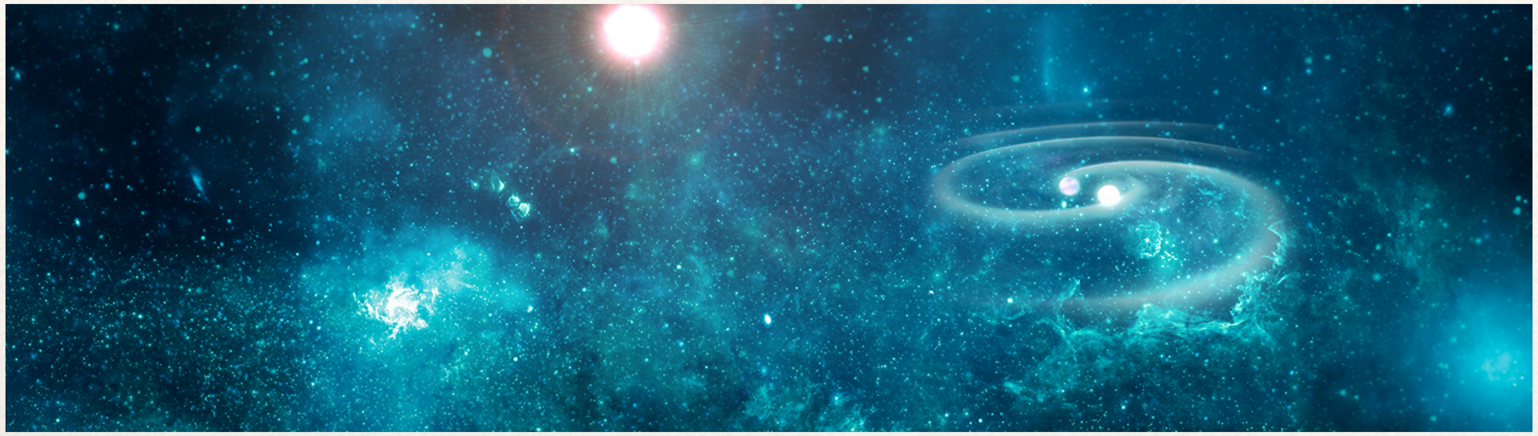
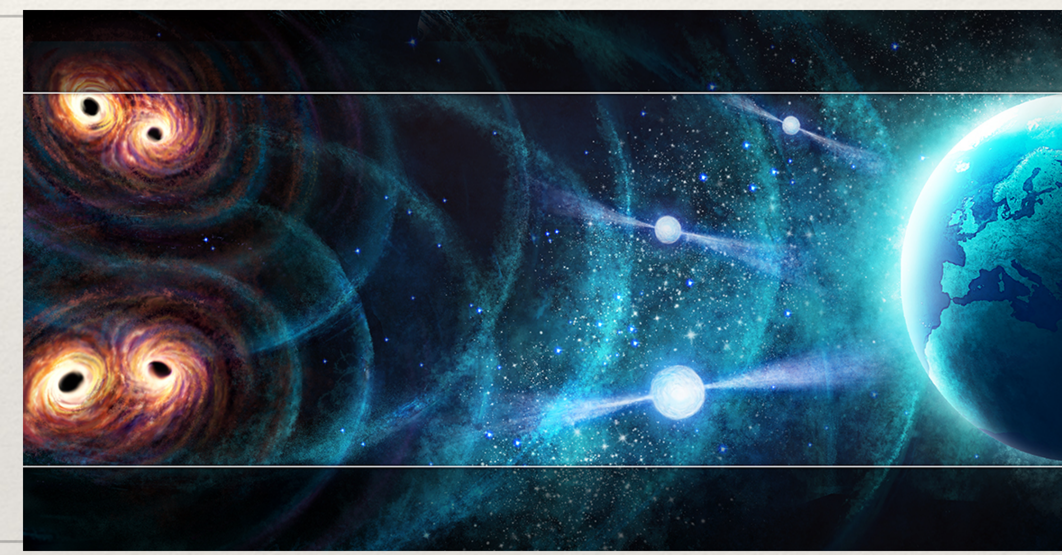
Stanislav (Stas) Babak.

AstroParticule et Cosmologie, CNRS (Paris)

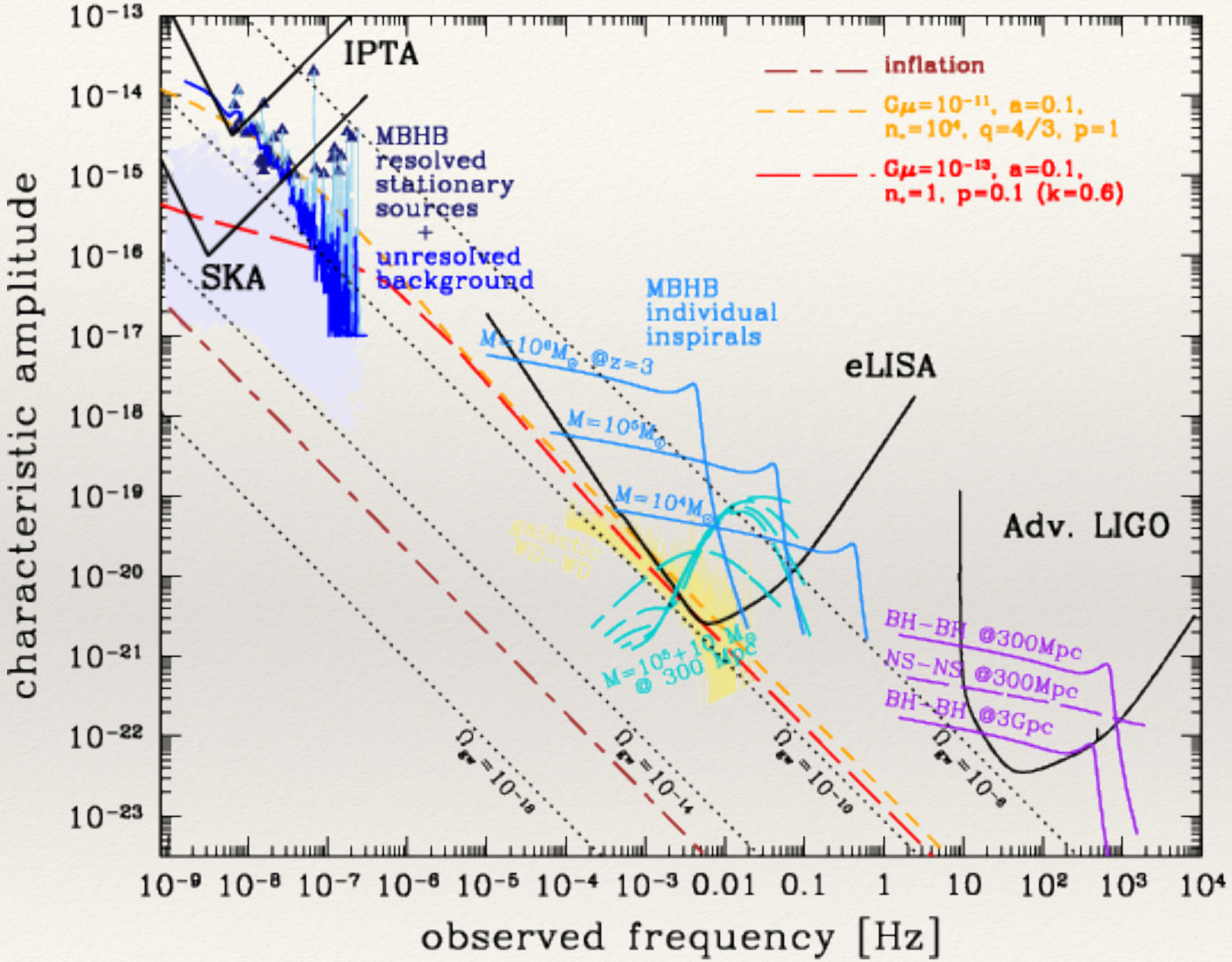


Pulsar Timing Array



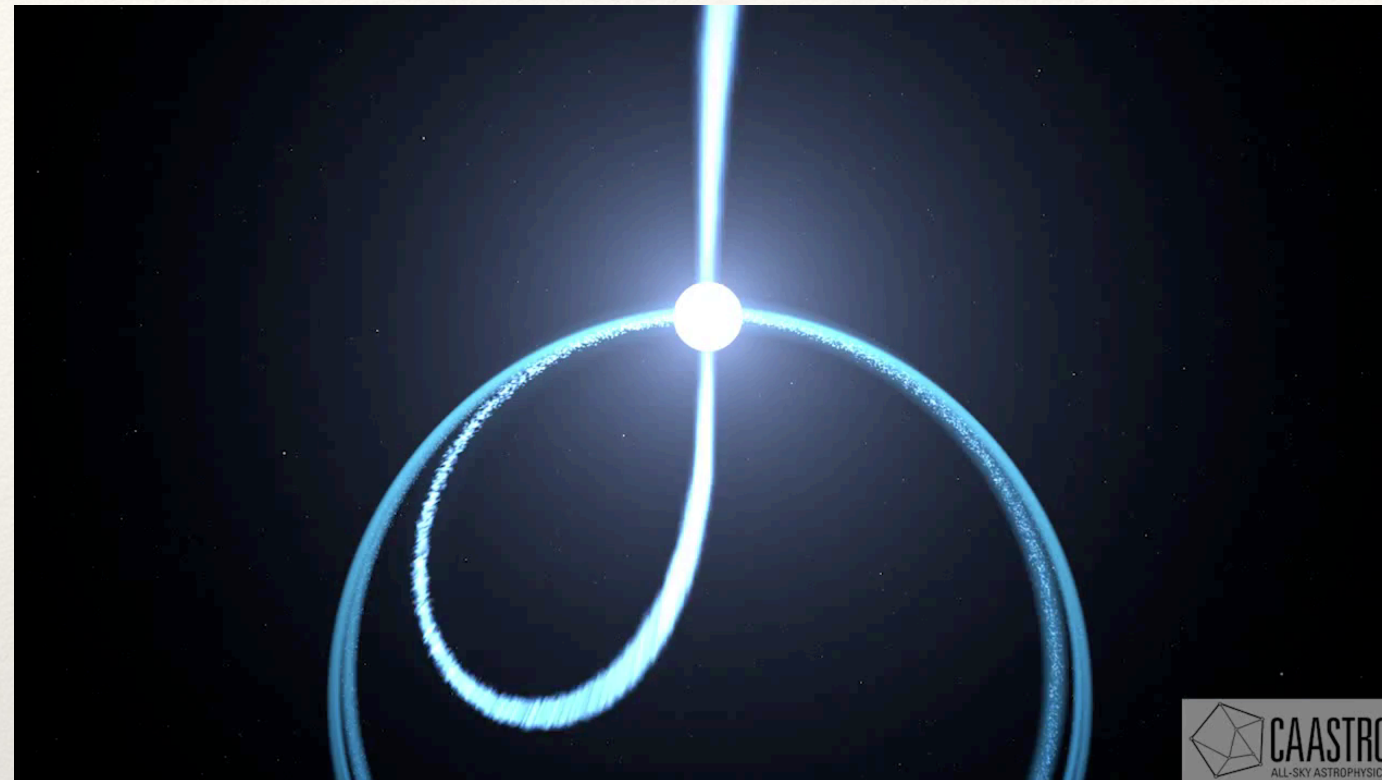
October 2024

GW landscape

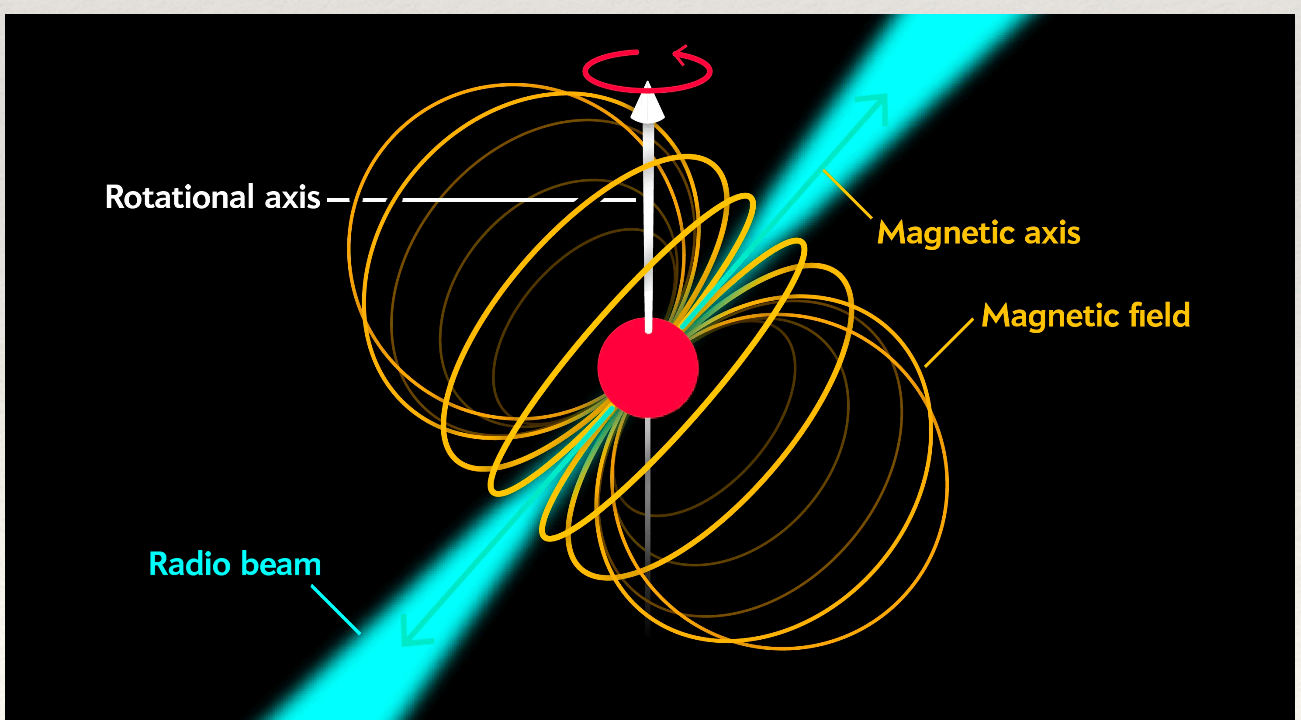


Millisecond pulsars

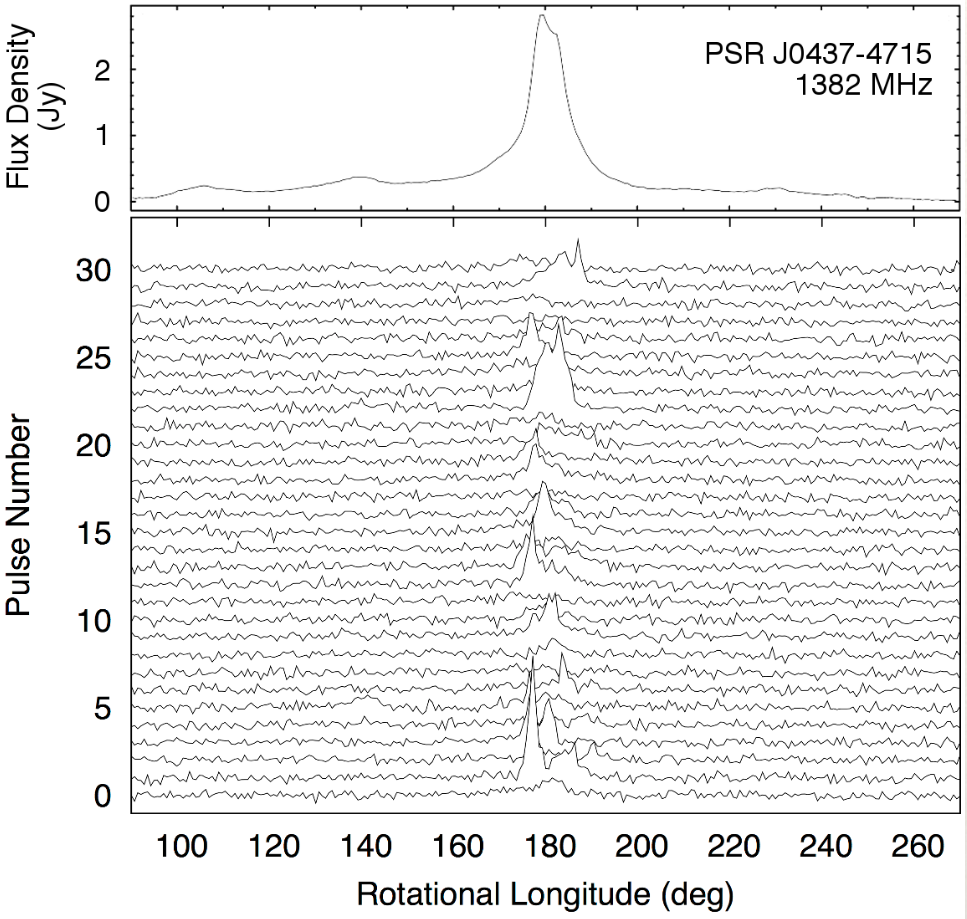
- Millisecond pulsars: period of rotation ~ millisec
- Often in binaries
- Very old NSs, very stable rotation
- The most accurate clock on the long time scale (decades)

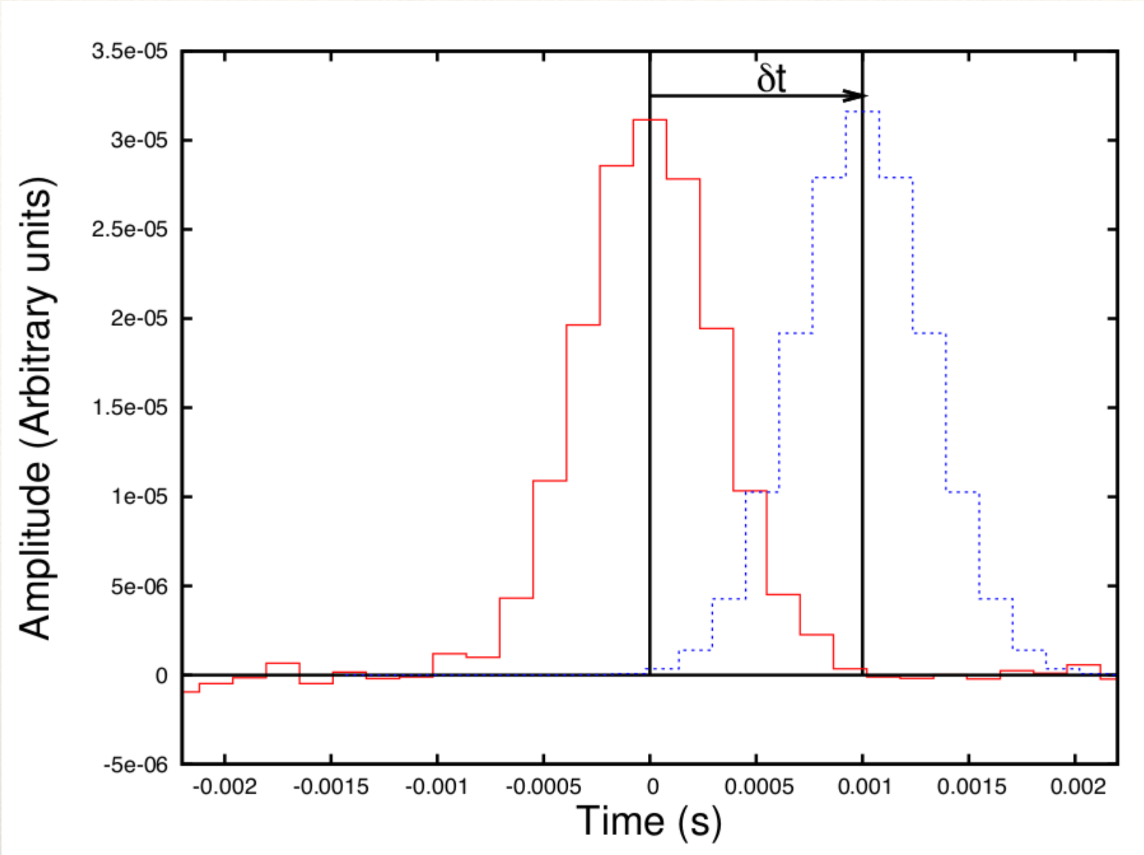


Jen Christiansen



Pulsar timing

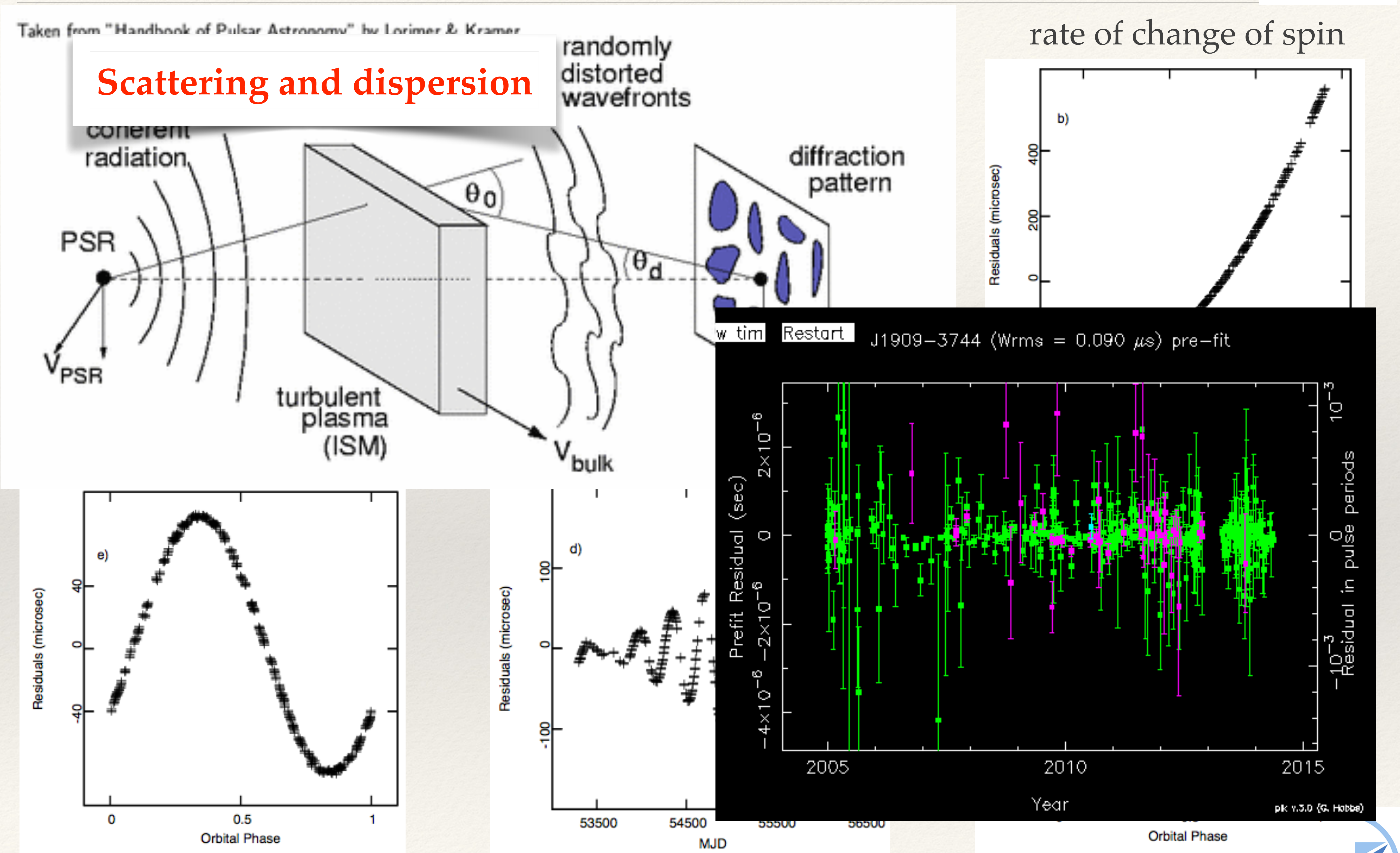




[Figs: credits
S. Burke-Spolar & L. Lentati]

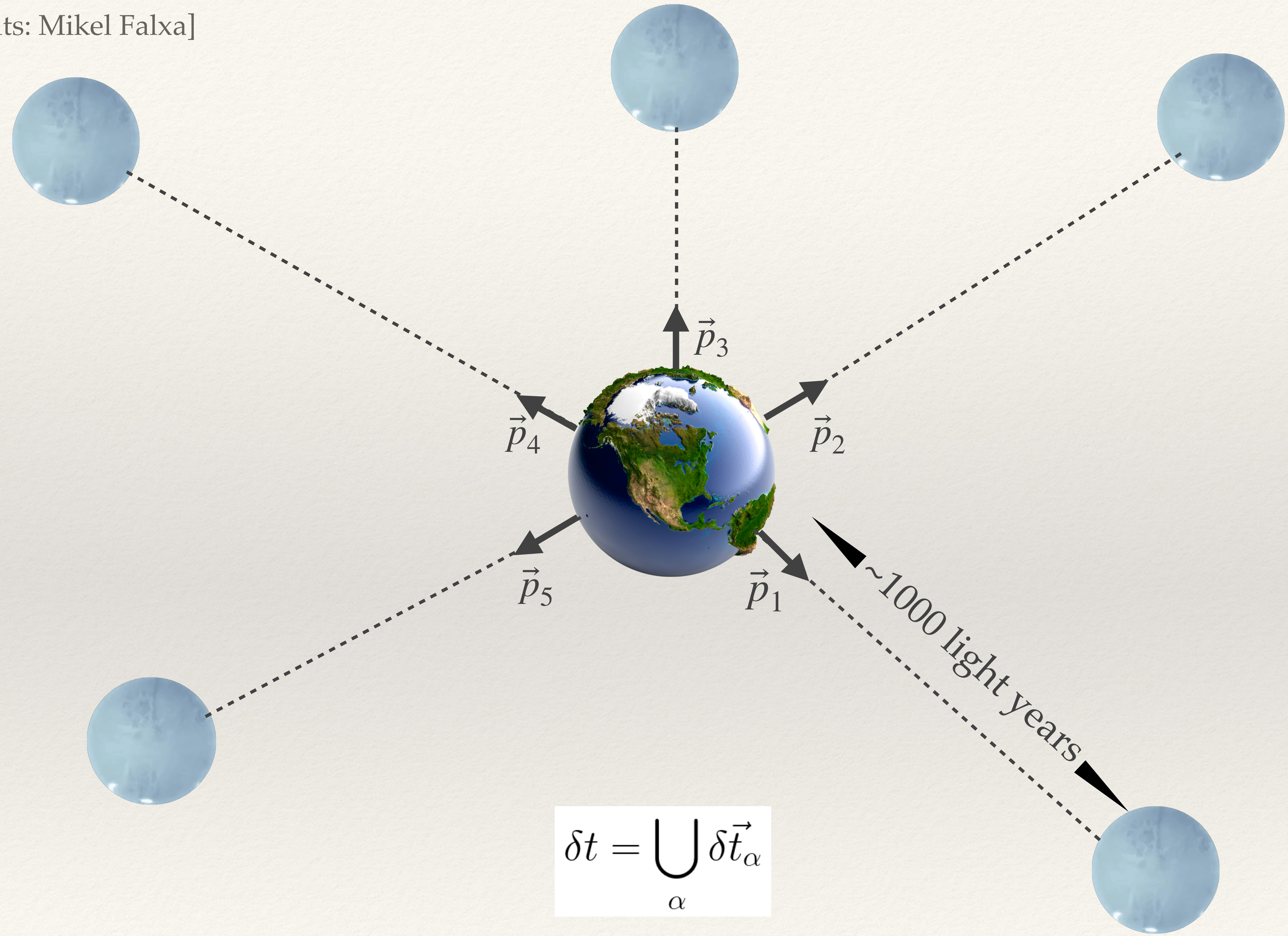
- Each observed radio pulse profile has a lot micro-structure. If we average over ~hour the (average) profile is very stable
- We can use the average pulse profile to estimate the time-of-arrival (TOA) of the pulses.
- The idea is to measure the TOA, and compare to the expected TOA. We know the spin of the pulsars, so we can predict the TOA. The difference between measure and expected TOA: ***residuals***

Predicting arrival time



Pulsar Timing Array

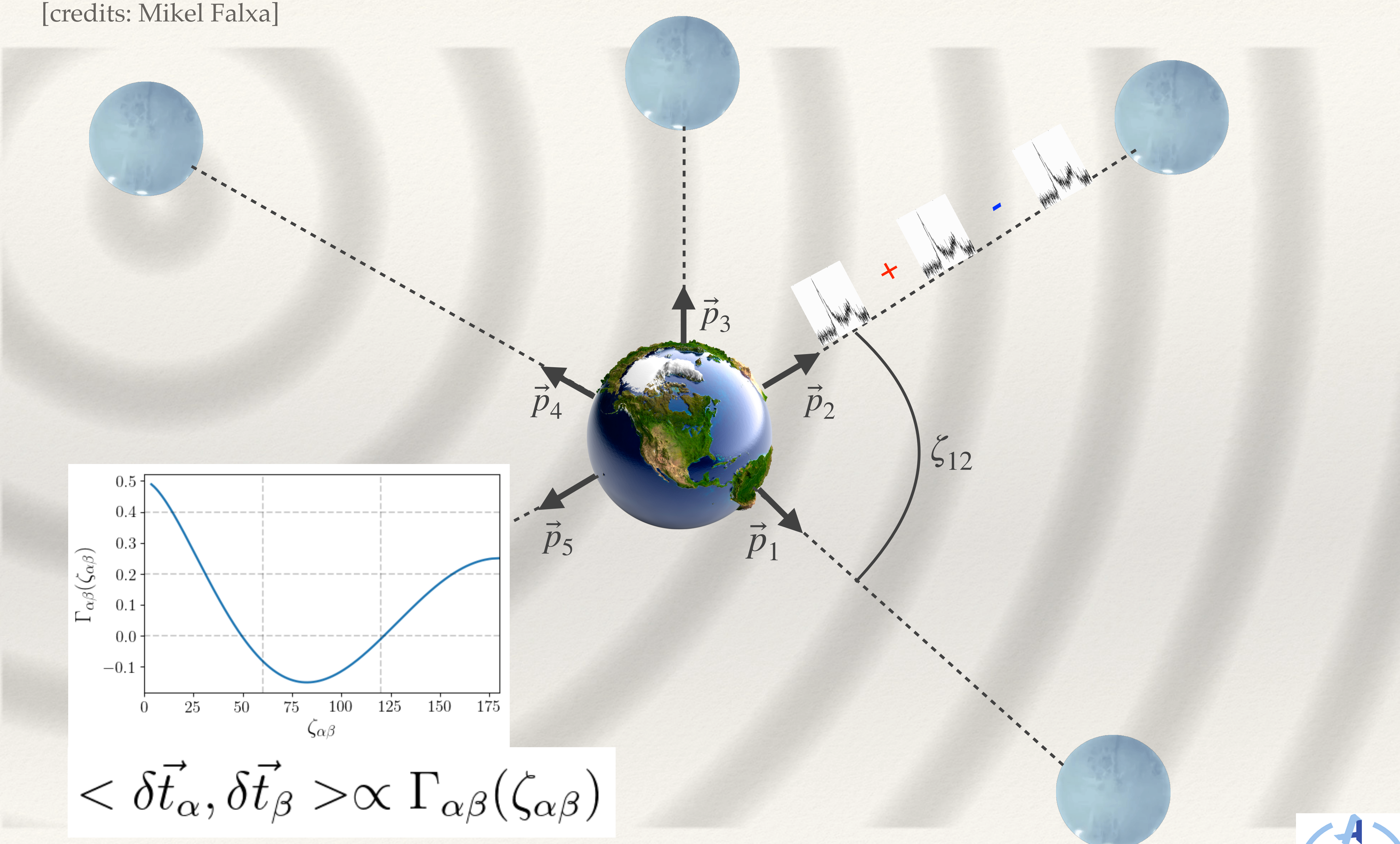
[credits: Mikel Falxa]



$$\delta t = \bigcup_{\alpha} \delta \vec{t}_{\alpha}$$

Pulsar Timing Array

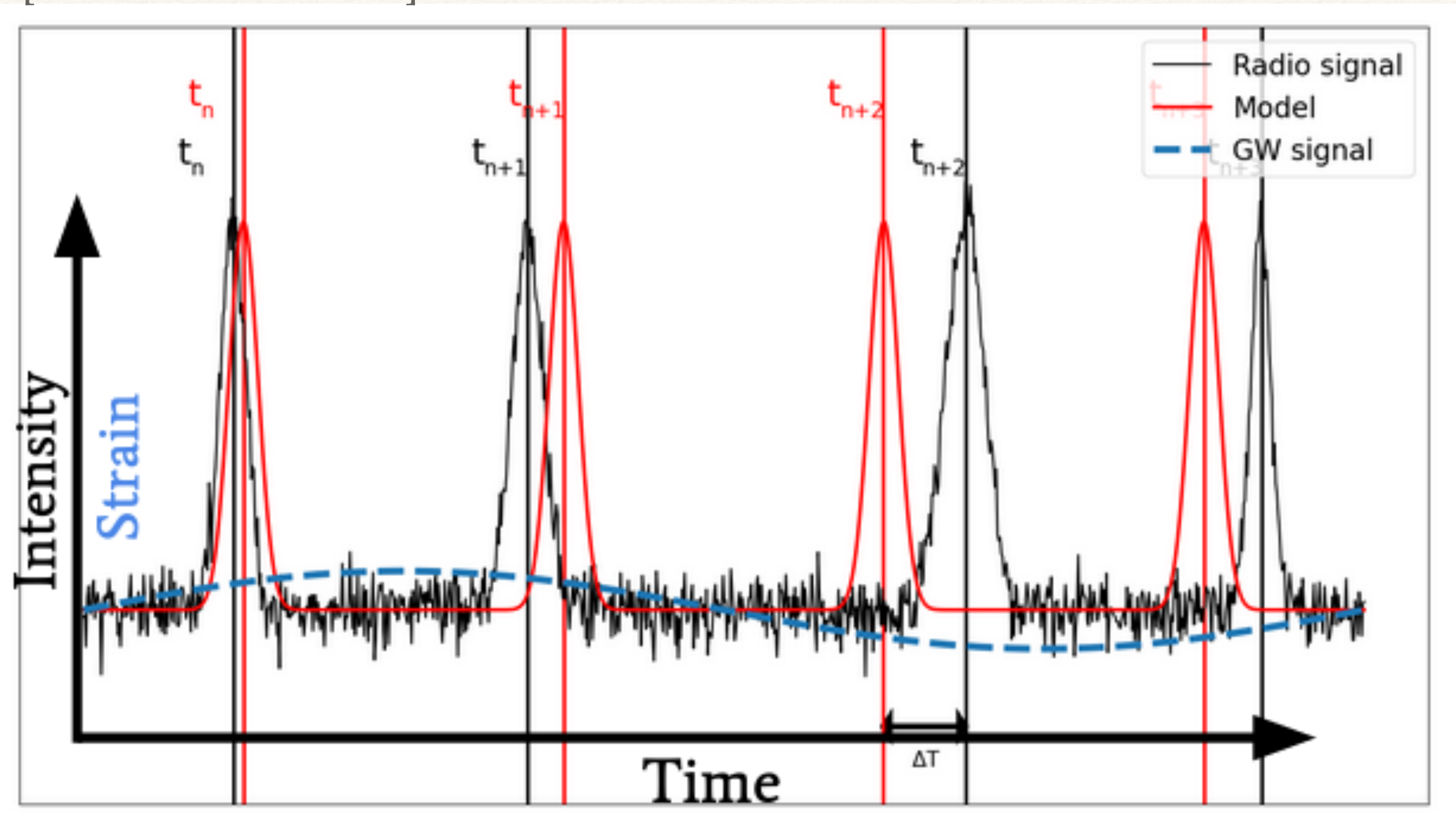
[credits: Mikel Falxa]



$$< \delta\vec{t}_\alpha, \delta\vec{t}_\beta > \propto \Gamma_{\alpha\beta}(\zeta_{\alpha\beta})$$

Timing Residuals

[credits: Mikel Falxa]



$$dt = t^{p}_{toa} - t^{o}_{toa} = dt_{errors} + \delta\tau_{GW} + noise$$

Errors in fitting the model

due to GWs

Detection statistic and search algorithm

- We assume that noise is Gaussian: the likelihood function (likelihood of the signal with given parameters) is

$$P(\vec{\delta t}, \vec{\theta}) = \frac{1}{\sqrt{(2\pi)^n det(C)}} \exp\left(-\frac{1}{2}(\vec{\delta t} - \vec{s})^T C^{-1} (\vec{\delta t} - \vec{s})\right),$$

- $\overrightarrow{\delta t}$ - concatenated residuals from all pulsars in the array: total size n
- $\vec{s}$ - is a model of deterministic signals (for example GW signals from individually resolvable SMBHBs)
- C is the noise variance-covariance matrix (size $n \times n$)

$$C_{\alpha i,\beta j} = C^{wn}\delta_{\alpha\beta}\delta_{ij} + C^{rn}_{ij}\delta_{\alpha\beta} + C^{dm}_{ij}\delta_{\alpha\beta} + C^{GW}_{\alpha i,\beta j} + \ldots$$

white measurement noise	red noise spin noise	dispersion variation noise	stochastic GW signal

Noise modelling in PTA

- White noise — not very interesting. Two parameters per backend per pulsar: unaccounted noise.
- Red noise: very generic noise description in freq. domain

$$S(f) = A_{rn}^2 f^{-\gamma}$$

common, uncorrelated red noise

$$S_\alpha(f) = A_{rn,\alpha}^2 f^{-\gamma_\alpha}$$

red noise in each pulsar

- DM (dispersion measurement variation) noise: depends on the radio-frequency of observation

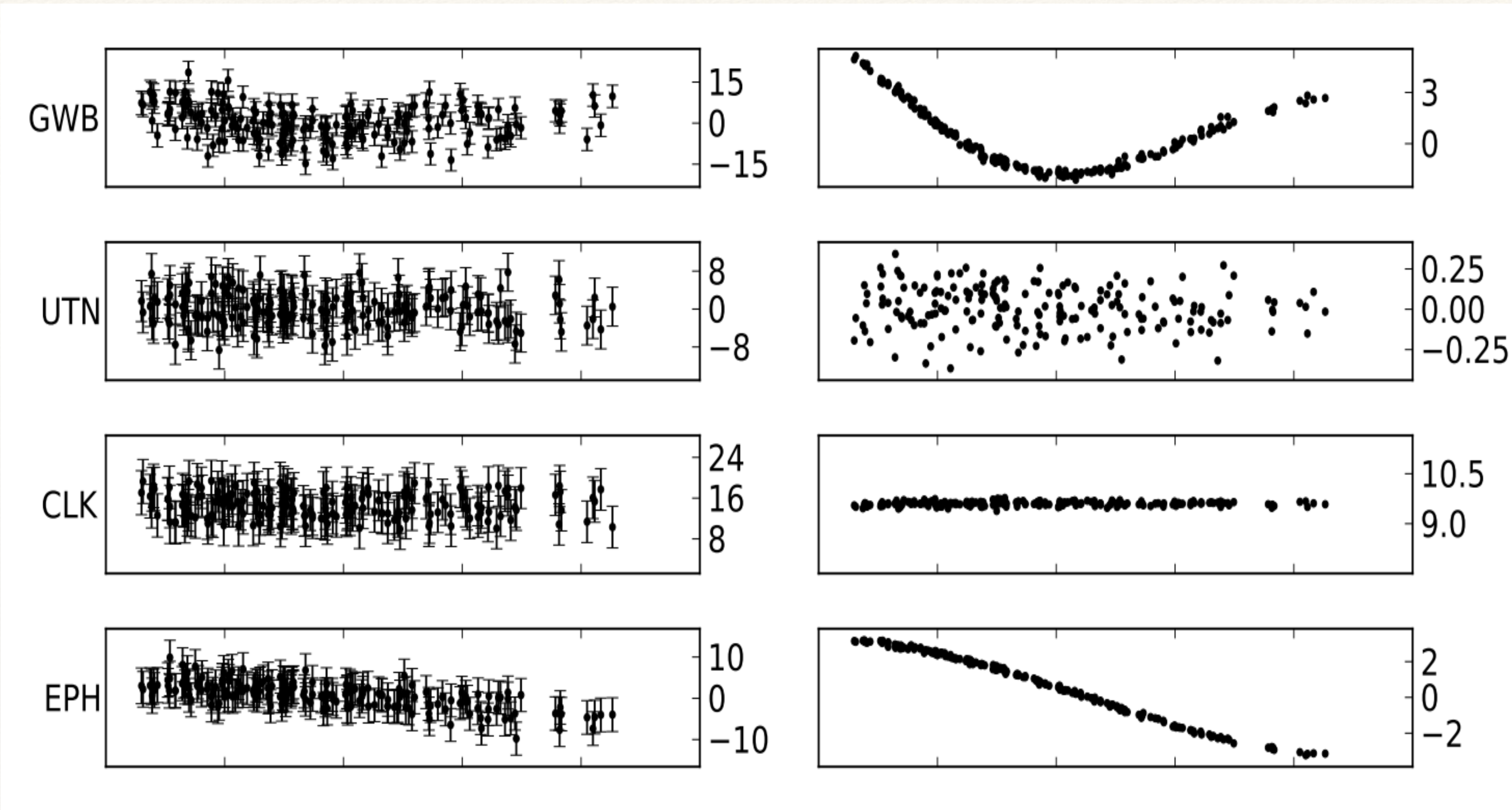
$$S_{DM}(f) \propto \frac{A_{dm}^2}{\nu^2} f^{-\gamma_{dm}}$$

- Correlated red noise processes

$$S_{\alpha\beta} = \Gamma_{\alpha\beta} A_{cor}^2 f^{-\gamma_{cor}}$$

— includes also cross spectrum between each pair of pulsars: $\Gamma_{\alpha\beta}$ - spacial correlation coefficients

Correlated noise



GWB (Quadrupole) Hellings-Downs

Uncorrelated RN

Clock error (monopole)

Ephemeris (dipole)

TOAs, time

Correlation, angular separation

stochastic GW from population of SMBHBs: $S_{\alpha\beta}^{SMBHB} = \Gamma_{\alpha\beta}^{H-D} A_{GW}^2 f^{-13/3}$

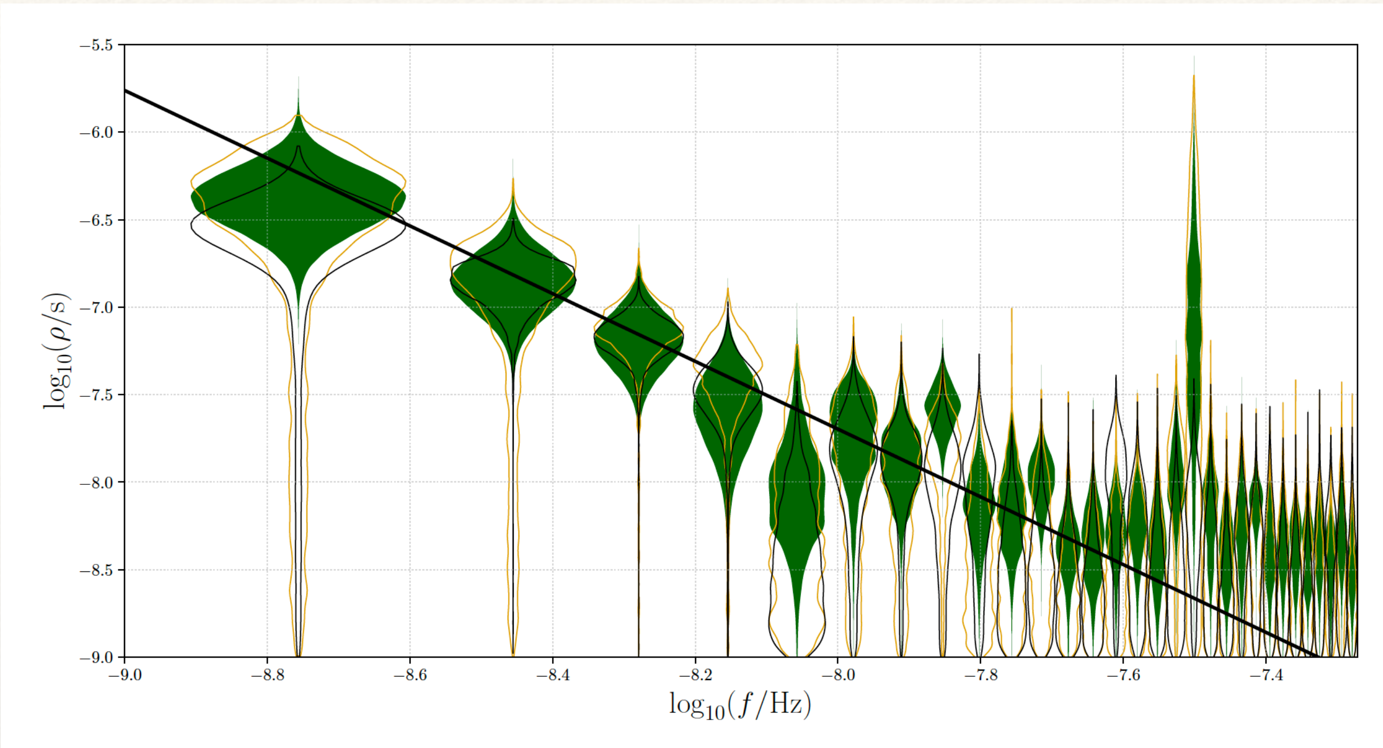
IPTA

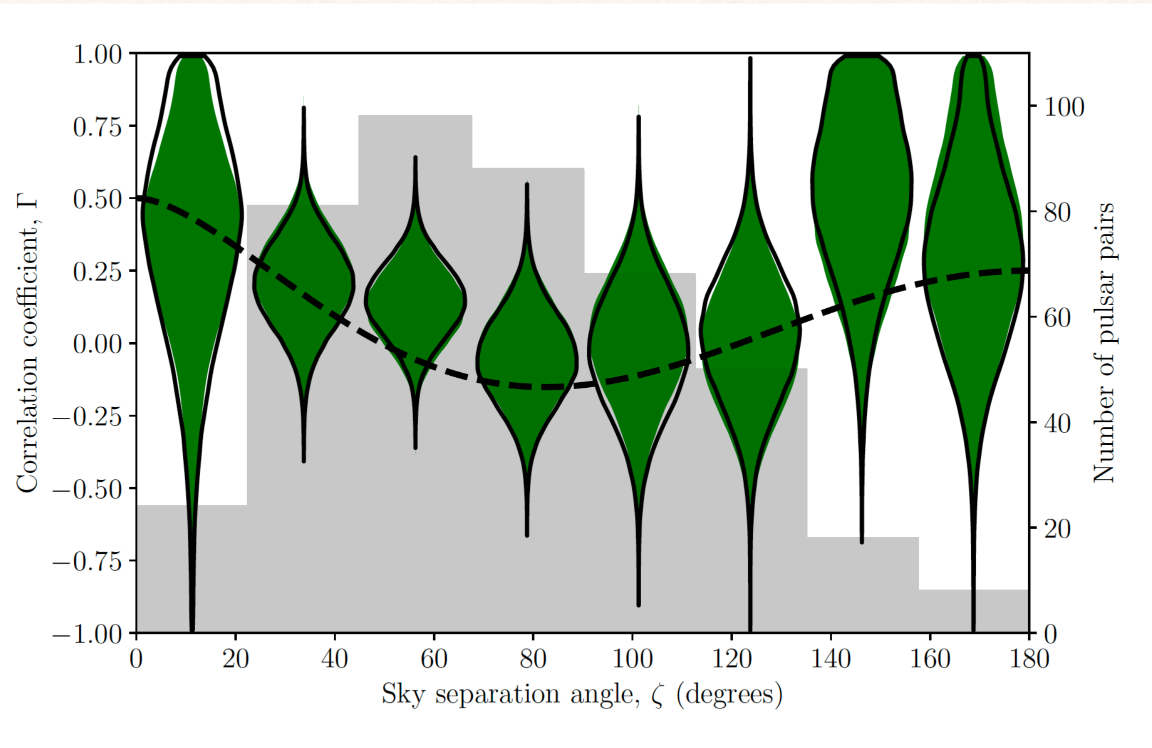
Lovell
Nançay
WSRT
SRT
Effelsberg
EPTA
GBT
Arecibo
VLA
CHIME
NANOGrav
FAST
CPTA
Parkes
PPTA
MeerKAT
MPTA
GMRT
InPTA
IPTA

PPTA results

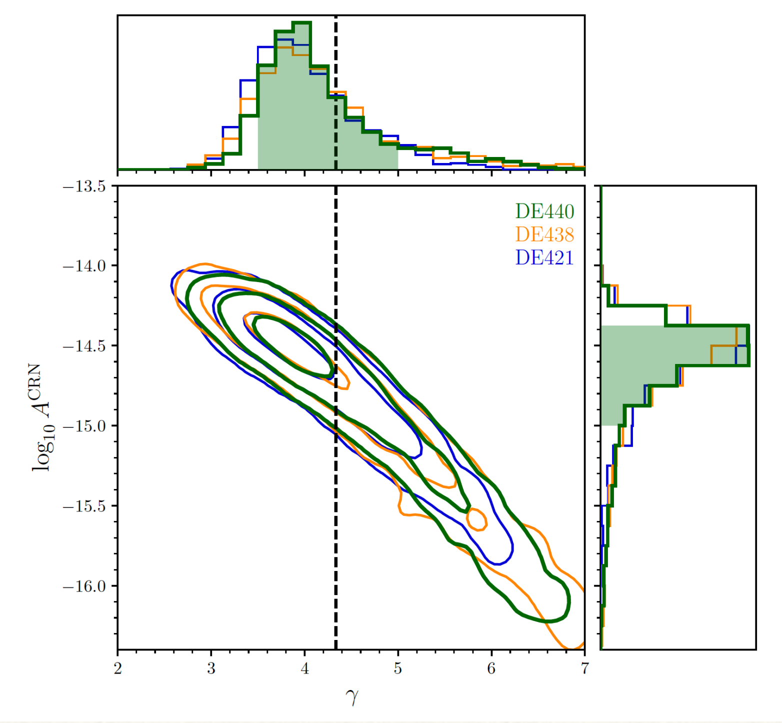
[PPTA 2306.16215]

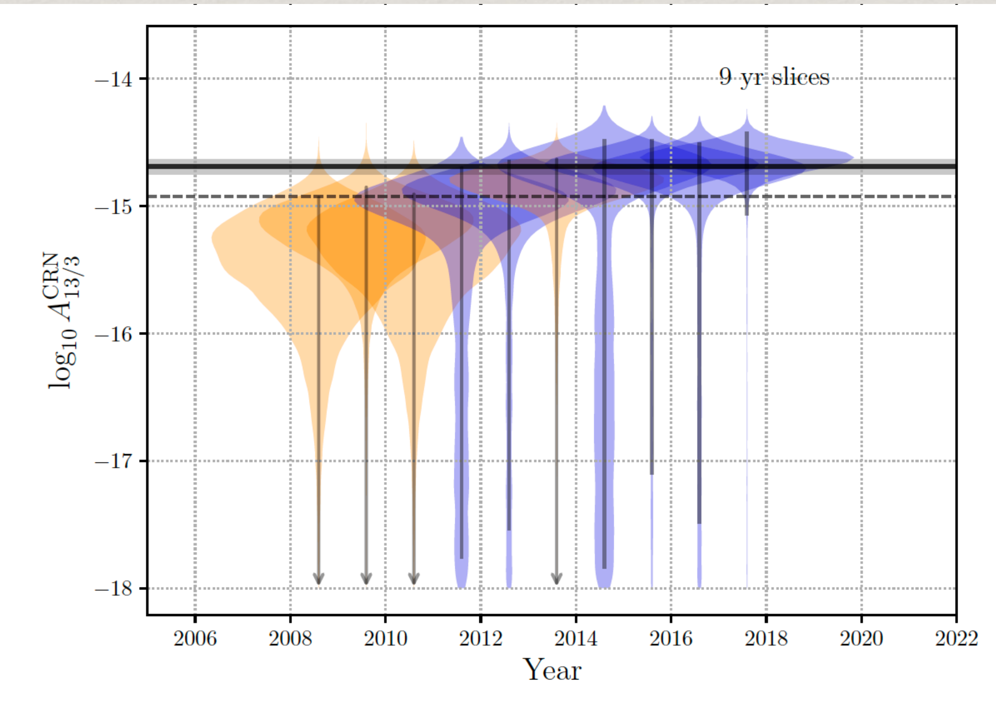
PPTA data: 18 years, 30 pulsars. 3 years of new ultra-widebandwidth radio observations





Estimating power at Fourier freq. (assuming independence).
Black: CURN, Gold: H-D



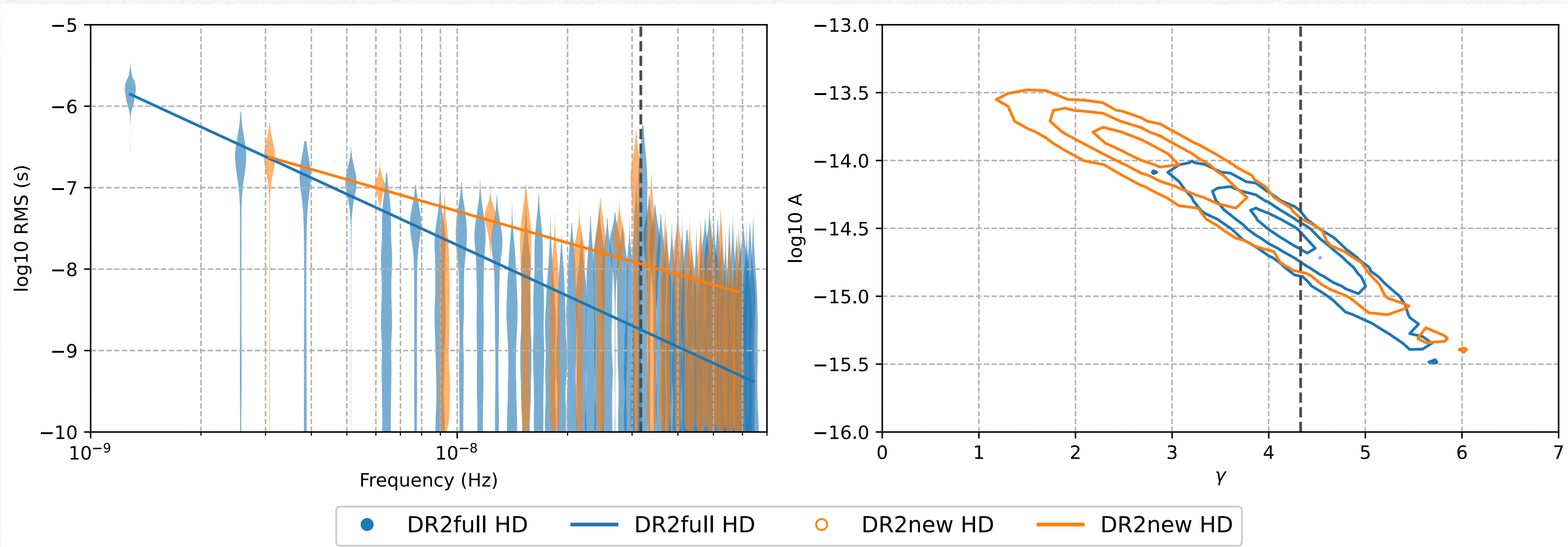


$$S_{\alpha\beta}^{SGWB} = \Gamma_{\alpha\beta}^{H-D} A_{GW}^2 f^{-\gamma}$$

EPTA + InPTA

[EPTA+InPTA2306.16214]

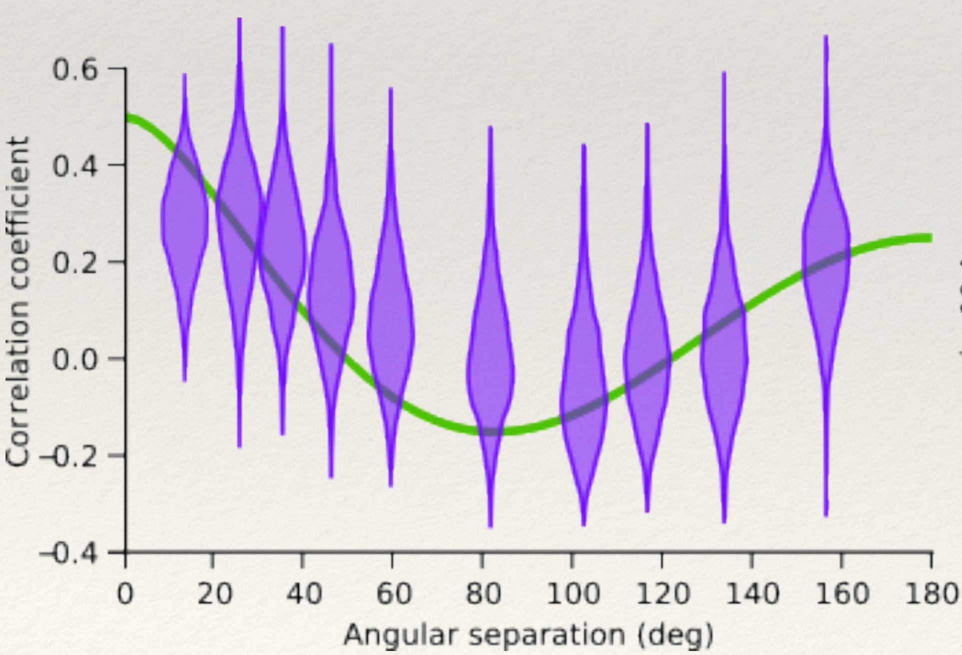
25 plsrs, DR2full: up to 25yrs, DR2new: latest 11 yrs, DR2new+ Includes InPTA data (3.5 yrs)

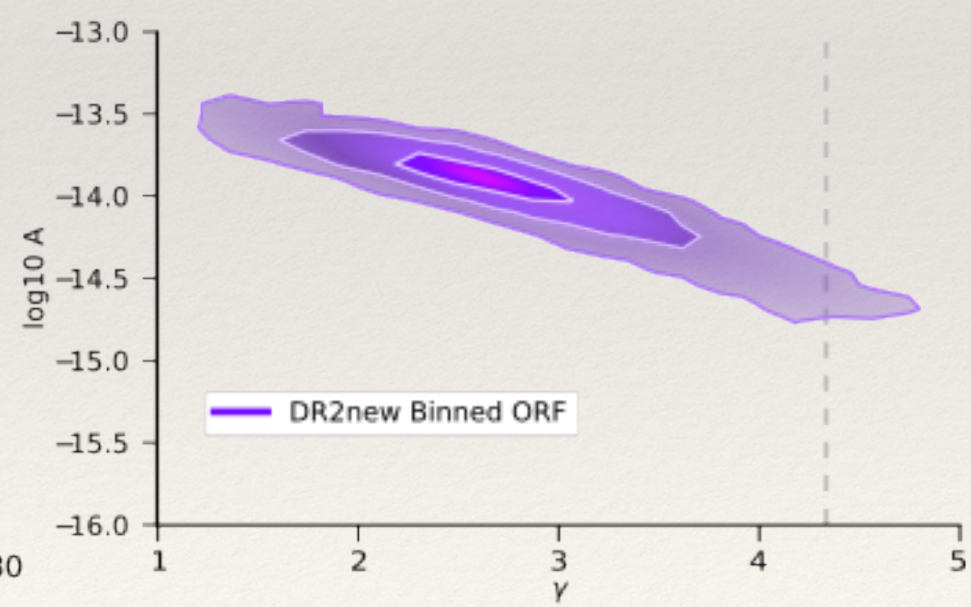


$$S_{\alpha\beta}^{SGWB} = \Gamma_{\alpha\beta}^{H-D} A_{GW}^{2} f^{-\gamma}$$

Statistic	DR2full	DR2new	DRnew+
$\mathscr{B}_{CURN}^{HD}$	4	60 33(+Ephem)	65 43 (+Ephem)

DR2new results: spatial correlations and amplitude-slope of power-law model

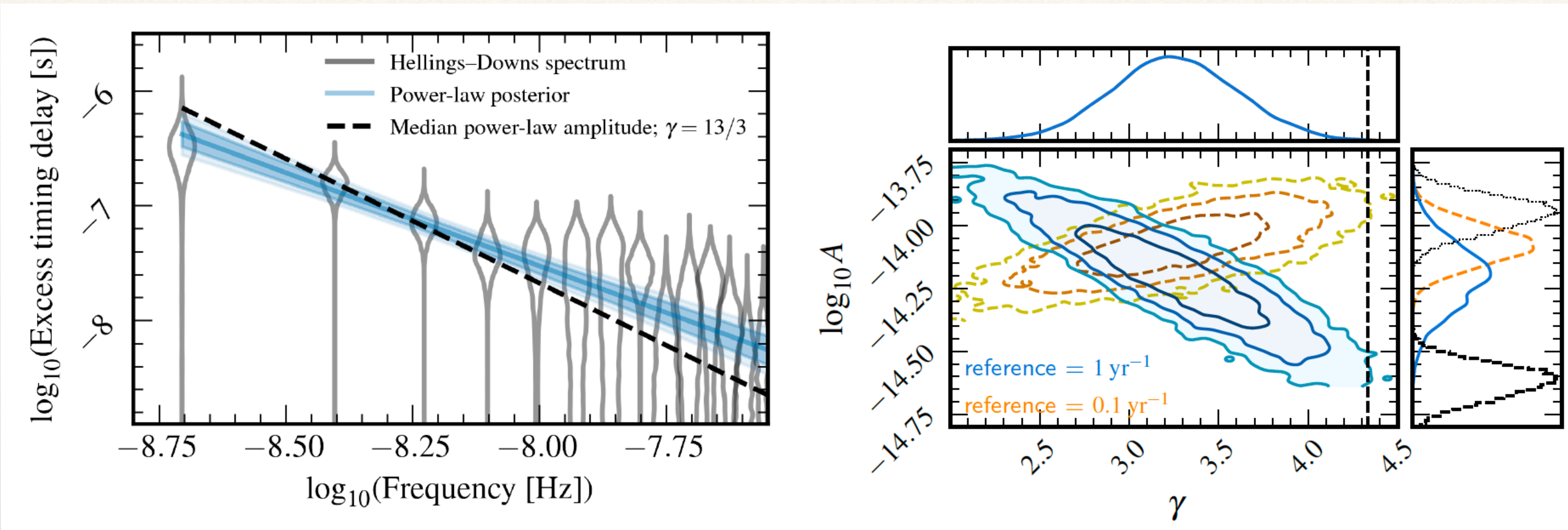


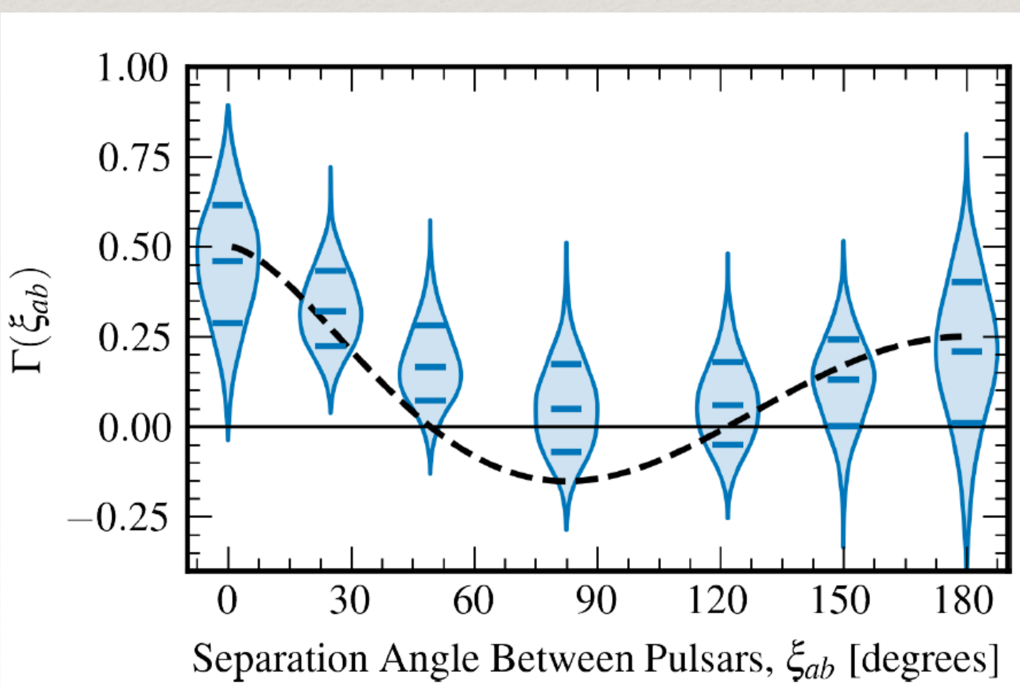


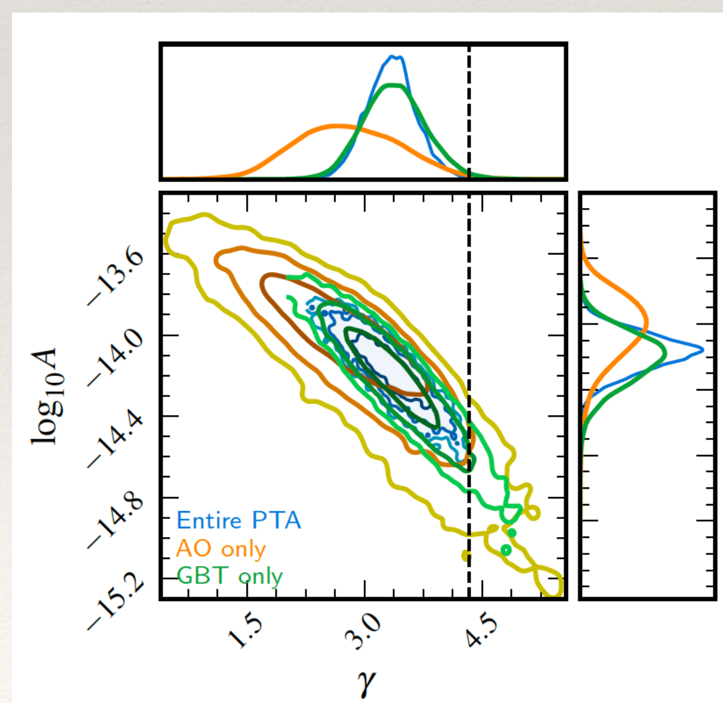
NanoGrav results

[NG 2306.16213]

NG data: 15 years of data, 67 pulsars. Arecibo + Green Bank







$$S_{\alpha\beta}^{SGWB} = \Gamma_{\alpha\beta}^{H-D} A_{GW}^2 f^{-\gamma}$$

Interpretation

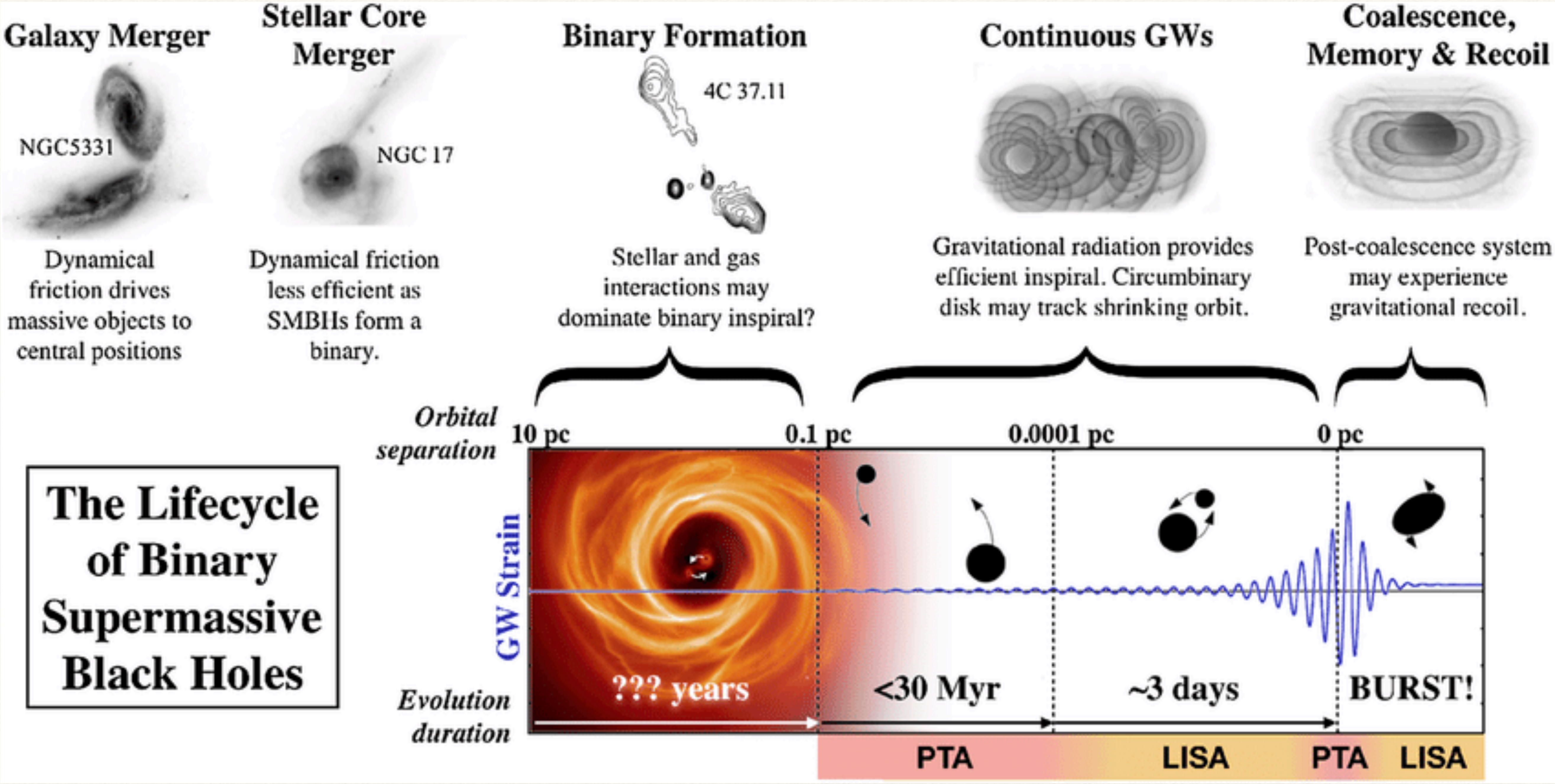
LET US ASSUME THAT WHAT WE OBSERVE IS STOCHASTIC GW BACKGROUND (SGWB)

What could produce SGWB with the power-law-like spectrum?
Apparently almost anything that falls in nHz band… and even more
I'll give only few examples

DISCLAIMER

preference in interpretation of observed signal and its siginficance: my personal view

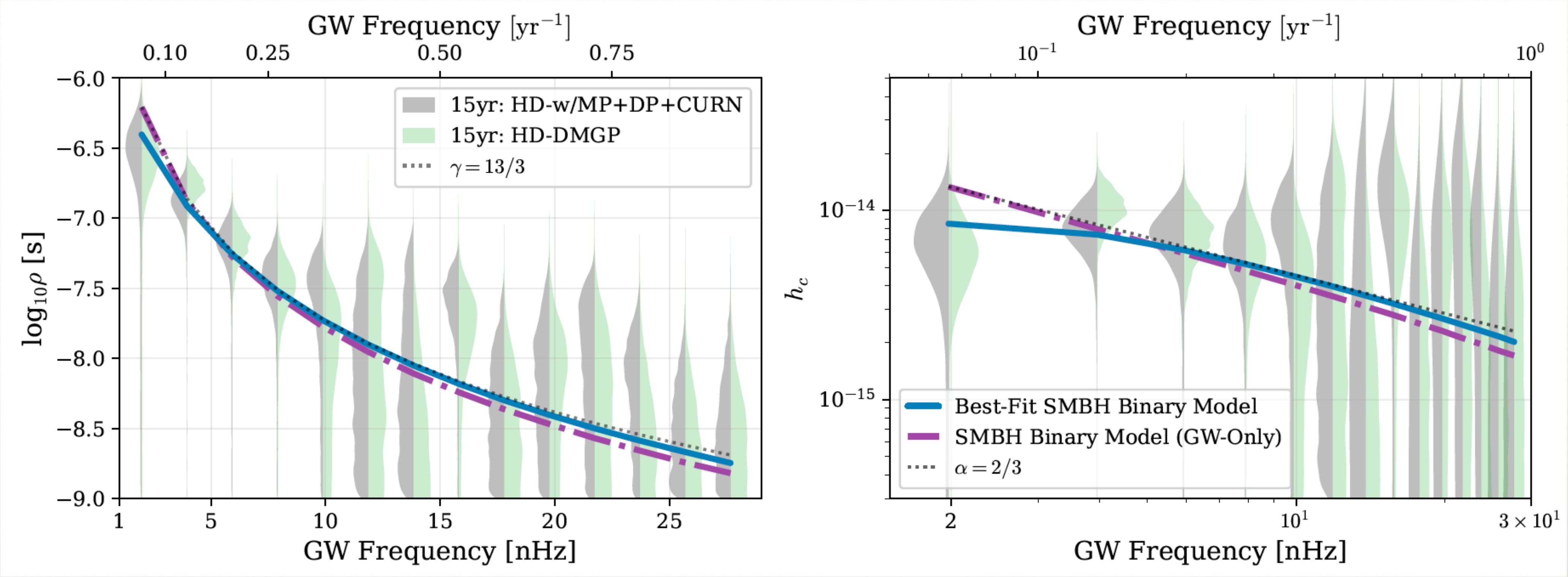
Massive black hole binaries



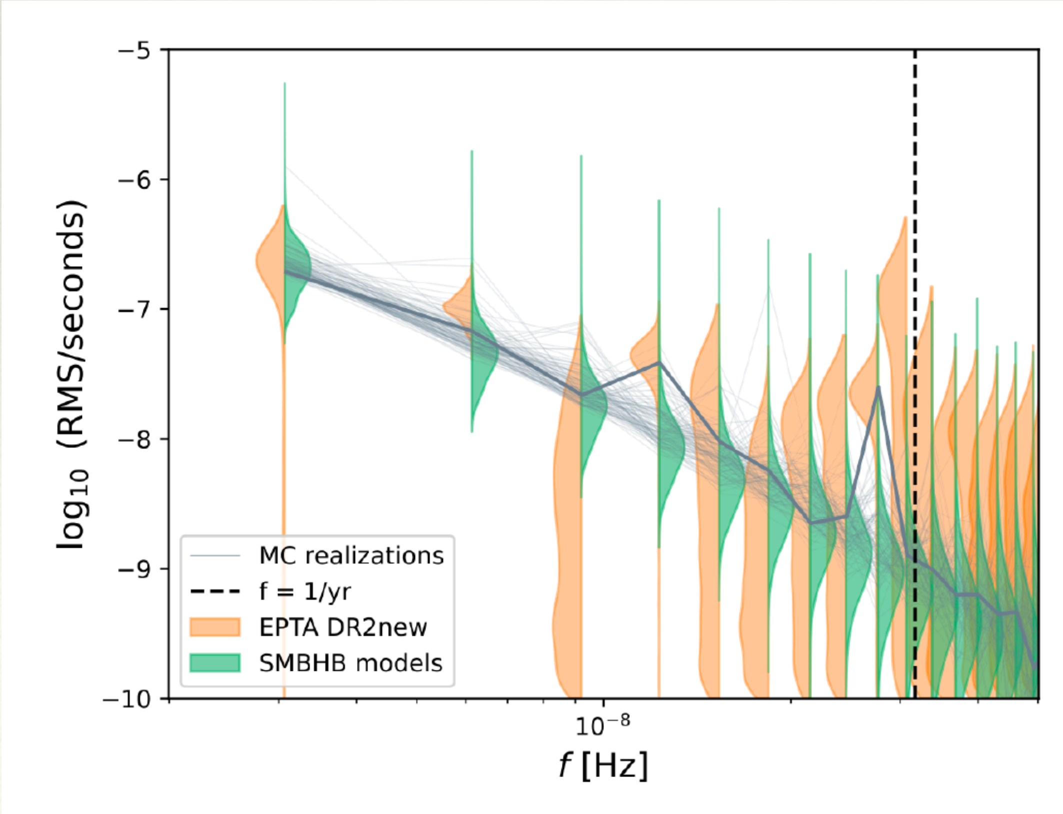
[S. Burke-Splolaor A&A review (2019)]

SGWB from population of SMBHBs

[NG: 2306.16220]



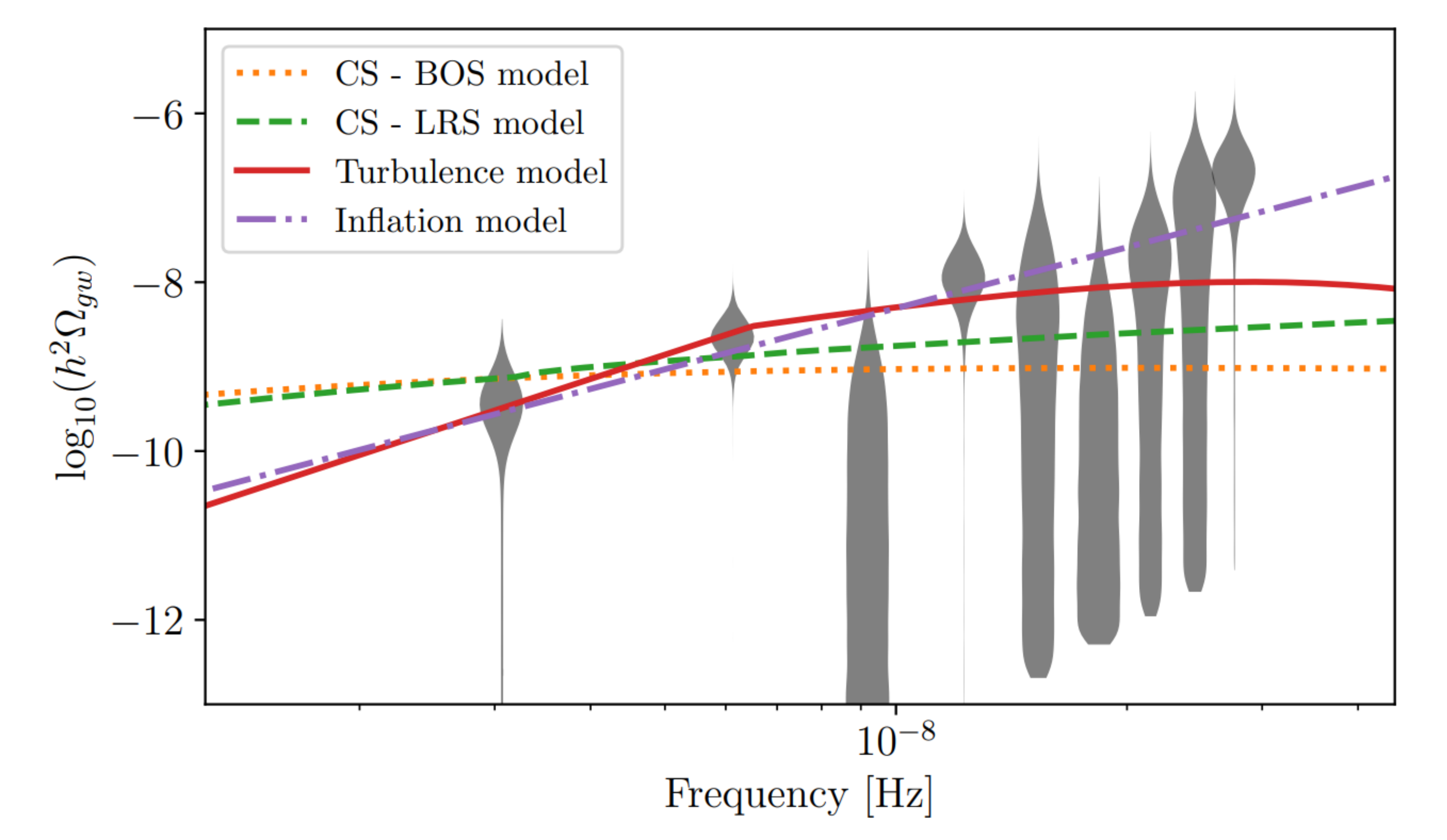
[EPTA 2306.16227]



The observed PTA signal could be stochastic GW signal from the population of SMBHBs in the local UNiverse

Interpretation of PTA signal

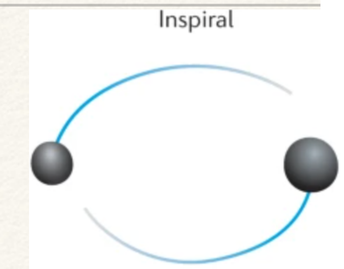
The signal is weak and poorly constrained:
almost "anything" can more-or-less explain it



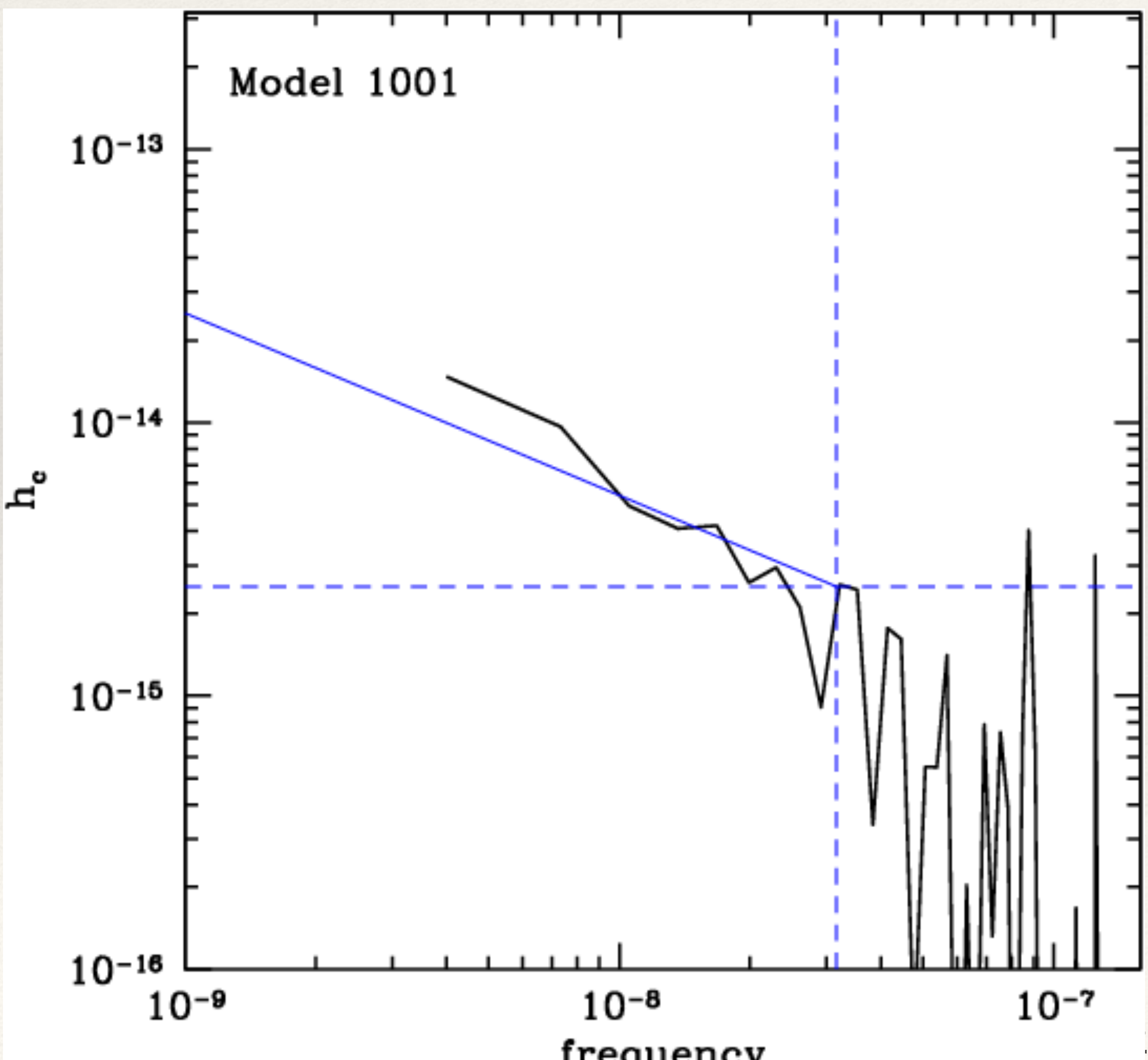
[Credits: Hippolyte Quelquejay]

Search for individual MBHBs: continuous GW signal

Searching for GW signal from individual SMBHB binary:

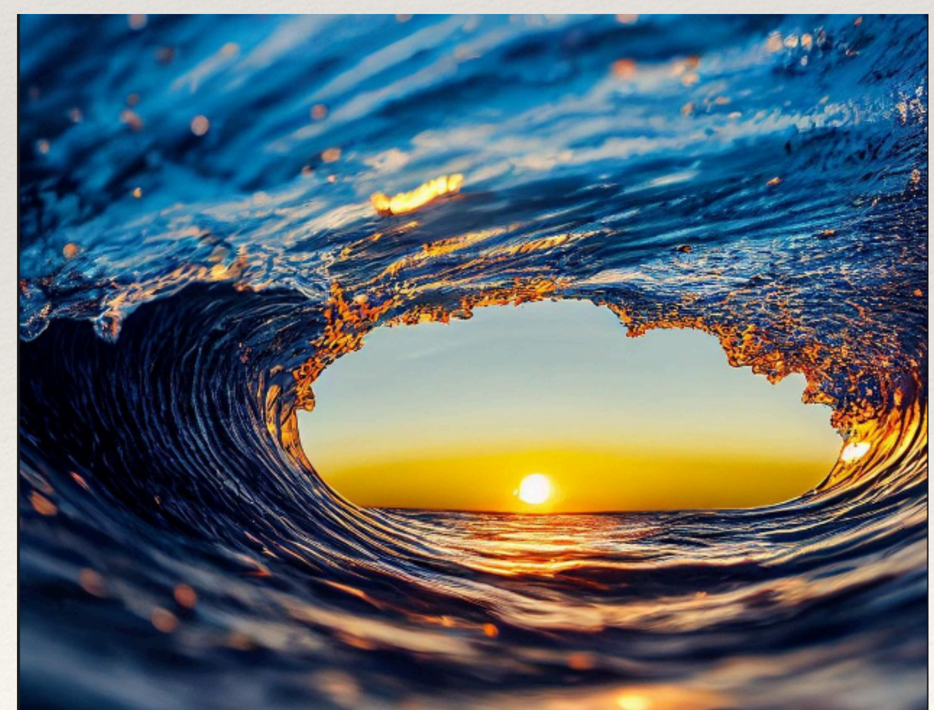


- Assume circular orbit
- Bayesian approach
- Strategy: all-sky search with simplistic model -> follow up candidates relaxing simplified assumptions on the reduced prior range

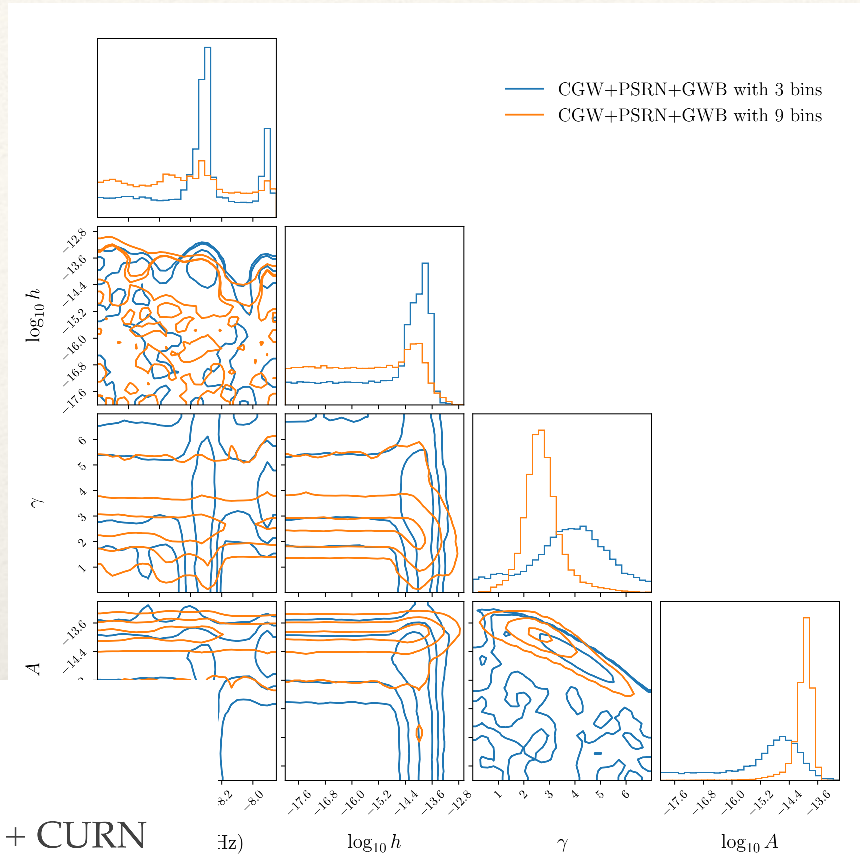


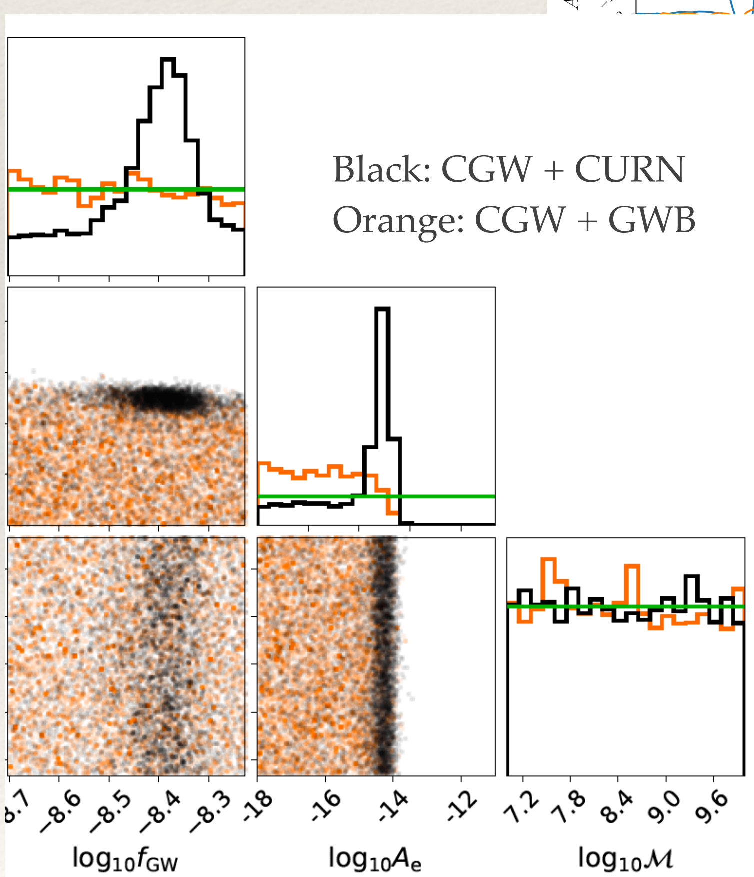
[NG: 2306.16222]

[EPTA+InPTA: 2306.16226]

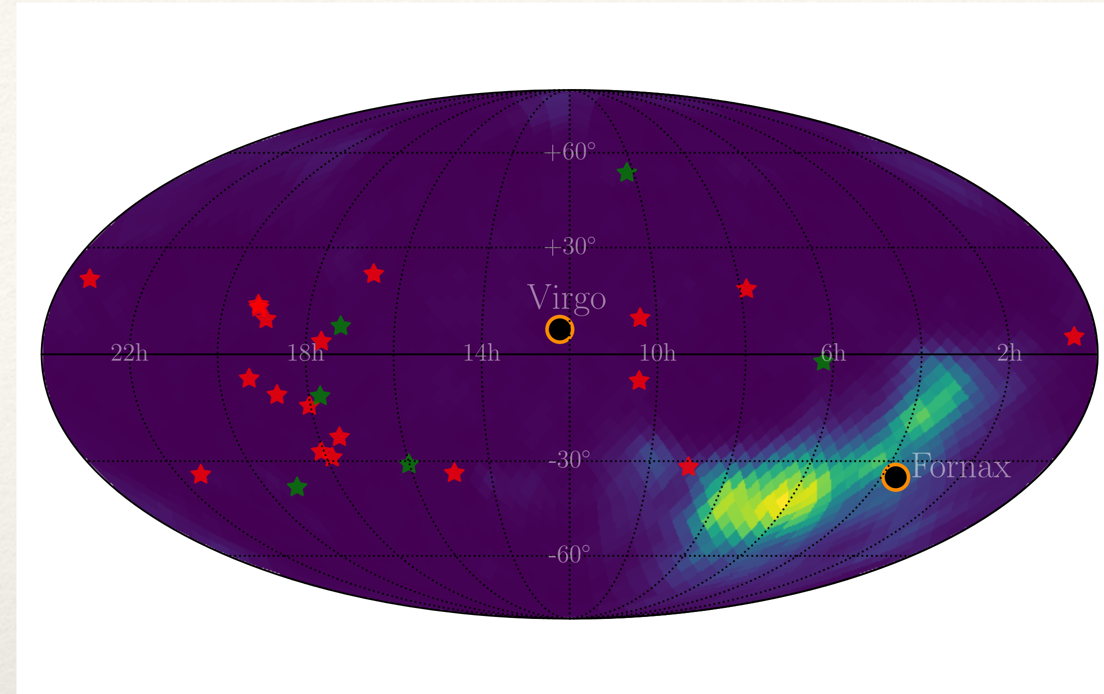


CGW signal in EPTA





$f \in (3.2, 6.0)$ nHz



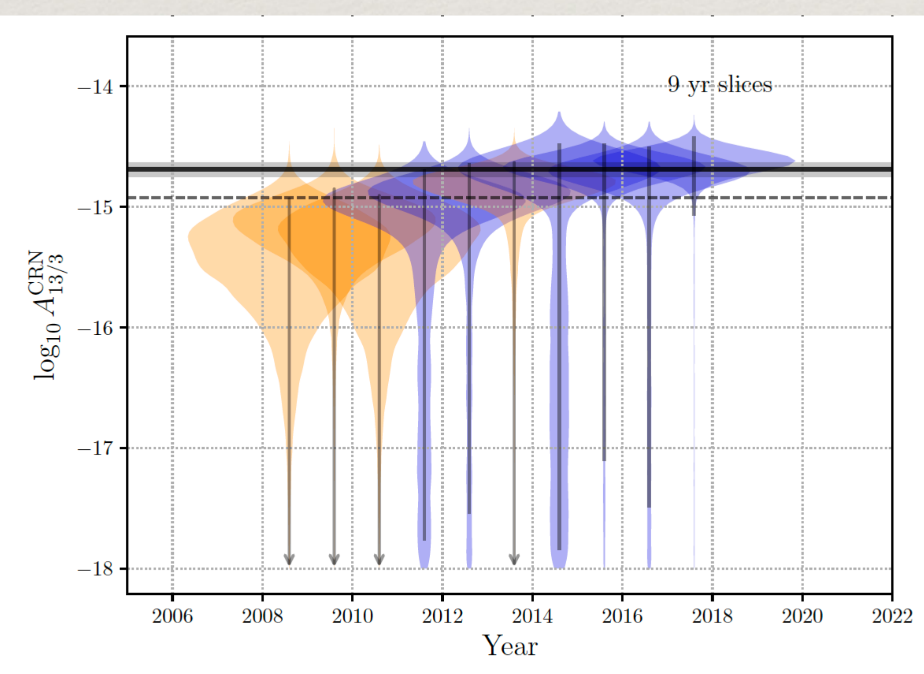
CGW: circular, Earth and Pulsar terms

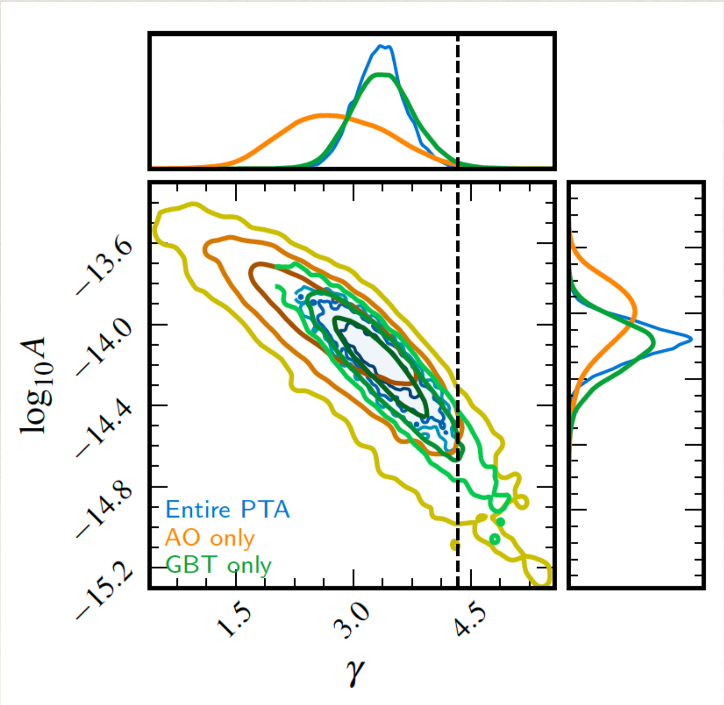
Model comparison	Bayes factor
CGW+PSRN vs PSRN	4000
CGW+PSRN+CURN vs PSRN+CURN, 3 bins	12
CGW+PSRN+CURN vs PSRN+CURN, 9 bins	4
CGW+PSRN+GWB vs PSRN+GWB, 3 bins	1
CGW+PSRN+GWB vs PSRN+GWB, 9 bins	0.7

Is it really GW signal?

- Error in ephemerides: JPL ephemerides D440, good measurement of Jupyter
- Modelling noise of each pulsar is very important: J1713+0747
- Quite different BF from each PTA: 1-2 (PPTA), 60-70 (EPTA), 230-950 (NG)
- EPTA “sees” the signal only in last 14 years, PPTA sees signs of non-stationarity
  - Is it non stationarity in the GWB?
  - or in the PSR noise model?
  - or evolution of how we deal with radioobservations?

Non-stationarity modelling: [Falxa+, PRD 2024]





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What's next?

IPTA data combination:

- We combine the data from IPTA: EPTA, NG, InPTA, PPTA
- We use additional data (MeerKAT, Chime)
- Better coverage (dense) in time (smaller cadence)
- Better coverage in radio freq: DM and scattering variations
- Not dominated by a single radiotelescope: should see/handle systematics

New IPTA dataset (DR3)

Credits: Kuo Liu

IPTA DR3 dimensions

- In total **121** pulsars in full DR3;
  - The biggest / most sensitive PTA dataset ever made !!

Dataset	Number of pulsars	Time span	Frequency range
EPTA DR2	25	24.5 yr	283 – 5107 MHz
NANOGrav 15-yr	68	15.9 yr	302 – 3988 MHz
PPTA DR3	24	18.1 yr	704 – 4032 MHz
InPTA DR1	15	3.5 yr	300 – 1460 MHz
MeerKAT DR2	83	4.5 yr	856 – 1712 MHz
CHIME DR1	11	2.5 yr	400 – 800 MHz
LOFAR+NenoFar	17	9.6 yr	35 – 190 MHz
IPTA DR3	121	~25 yr	~30 – 5000 MHz

3

New IPTA dataset (DR3)

IPTA DR3 dimensions

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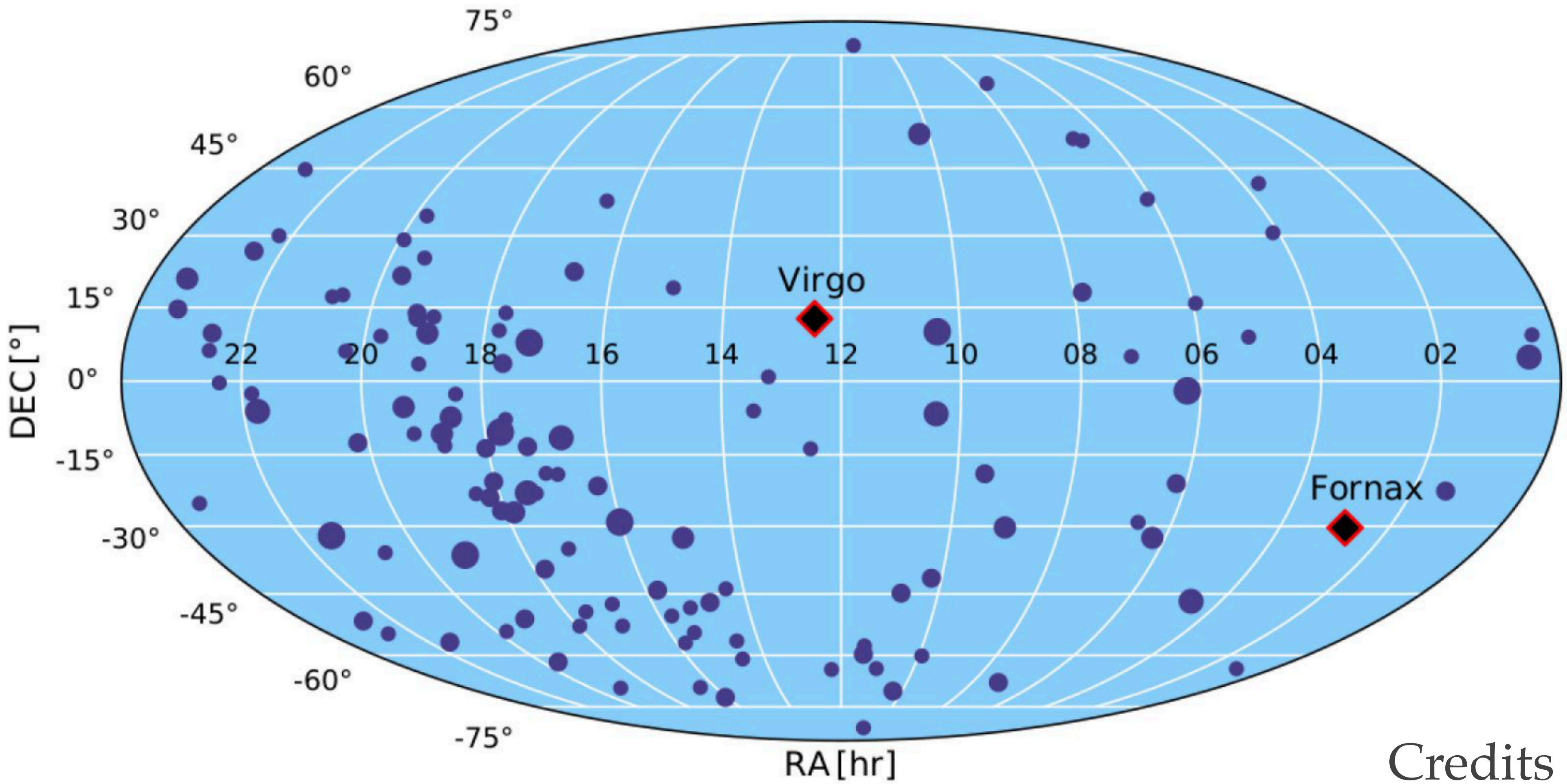
  - The biggest / most sensitive PTA dataset ever made !!



Credits Kuo Liu

4

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- Better coverage in radio freq: DM and scattering variations
- Not dominated by a single radiotelescope: should see/handle systematics

Kind of summary…

- We are pretty sure that the observed signal is GW
- We are not sure about its nature
- We got so excited that made a big press release
- In relaity we need to look at IPTA data, we need longer high quality data. It is "GW detection in slow motion"