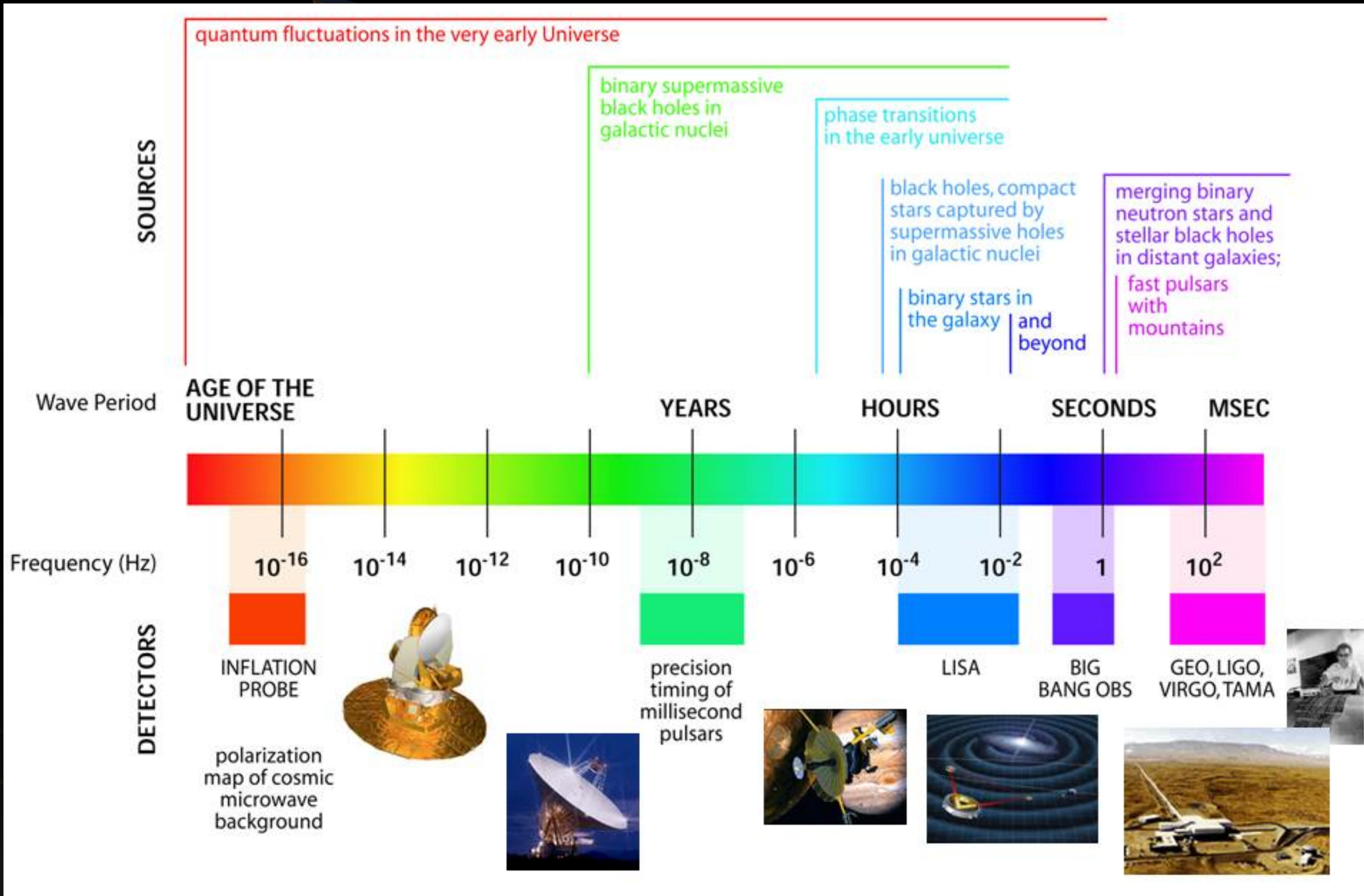
The latest results from Pulsar Timing Arrays: strong evidence for gravitational wave at very low frequency

Antoine Petiteau (CEA/IRFU/DPhP)

Member of EPTA and IPTA collaborations

Seminar DPhP - 10th July 2023

GW spectrum


SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
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10^{-14}
10^{-12}
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1
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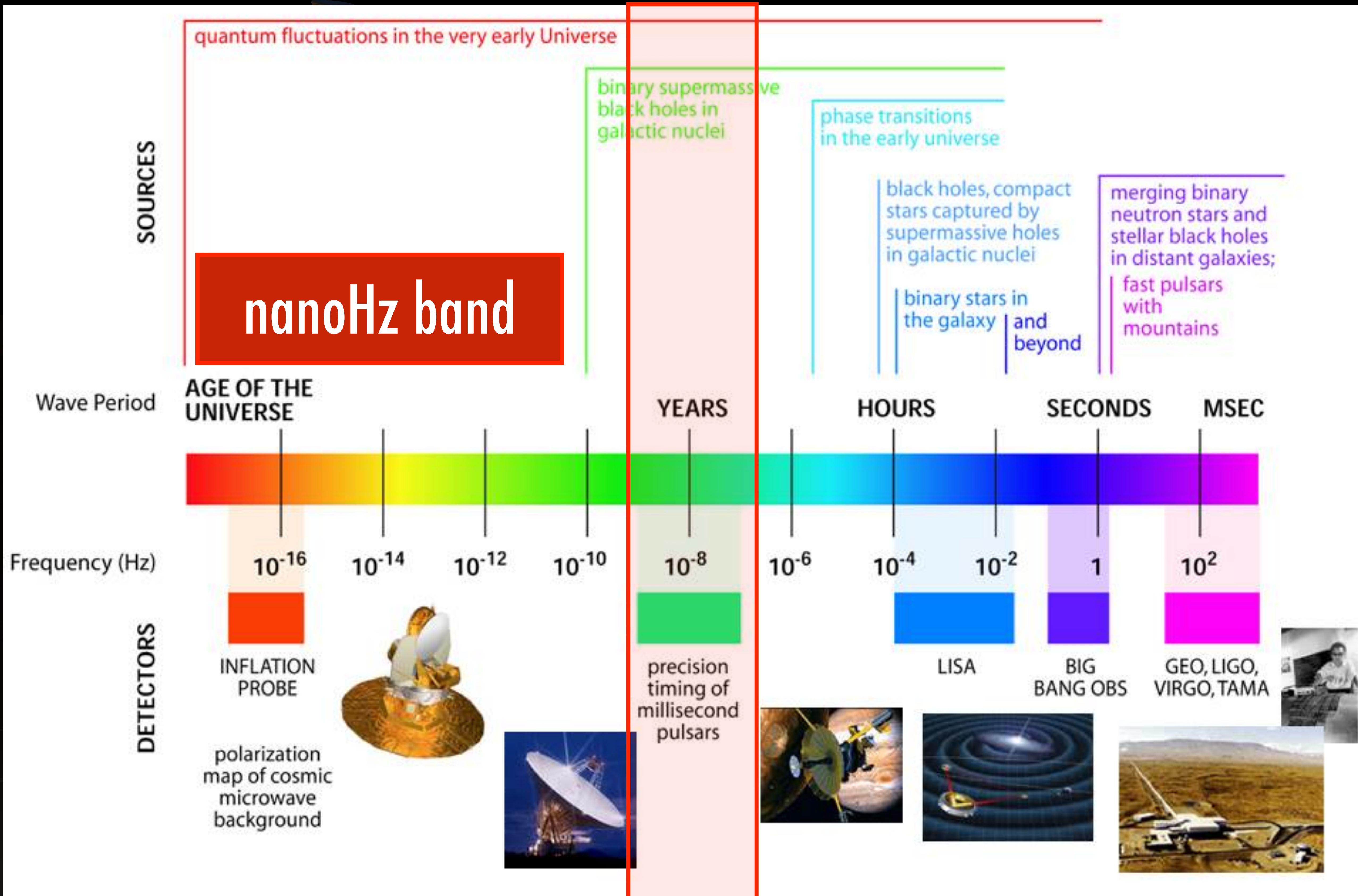
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA

GW spectrum



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nanoHz band
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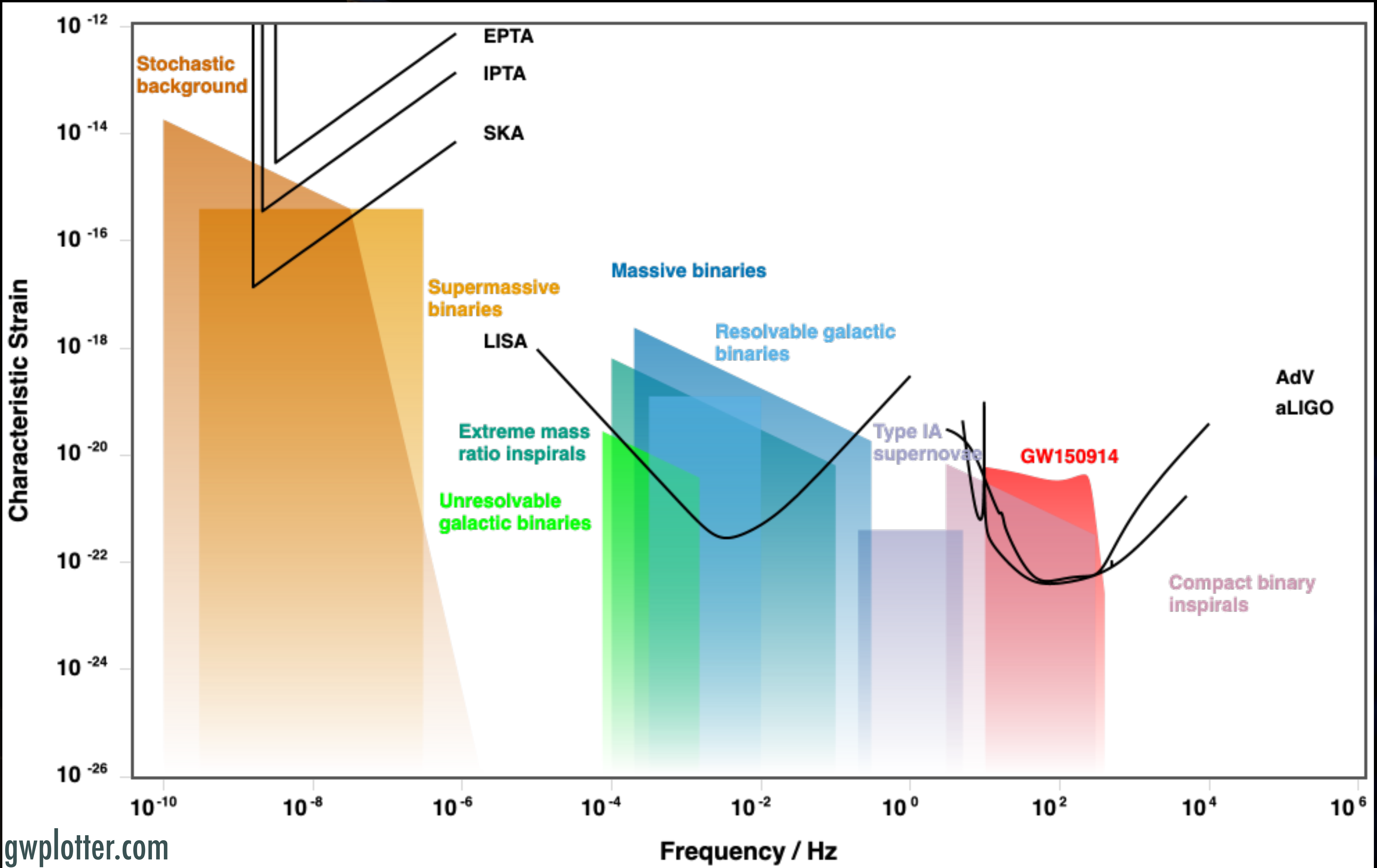

gwplotter.com

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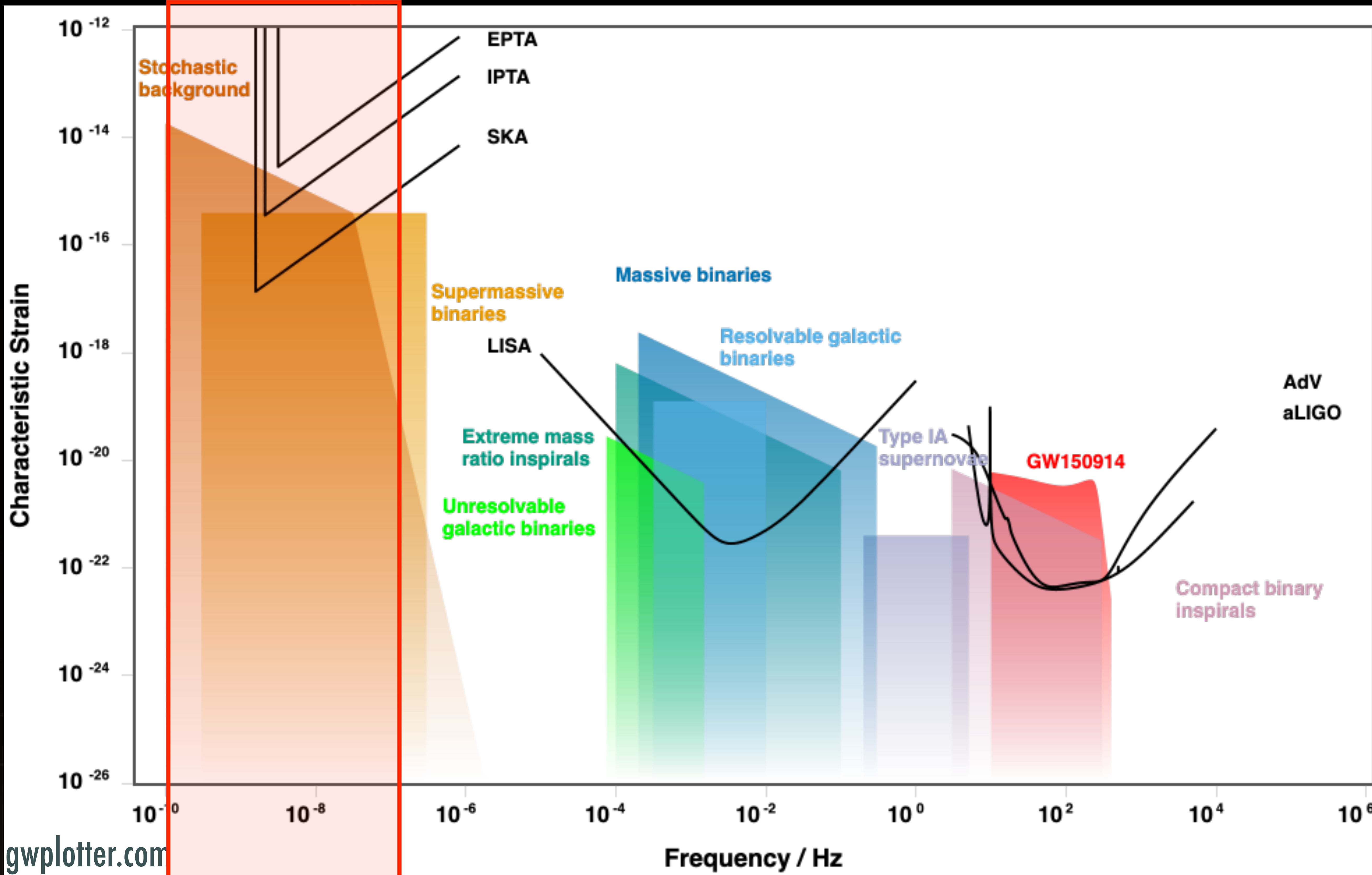
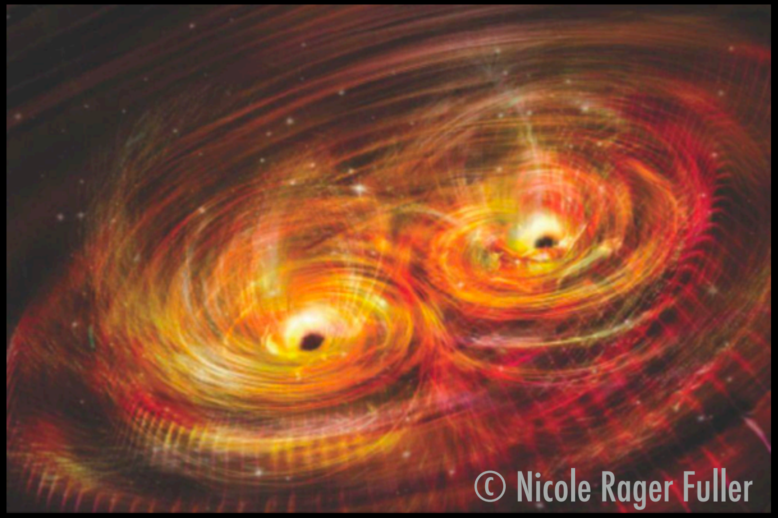


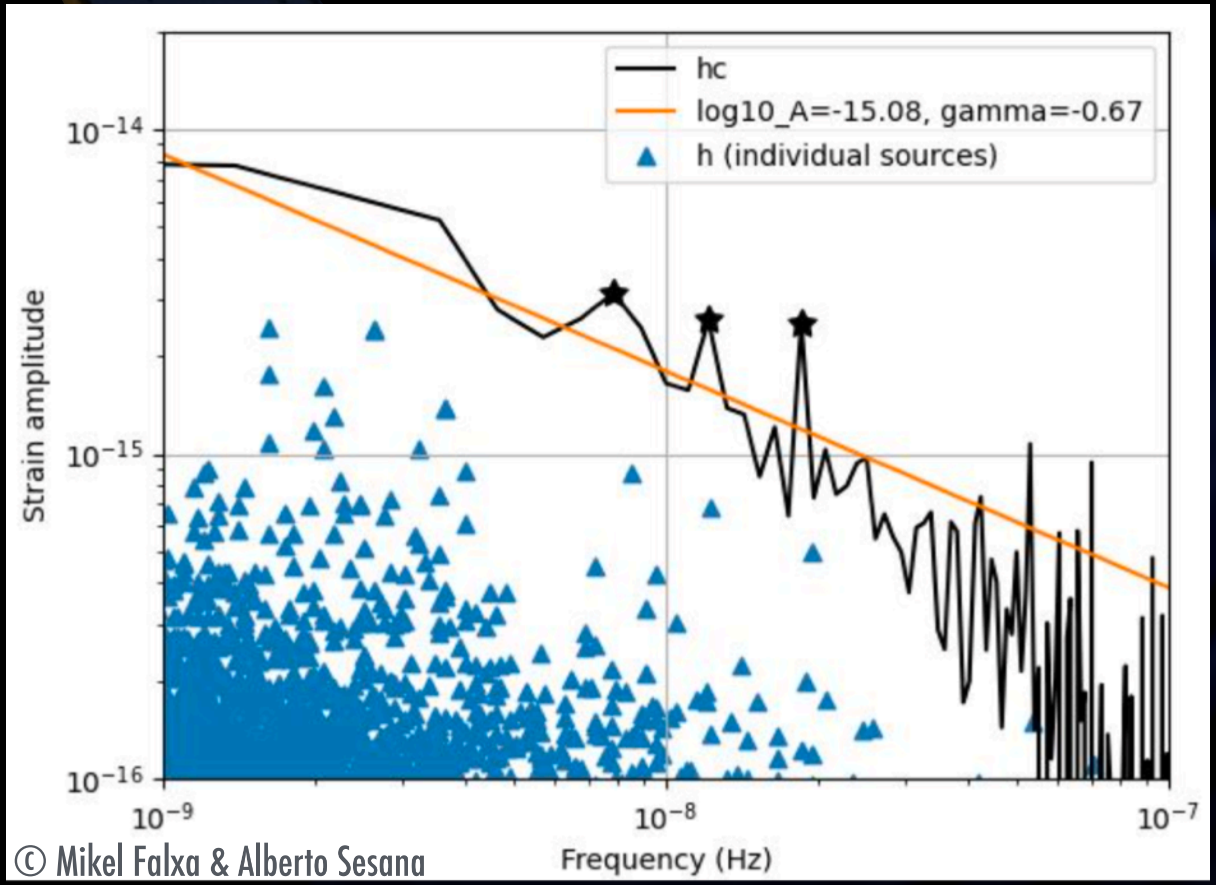
gwplotter.com

GW sources in the nHz band

- **Supermassive black hole binaries**
  - Example:
    - Chirp mass = 10^9 M_{Sun} , 1000 years before merger
      => f = 5×10^{-8} Hz : nanoHertz band
      => df/dt = 9×10^{-18} Hz/s : very slow evolution



  - 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

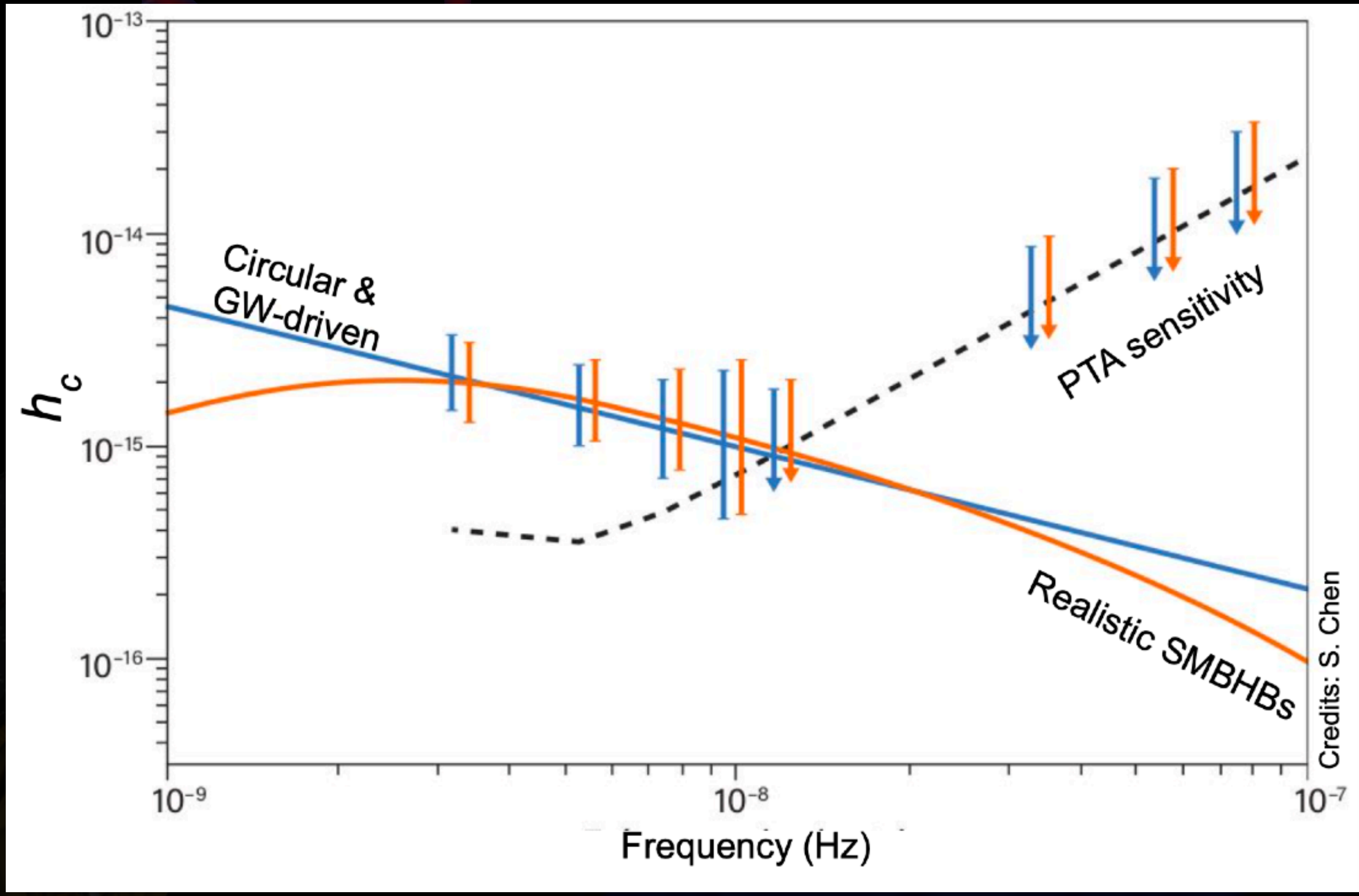


GW sources in the nHz band

- Stochastic background from supermassive black hole binaries
  - Modelling: red-process, power law approximation

$$S_P^{GWB}(f) = \frac{A_{GWB}^2}{12\pi^2}\left(\frac{f}{yr^{-1}}\right)^{\gamma_{GWB}} yr^3$$

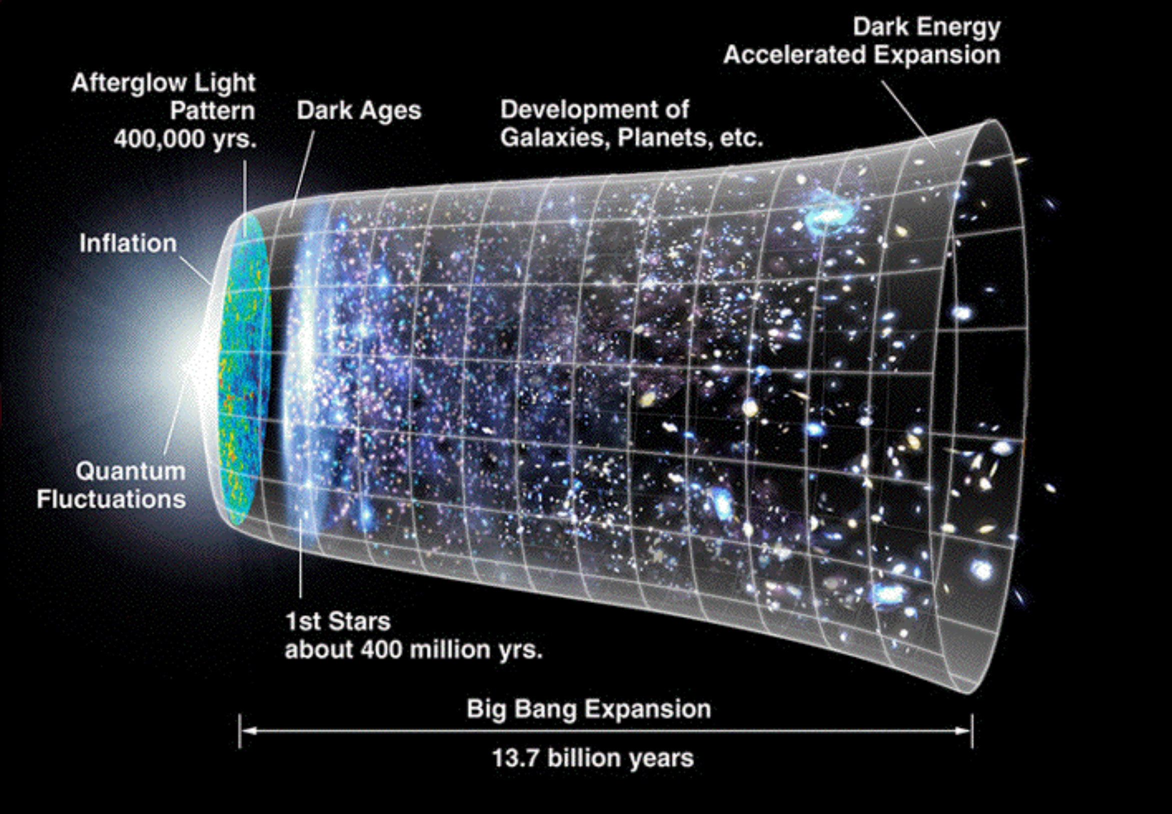
$\gamma_{GWB} = 13/3$ for circular & GW-driven SMBHBs

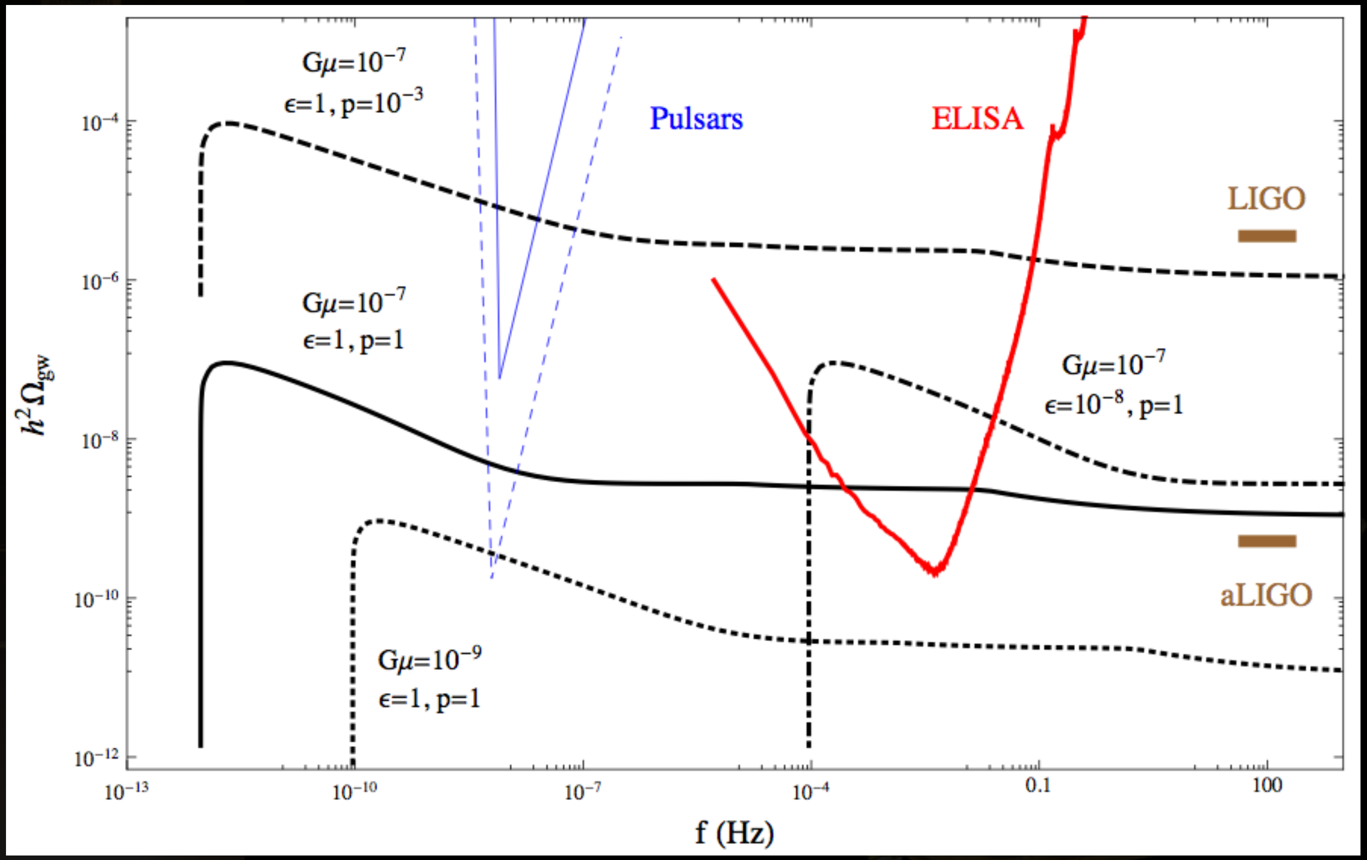


+ Hellings-Downs spatial correlations

GW sources in the nHz band

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





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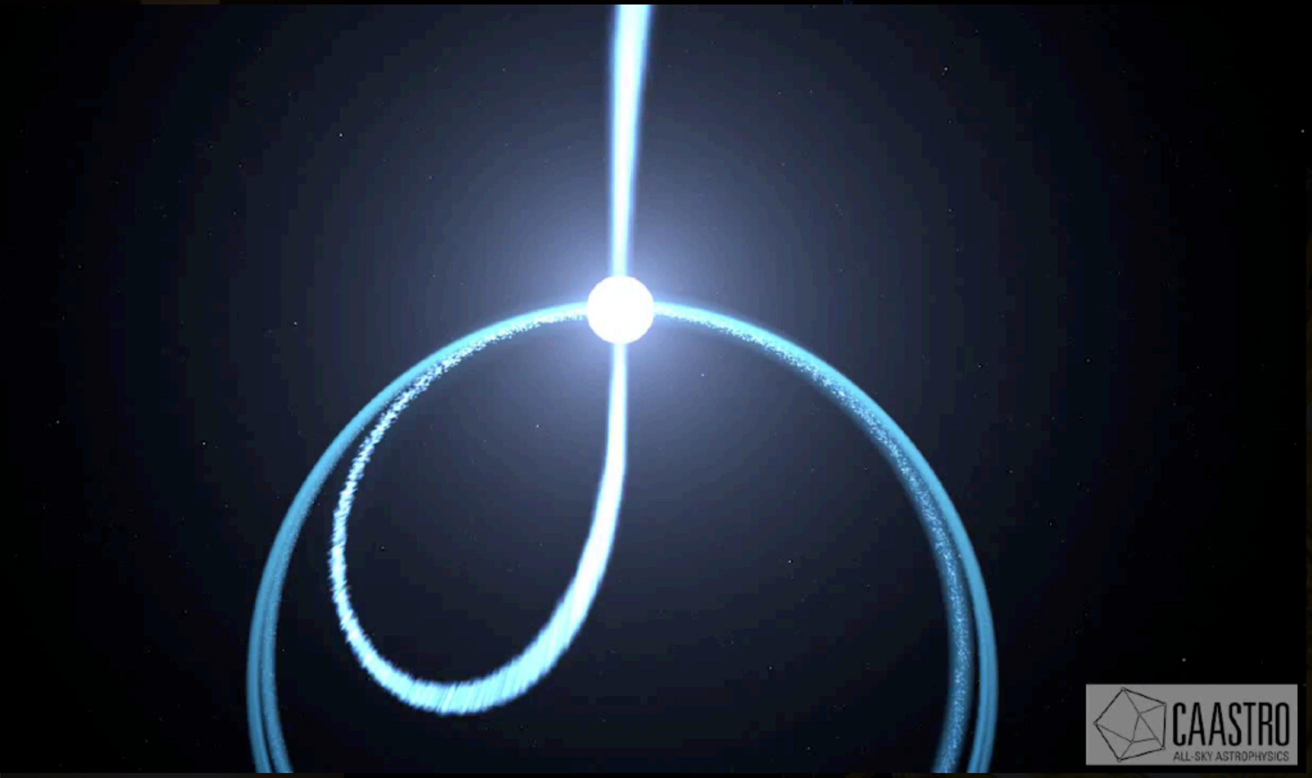
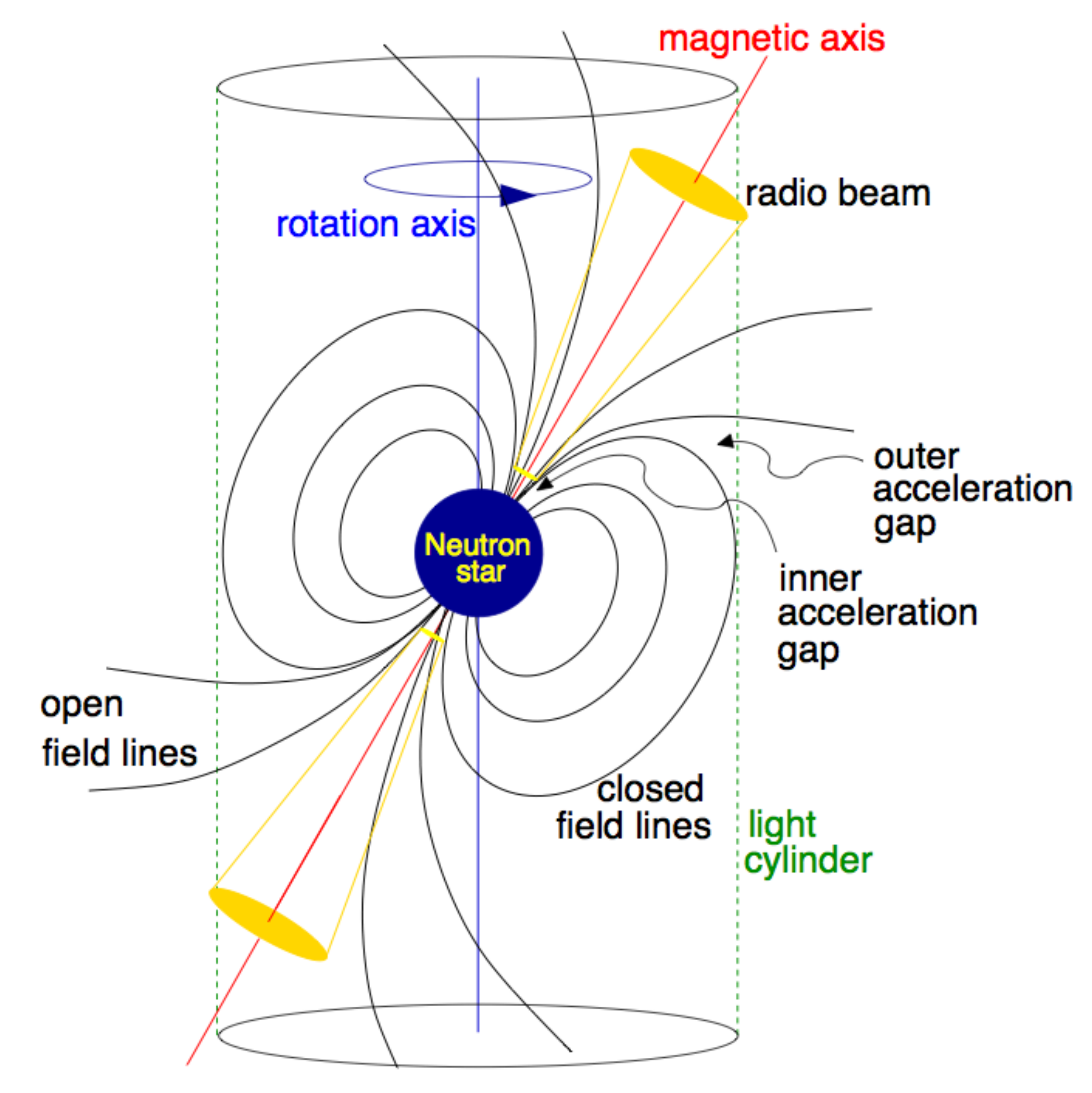
Pulsars

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





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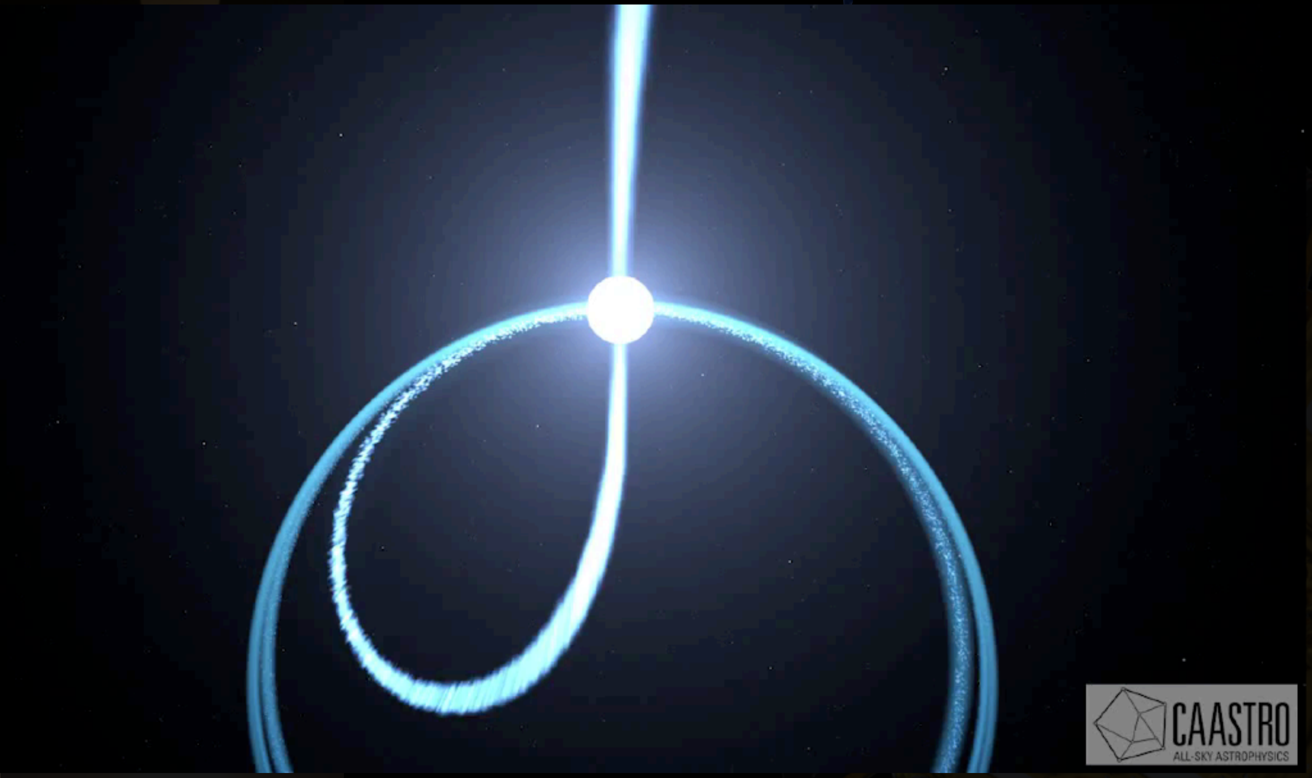
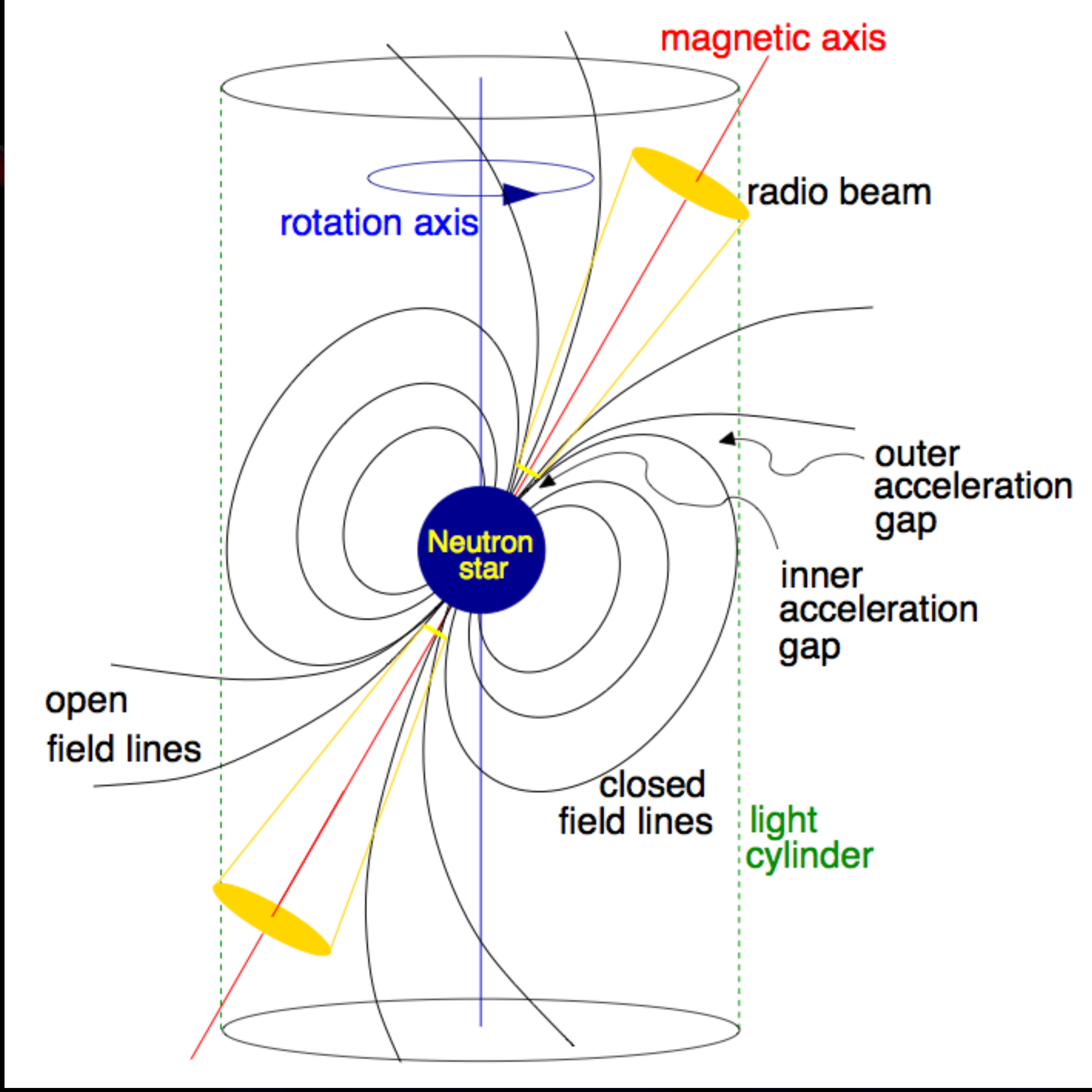
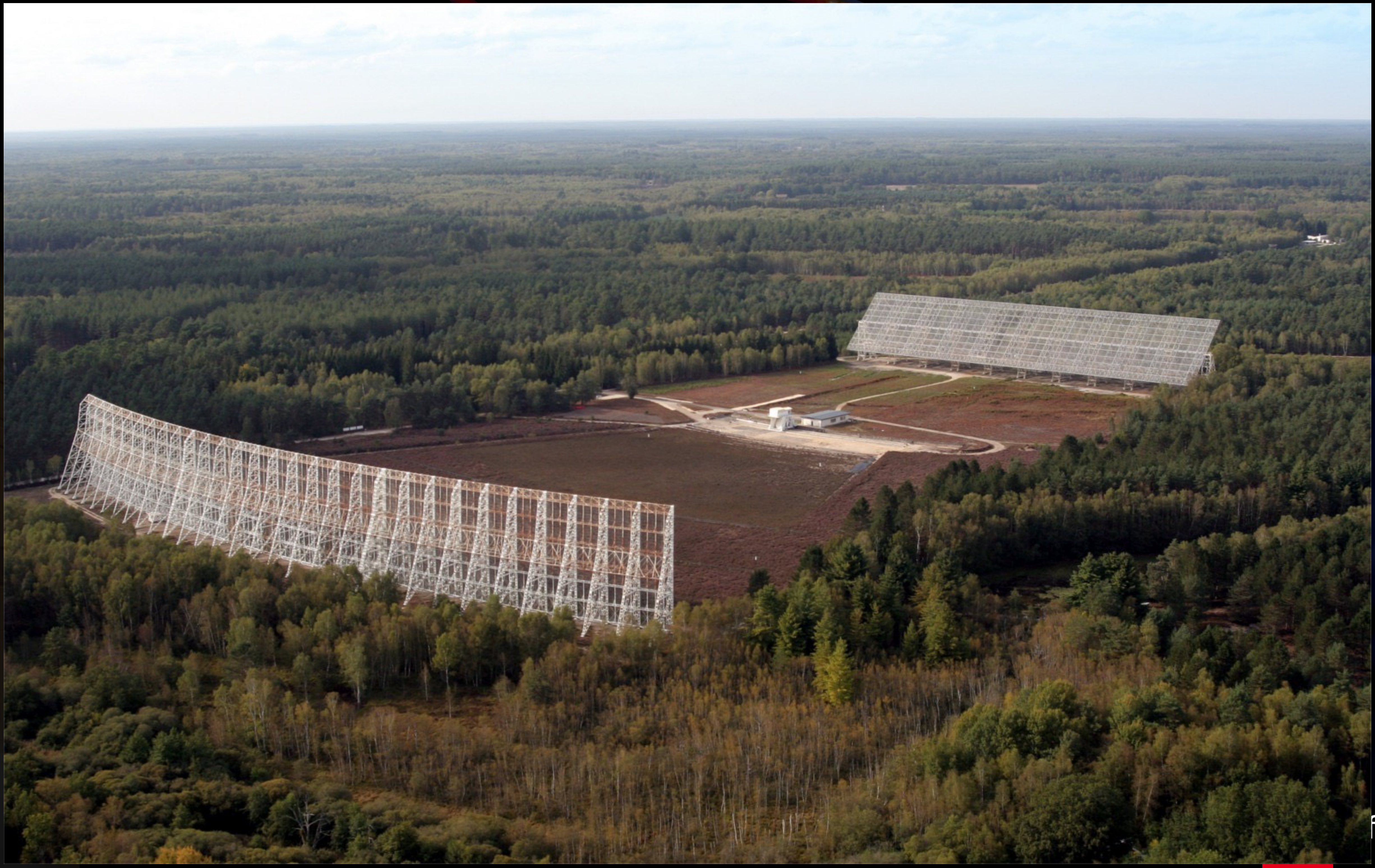




Pulsars observations

- Somewhere in Sologne ... the Nançay radio telescope



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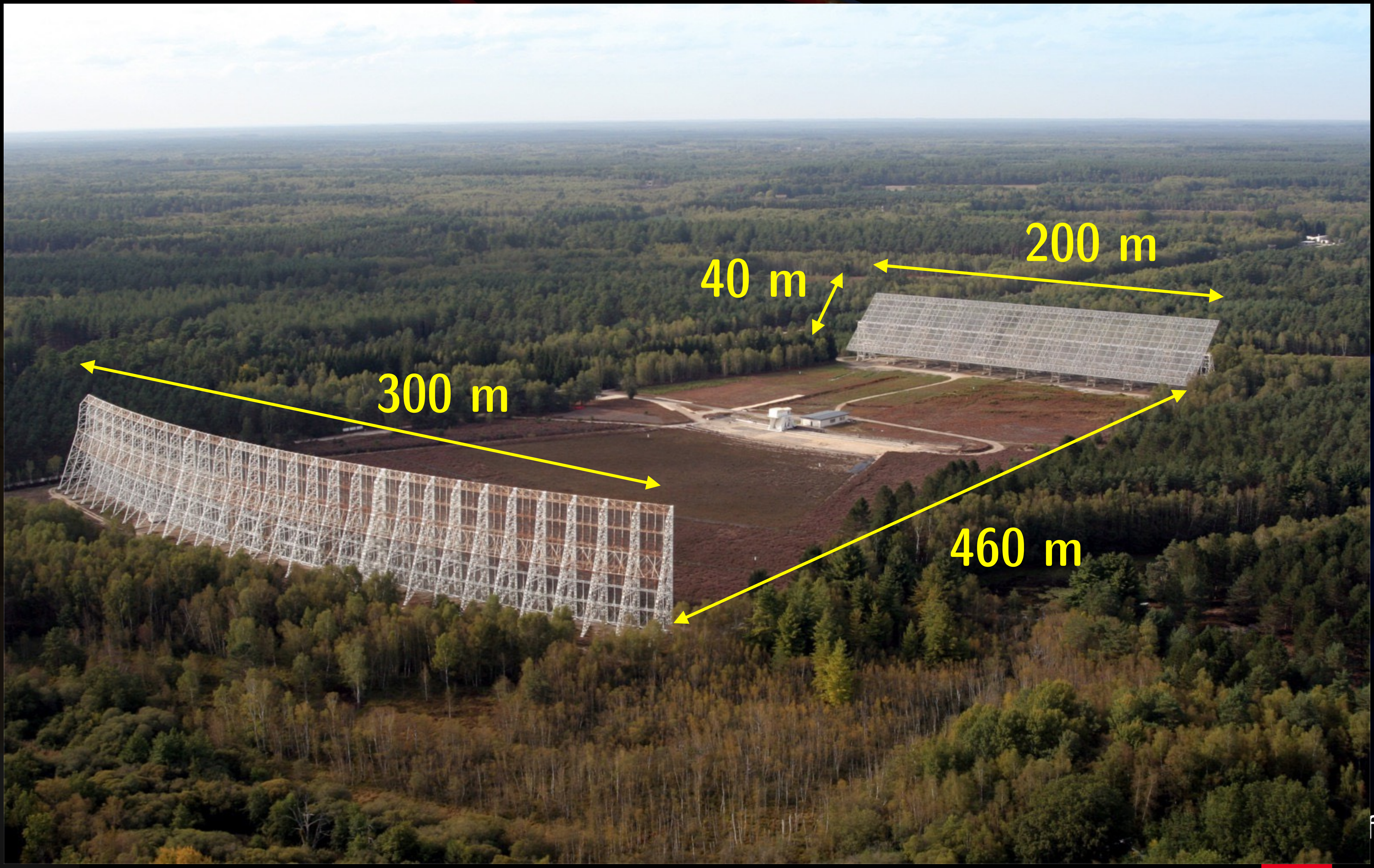
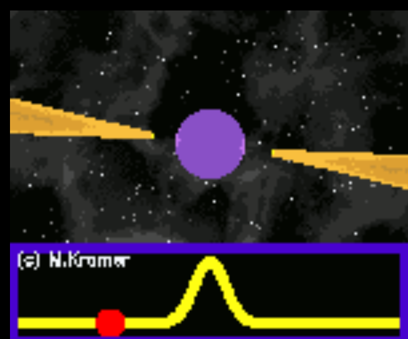


Pulsar timing

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



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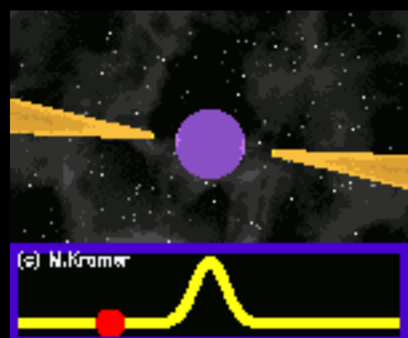

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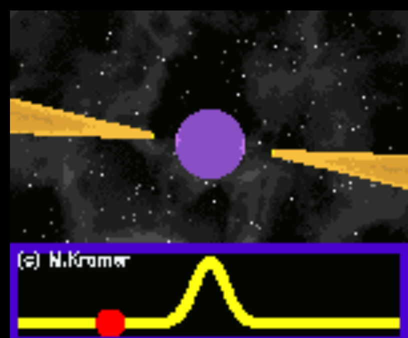
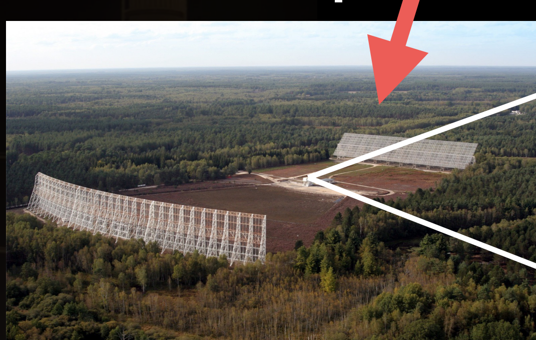


Radiotelescope



Receiver (GHz)

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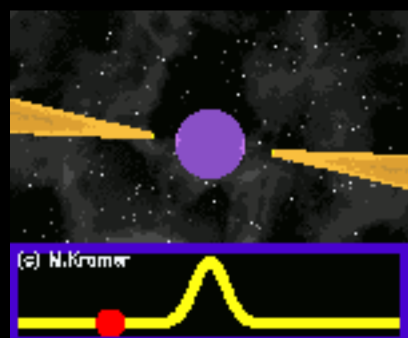

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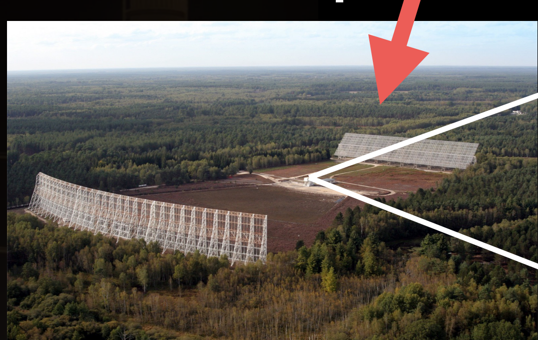
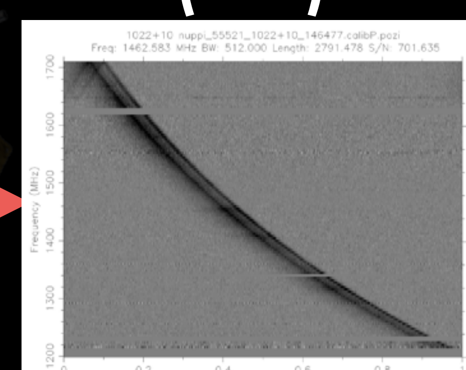


Receiver (GHz)

Coherent dedispersion (GPU)



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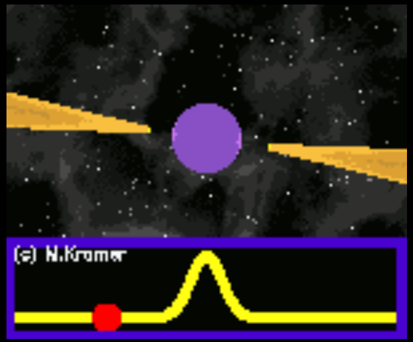

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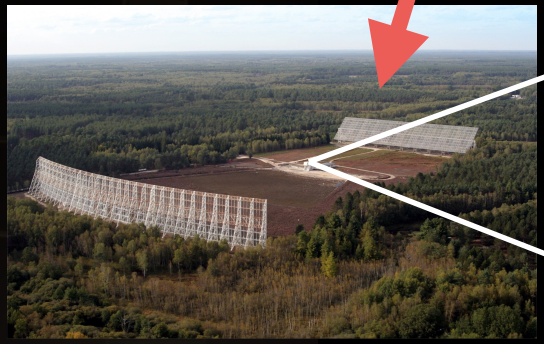

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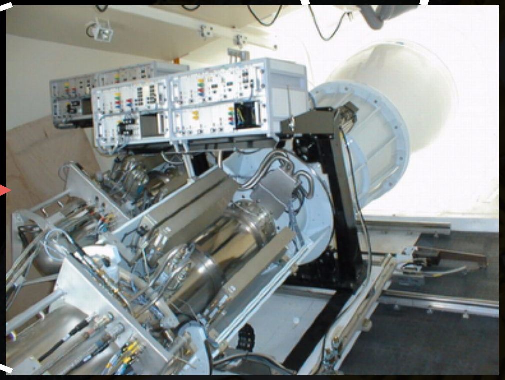

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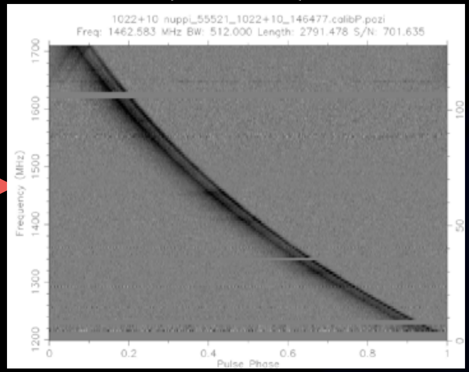
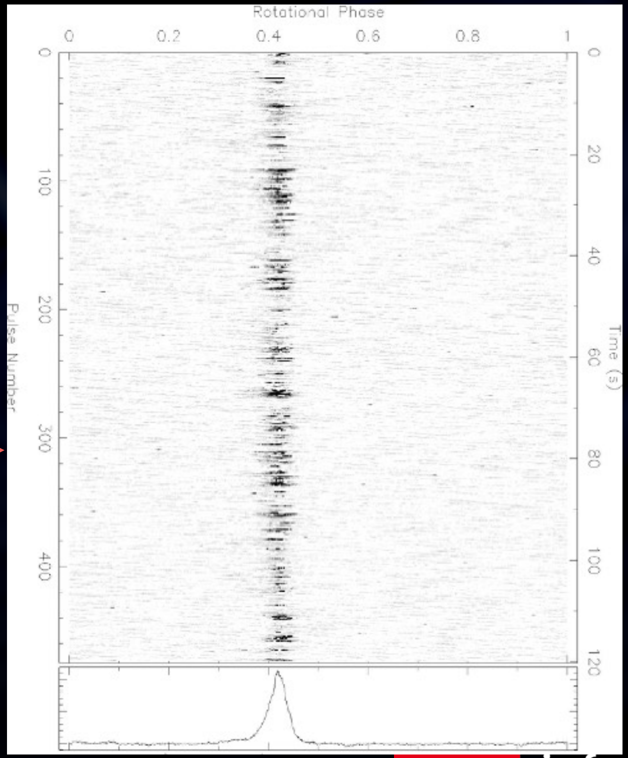


Folding



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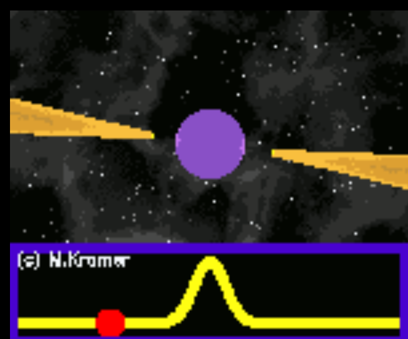
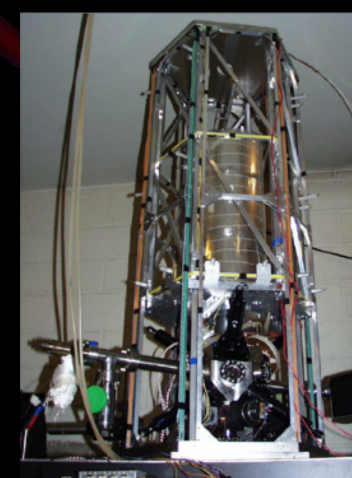
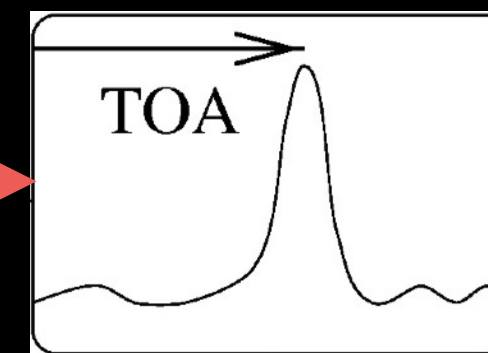


Reference clock



Integrated pulse



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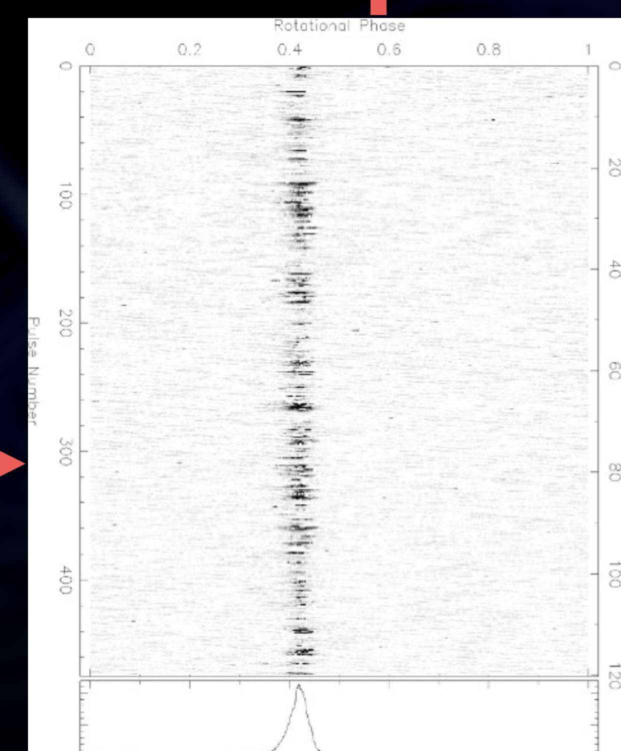

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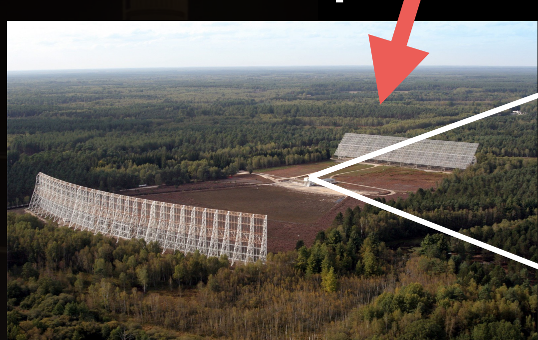

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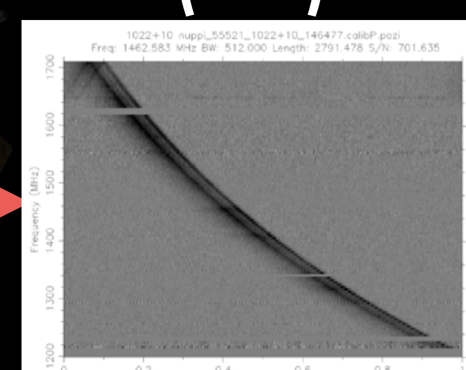
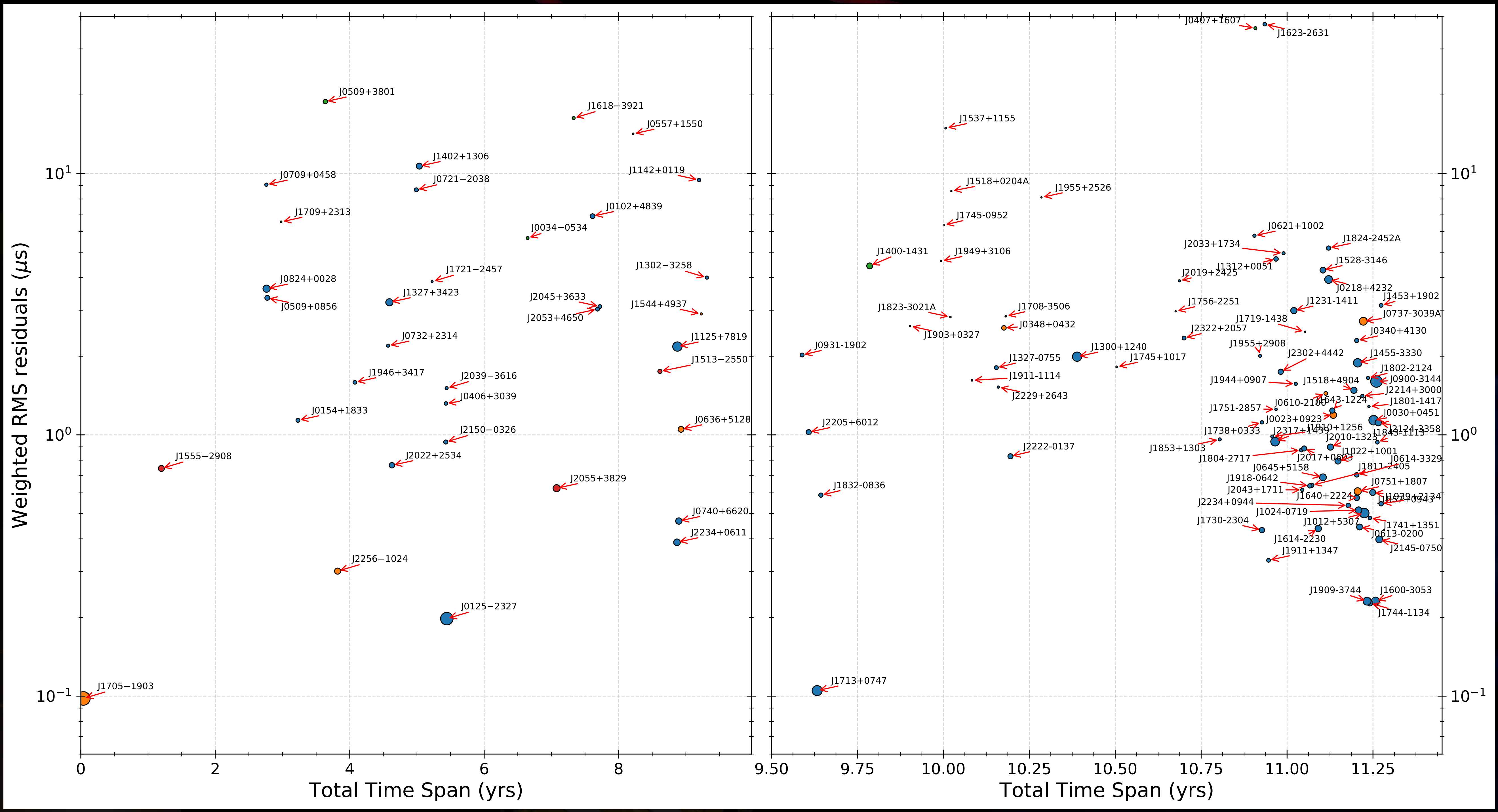


Pulsar timing

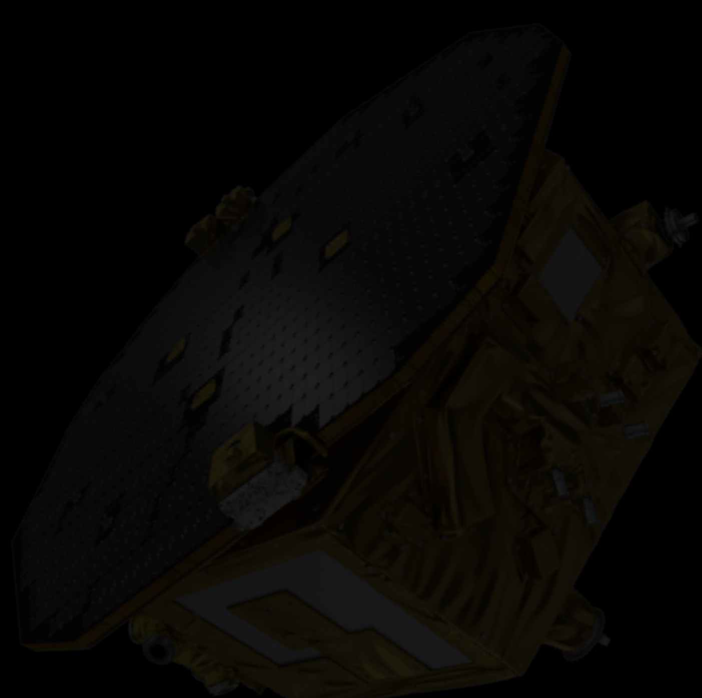
- Precise timing of arrival time of pulses => Time Of Arrival (TOA)
- One measurement point per observation (few minutes to few hours)
- Typically, one observation every week - every month
  => sampling cadence of the data (irregular)
- Very stable pulsars are milliseconds pulsars (MSPs)
- Timing with few tens nanoseconds precision
- More than 25 years of observation for some pulsars
- For example, Nançay Radio Telescope: 62 MSPs monitored with timing precison better than 2 μs and cadence better than 30 days

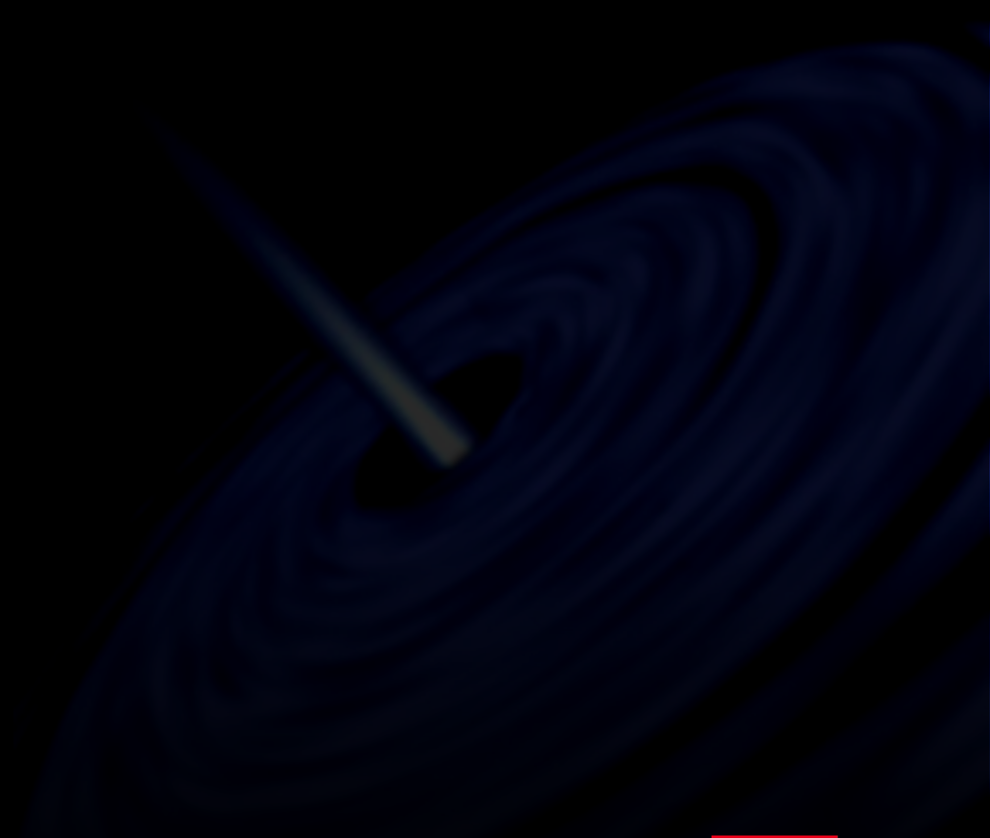
Pulsar timing

- Example: MSPs observed at Nançay



Pulsar timing





Pulsar timing

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Pulsar timing

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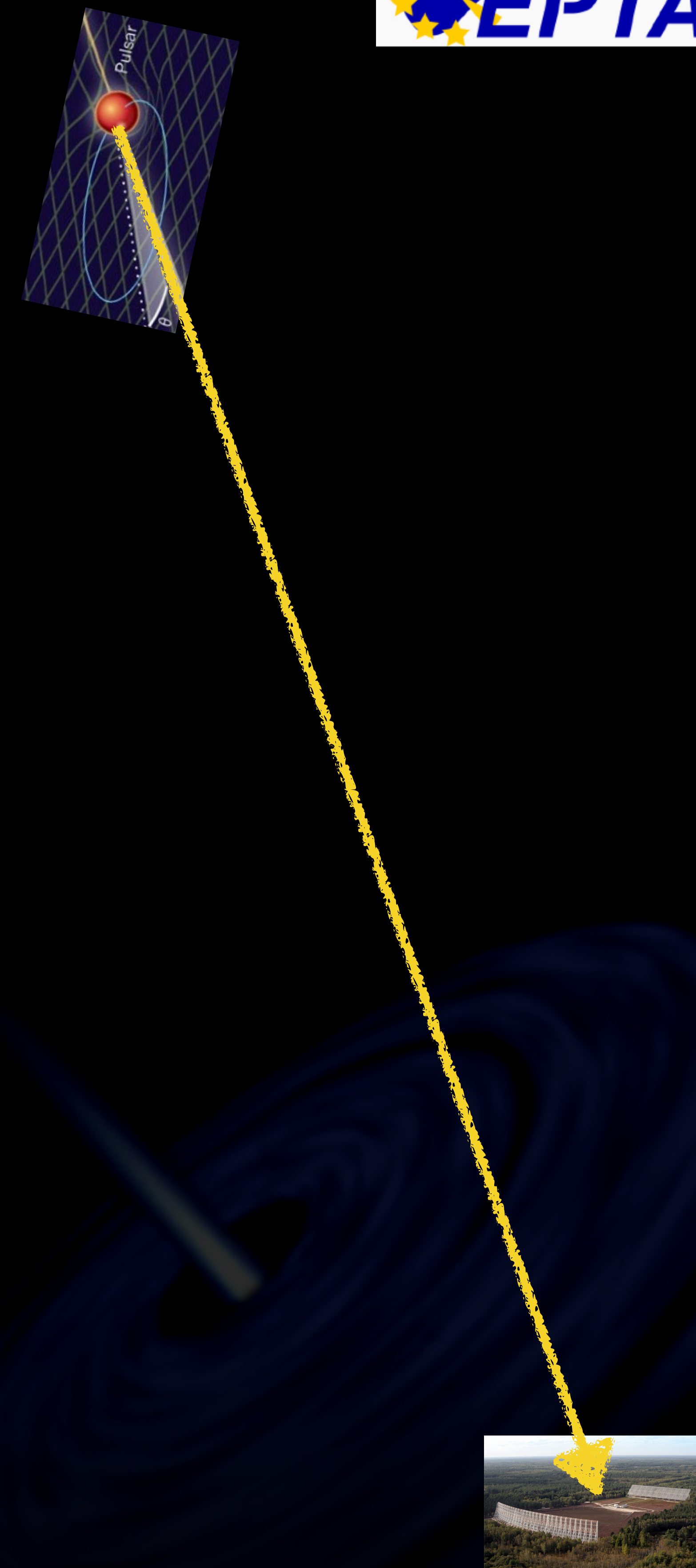
  - Pulsar itself:
    - period,
    - evolution of the period,
    - sky position



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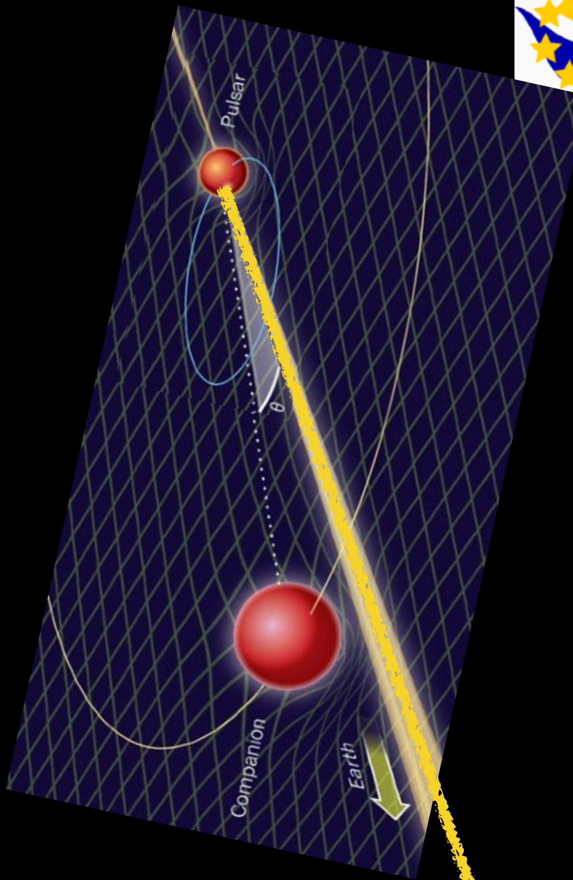

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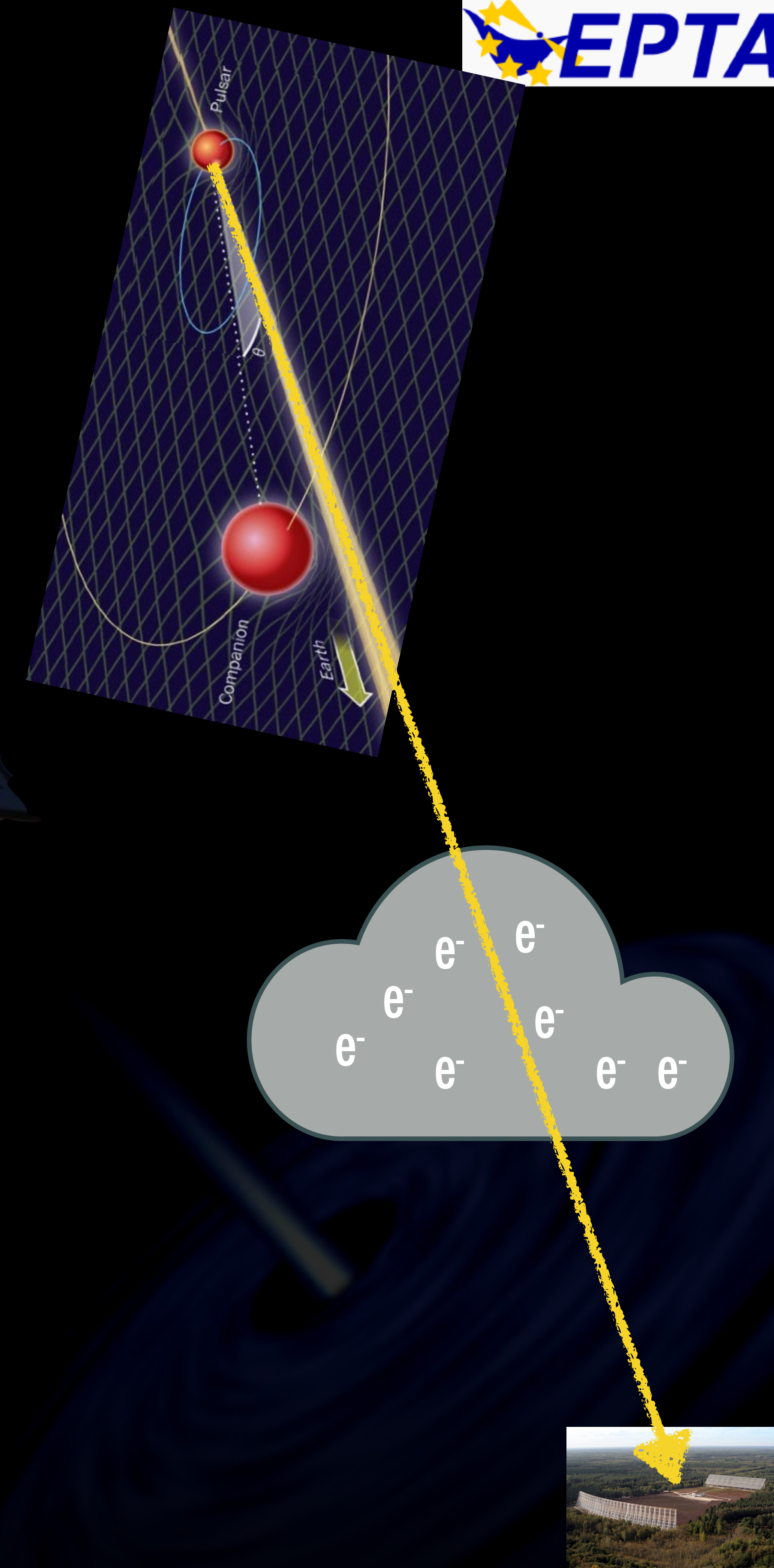

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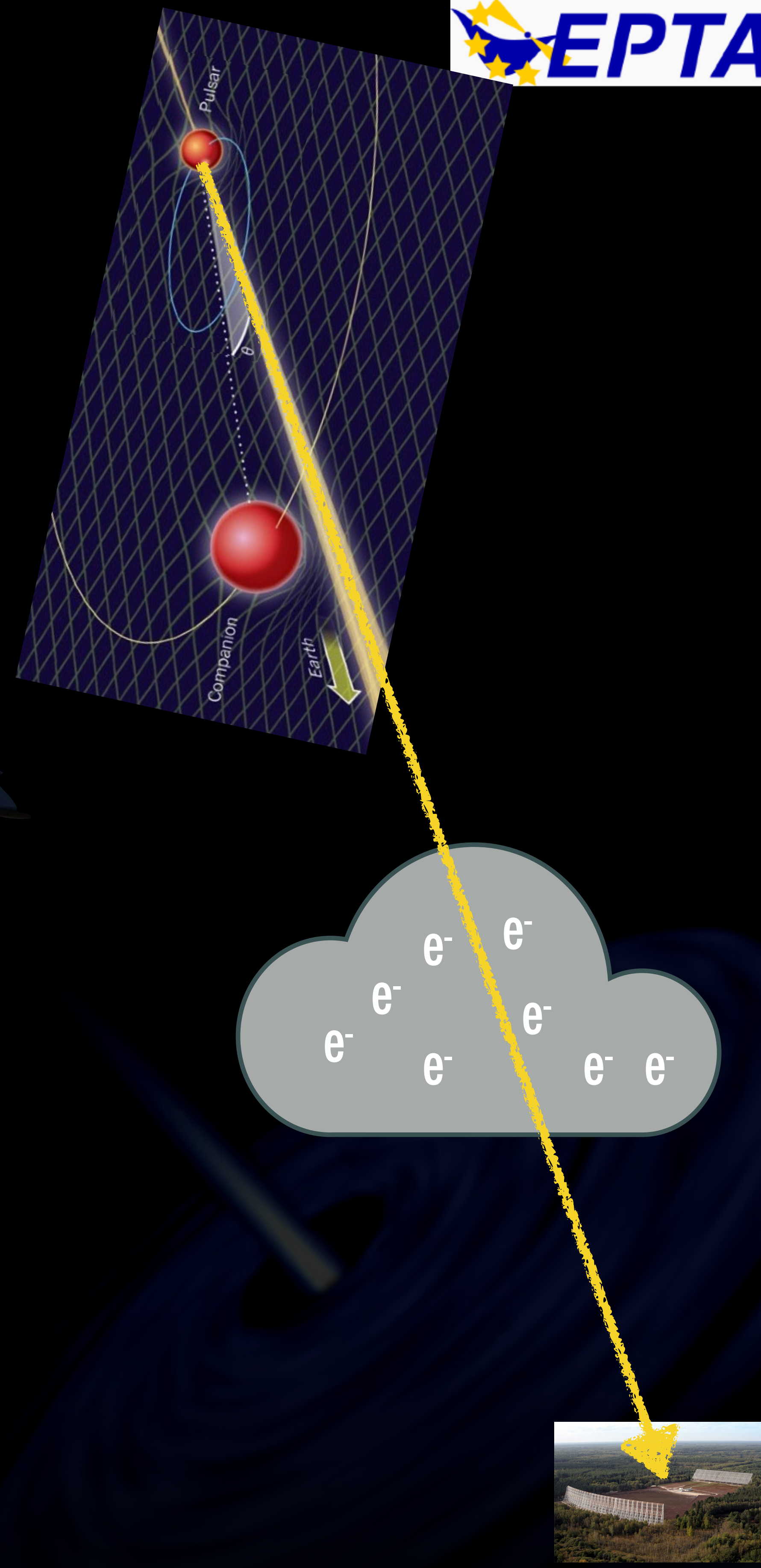

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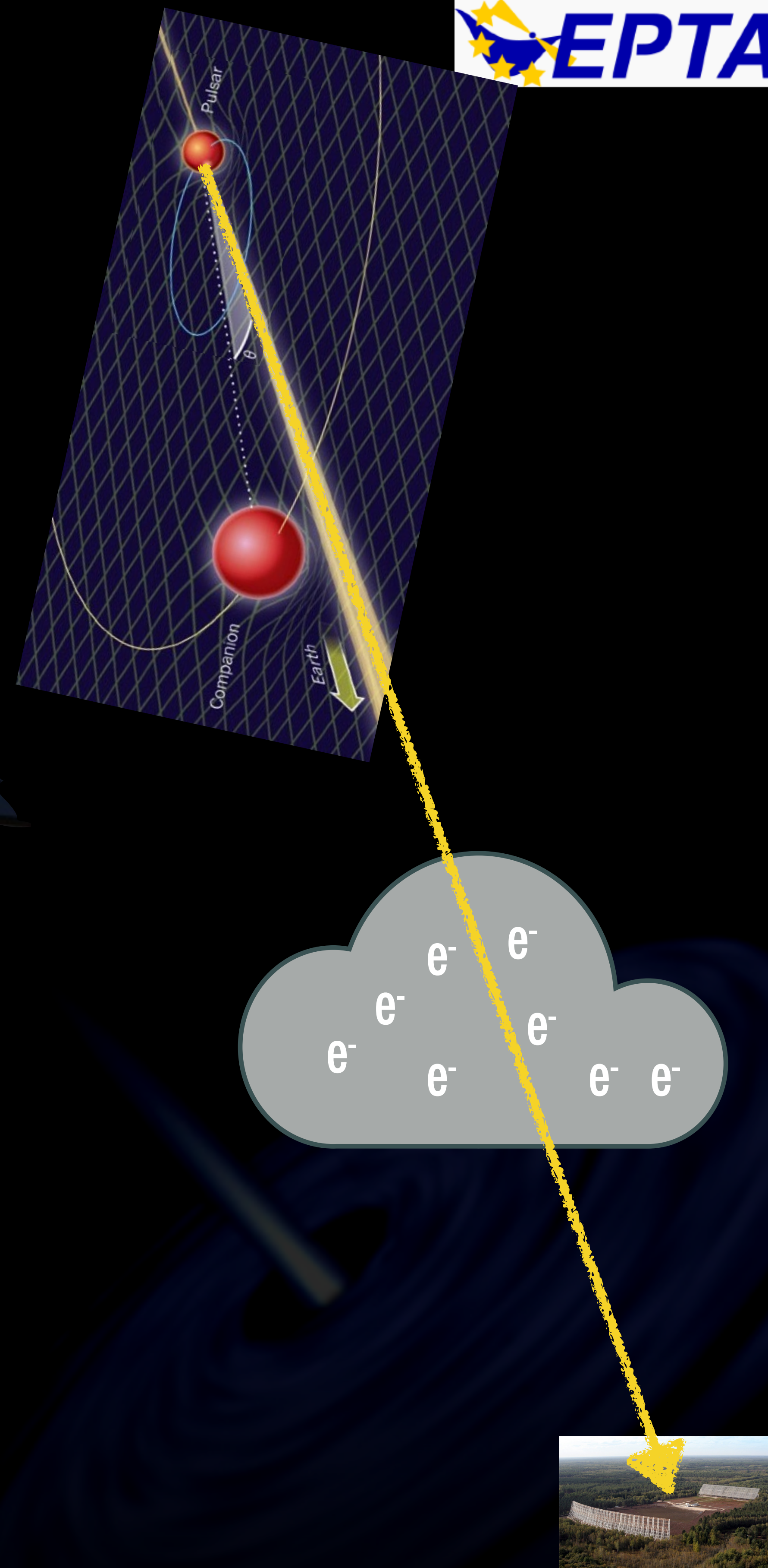
  - Gravitational waves …



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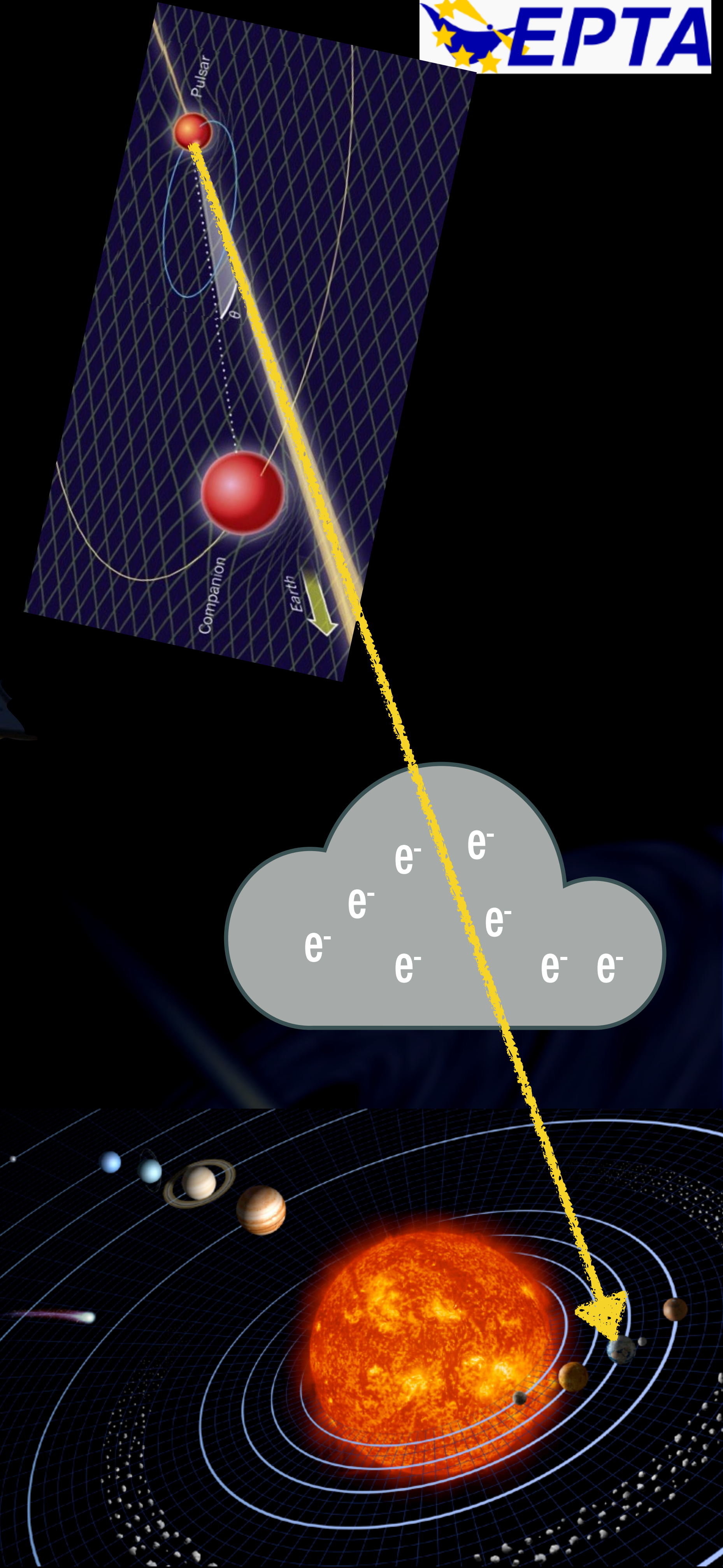
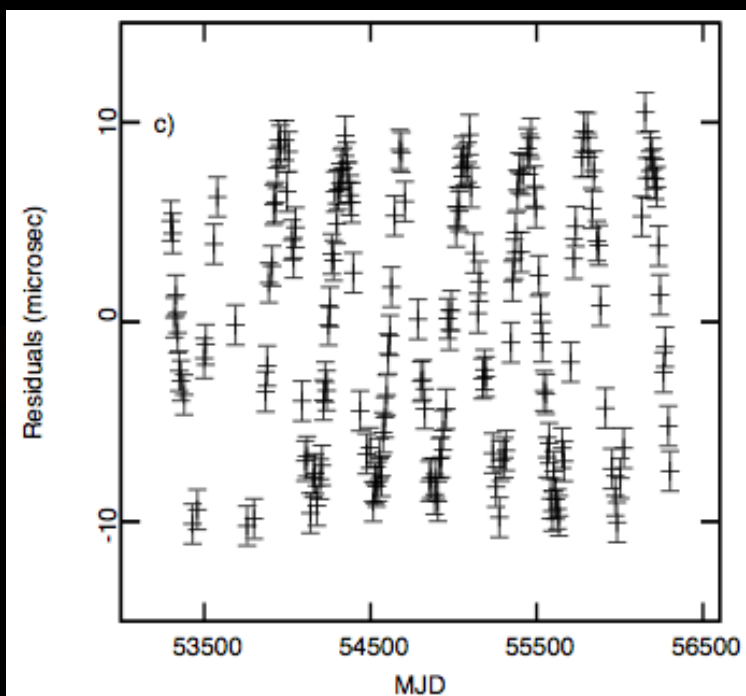
  - **Gravitational waves** ...
- Modelling of each pulsars

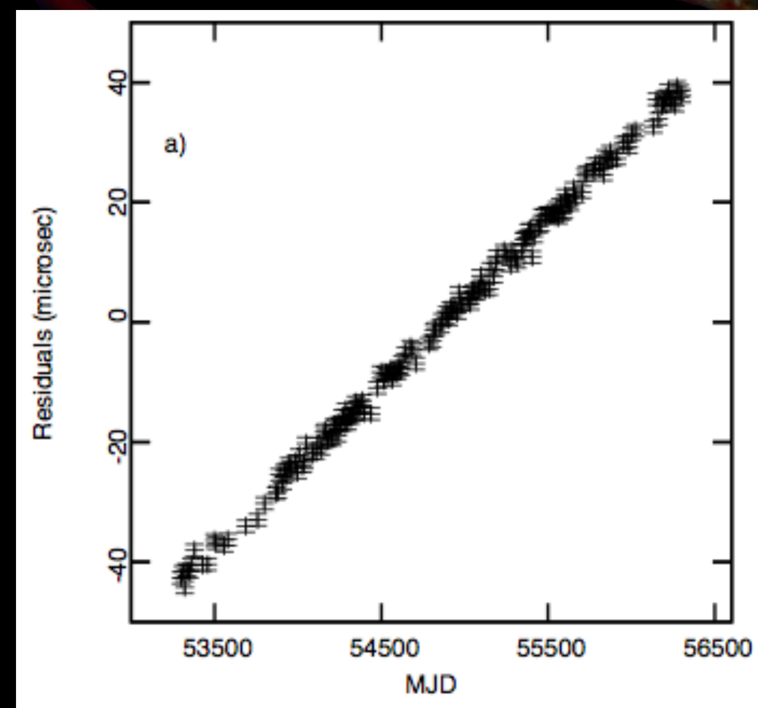


Pulsar timing

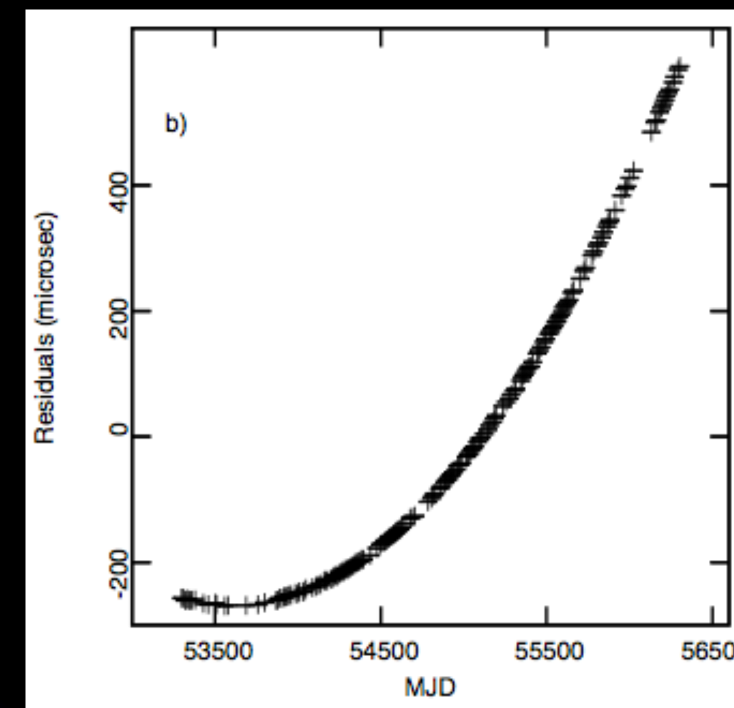
Error on sky position



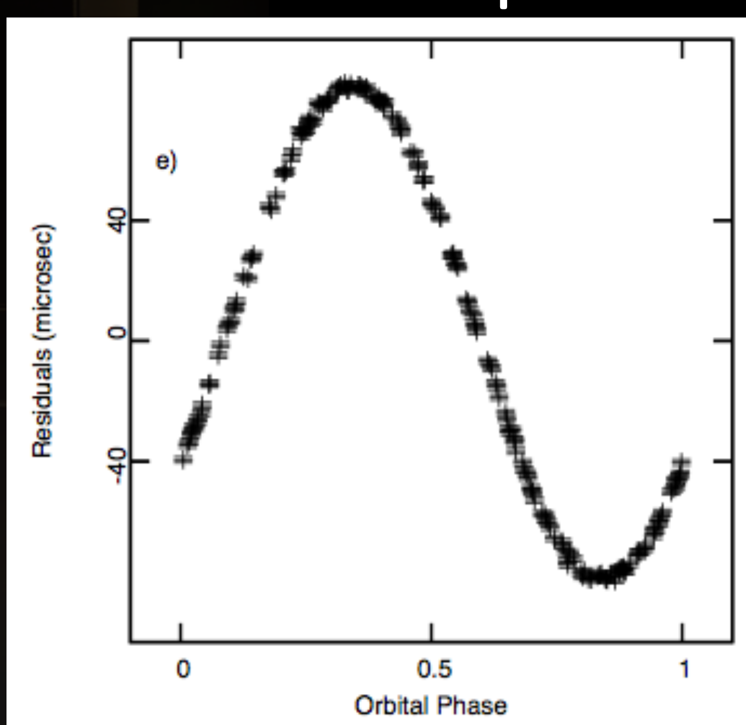
Error on period



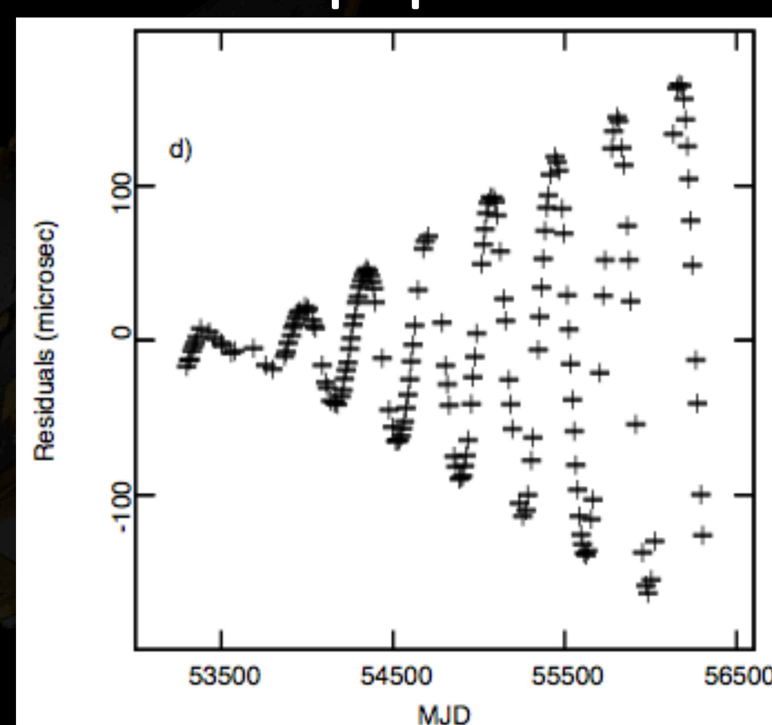
Error on period derivative



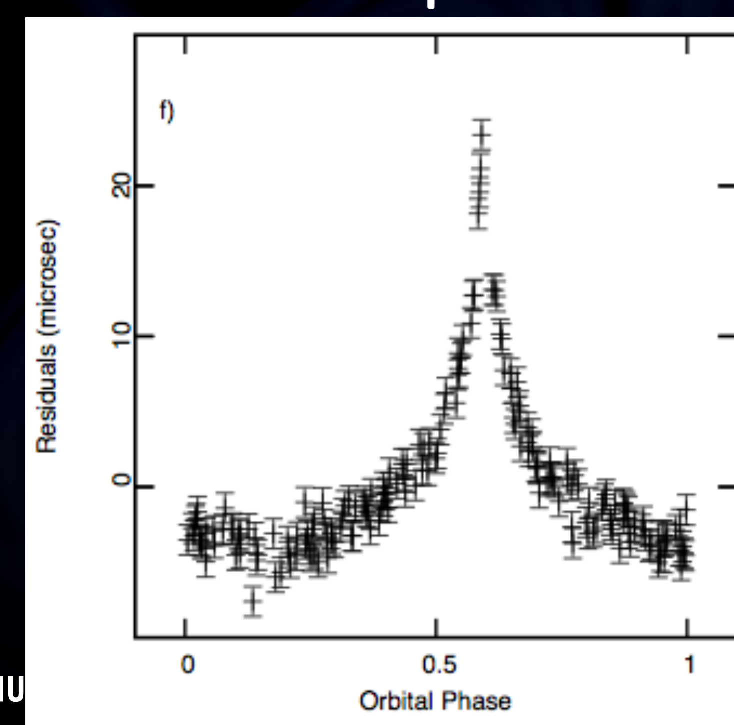
Error on orbital period



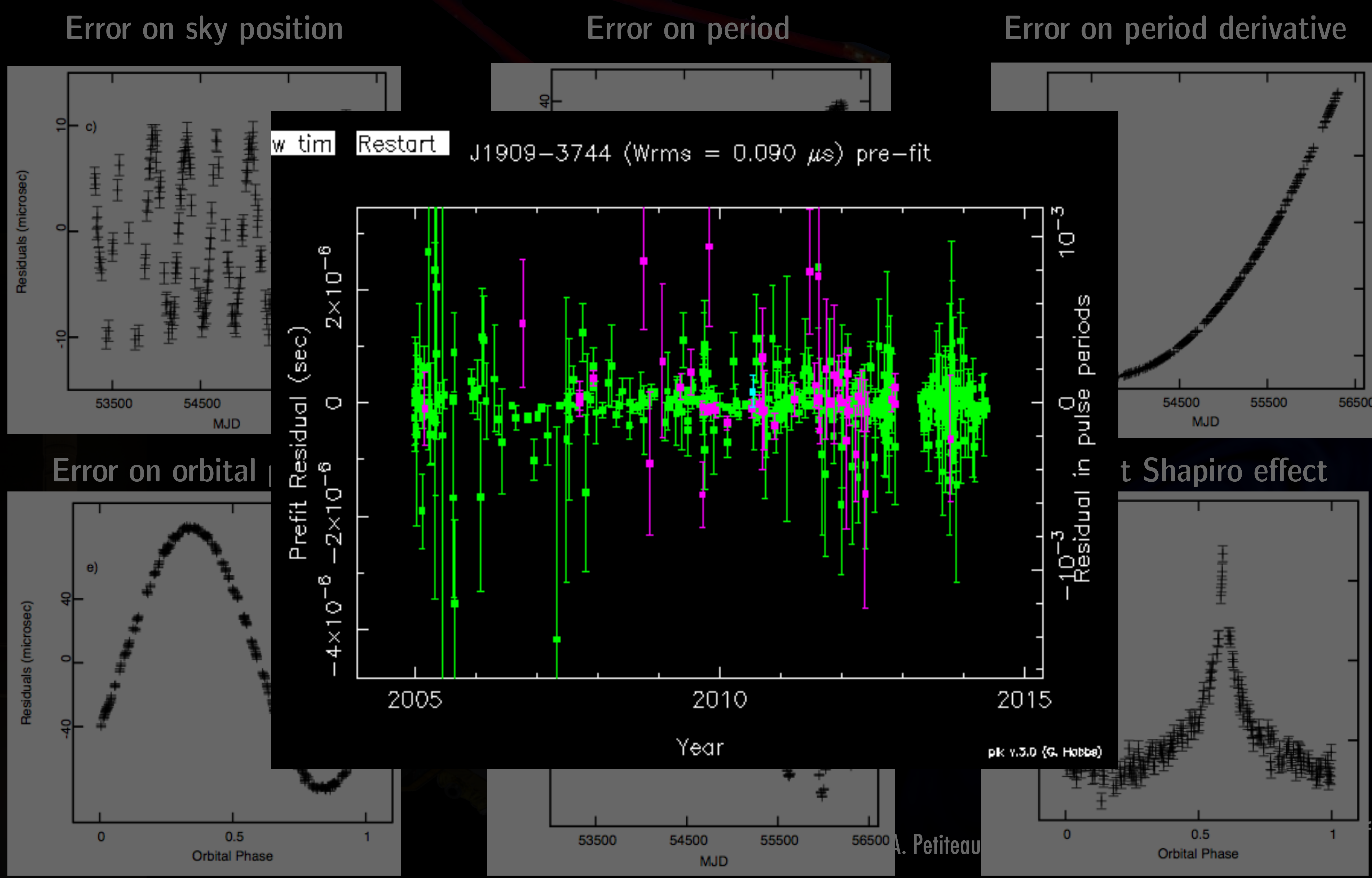
Error on proper motion



Without Shapiro effect



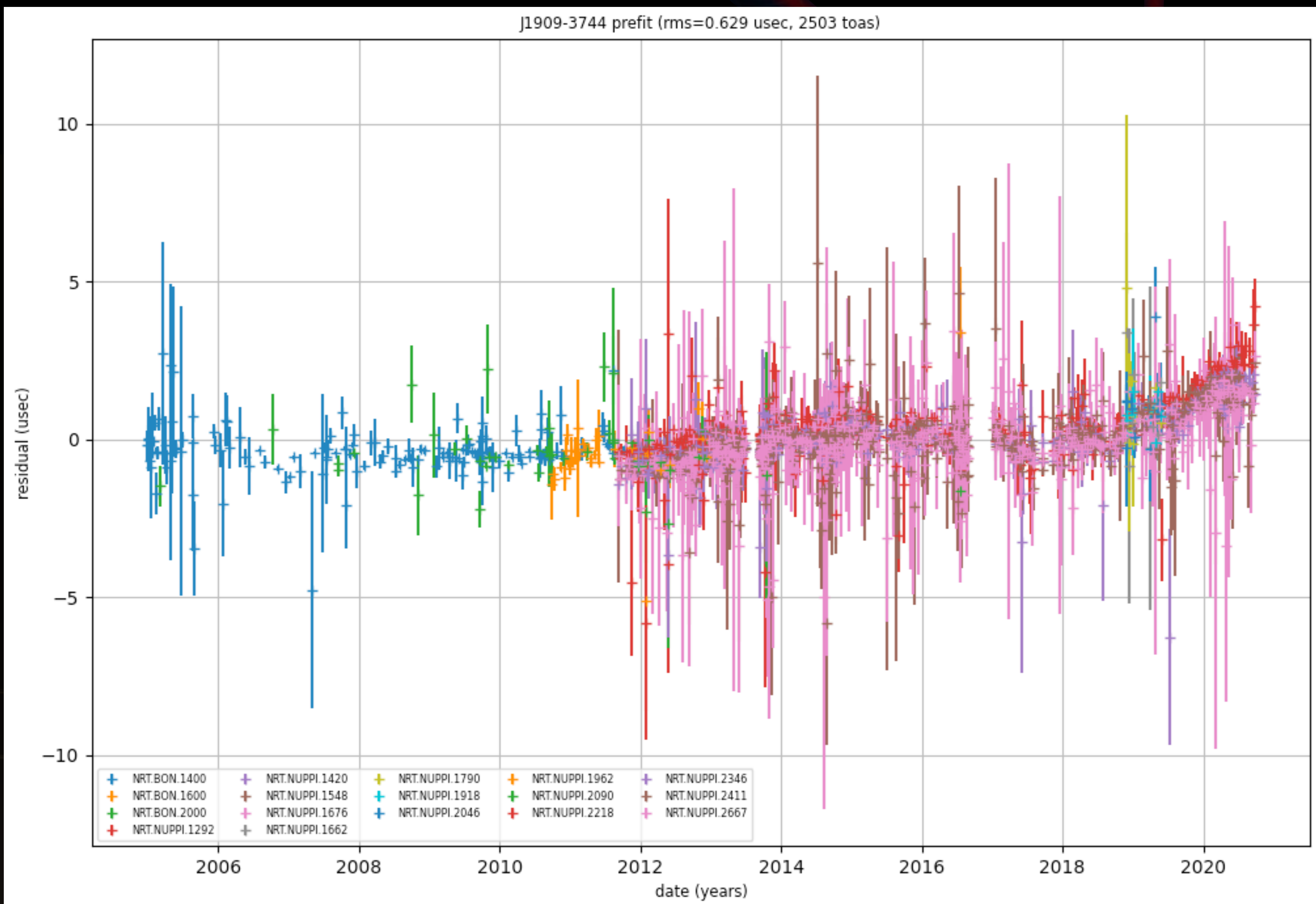
Pulsar timing



A. Petiteau

Pulsar timing

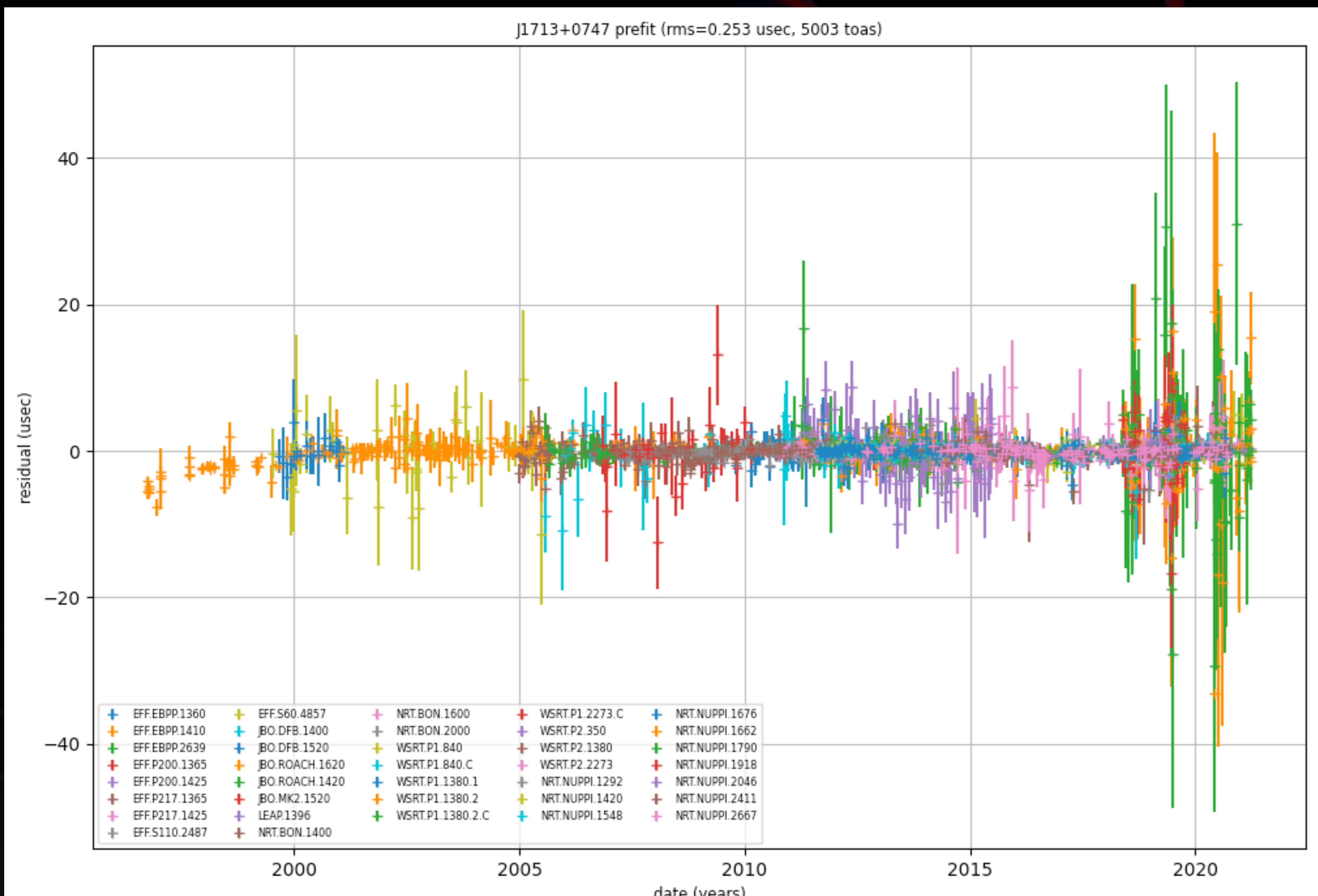
- Examples:
  - J1909-3744:



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 :
  - $\sigma^2_{\text{scaled}} = \boxed{\text{EFAC}^2} \times \sigma^2_{\text{original}} + \boxed{\text{EQUAD}^2}$, with $\sigma^2_{\text{original}}$ the original errorbars

+2

- Red noises:

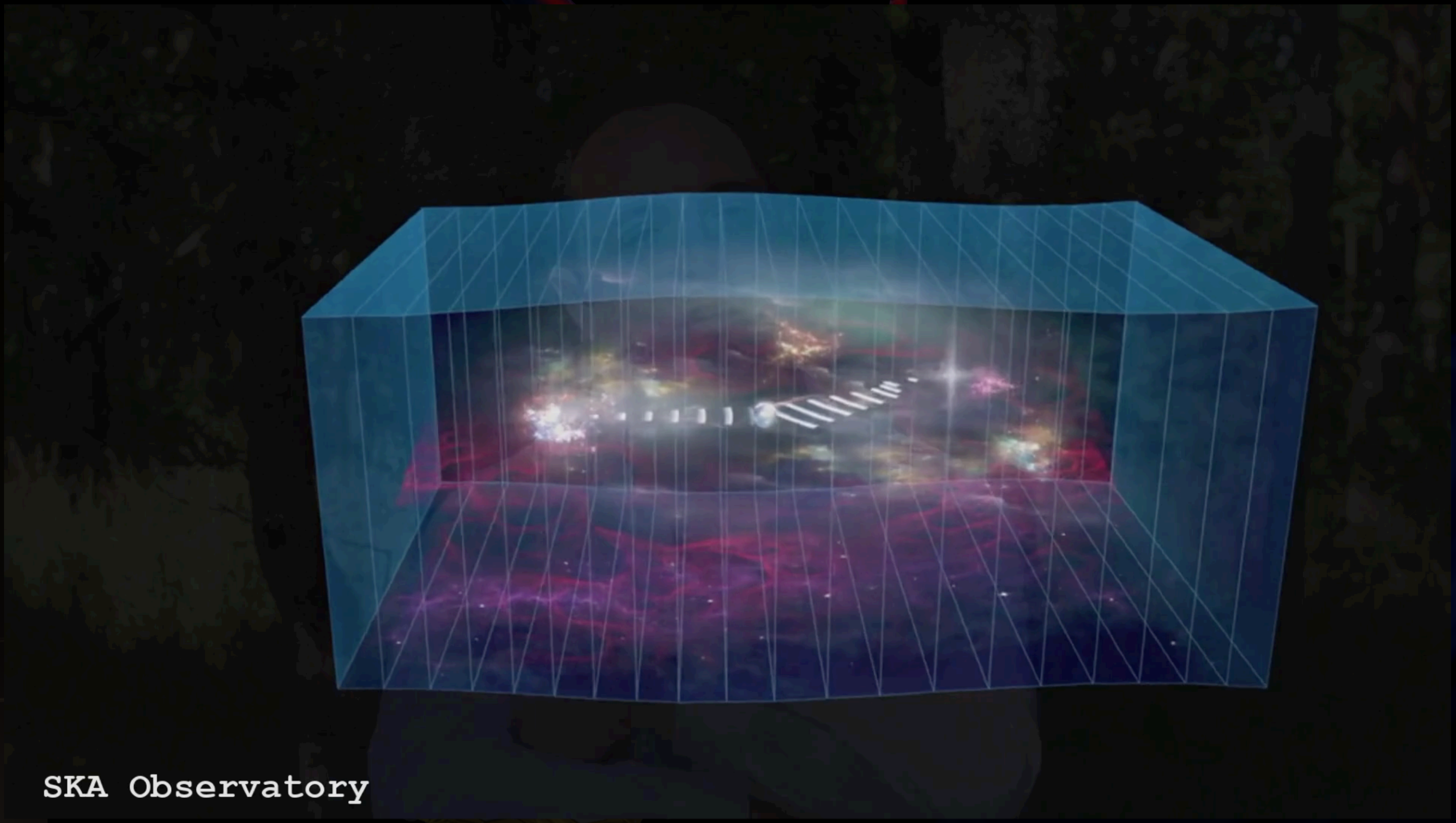
$$S_k = \frac{\boxed{A^2}}{12\pi^2} \frac{K_{scale}}{\nu^{-k}} \left(\frac{f}{1\text{yr}}\right)^{\boxed{-\gamma}} \frac{\text{yr}^3}{T_{span}}$$

with ν the observation frequency

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

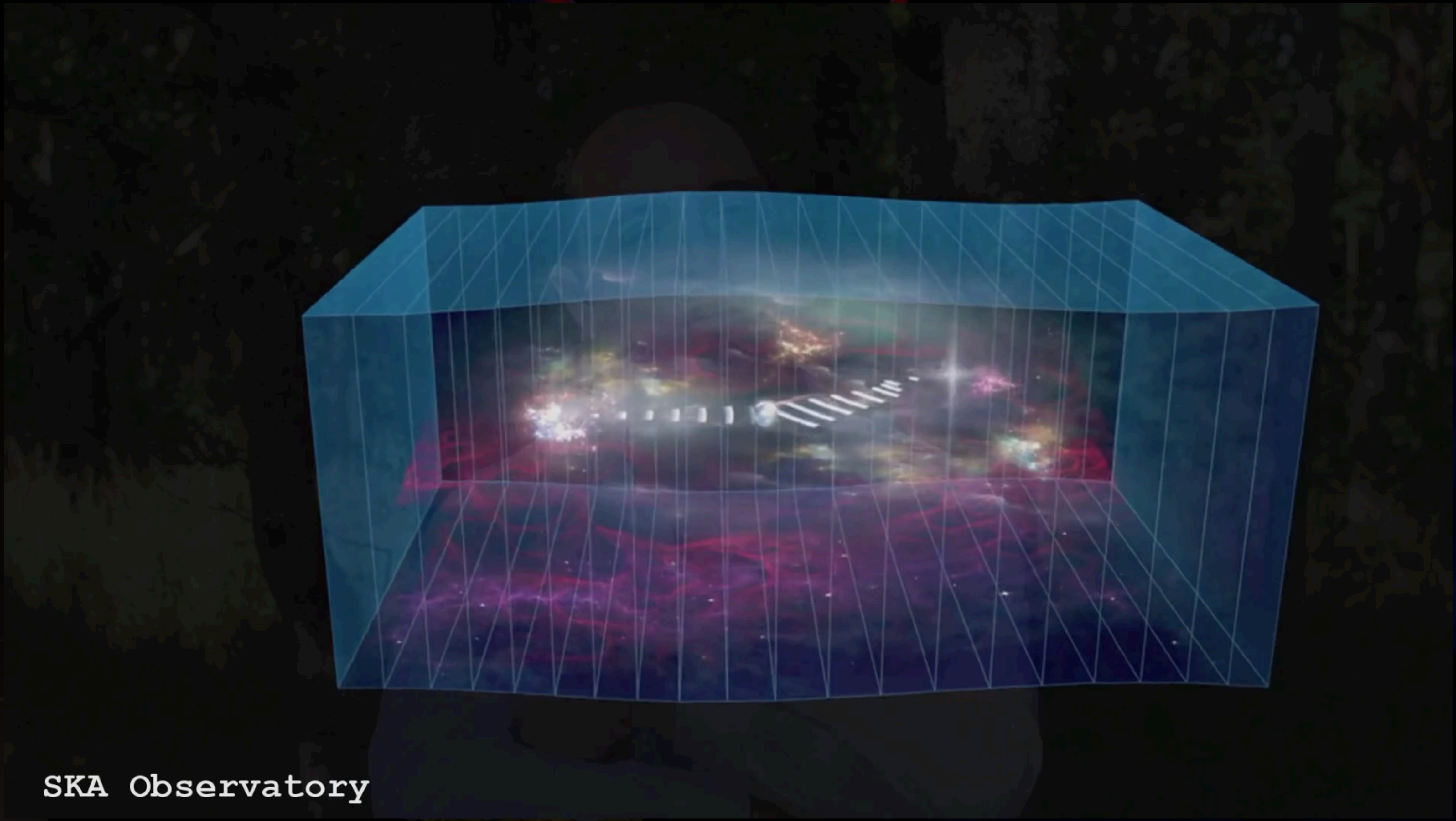
- Specific features for some pulsar: exponential dips

Pulsar timing and GWs

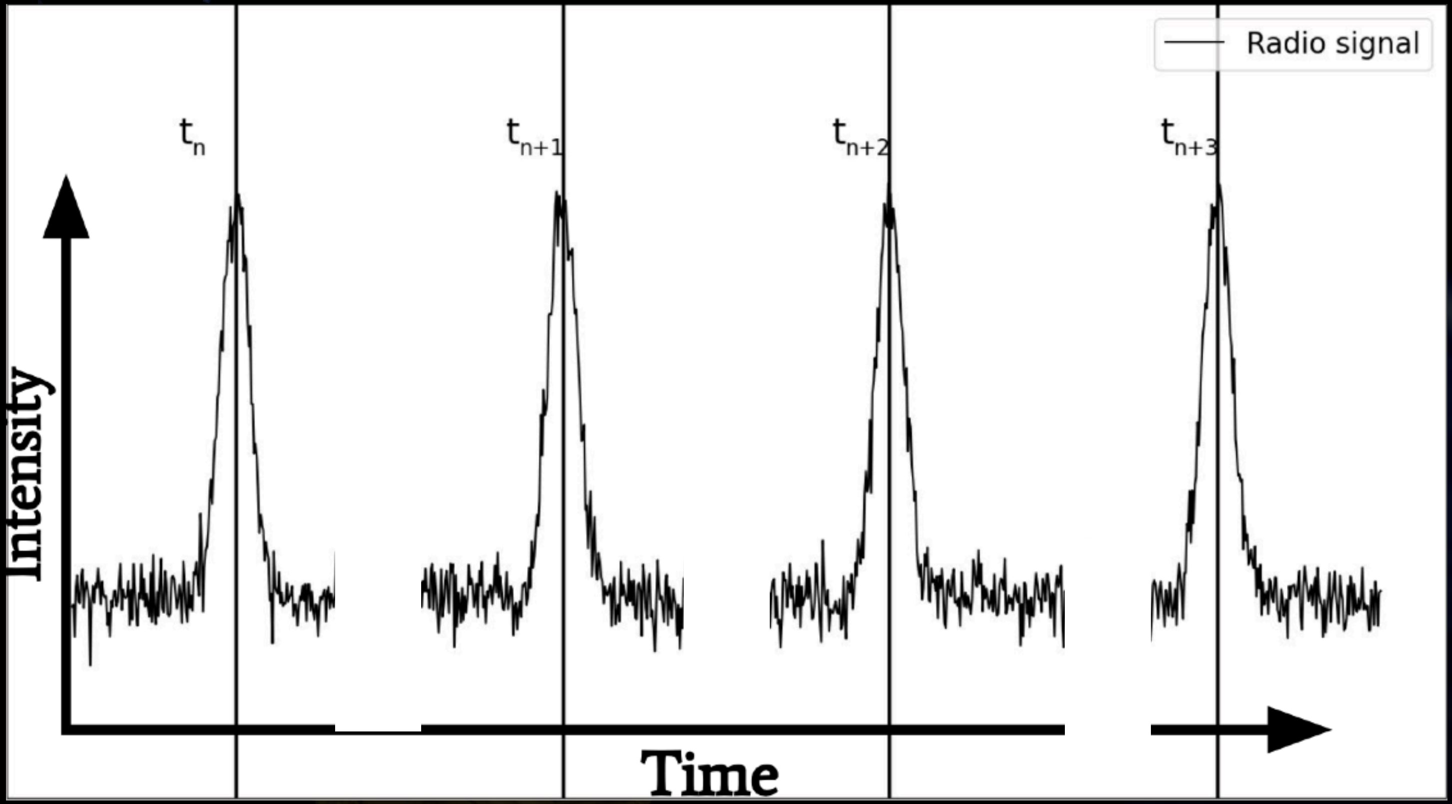


Pulsar timing and GWs

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



Pulsar timing and GWs



Pulsar timing and GWs

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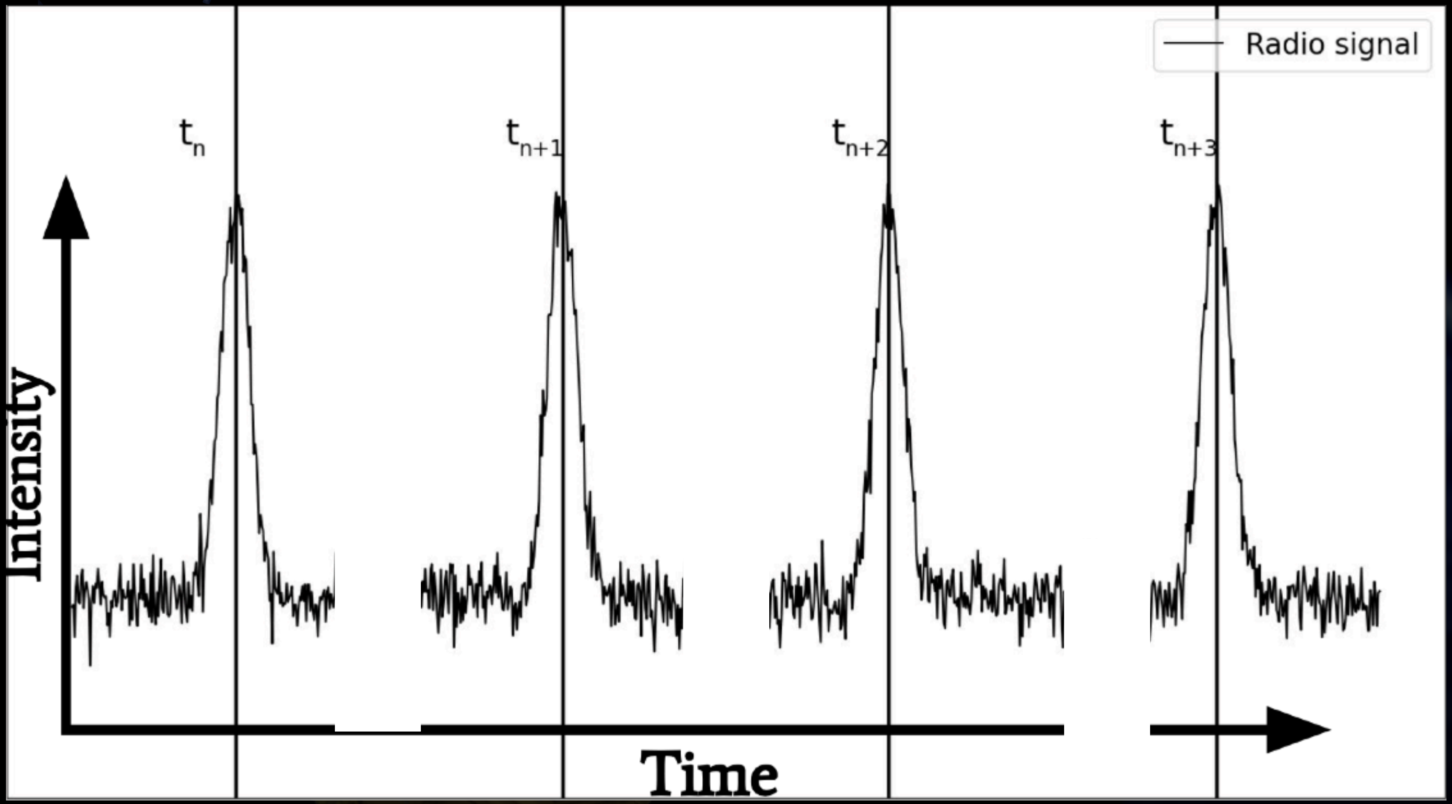
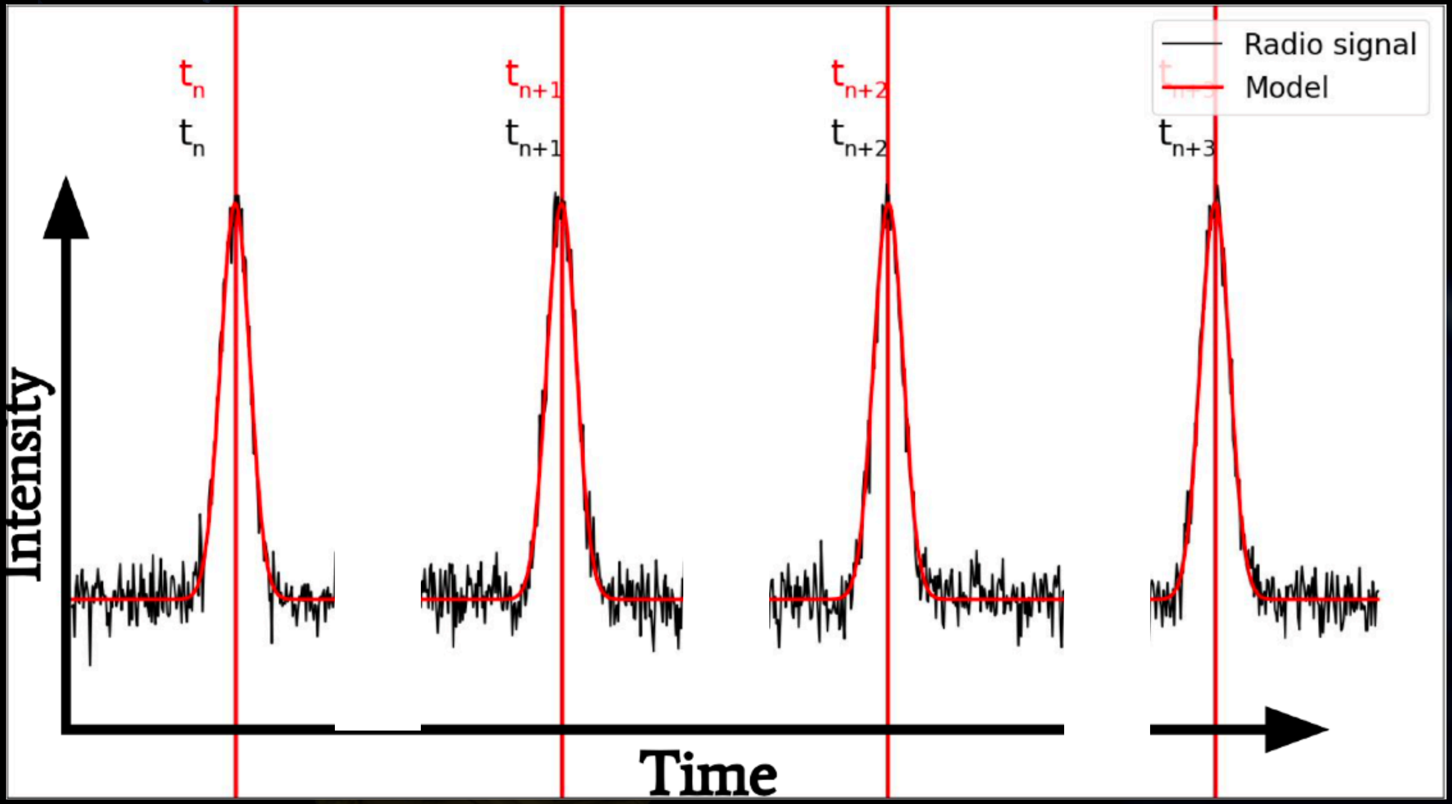


Pulsar timing and GWs

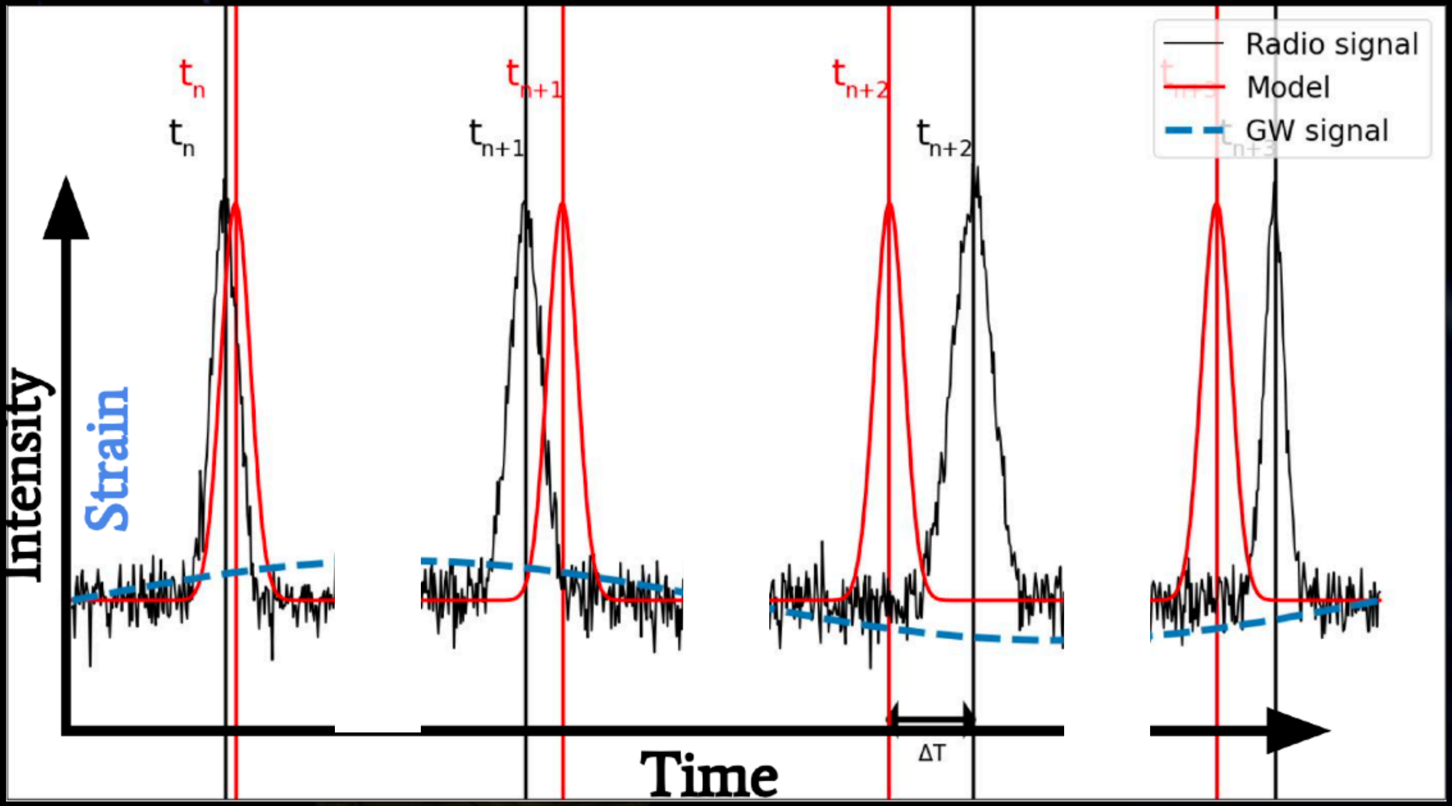
- When gravitational waves (GWs) are passing between pulsar and Earth, they will slightly modified the arrival time of pulses, i.e. the TOA
- We have a model for the TOA



Pulsar timing and GWs

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

=> GWs observed in the residuals = data - model



Pulsar timing and GWs

- GWs => correlated fluctuations in TOAs of multiple pulsars

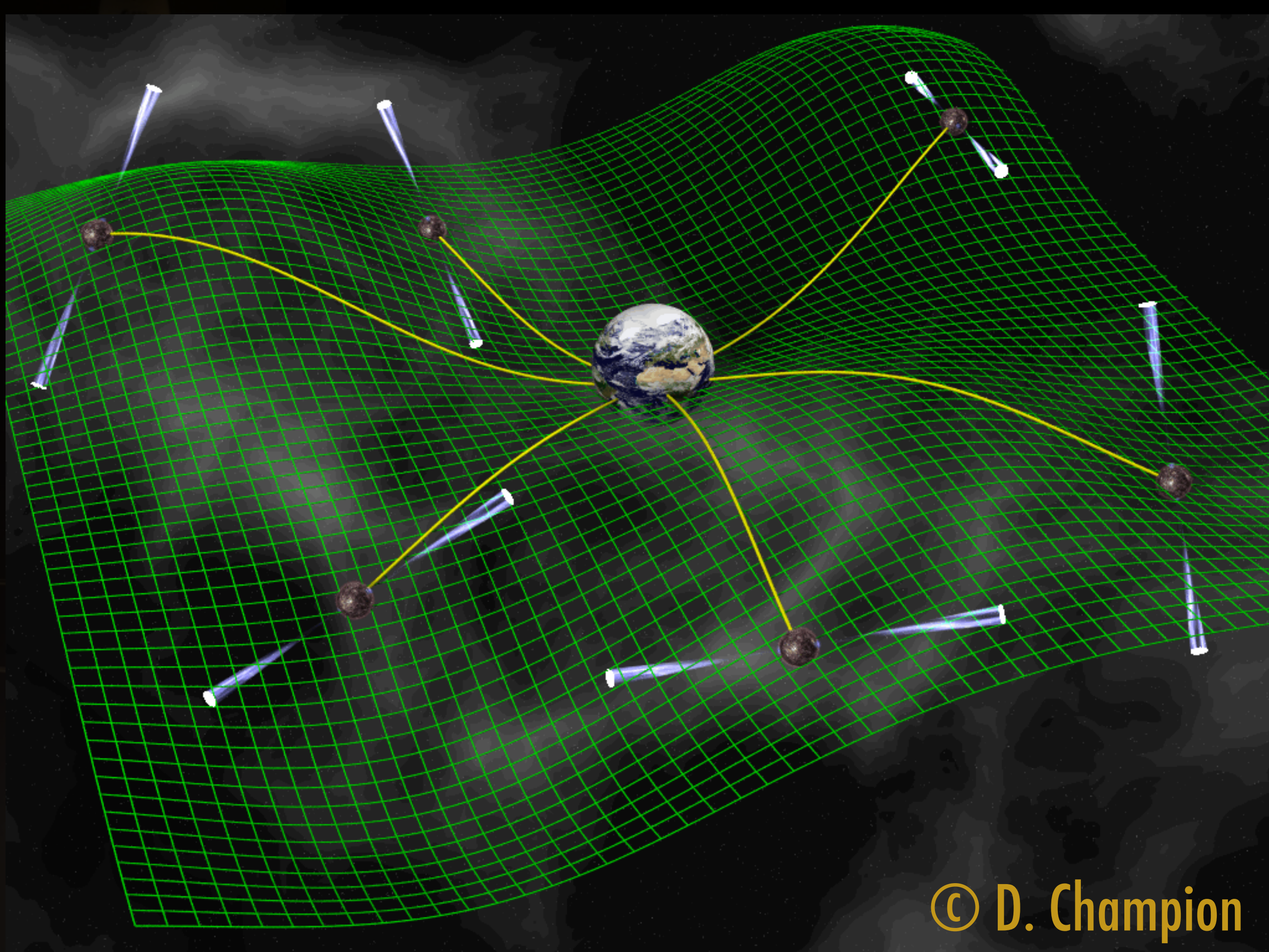
Observed & emitted pulsar spin frequency

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

Emission & reception times of pulses

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

Pulsar & GW source sky location


© D. Champion

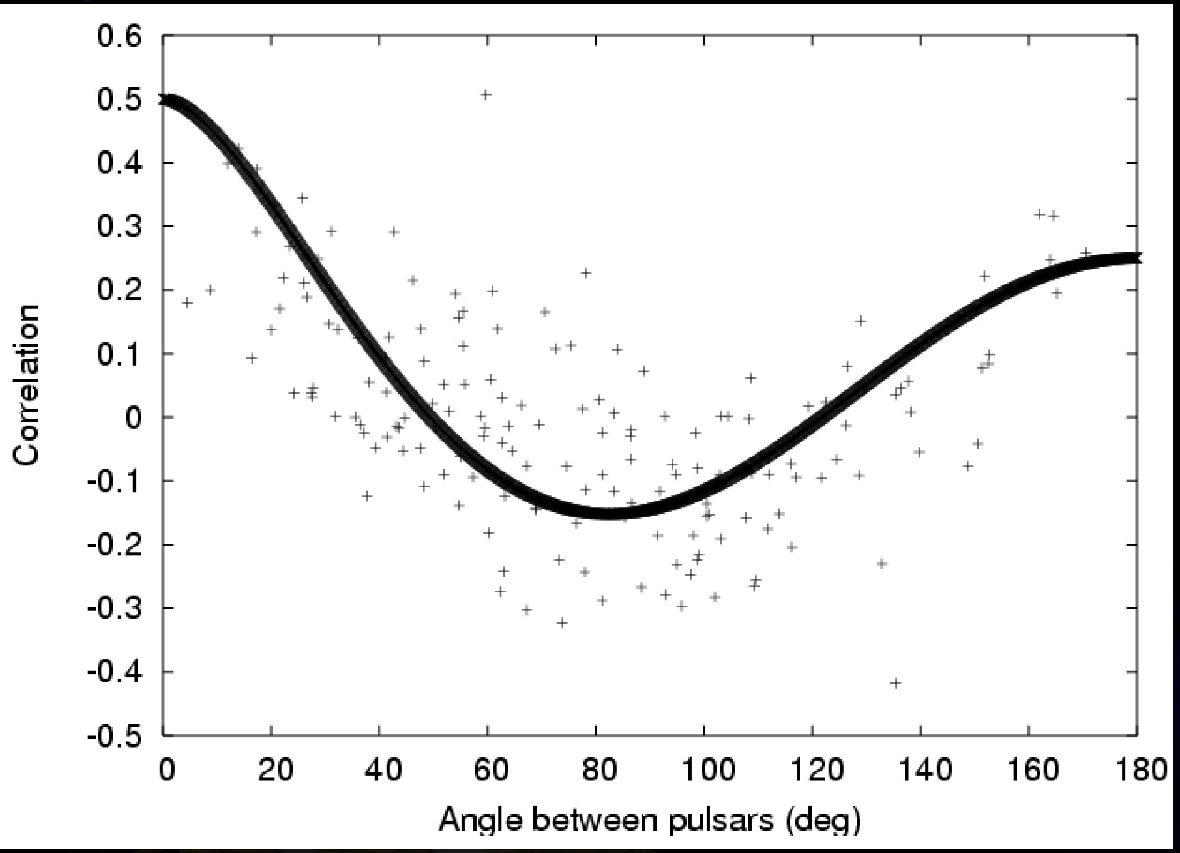
$$\Delta h_{ij} = h_{ij}(t_e) - h_{ij}(t_a)$$

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

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



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

EPTA

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

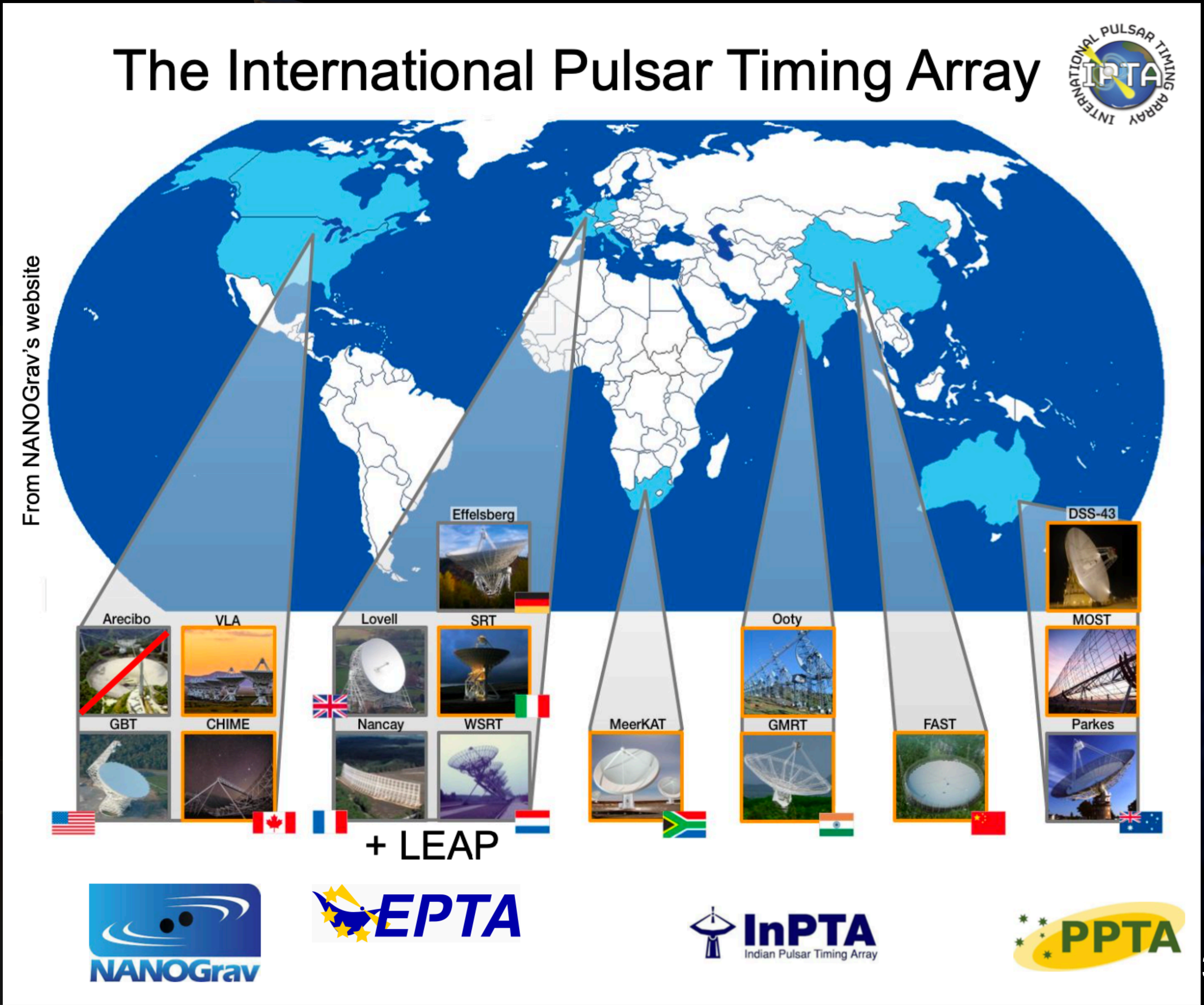
IPTA

- 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



EPTA data DR2

https://arxiv.org/abs/2306.16224

- 25 pulsars
- 25 years
- 5 radio telescopes
- 14 backends
- Observed frequencies from 300 MHz to 3 GHz

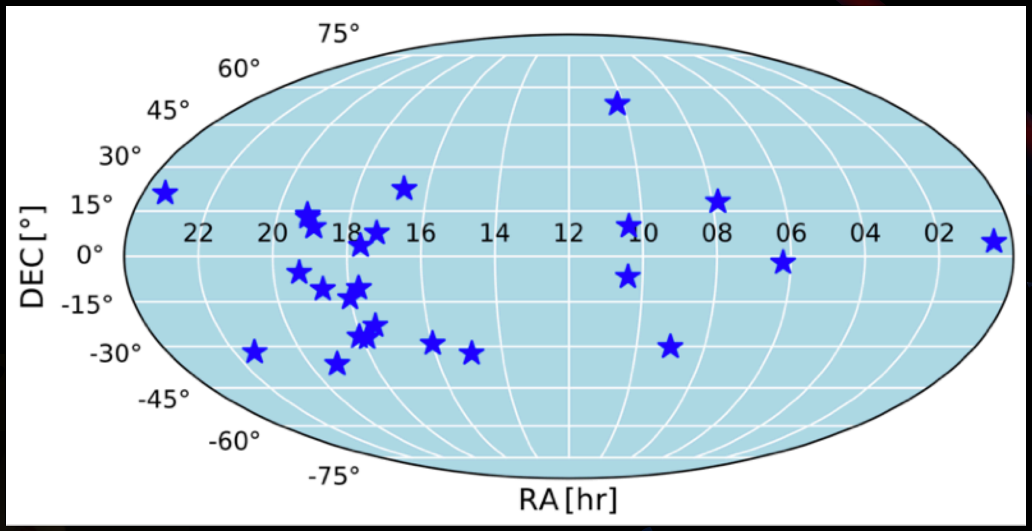
Telescope (Abbreviation)	Receiver or Backend	Centre Frequency (MHz)	Sub-bands (MHz)	Category	Polarisation
Effelsberg 100-m Radio Telescope (EFF)	EBPP	1360, 1410 and 2639	-	Legacy	Full Stokes
	P200	1380	1365 and 1425	Modern	Full Stokes
	P217	1380	1365 and 1425	Modern	Full Stokes
	S110	2487	-	Modern	Full Stokes
	S60	4857	-	Modern	Full Stokes
Jodrell Bank Observatory (JBO)					
+ Lovell Telescope	DFB	1400 and 1520	-	Legacy	Full Stokes
	ROACH	1520	1420 and 1620	Modern	Full Stokes
+ Mark II	MK2	1520	-	Modern	Full Stokes
Nançay Radio Telescope (NRT)	BON	1400, 1600 and 2000	-	Legacy	Full Stokes
	NUPPI	1484, 1854, 2154 and 2539	1292, 1420, 1548 and 1676; 1662, 1790, 1918 and 2046; 1962, 2090, 2218 and 2346; 2411 and 2667	Modern	Full Stokes
Westerbork Synthesis Radio Telescope (WSRT)	PuMaI	323, 328, 367, 382, 840, 1380 and 2273	-	Legacy	Dual
	PuMaII	350, 1380 and 2273	-	Modern	Full Stokes
The Large European Array for Pulsars (LEAP)	LEAP	1396	-	Modern	
Sardinia Radio Telescope (SRT)†	ROACH	357 and 1396	-	Modern	-

† Data from SRT were only included as part of the LEAP mode of observations for this data release.

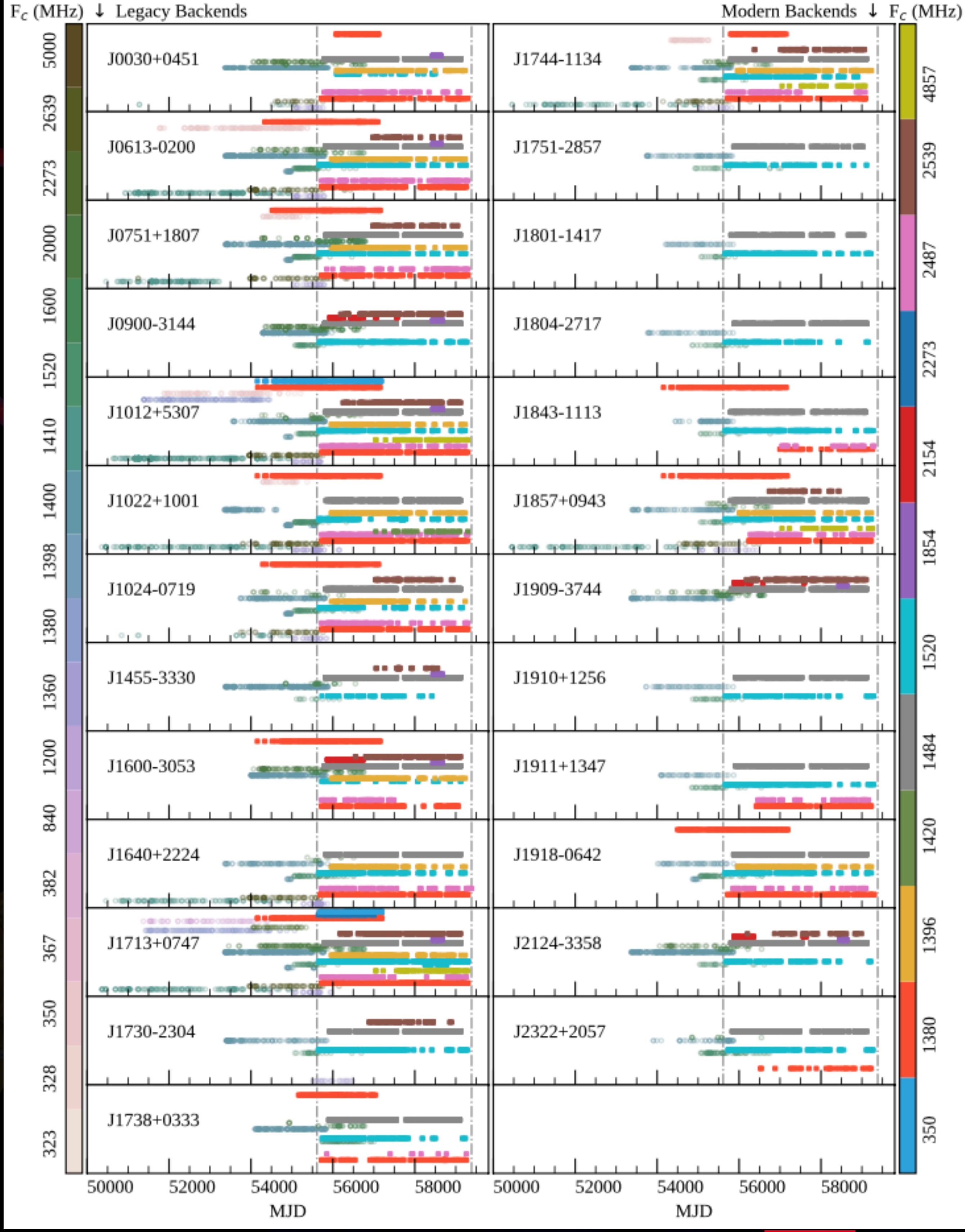
- Raw data = observations:
  - Output of the coherent dedispersion system
  - Time evolution of the 4 stokes values in multiple frequency channels (for Nançay, band of 4 MHz)

EPTA data DR2

- 25 pulsars



Pulsar Jname	Telescopes	MJD range	T_{span} (yr)	N_{TOA}	Median σ_{TOA} (μs) P	L	S	C	wrms (μs)	wrms, whitened (μs)
J0030+0451	EFF, LT, NRT, WSRT, LEAP	51275–59294	22.0	4069	—	3.40	6.07	—	2.85	2.30
J0613−0200*	EFF, LT, NRT, WSRT, LEAP	50931–59293	22.9	2909	7.40	1.43	6.16	—	2.47	1.06
J0751+1807*	EFF, LT, NRT, WSRT, LEAP	50460–59294	24.2	3613	—	2.22	4.43	—	2.12	1.50
J0900−3144	LT, NRT	54286–59269	13.6	6064	—	2.95	8.92	—	4.28	2.60
J1012+5307*	EFF, LT, NRT, WSRT, LEAP	50647–59295	23.7	5325	3.77	1.76	5.59	4.78	1.28	1.02
J1022+1001*	EFF, LT, NRT, WSRT, LEAP	50361–59294	24.5	2445	11.3	2.19	4.42	2.99	1.78	1.56
J1024−0719	EFF, LT, NRT, WSRT, LEAP	50841–59294	23.1	2522	—	2.38	7.64	—	1.10	1.02
J1455−3330	LT, NRT	53375–59117	15.7	2815	—	7.23	17.8	—	2.52	2.46
J1600−3053*	EFF, LT, NRT, WSRT, LEAP	53998–59230	14.3	2982	—	0.48	1.50	—	2.68	0.37
J1640+2224	EFF, LT, NRT, WSRT, LEAP	50459–59385	24.4	2006	—	3.57	7.65	—	1.13	1.10
J1713+0747*	EFF, LT, NRT, WSRT, LEAP	50360–59295	24.5	5003	3.13	0.32	0.54	0.67	0.43	0.20
J1730−2304	EFF, LT, NRT	53397–59279	16.1	1315	—	1.57	7.26	—	1.00	0.83
J1738+0333	EFF, LT, NRT, WSRT	54103–59259	14.1	1019	—	4.31	—	—	2.90	2.33
J1744−1134*	EFF, LT, NRT, WSRT, LEAP	50460–59230	24.0	1946	3.60	0.90	2.29	1.15	1.01	0.56
J1751−2857	LT, NRT	53746–59111	14.7	398	—	3.17	—	—	3.73	2.34
J1801−1417	LT, NRT	54206–59214	13.7	449	—	4.09	—	—	3.94	2.46
J1804−2717	LT, NRT	53766–59145	14.7	723	—	5.94	—	—	1.80	1.63
J1843−1113	EFF, LT, NRT, WSRT	53156–59293	16.8	893	—	1.37	2.64	—	3.47	0.81
J1857+0943*	EFF, LT, NRT, WSRT, LEAP	50458–59258	24.1	1540	—	1.70	4.05	6.85	1.38	1.05
J1909−3744*	NRT	53368–59115	15.7	2503	—	0.29	0.57	—	0.73	0.14
J1910+1256	LT, NRT	53725–59282	15.2	538	—	2.65	—	—	2.03	1.77
J1911+1347	EFF, LT, NRT	54095–59282	14.2	882	—	1.22	1.36	—	1.06	0.75
J1918−0642	EFF, LT, NRT, WSRT, LEAP	52095–59294	19.7	1361	—	2.04	4.14	—	1.78	1.31
J2124−3358*	LT, NRT	53365–59213	16.0	2018	—	3.70	12.6	—	2.24	2.17
J2322+2057	EFF, LT, NRT	53905–59268	14.7	804	—	10.9	—	—	4.08	4.08



EPTA data analysis

- Ideally, we would like to go from raw data to parameters directly but too heavy (too much data, too many parameters).
- Analysis done by steps:
  1. Construct one or several TOAs per observation:
     a. Folding in time and frequency to obtain one profile
     b. Compare to a template profile to obtain the reference time for the observation = TOA
        * For high SNR pulsar can be done in multiple frequency bands
  2. For each pulsars using all TOAs collected:
     a. Estimate the pulsar timing parameters with the pulsar model
     b. Identify the best noise model with its parameters
  3. Using all pulsars with their timing parameters and noise model, search for correlated signals putting constraints on spectral parameters and spatial correlations.

EPTA data analysis

- Multiple noise sources => single pulsar noise 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

EPTA data analysis

https://arxiv.org/abs/2306.16225

- For single pulsar analysis:
  - Gaussian likelihood
  - Bayes factor estimation to compare models
  - Red Noise, DM variations and scattering variations:
    - described as stationary Gaussian processes, following the Fourier-sum with a discrete and finite set of sine/cosine basis functions and a power-law power spectral density (PSD);
    - Set of frequencies for each Gaussian process is chosen linearly distributed $1/T_{span}, 2/T_{span}, \ldots N_{coef}/T_{span}$
    - N_{coef} is a free parameters (transition red noise - white noise)

EPTA data analysis

https://arxiv.org/abs/2306.16214

- For correlated signal analysis (GWB):
  - For spectral parameters constraints:
    - Similar to single pulsar analysis
    - Many parameters to estimate (about 200): GWB parameters + noises parameters of all pulsars
  - For spatial correlation constraints:
    - Search for generic spatial correlations and compare against expected HD curves
    - Several methods

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

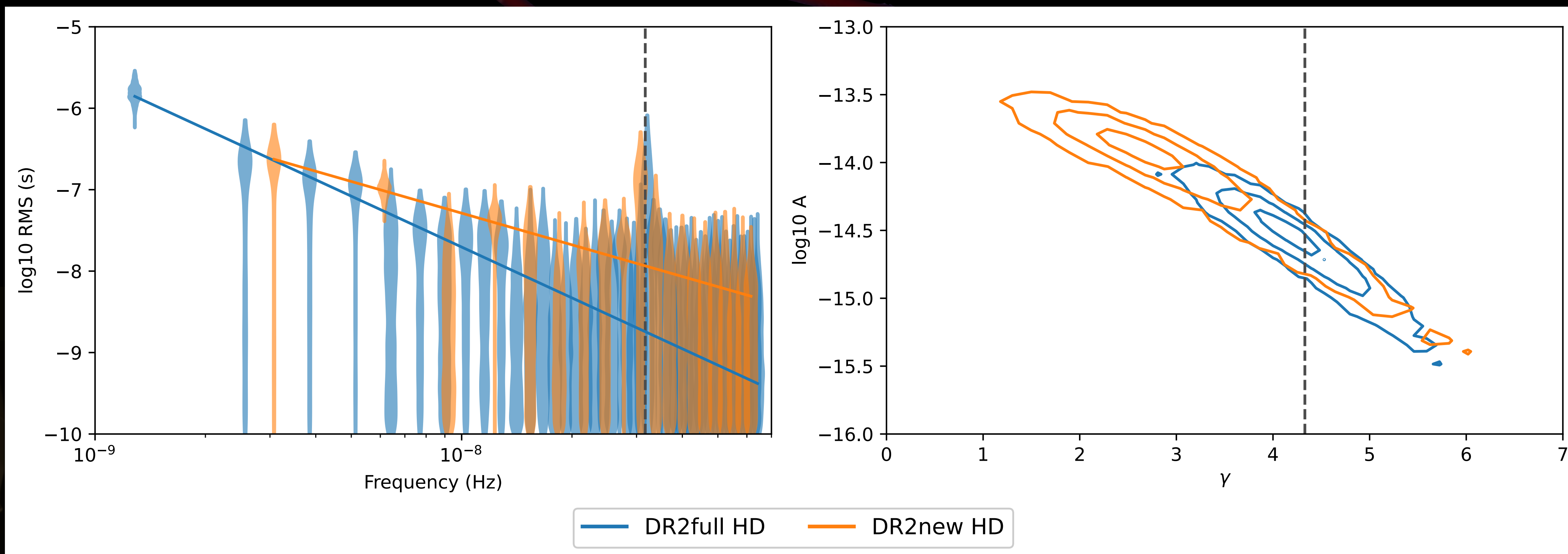
- Acronyms:
  - PSRN: Pulsar noise
  - CURN: Common Uncorrelated Red Noise
  - CLK: Clock Noise (monopole)
  - EPH: Solar system ephemeris (dipole)

- 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

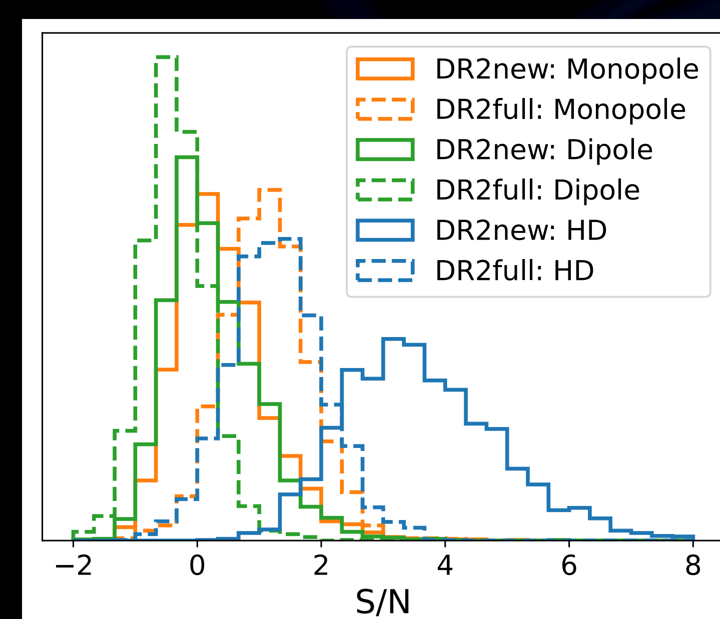
EPTA results: GWB

https://arxiv.org/abs/2306.16214

- Free spectrum — Posterior for GWB parameters



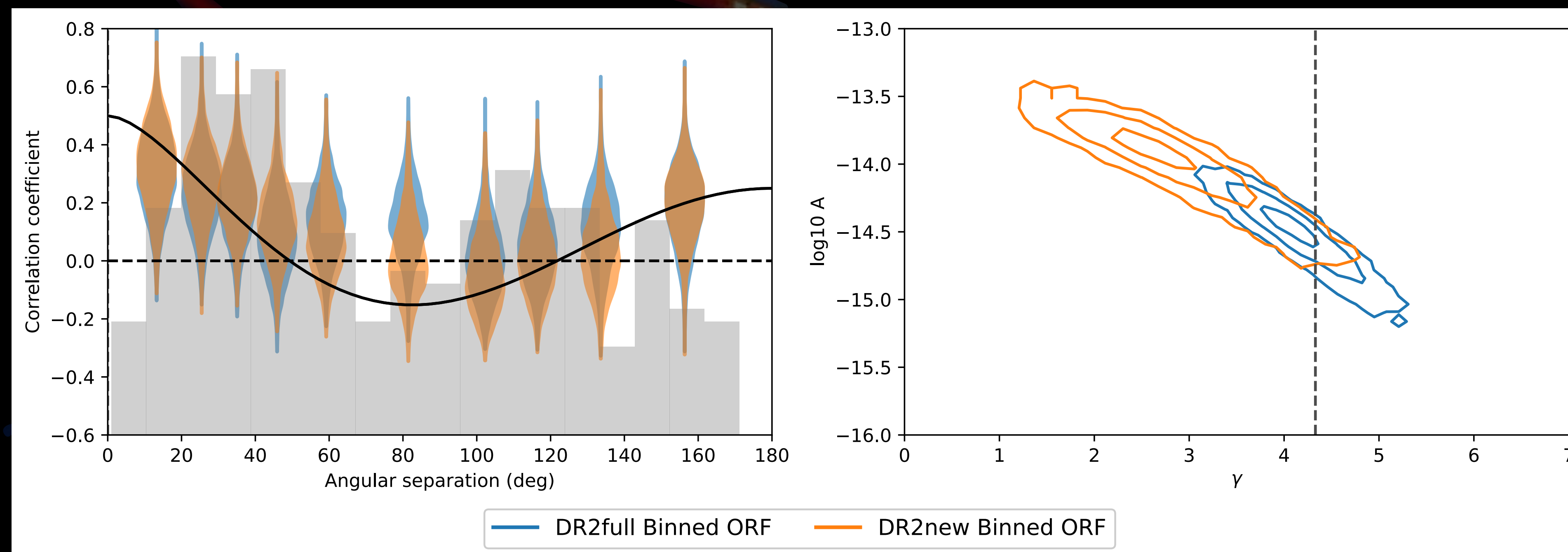
- GWB parameters (DR2new):
  - logarithmic amplitude: $\log_{10} A = -13.94^{+0.23}_{-0.48}$
  - spectral index: $\gamma = 2.71^{+1.18}_{-0.73}$
- No dipole and no monopole
-



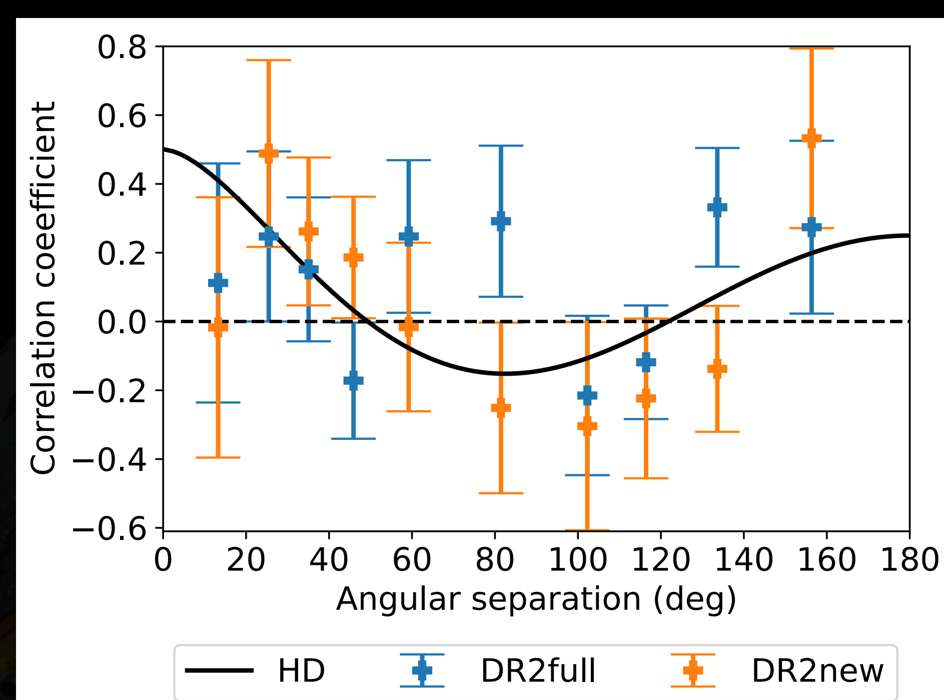
EPTA results: GWB

https://arxiv.org/abs/2306.16214

- Spatial correlation: overlap reduction function
  - Binned



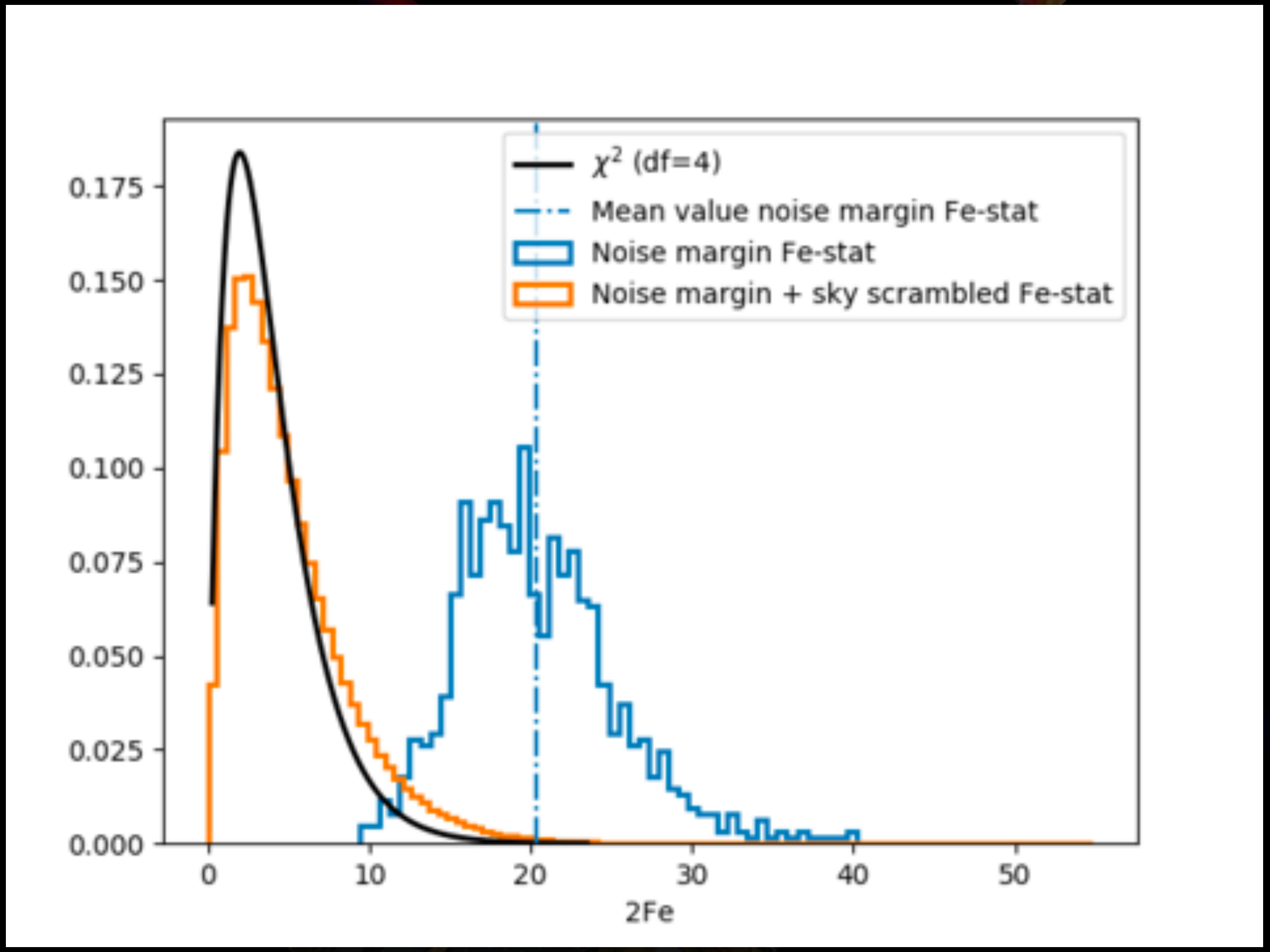
  - Optimal statistic



EPTA results: GWB

https://arxiv.org/abs/2306.16214

- Scrambling the sky position of pulsar, destroy the signal

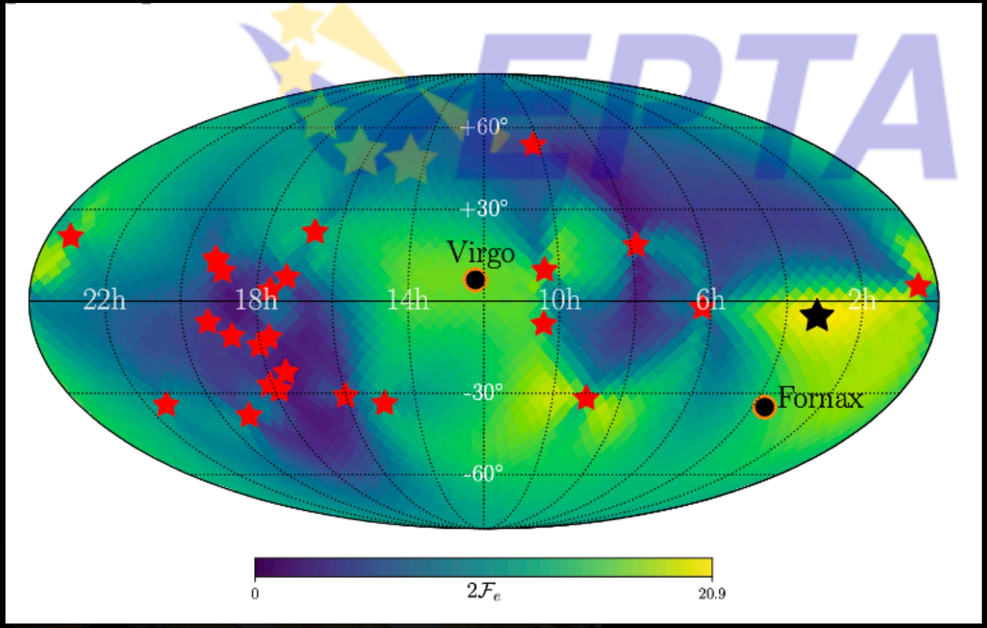


- Many other tests see https://arxiv.org/abs/2306.16214

EPTA results: individual sources

https://arxiv.org/abs/2306.16226

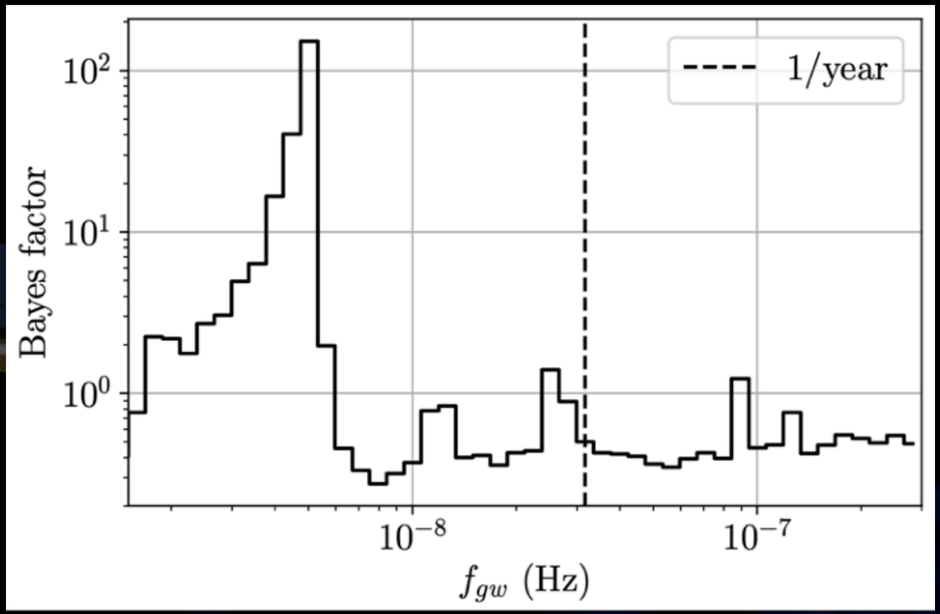
- Continuous GW search = Super Massive Black Hole Binary
- GW described by $8 + 2 \times N_{PSR}$ parameters:
  - Amplitude, frequency, chirp mass, sky position, inclination, polarisation, initial phase, phase at pulsar, pulsar distance
- Frequentist analysis:
  - Maximum F-statistic (equivalent to likelihood)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



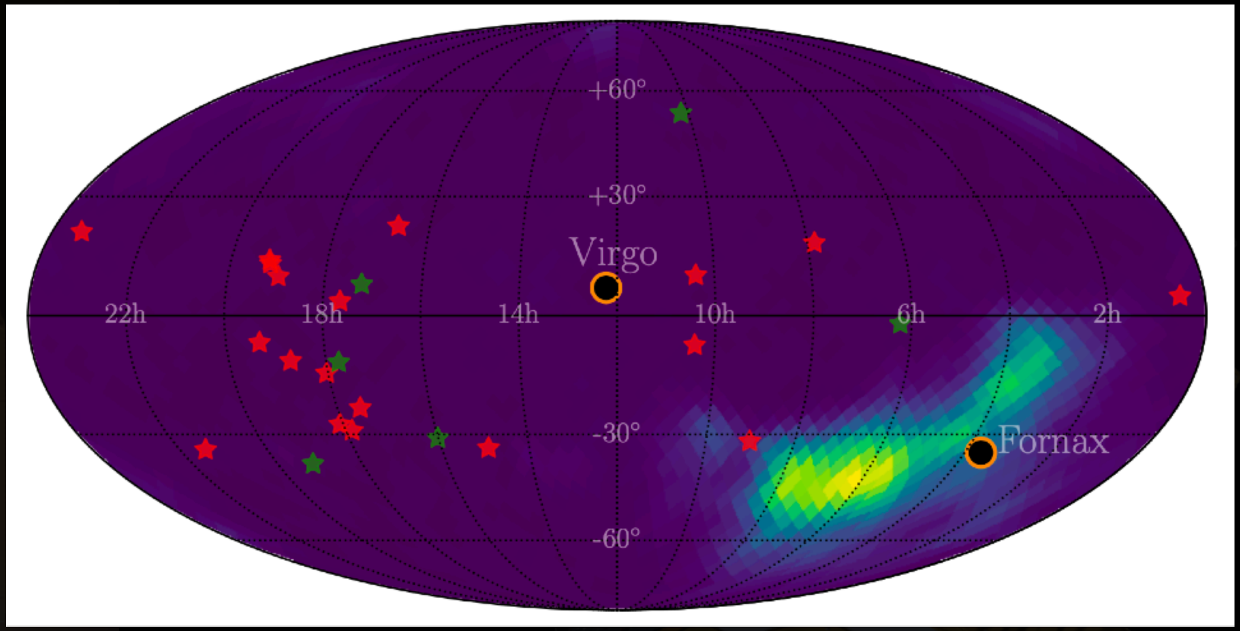
EPTA results: individual sources

https://arxiv.org/abs/2306.16226

- Bayesian analysis:
  - Bayes factor PRSN+CURN+CGW vs PRSN+CURN



  - Sky localisation:



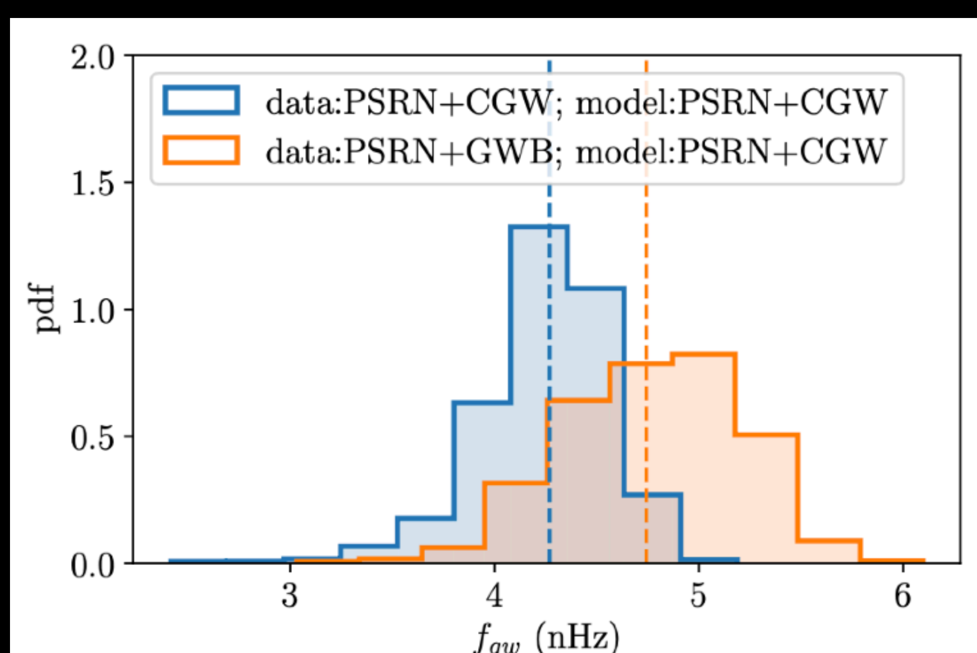
EPTA results: individual sources

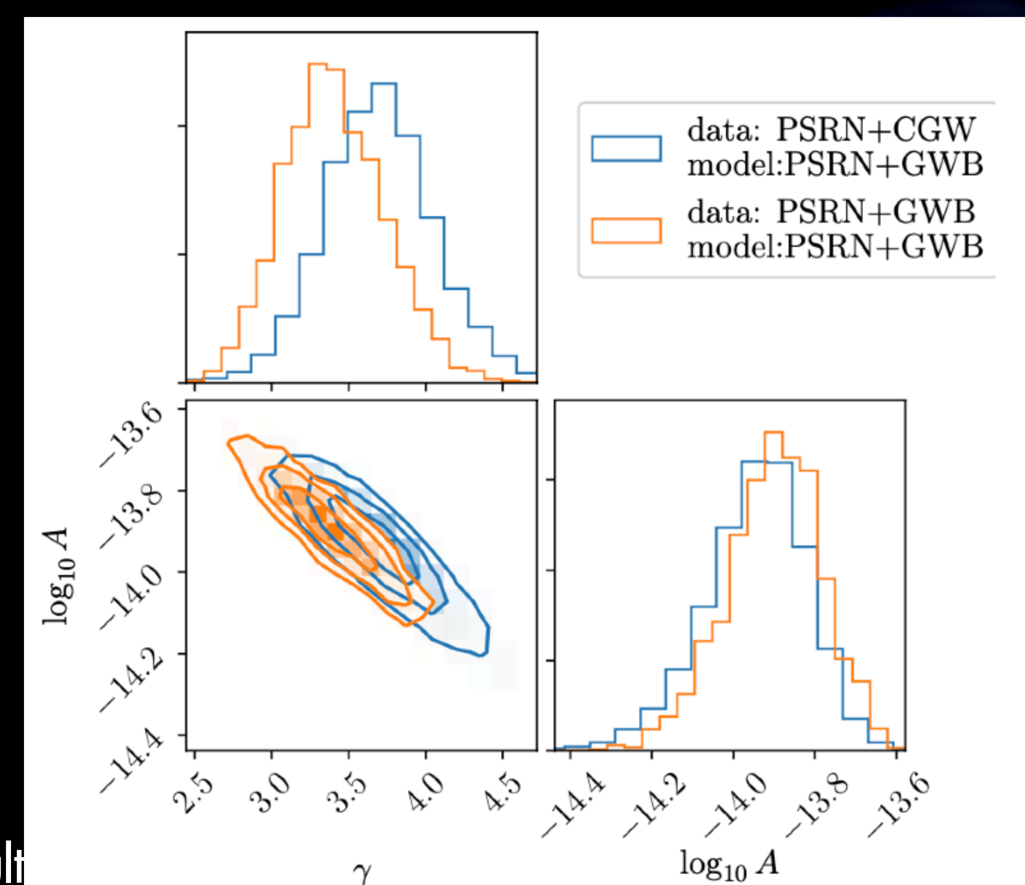
https://arxiv.org/abs/2306.16226

- Bayesian analysis:
  - Hard to distinguish between individual source and background.
    - Bayes factors:

Model comparison	Bayes factor
CGW+PSRN vs PSRN	4000
CGW+PSRN+CURN vs PSRN+CURN, 3 bins	12
CGW+PSRN+CURN vs PSRN+CURN, 9 bins	4
CGW+PSRN+GWB vs PSRN+GWB, 3 bins	1
CGW+PSRN+GWB vs PSRN+GWB, 9 bins	0.7

    - Simulations:

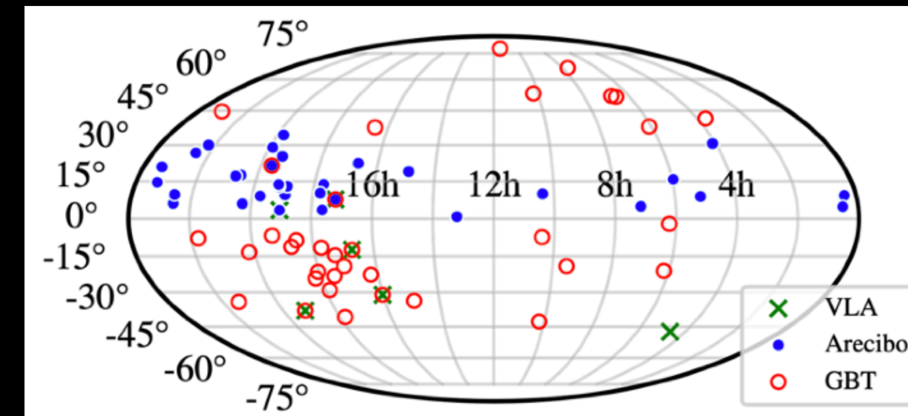


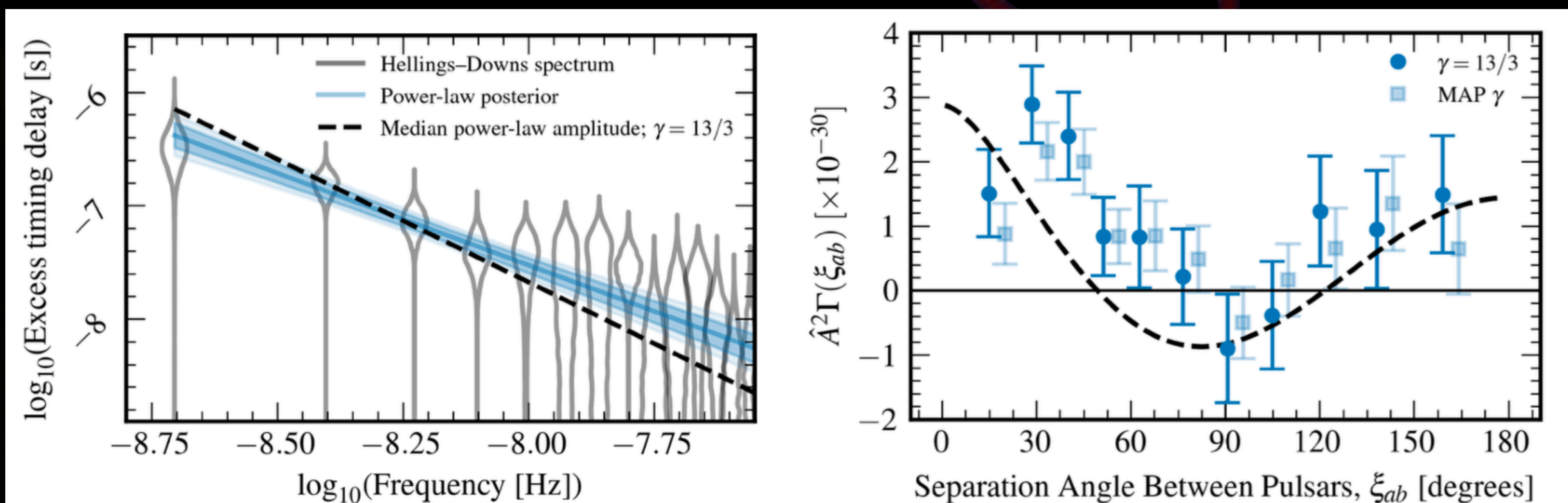


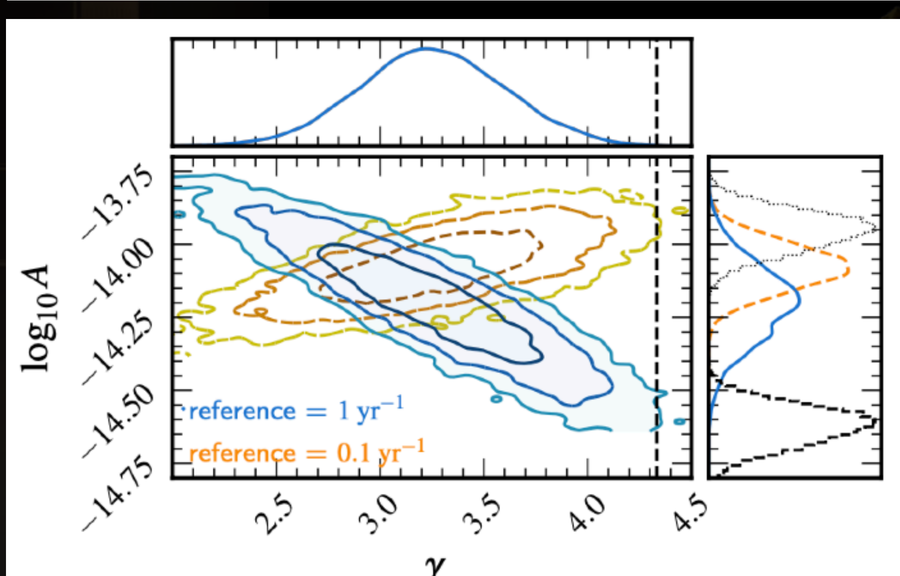
NANOGrav results

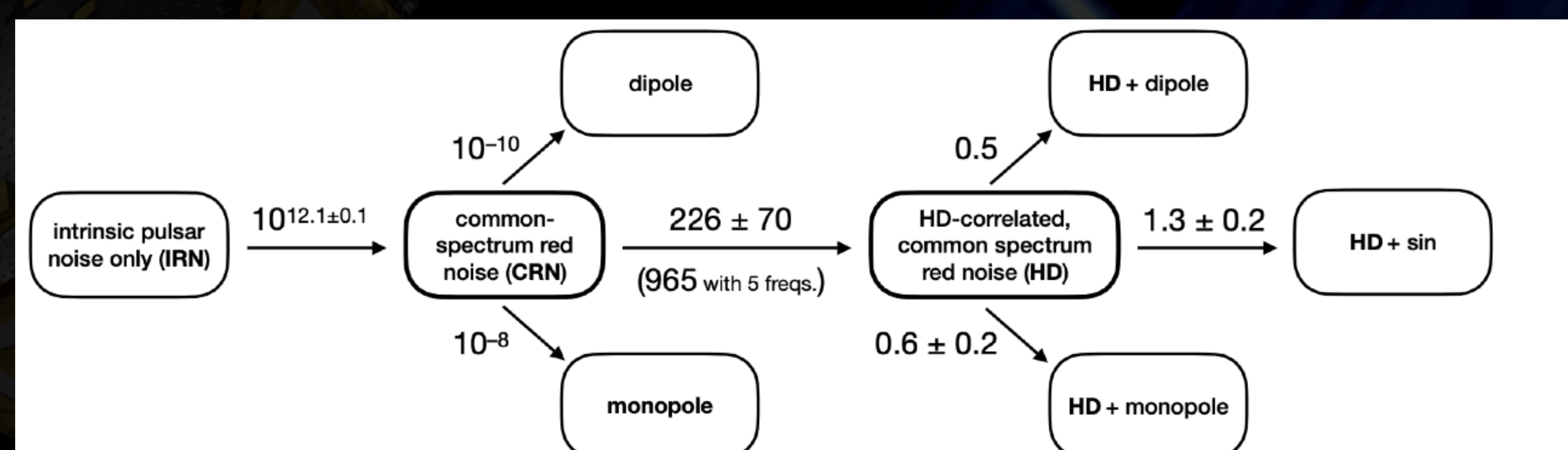
https://arxiv.org/abs/2306.16213

- 67 pulsars during 15 years
- GW Background:
  - Bayes factor: 200-1000 (about 4 sigma)





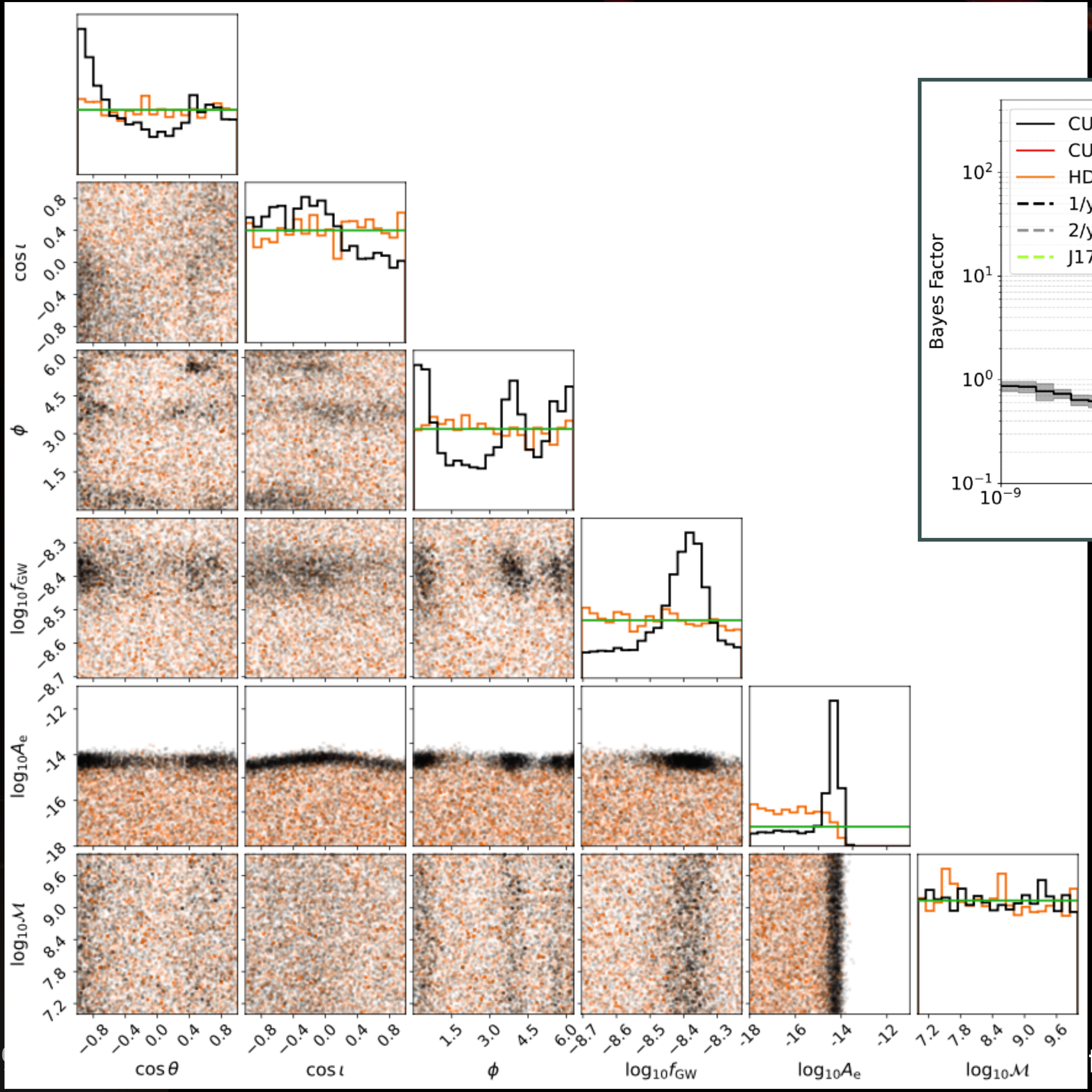


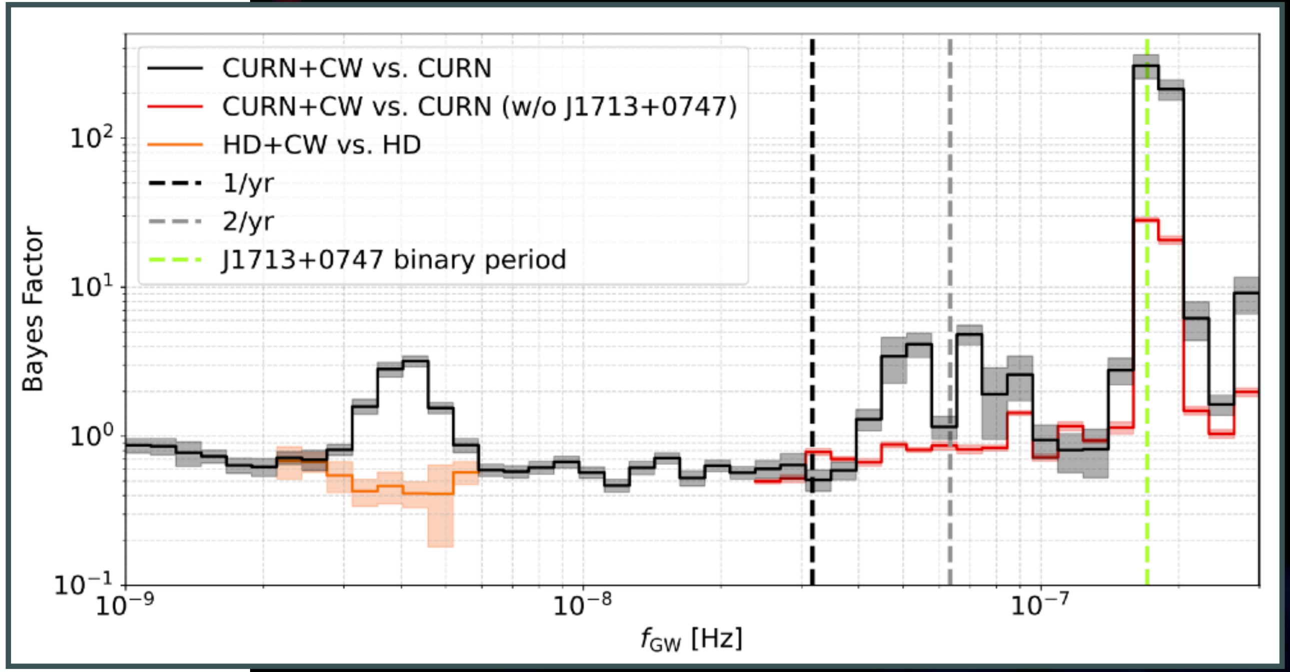


NANOGrav results

https://arxiv.org/abs/2306.16222

- Continuous GW search

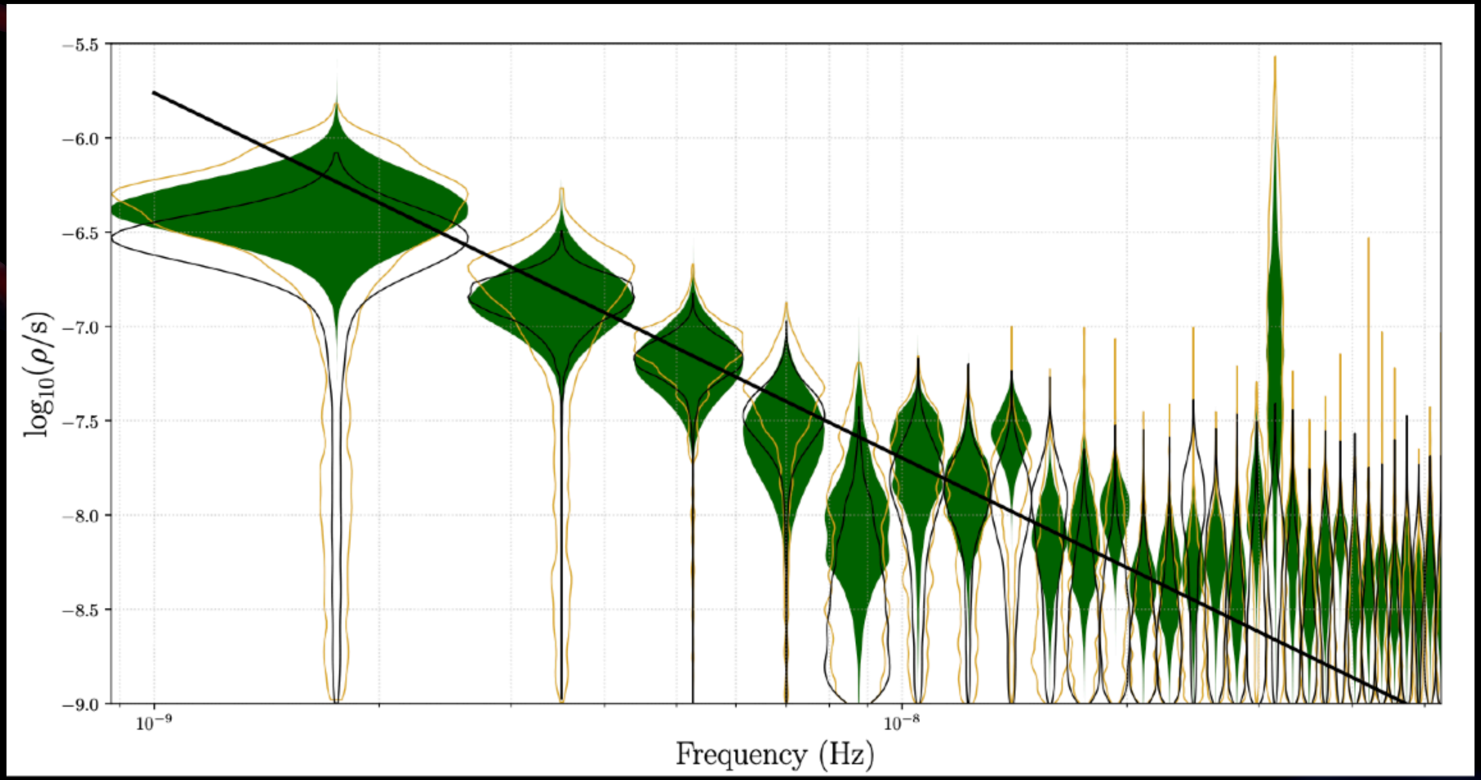


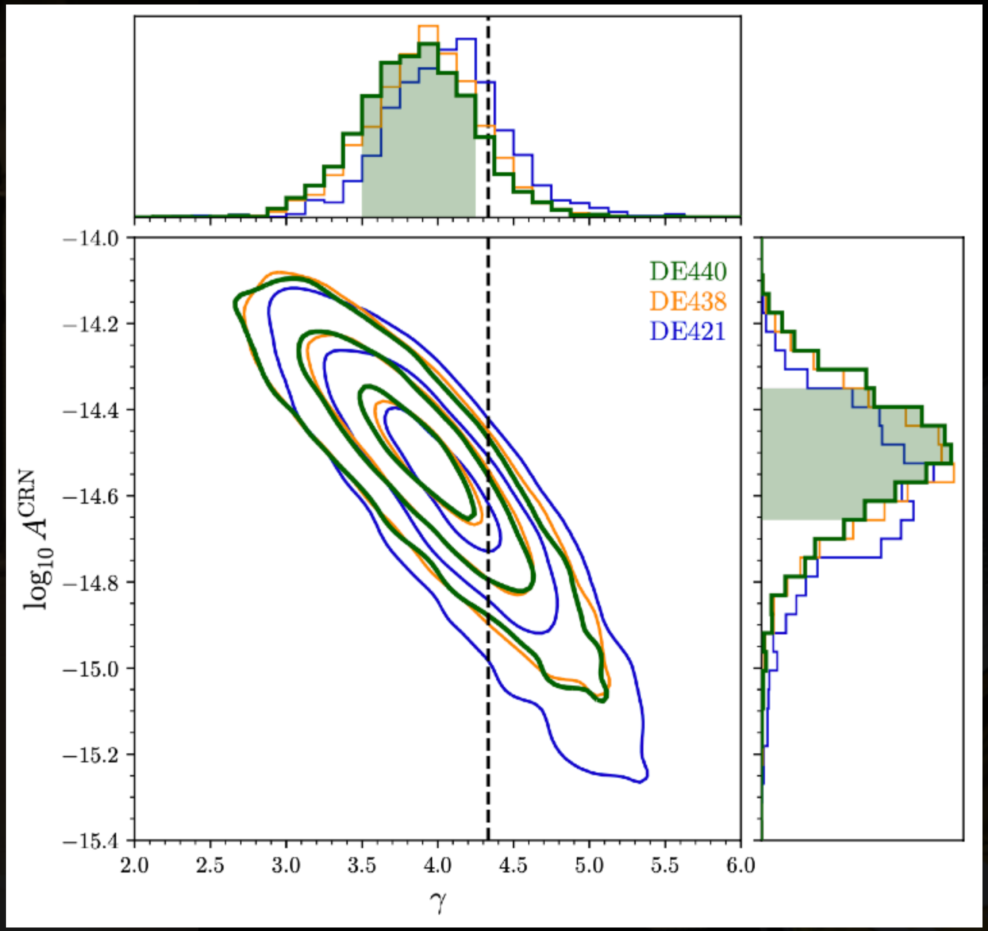


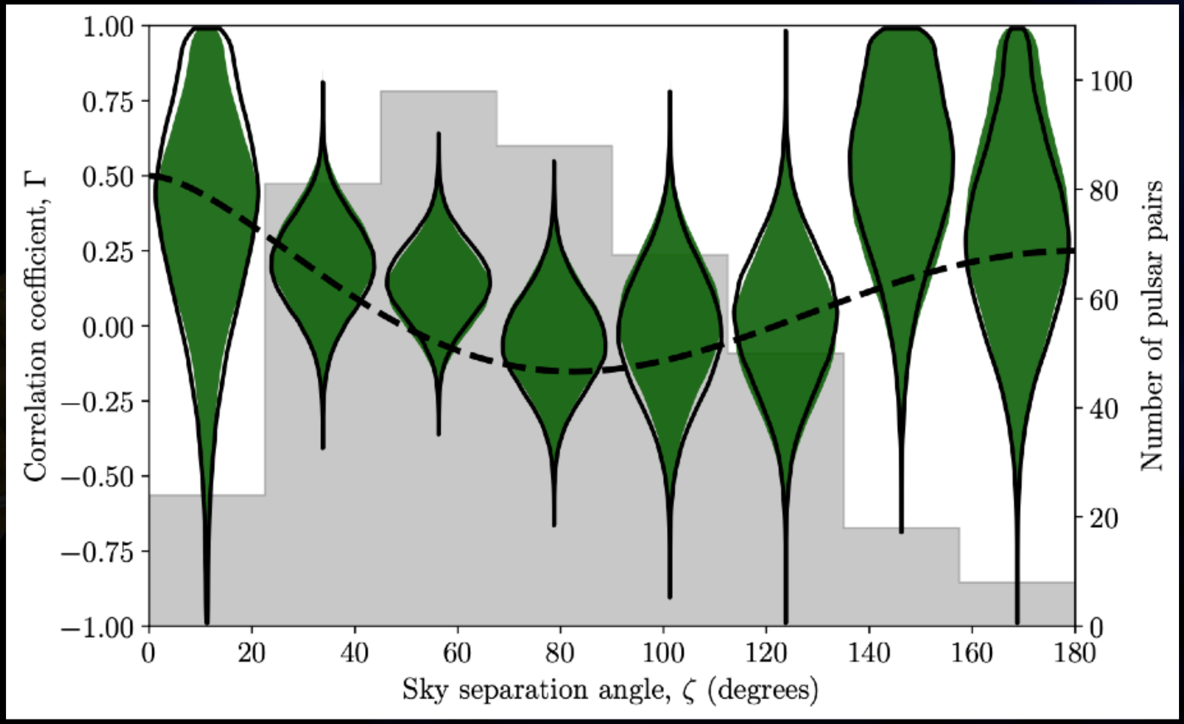
PPTA results

https://arxiv.org/abs/2306.16215

- 32 pulsars during 18 years





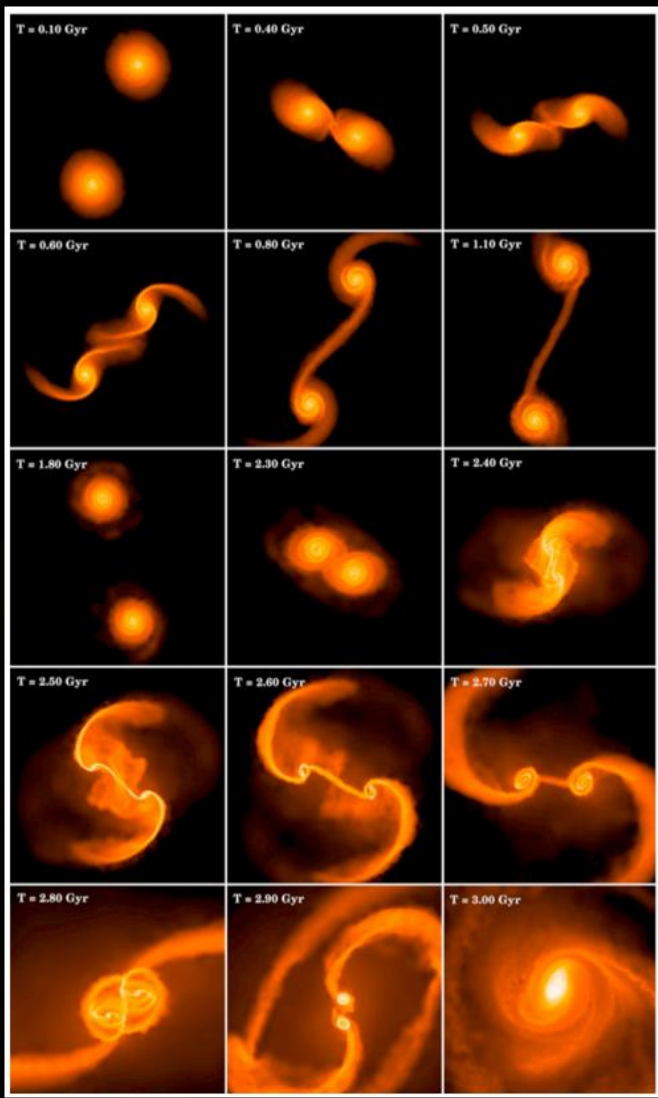


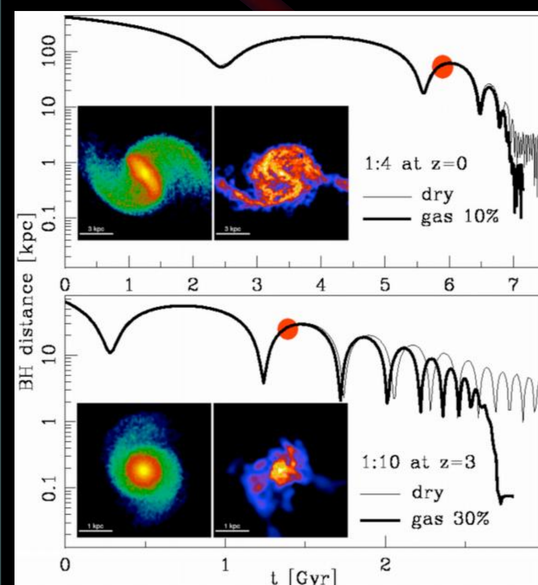
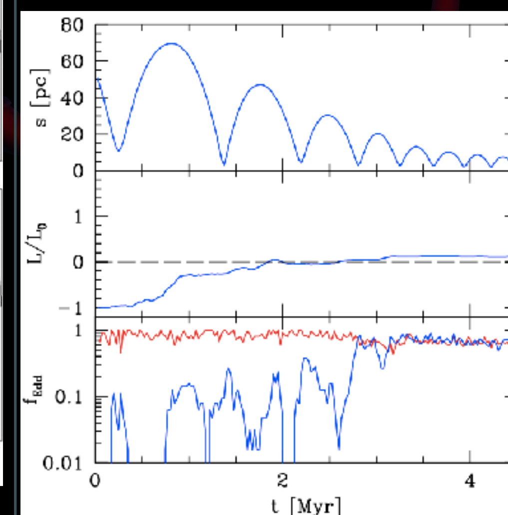
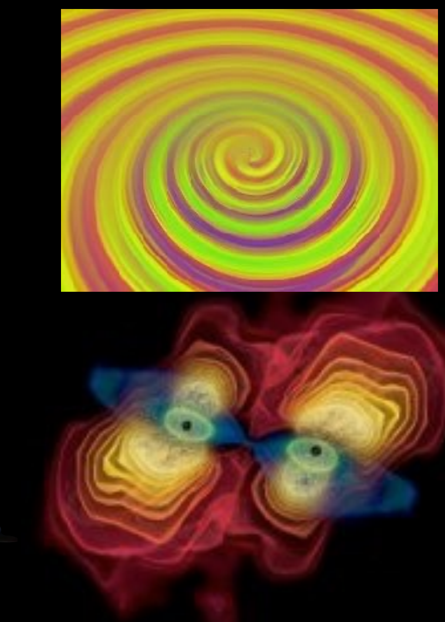
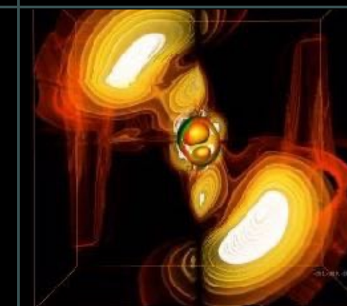
First EPTA interpretation

https://arxiv.org/abs/2306.16227

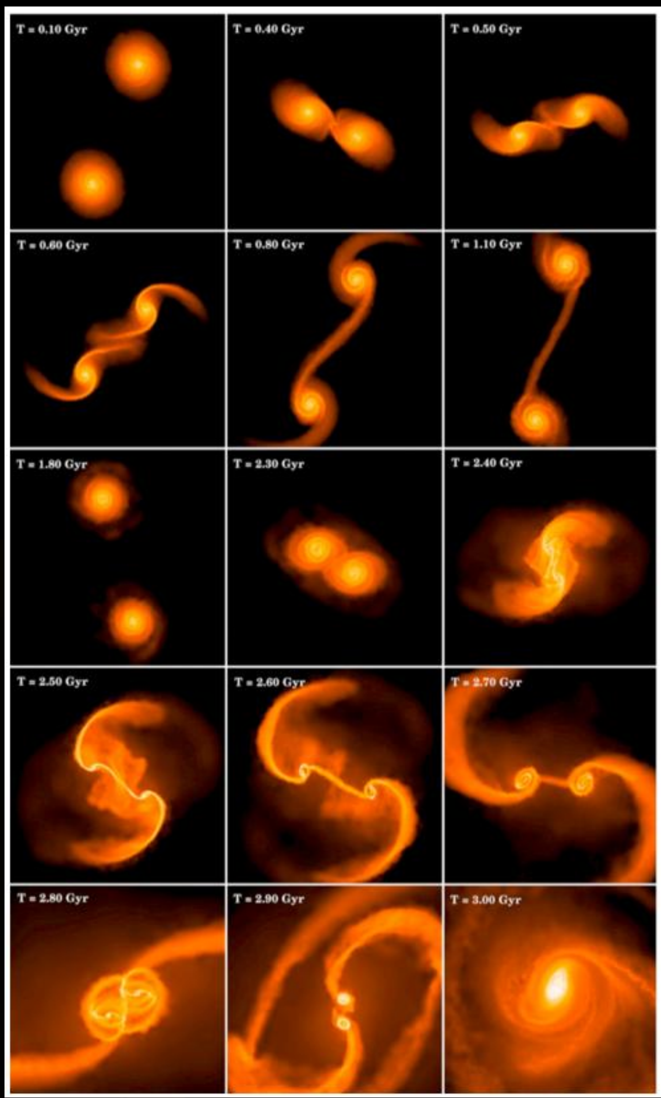
- Implications of the EPTA results, DR2new:
  - $\log_{10} A = -13.94^{+0.23}_{-0.48}$
  - $\gamma = 2.71^{+1.18}_{-0.73}$
- For:
  - Supermassive black hole binaries
  - Physics of the early Universe
  - Dark matter

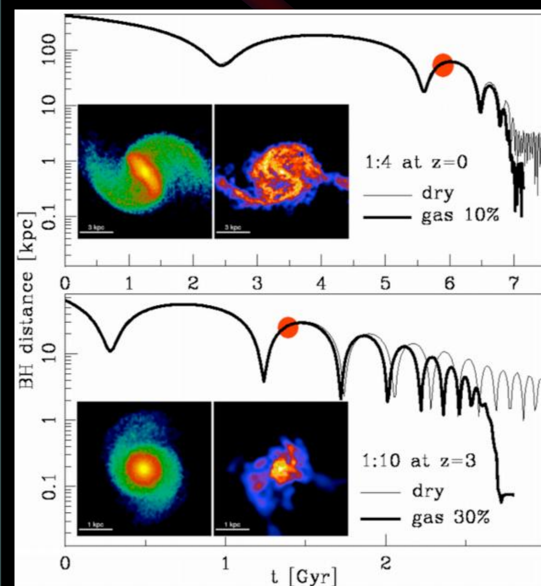
SMBH: Formation & Evolution

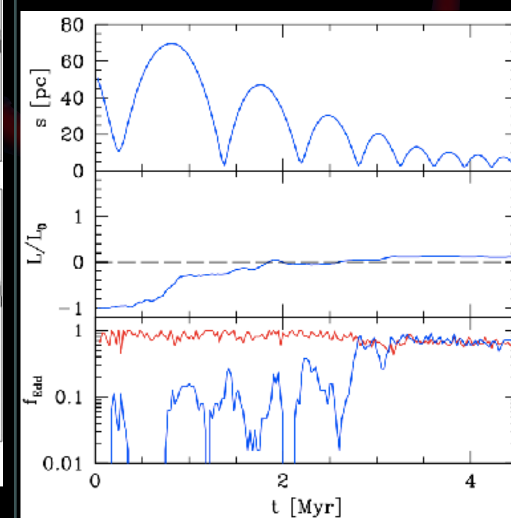


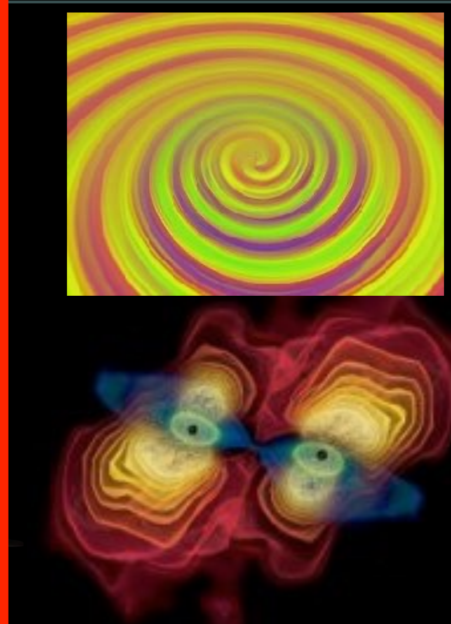
Galaxy mergers	Formation	Closed binary	Merger
			
100 kpc → 100 pc	100 pc → sub-parsec	sub-pc→qq M (au)	
~ few Gyr	~ few Myr		~ few hours
★ Dynamical friction ★ Stellar formation ★ Tidal chocs ★ Gas dynamics ✤ Callegari & al. (2009) ApJ 696 L89	★ Gaz friction ★ Circularisation ★ Possible inversion of angular momentum ★ 3 bodies interaction ✤ Dotti & al. (2009) MNRAS 396-1640	Inspiral of the 2 BHs due to Gravitational Wave emission	★ GW "burst", ★ Recoil velocities of remnant BH.

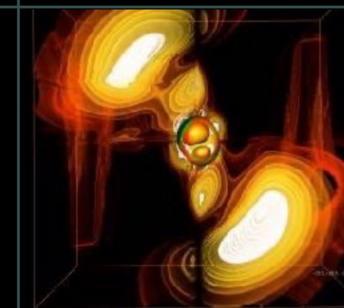
SMBH: Formation & Evolution











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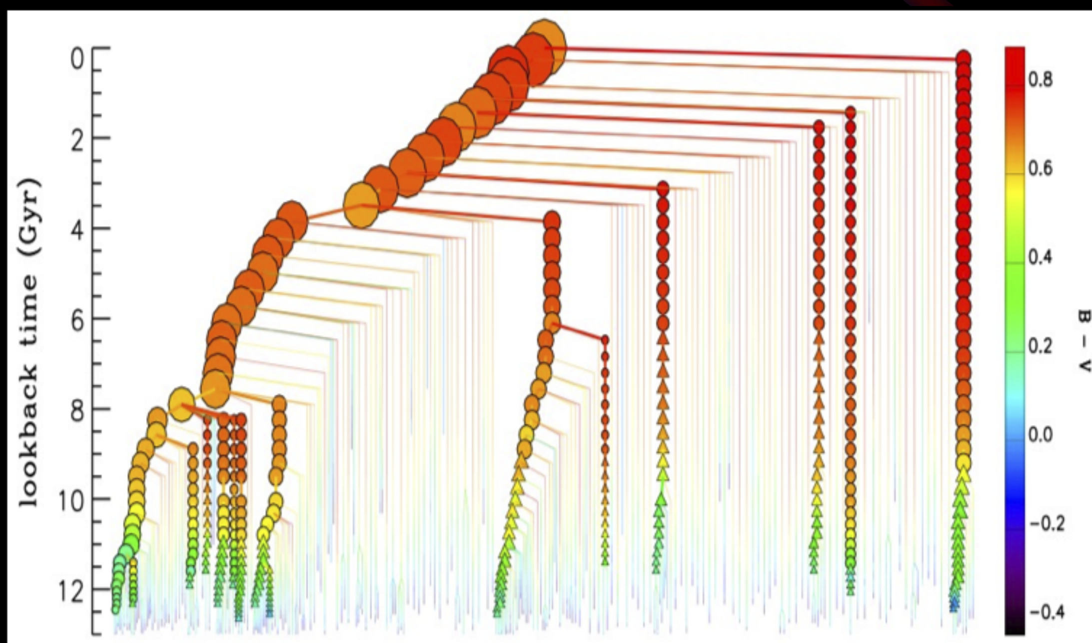
Population of SMBHB: Semi-Analytical model

Galaxies merger tree
(cosmological simulation)



From De Lucia et al 2006

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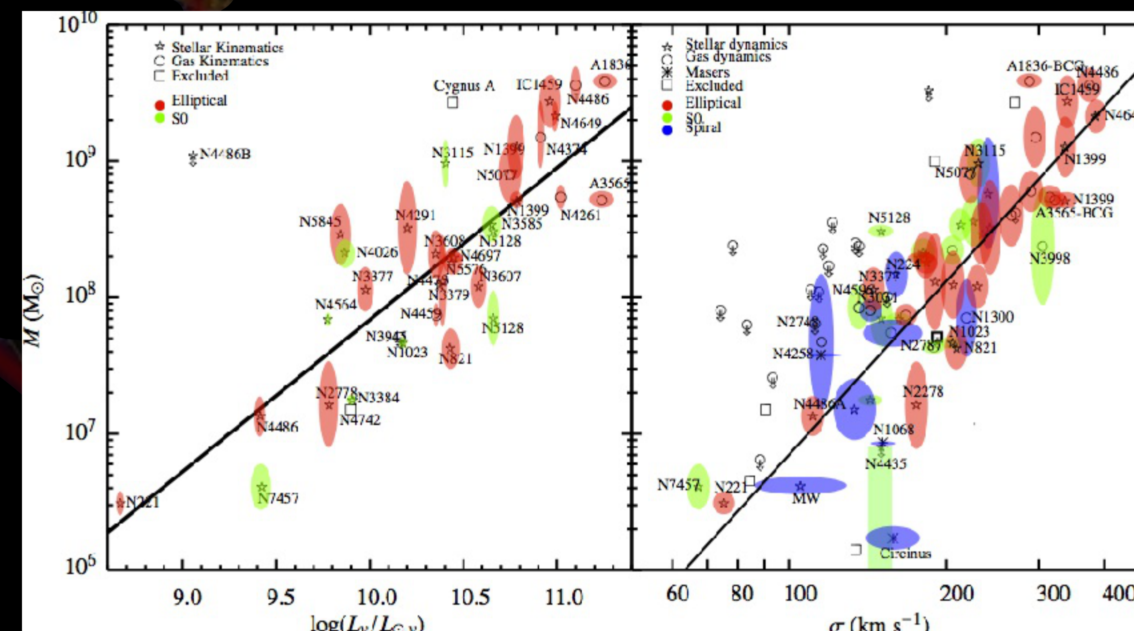
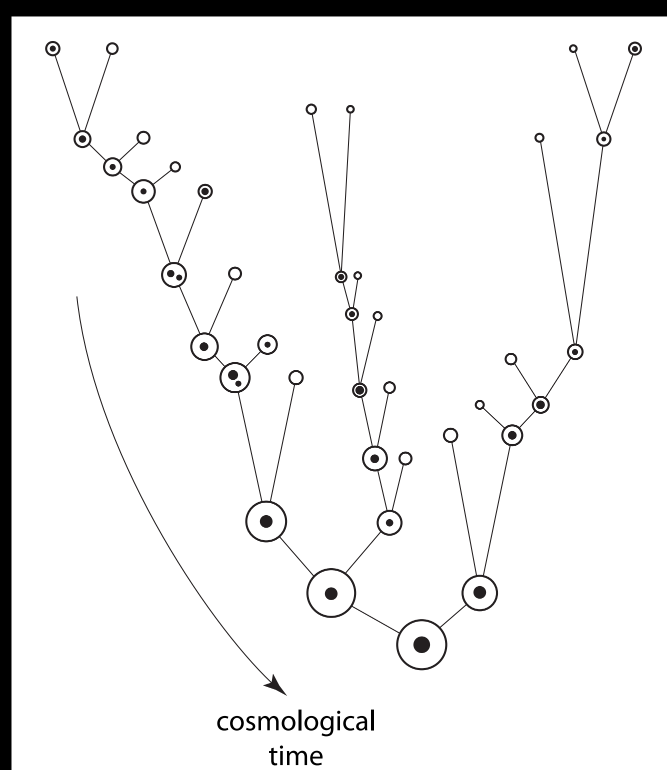
"M - σ relation": the speed of stars in bulge is linked to the central MBH mass



Gultekin 2009

=

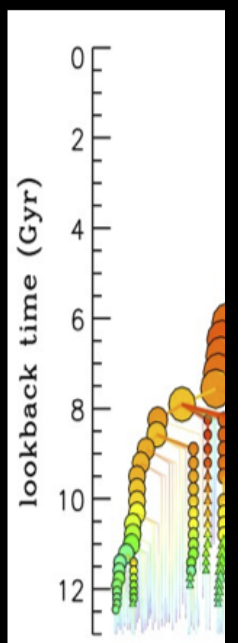


Population of SMBHB: Semi-Analytical model

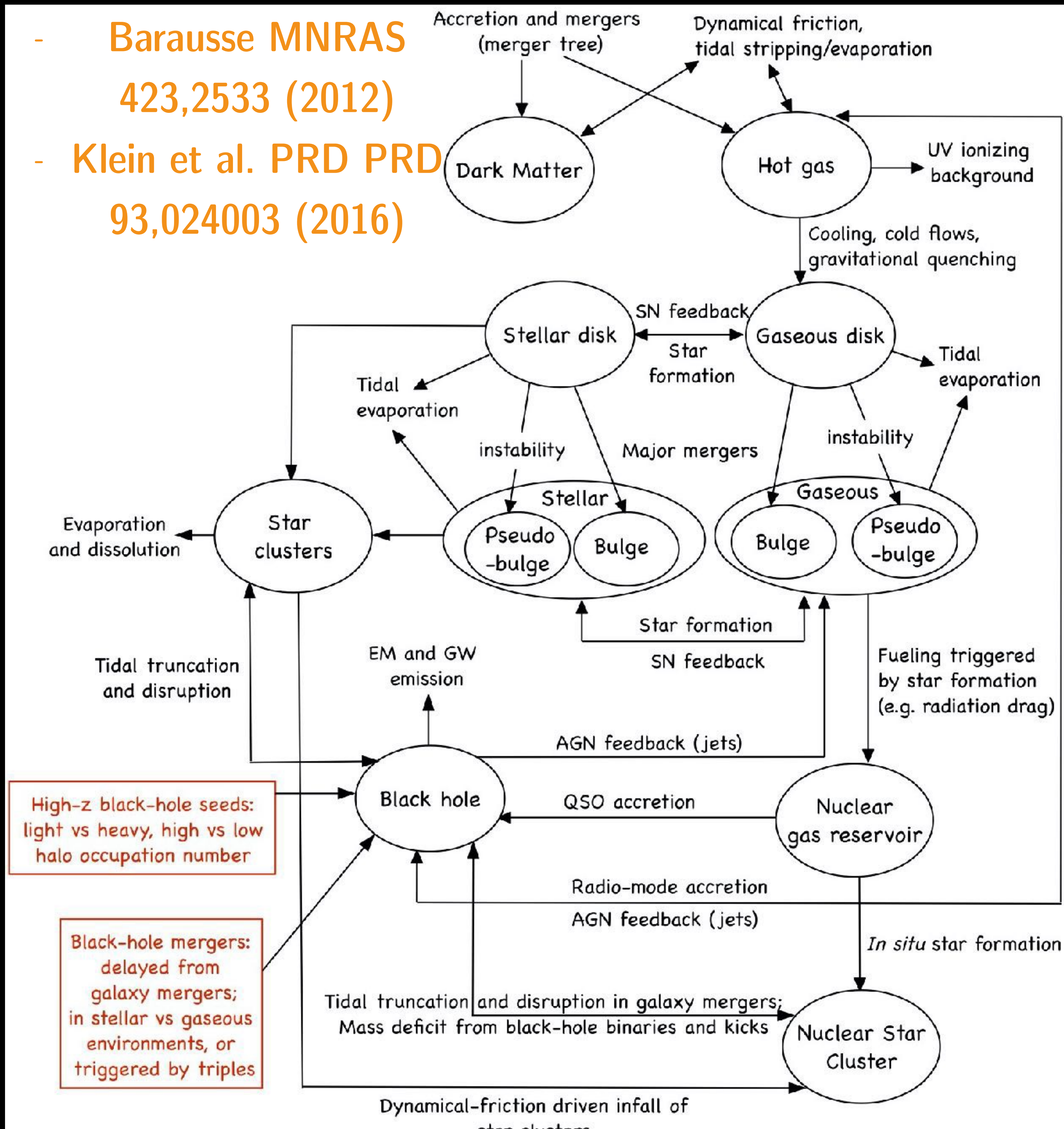
- Barausse MNRAS 423,2533 (2012)
- Klein et al. PRD PRD 93,024003 (2016)

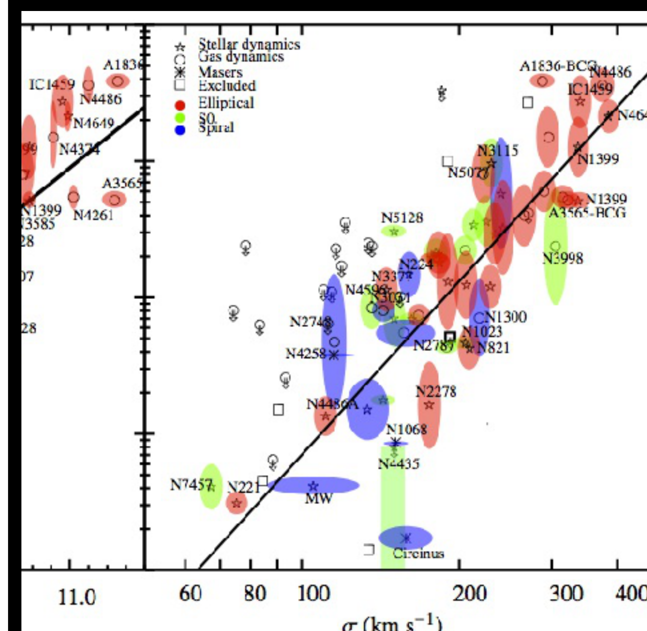
(

”: the speed of stars in to the central MBH mass



From De

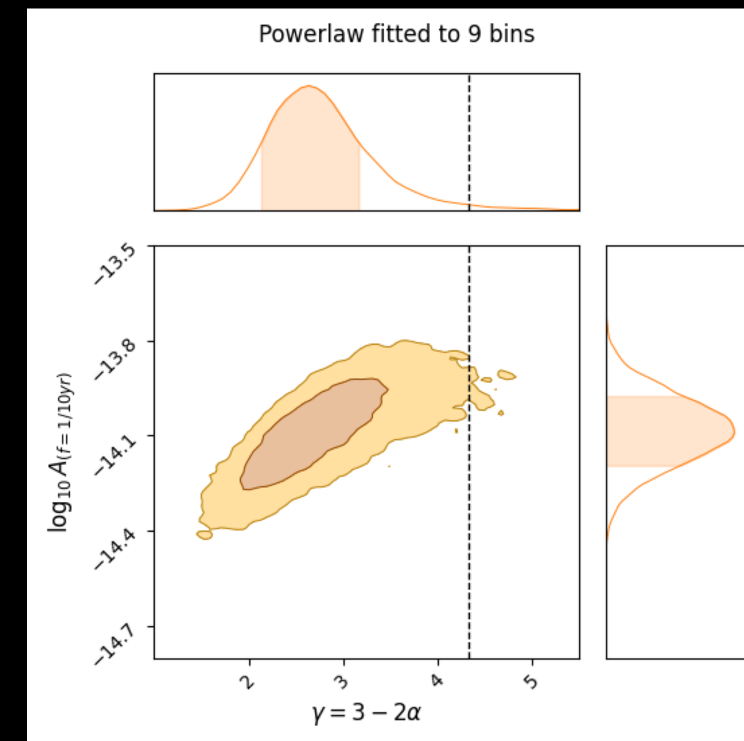


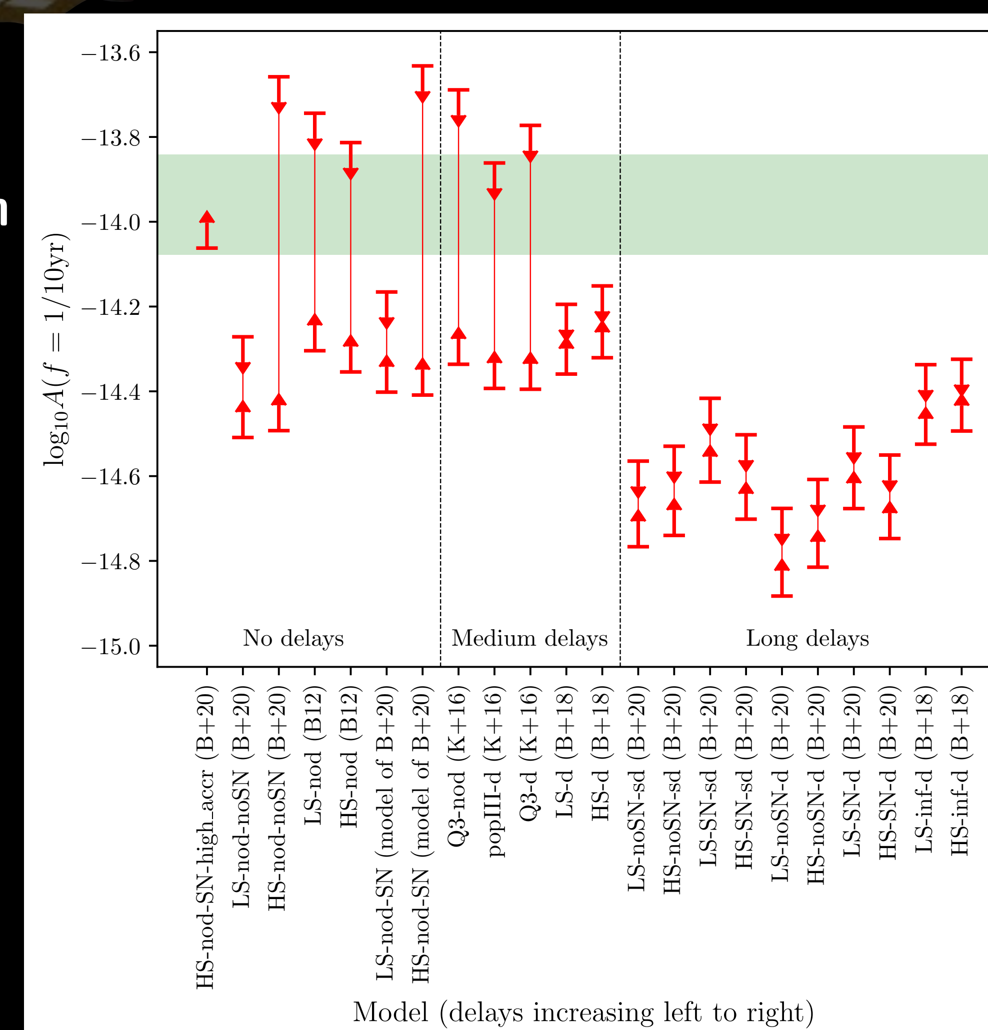


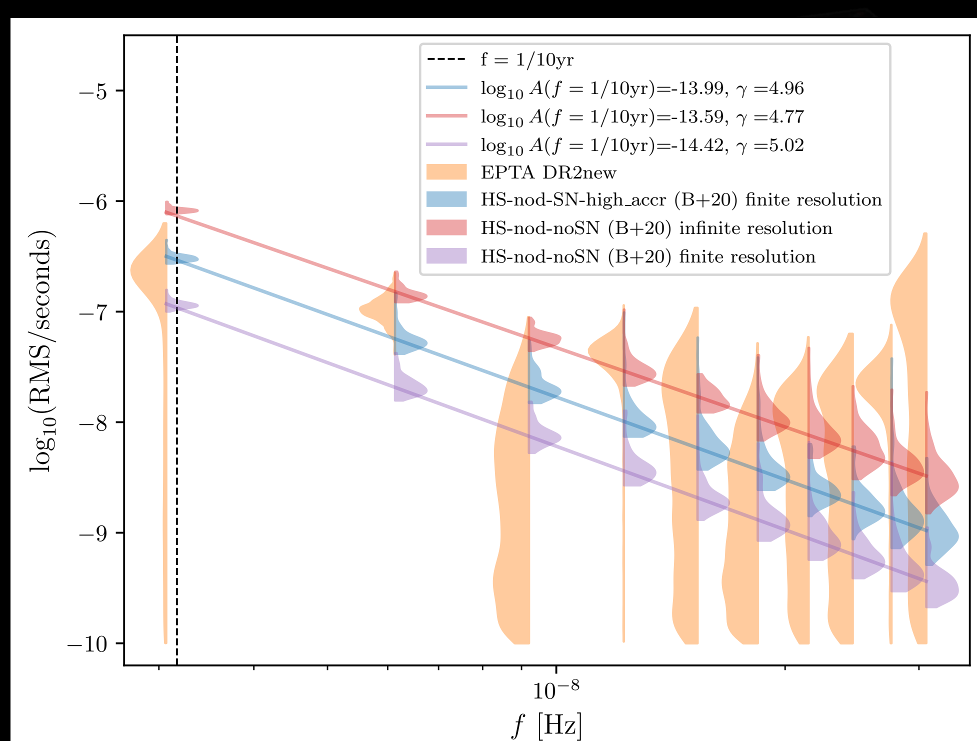
First EPTA interpretation

https://arxiv.org/abs/2306.16227

- Supermassive black hole binaries
  - Amplitude higher than expected ...
  - but some models are compatible with the data:
    - Quasicircular orbits and no environmental interaction ($\gamma = 13/3$)
    - Toward no delays between merger of galaxies and merger of SMBHs
  - Adding eccentricity and more complex effect helps to resolve the small tension on γ
  - If SMBHBs nature confirmed:
    - First observation of merger of SMBHs
    - Major breakthrough in observational astro. and galaxy formation



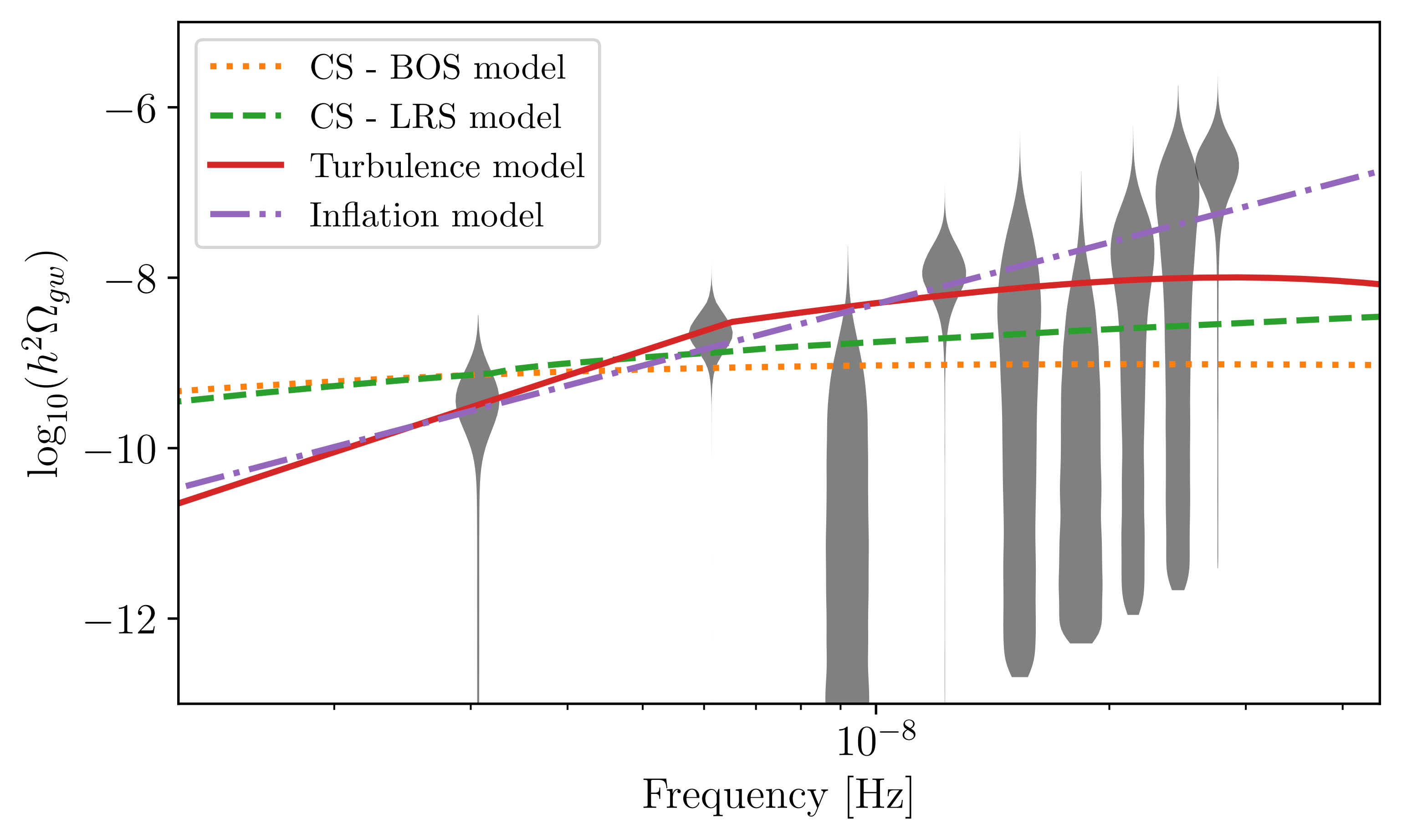




First EPTA interpretation

https://arxiv.org/abs/2306.16227

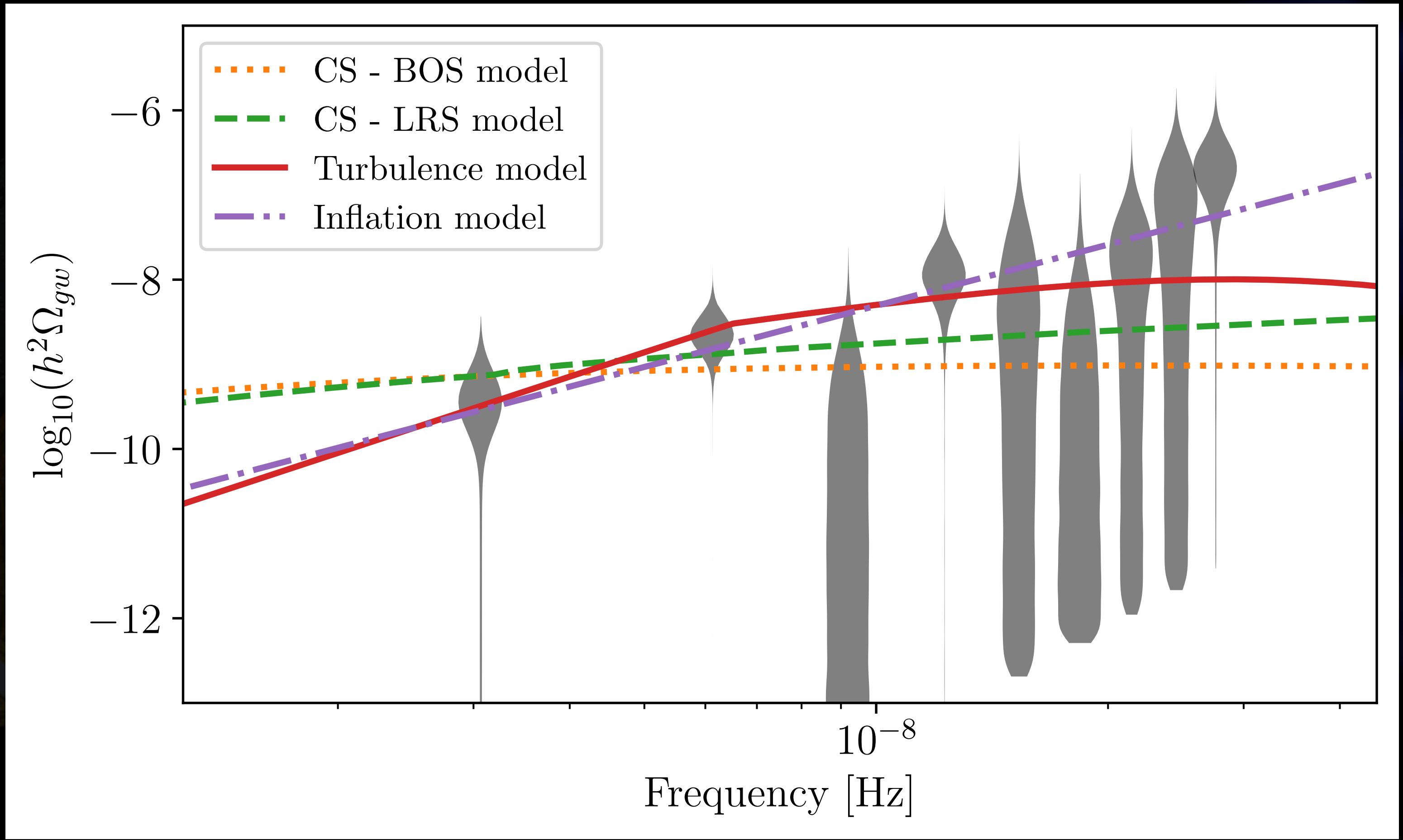
- Physics of the early Universe
  - Implications on a stochastic background of primordial (inflationary) GW
    - "requires non-standard inflationary scenarios breaking the slow-roll consistency relation, leading to a blue-tilted spectrum"
  - Implications on a background of cosmic strings
    - "Allow narrowing down the string tension to values of $-11 \lesssim \log_{10} G\mu \lesssim -9.5$, depending on the specific distribution of loops in the string network."
    - "the number of kinks cannot be constrained."
  - ...



First EPTA interpretation

https://arxiv.org/abs/2306.16227

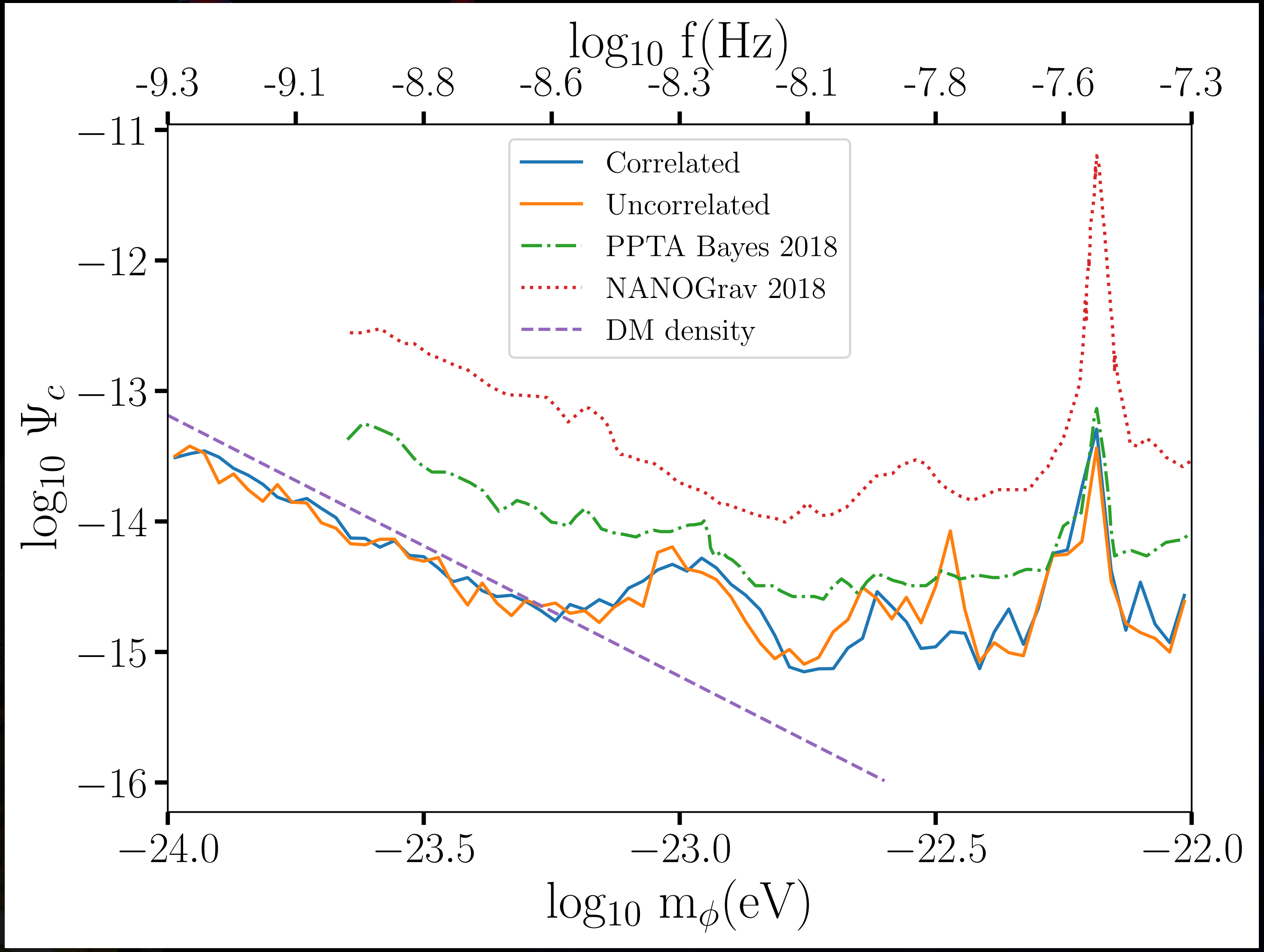
- Physics of the early Universe
  - Implications on background from turbulence around the QCD energy scale
    - "can also potentially explain the common red noise, but requires either high turbulent energy densities, of the same order of the radiation energy density, or a characteristic turbulent scale close to the horizon at the QCD epoch."
  - Implications on the 2nd-order GWB produced by primordial curvature perturbations
    - "can be produced by the evolution of scalar perturbations at second order only if an excess of their primordial spectrum is present at large wavenumbers, compared to the level derived from CMB observations at small wave numbers.
    Notably, such an excess will lead to the production of PBHs which can non-negligibly contribute to the CDM density."



First EPTA interpretation

https://arxiv.org/abs/2306.16227

- Ultralight scalar-field dark matter (ULDM)
  - Similar to a Continuous GW from a SMBHB, i.e. prominent only in one frequency bin
  - No ULDM
  - Upper limit



Future

- Next steps:
  - Confirmed the strong evidence => observation
  - Stochastic background or individual source or sources? Combination of both?
  - If stochastic background, better identified the spectral shape.
- Future data:
  - IPTA combination of the EPTA, NANOGrav and PPTA
  - Add MeerKAT data
  - SKA