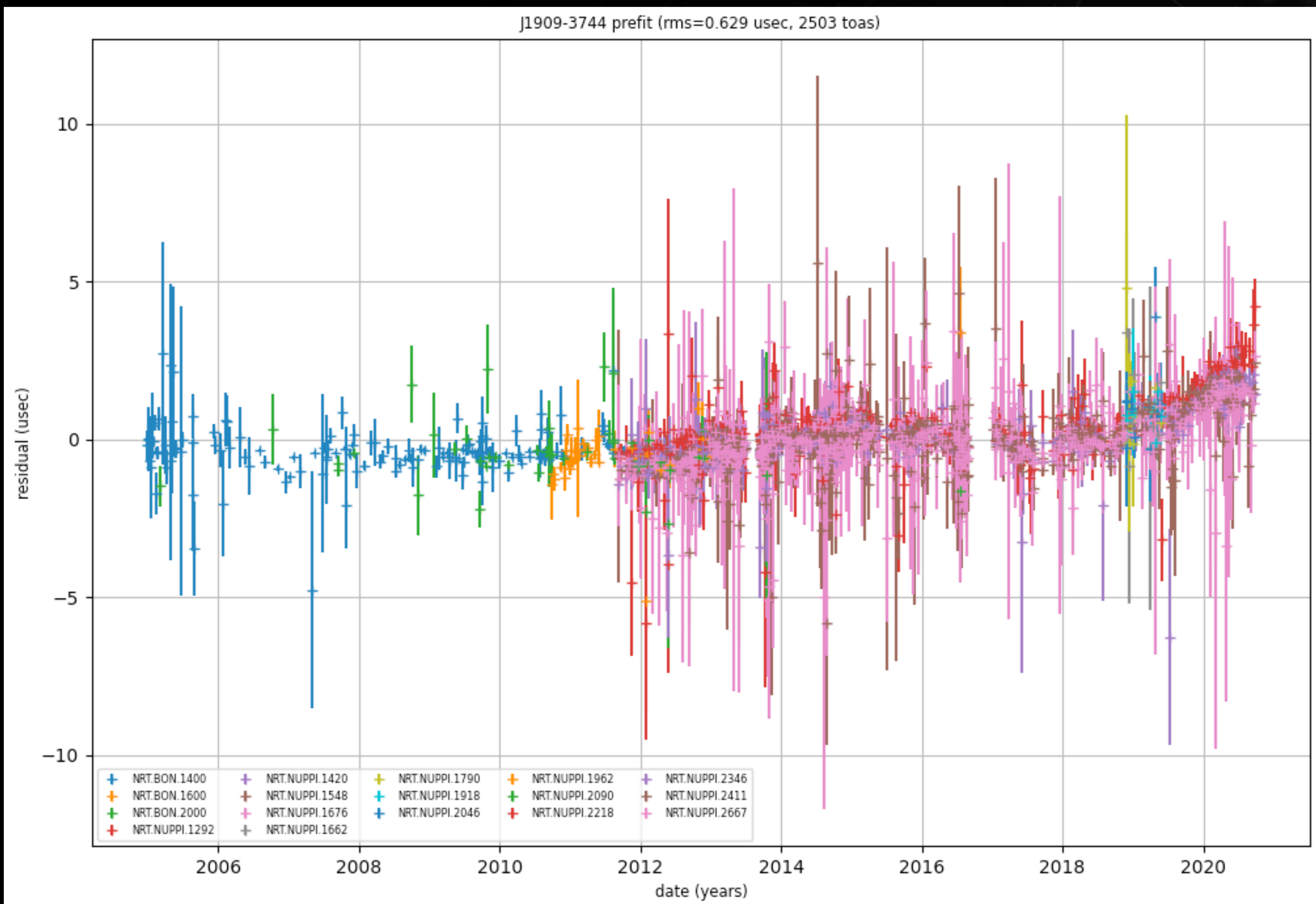
# Conclusion

- Since the first direct detection of gravitational waves in 2015, there are a lot of new results:
  - At high frequency (10-1000 Hz), LVK detected ~300 binaries with many outstanding events
  - At very low frequency, strong evidence for GW signal from 3 PTA collaborations
- Many more results in the next decades from decided projects:
  - ~2026 : IPTA
  - ~2032 : SKA PTA
  - ~ 2037 : LISA
  - ~ 2040 : Einstein Telescope & Cosmic Explorer
- Many more ideas:
  - Advanced interferometer in space,
  - Atoms interferometry,
  - Resonant artificial binaries,
  - Ultrahigh frequency
- Observation of Universe with GW is a new field growing very quickly with a very bright future and many connexion with others fields !

# Thank you

# Pulsar timing

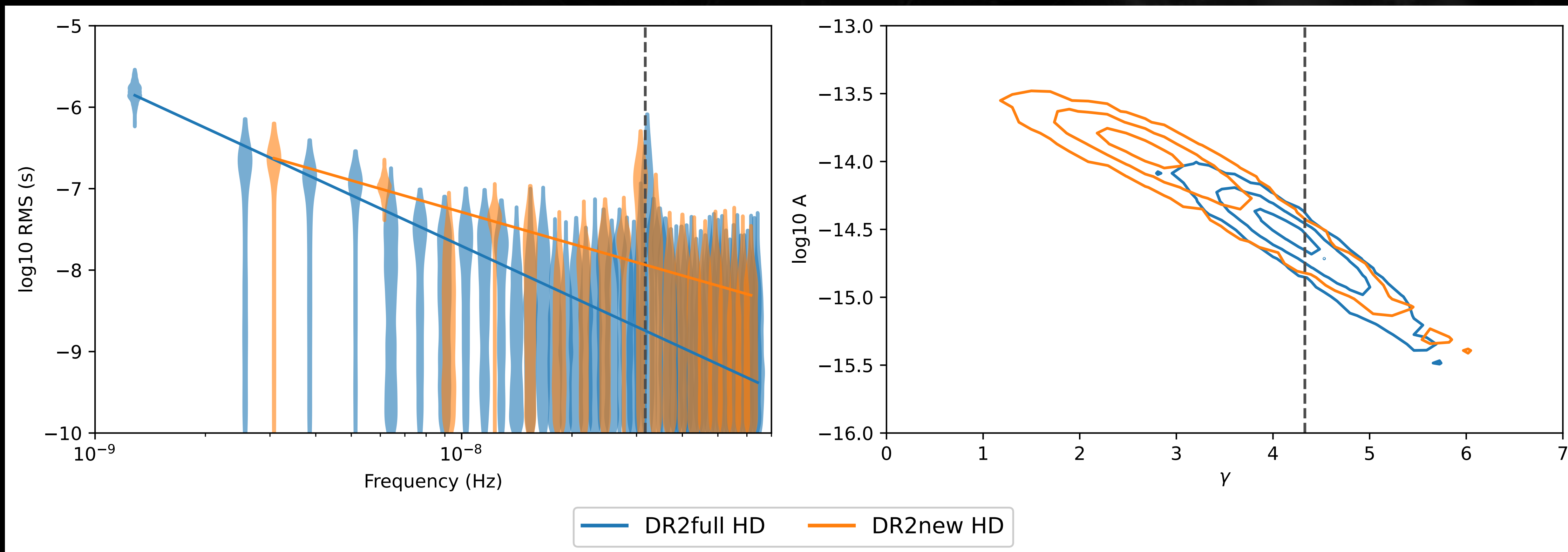
- Examples:
  - J1909-3744:




| 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 |

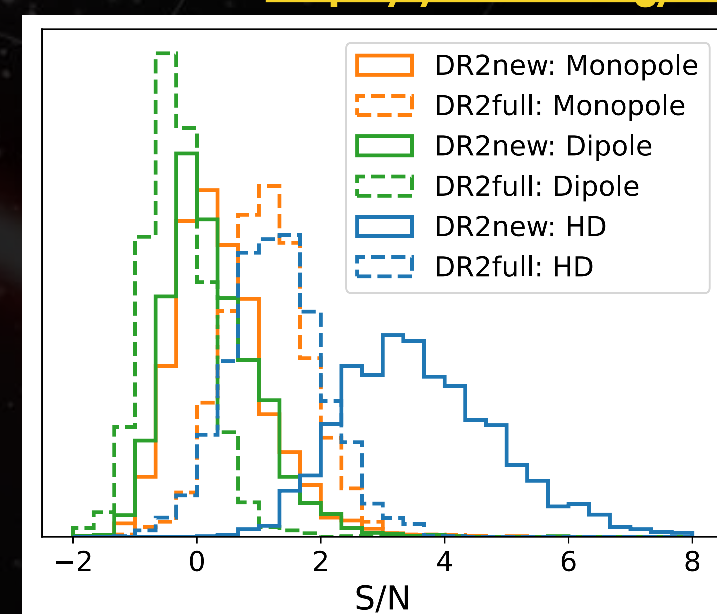
# EPTA results: evidence for GWs

- Free spectrum — Posterior for GWB parameters



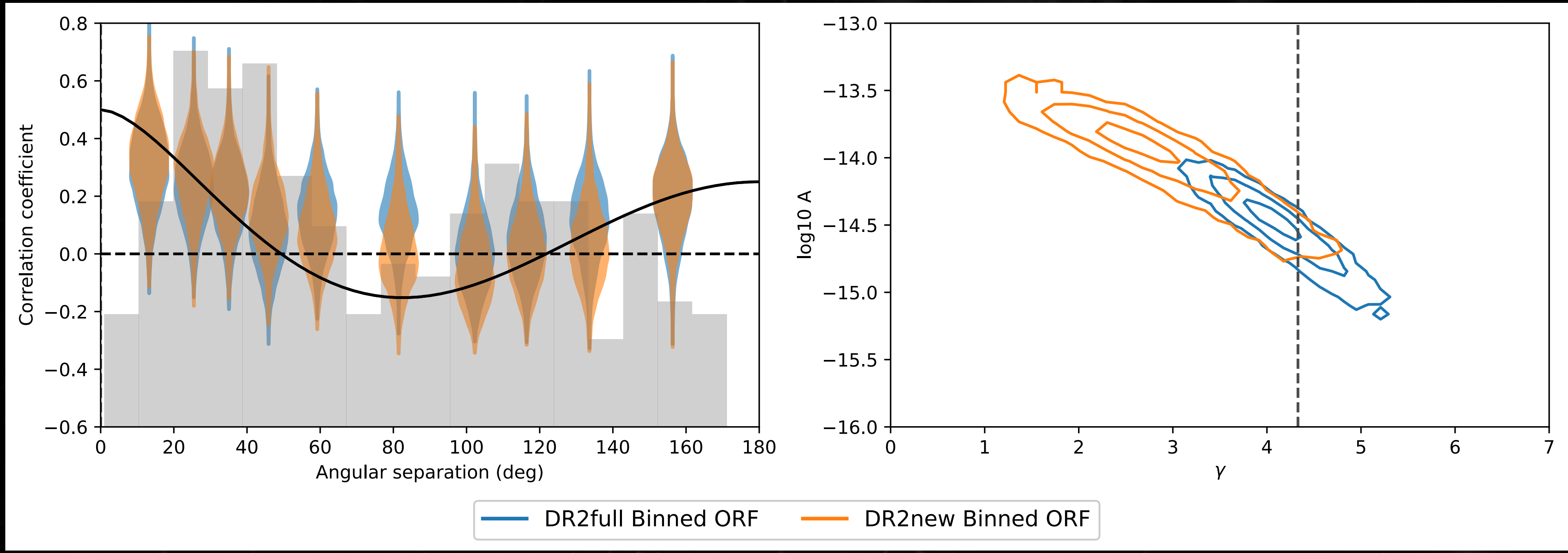

https://arxiv.org/abs/2306.16214

- 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

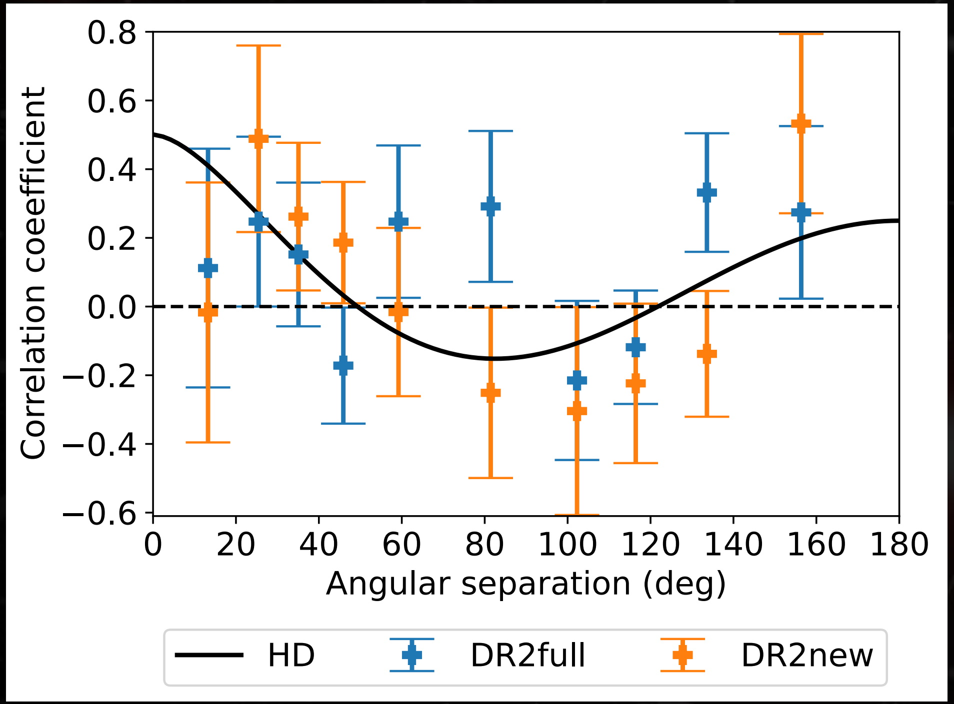


# EPTA results: evidence for GWs

- Spatial correlation: overlap reduction function
  - Binned



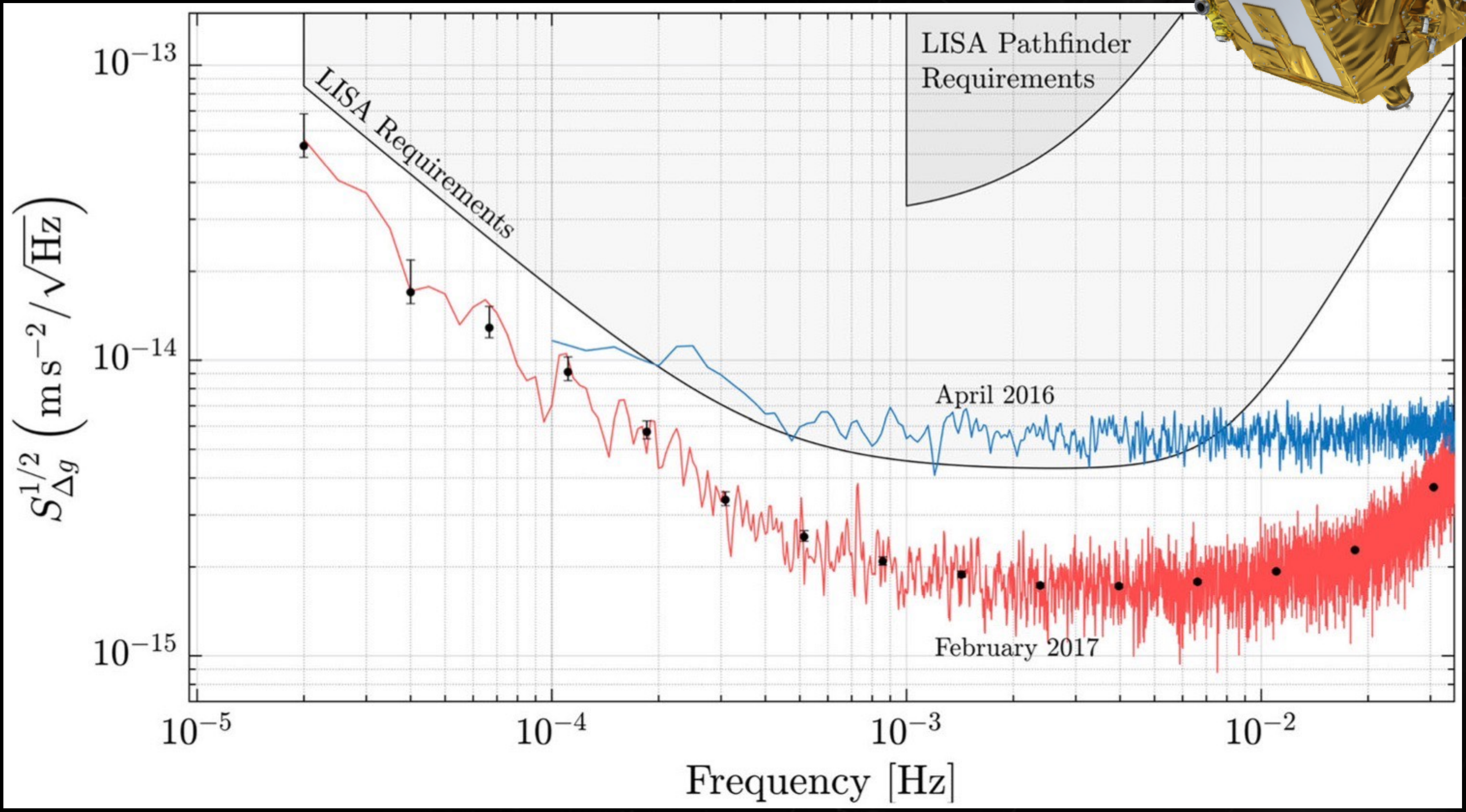

  - Optimal statistic

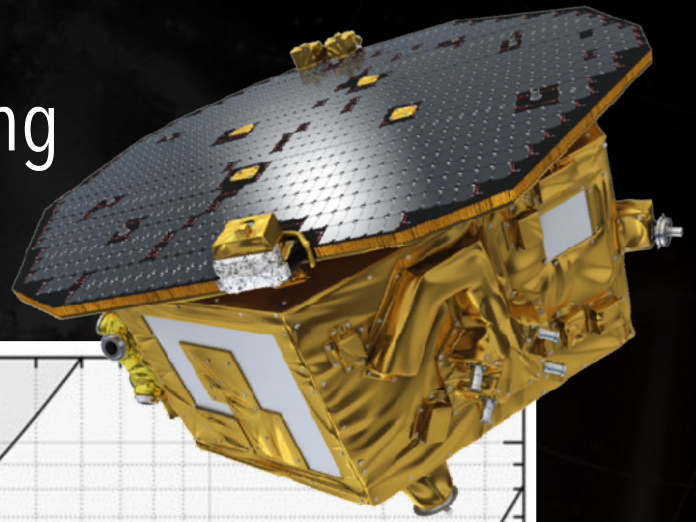



https://arxiv.org/abs/2306.16214

# LISAPathfinder final main results

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

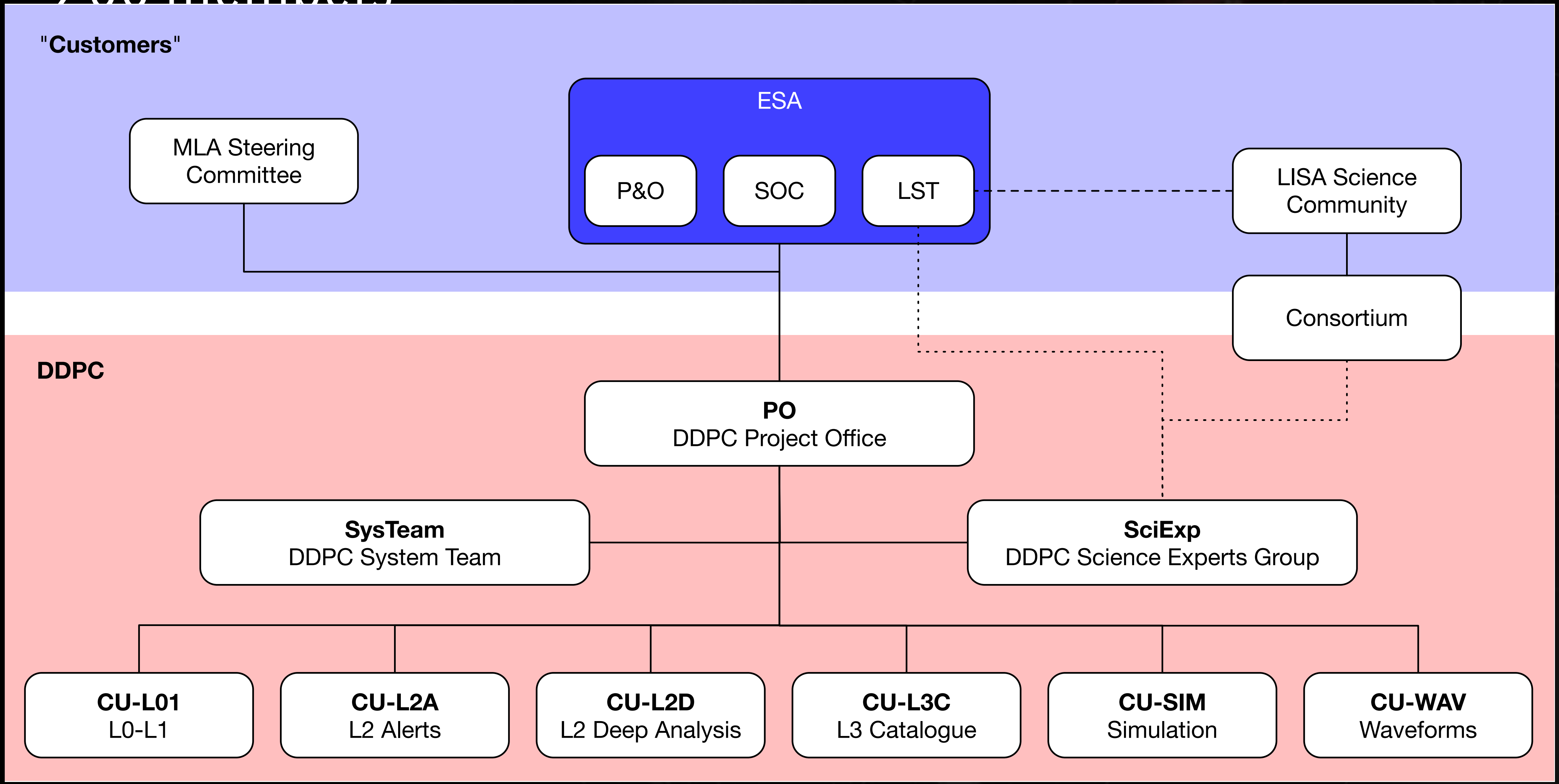


M. Armano et al. PRL 120, 061101 (2018)

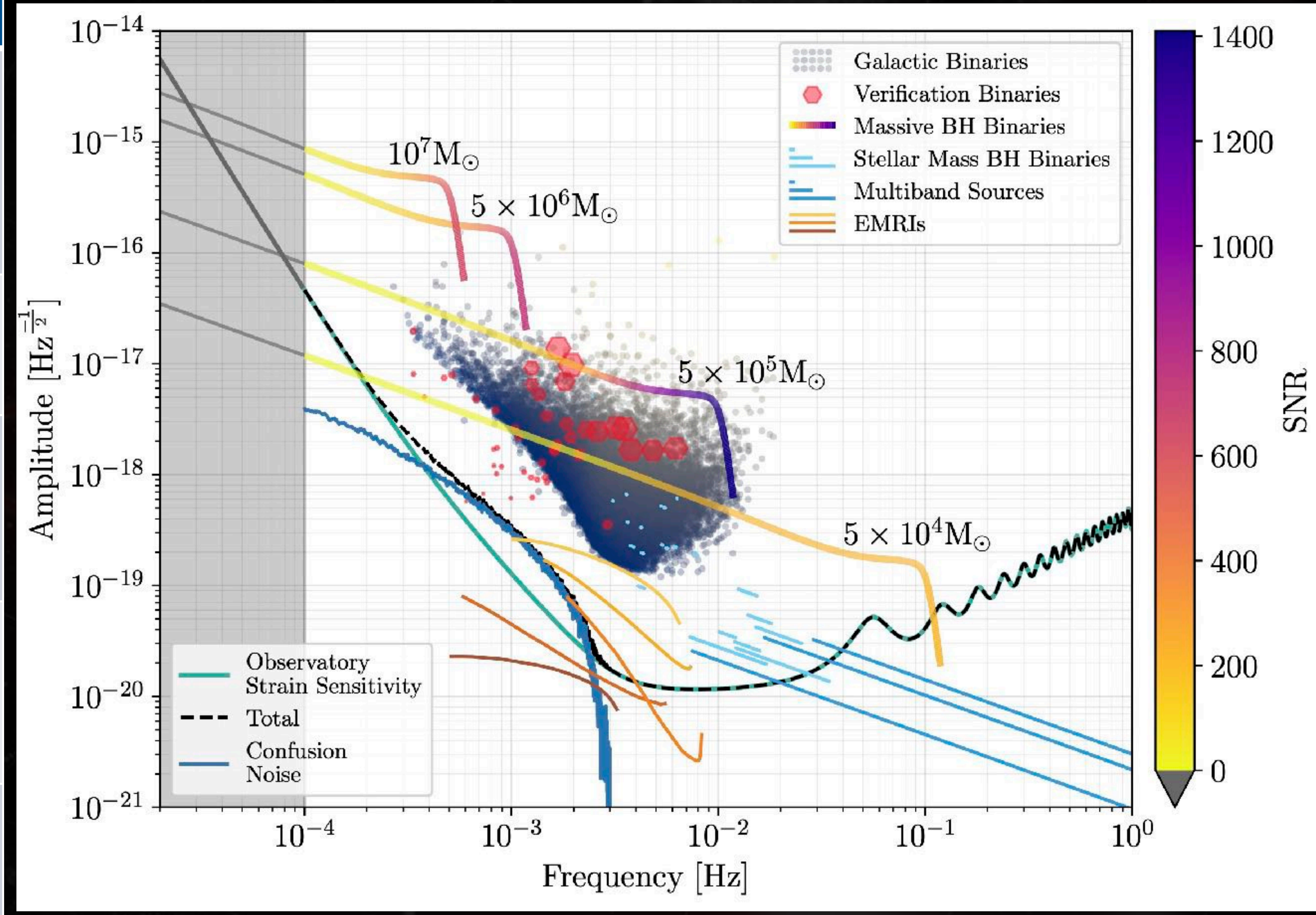
# Timeline and status

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



# 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 |



# 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