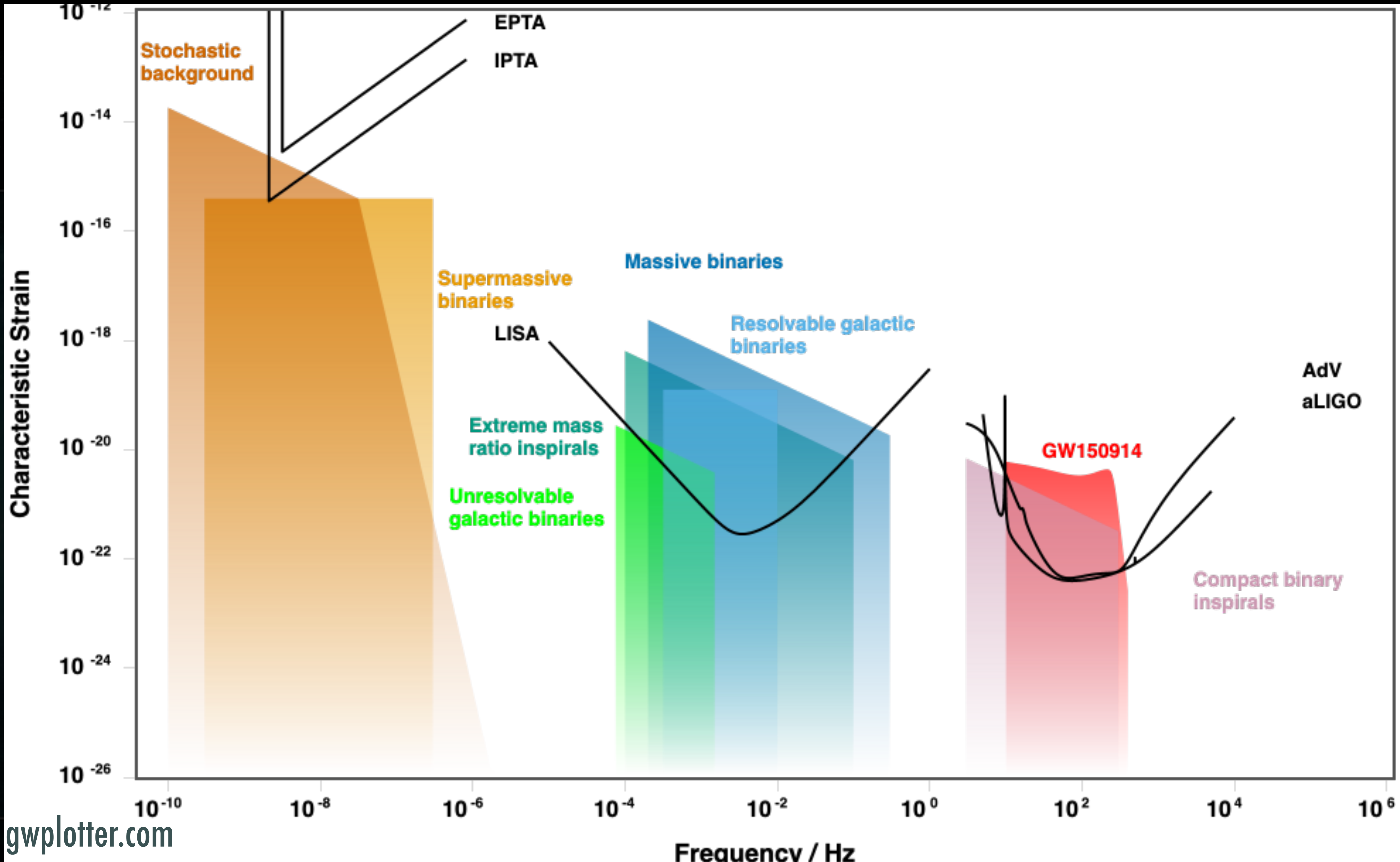
Gravitational waves & Pulsars Timing Array

Antoine Petiteau (CEA/IRFU/DPhP)

Mini-workshop on Gravitational waves and the QGP-hadron transition in the early universe

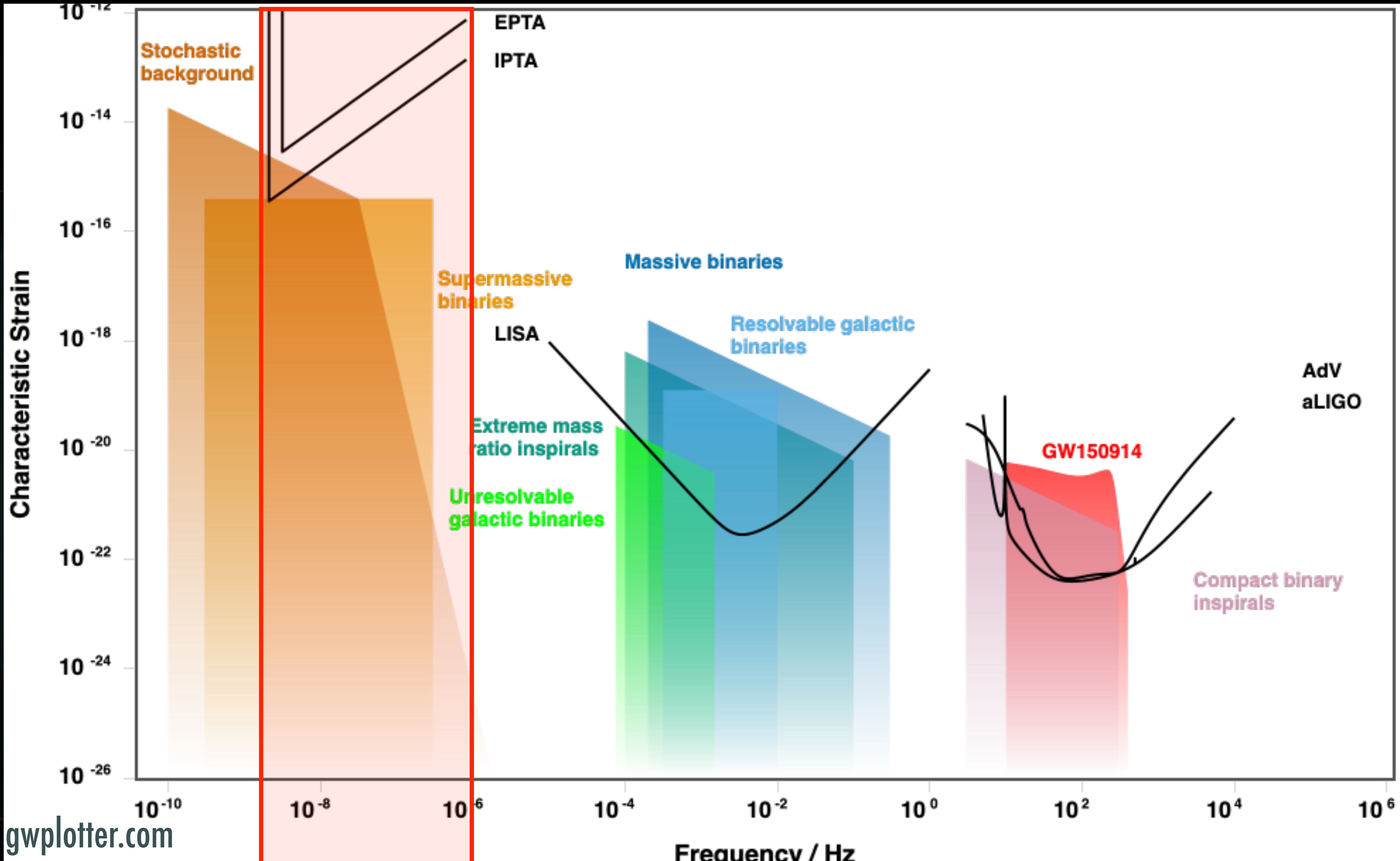
CEA/IRFU/DPhN - 12th December 2024

GW spectrum



gwplotter.com

GW spectrum



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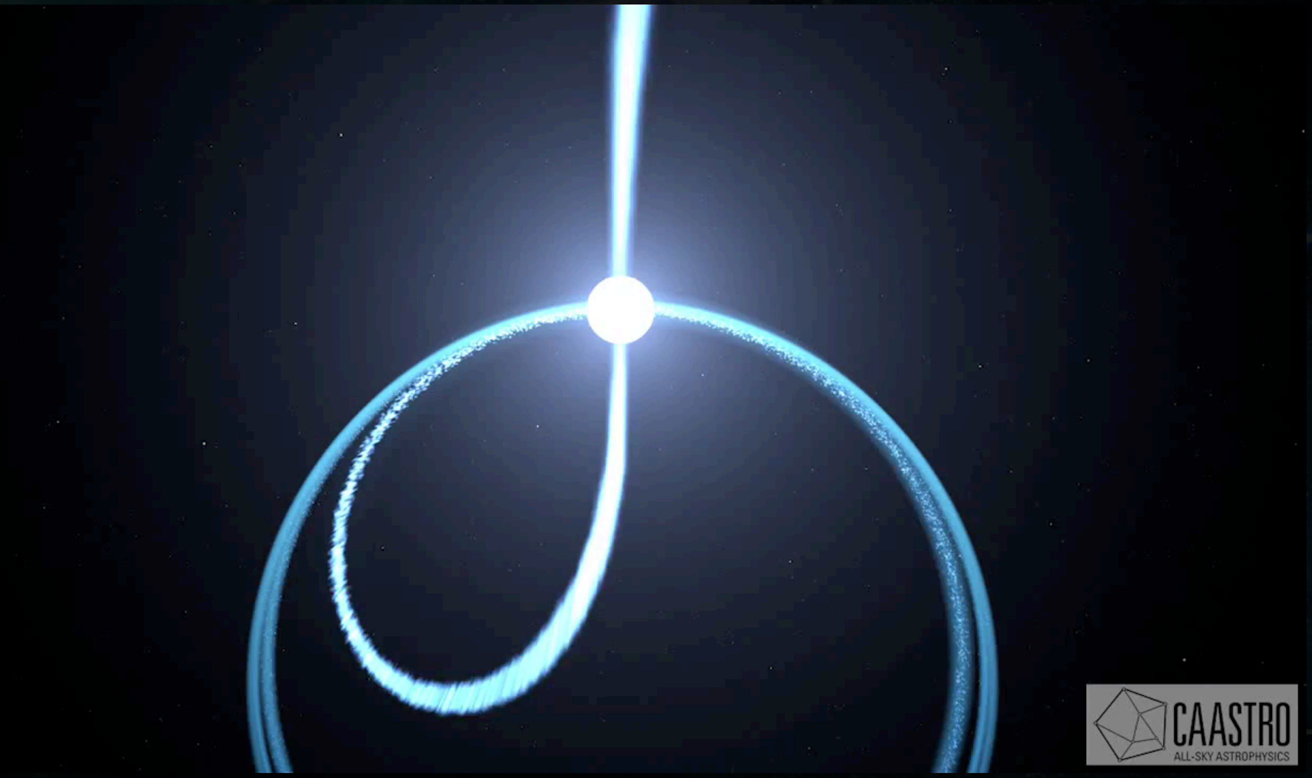
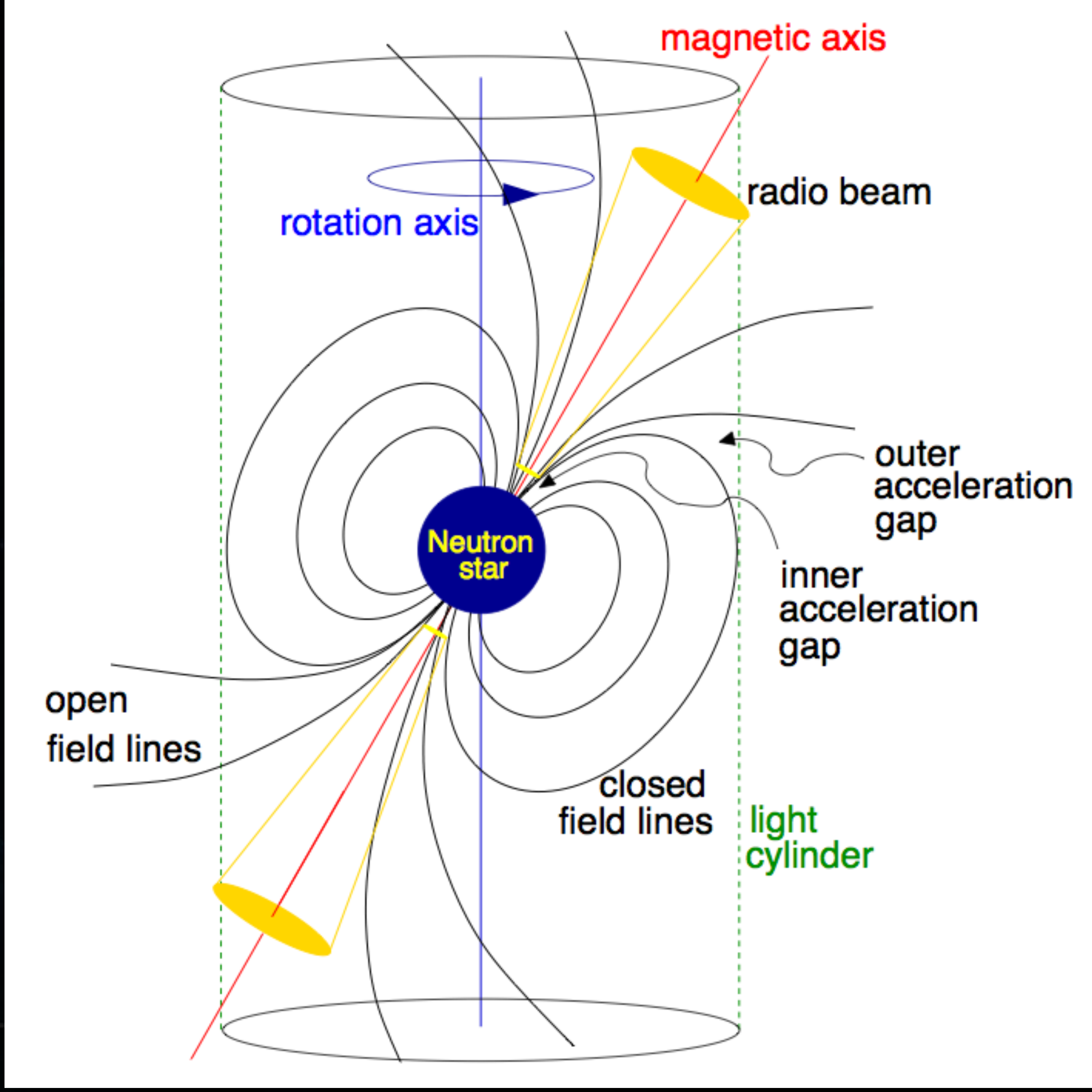
Pulsars

- Neutron star with high magnetic field
- Rotation axis ≠ magnetic axis => lighthouse effect
- Emission:
  - Radio, gamma, etc





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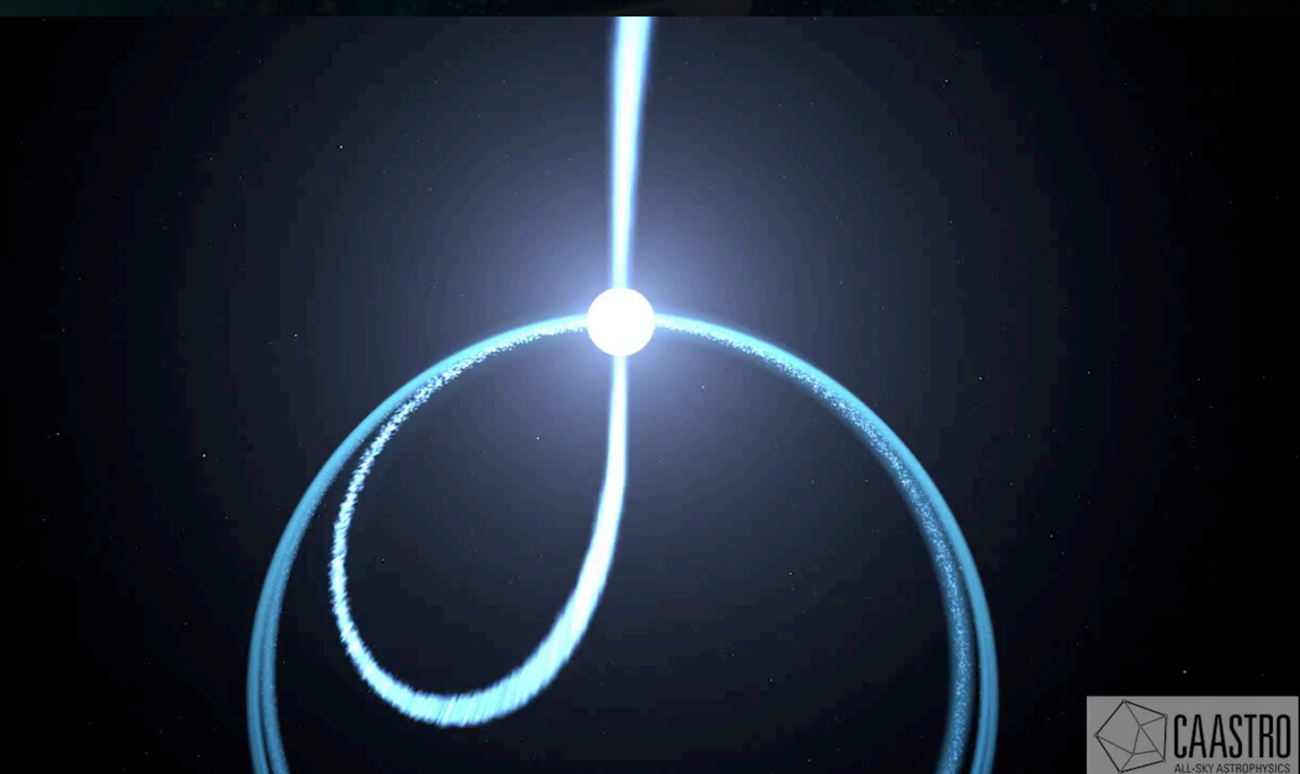

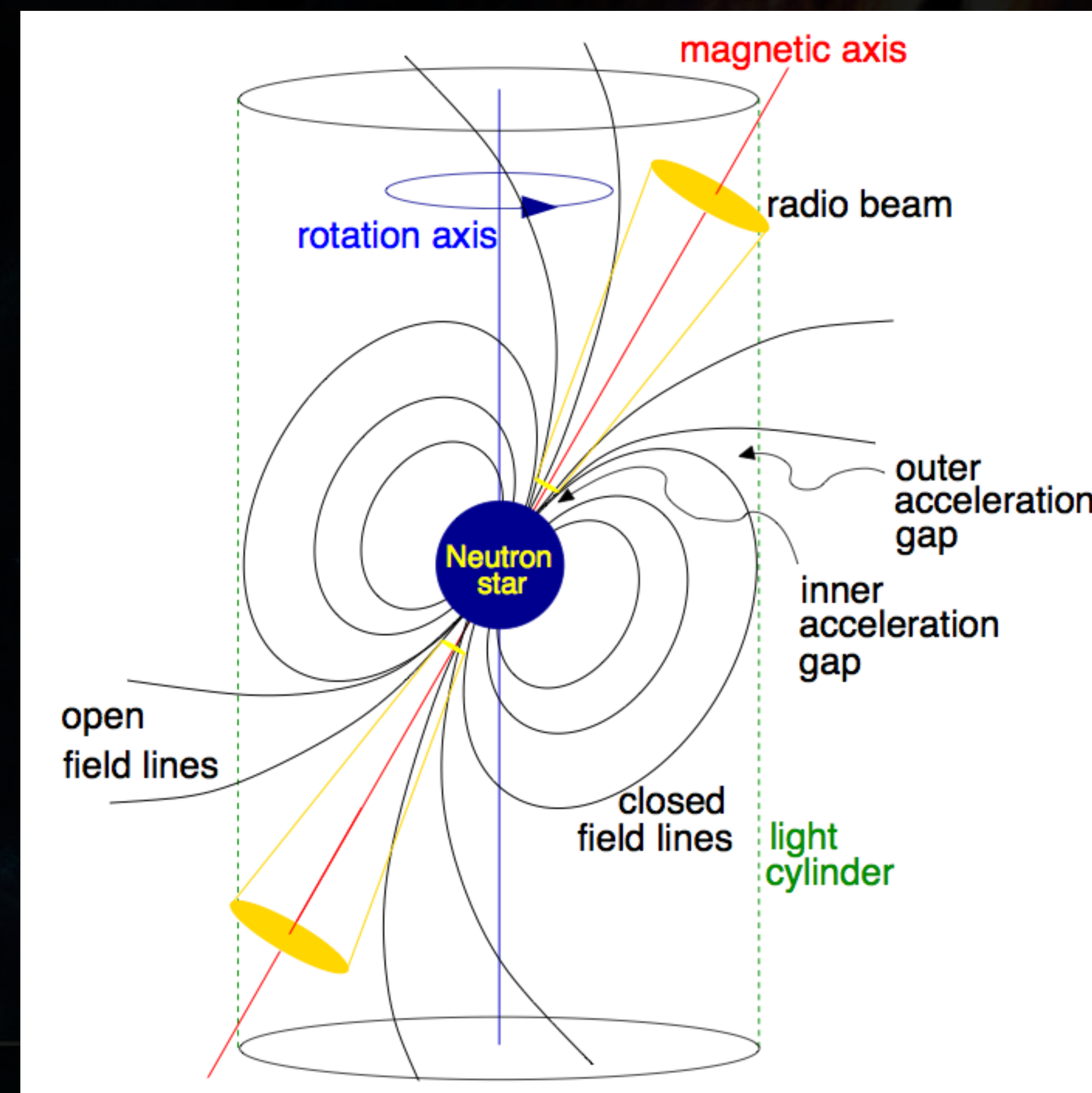

Pulsars observations

- Somewhere in Sologne ... the Nançay radio telescope

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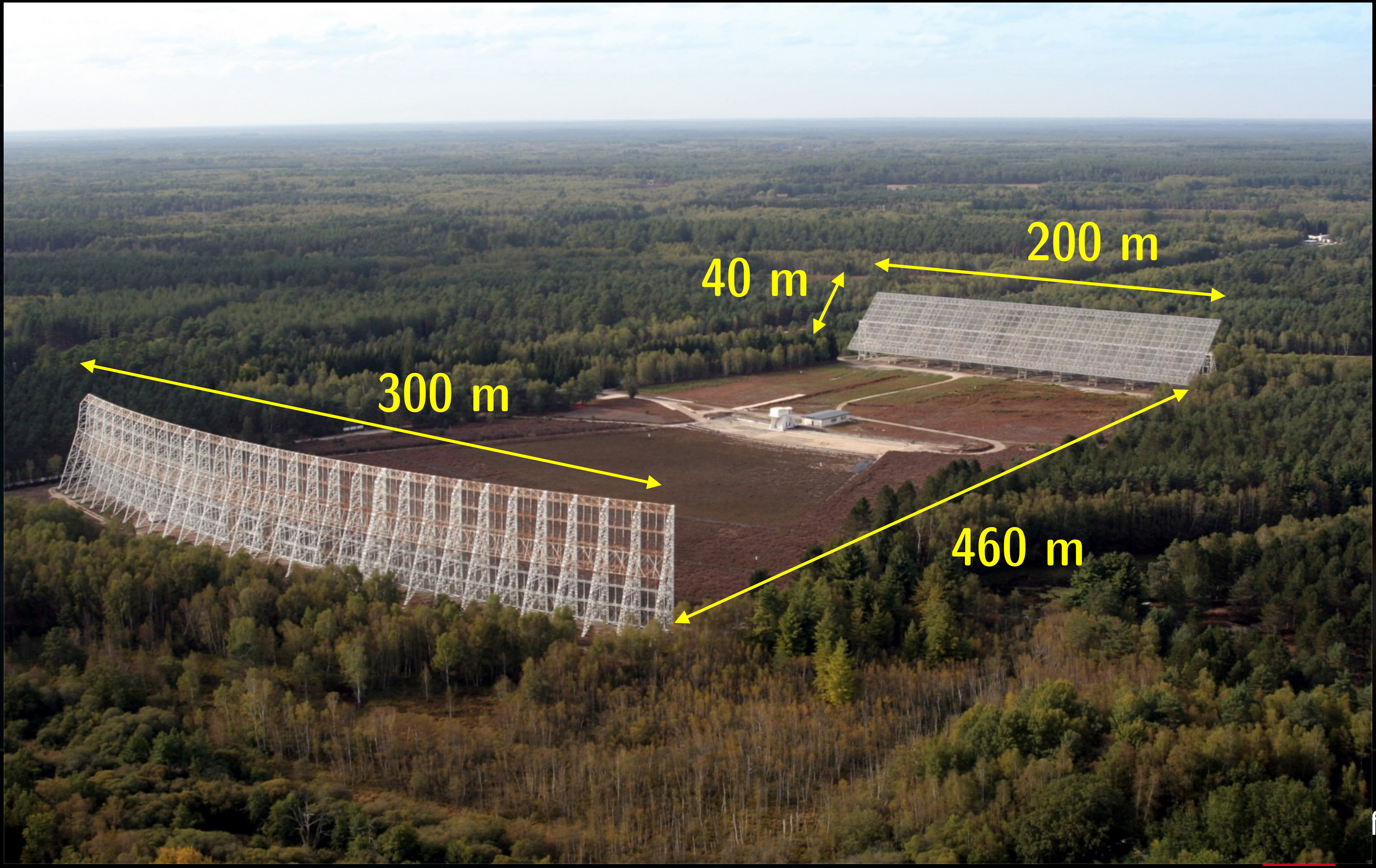
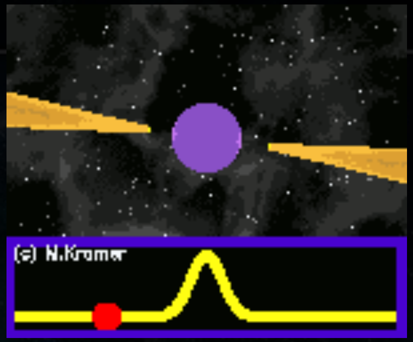


Pulsar timing

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



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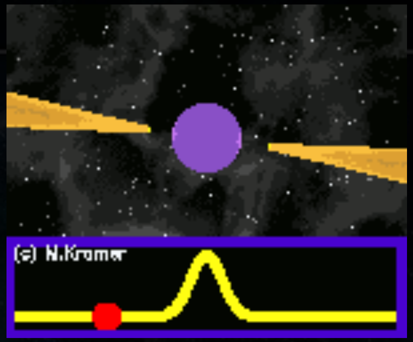

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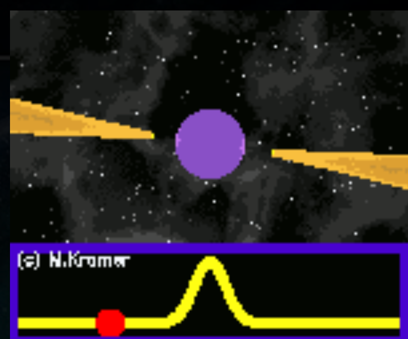
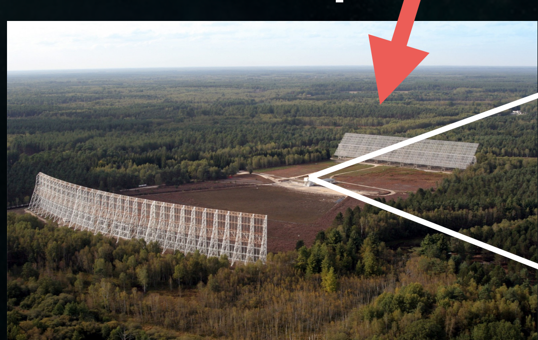


Radiotelescope



Receiver (GHz)

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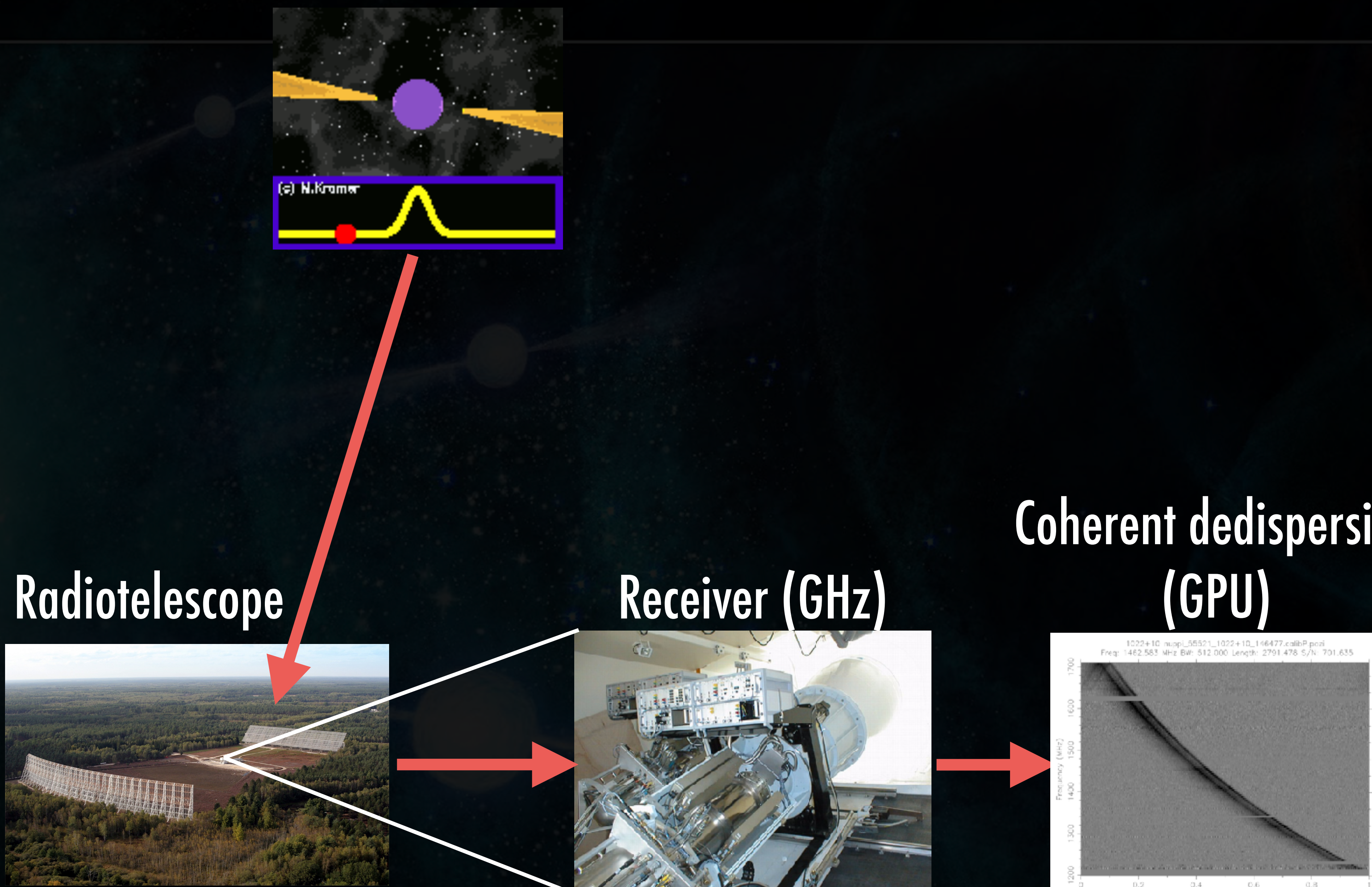

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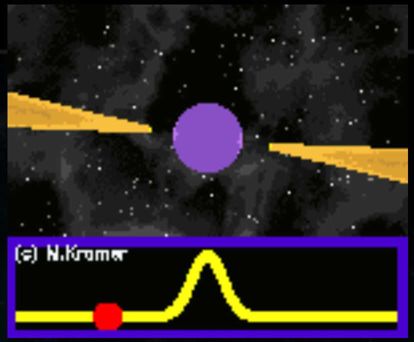

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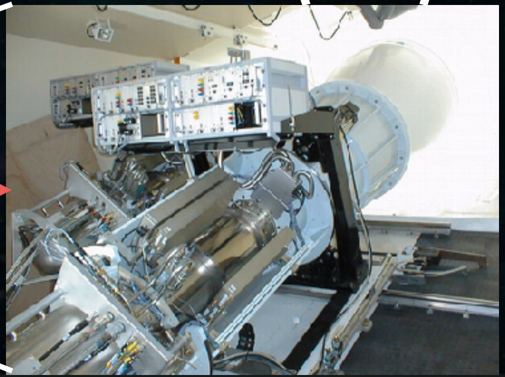
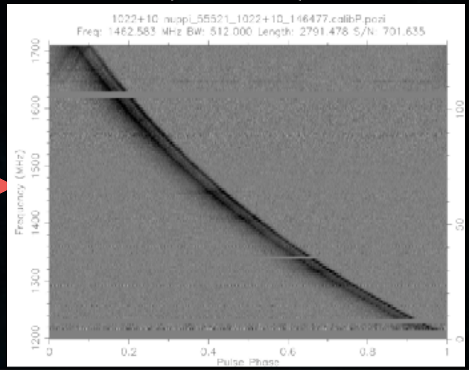
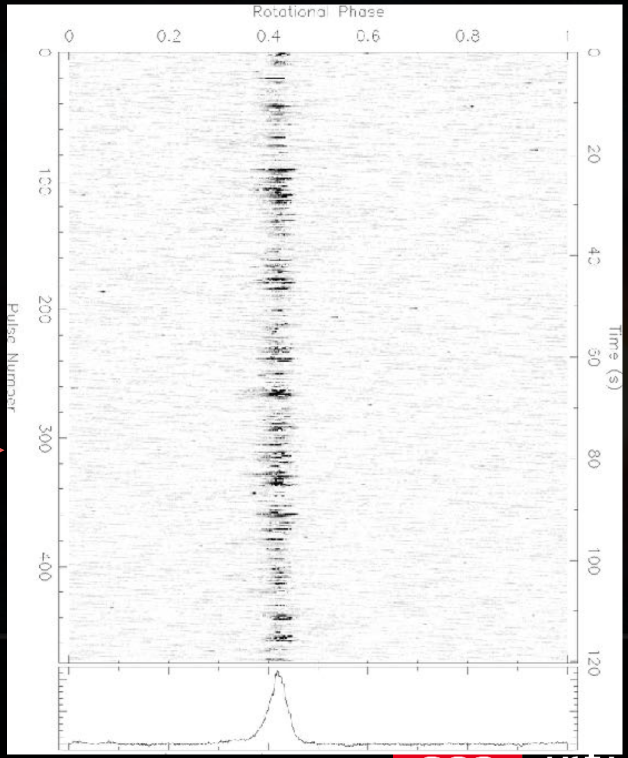


Coherent dedispersion (GPU)



Folding



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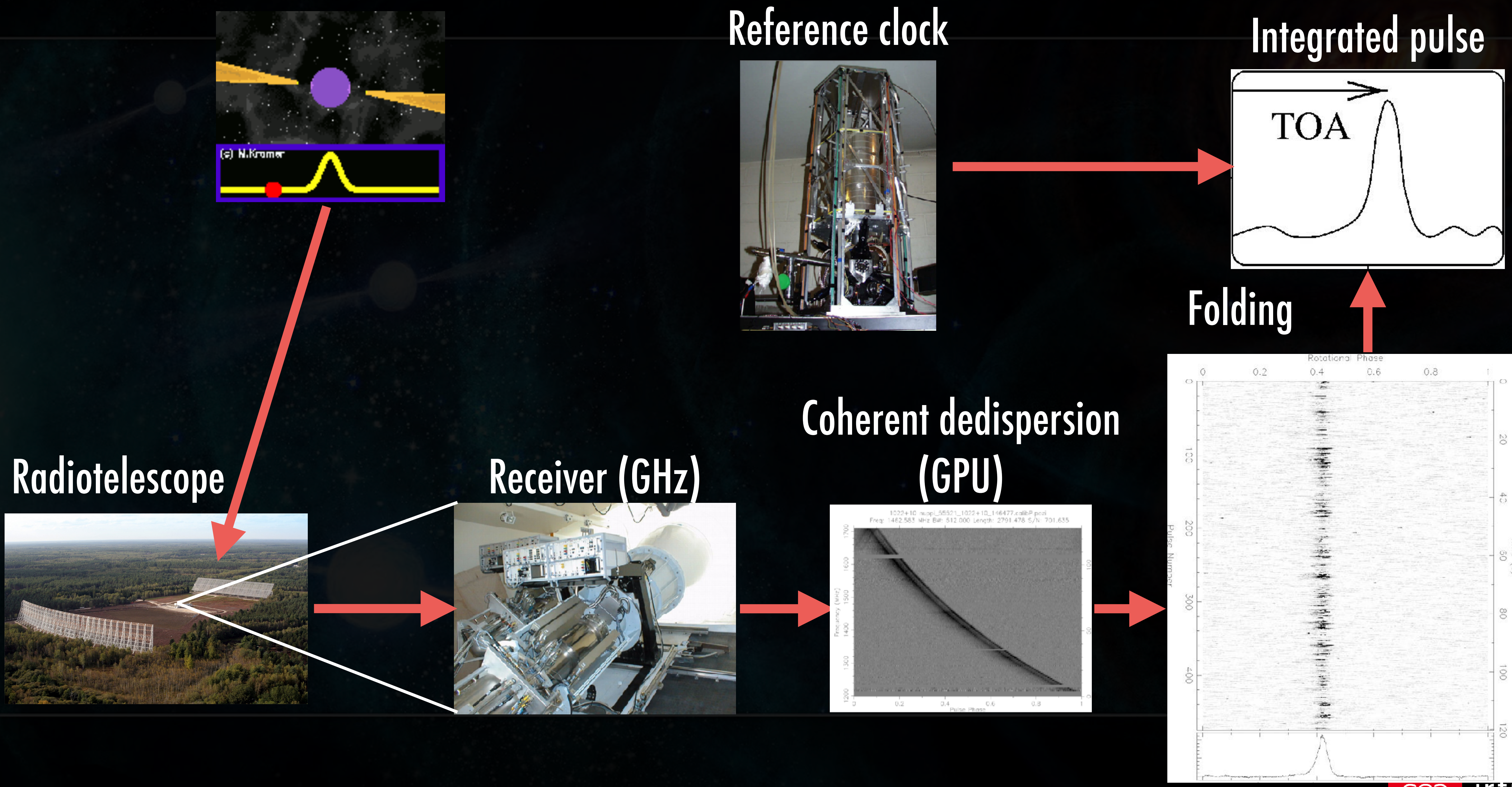

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    - period,
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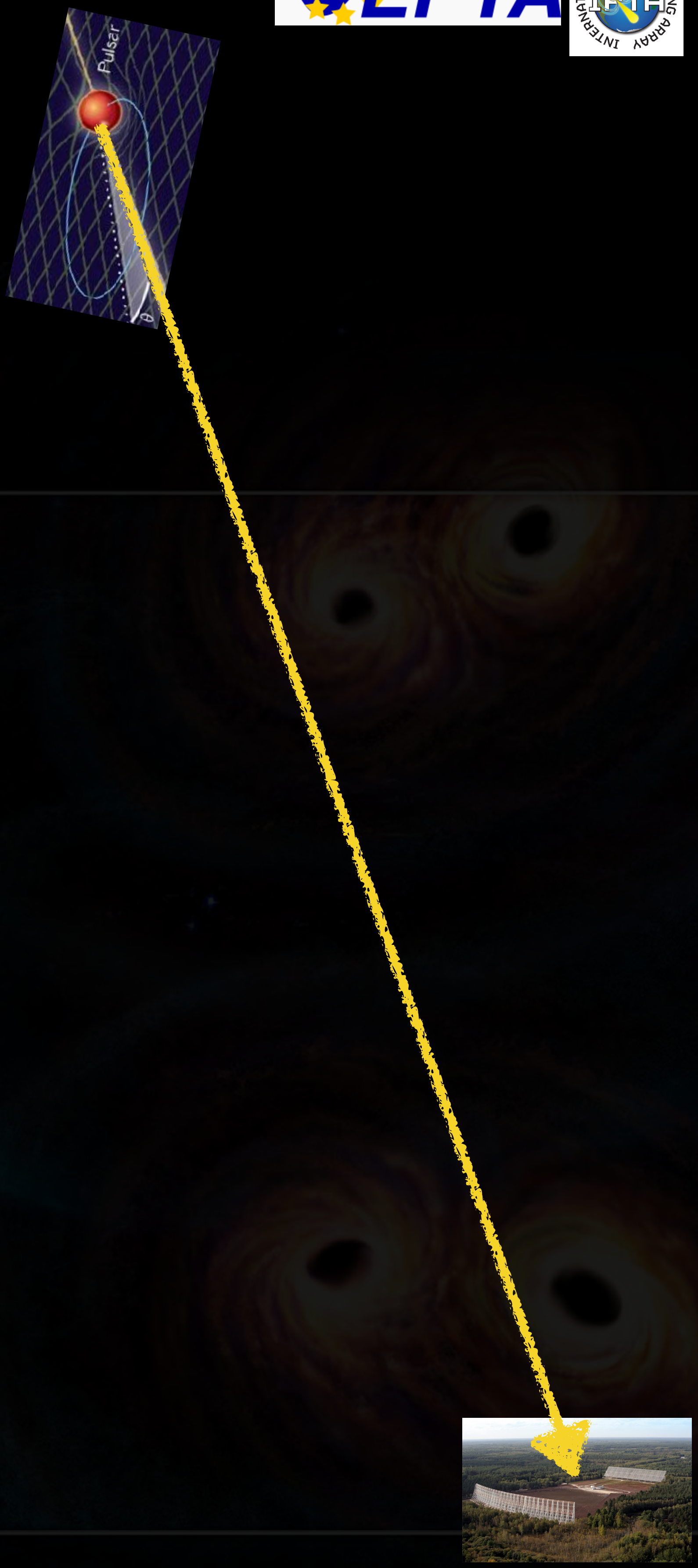
    - sky position



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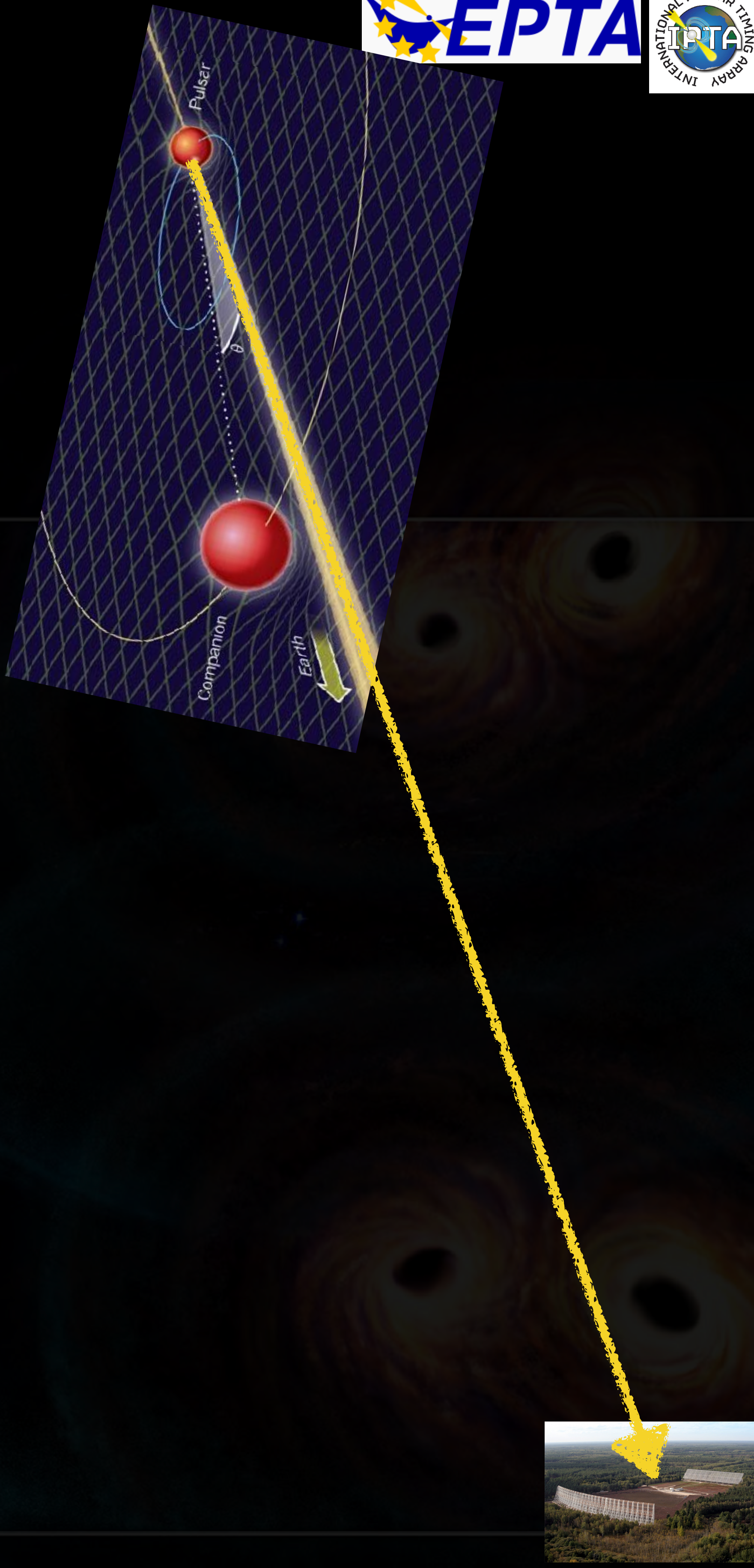

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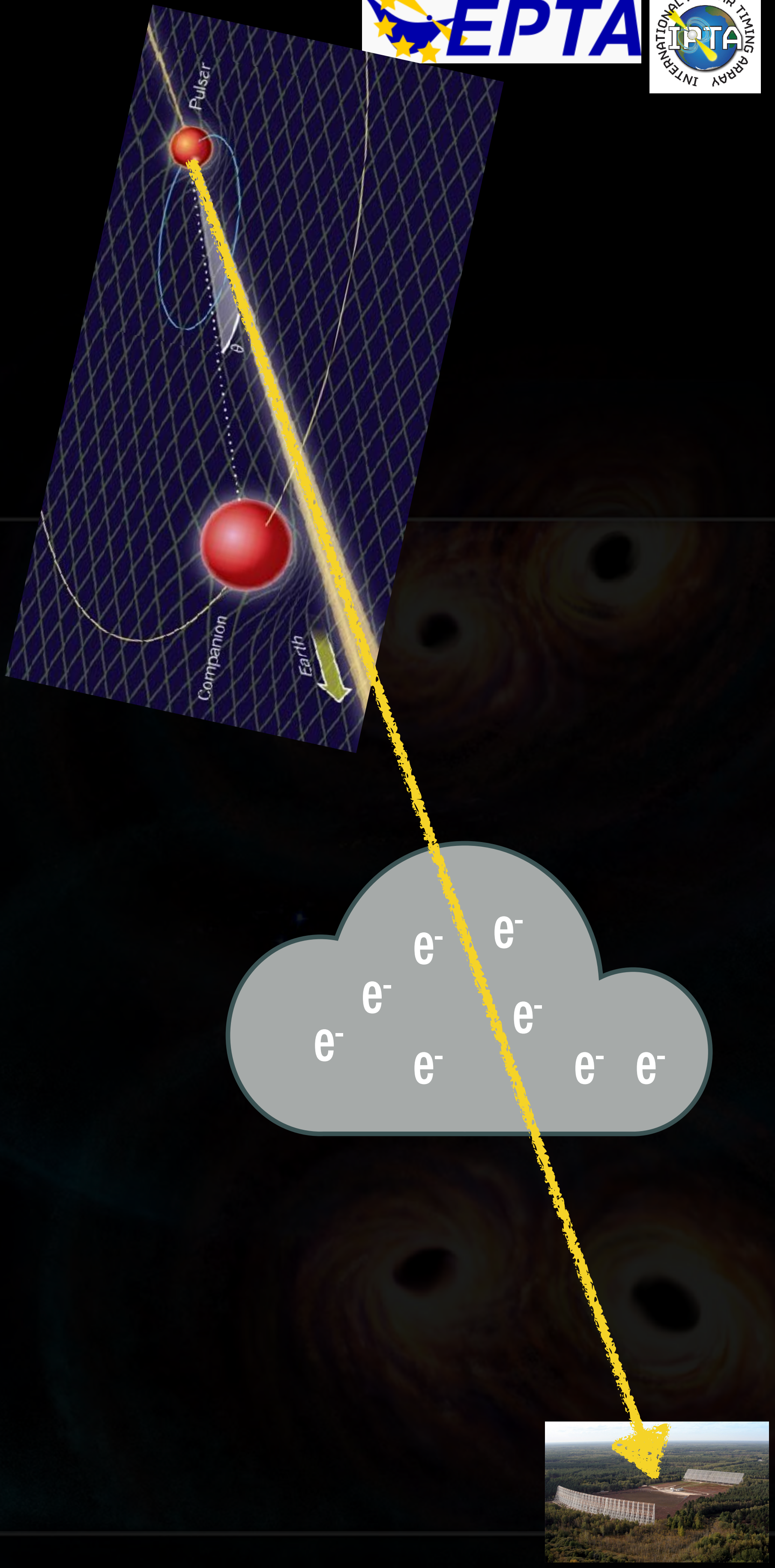

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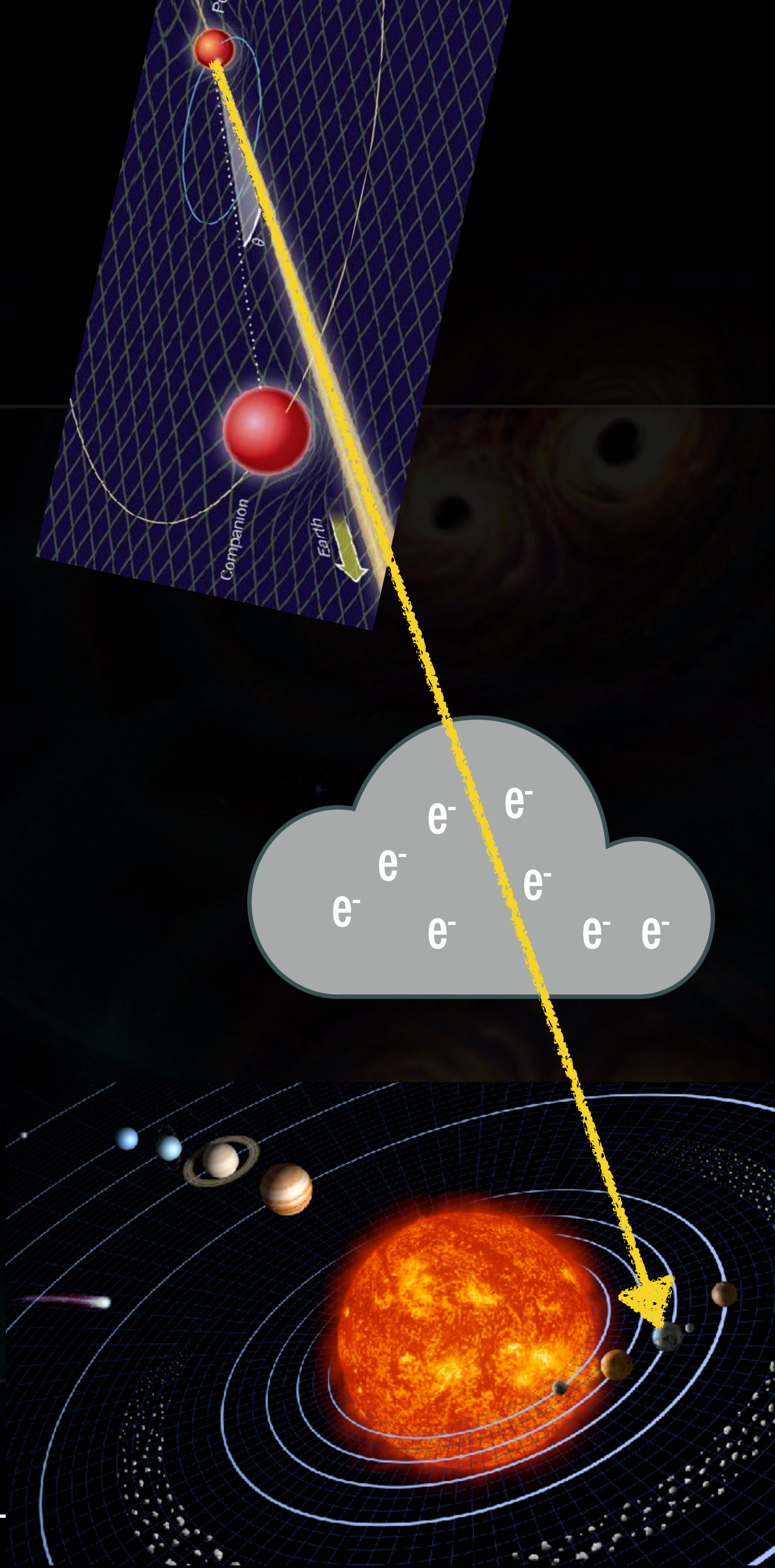

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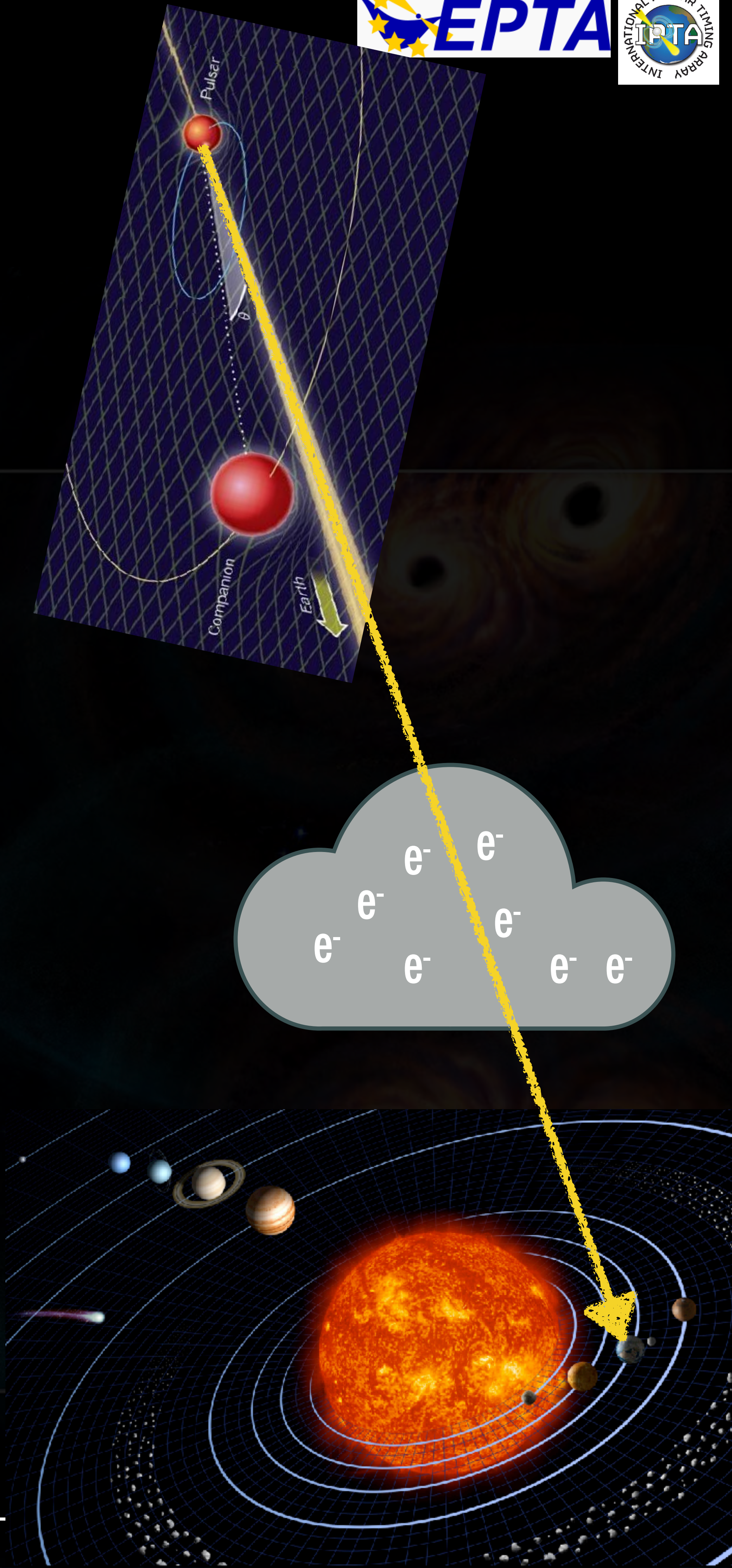
  - Gravitational waves …



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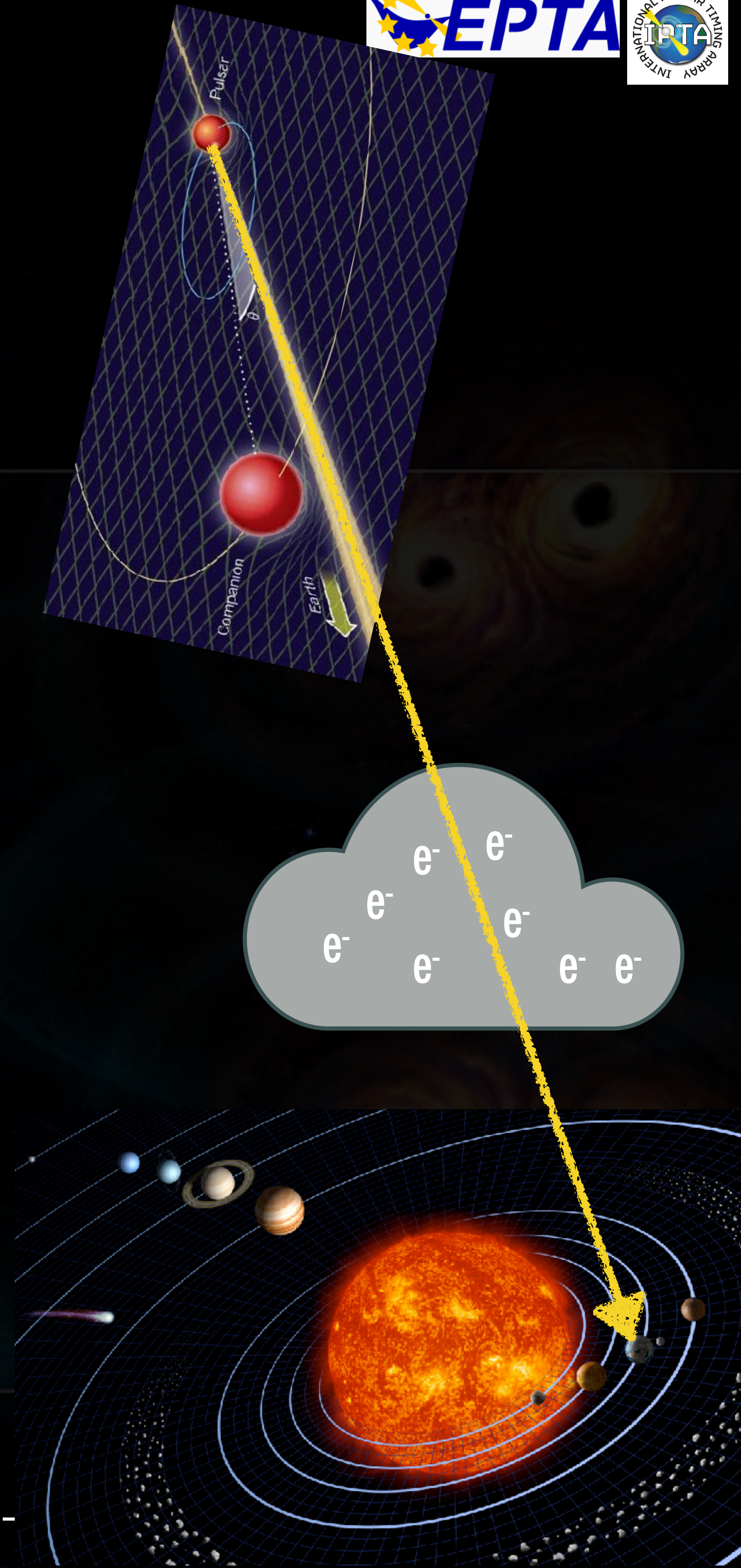
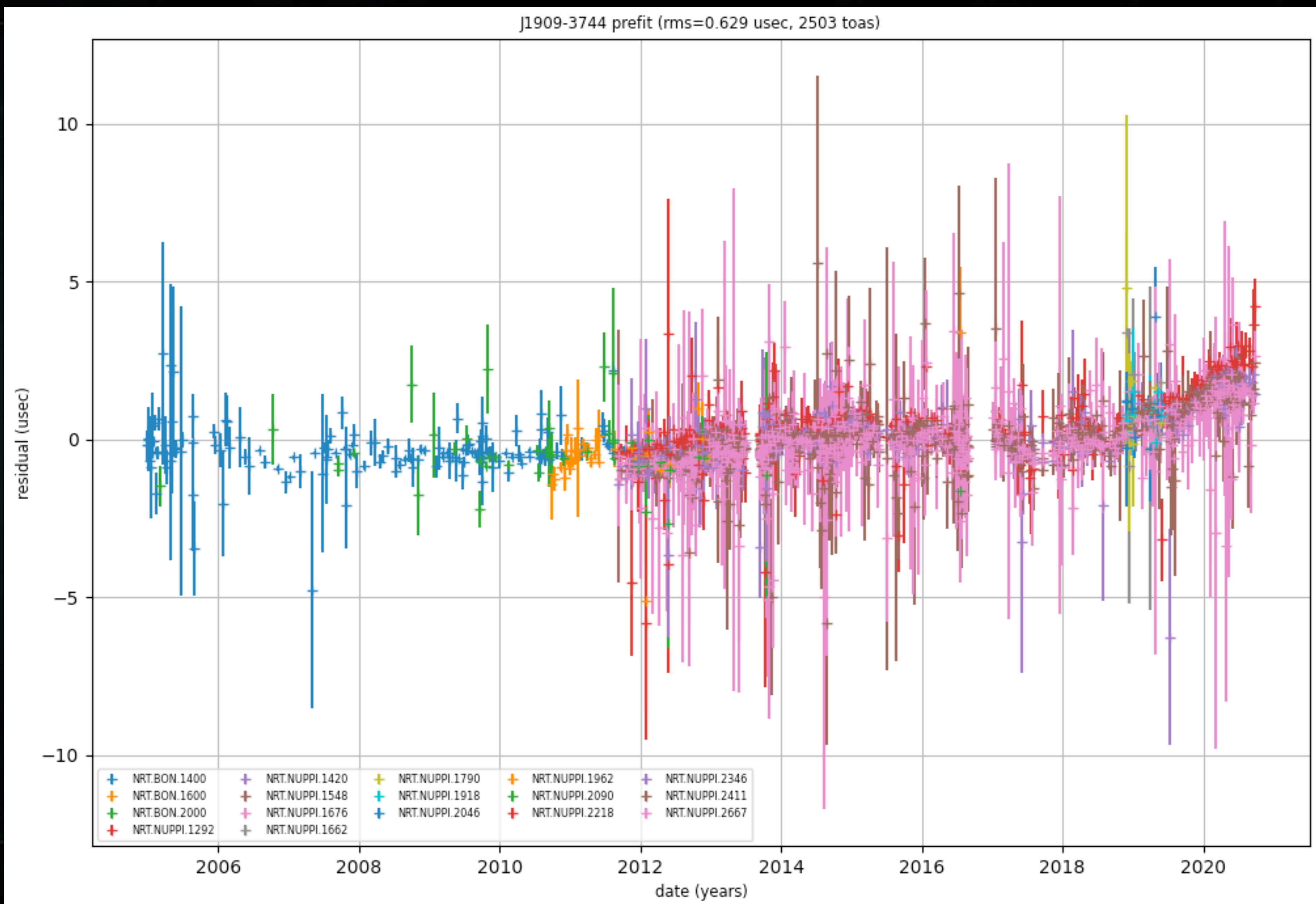
  - Gravitational waves …
- Modelling of each pulsars



Pulsar timing

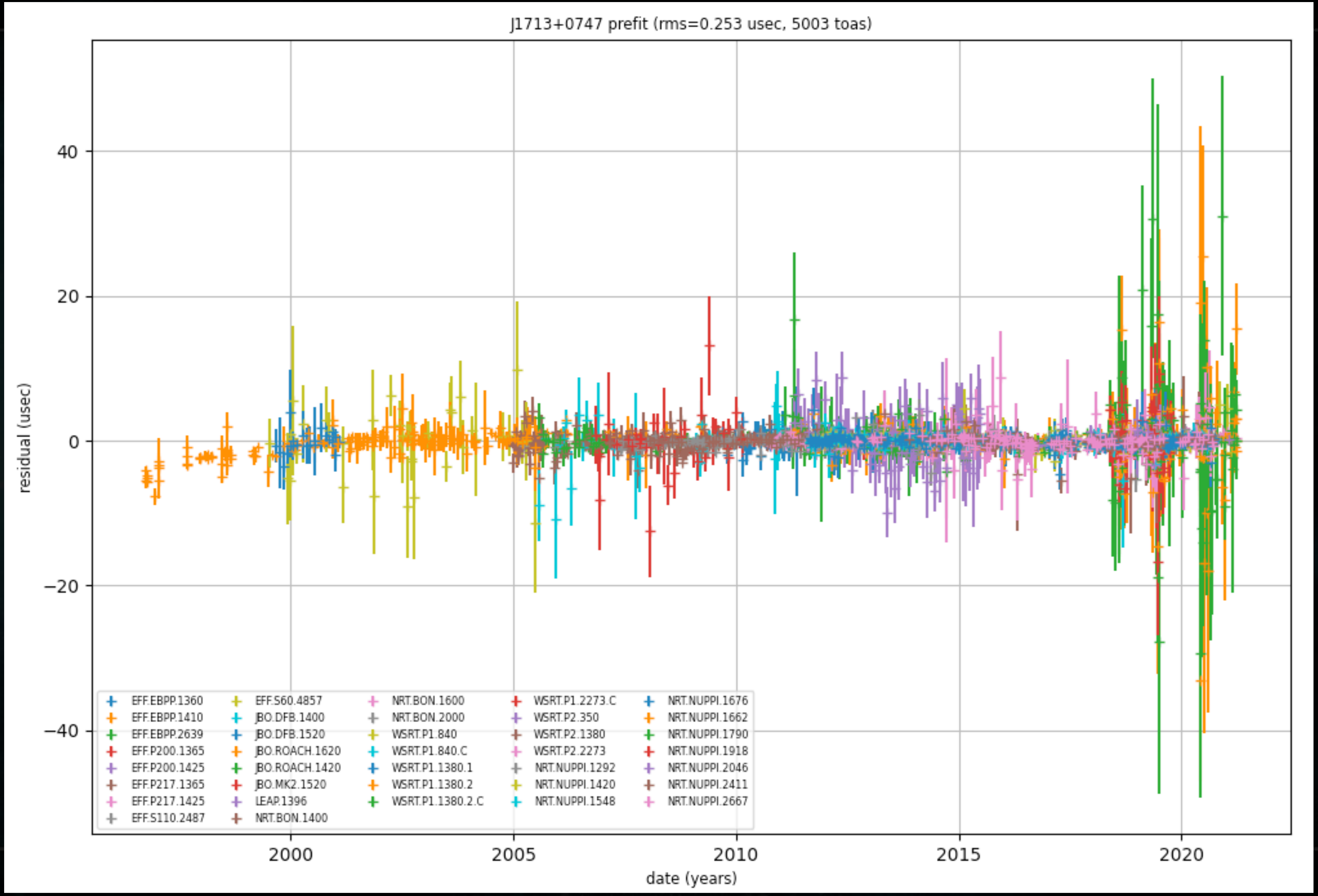
- Examples:
  - J1909-3744:



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 ν the observation frequency

  - RN: standard red noise ($k = 0$)
  - DM: Dispersion Measure variations ($k = 2$)
  - SV: scattering variations ($k = 4$)

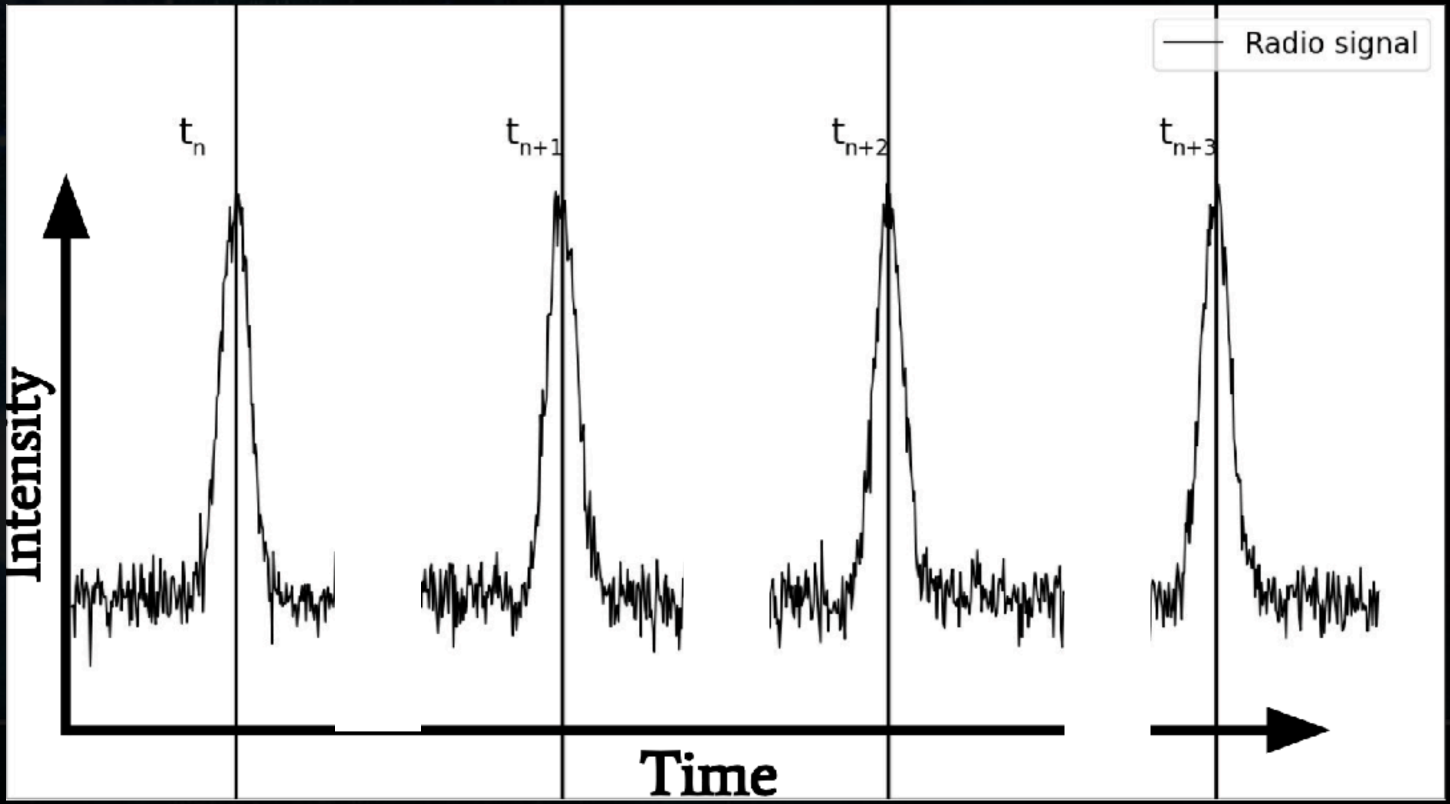
+2

+2

+2

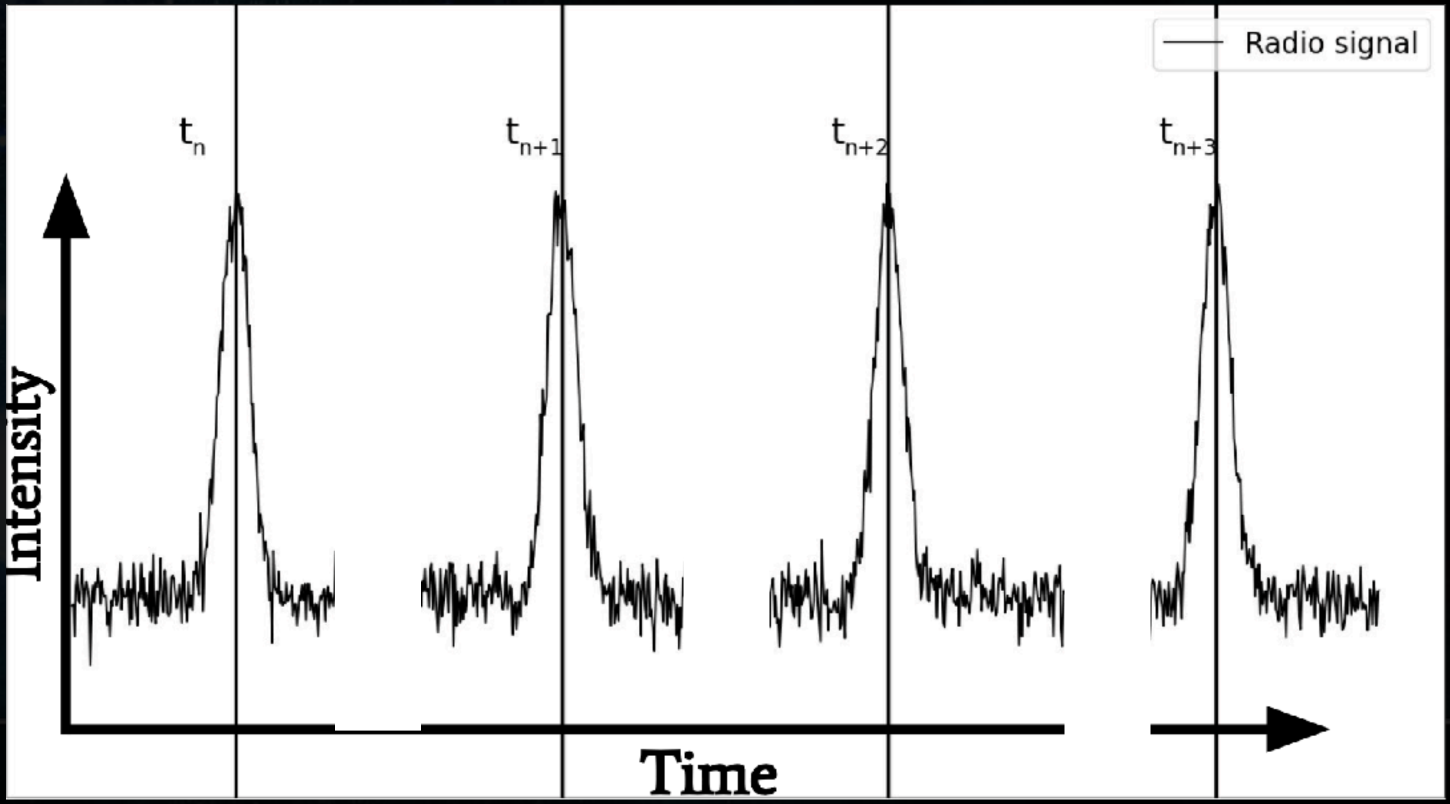
- Specific features for some pulsar: exponential dips

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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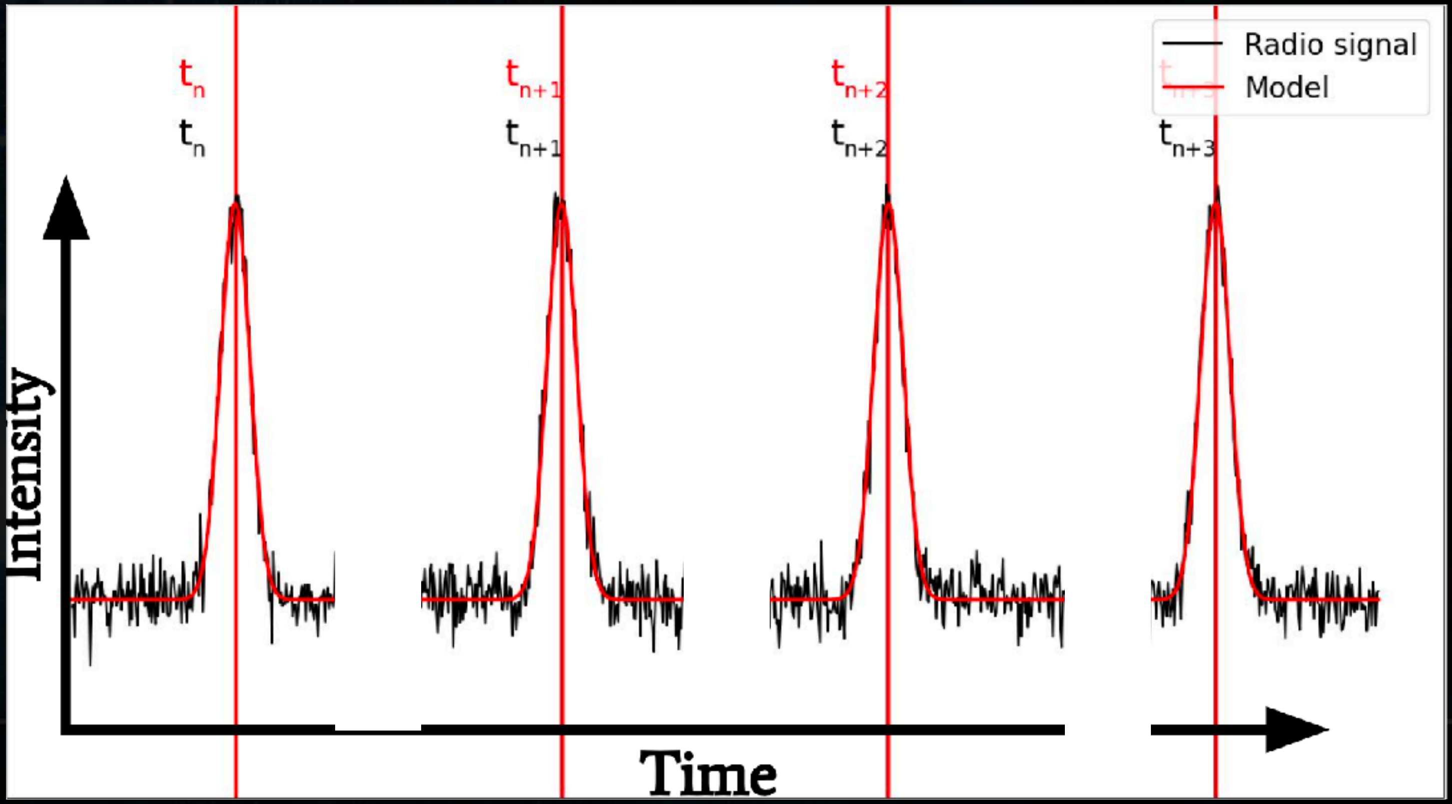
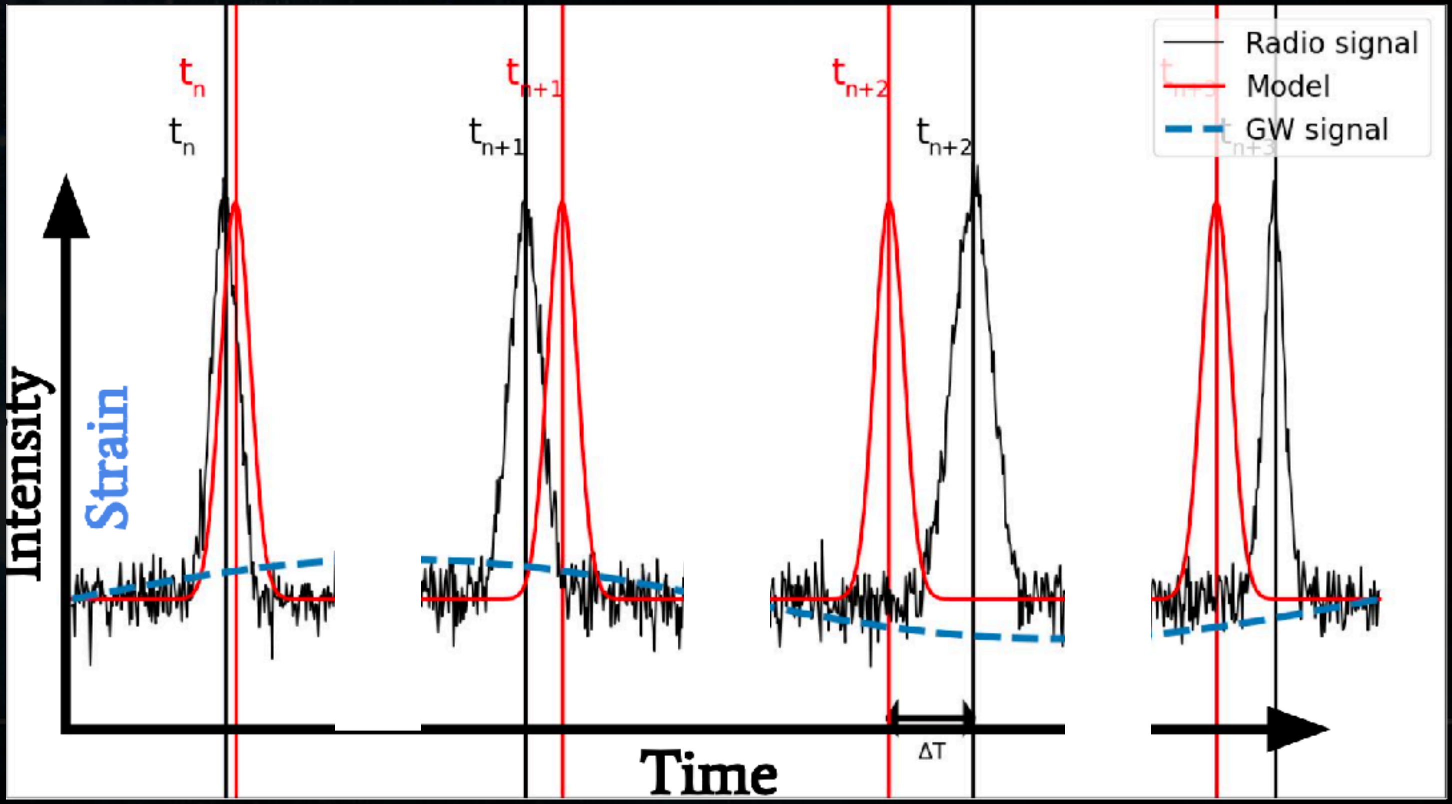


Pulsar timing and GWs

- 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

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Pulsar timing and GWs

- GWs => correlated fluctuations in TOAs of multiple pulsars

Observed & emitted pulsar spin frequency

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

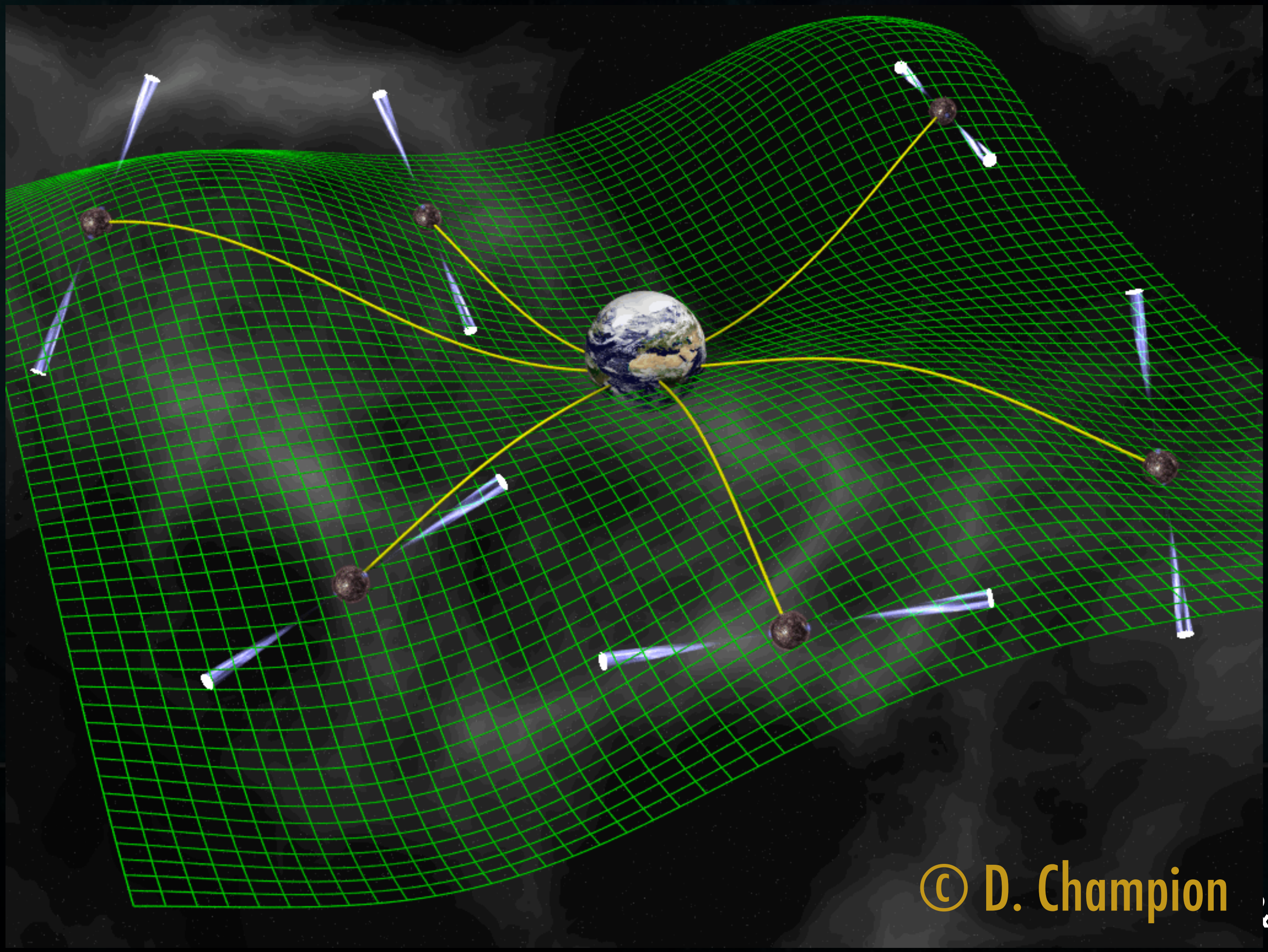
Emission & reception times of pulses

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

Pulsar & GW source sky location

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

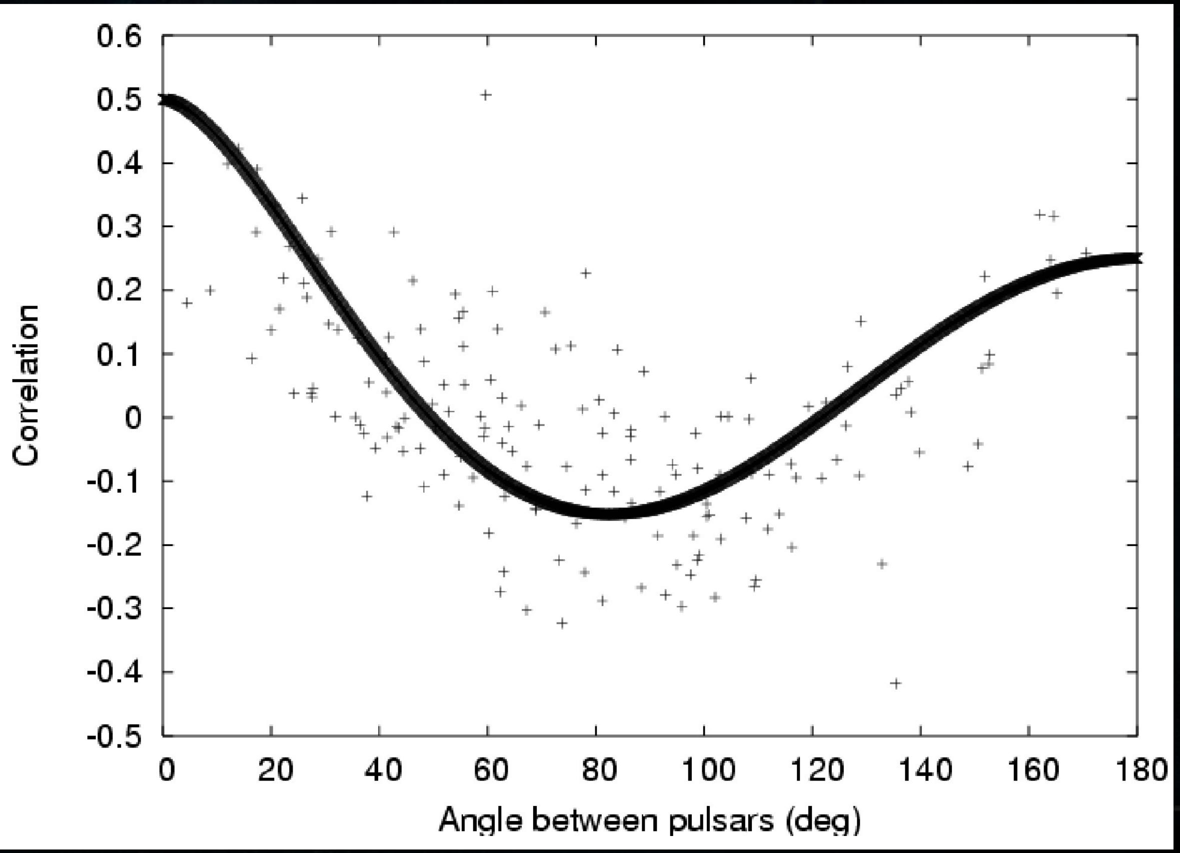
GW characteristic strain



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

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

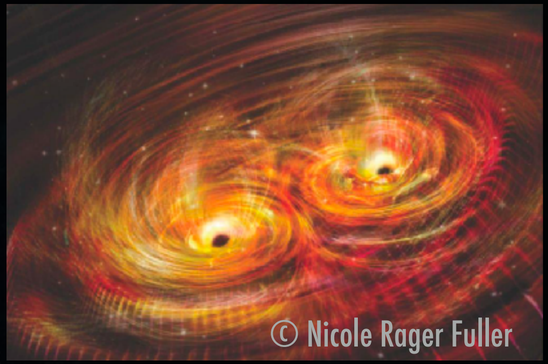


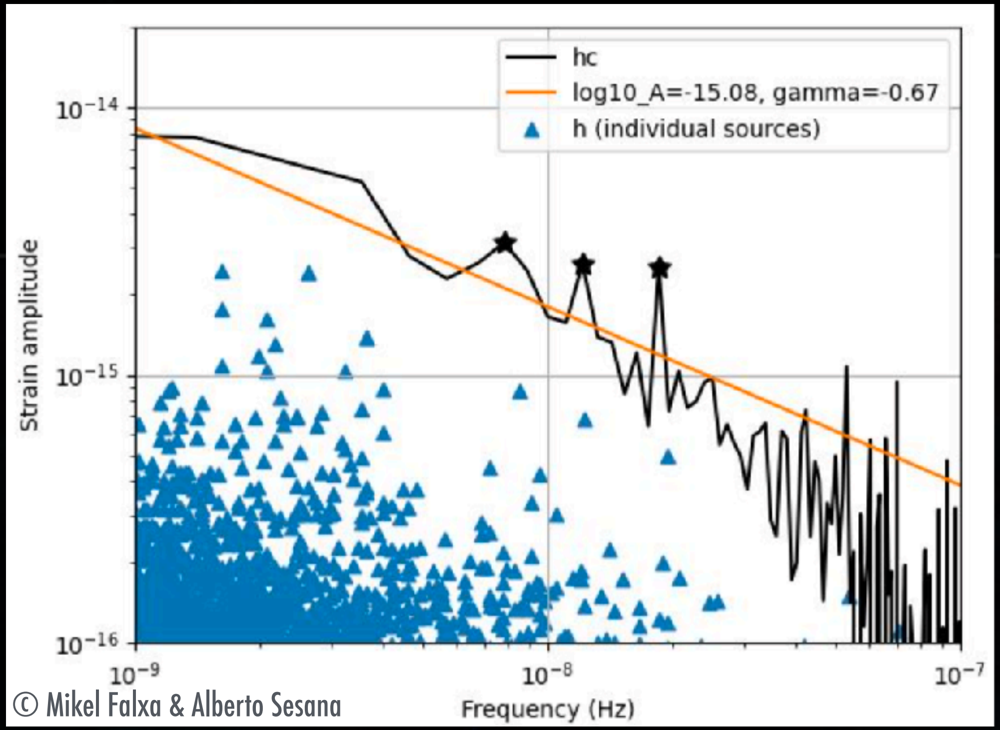
Correlated signals

- 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





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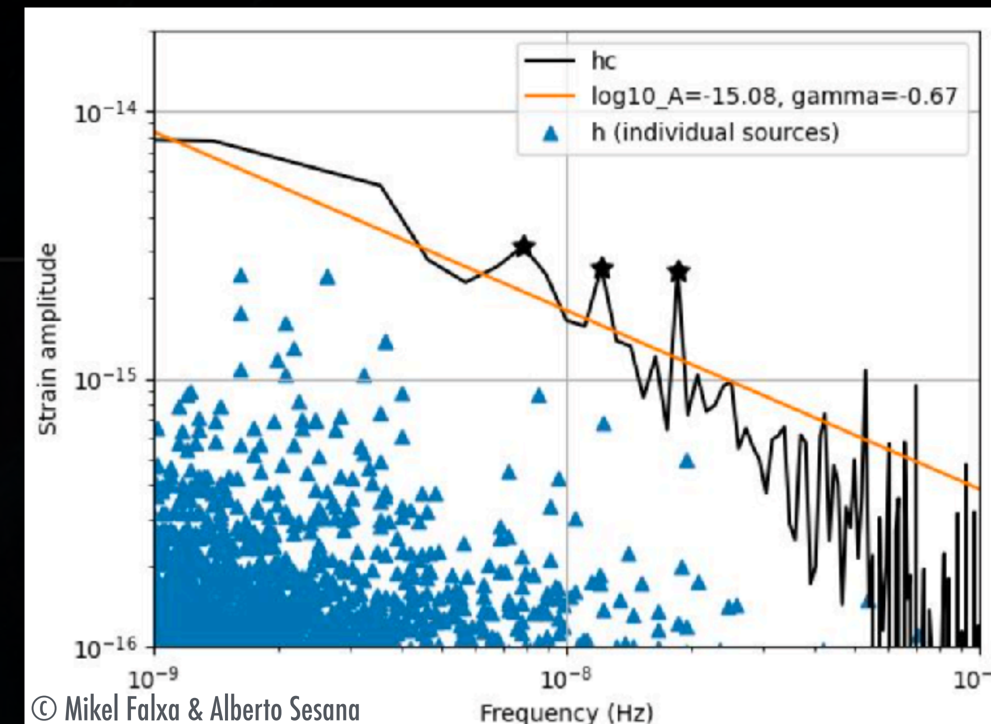
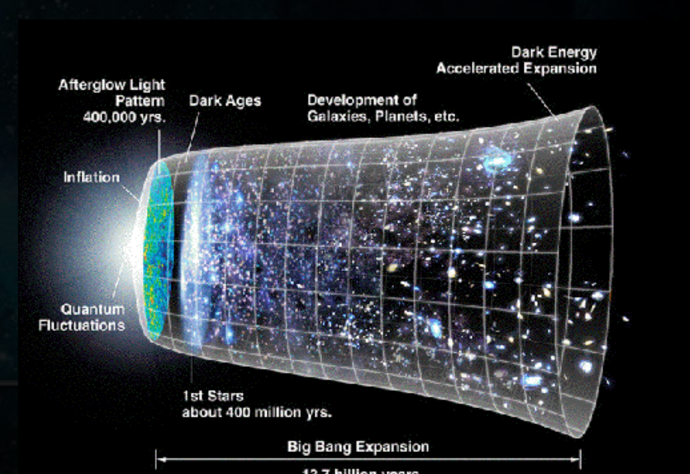


- Stochastic GW background (SGWB) from cosmological origin:
  - First order phase transition
  - Cosmic strings
  - Primordial GWs
  - …



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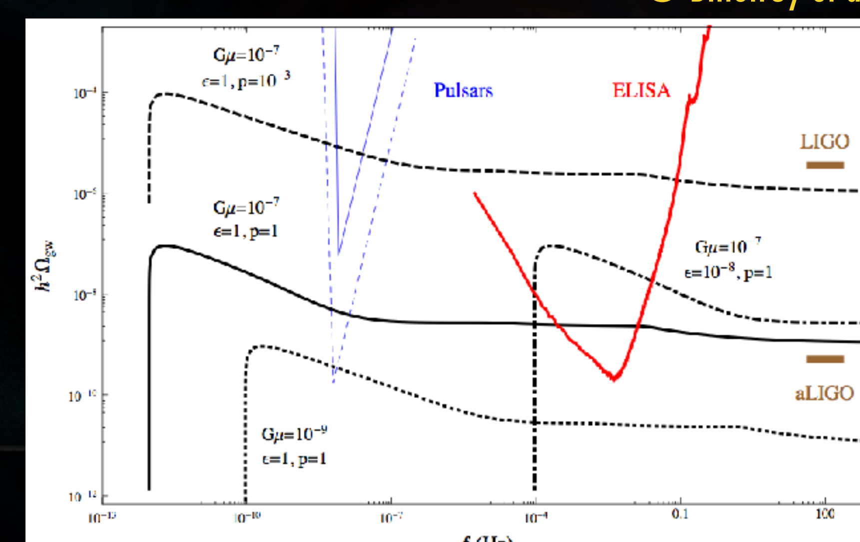
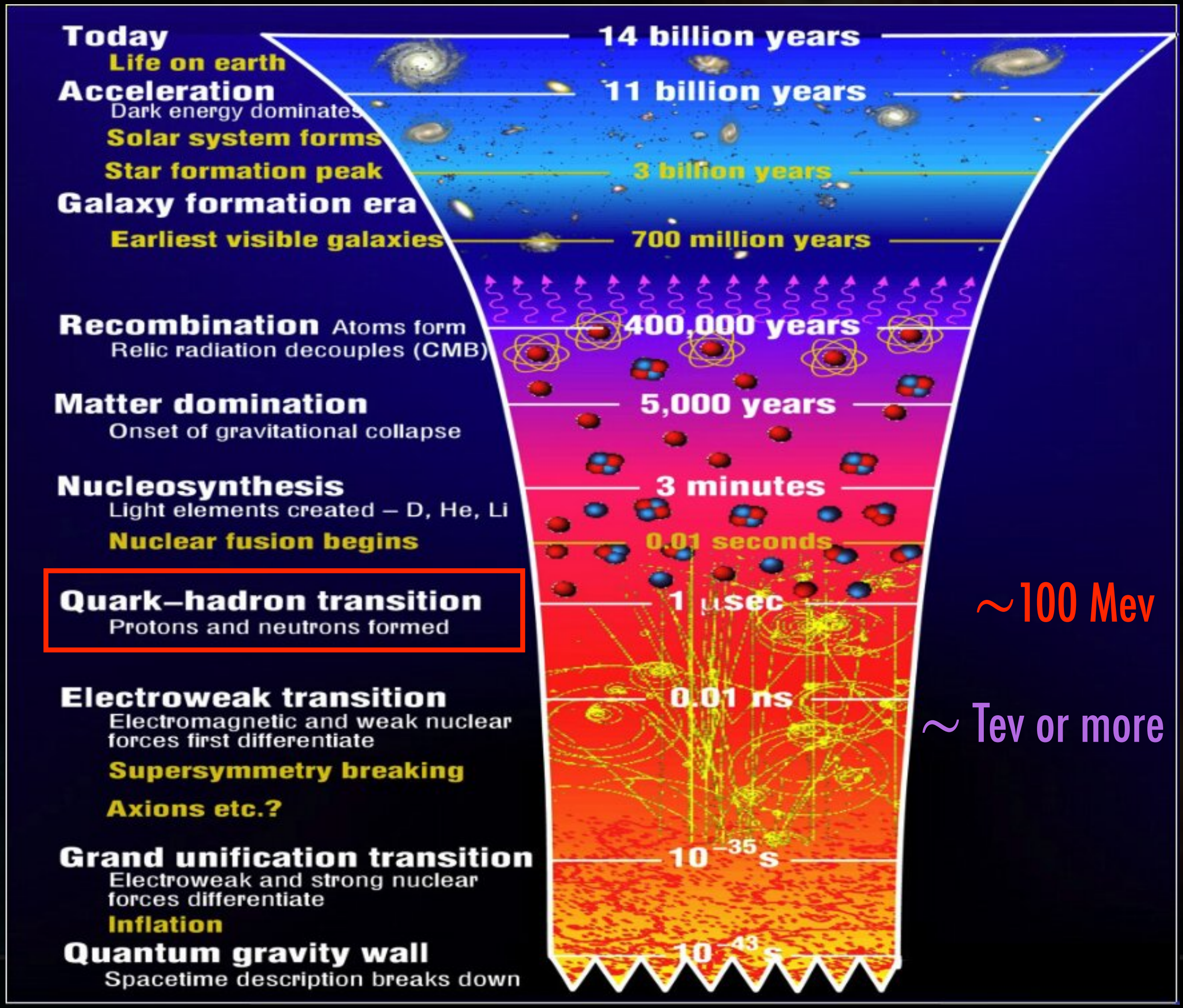


GWs from phase transition

- During 1st order transition phase, "bubbles" collisions create GWs with a wavelength depending on the size of the Universe at the time of the transition => SGWB
- QCD => nanoHz
- Typical model: 2 components (Caprini et al. 2010):
  - Bubbles collisions
  - Kinetic energy of the turbulent motions and magnetic fields sustained by the MHD turbulence.
- Example of a model (Robert Pol et al. 2022): magnetic fields and bulk fluid motions in the early universe
  => SGWB generated during phase transition
  => PTA can constrain: temperature generation, magnetic field amplitude and magnetic field characteristic scale.
- More details in Hippolyte's talk

PTA →

LISA →

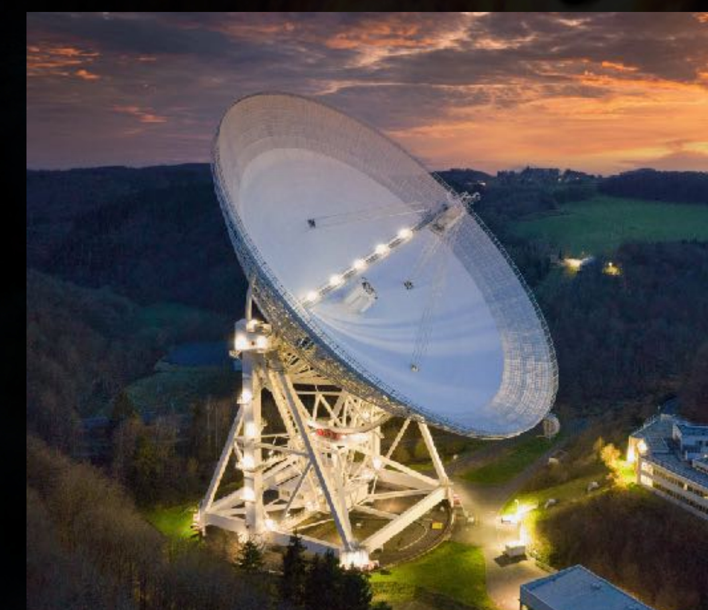


~100 Mev

~ Tev or more

EPTA

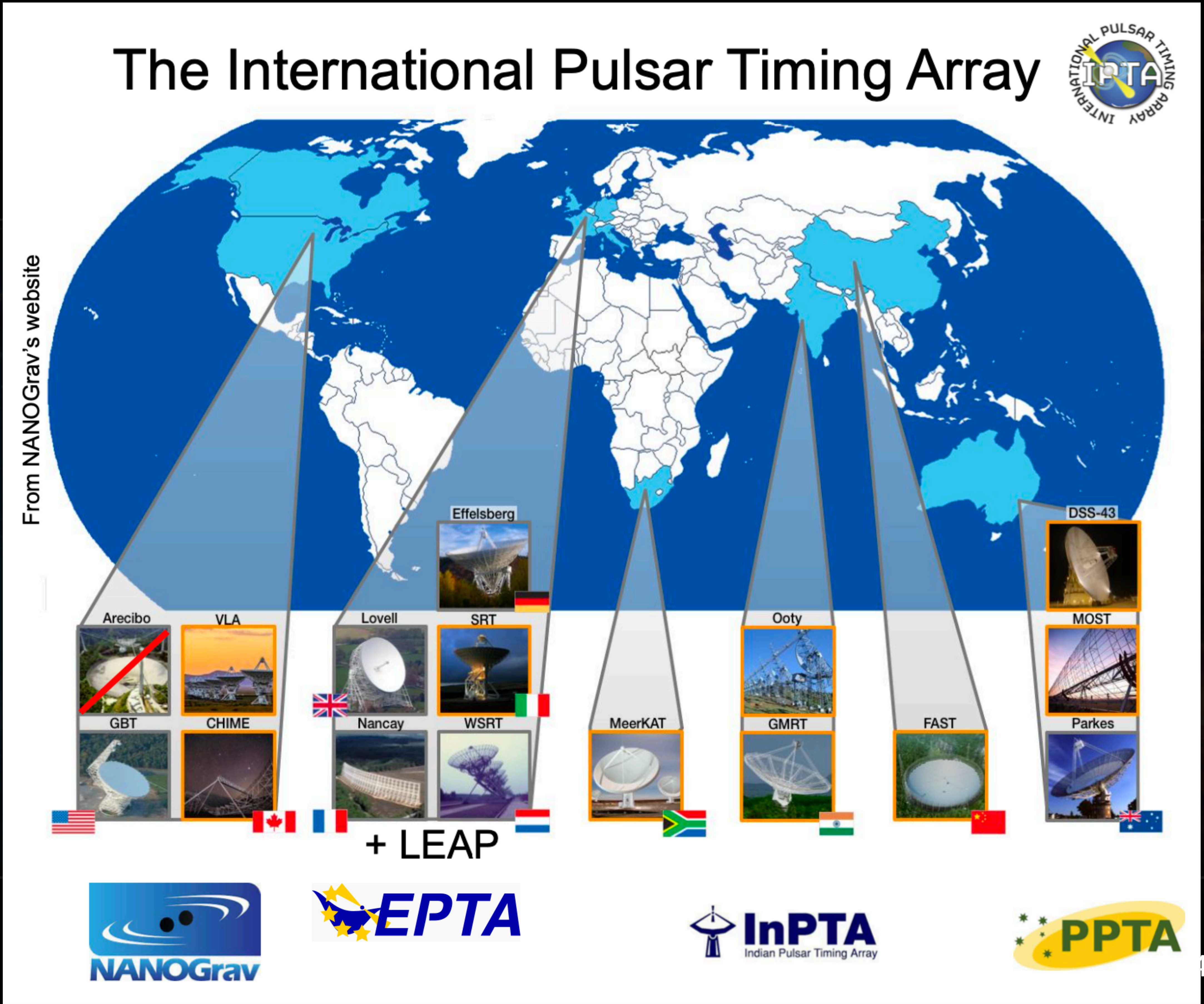
- European collaboration:
  - Nancay RT (FR),
  - Effelsberg RT (G),
  - Jodrell Bank Obs. (UK),
  - Westerbork Synthesis RT(NL),
  - Sardinia RT (I).



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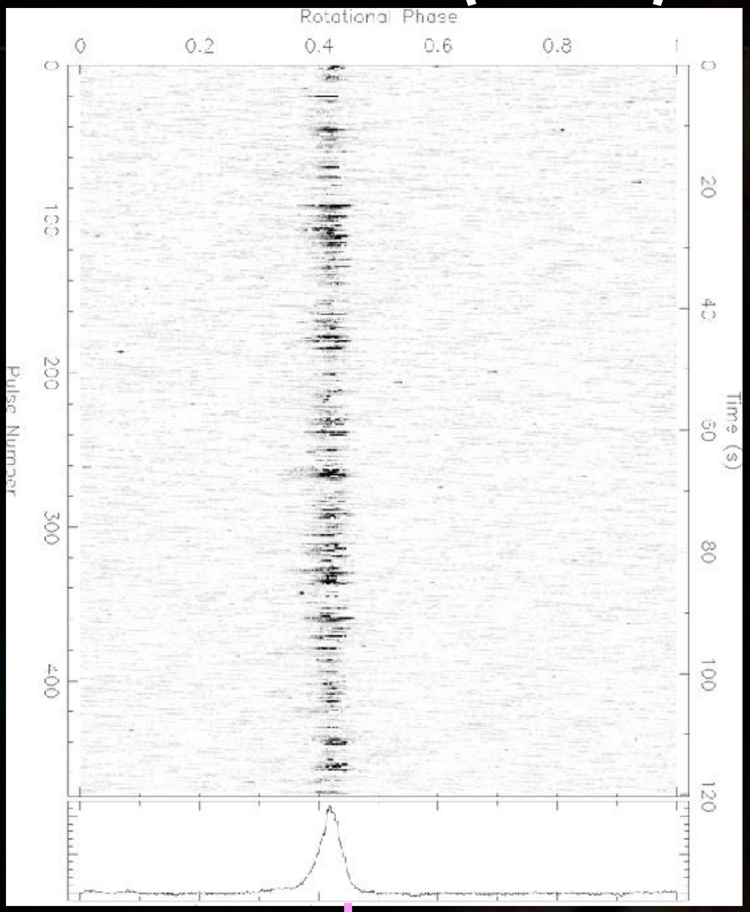
  1. Building Time of Arrival (TOA): processing of the raw data taken during one observation to extract the TOA of the pulse with extremely high precision;

One observation (1.5 Go)



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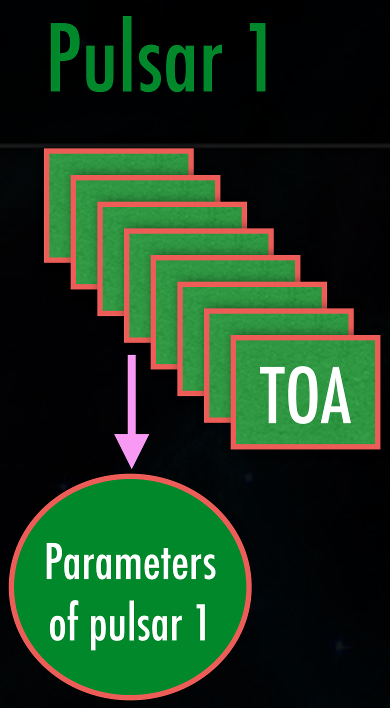
2. Single pulsar analysis: processing of all TOAs for a given pulsar to estimate the parameters of the pulsar (~20 parameters) and the noise model (~10 models with about ~20-40 parameters each);



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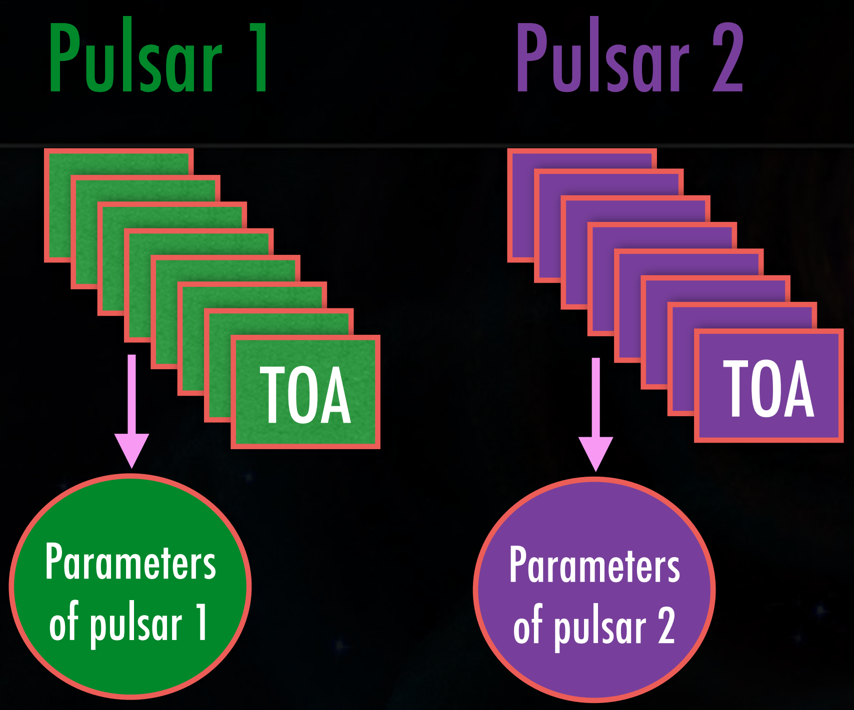

PTA data analysis

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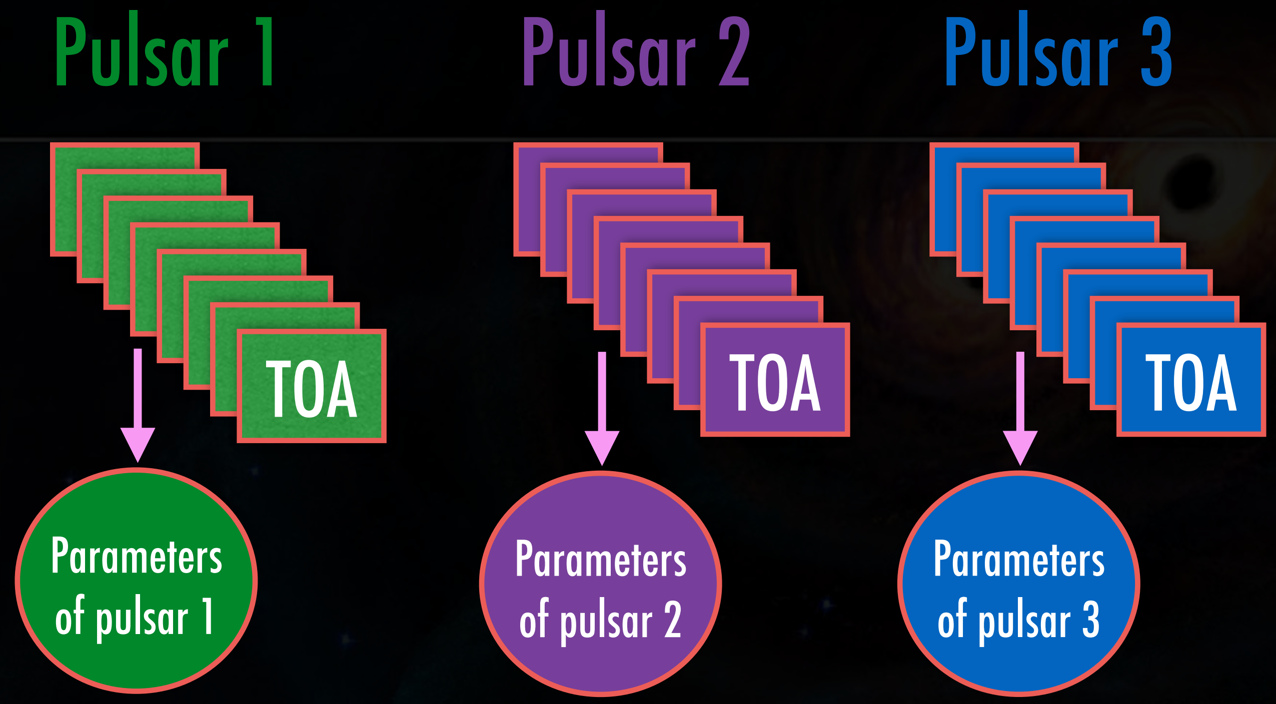

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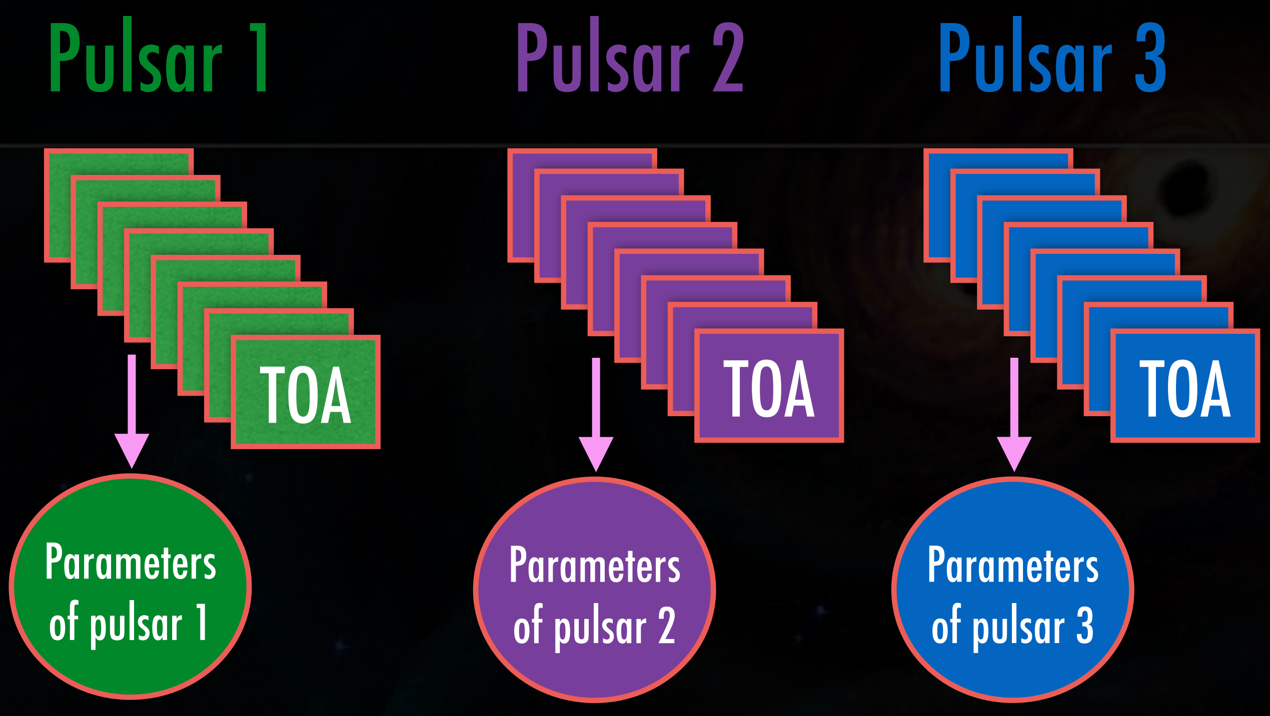

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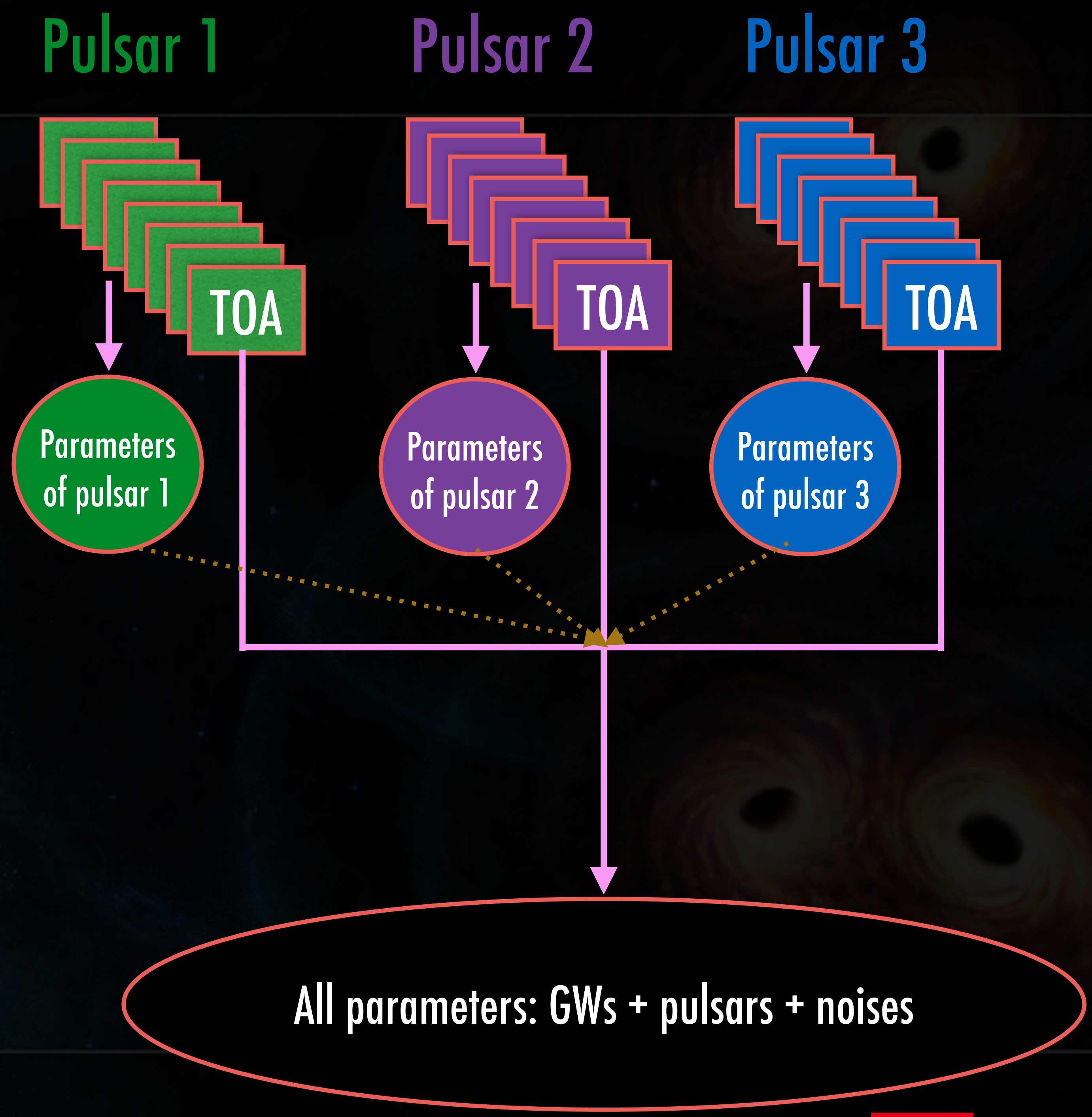
- Several tools for each steps developed either locally or within the international collaboration



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: Σ
      - 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, Σ^{-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: GWB

https://arxiv.org/abs/2306.16214

- Bayes factor:

ID	Model	DR2full		DR2full+	DR2new		DR2new+
		ENTERPRISE	FORTYTWO	ENTERPRISE	ENTERPRISE	FORTYTWO	ENTERPRISE
1	PSRN + CURN	–	–	–	–	–	–
2	PSRN + GWB	4	5	4	60	62	65
3	PSRN + CLK	< 0.01	< 0.01	< 0.01	0.2	1.2	0.3
4	PSRN + EPH	< 0.01	$\sim 10^{-4}$	< 0.01	0.2	0.2	1.3
5	PSRN + CURN + CLK	2	1	2.7	0.8	2	1.6
6	PSRN + CURN + EPH	1	0.1	1	1	1	1.6
7	PSRN + GWB + CURN	3	3	4	27	13	25
8	PSRN + GWB + CLK	5	12	7	28	35	57
9	PSRN + GWB + EPH	3	3	3.6	33	29	43

- Acronyms:
  - PSRN: Pulsar noise
  - CURN: Common Uncorrelated Red Noise
  - CLK: Clock Noise (monopole)
  - EPH: Solar system ephemeris (dipole)

- Significance: when using only new backends, Bayes factor at 60, p-value of ≈ 0.001, $\gtrsim 3\sigma$ confidence => strong evidence for the existence of GWB

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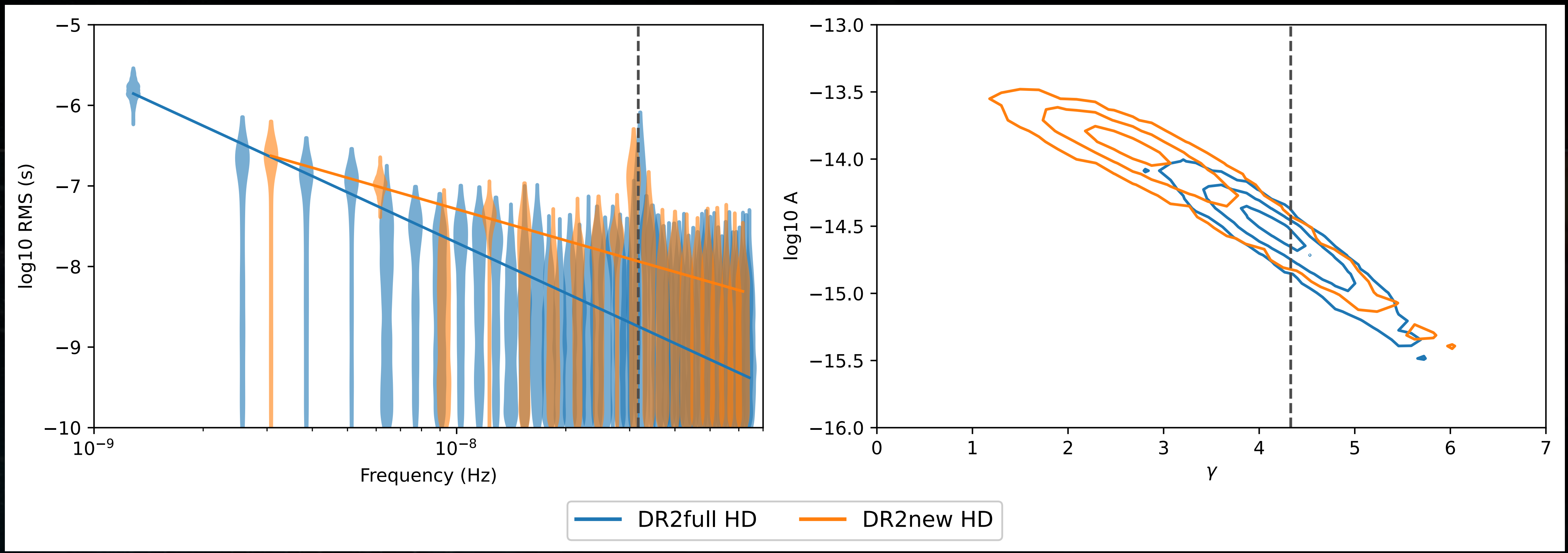
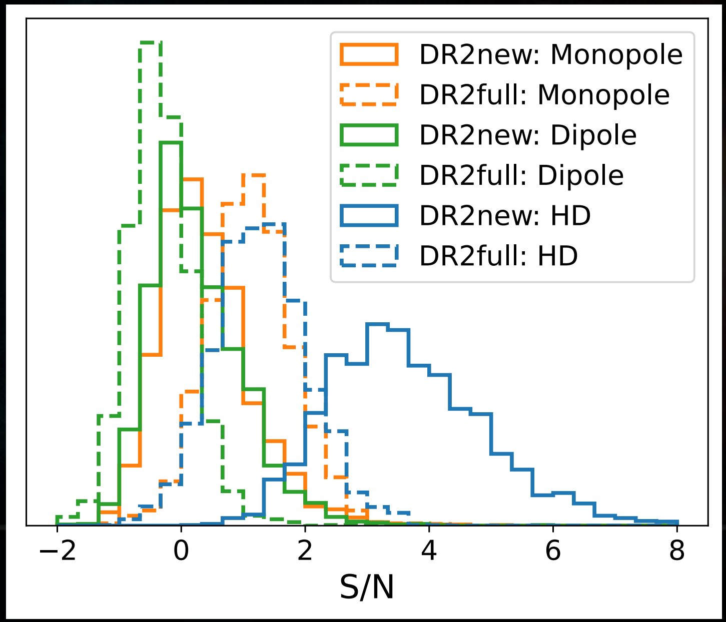
EPTA results: GWB

https://arxiv.org/abs/2306.16214

- Free spectrum — Posterior for GWB parameters



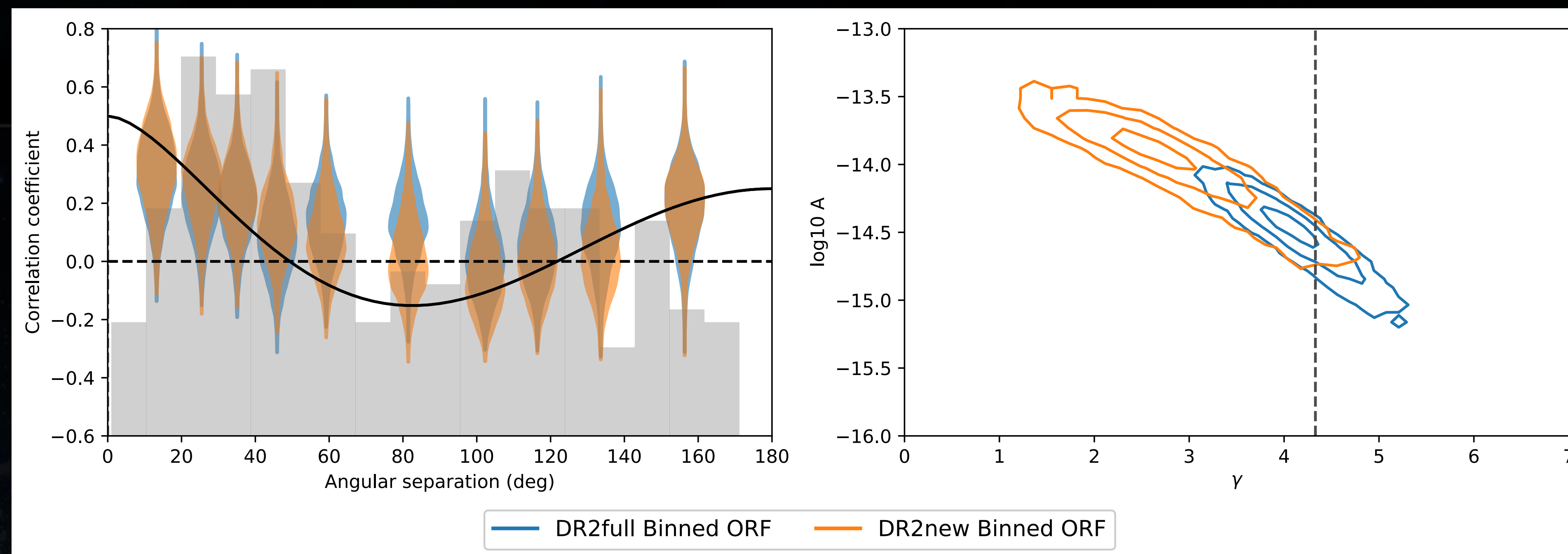
- GWB parameters (DR2new):
  - logarithmic amplitude: $\log_{10} A = -13.94^{+0.23}_{-0.48}$
  - spectral index: $\gamma = 2.71^{+1.18}_{-0.73}$
- No dipole and no monopole



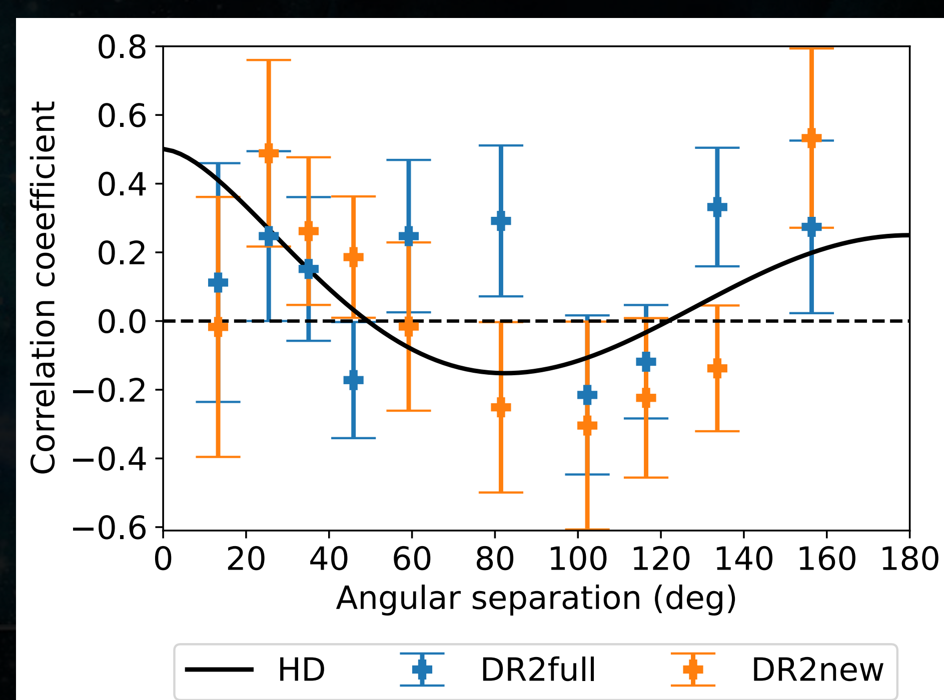
EPTA results: GWB

https://arxiv.org/abs/2306.16214

- Spatial correlation: overlap reduction function
  - Binned



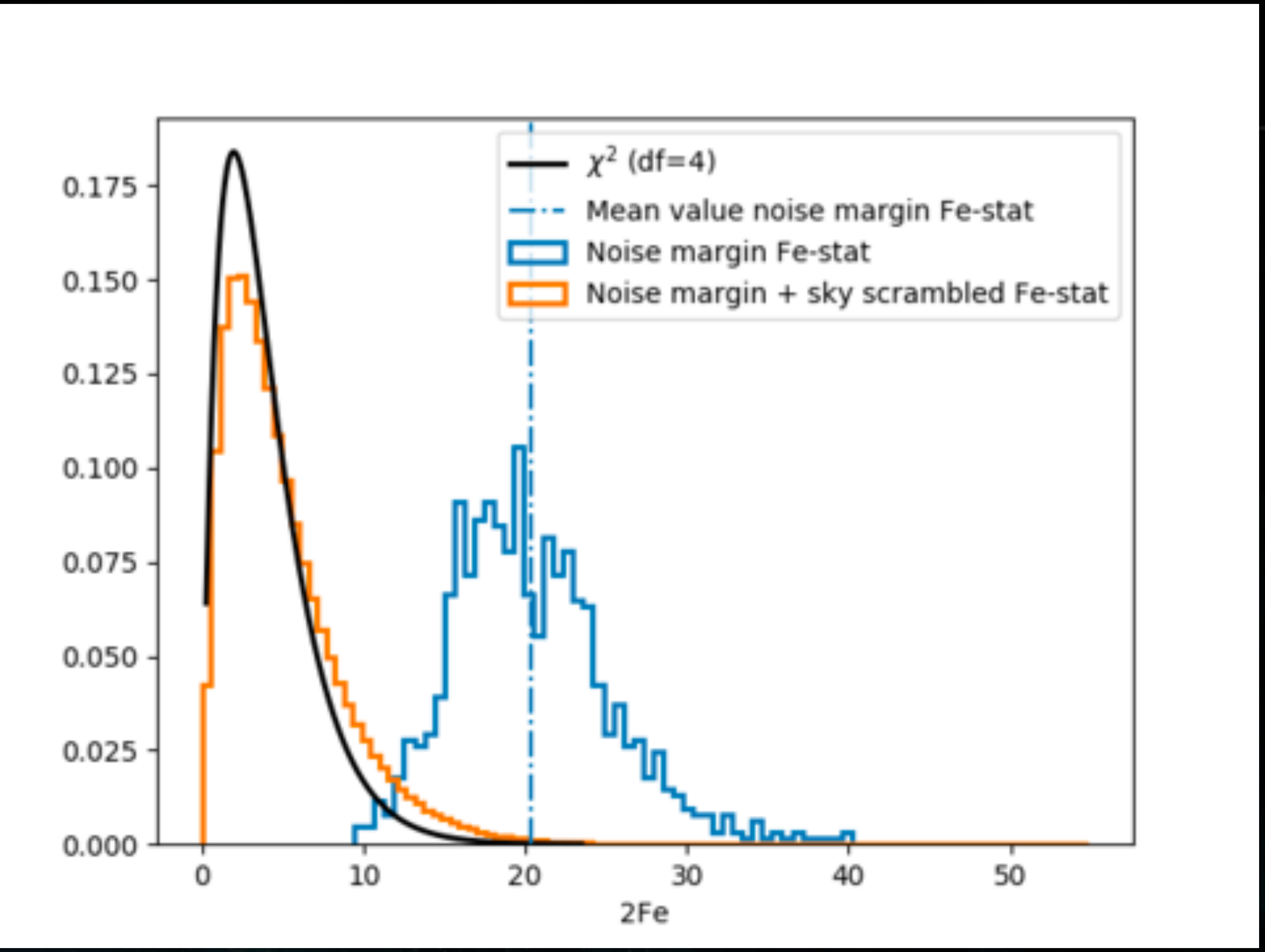
  - Optimal statistic



EPTA results: GWB

https://arxiv.org/abs/2306.16214

- Scrambling the sky position of pulsar, destroy the signal

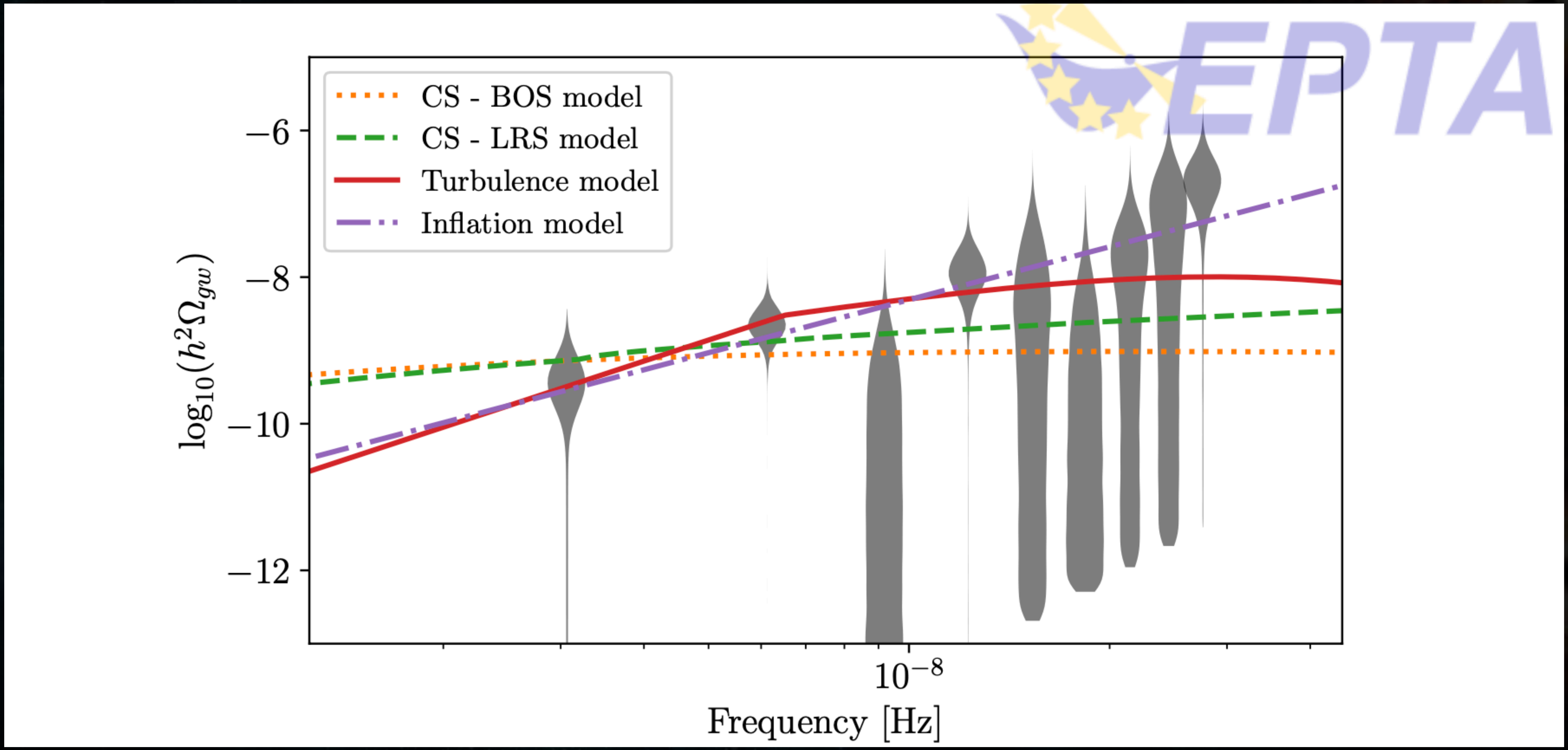


- Many other tests see https://arxiv.org/abs/2306.16214

EPTA results: GWB

- Comparison between EPTA and some Stochastic GW Backhground from cosmological origin

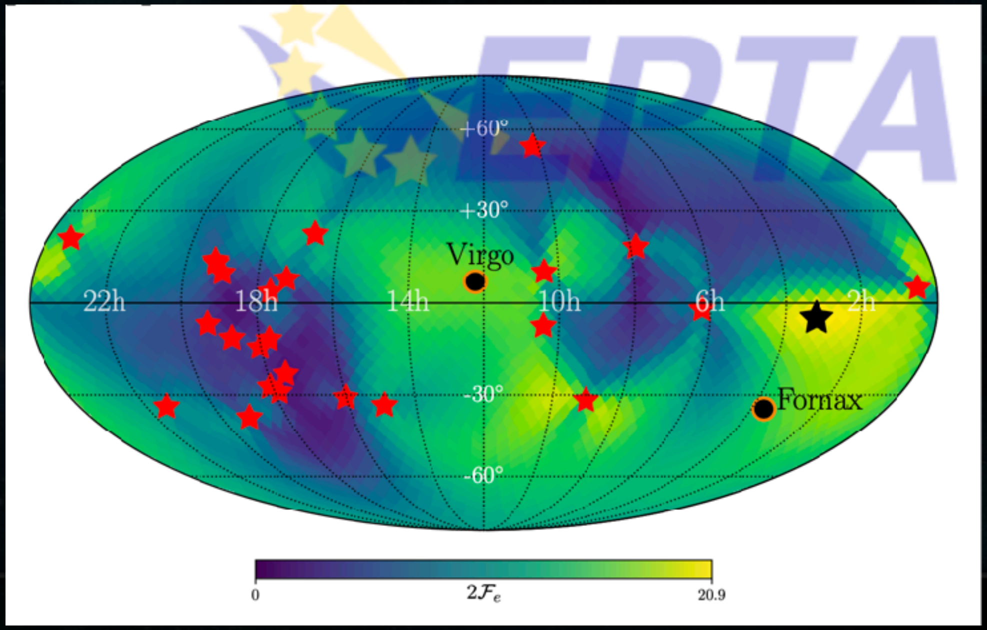
Antoniadis et al., A&A June 28, 2023



EPTA results: individual sources

https://arxiv.org/abs/2306.16226

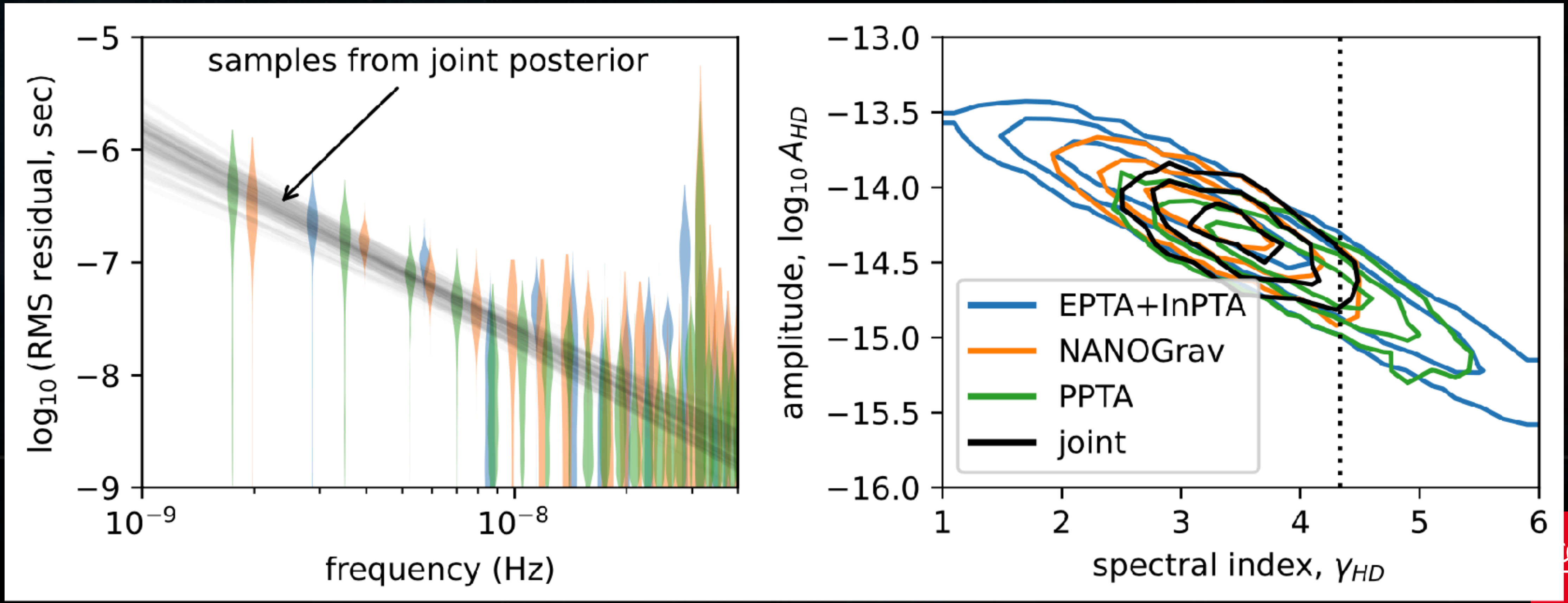
- Continuous GW search = Super Massive Black Hole Binary
- GW described by $8 + 2 \times N_{PSR}$ parameters:
  - Amplitude, frequency, chirp mass, sky position, inclination, polarisation, initial phase, phase at pulsar, pulsar distance
- Frequentist analysis:
  - Maximum F-statistic (equivalent to likelihood)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



IPTA results

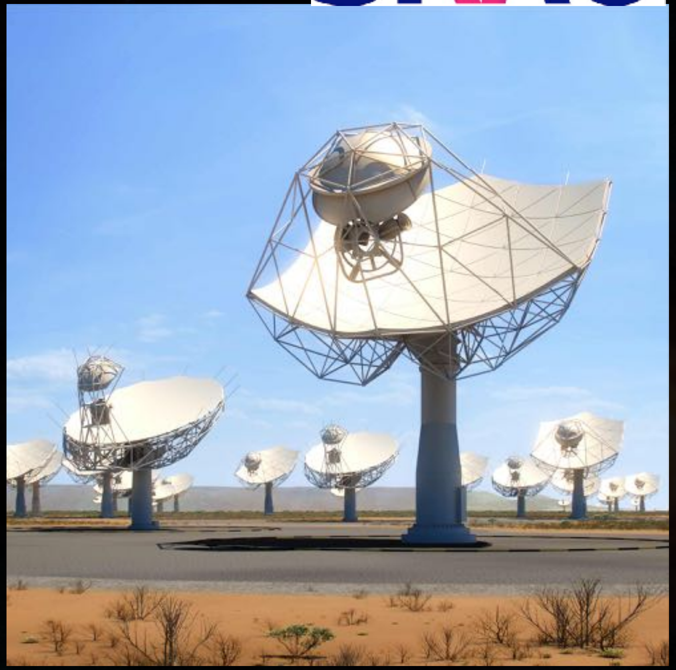
- Similar results from other PTA collaborations
- The origin of the signal is still to be understood.
- IPTA is working on a joined analysis :
  - All TOAs together
  - We should be able to confirm the detection and have a better characterisation soon …
  - But complex analysis

https://arxiv.org/abs/2309.00693



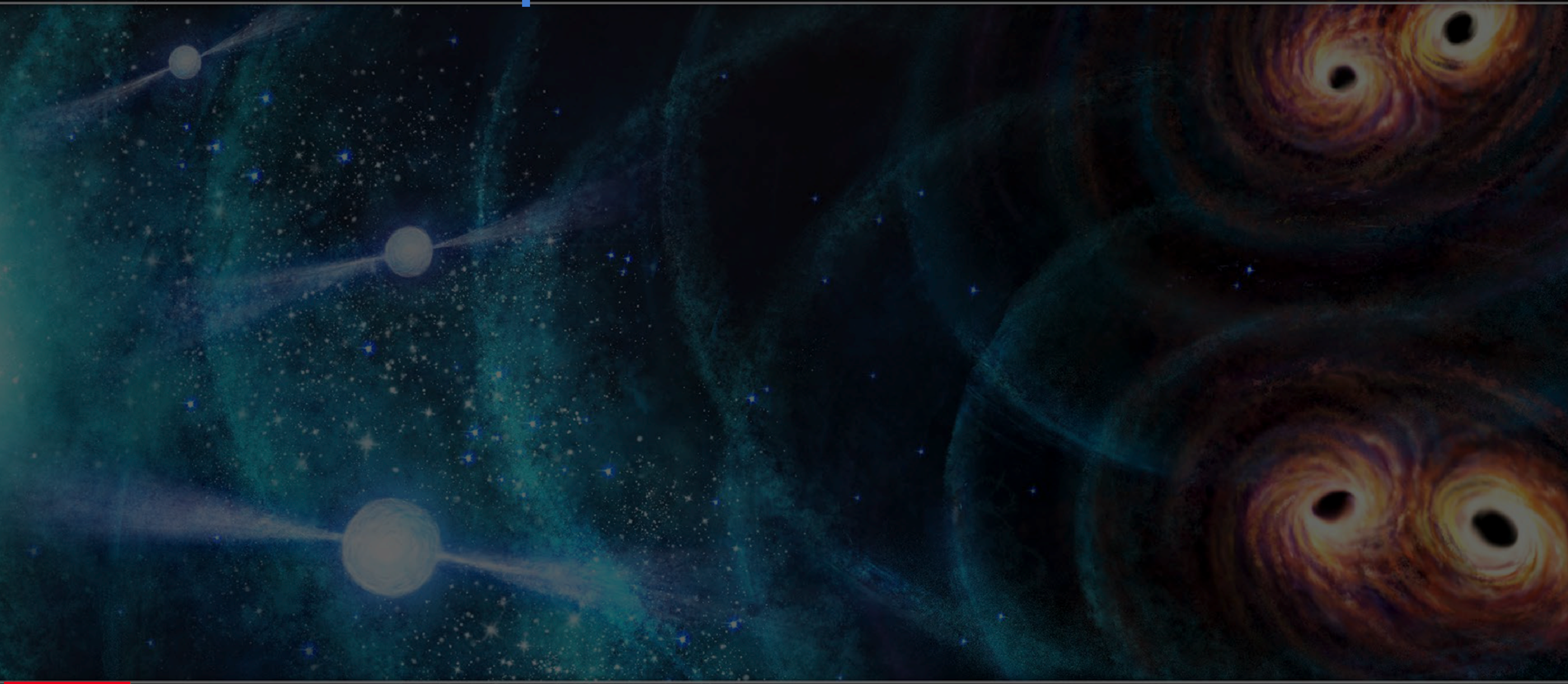
Future

- Soon (2025-2026) : IPTA Data Release 3
  - Combination of 120 pulsars from almost all radio telescope in the world
  - Expected results:
    - Confirmation of the signal
    - Better characterisation
- Later (2030) : Square Kilometre Array (SKA):
  - ~100 pulsars (?) Few tens thousands of TOAs with better timing precision
  - Large improvement in sensitivity
  - => Characterise in details the signal (background and/or individual sources):
    - 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
  - Search new sources: memory bursts (during), others …



Thank you !

And now Hippolyte will present the GW from QCD phase transition …



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