# Data analysis for observing the Universe with Gravitational Waves at low frequency

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Workshop "Artificial Intelligence for HPC@Exscale"

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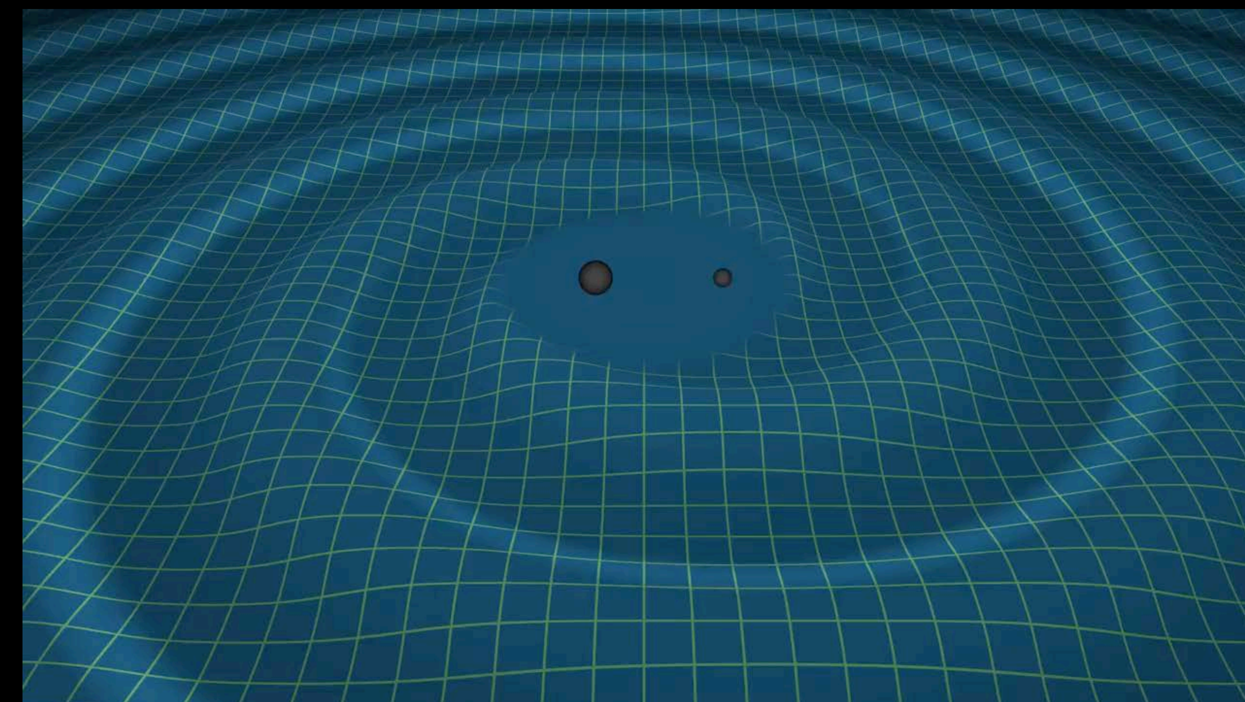
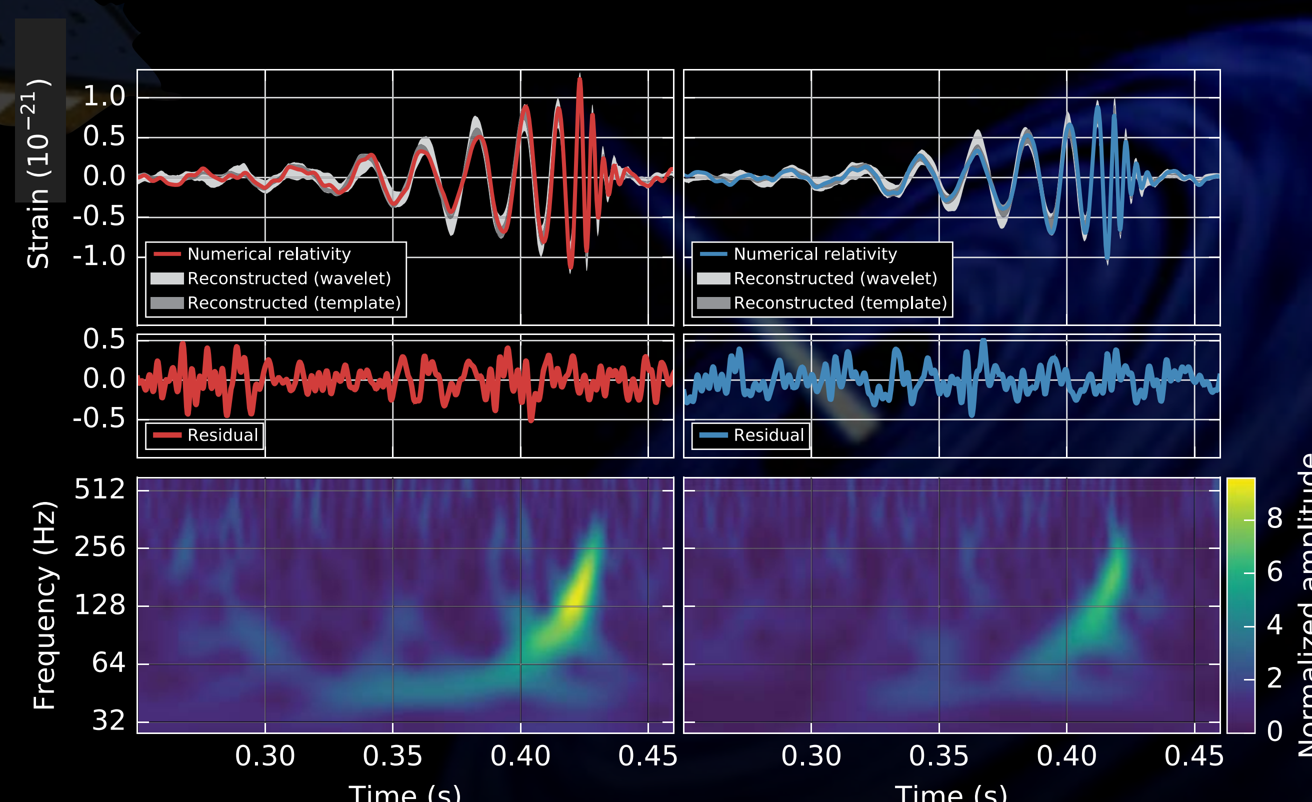
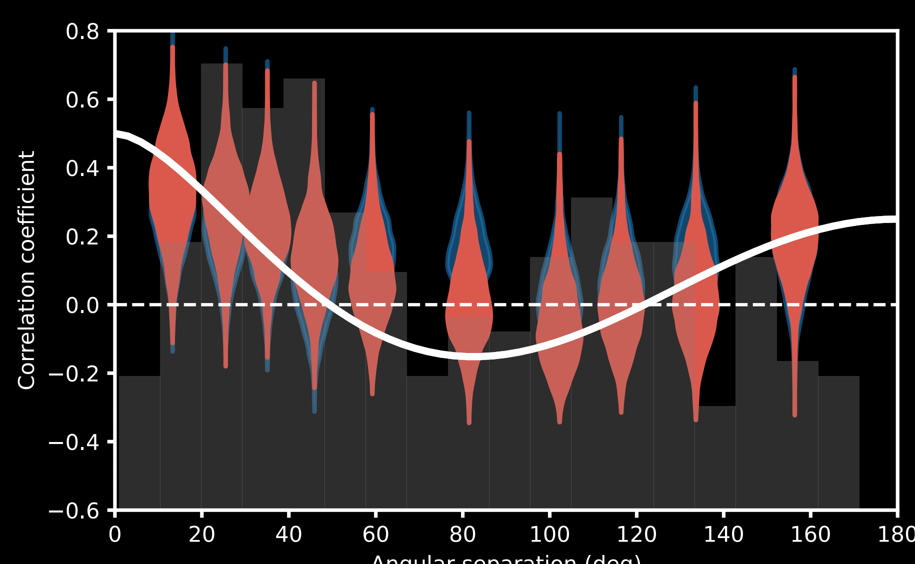
# Gravitational waves (GWs)

- General Relativity:
  - Space is deformed by its mass content;
  - Energy dissipation in the deformation of space-time => Gravitational Waves (GWs)
- Created when there is non-spherical acceleration of one or several bodies => typical source : binary
- New way to observe the Universe
- GWs are real!
  - Already detected at high frequency (LIGO/Virgo)
  - Strong evidence at very low frequency (PTA)





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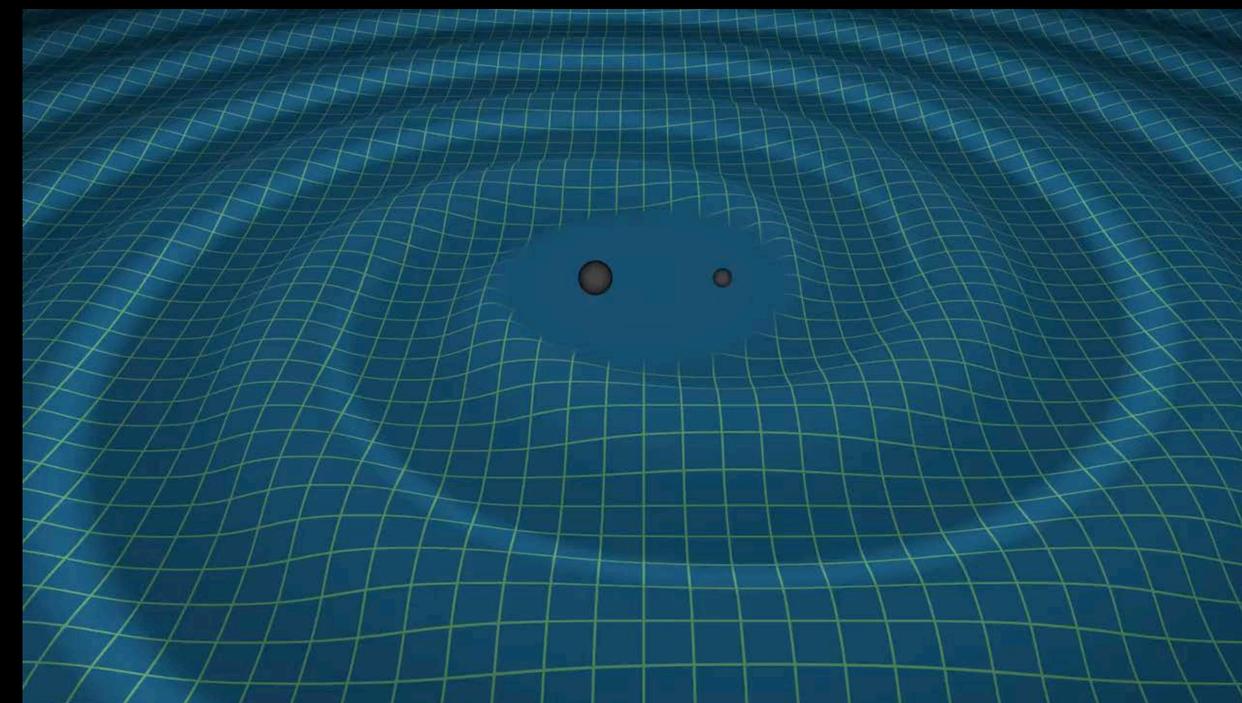
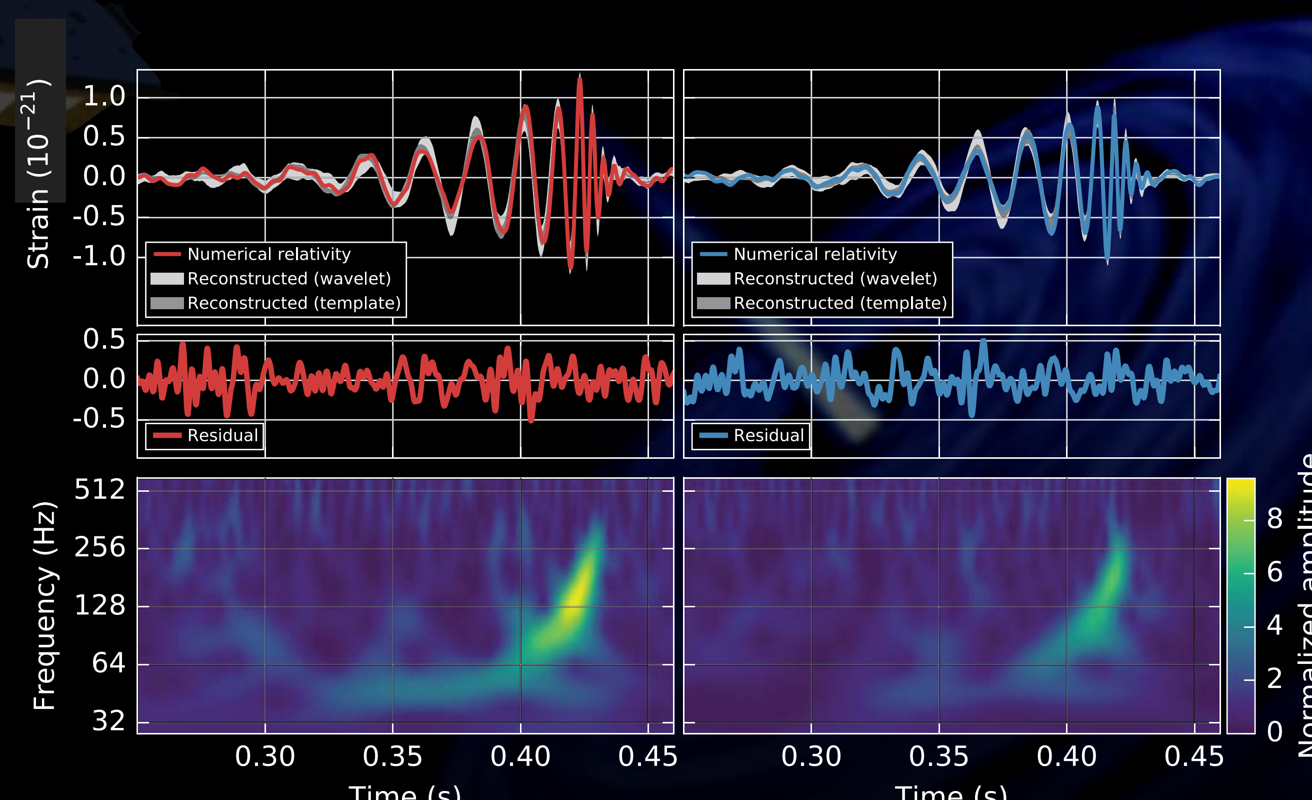
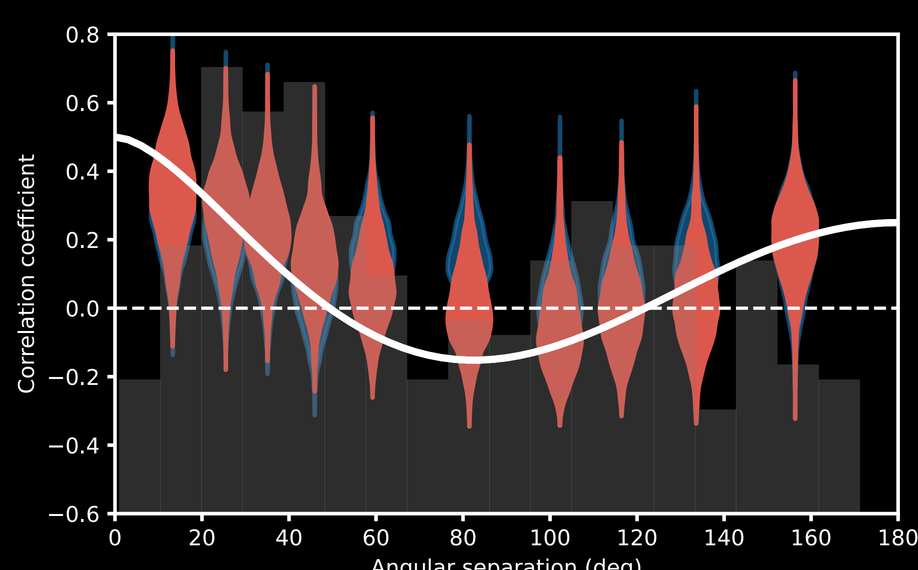
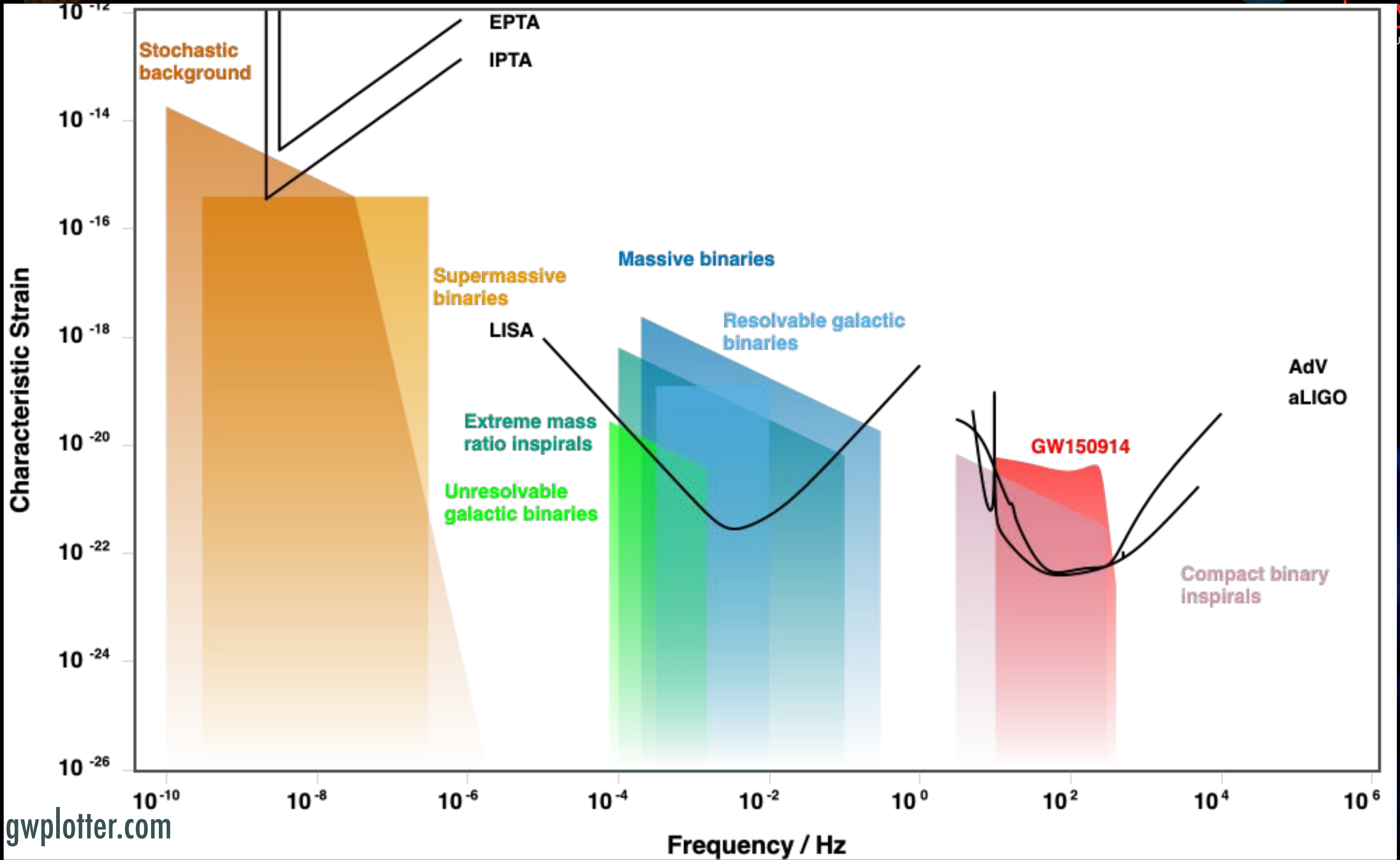




# GW spectrum




gwplotter.com

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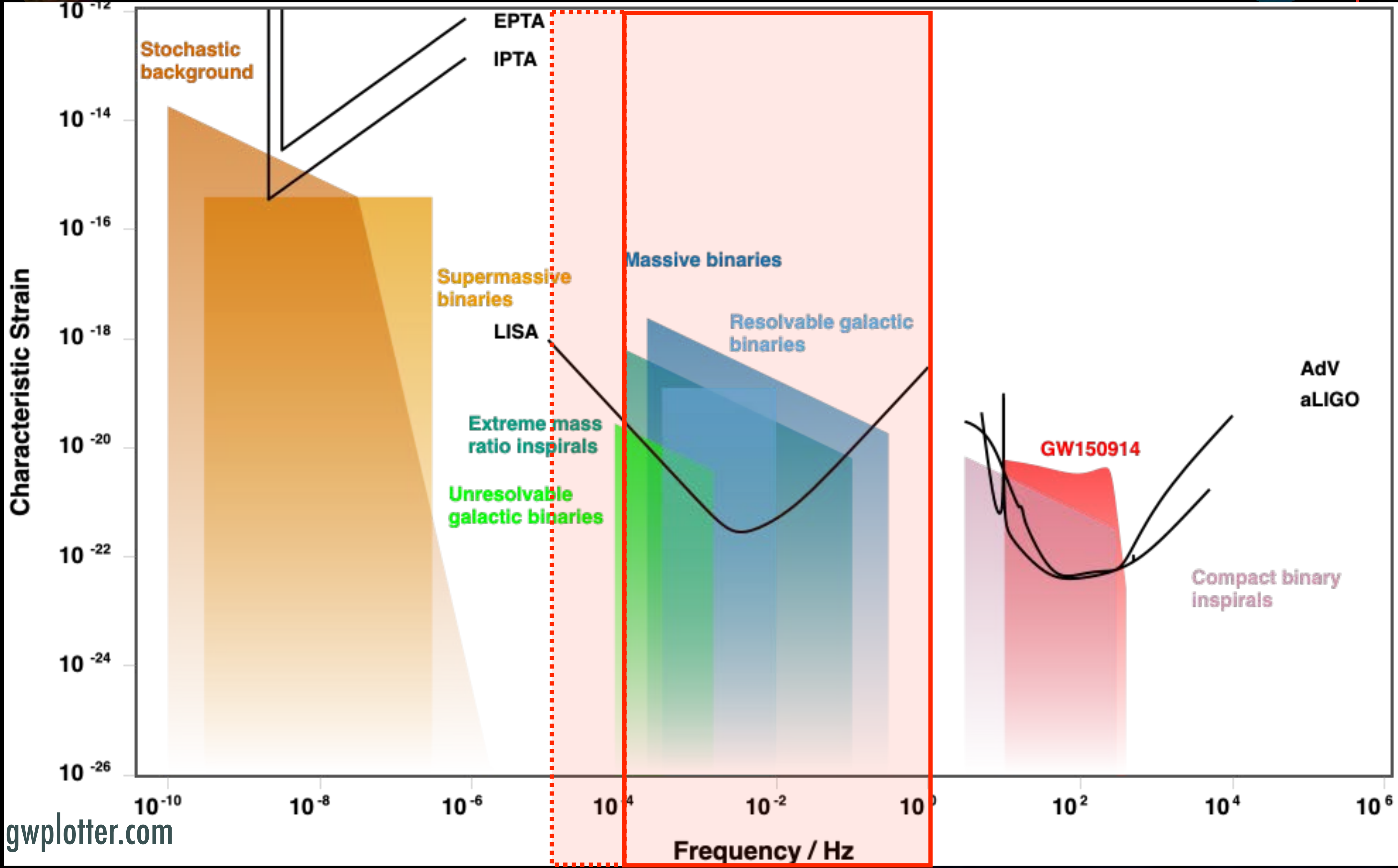


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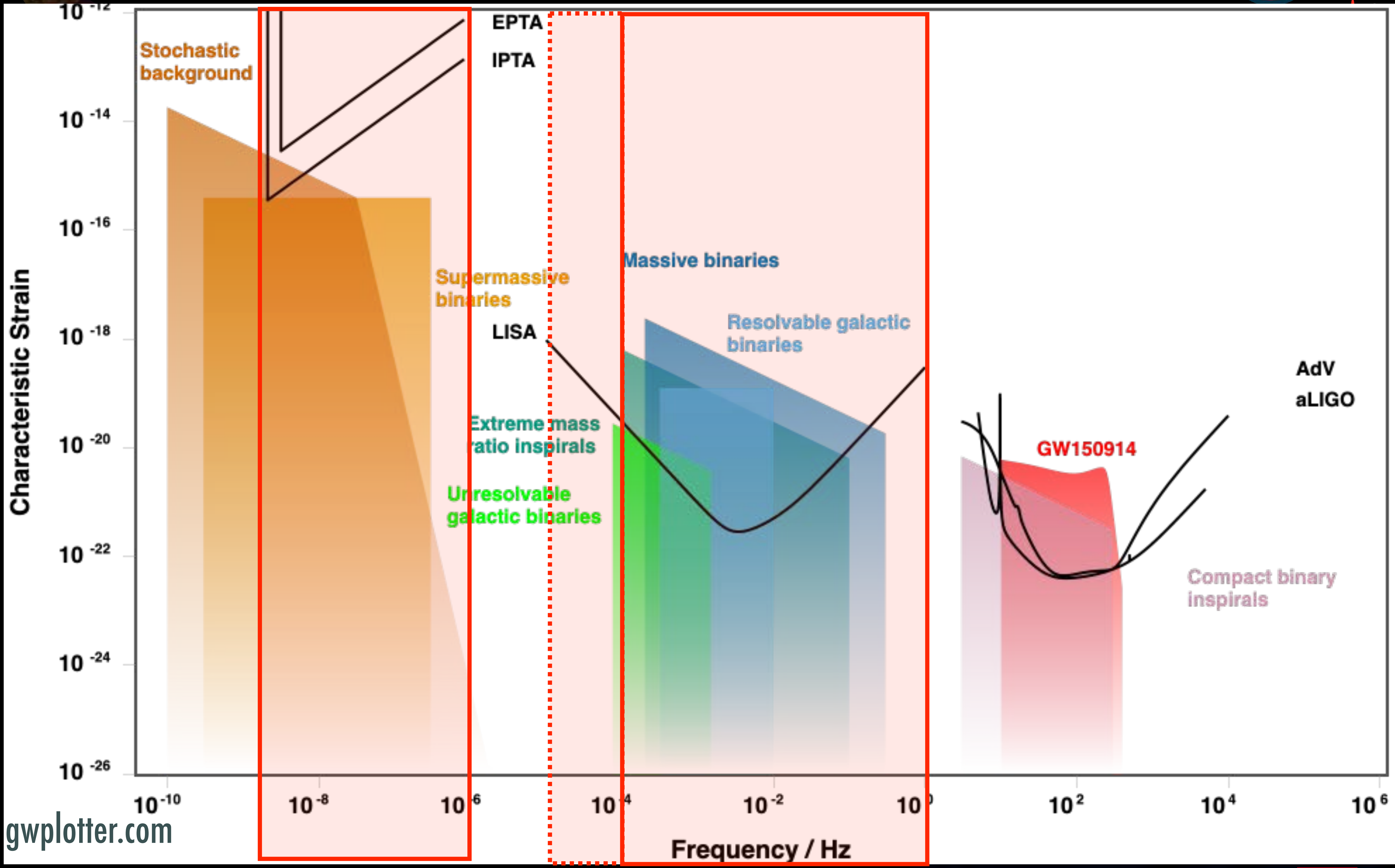


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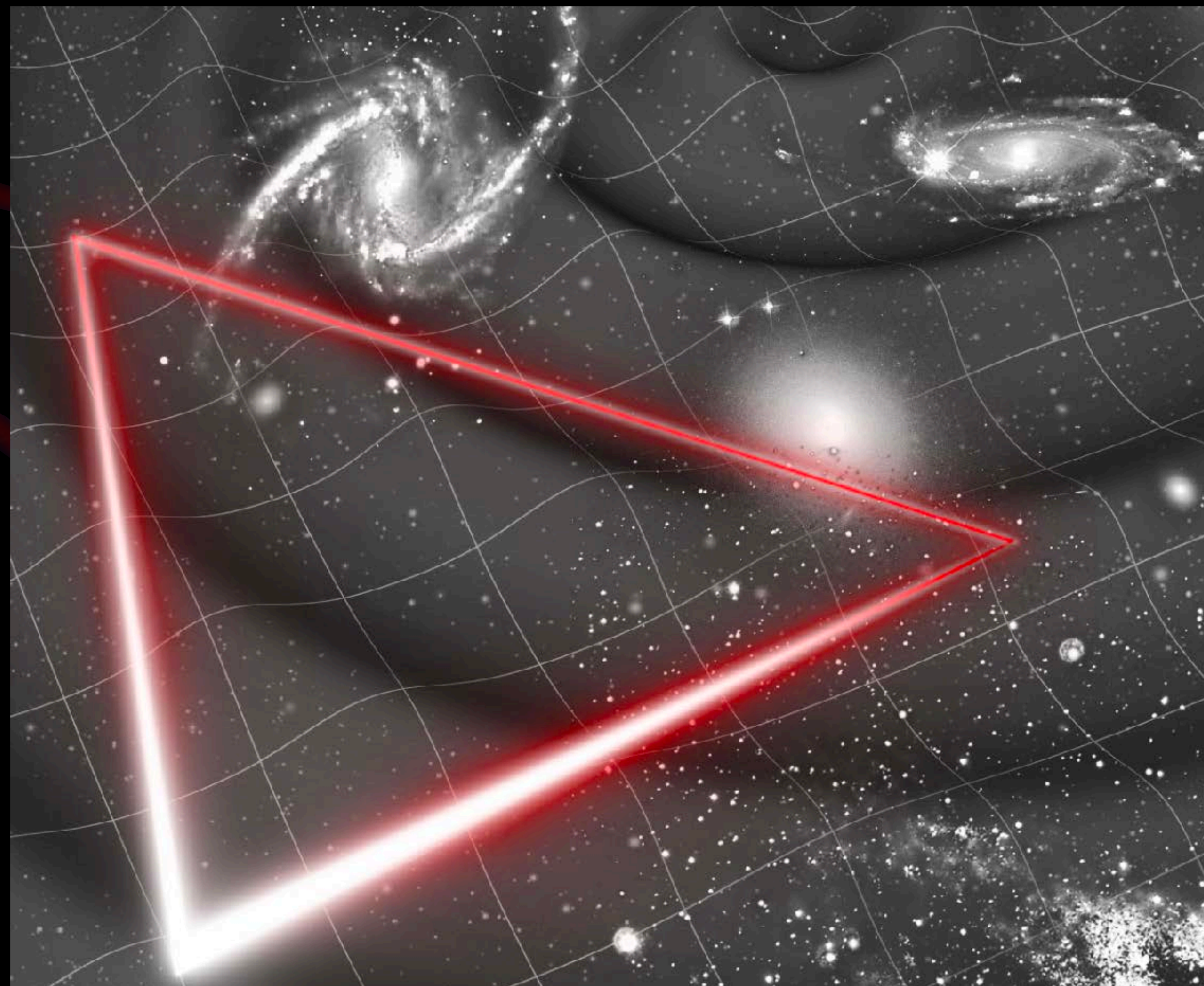
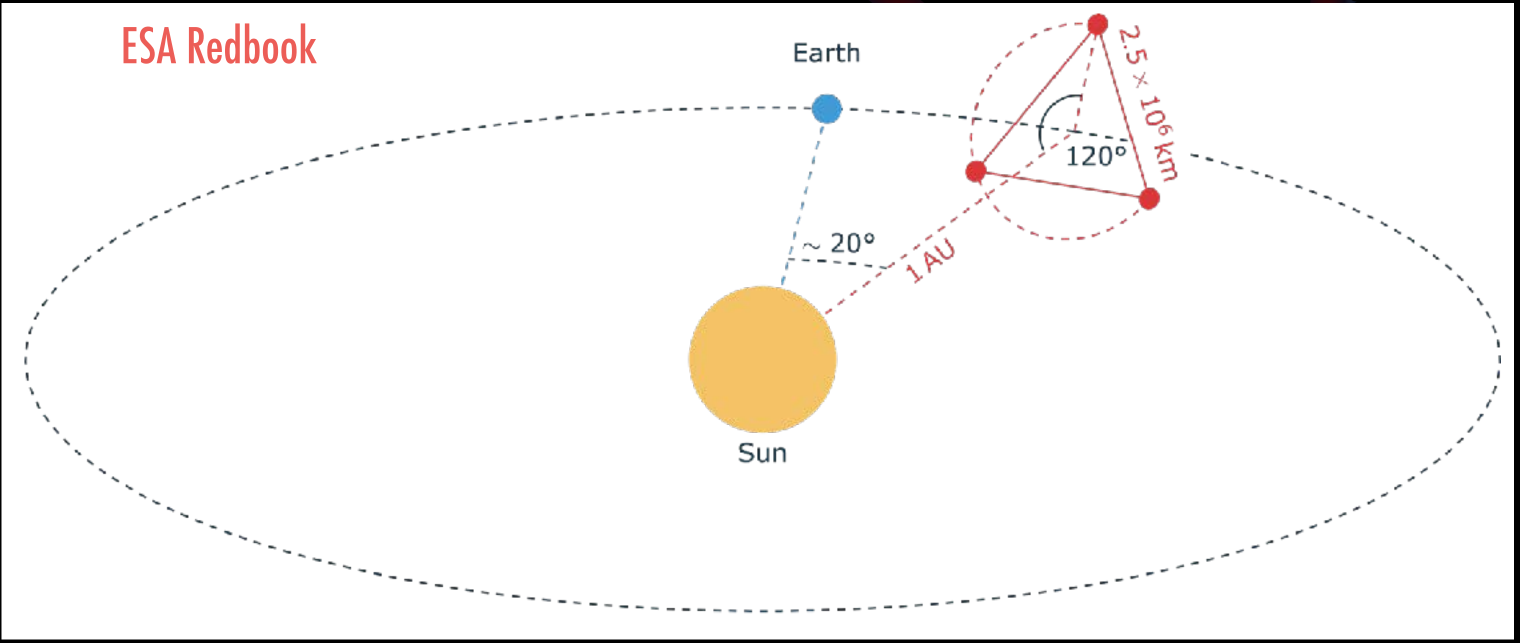


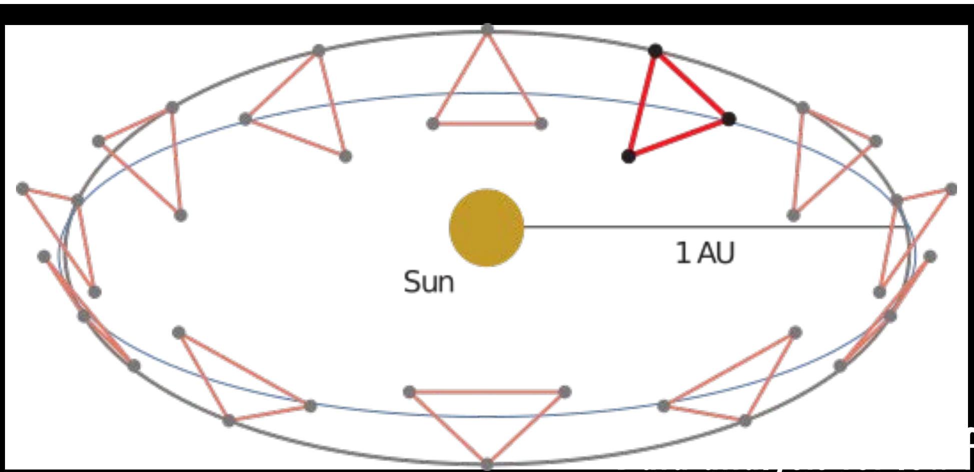
# LISA

# LISA

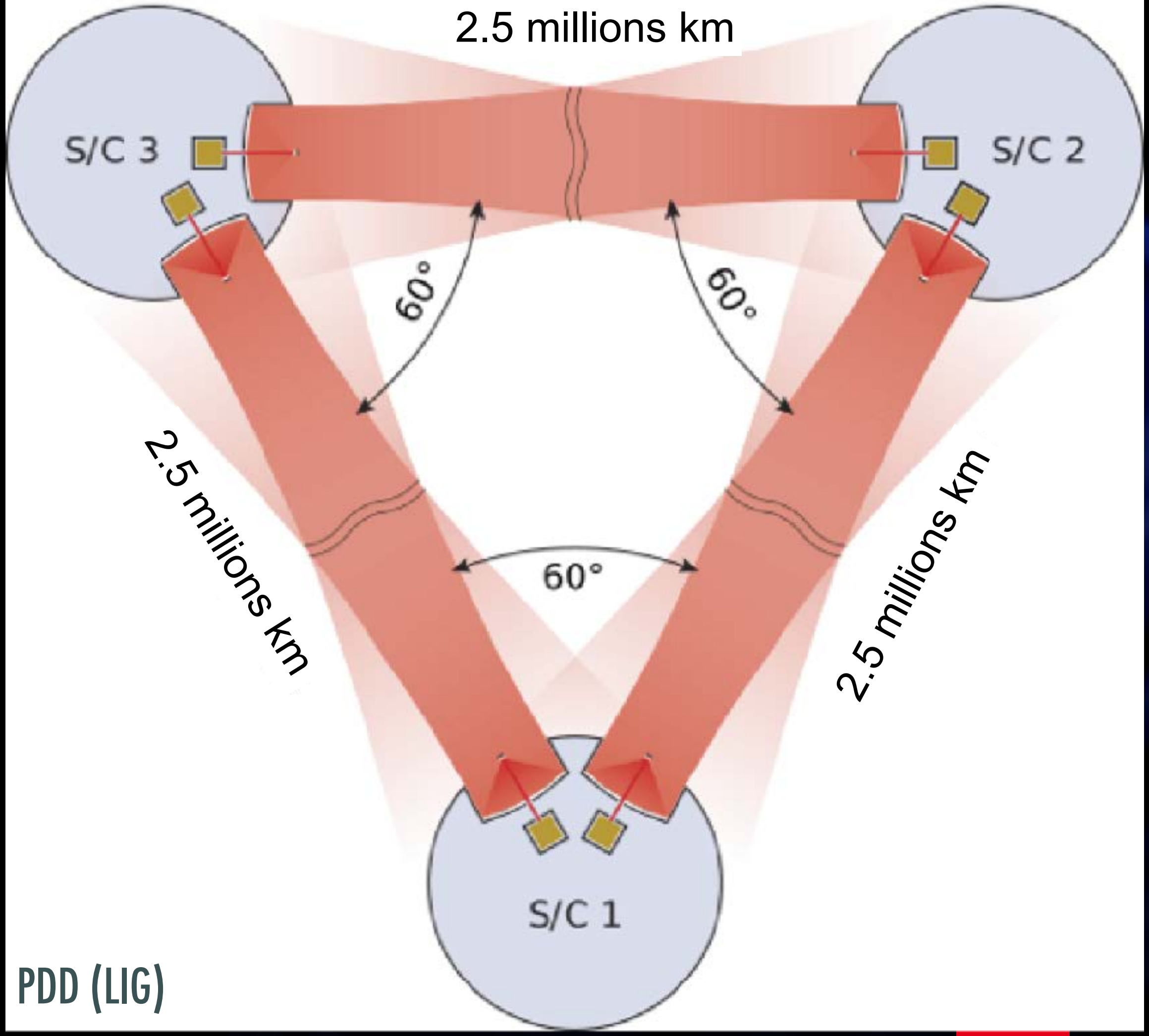
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits separated by 2.5 millions km
- Goal: detect strains of $10^{-21}$ by monitoring arm length changes at the few picometre level
- Sensitive only to gravity => reference masses protected in spacecraft
- High precision measurements => multiple interferometers




ESA Redbook



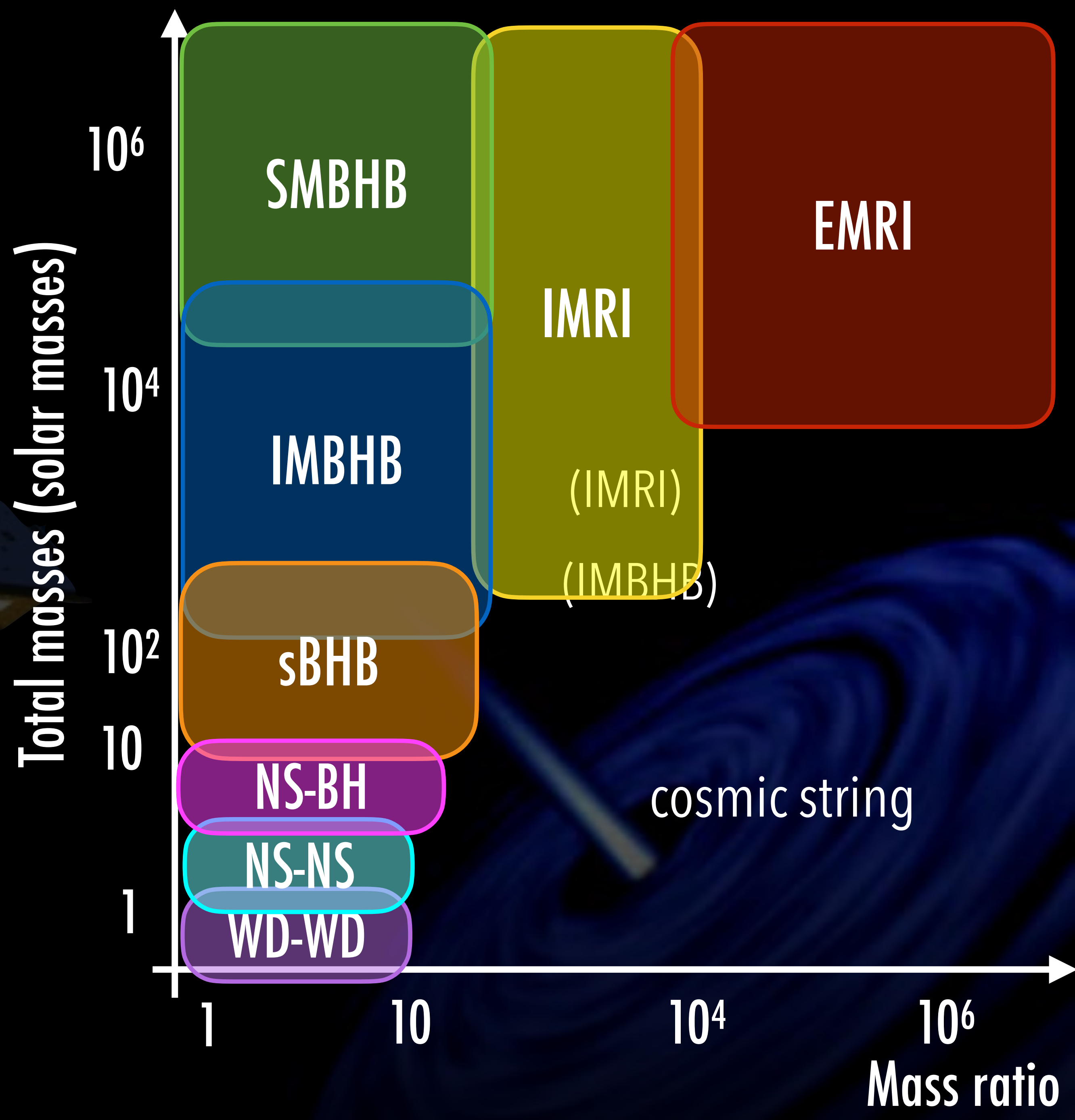

L3 proposal (LISA Consortium)




PDD (LIG)

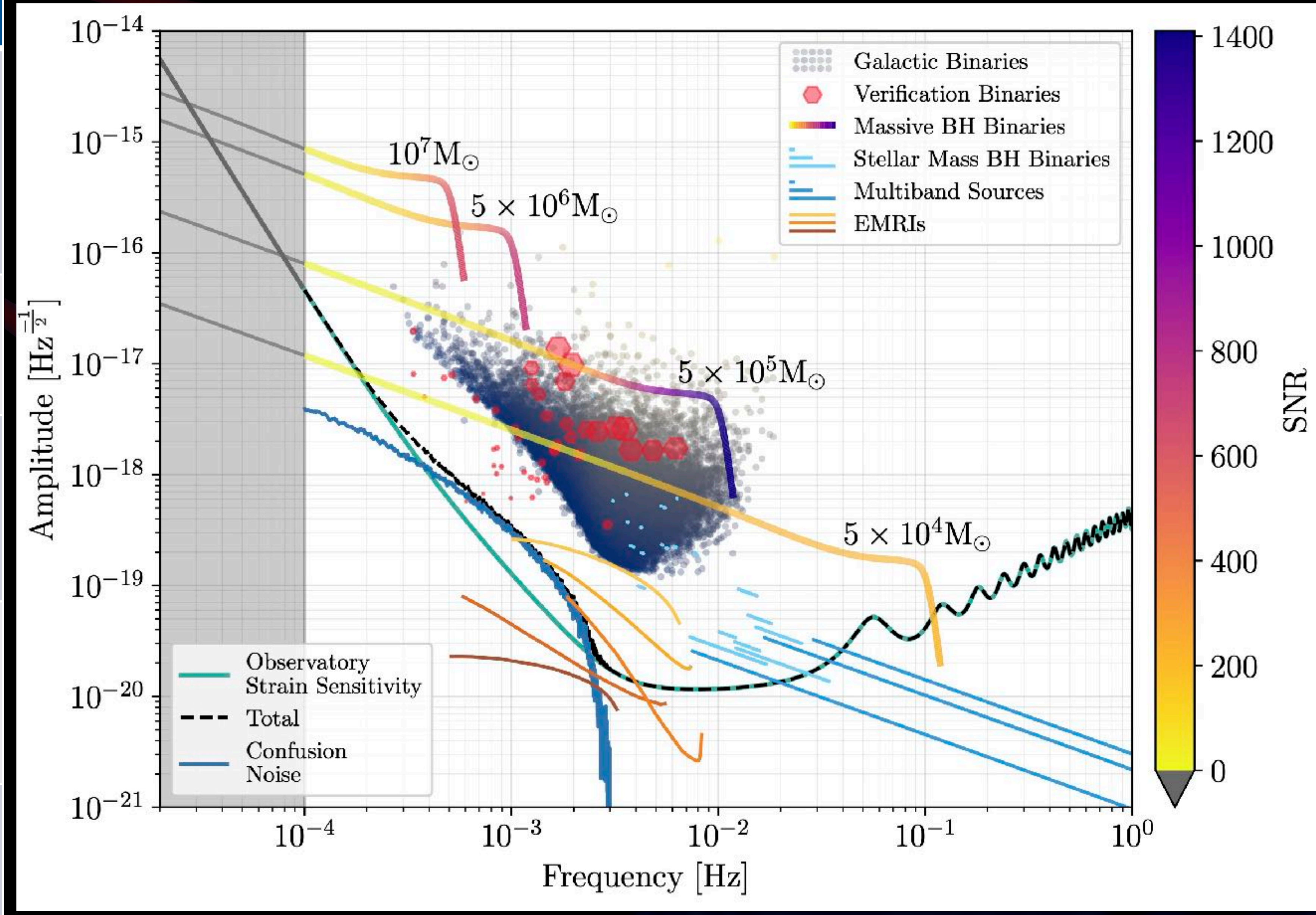
# GW sources in the mHz band

- 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
    - Intermediate Mass BH Binaries
- 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

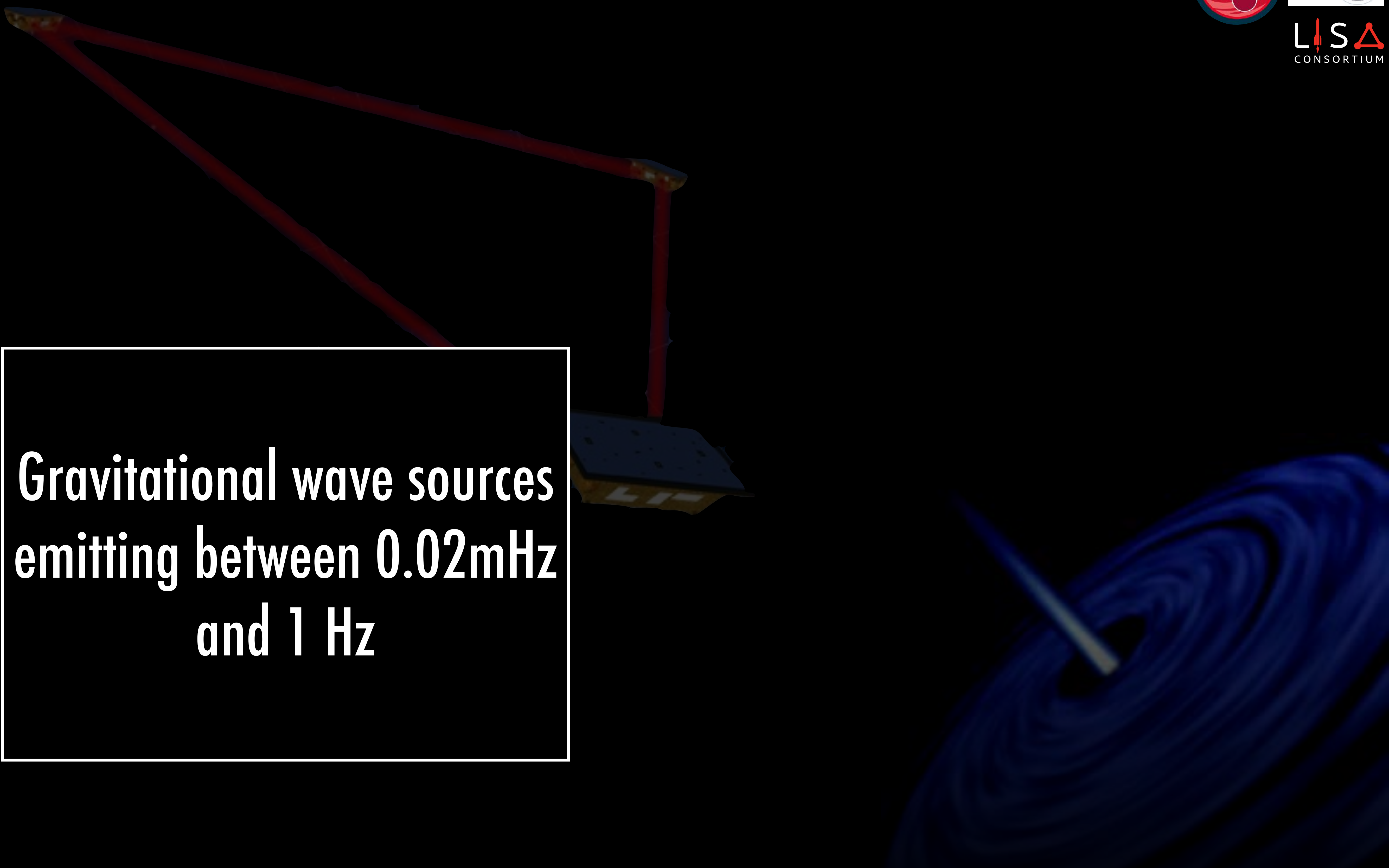
- SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages.
- SO3: Probe the properties and immediate environments of black holes in the local Universe using EMRIs and IMRIs.
- 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

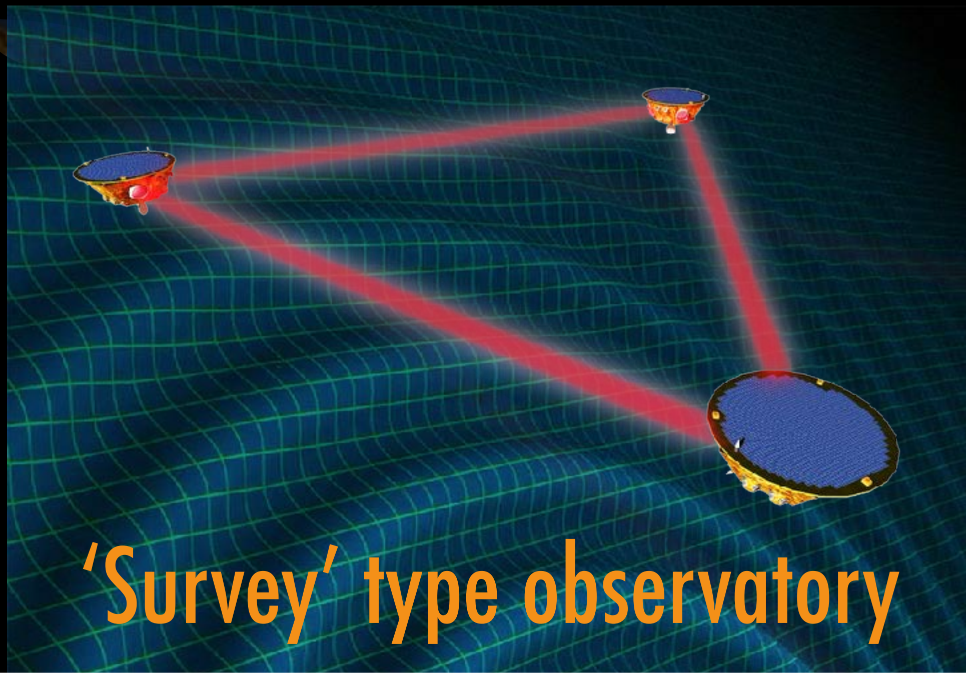
Cosmology

# Data



Gravitational wave sources emitting between 0.02mHz and 1 Hz

# Data

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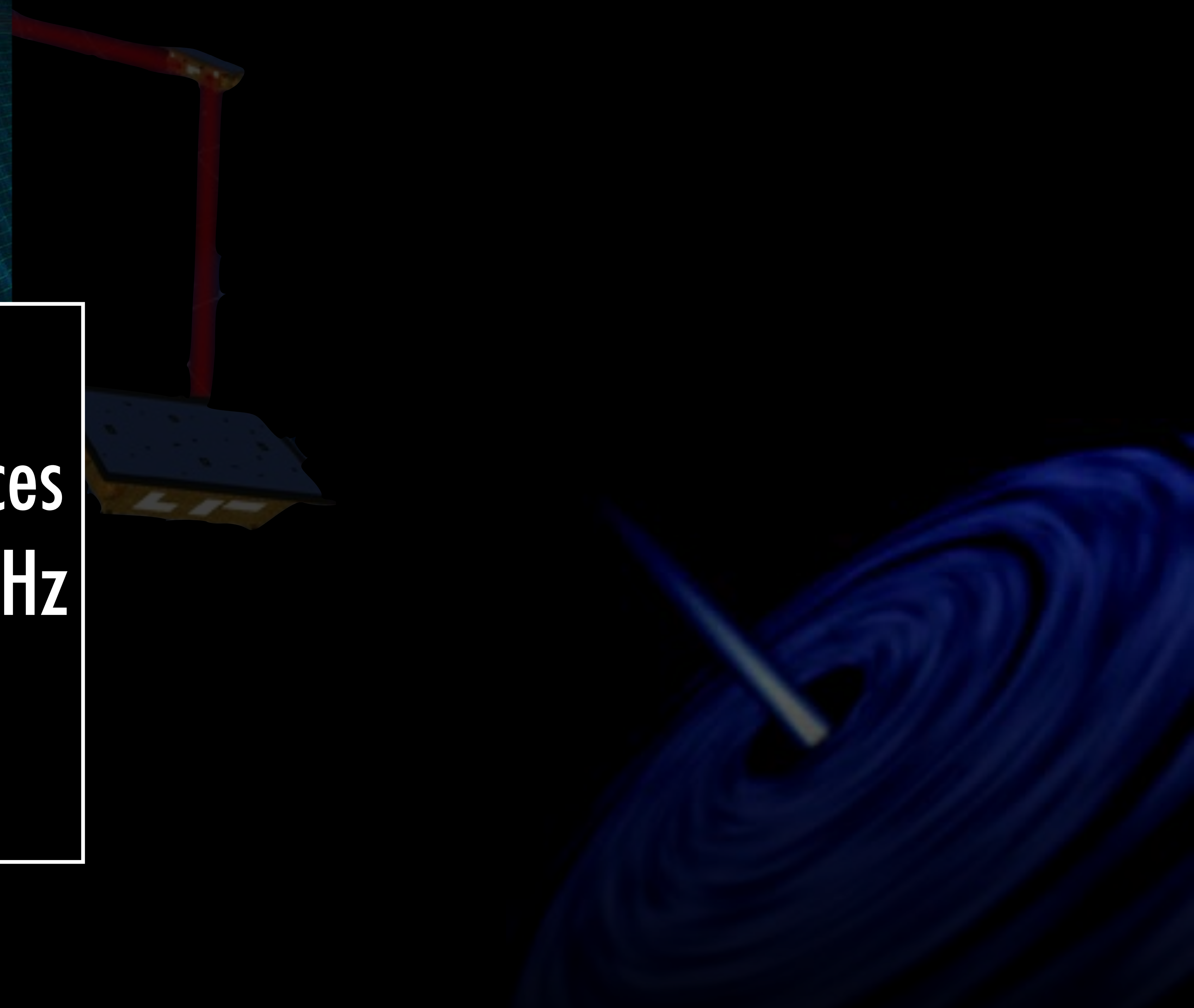

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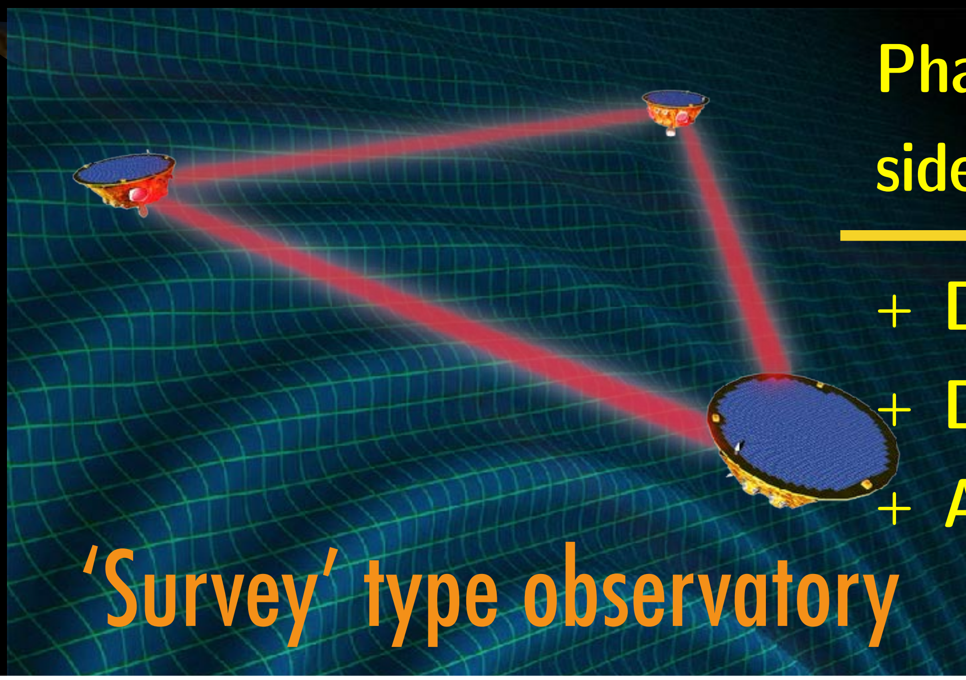



Phasemeters (carrier, sidebands, distance)

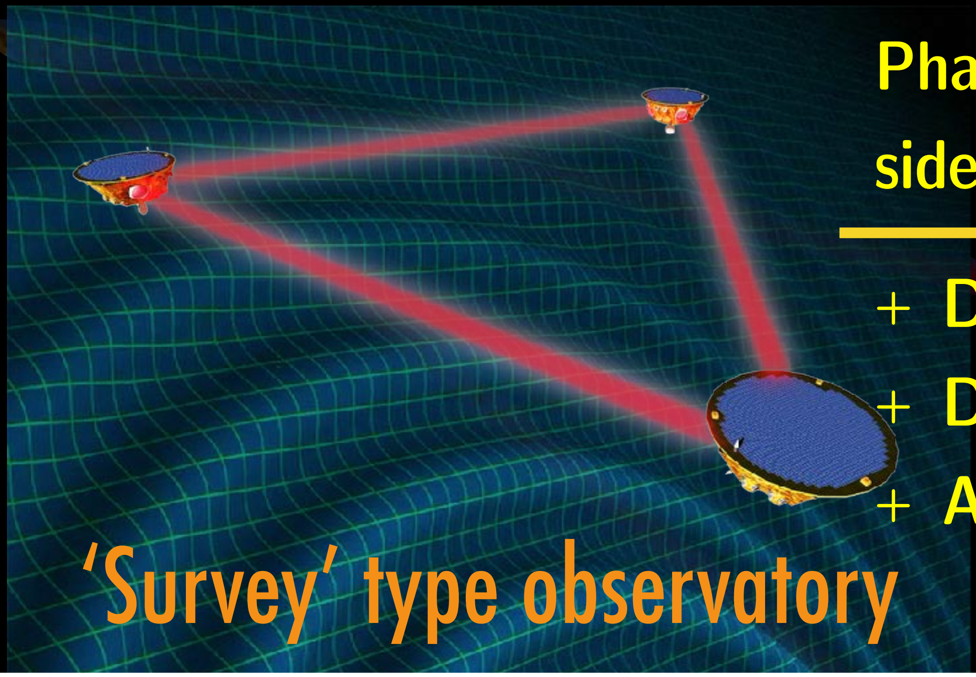
+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

** Charge Management Device

# Data



'Survey' type observatory

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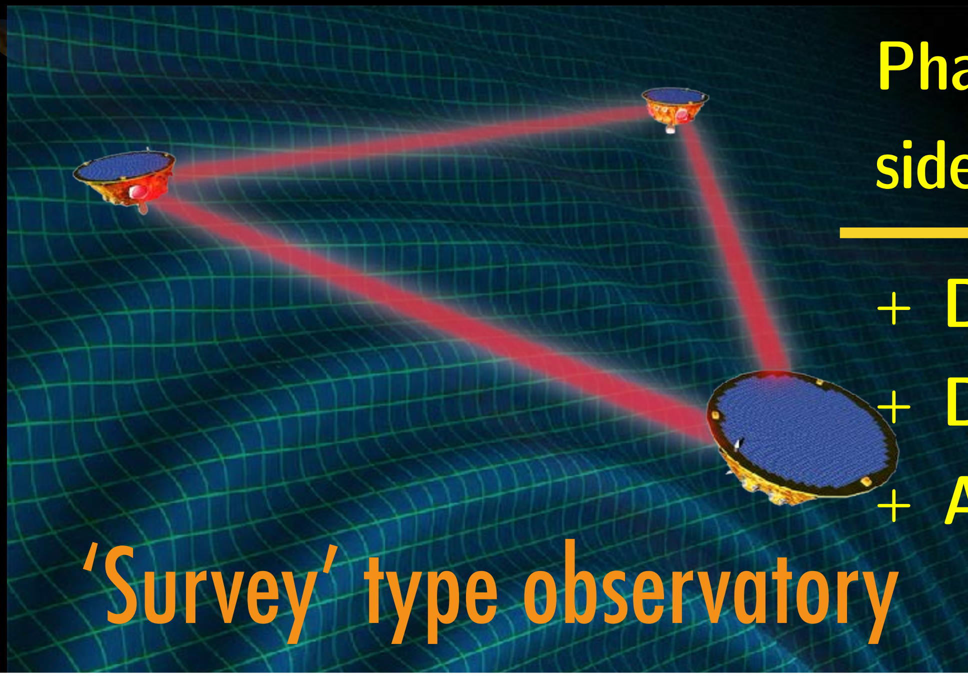


Phasemeters (carrier, sidebands, distance)

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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

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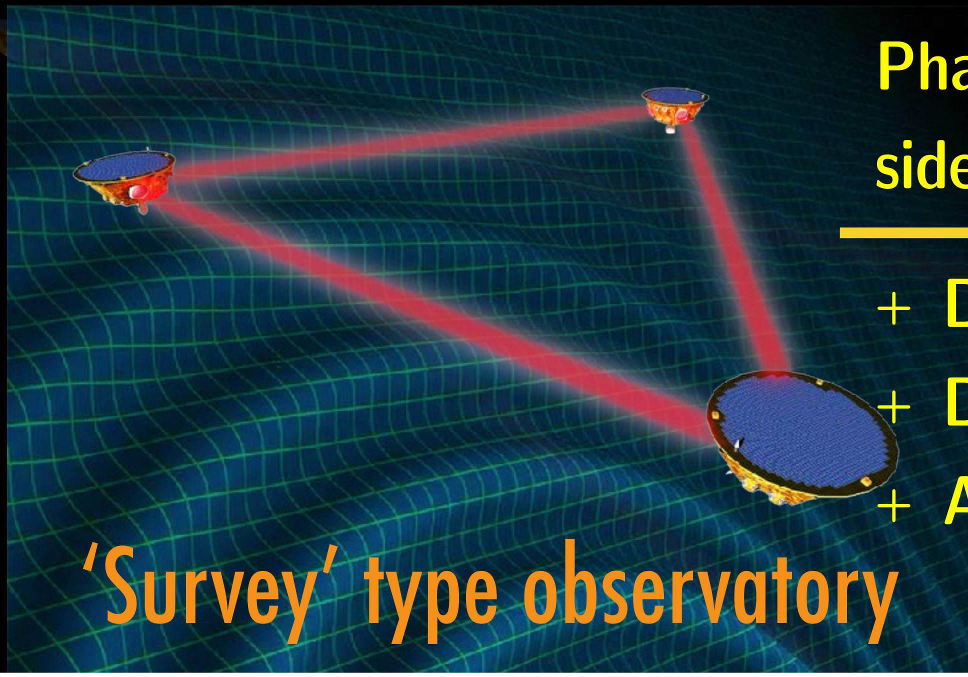


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Data Analysis of GWs

Catalogs of GWs sources
with their waveform

Gravitational wave sources emitting between 0.02mHz and 1 Hz

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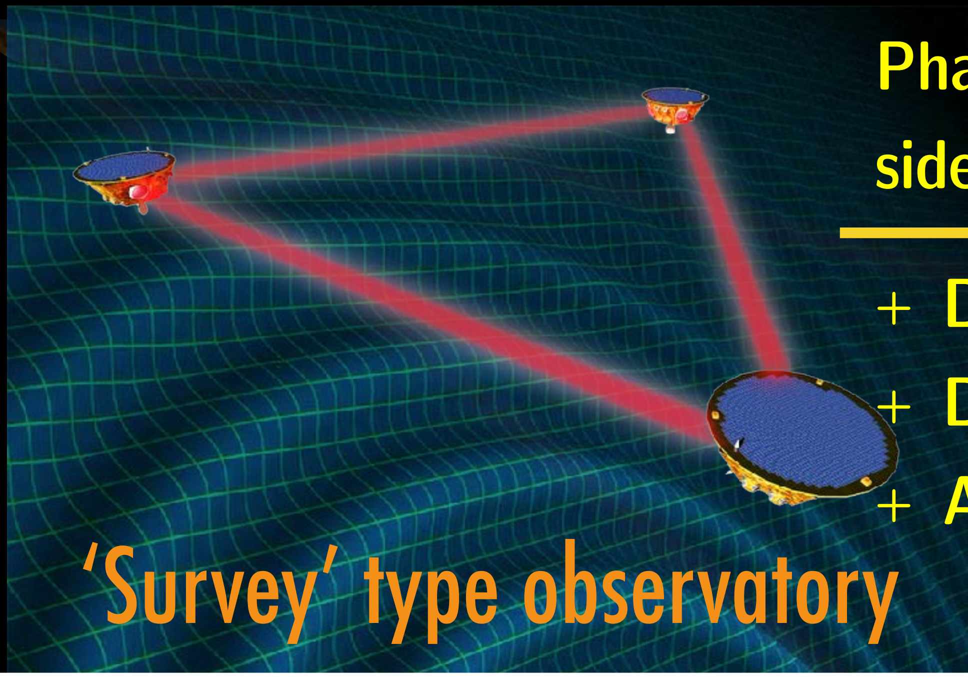
# Data




Phasemeters (carrier, sidebands, distance)

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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

# 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

# Data Analysis

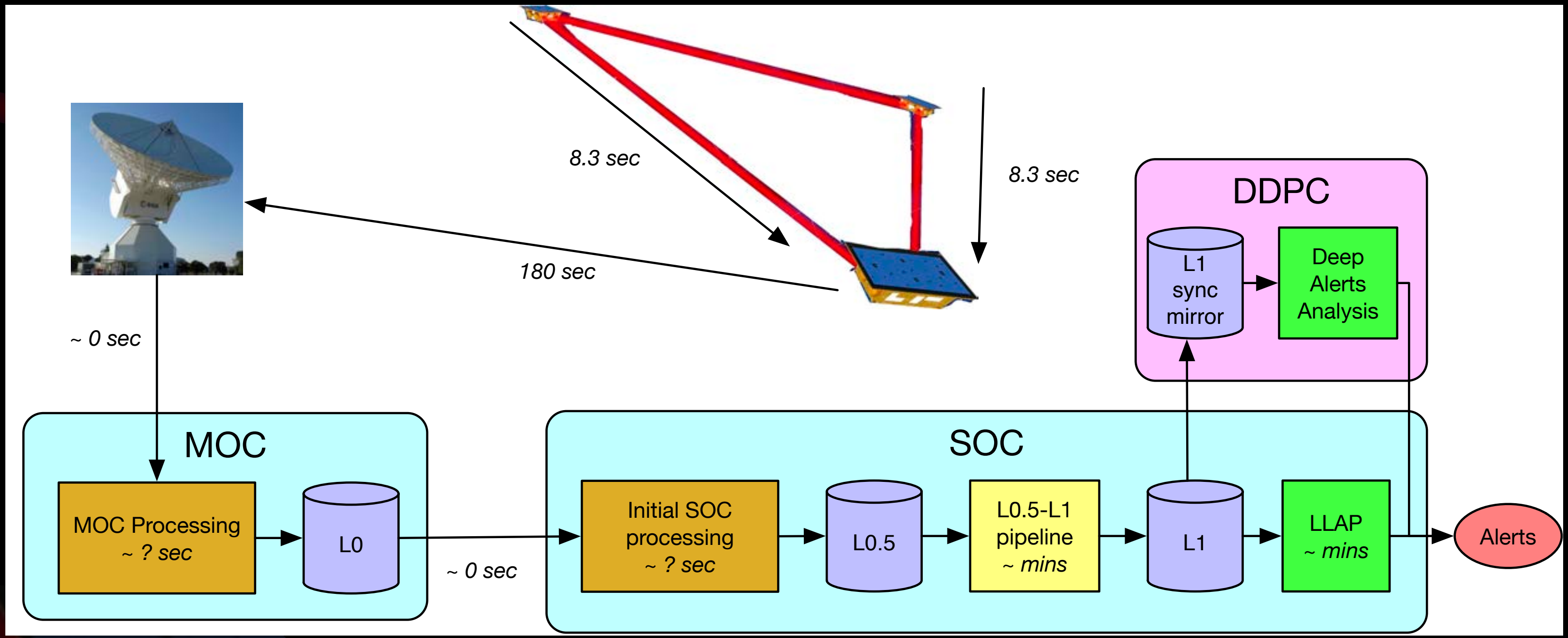
- Analysis of all signals and noises together => global analysis
- Flexibility: first data of this kind challenge:
  - Multiple approaches, multiple pipelines
  - Quick development from prototyping to production
- General approach with with multiple iterative (interconnection between products):


1. Reduce dominant noises (Time Delay Interferometry) and partial correction on instrument artefacts => L1 data (TDI data)
2. GLOBAL FITS: GW sources extraction + better understanding of noises and instrument with multiple pipelines => L2 data
3. Cross-check, combination, merging of L2 data to produce catalogs + associated scientific products => L3 data

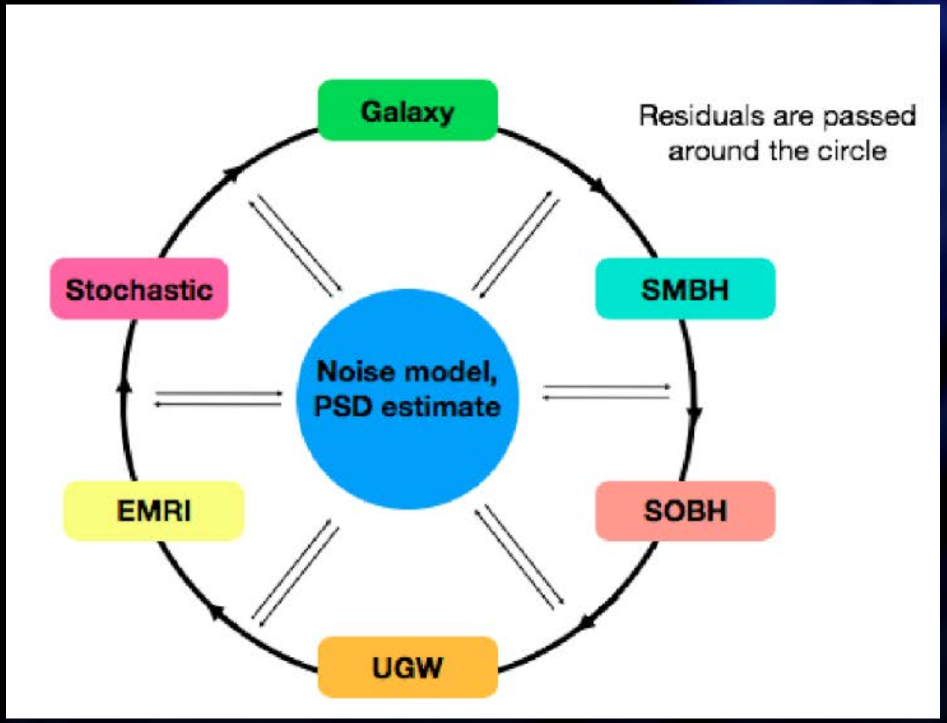
- Distributed Data Computing Center (DDPC)

# LISA Data analysis

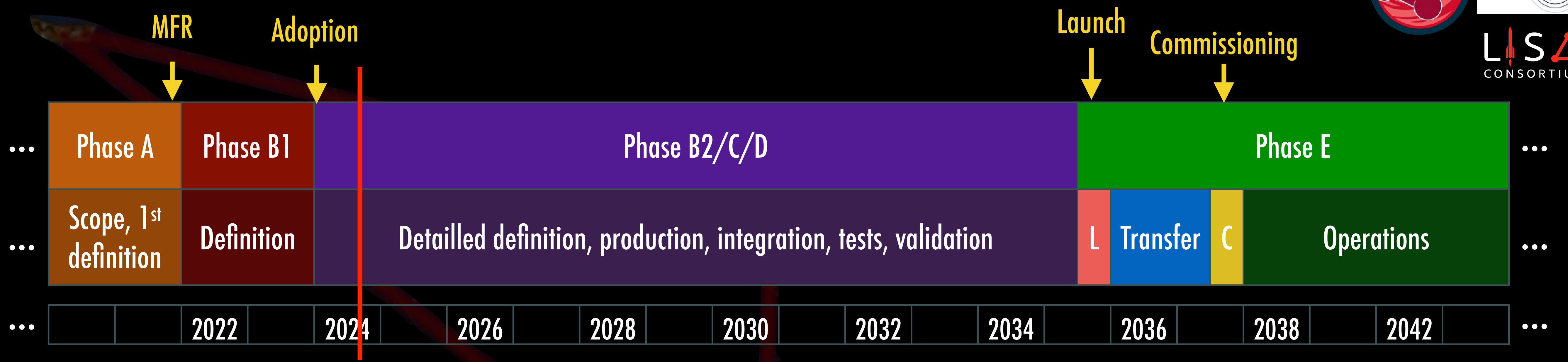
- Low Latency Alert Pipeline:
  - Fast and online
  - Multiple approaches/pipelines in parallel



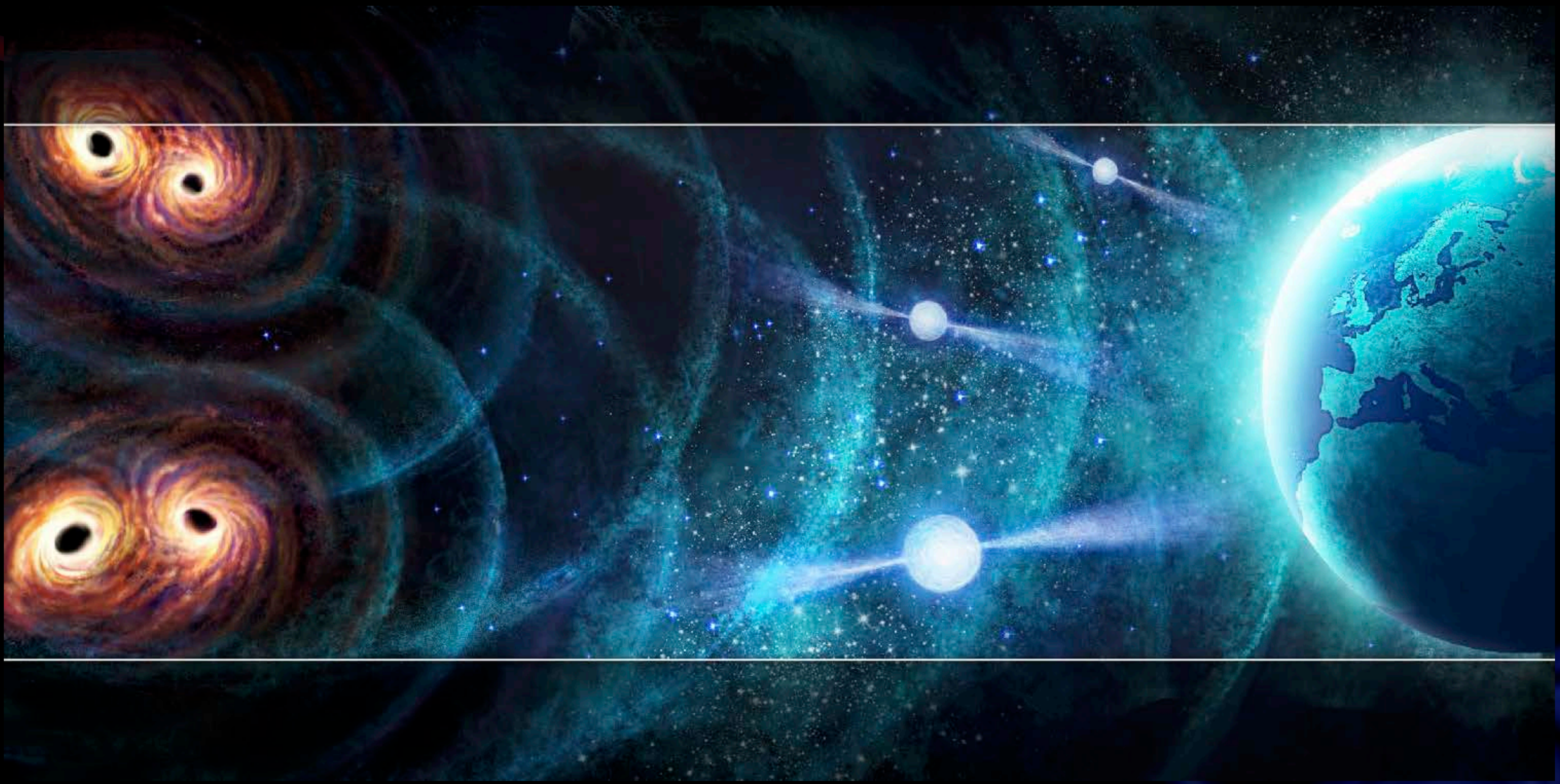

- Deep Analysis: multiple global fits:
  - Large number of parameters
  - Disentangle sources
  - Several timescale for the analysis depending on sources
  - Current approaches in the prototypes:
    - Bayesian analysis, matched filtering;
    - Start to use some AI;
    - Others approaches (sparsity, ...).
  - Cost for one global fit ~ 200 millions cpu.h per year



# LISA now



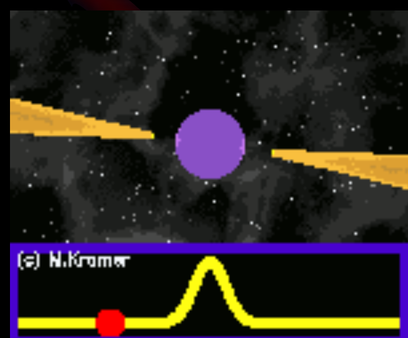

- Adopted in January 2024 : ressources available, building started
- Launch in 2035
- Distributed Data Processing Center:
    - Led by France
    - Activities are really starting now
    - Simulation tools and simulated datasets
    - Many available prototypes of data analysis pipelines



# Pulsar Timing Array

# Pulsar timing

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



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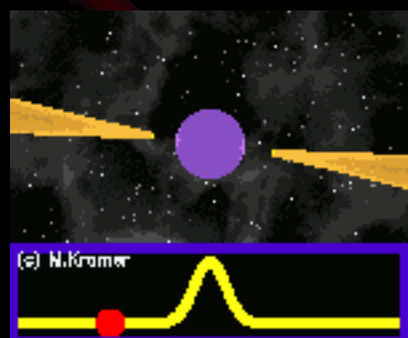

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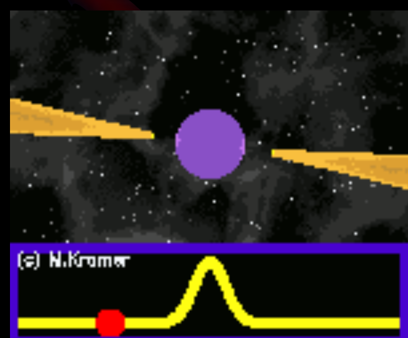


Radiotelescope

Receiver (GHz)

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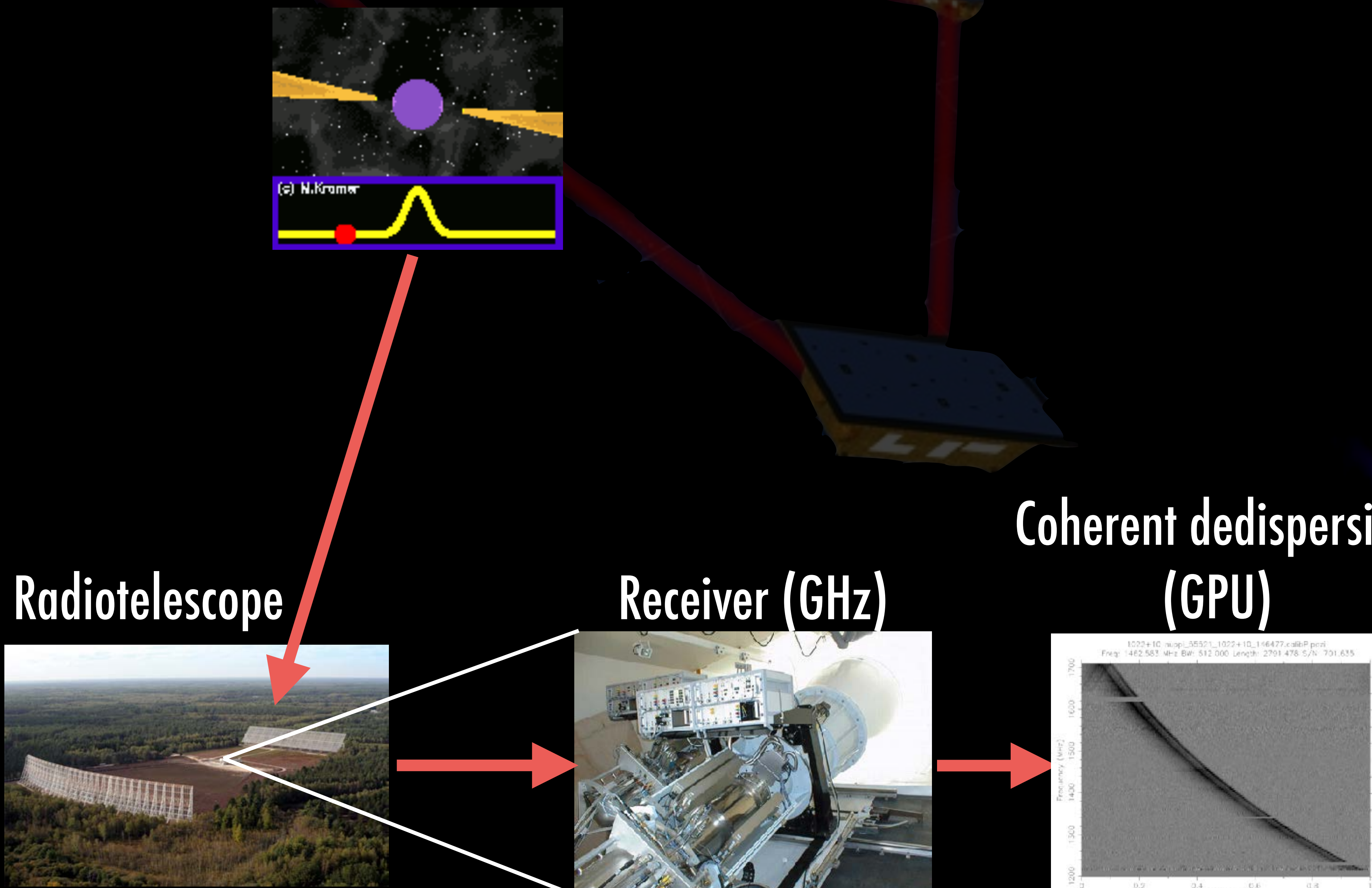

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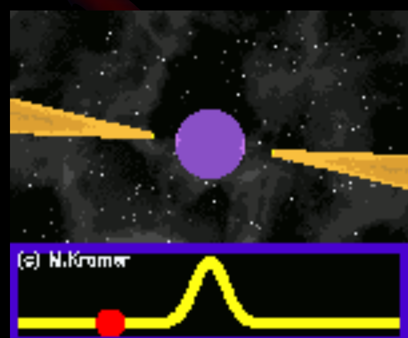
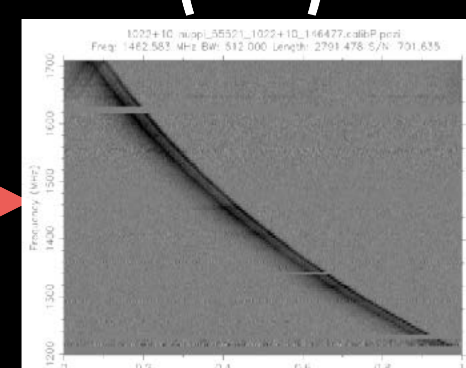


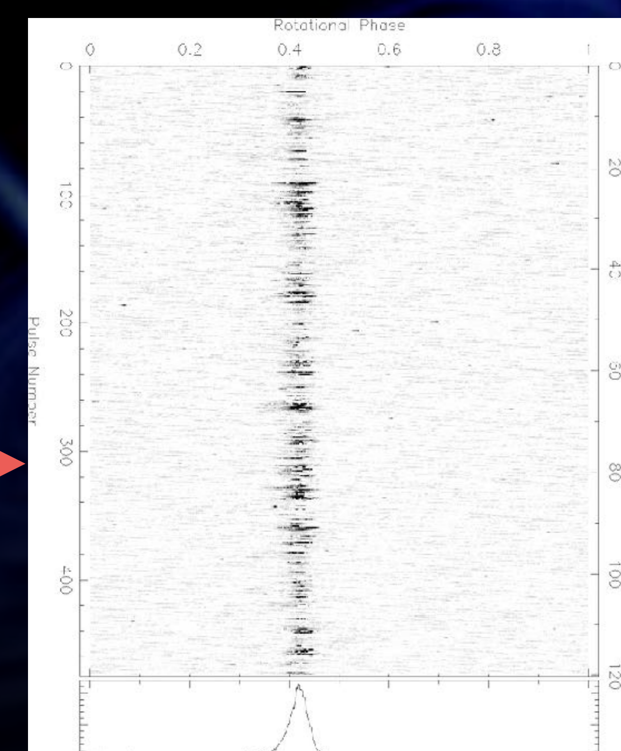

Radiotelescope

Receiver (GHz)

Coherent dedispersion (GPU)




Folding



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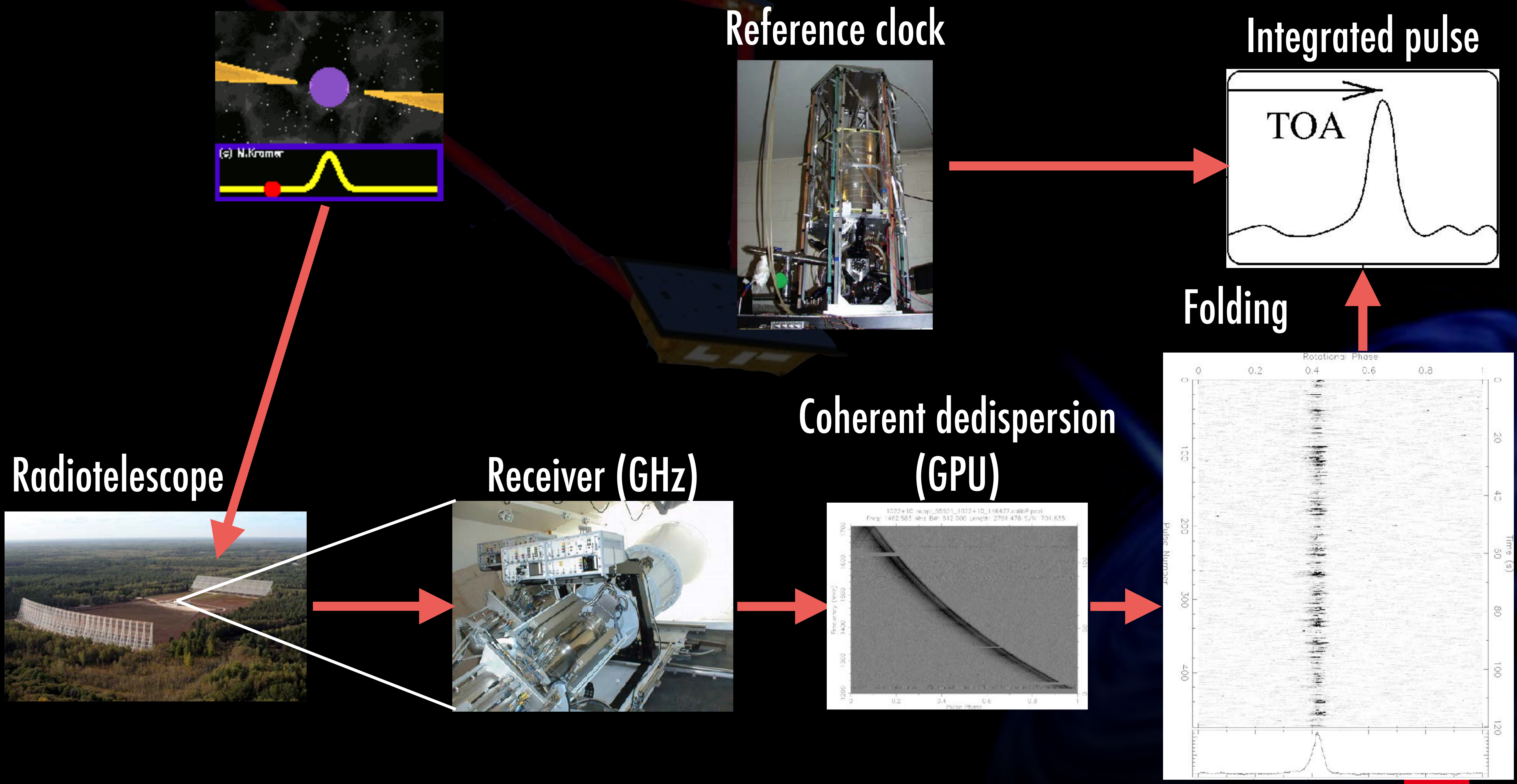

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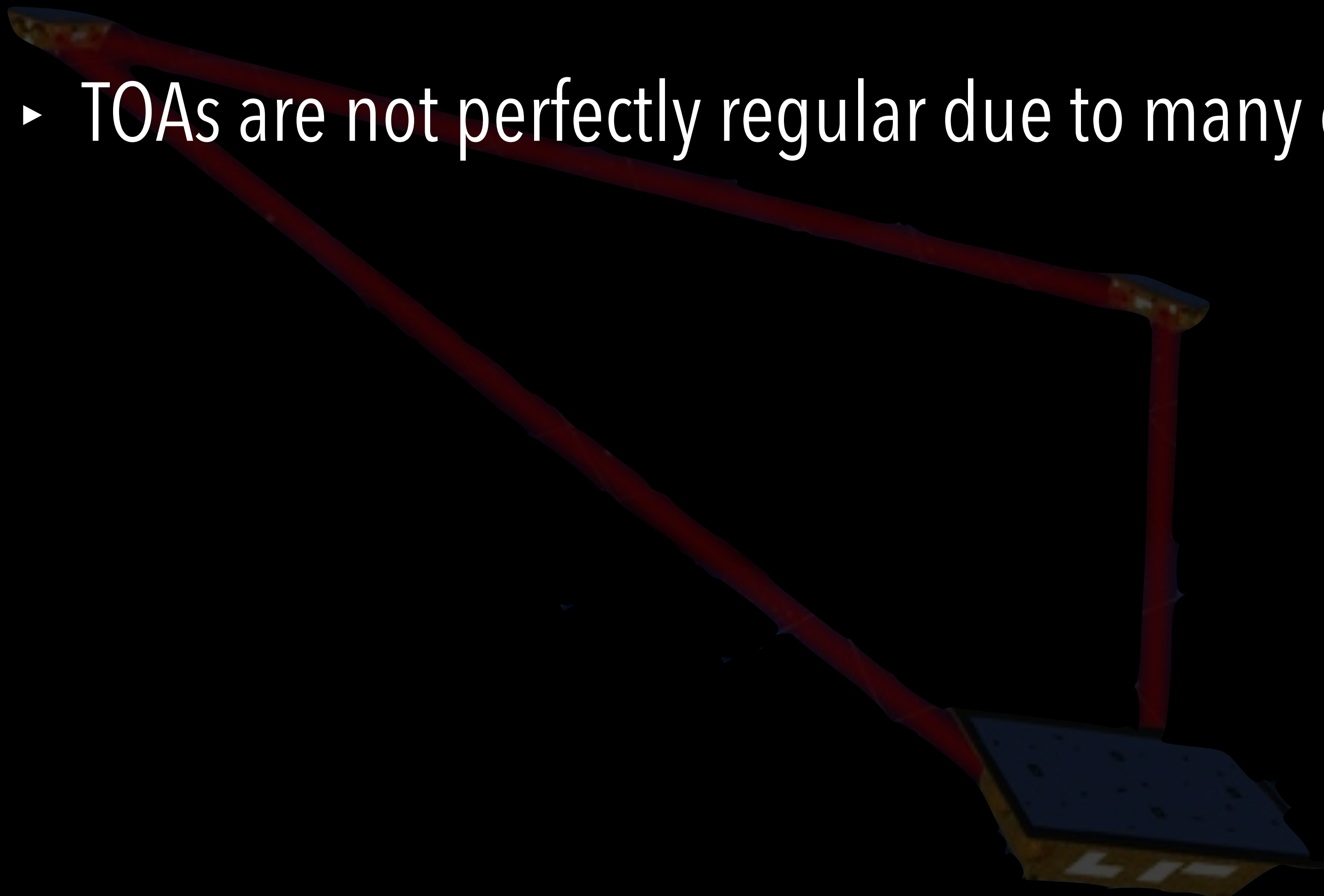
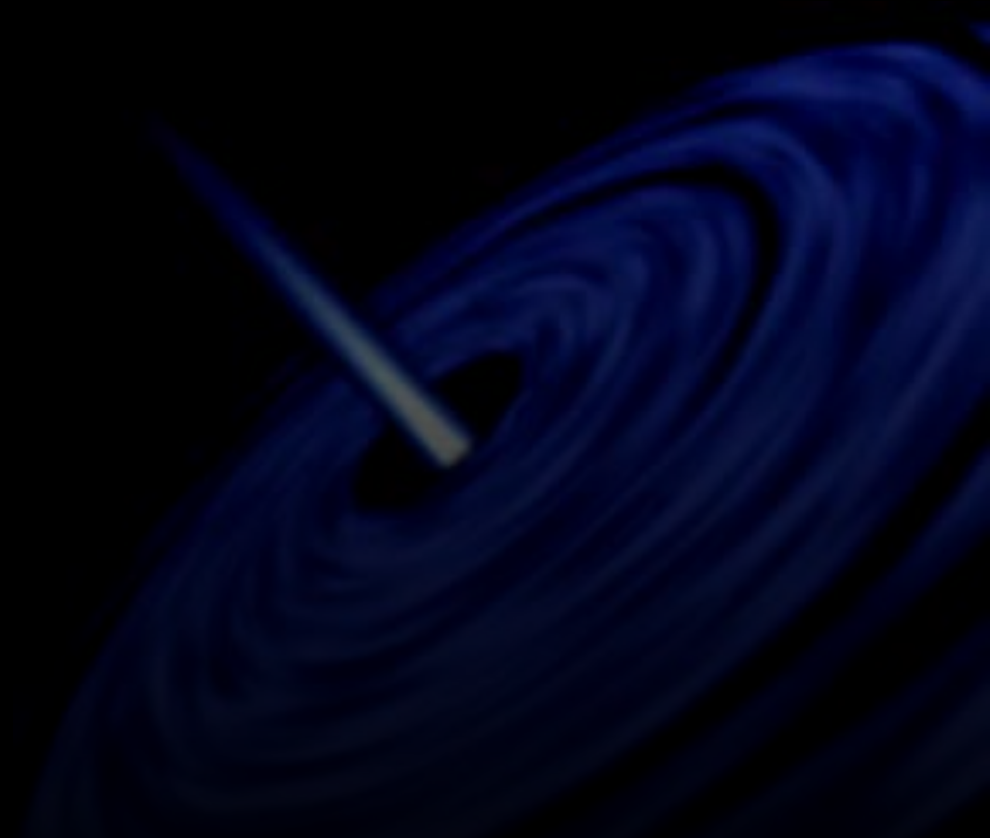
- TOAs are not perfectly regular due to many effects:





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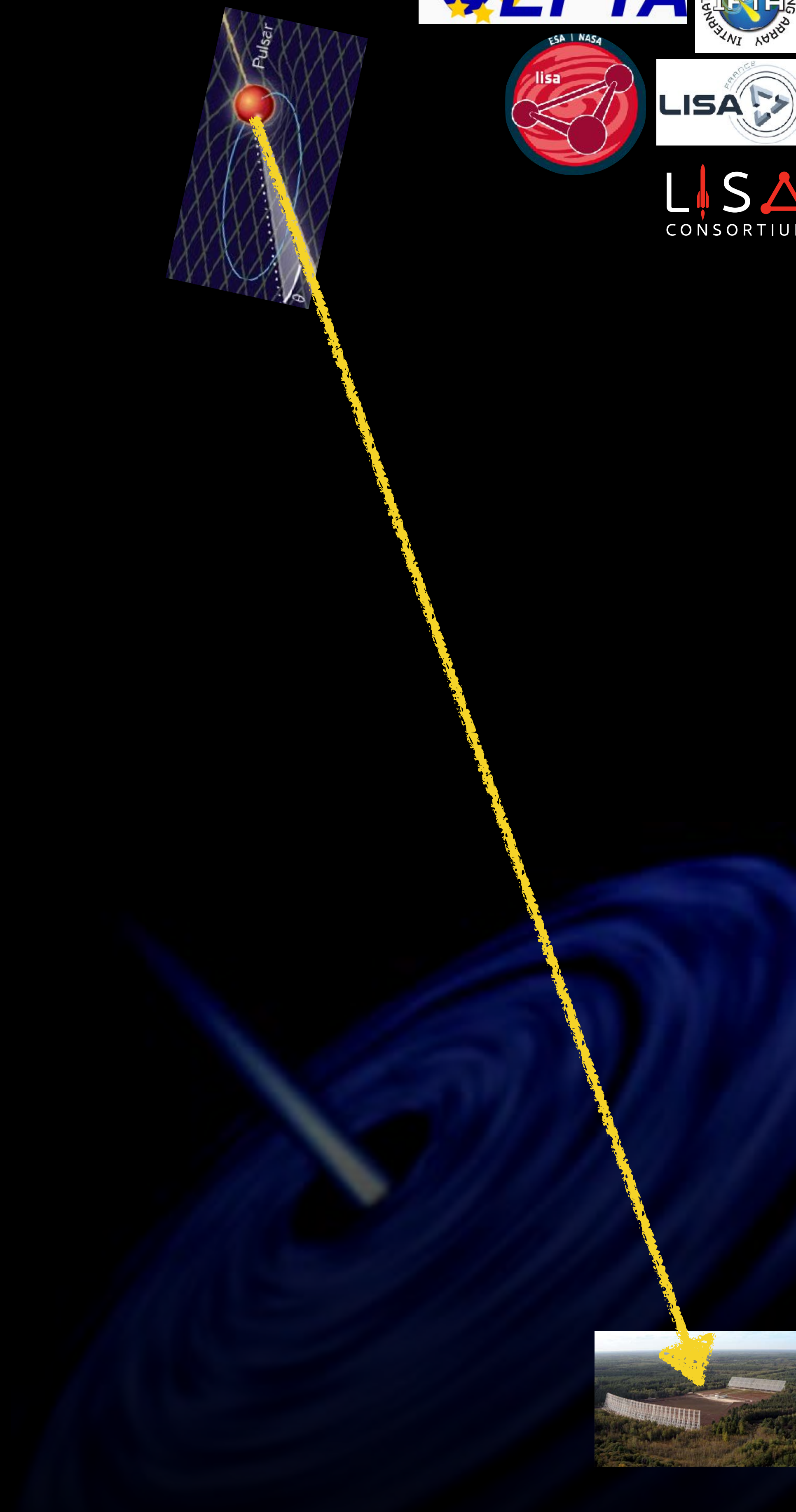
- TOAs are not perfectly regular due to many effects:
    - Pulsar itself:
        - period,
        - evolution of the period,
        - sky position



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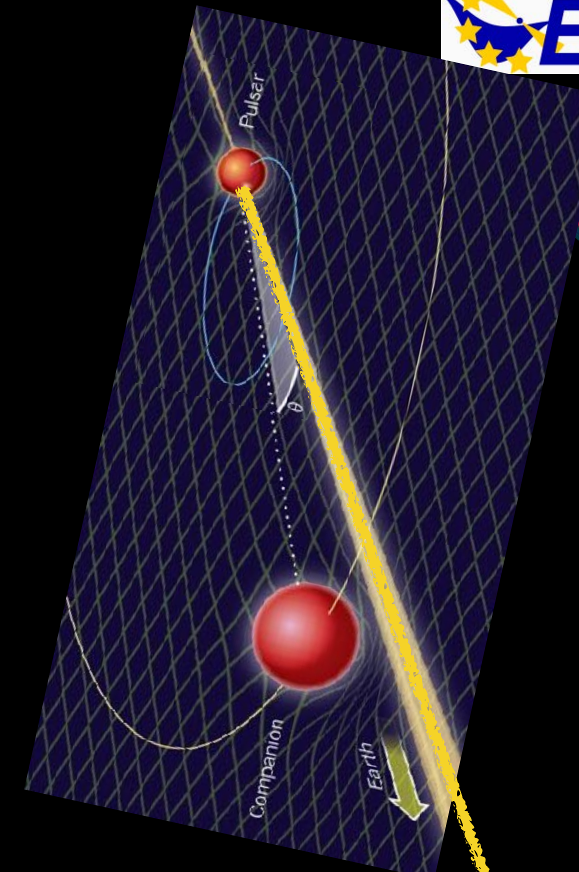
  - Pulsar environnement:
    - binary system,
    - proper motion

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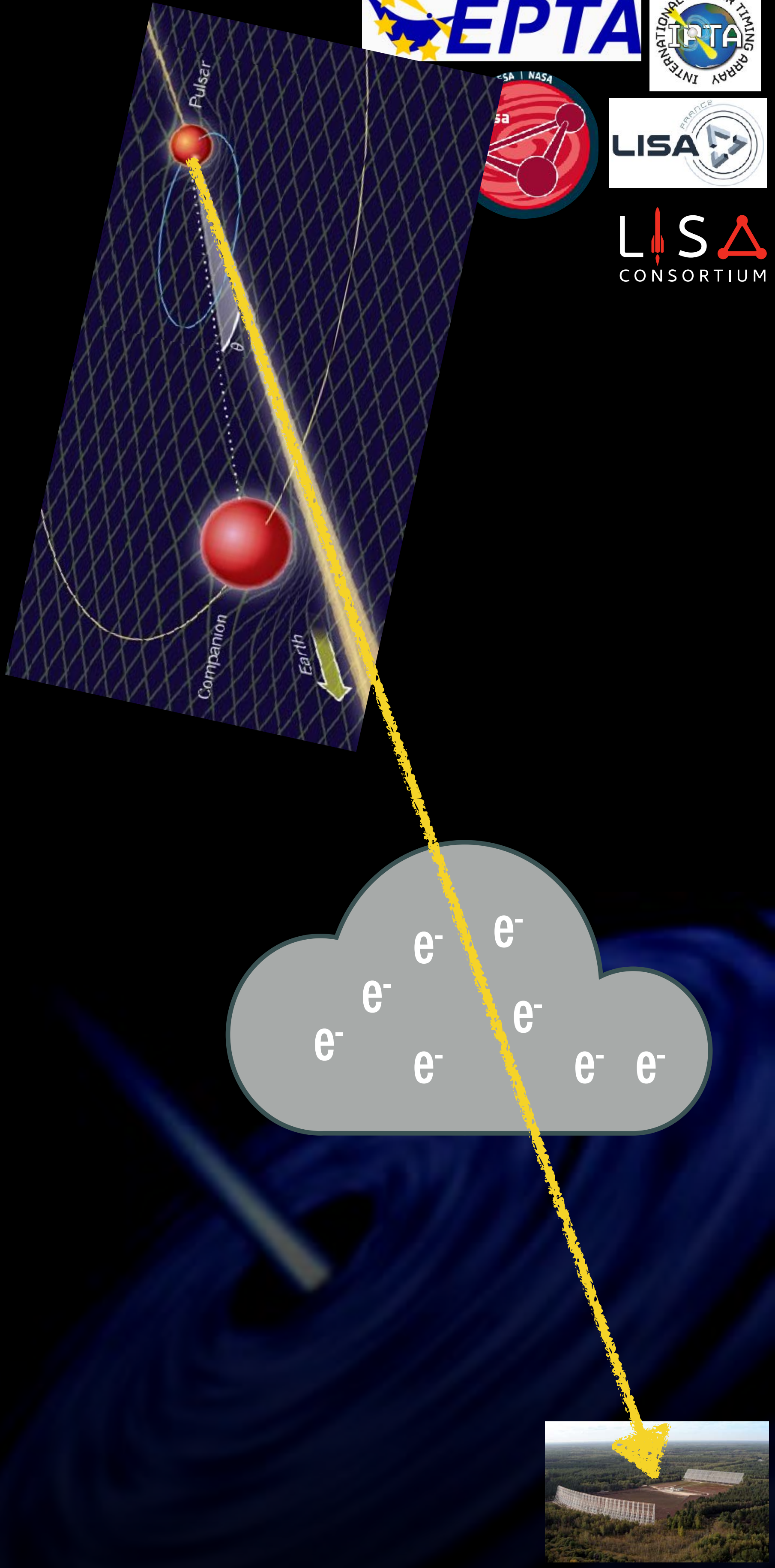
  - Beam propagation: interstellar medium



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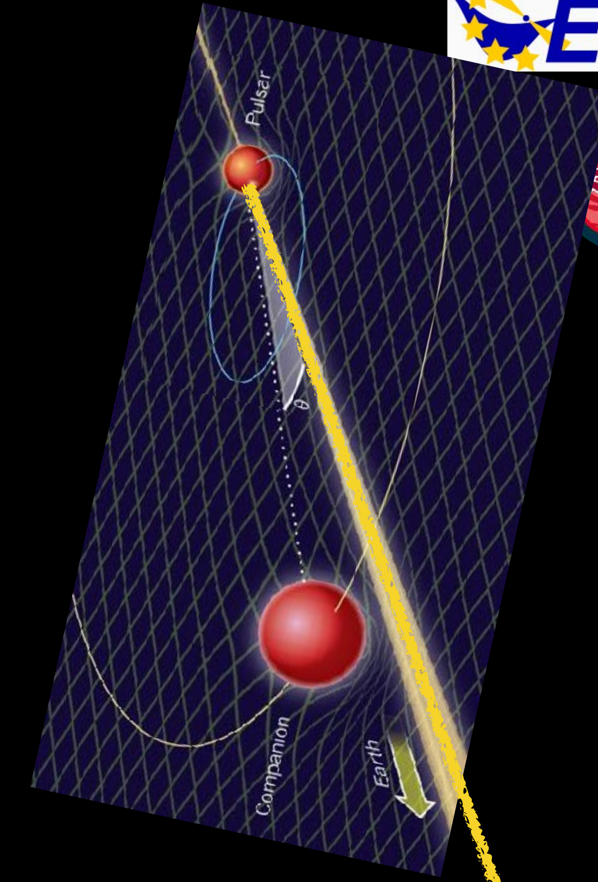
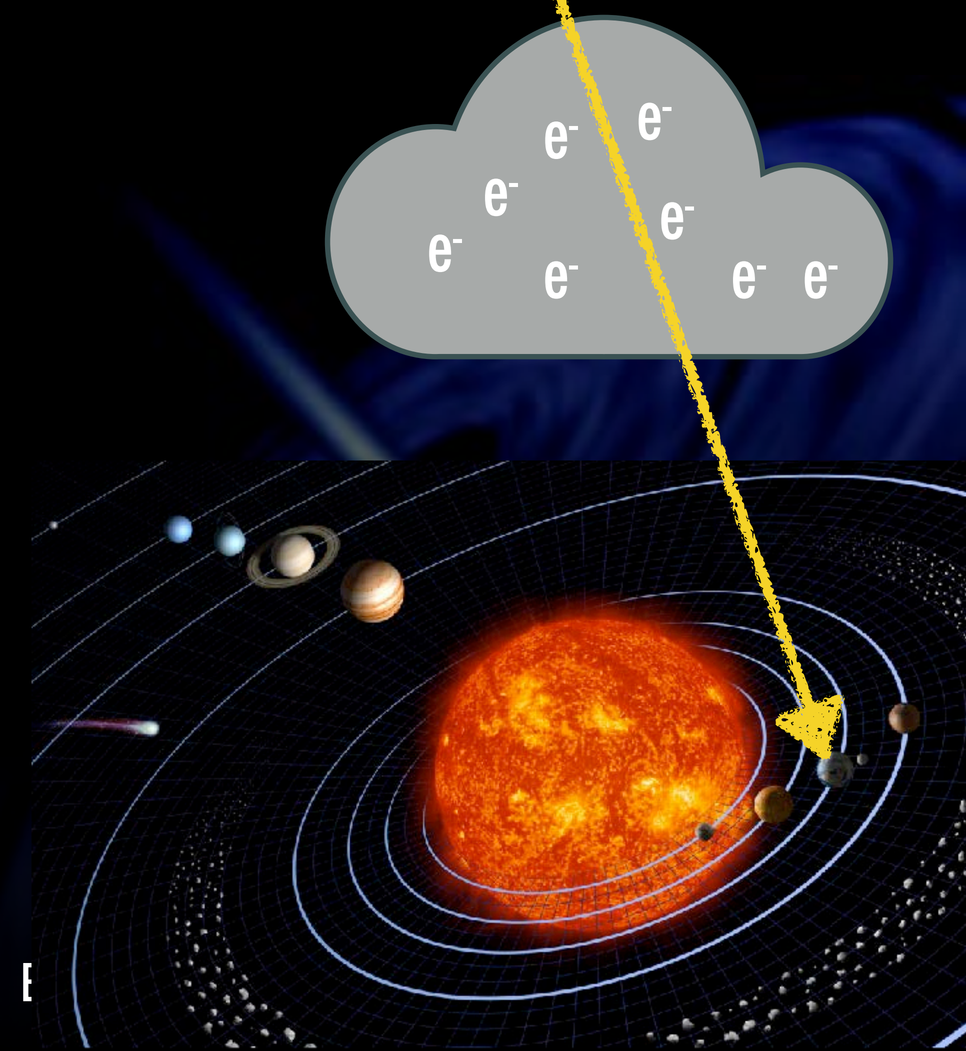
  - Earth position (ephemerides of the Solar System)



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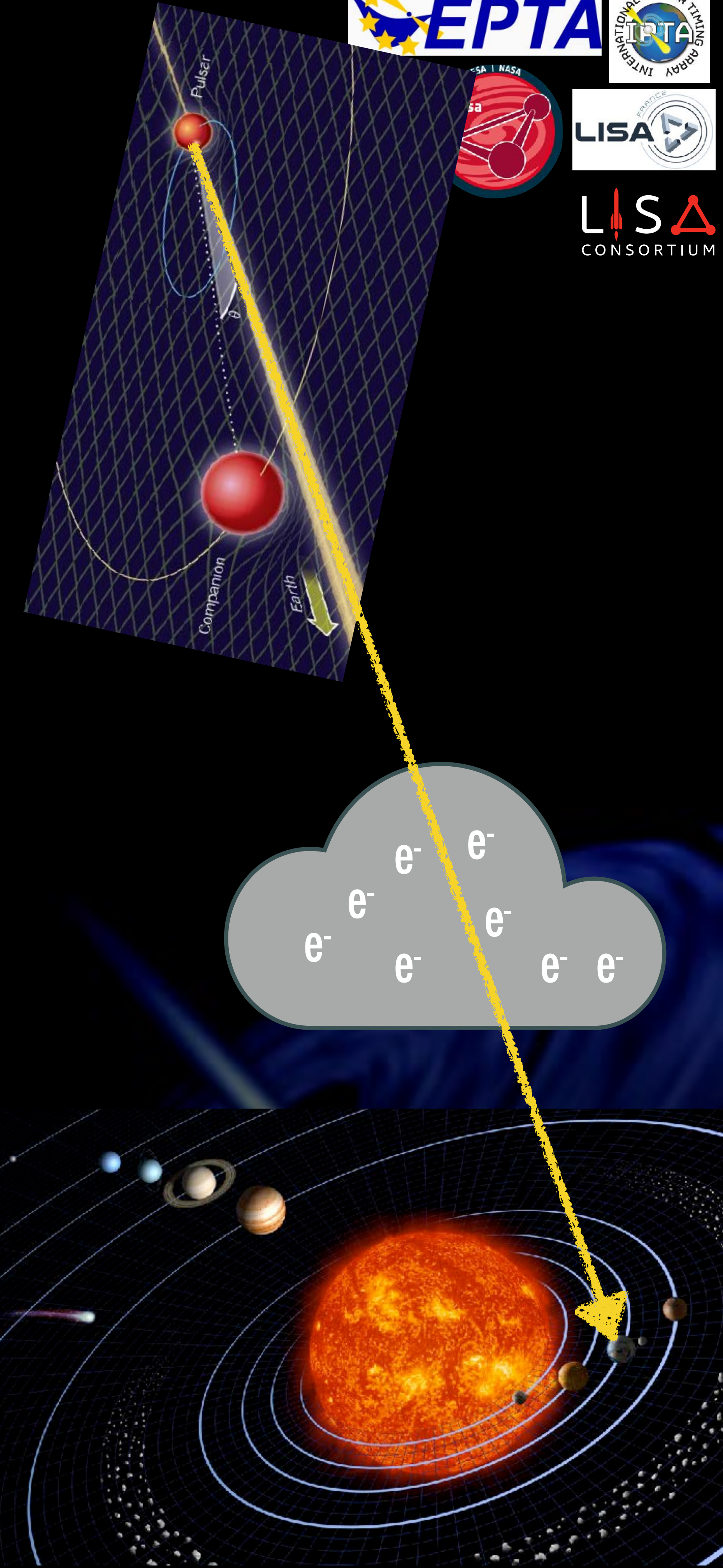
  - Beam propagation: interstellar medium
  - Earth position (ephemerides of the Solar System)
  - Gravitational waves …



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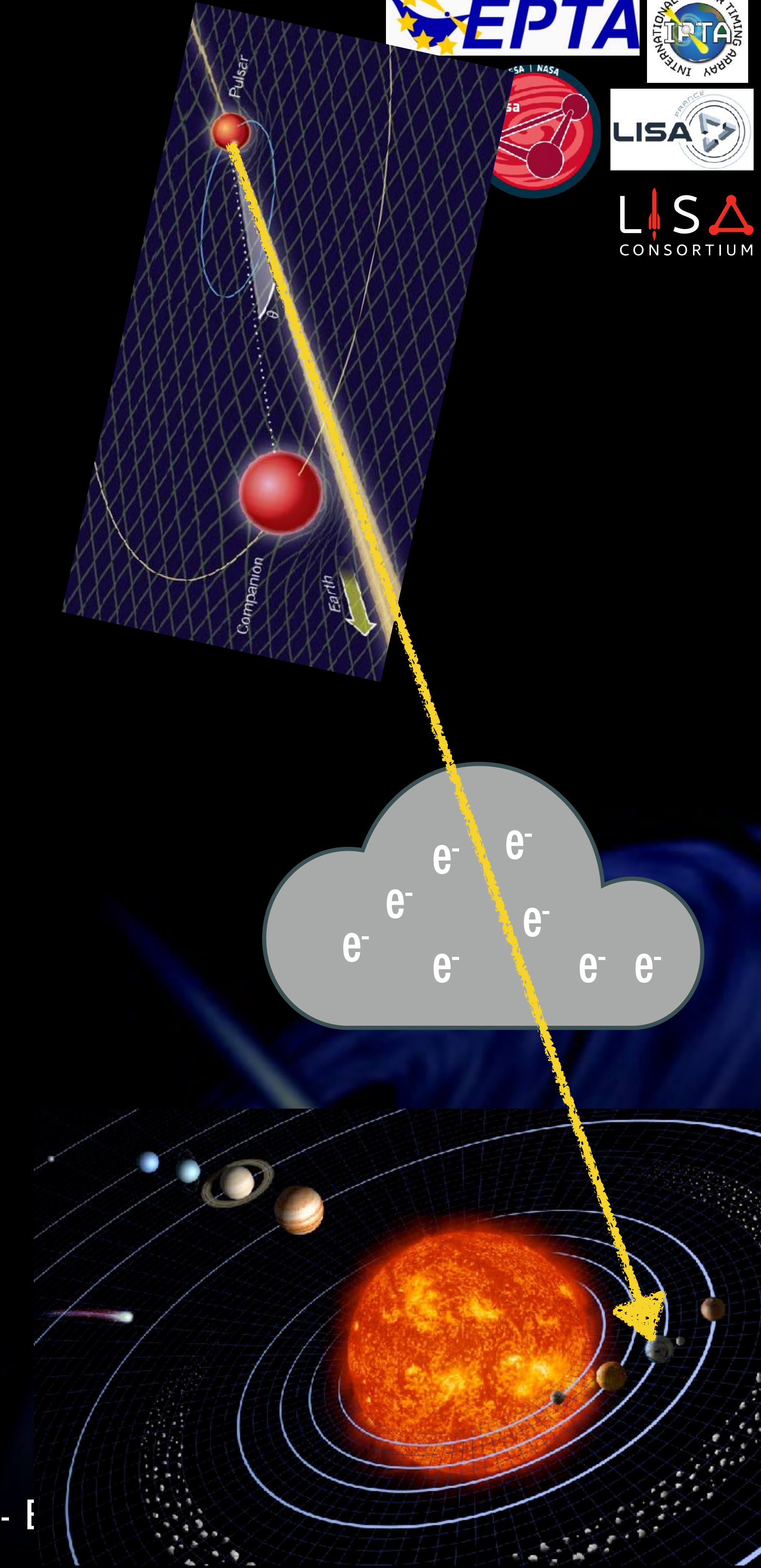
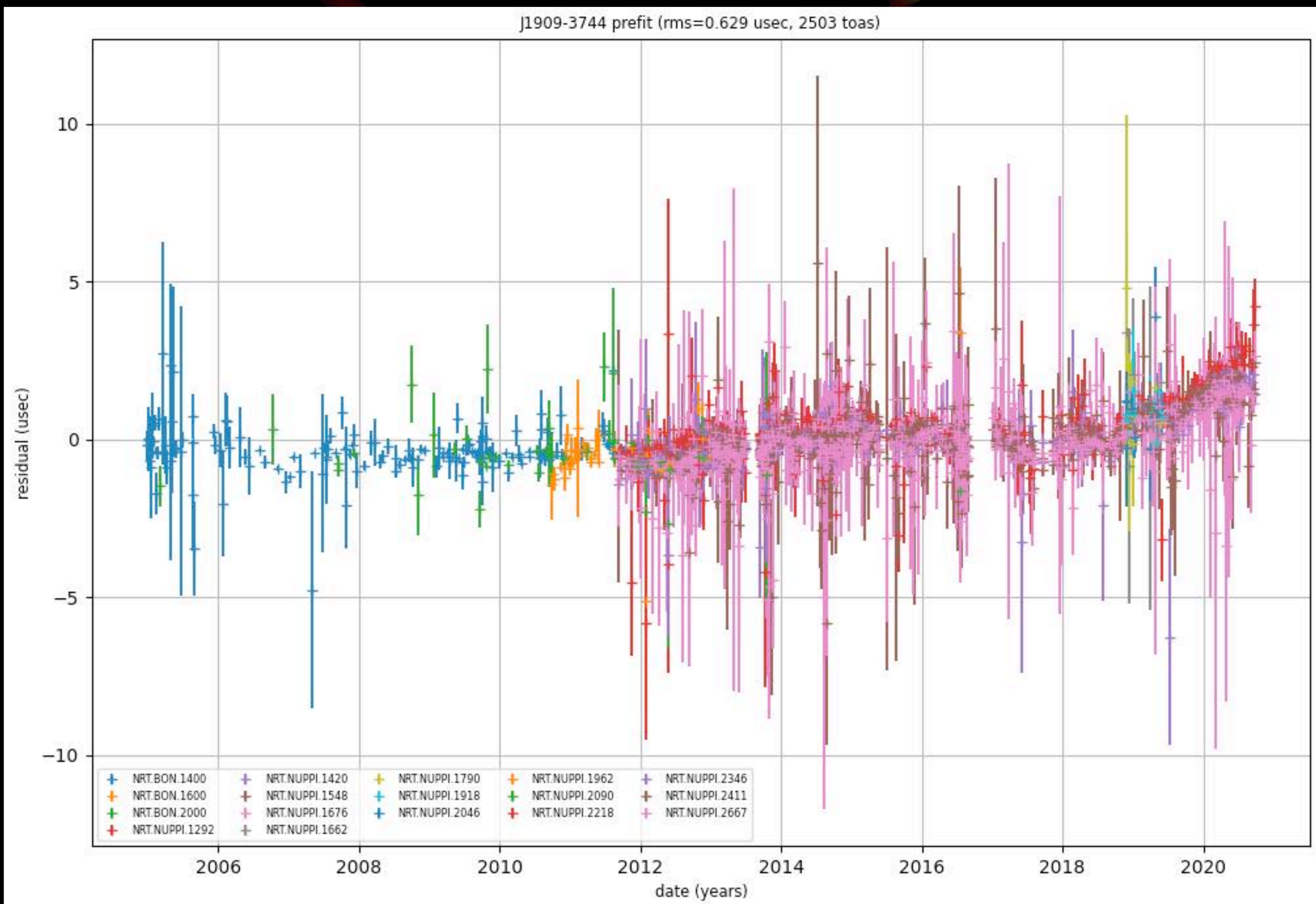
  - Earth position (ephemerides of the Solar System)
  - Gravitational waves …
- Modelling of each pulsars



# Pulsar timing

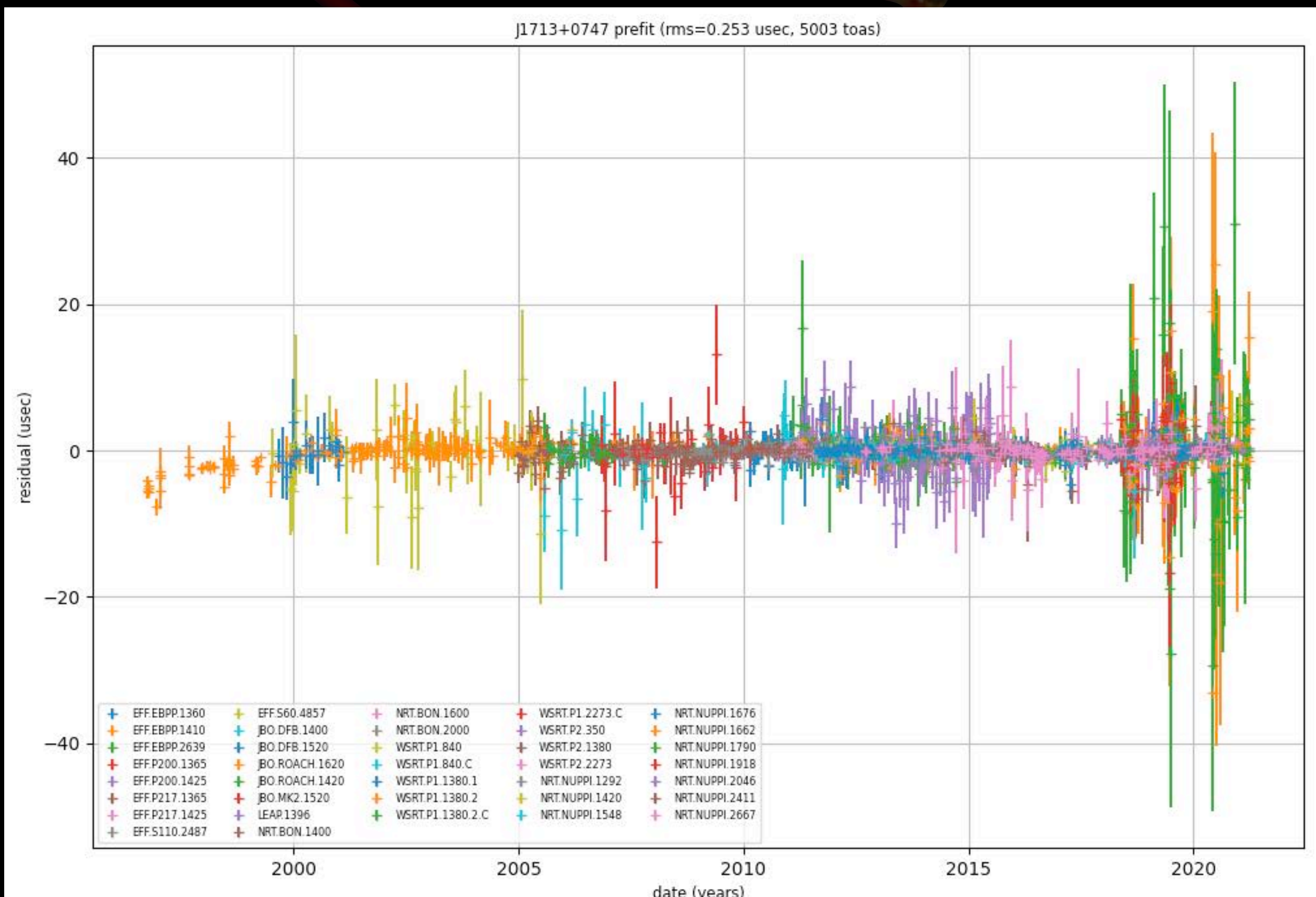
- Examples:
  - J1909-3744:




| 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

- Examples:
  - J1713+0747:




| Name | fit | prefit |
|---|---|---|
| RAJ | yes | 4.51091 +/- 4.51091 |
| DECJ | yes | 0.136027 +/- 0.136027 |
| F0 | yes | 218.812 +/- 218.812 |
| F1 | yes | -4.08396e-16 +/- -4.08396e-16 |
| DM | yes | 15.9926 +/- 15.9926 |
| DM1 | yes | 1.42664e-05 +/- 1.42664e-05 |
| DM2 | yes | -9.12919e-06 +/- -9.12919e-06 |
| PMRA | yes | 4.92273 +/- 4.92273 |
| PMDEC | yes | -3.91239 +/- -3.91239 |
| PX | yes | 0.92902 +/- 0.92902 |
| PB | yes | 67.8251 +/- 67.8251 |
| T0 | yes | 48742 +/- 48742 |
| A1 | yes | 32.3424 +/- 32.3424 |
| OM | yes | 176.21 +/- 176.21 |
| ECC | yes | 7.49383e-05 +/- 7.49383e-05 |
| PBDOT | yes | 7.11226e-13 +/- 7.11226e-13 |
| M2 | yes | 0.396039 +/- 0.396039 |
| KOM | yes | 99.0463 +/- 99.0463 |
| KIN | yes | 66.9501 +/- 66.9501 |
| JUMP1 | yes | 0.000593315 +/- 0.000593315 |
| JUMP2 | yes | 0.000592716 +/- 0.000592716 |
| JUMP3 | yes | 0.000593452 +/- 0.000593452 |
| JUMP4 | yes | 0.000619147 +/- 0.000619147 |

…

# Pulsar noises

https://arxiv.org/abs/2306.16225

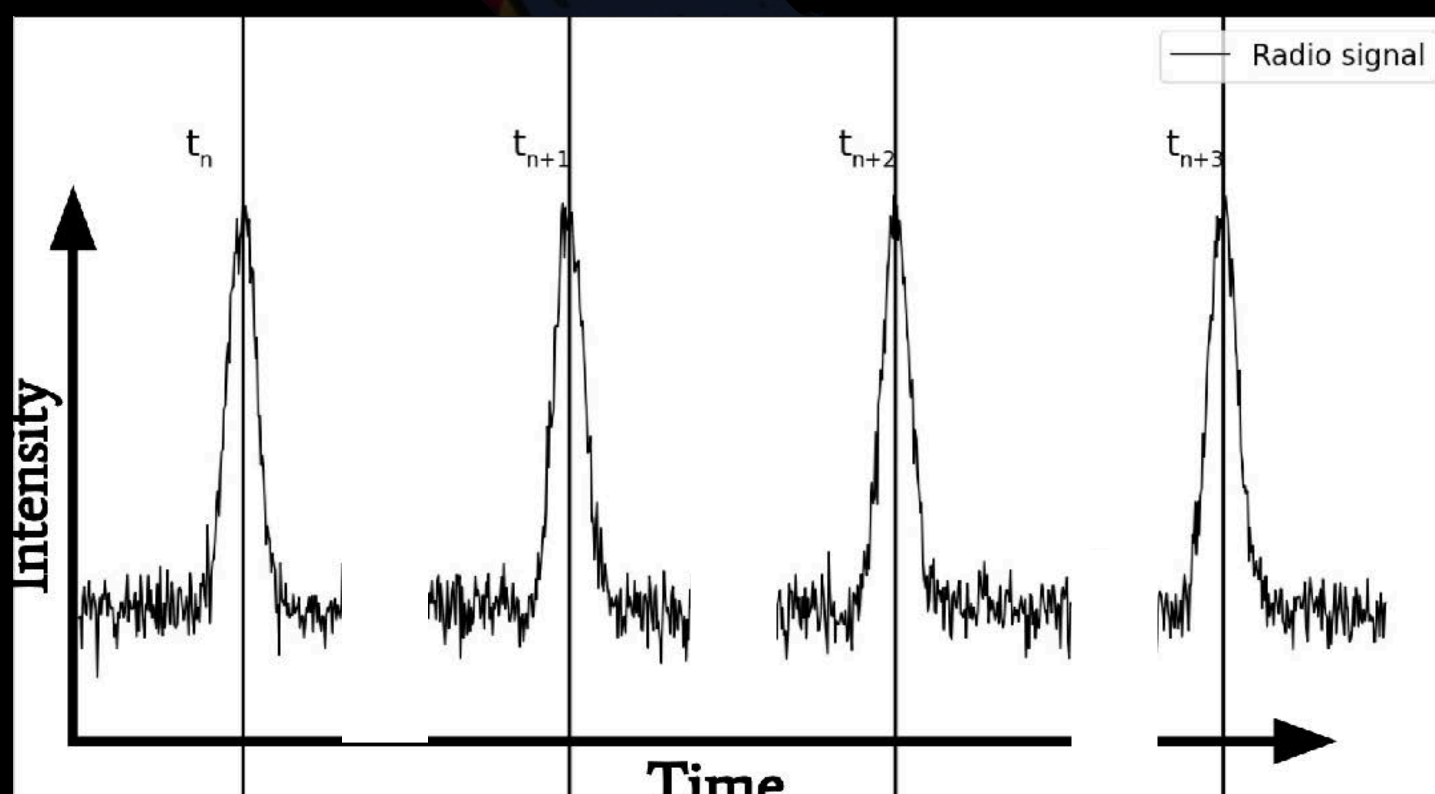
- White noise :
  - $\sigma^2_{\text{scaled}} = \text{EFAC}^2 \times \sigma^2_{\text{original}} + \text{EQUAD}^2$. with $\sigma^2_{\text{original}}$ the original errorbars
    +2
- Red noises:

$$S_k = \frac{A^2}{12\pi^2} \frac{K_{scale}}{\nu^{-k}} \left( \frac{f}{1\text{yr}} \right)^{-\gamma} \frac{\text{yr}^3}{T_{span}}$$

with $\nu$ the observation frequency

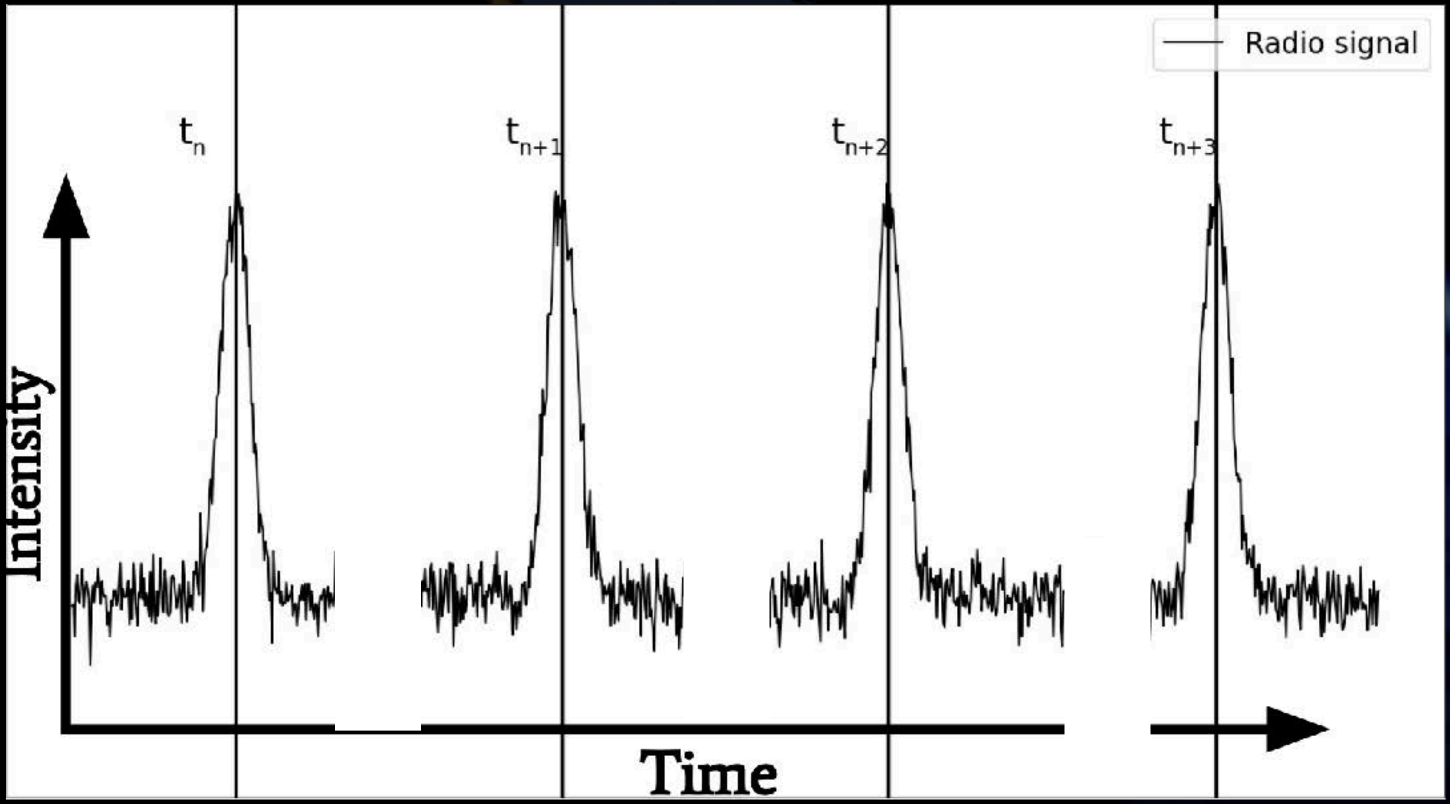
  - RN: standard red noise ($k = 0$) +2
  - DM: Dispersion Measure variations ($k = 2$) +2
  - SV: scattering variations ($k = 4$) +2
- Specific features for some pulsar: exponential dips

# 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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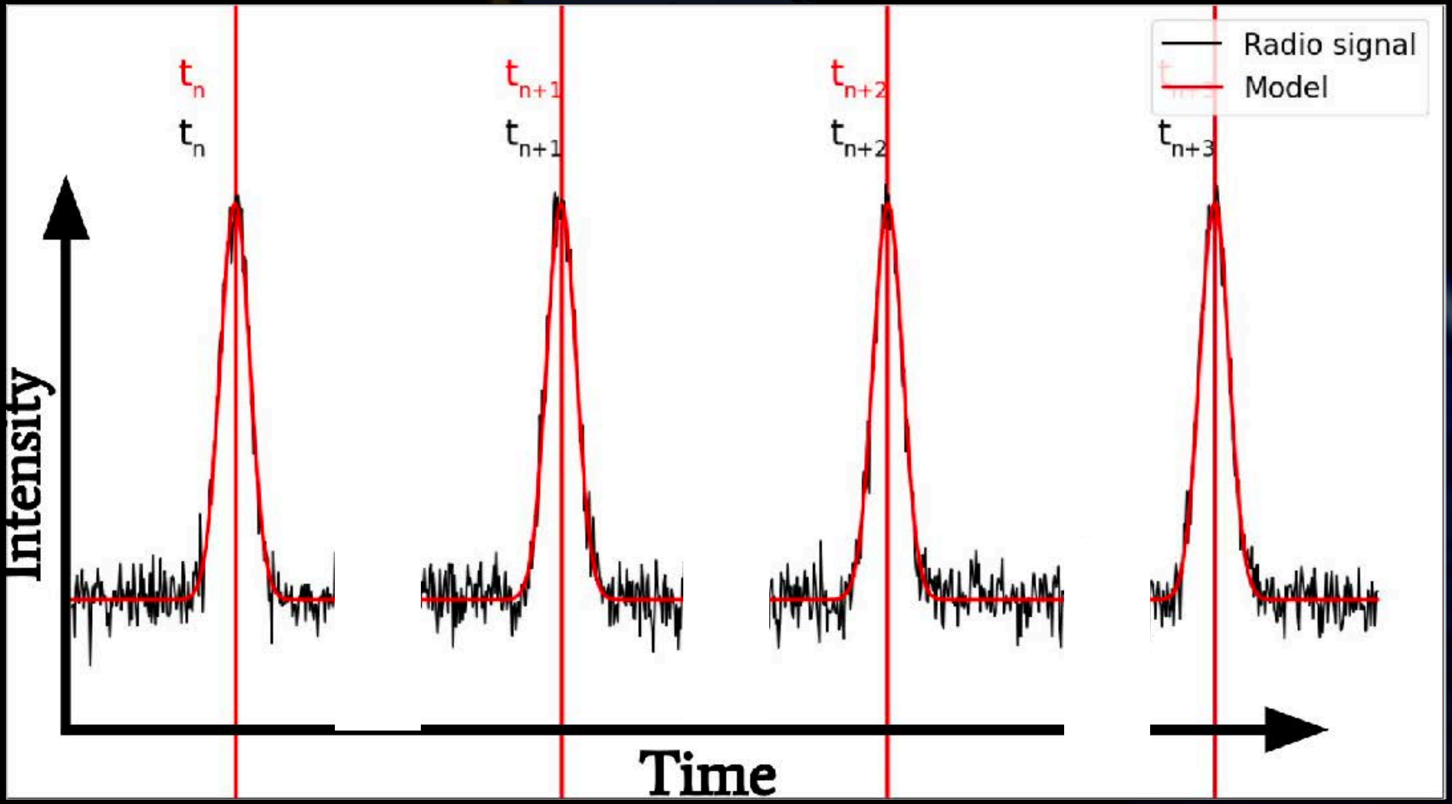
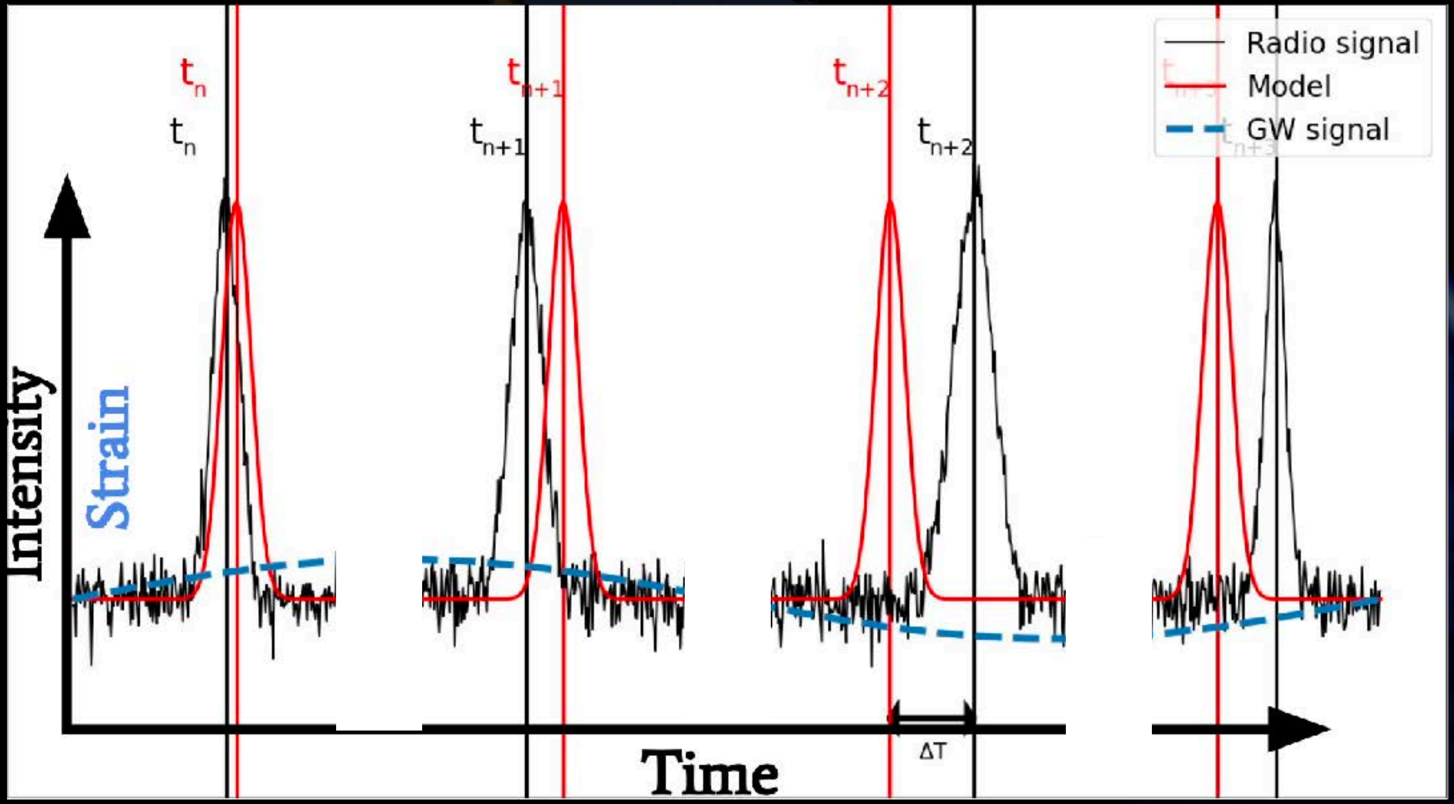
- We have a model for the TOA



# 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

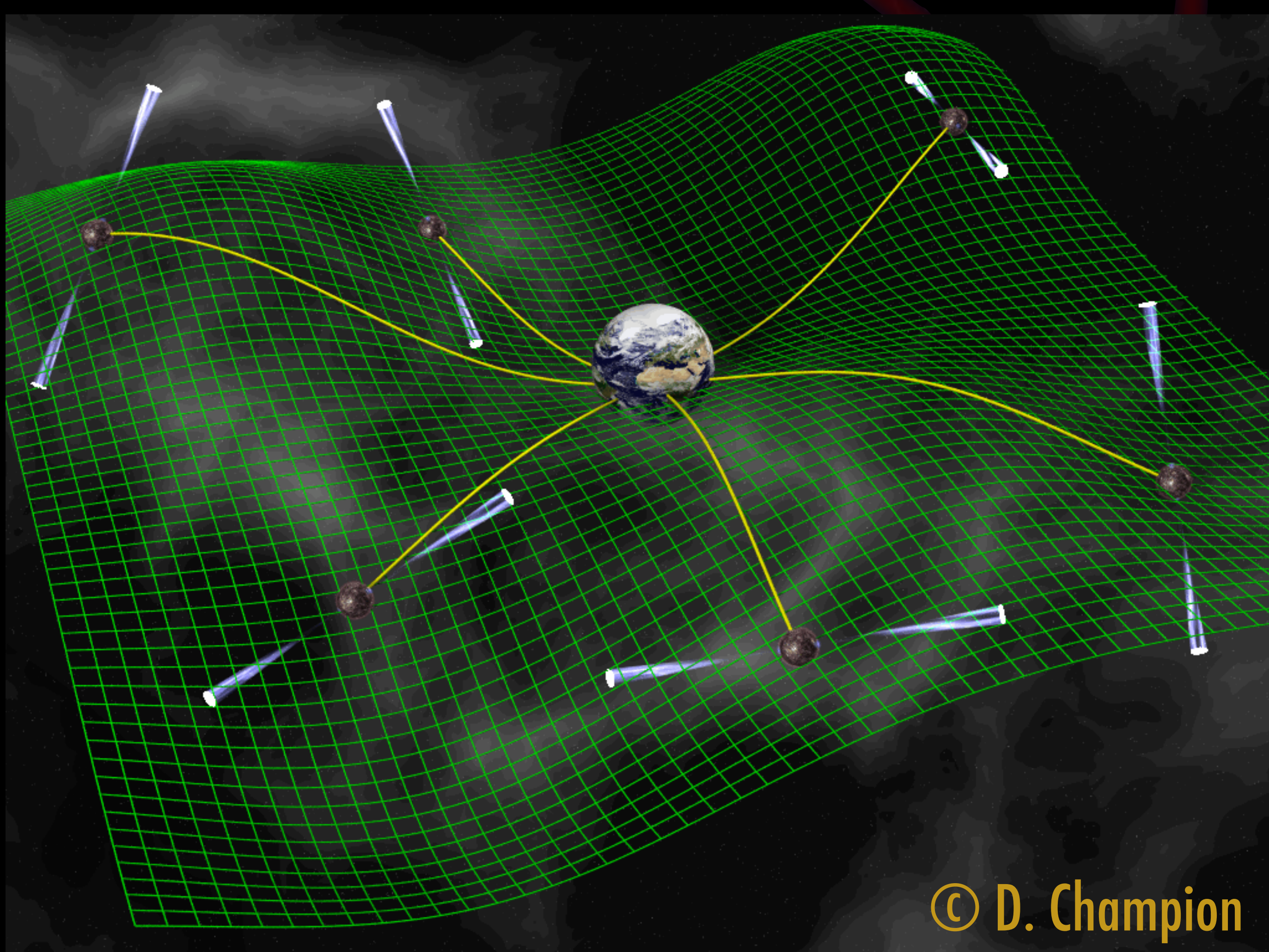
Observed & emitted pulsar spin frequency

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

Emission & reception times of pulses

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

Pulsar & GW source sky location



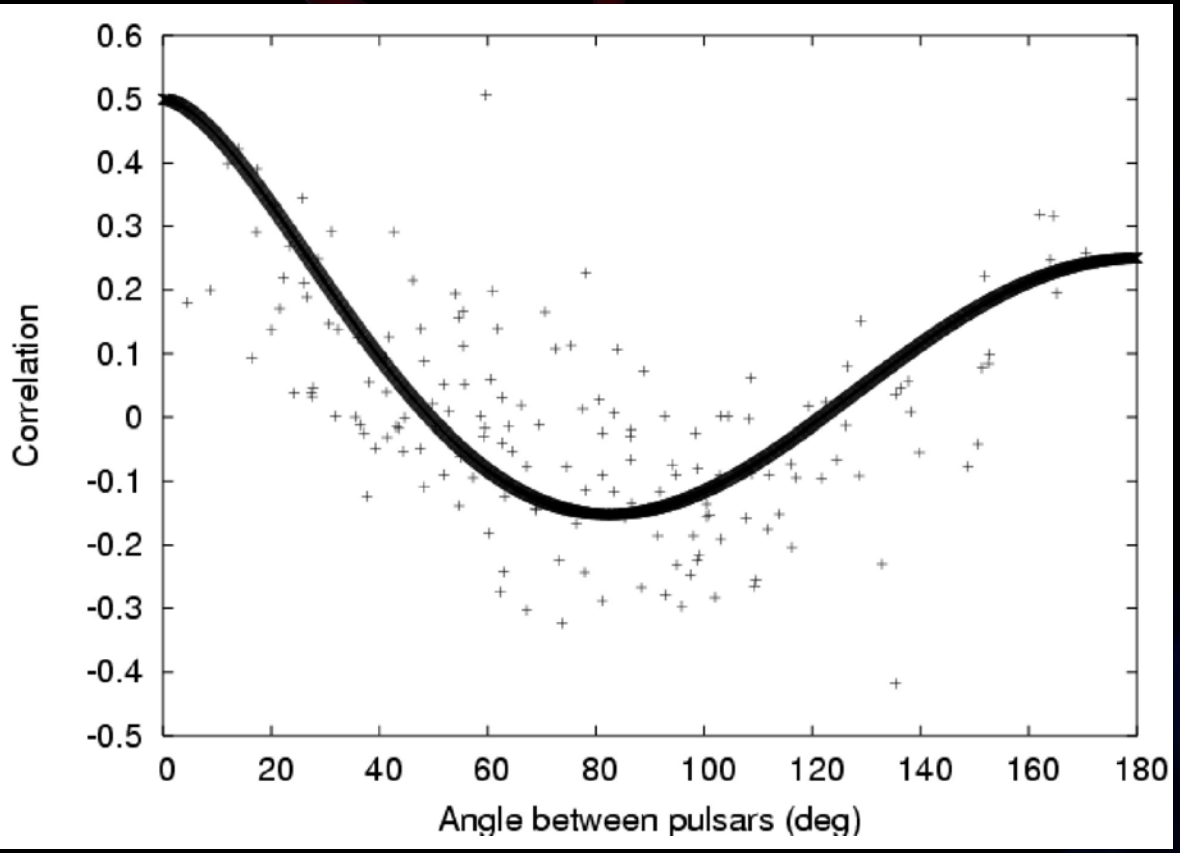

$$\Delta h_{ij} = h_{ij}(t_e) - h_{ij}(t_a)$$

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

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



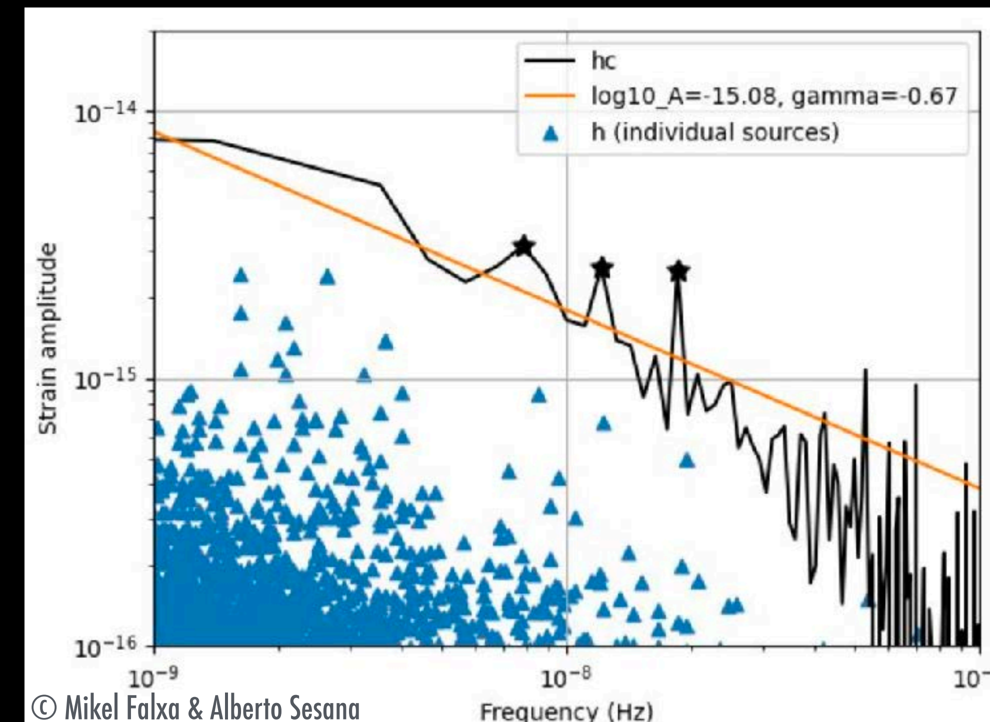
# Correlated signals

- 3 potential types of signal correlated between pulsars:
  - Quadrupole:
    - Gravitational waves
  - Dipole:
    - Systematic in the model of the position of the Earth, i.e. solar system ephemeris
  - Monopole:
    - Clock time errors

# 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

© Nicole Rager Fuller

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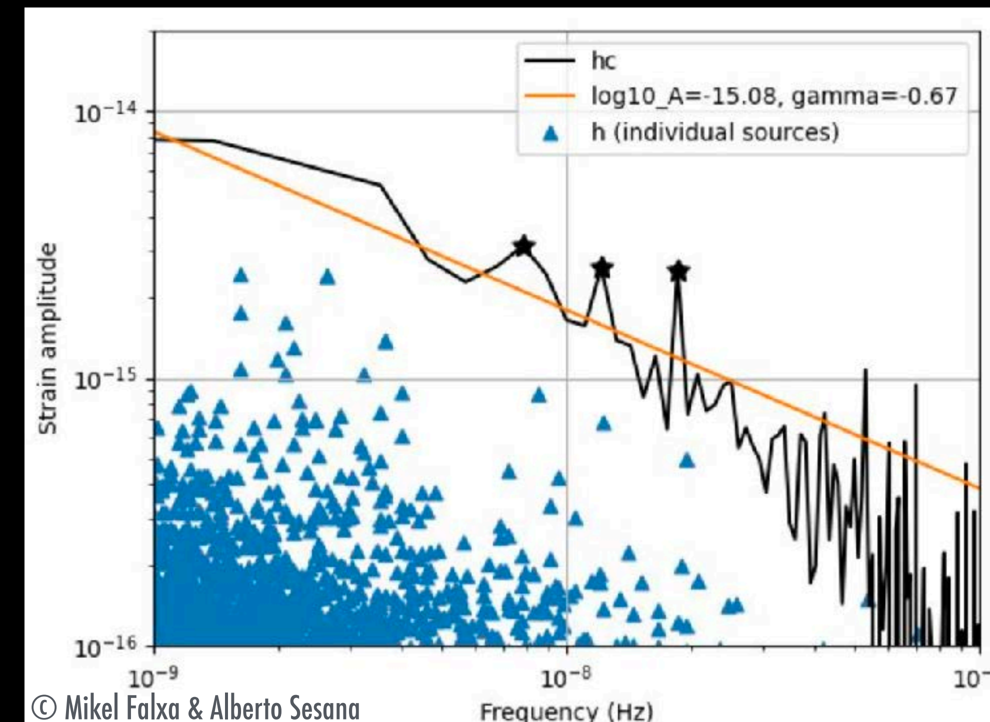
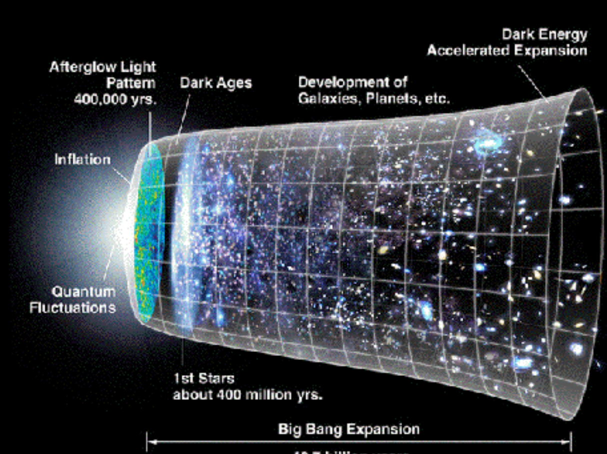
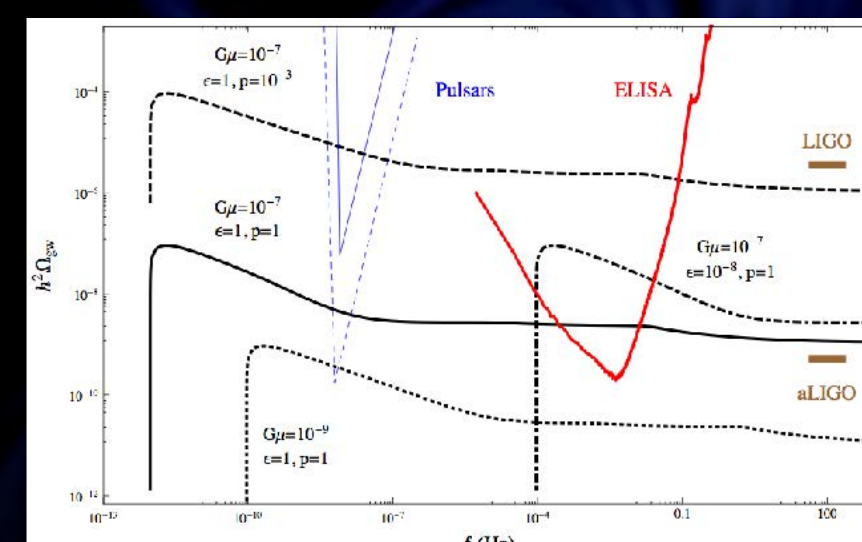



- Stochastic background from cosmological origin:
  - First order phase transition
  - Cosmic strings
  - Primordial GWs
  - …

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# EPTA

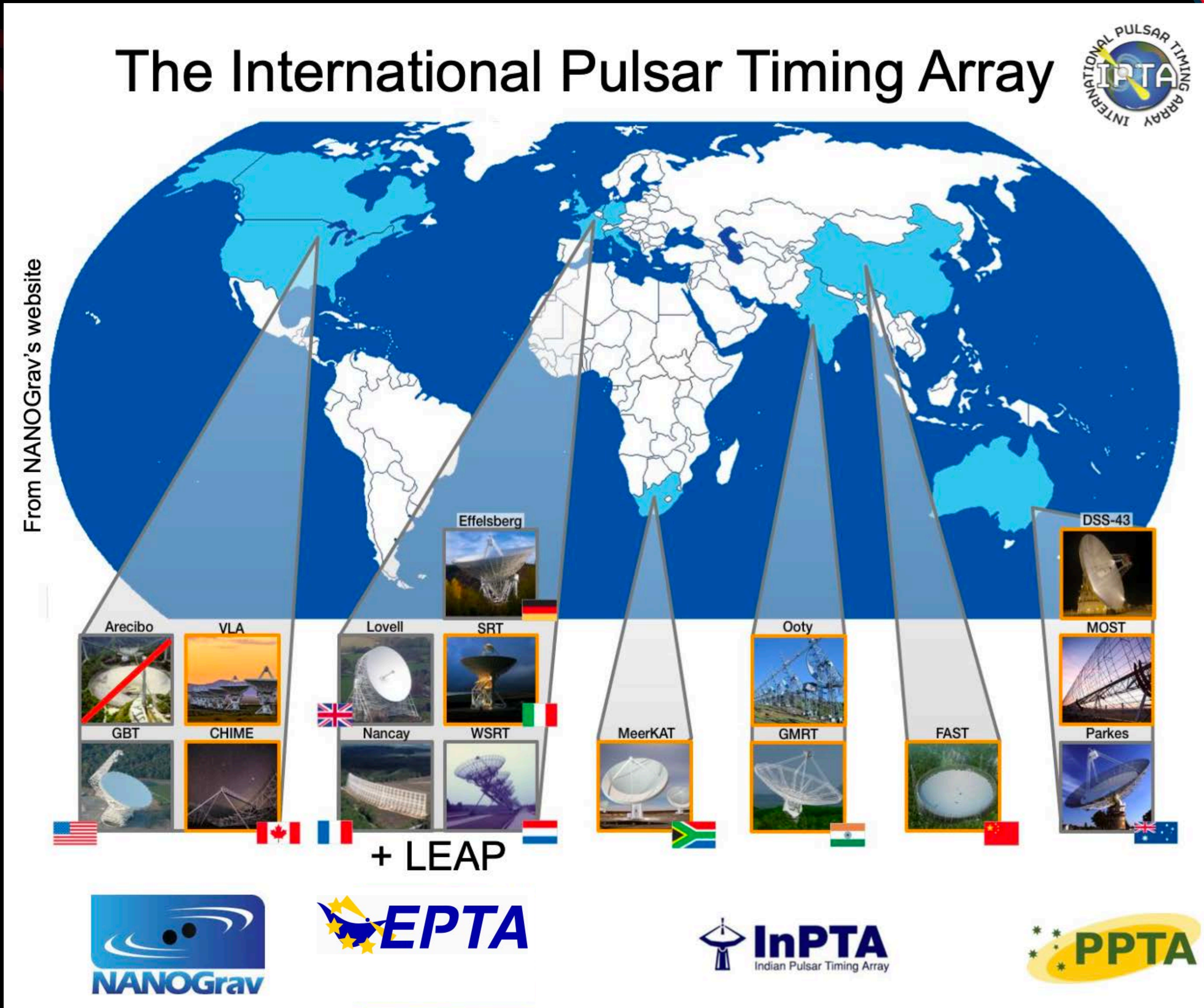
- European collaboration:
  - Nancay RT (FR),
    70% of the data
  - Effelsberg RT (G),
  - Jodrell Bank Obs. (UK),
  - Westerbork Synthesis RT(NL),
  - Sardinia RT (I).



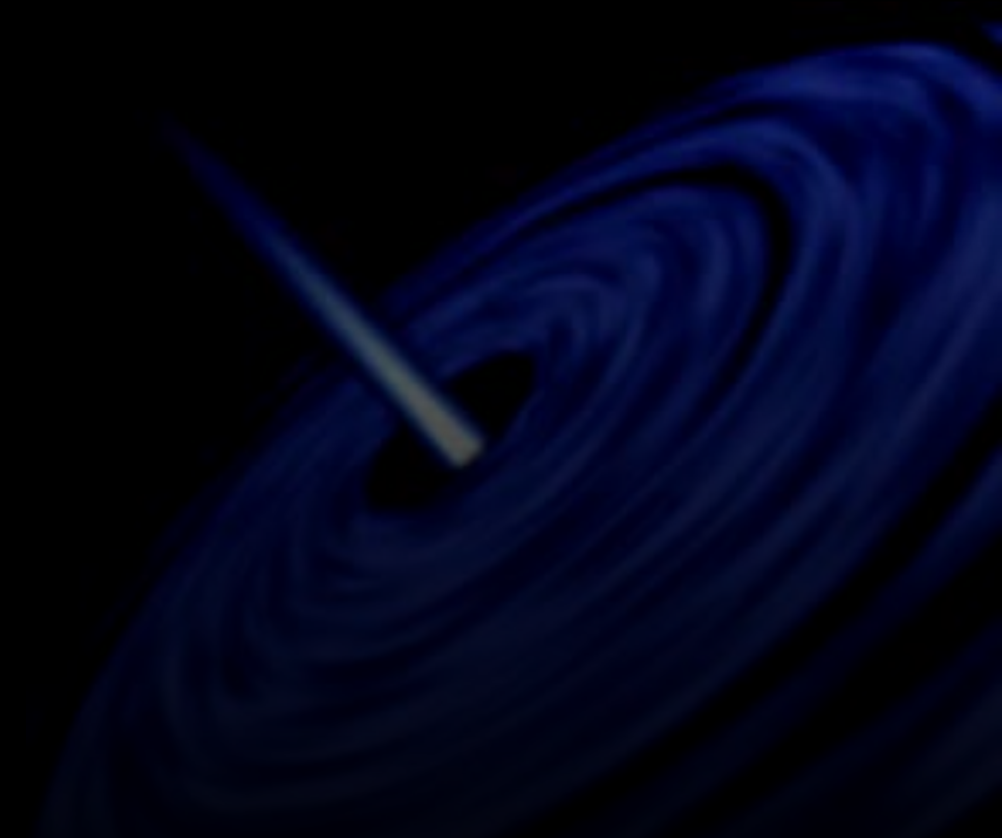
# IPTA

- Two others collaborations
  - Parkes PTA (Australia)
    - Parkes radiotelescope
  - NANOGrav (USA):
    - ~~Arecibo~~
    - Green Bank
- Recent collaborations:
  - InPTA: GMRT, ORT (Inde)
  - CPTA: FAST, … (Chine)
  - MeerKAT (Afrique du Sud)
- Worldwide collaboration: International PTA

# PTA collaborations



# PTA data analysis



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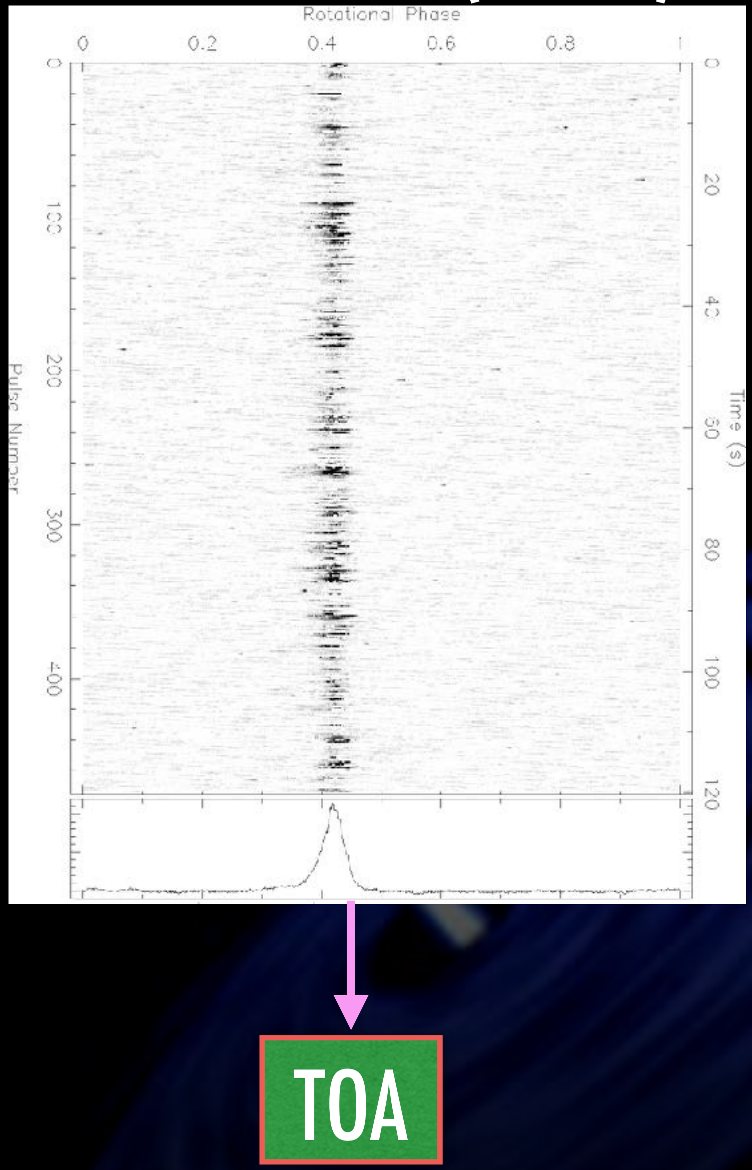
   1. Building Time of Arrival (TOA): processing of the raw data taken during one observation to extract the TOA of the pulse with extremely high precision;

One observation (1.5 Go)



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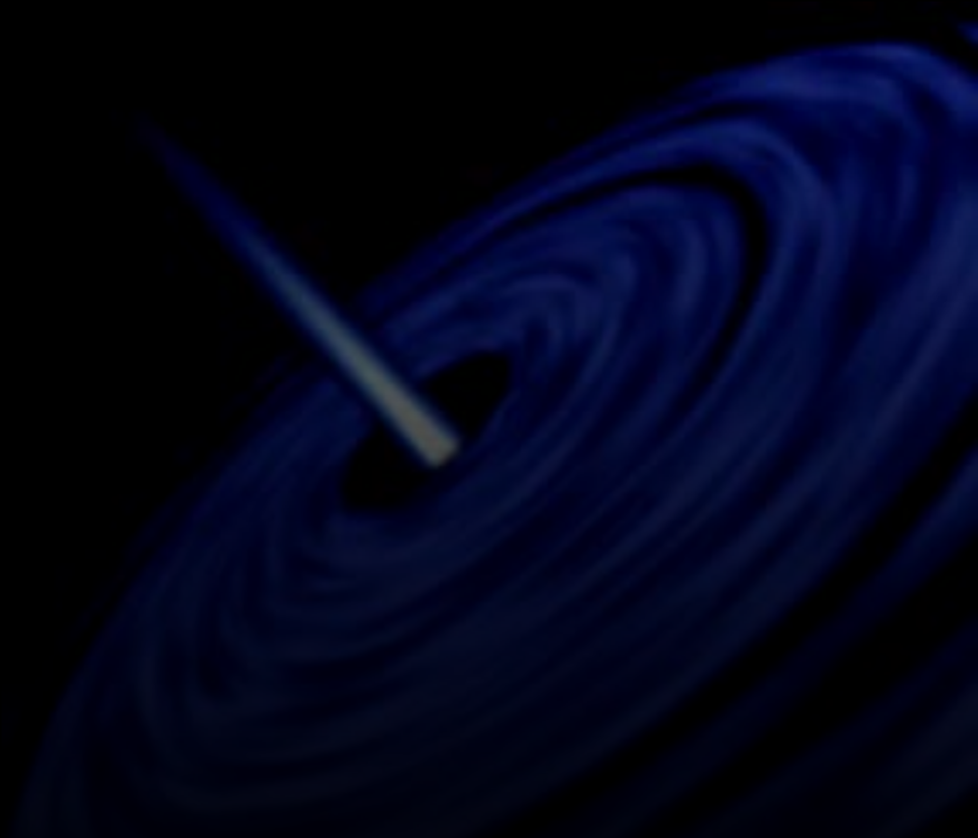
TOA



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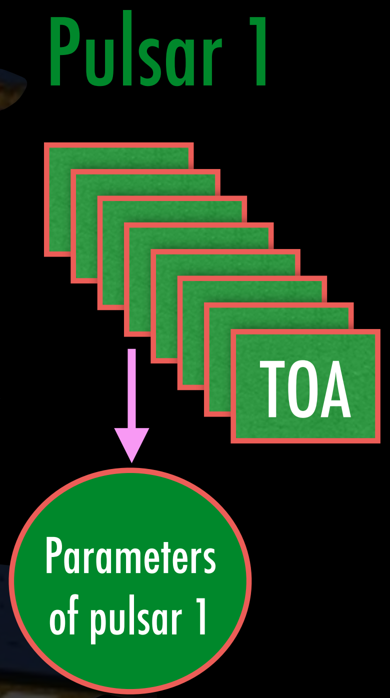

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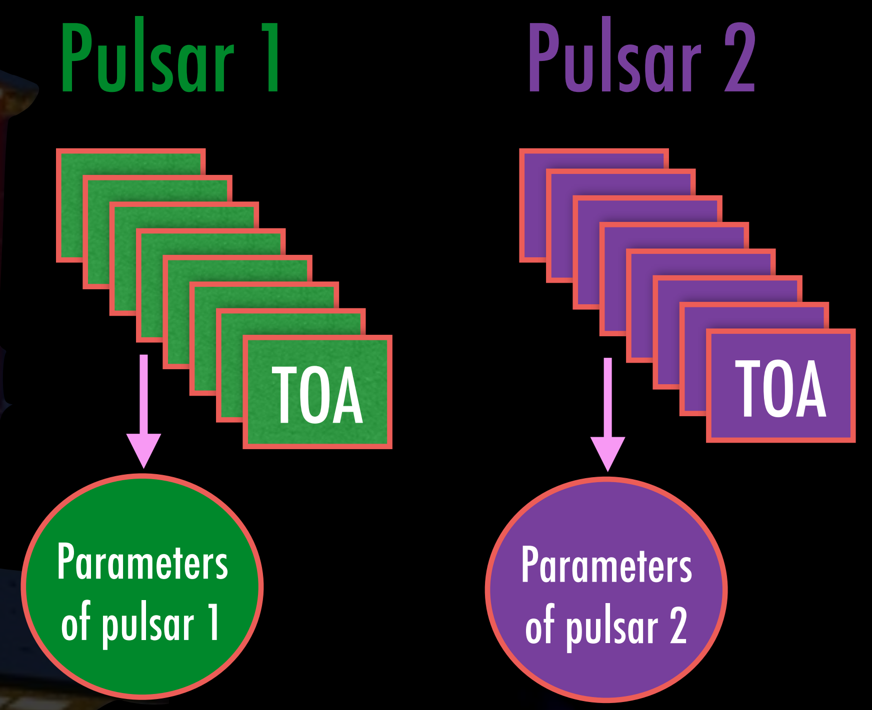

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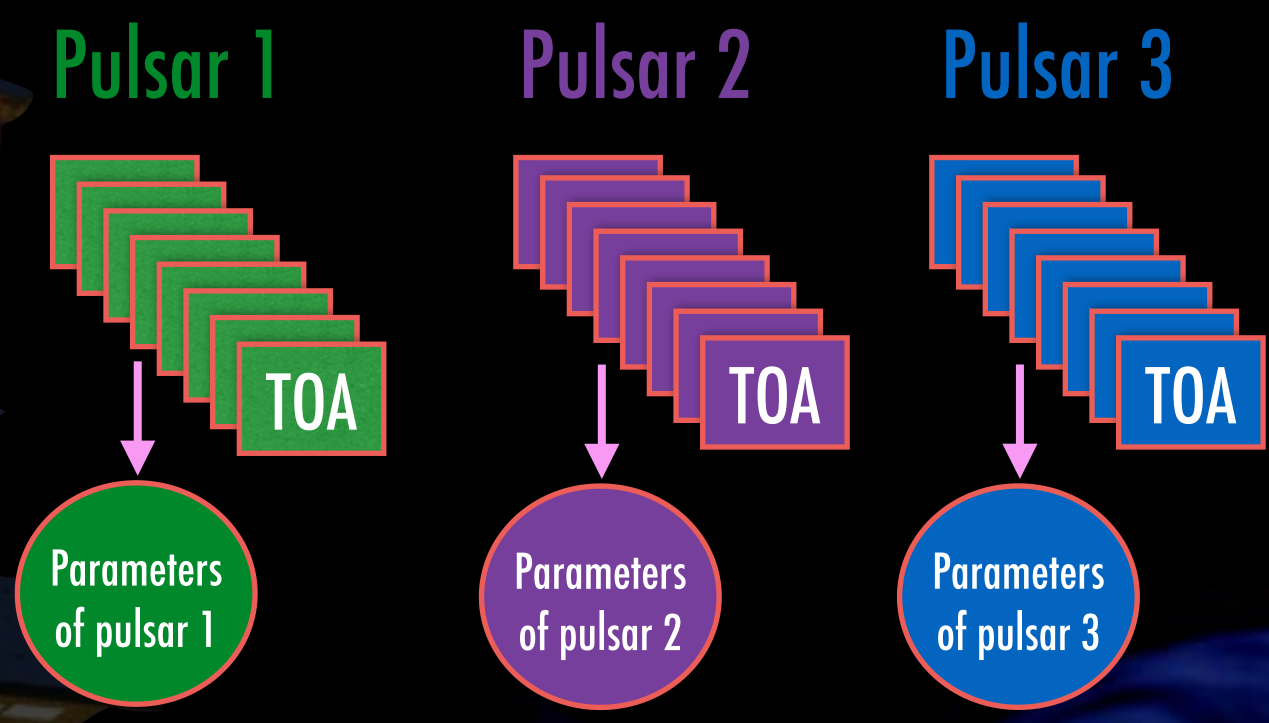

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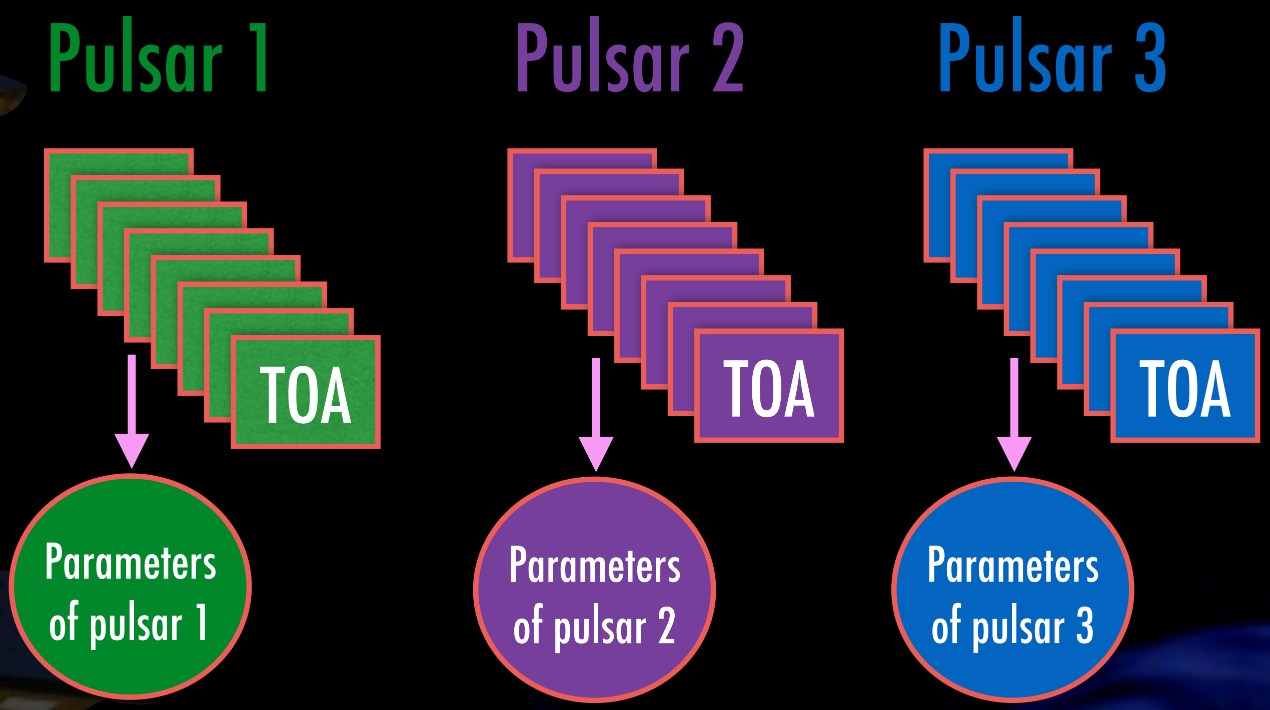

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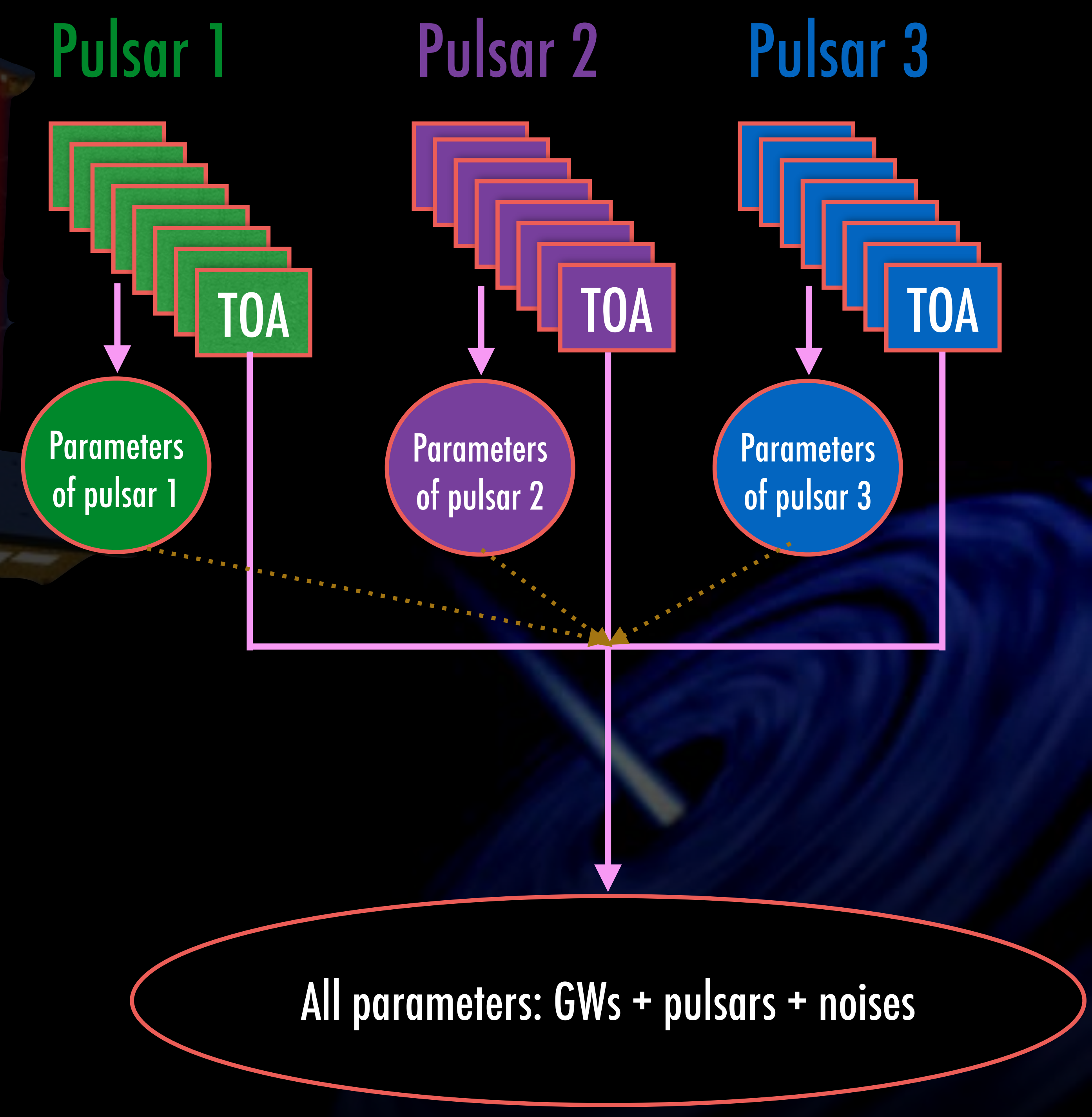
- Several tools for each steps developed either locally or within the international collaboration



# PTA data analysis

- (Step 3) Global analysis:
  - Systematics: ephemerides, clock stability, …
  - Bayesian analysis:

$$p(\delta t \,|\, \vec{\theta}) = \frac{1}{\sqrt{det(2\pi\Sigma)}} exp\left(-\frac{1}{2}\delta t^T \Sigma^{-1} \delta t\right)$$

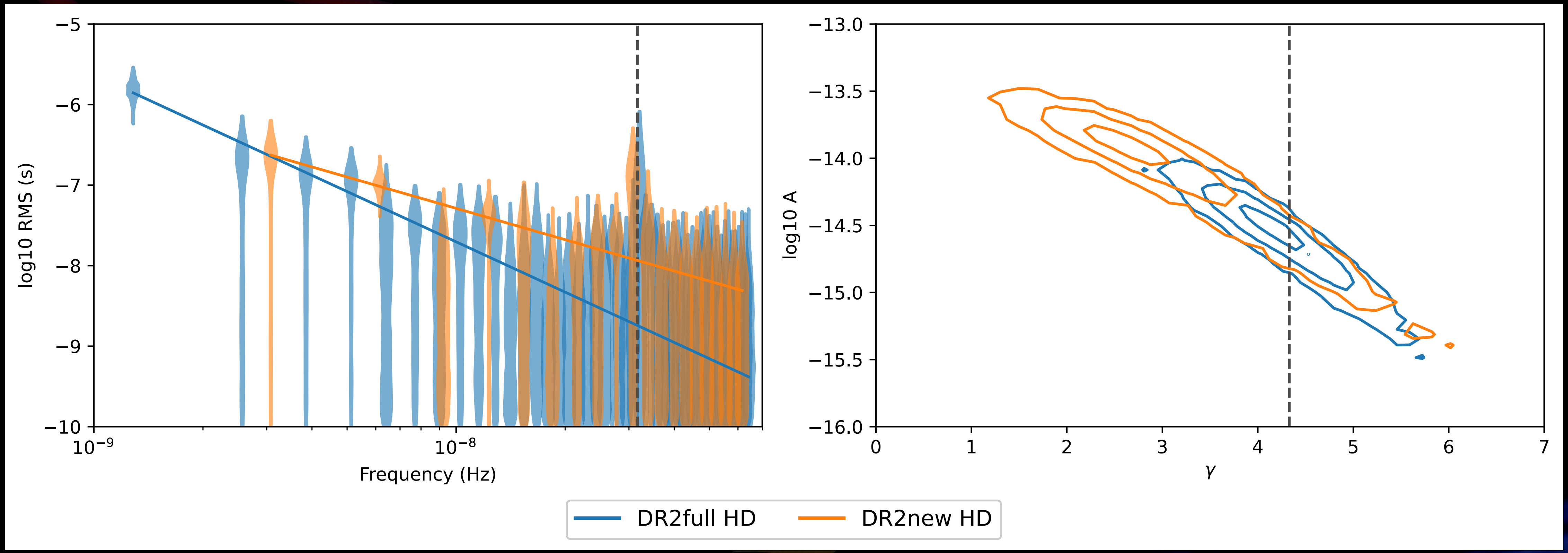
- Continuous waves (i.e. individual sources): $\delta t \rightarrow \delta t - \sum_{i=1}^{N_{signals}} h_i$
- Stochastic: $\Sigma$
  - GW Background: common noise
  - Noises:
    - White noise: measurement errors + systematics
    - Red noise: low frequency noise on pulsar rotation
    - Dispersion noise due to the propagation through interstellar medium
- Timing parameters (pulsars parameters) also considered

# PTA data analysis

- PTA data analysis is challenging and very demanding in term of computing resources.
- Several stages of processing:
  1. Building Time of Arrival (TOA)
  2. Single pulsar analysis
  3. Global analysis
- Ideally all the processing steps to be done simultaneously BUT the trans-dimensionality and the size of the parameter space and of the model space to explore, would be enormous and not tractable with the current methods and computing facilities.
- Methods currently used: Bayesian with hypermodel selection (MCMC & nested sampling)
- Data: 30 to 60 pulsars are currently analysed with about 5000 to 10 000 TOAs per pulsar.
- TOAs not regularly sampled => likelihood computation required the inversion of a big matrix, $\Sigma^{-1}$ ($\sim 10^5 \times 10^5$ but soon $\sim 10^6 \times 10^6$).
- Current methods are performing some approximations to avoid this inversion.
- Some exploration of machine learning methods, but not yet full-scale application and very low level of maturity.

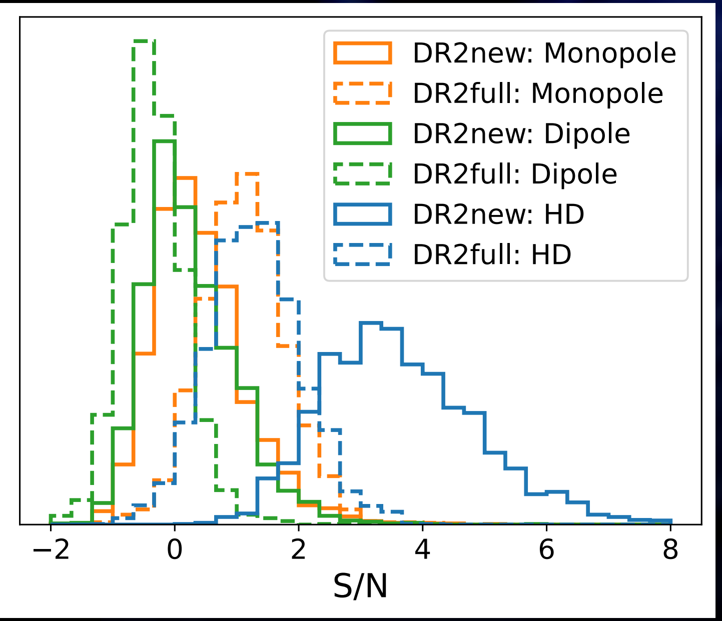
# EPTA results: evidence for GWs

- Free spectrum — Posterior for GWB parameters



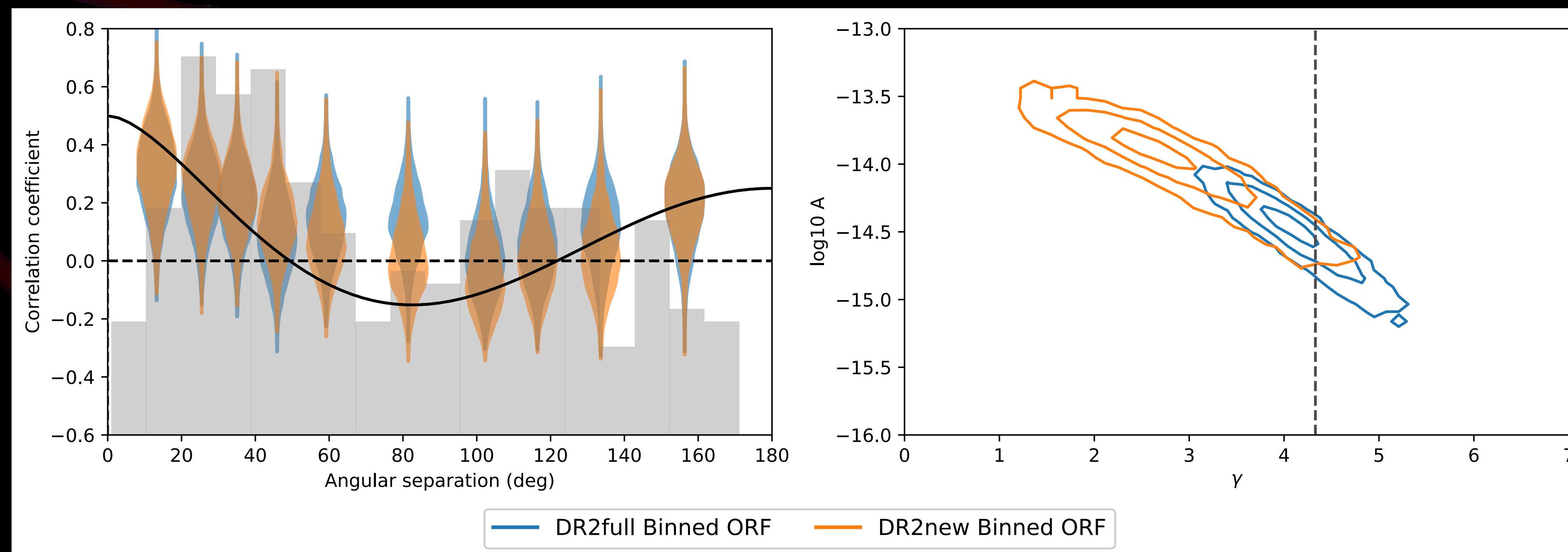

https://arxiv.org/abs/2306.16214

- 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

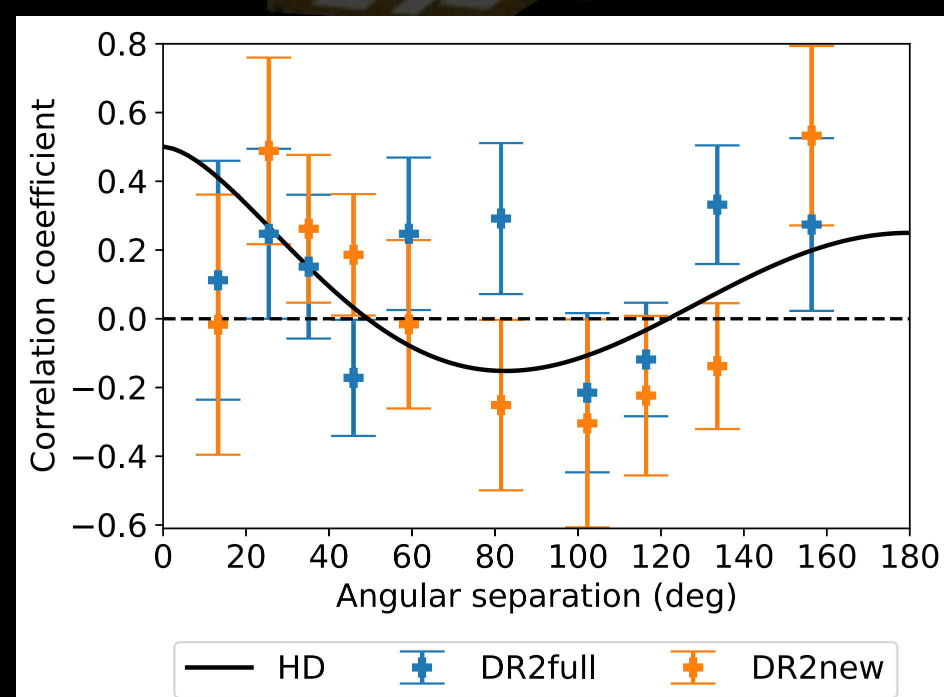


# EPTA results: evidence for GWs

- Spatial correlation: overlap reduction function
  - Binned




  - Optimal statistic

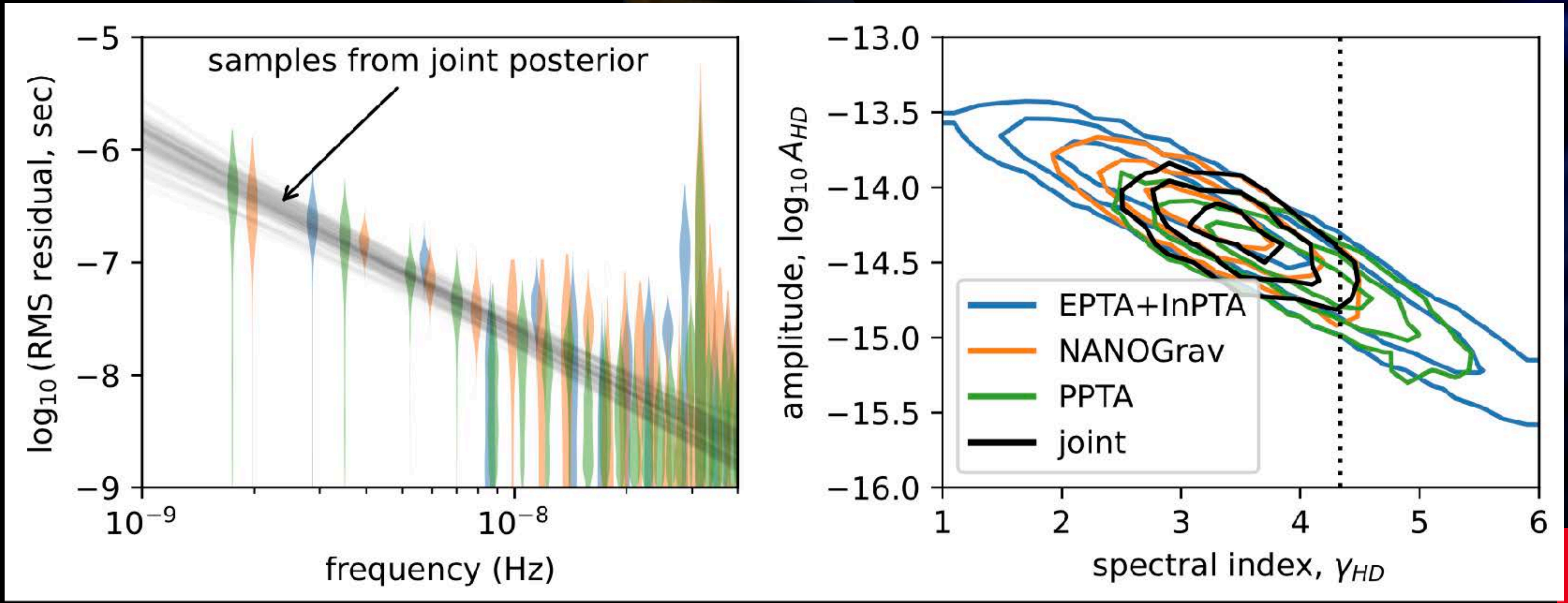



https://arxiv.org/abs/2306.16214

# 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

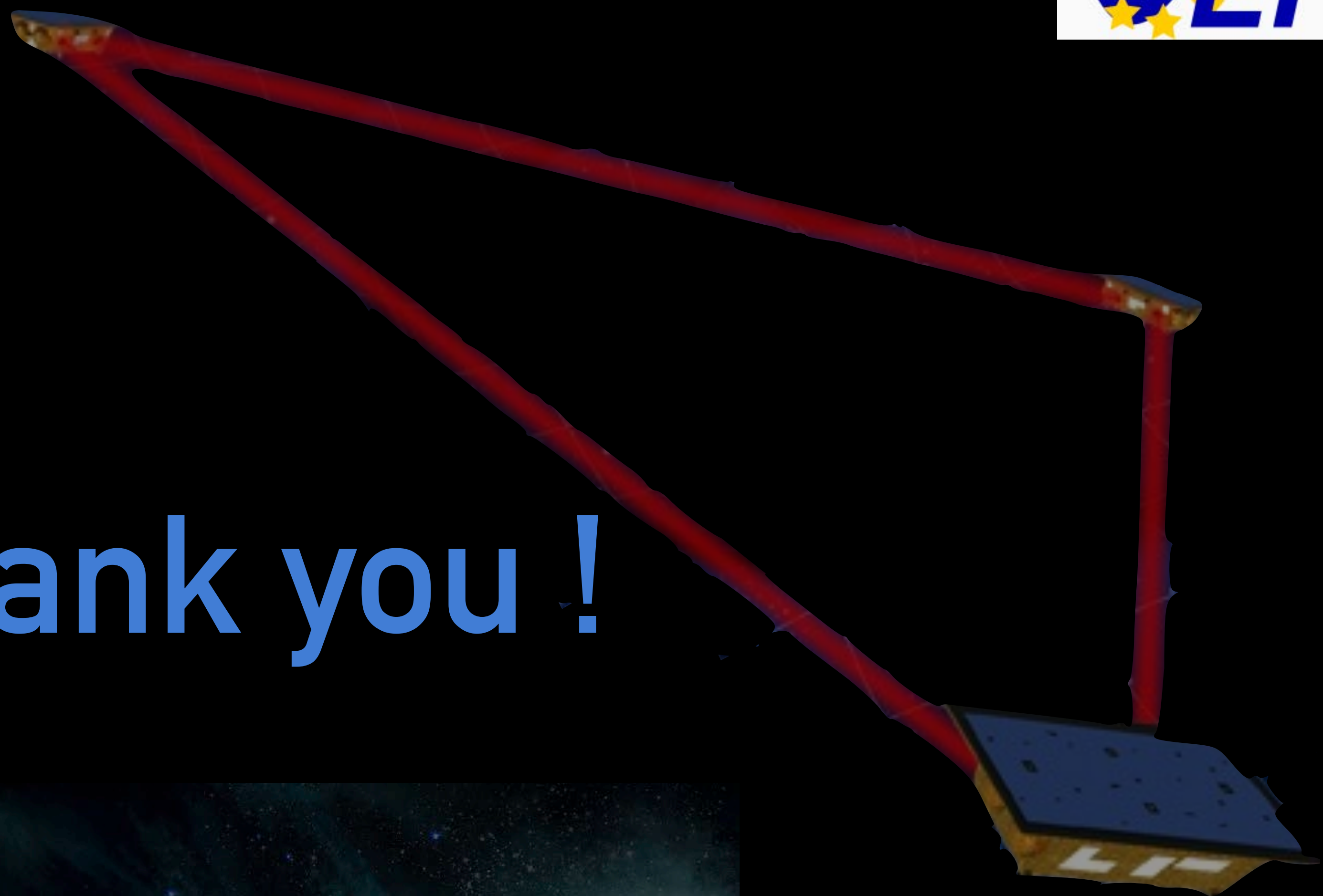


# PTA near futur

- More data !
  - IPTA: all PTAs (EPTA, NANOGrav, PPTA) + MeerKAT +CHIME  (+ FAST ?)
  - SKA soon ( ~ 100 pulsars with few tens thousands of TOAs per pulsar) !
- Also more parameters
- Data analysis complex and heavy: clear technical bottleneck to improve the precision and ingest all currently available data !
- How to address the challenge?
  - More approximations? 😕
  - More computing ressources?
  - Better data analysis strategies (ideally all steps in one!)
  - …

# Conclusion and perspective

- Similar data analysis challenges:
  - Searching in a large parameter space
  - High precision modelling
  - Coherent integration of all steps of the analysis
- Not the same timescale between LISA and PTA
- LISA data analysis in a prototyping phase; large simulated data available
- PTA:
  - Data already available and more are coming in particular with SKA
  - Very close to detection => close to the scientific discovery
  - First tools available
  - Data analysis is already a challenge!



# Thank you !