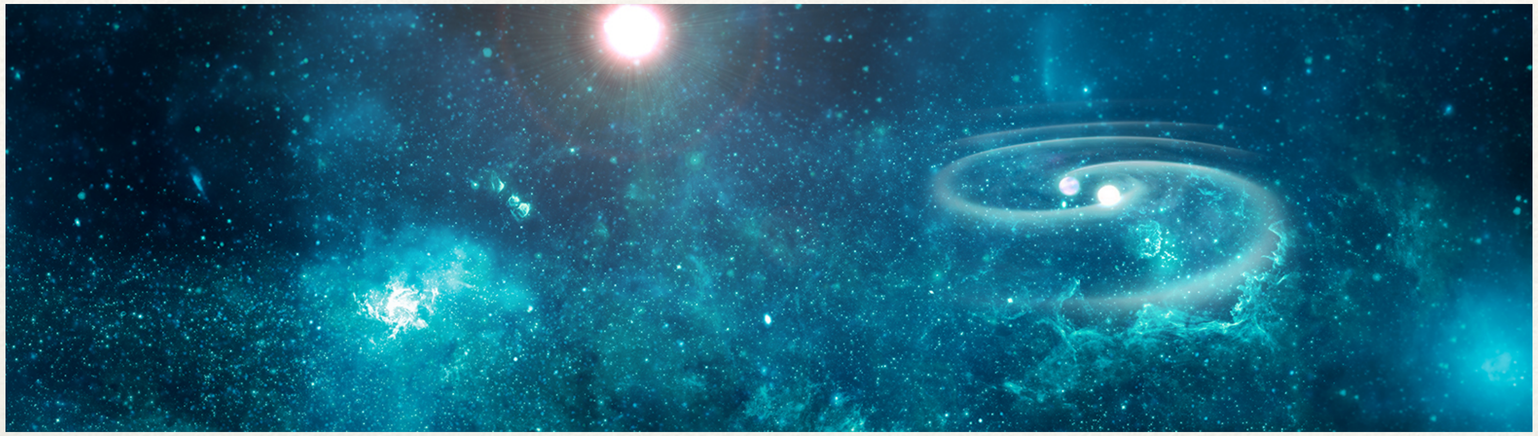
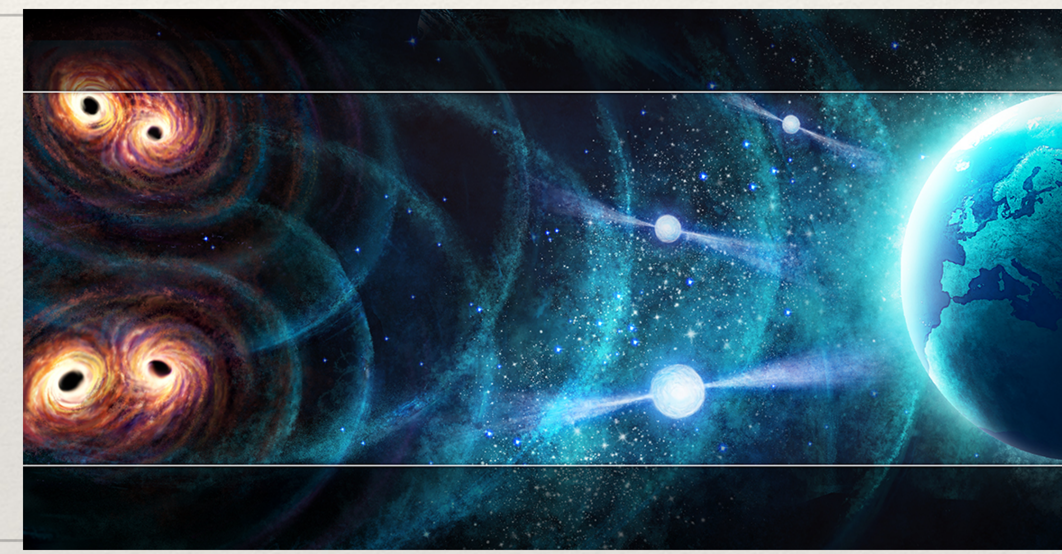
Stanislav (Stas) Babak.

AstroParticule et Cosmologie, CNRS (Paris)

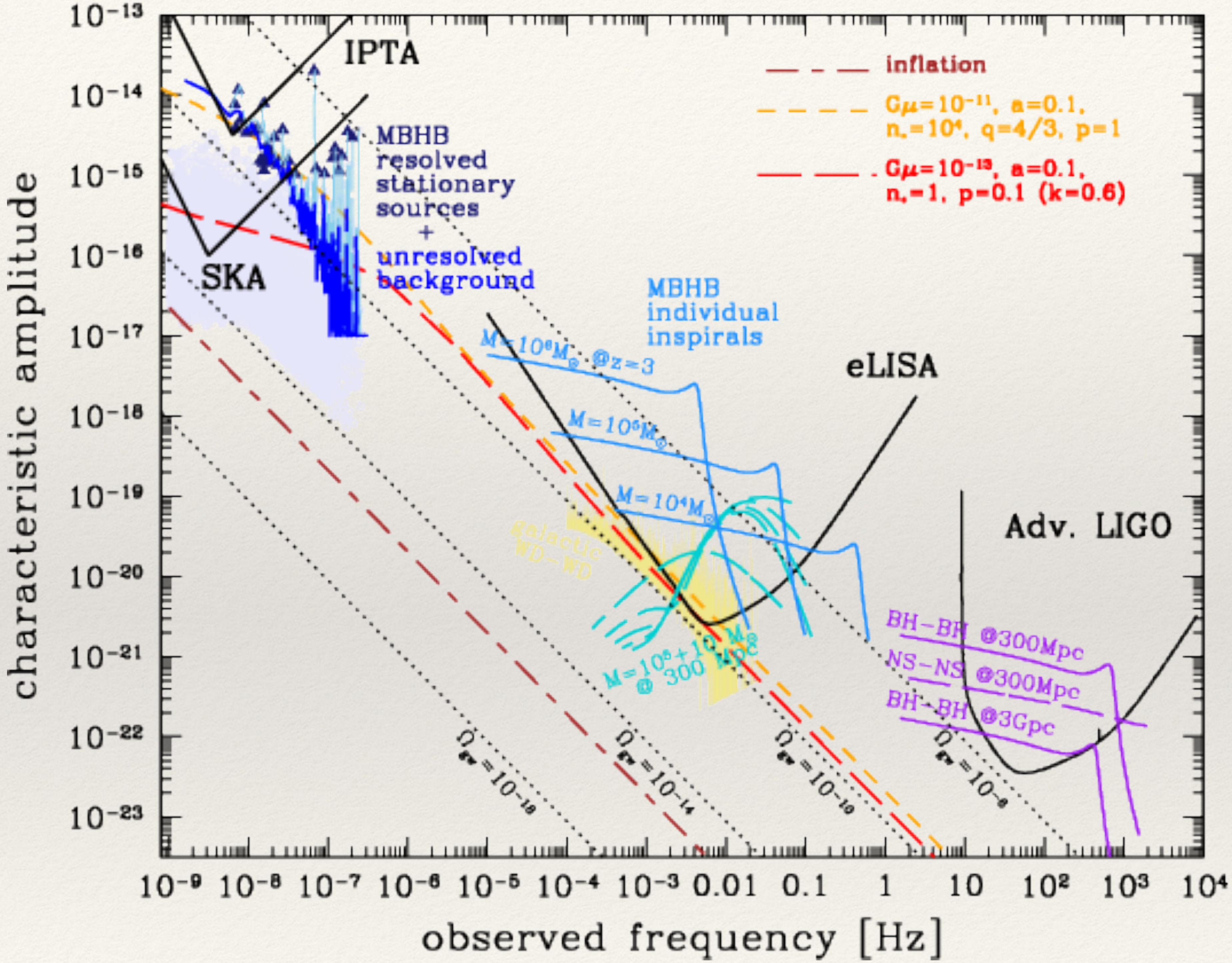


Pulsar Timing Array



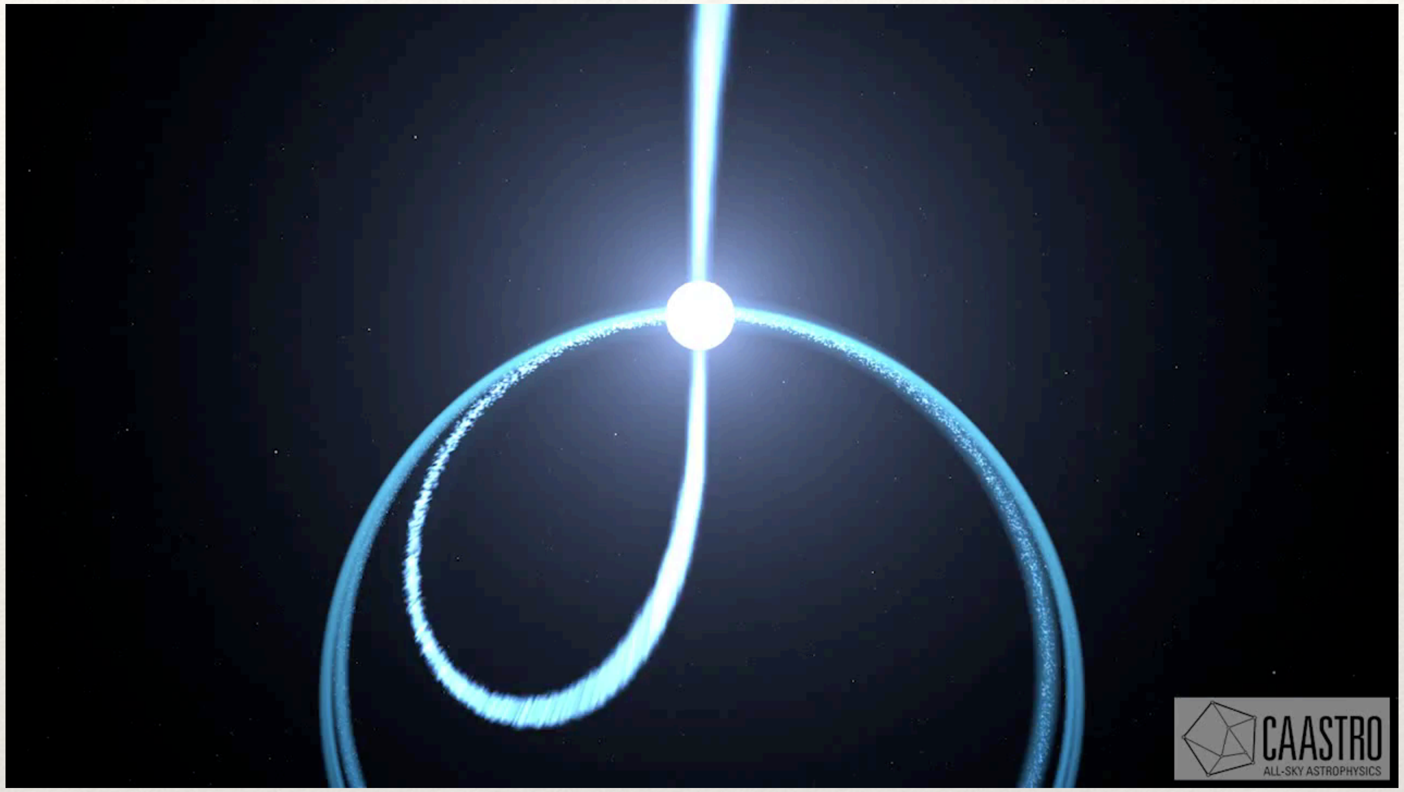
June 2025

GW landscape

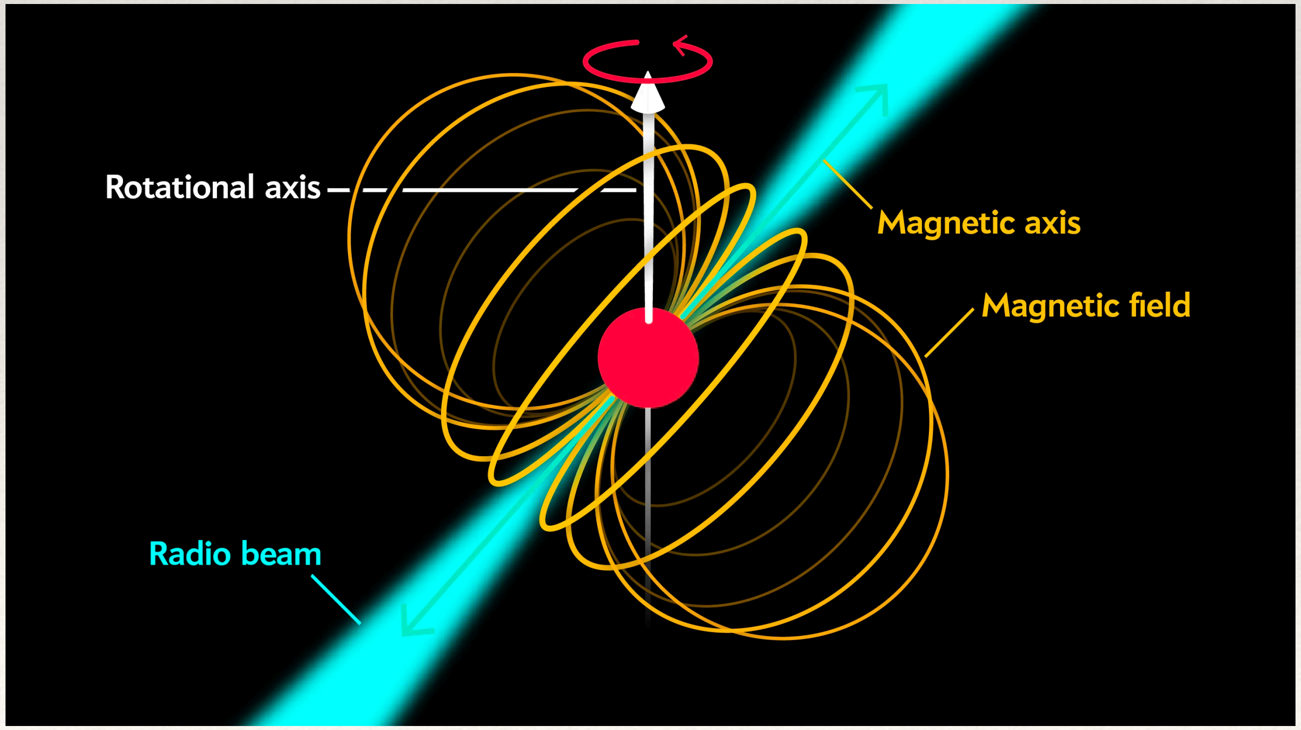


Millisecond pulsars

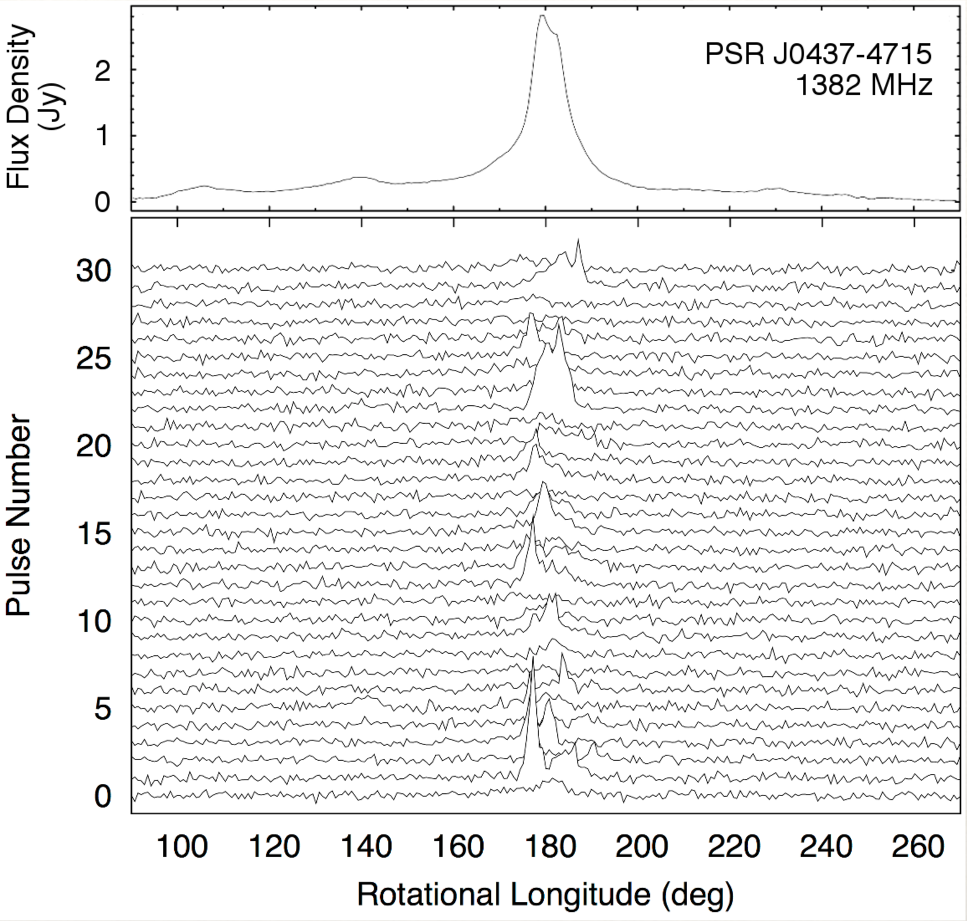
- Millisecond pulsars: period of rotation ~ millisec
- Often in binaries
- Very old NSs, very stable rotation
- The most accurate clock on the long time scale (decades)

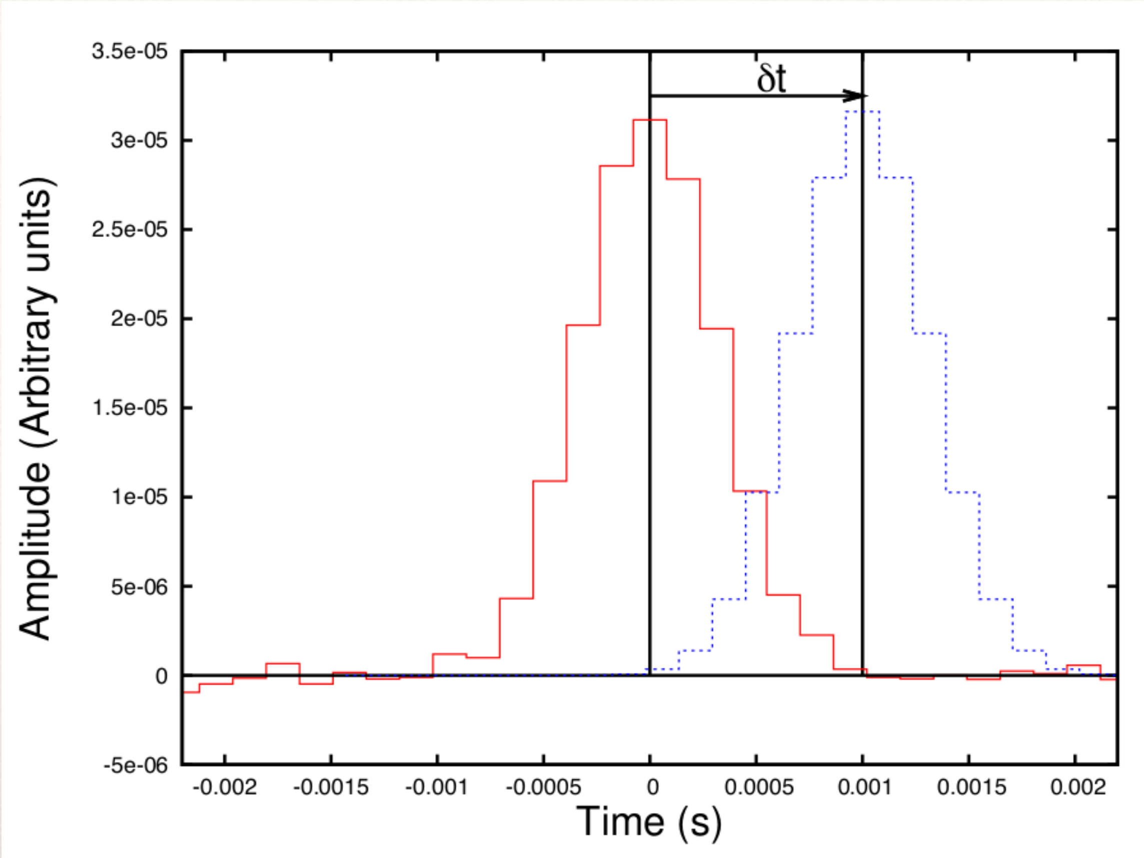


Jen Christiansen



Pulsar timing

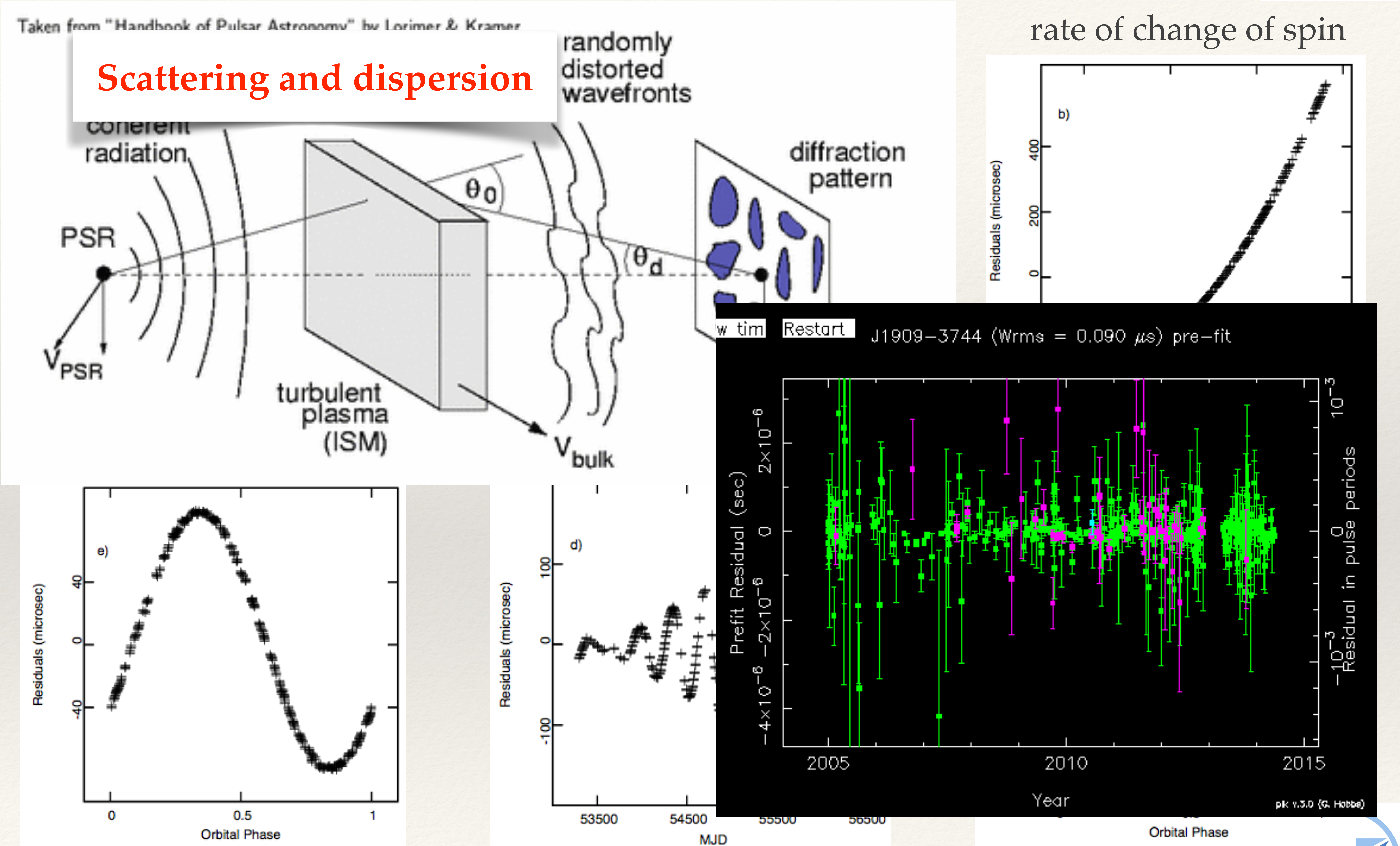




[Figs: credits
S. Burke-Spolar & L. Lentati]

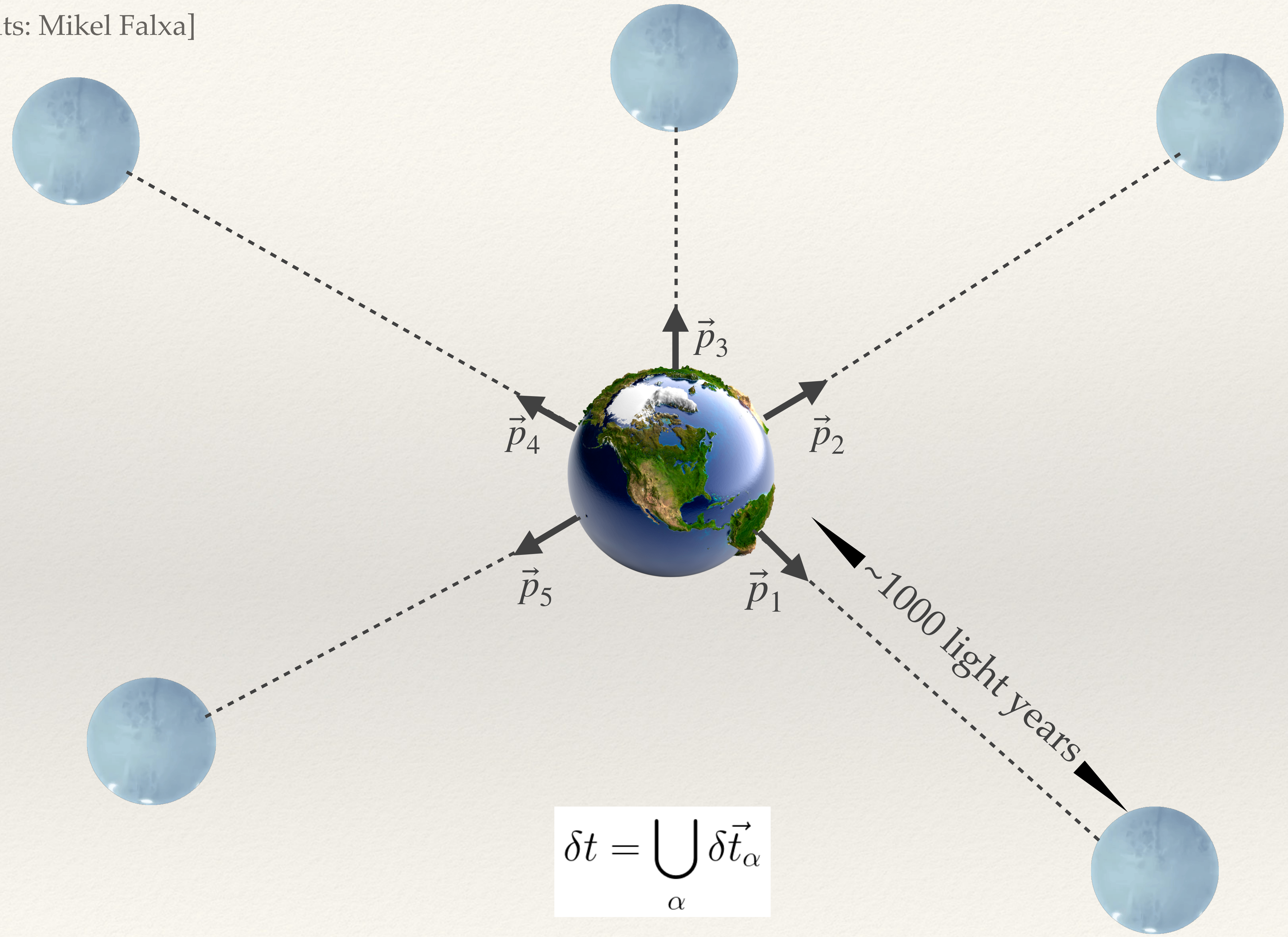
- Each observed radio pulse profile has a lot micro-structure. If we average over ~hour the (average) profile is very stable
- We can use the average pulse profile to estimate the time-of-arrival (TOA) of the pulses.
- The idea is to measure the TOA, and compare to the expected TOA. We know the spin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

Predicting arrival time



Pulsar Timing Array

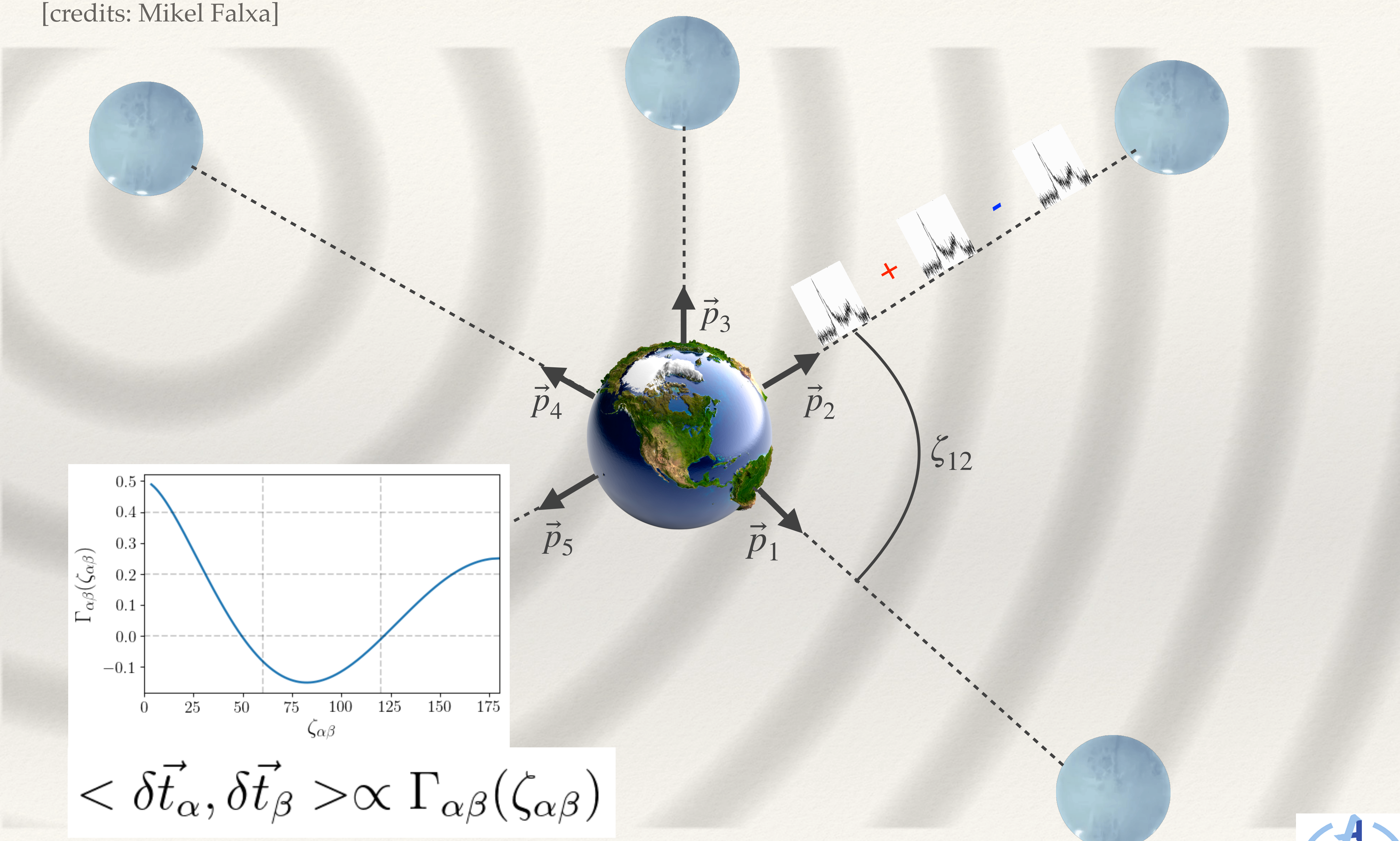
[credits: Mikel Falxa]



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

Pulsar Timing Array

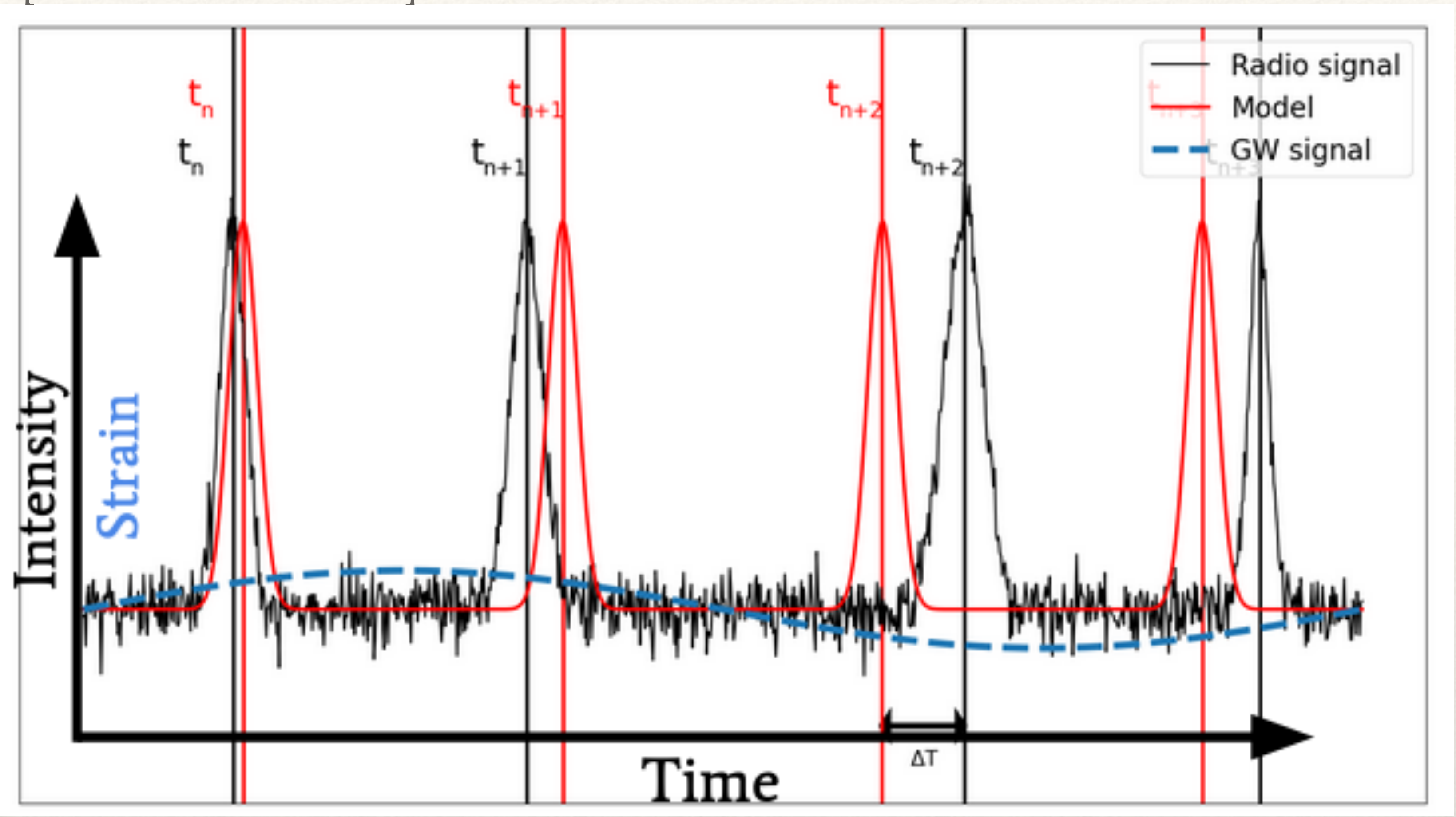
[credits: Mikel Falxa]



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

Timing Residuals

[credits: Mikel Falxa]

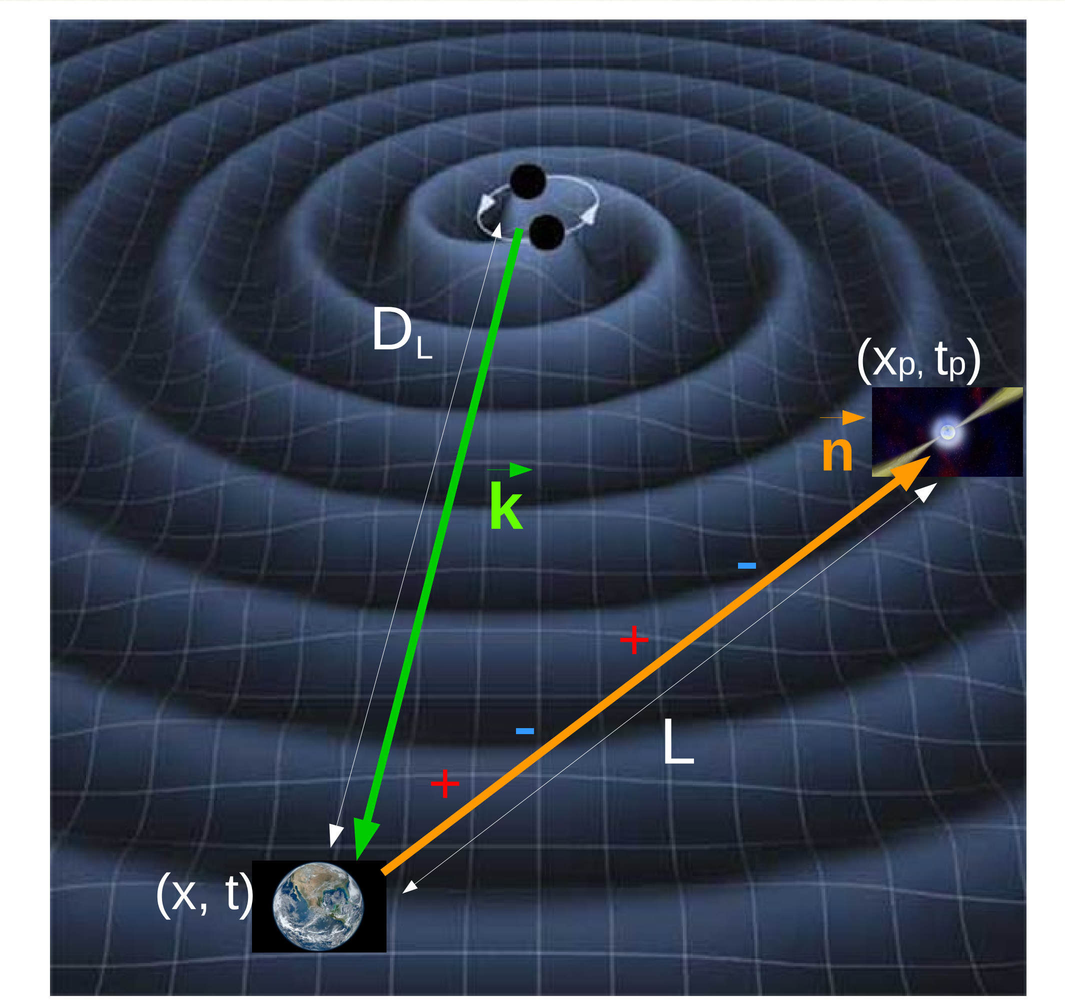


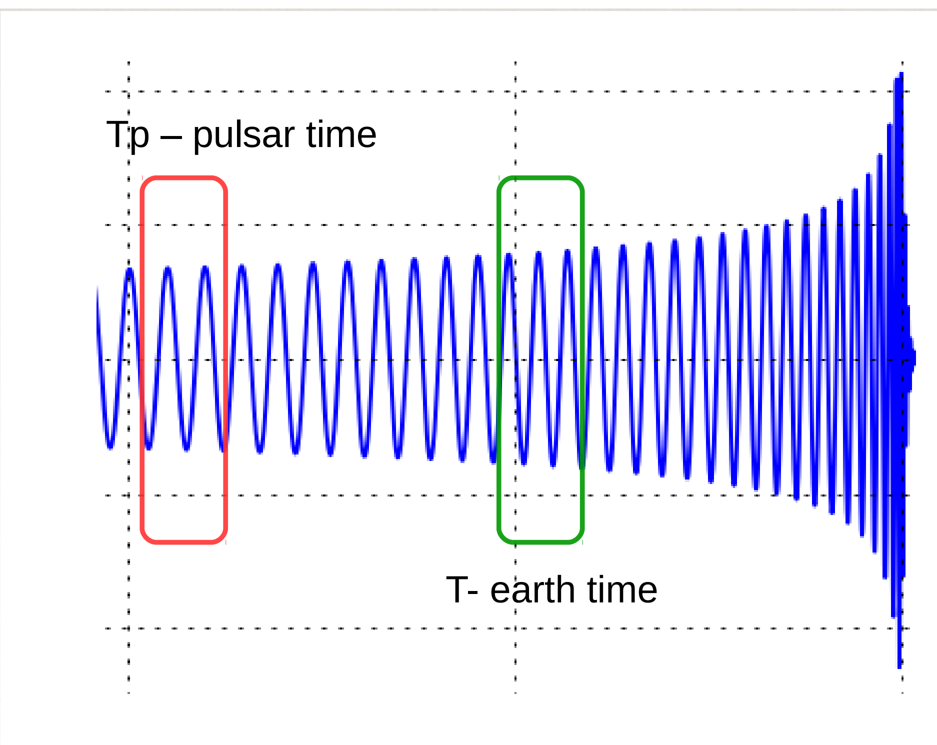
$$dt = t^p_{toa} - t^o_{toa} = dt_{errors} + \delta\tau_{GW} + noise$$

Errors in fitting the model

due to GWs

Response to GW signal





$$dt = t^p_{toa} - t^o_{toa} = dt_{errors} + \delta\tau_{GW} + noise$$

$$\delta\tau_{GW} = r(t) = \int_0^t \frac{\delta\nu}{\nu_0}(t')dt'; \quad \frac{\delta\nu}{\nu_0} = \frac{1}{2}\frac{\hat{n}^i\hat{n}^j\Delta h_{ij}}{1+\hat{n}.\hat{k}}$$

Familiar from LISA

$$\Delta h_{ij} = h_{ij}(t_p = t - L(1+\hat{n}.\hat{k})) - h_{ij}(t)$$

t_p — pulsar time, ~ time of emission of the radio pulse:

- depends on the relative position of a pulsar and GW source
- depends on the distance to the pulsar L
- L ~ few kpc ~5 000 years — “pulsar” term $h(t_p)$ contains info about the system 10^4 years in the past as compared to the “earth” term
- pulsar term depends on the pulsar.

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

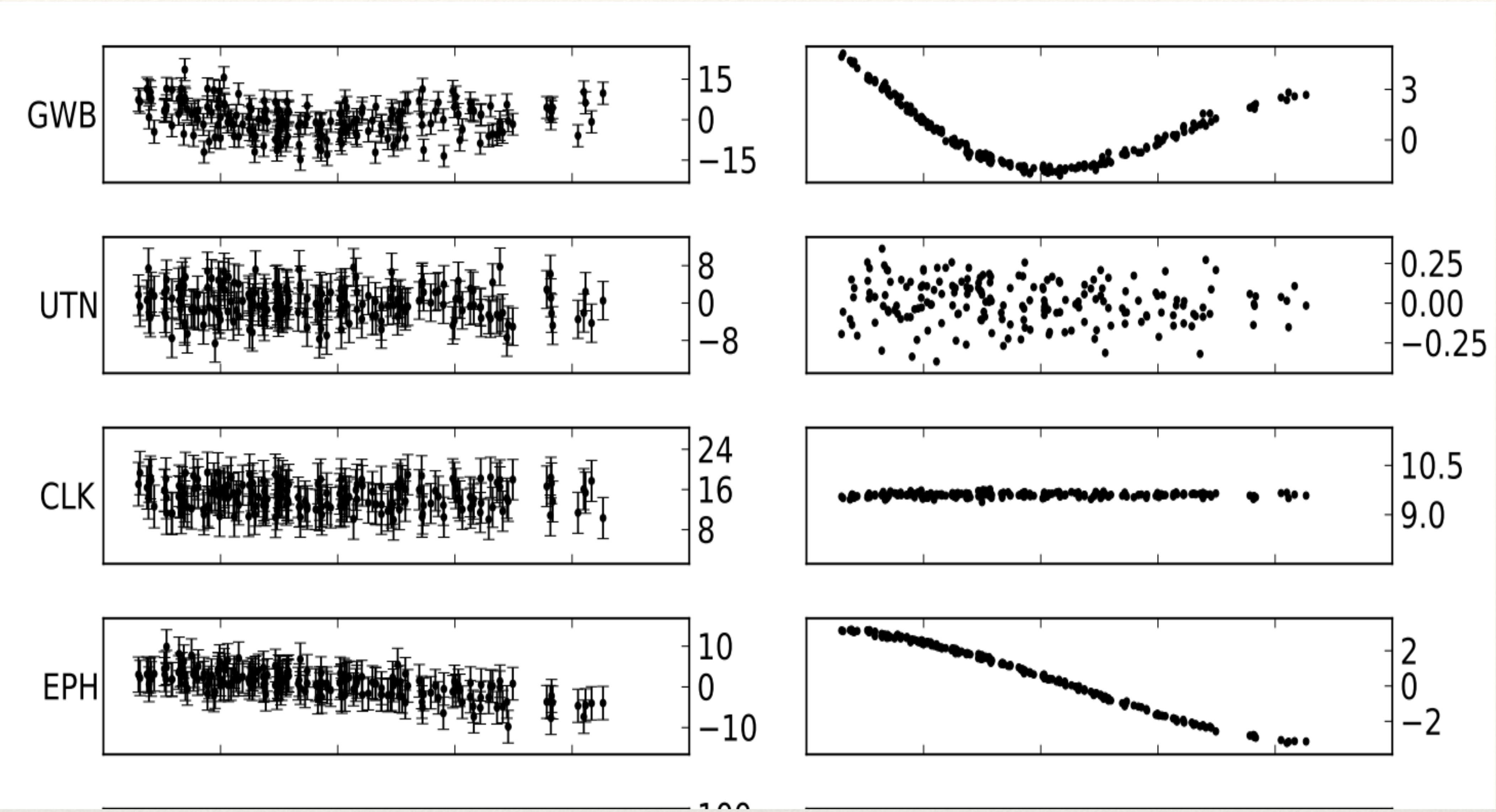
$$S_{DM}(f) \propto \frac{A_{dm}^2}{\nu^2} f^{-\gamma_{dm}}$$

- 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

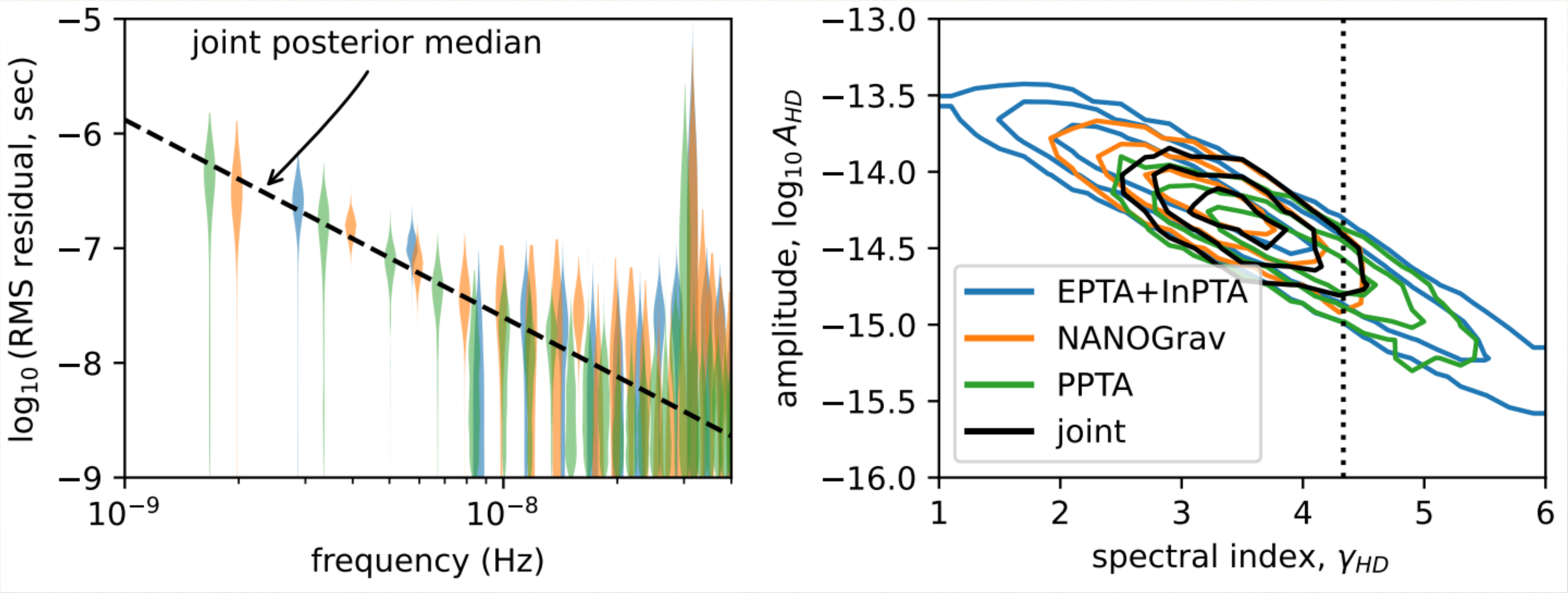
stochastic GW from population of SMBHBs: $S_{\alpha\beta}^{SMBHB} = \Gamma_{\alpha\beta}^{H-D} A_{GW}^2 f^{-13/3}$

IPTA


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

3P+ results (summary)

[G. Agazie et al 2024 ApJ 966 105]



Results of the search for stochastic Gravitational Wave Background (GWB) from three+ PTA collaborations

SGWB is modelled as power-law

Interpretation

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

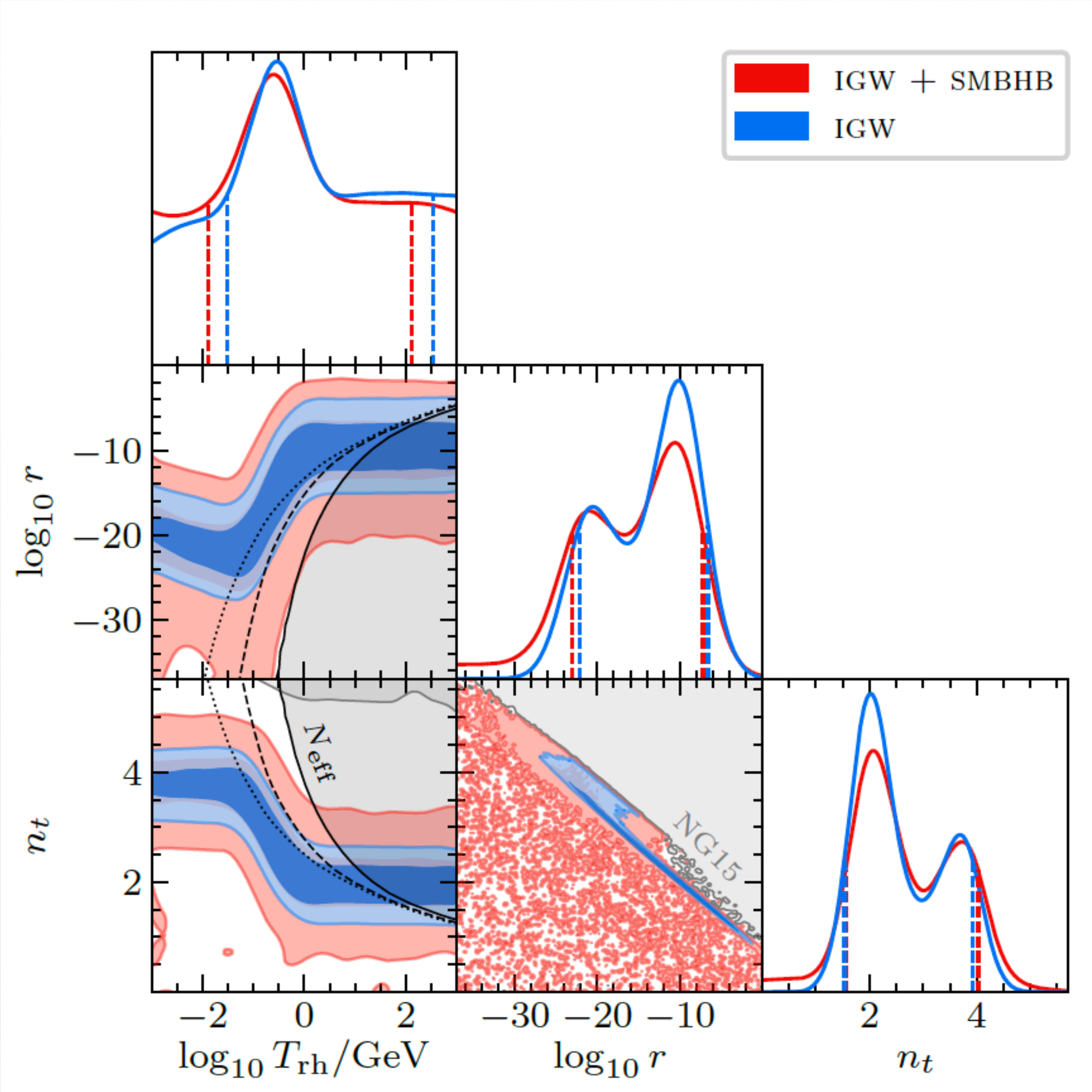
What could produce SGWB with the power-law-like spectrum?
Apparently almost anything that falls in nHz band… and even more
I'll give only few examples

DISCLAIMER

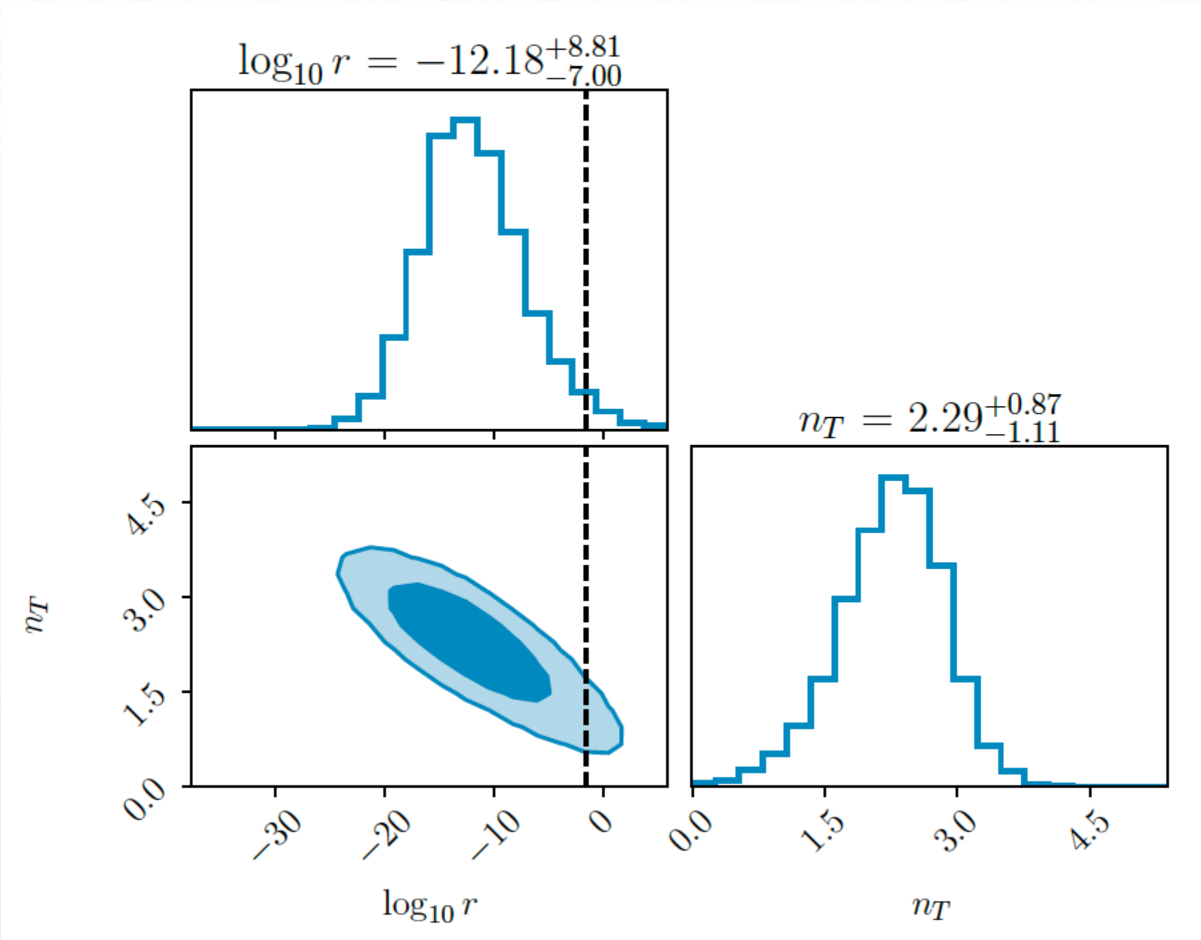
preference in interpretation of observed signal and its siginficance: my personal view

Relic SGWB

[NG, 2306.16219]



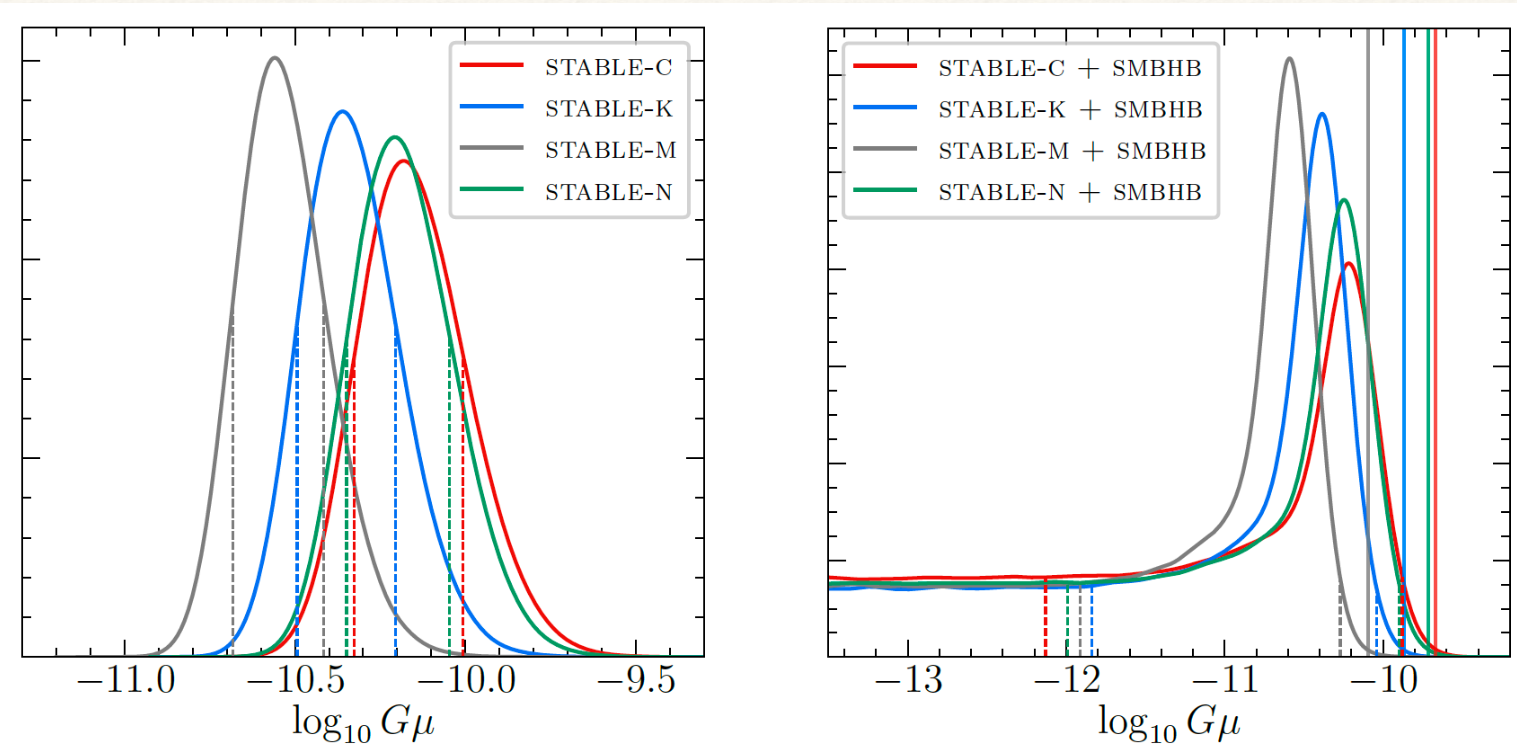
[EPTA+InPTA, 2306.16227]



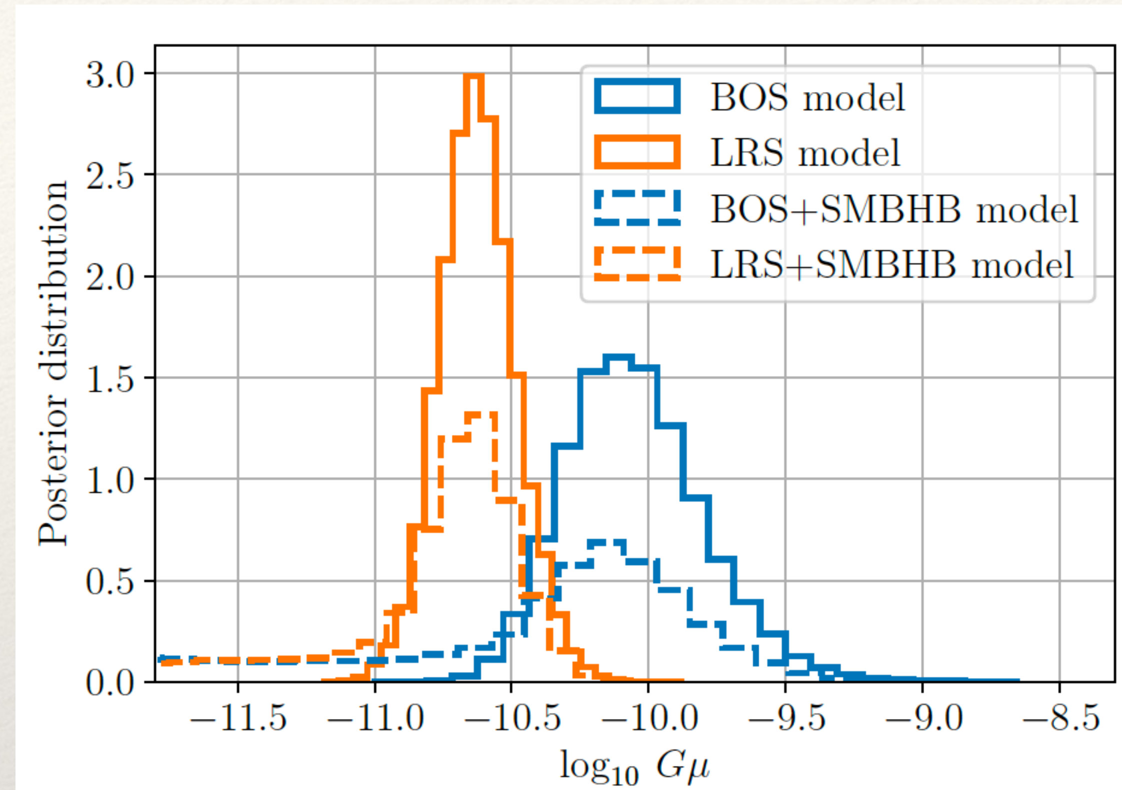
- agnostic about the microphysics of inflation and restrict ourselves to a model-independent analysis.
- the tensor-to-scalar ratio r and tensor spectral index n_t at the CMB pivot scale, reheating temperature T_{rh}

SGWB: Network of cosmic strings

[NG, 2306.16219]



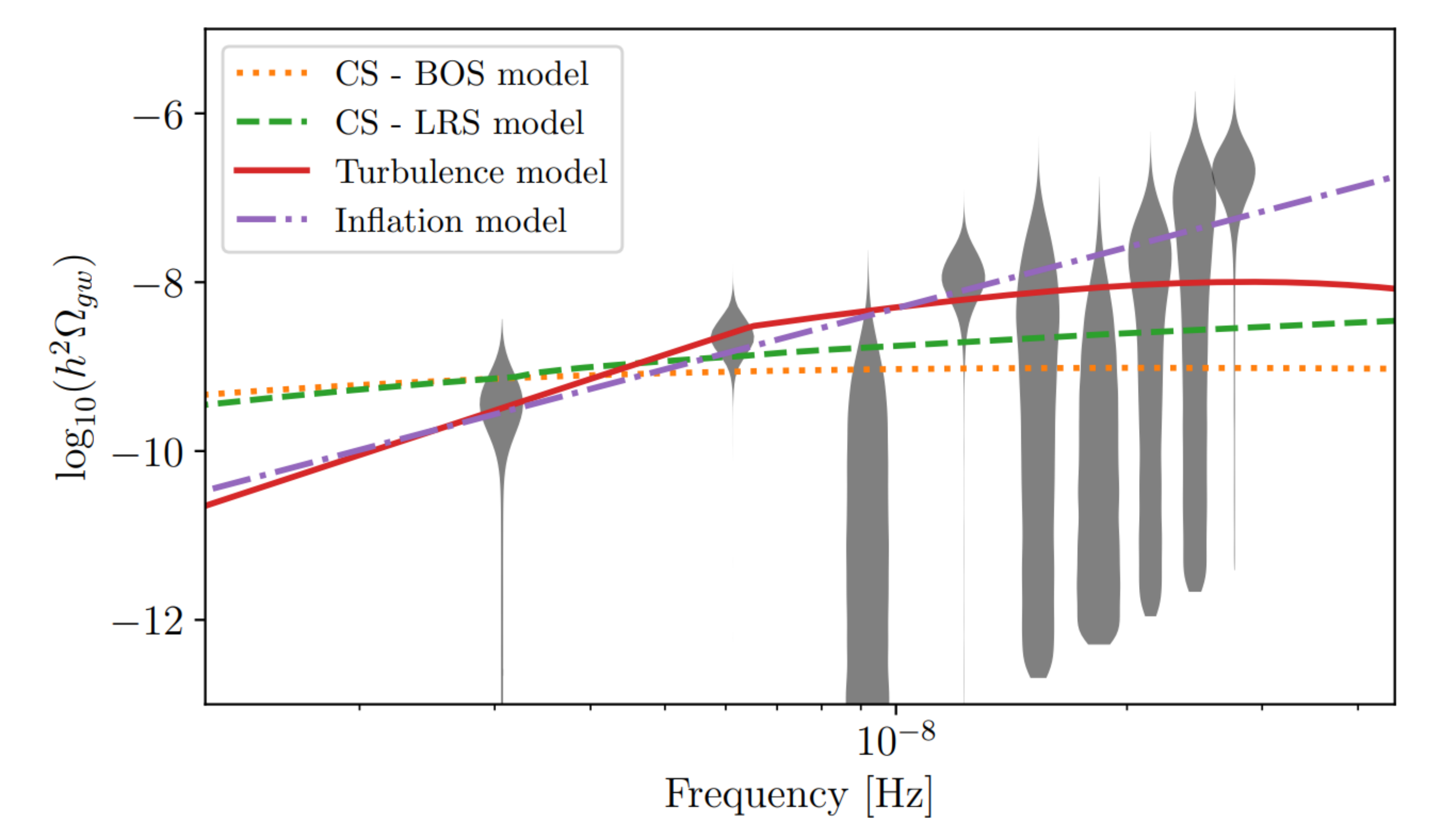
[EPTA+InPTA, 2306.16227]



- We can constrain the tension of cosmic strings (model dependent) assuming the observed signal is entirely produced by the network of cosmic strings
- We can set un upper limit in two-component model of SGWB: CSs + SMBHBs

Interpretation of PTA signal

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

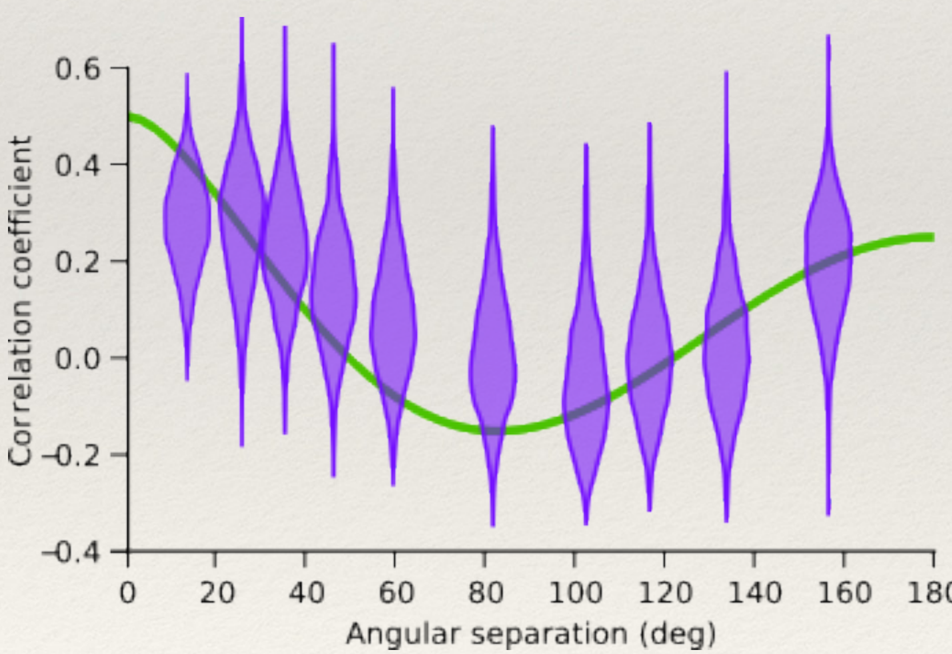


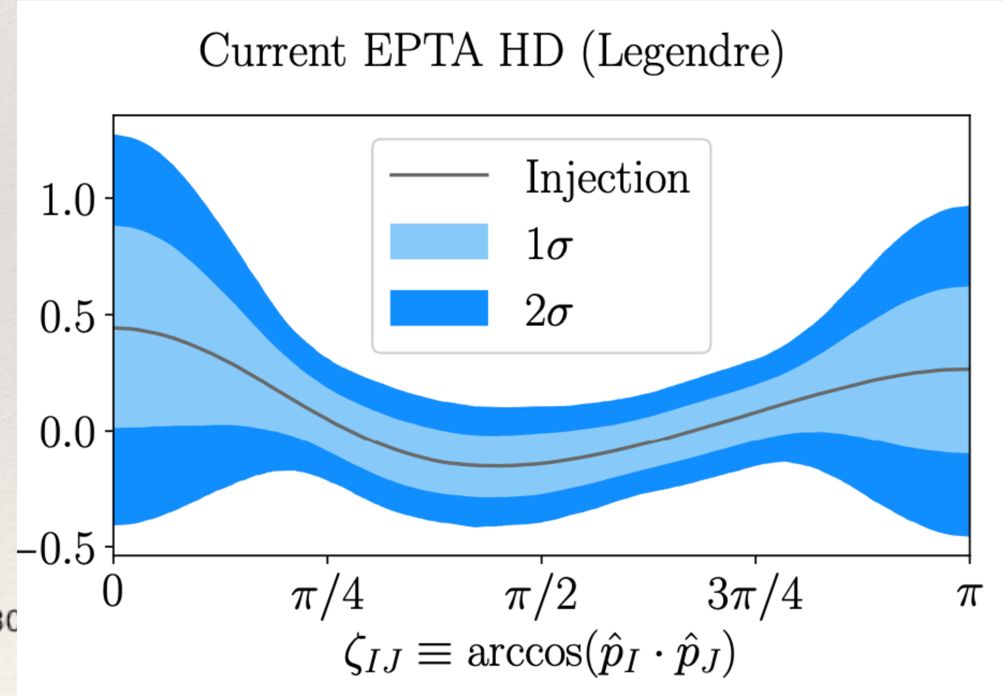
[Credits: Hippolyte Quelquejay]

Do it yourself

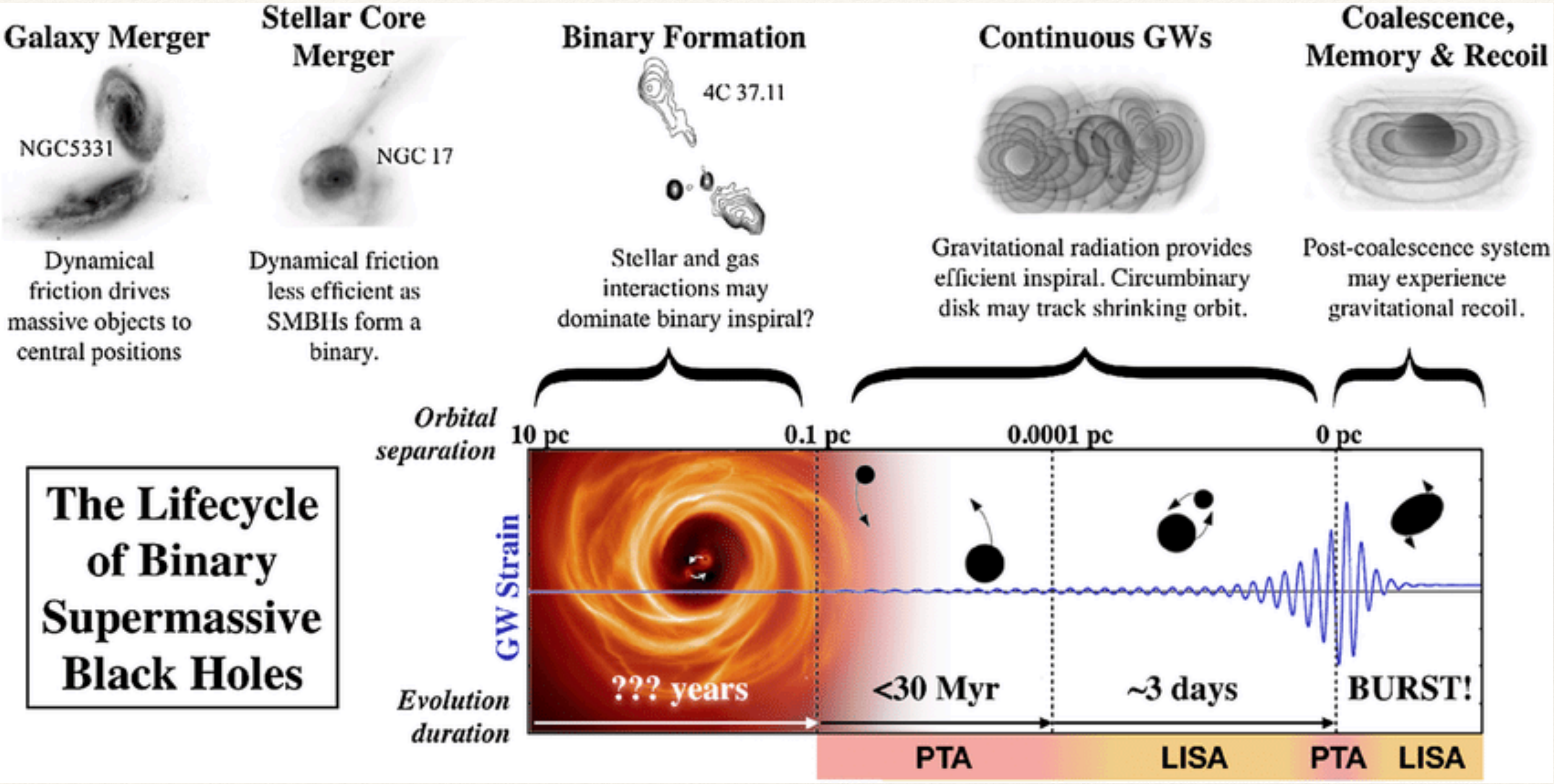
[ArXiV:2404.02864] https://github.com/Mauropieroni/fastPTA/

- You create your own PTA
  - based on existing and MaxLik estimation of noise parameters
  - make your own future PTA (based on SKA)
- Check how well we can detect and measure parameters of your favourite SGWB model





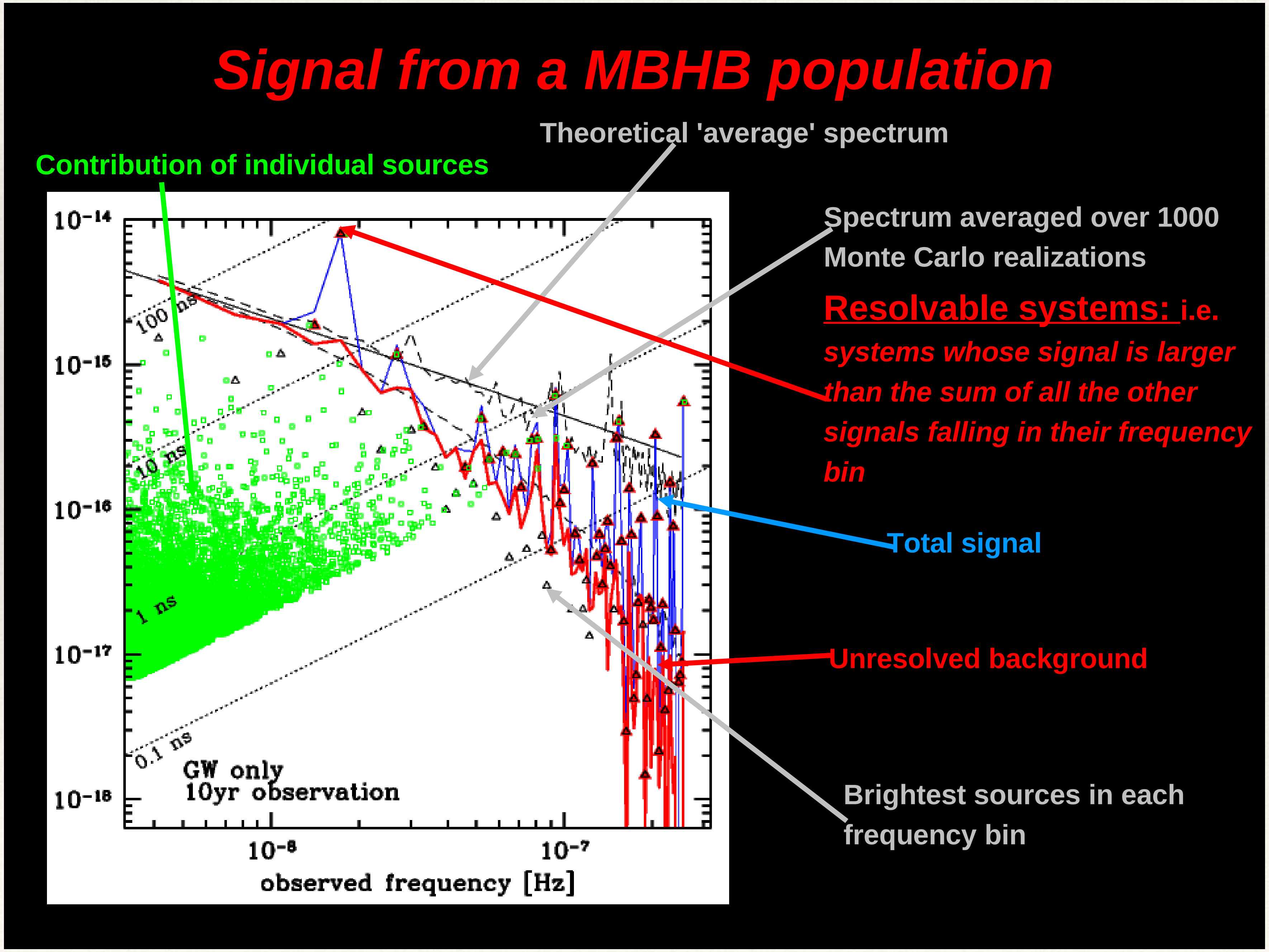
Massive black hole binaries



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

Supermassive black hole binaries

- Main sources are supermassive black hole binaries (mass 10^7 — 10^{10} solar) on very broad orbit (period ~ year(s))
- The orbital evolution due to GW emission is very slow: $\frac{dE}{dt} \propto \eta (M/r)^5$ signal is (almost) monochromatic over period of observations

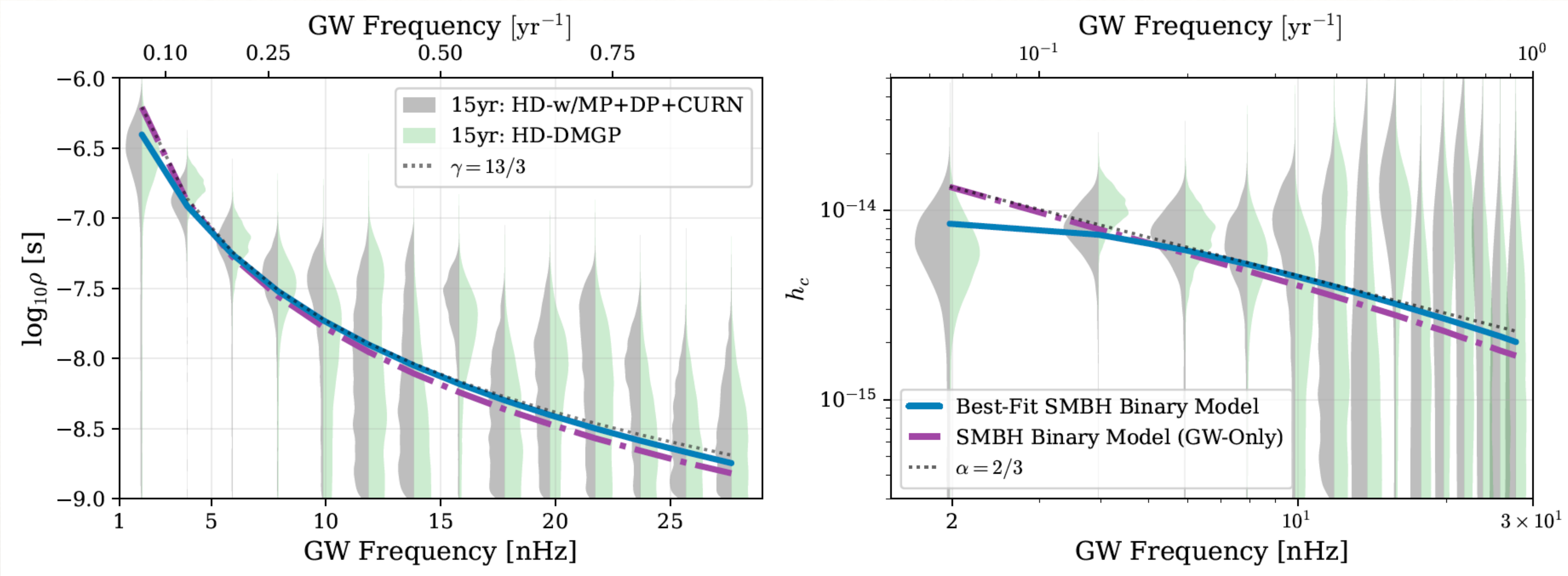


GW signal from the population of SMBH binaries: forms a stochastic signal at low freqs. (similar to Galactic binaries in LISA

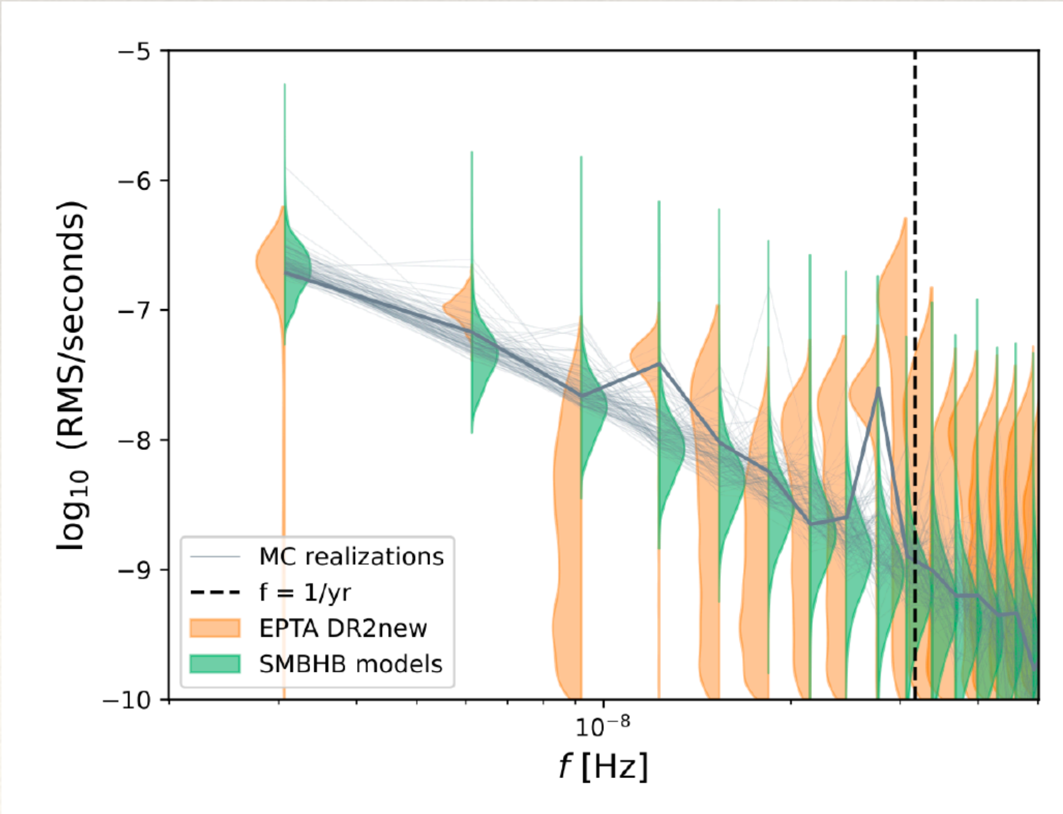
[Credits: A. Sesana]

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

SMBHBs?

[Goncharov et al 2024 - arXiv:2409.03627]

Tension with theoretical predictions!

→ Too high amplitude at 1/year

→ noise modeling?

[Goncharov et al 2024]

→ individual bright binary?

[Sesana et al. 2008]

→ bias?

→ Too shallow spectral shape

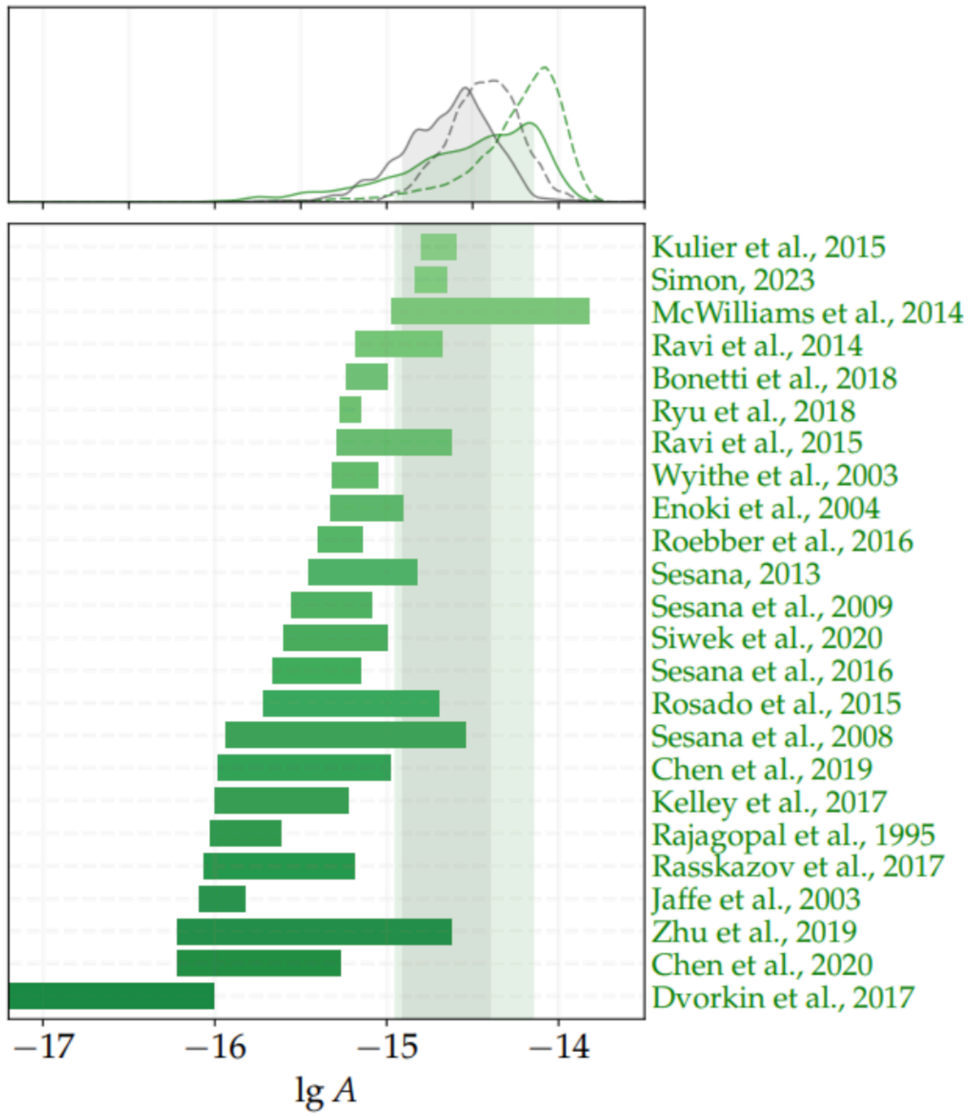
→ environmental effects?

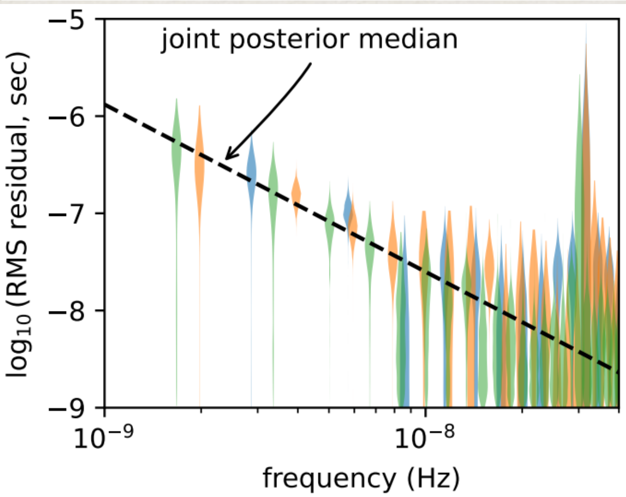
[Sesana 2013]

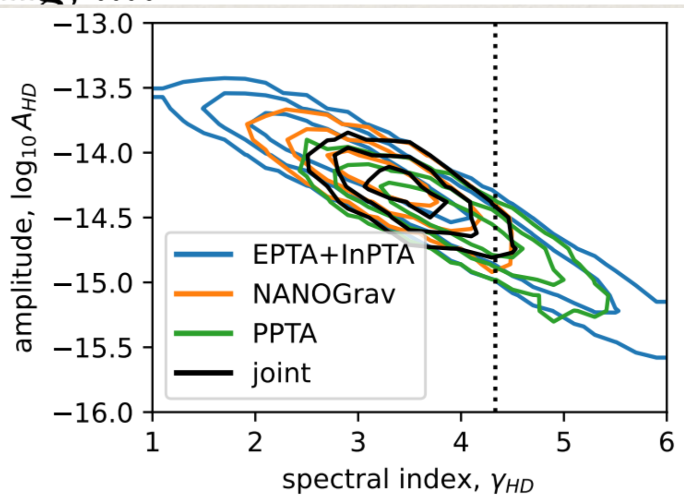
→ eccentricity?

[Enoki et al. 2007]

→ noise modeling, ...?







Ensemble average estimation

[Quelquejay+ 2025]

- Assuming stochastic (large number) incoherent sources in time/frequency
- Assuming steady state

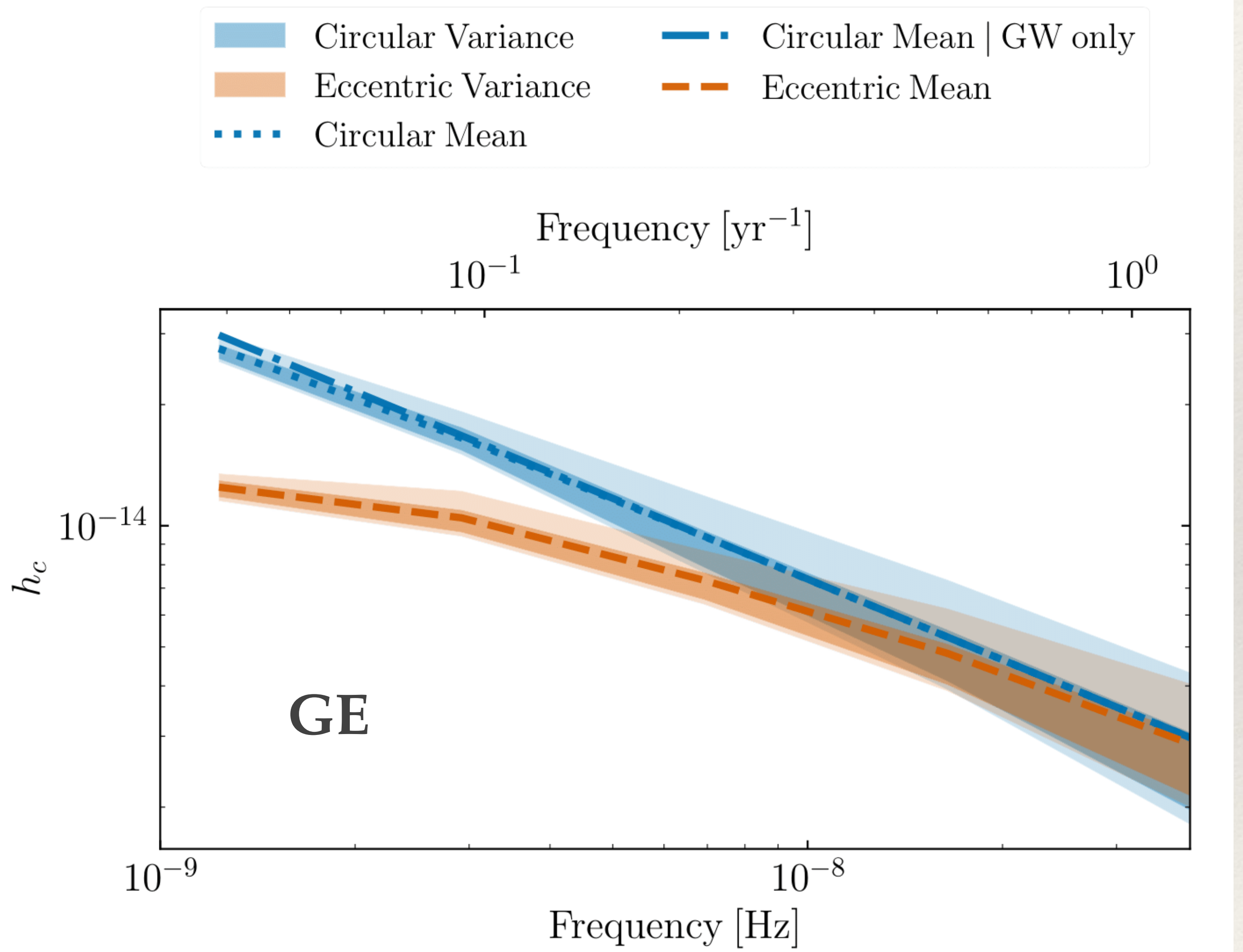
[Phinney, 2001]

$$h_c^2(f) = \int \mathrm{d}z \mathrm{d}\vec{\xi} \mathrm{d}\ln f_{\mathrm{orb}} \frac{\mathrm{d}^3 N_i}{\mathrm{d}z \mathrm{d}\vec{\xi} \mathrm{d}\ln f_{\mathrm{orb}}} h_{\mathrm{c},1}^2(f; z, \vec{\xi}, f_{\mathrm{orb}})$$

$$S_{\mathrm{res}}^{(\mathrm{GWB})}(f) = \frac{h_c^2(f)}{12\pi f^3}$$

[Rosado et al. (2015), Hazboun et al. (2019)]

Based on Horizon-AGN cosmological simulation



GW from SMBHBs: stochasticity?

Num. of sources contributing 75%

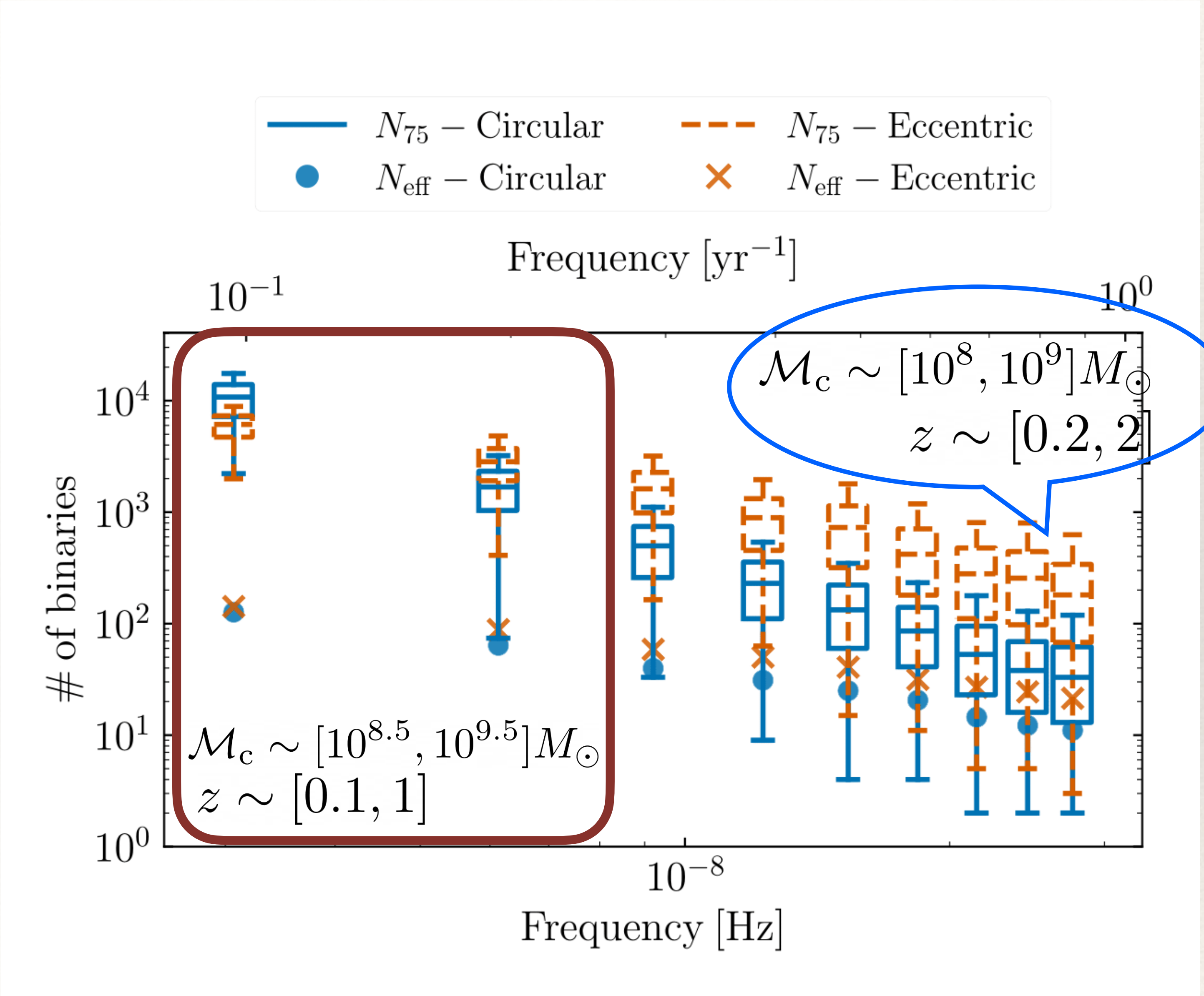
$$N_{\alpha_{\rm tot}}(f) = \min\left\{ N \left| \frac{\sum_{l=1}^{N} h_{c,l}^2(f)}{\sum_l h_{c,l}^2(f)} > \alpha_{\rm tot} \right. \right\}$$

Effective number of sources

$$N_{\rm eff}(f) = \frac{\left[\sum_l h_{c,l}^2(f)\right]^2}{\sum_l \left[h_{c,l}^2(f)\right]^2}$$

Stochasticity is lost ~20nHz (circular)

[Quelquejay+ 2025]



Cosmic variance: simulating Universe

Population (Pop) approach
(circular ensemble only)

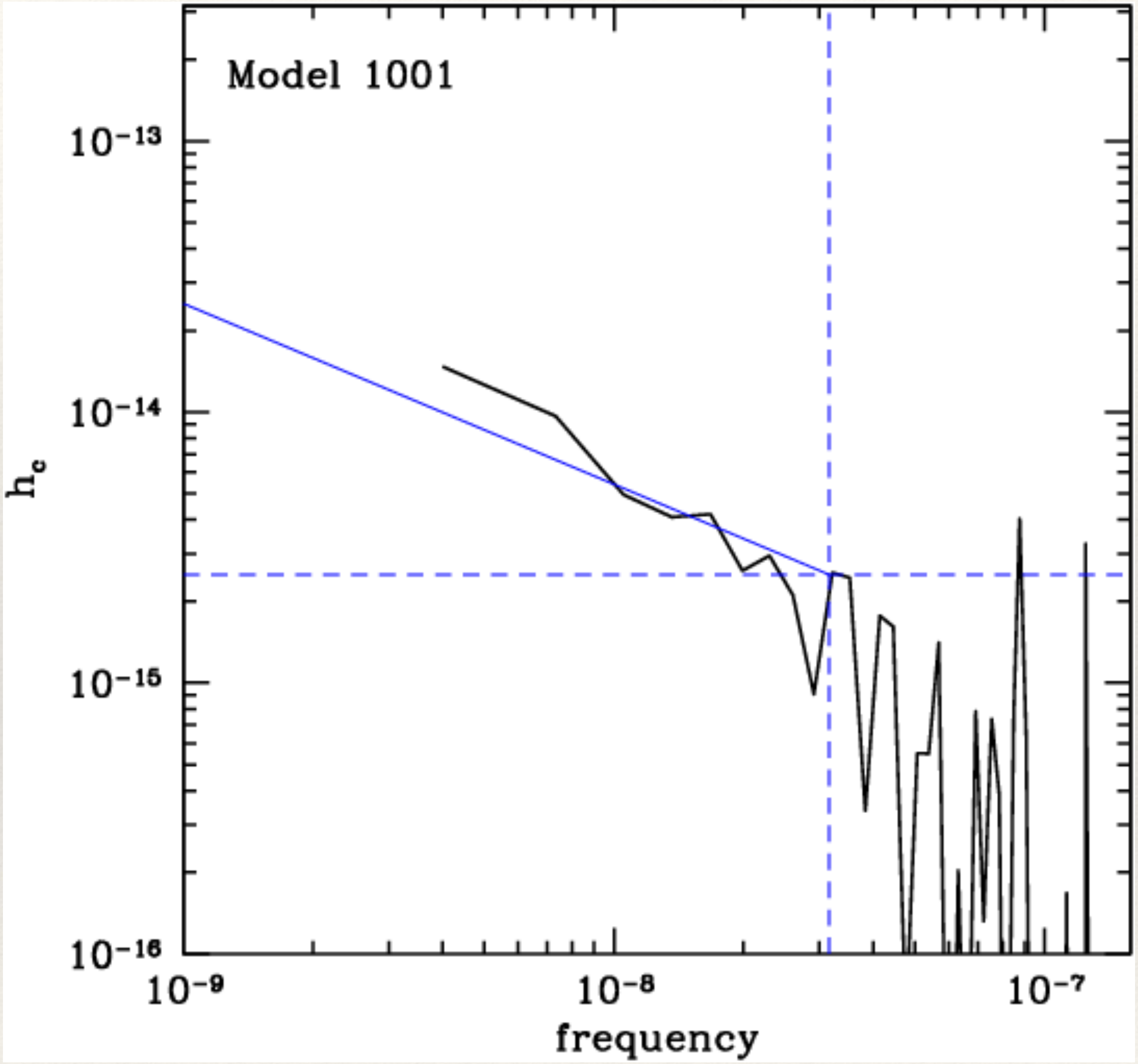
→ We compute the residuals waveform of all the binaries from a universe realisation population, drawing uniformly extrinsic sources parameters (sky location, polarisation angle, …)

→ We then infer the GWB spectrum using the PTA data analysis pipeline (enterprise, …) on the simple timing residuals time series:

GWB + Gaussian noise

[Bécsy et al. (2022), Ferranti et al. (2024)]

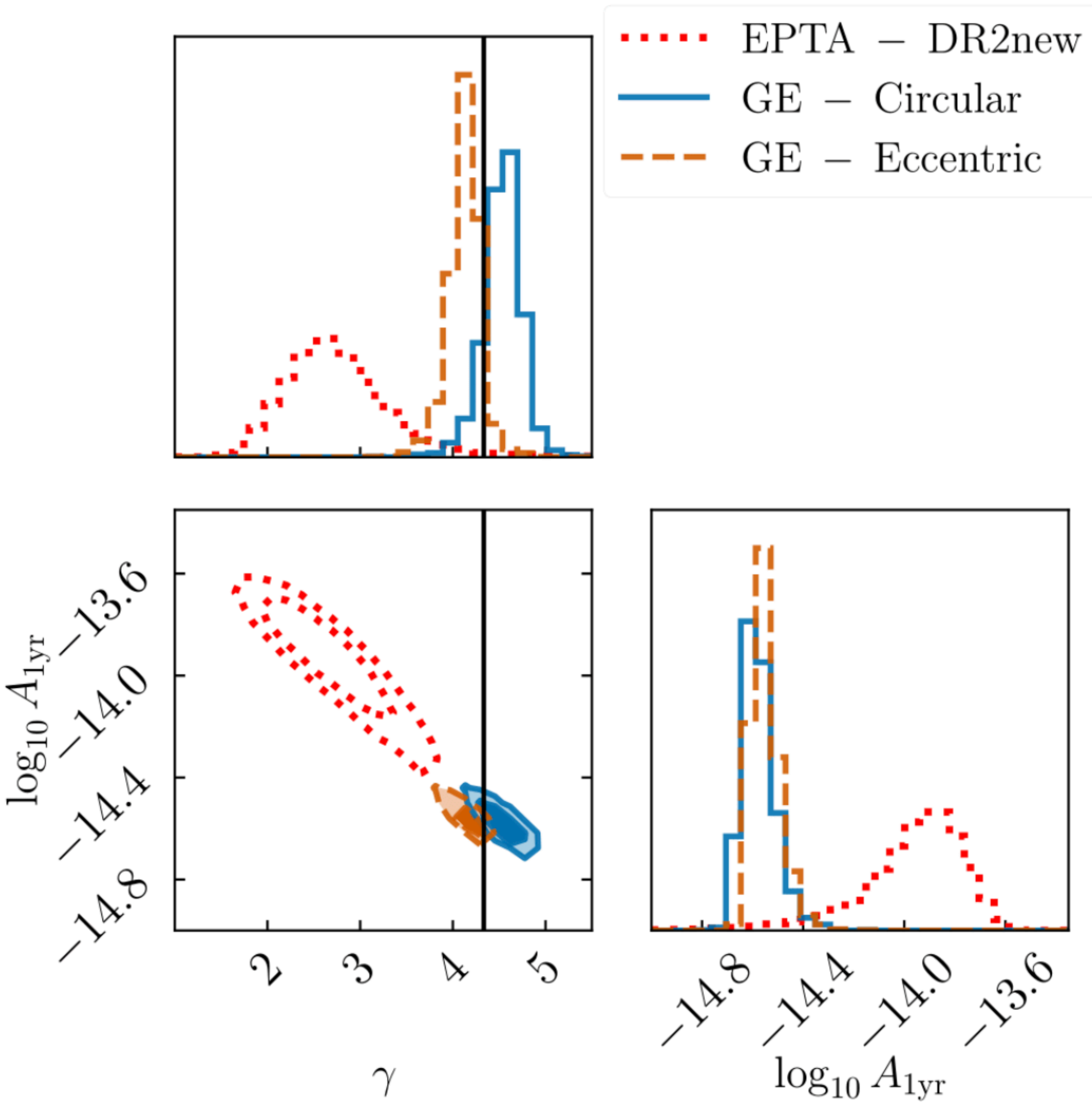
Pop.



EPTA predictions based on AGN-Horizon simulations

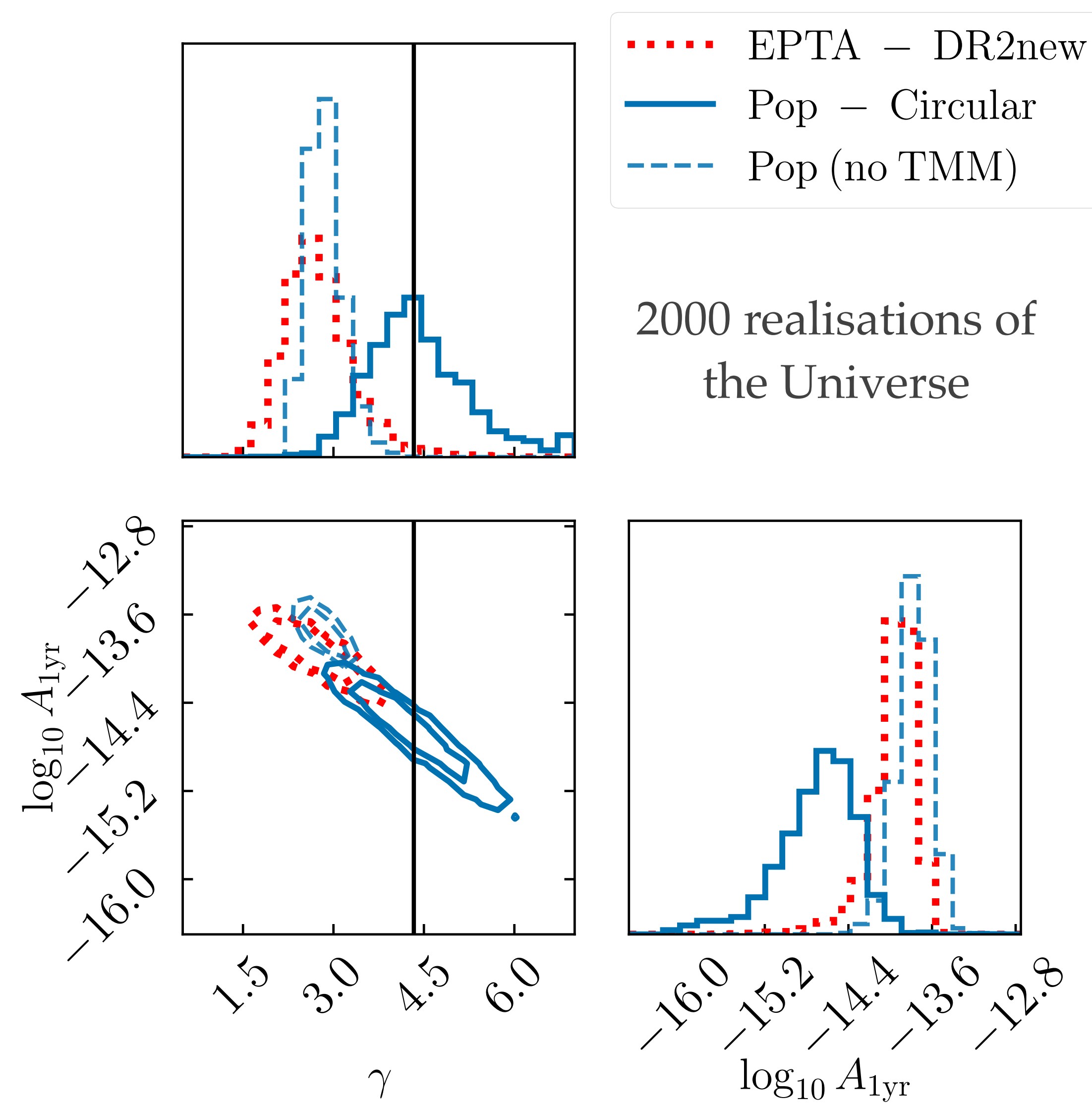
[Quelquejay+ 2025]

Comparing the GE and Pop approaches



Least-square fits of $S_{\mathrm{res}}^{(\mathrm{GWB})}(f) = \frac{h_c^2(f)}{12\pi f^3}$

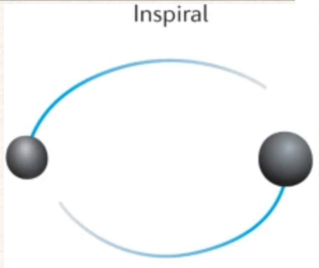
With EPTA sensitivity



2000 realisations of the Universe

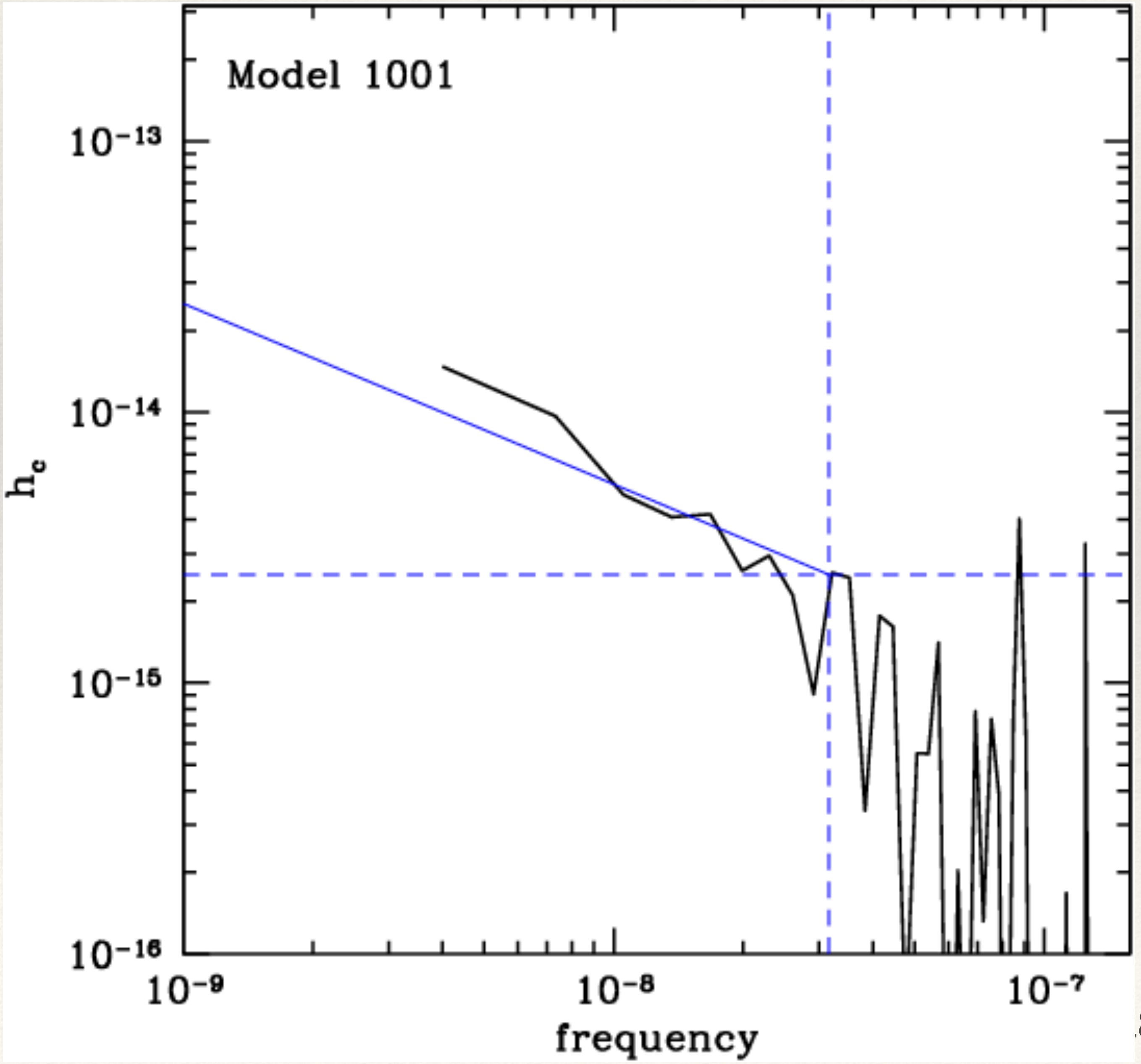
Maximum-a-posteriori samples $\hat{S}_{\mathrm{res}}^{(\mathrm{GWB})}(f)$

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

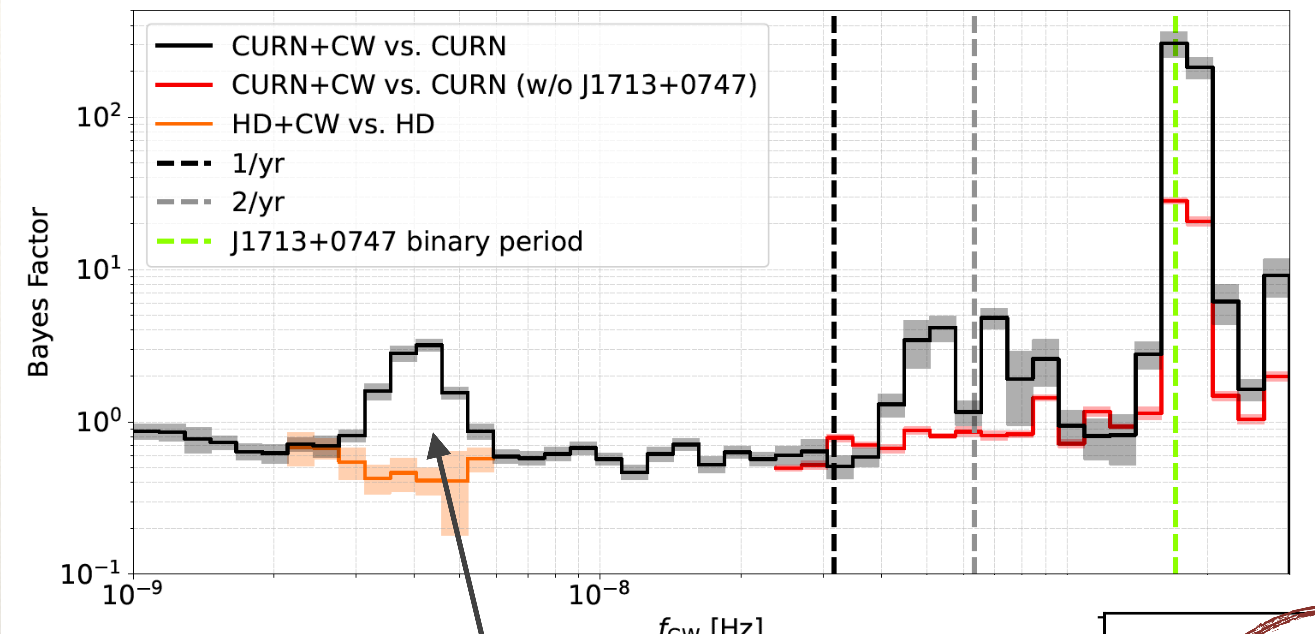


[NG: 2306.16222]

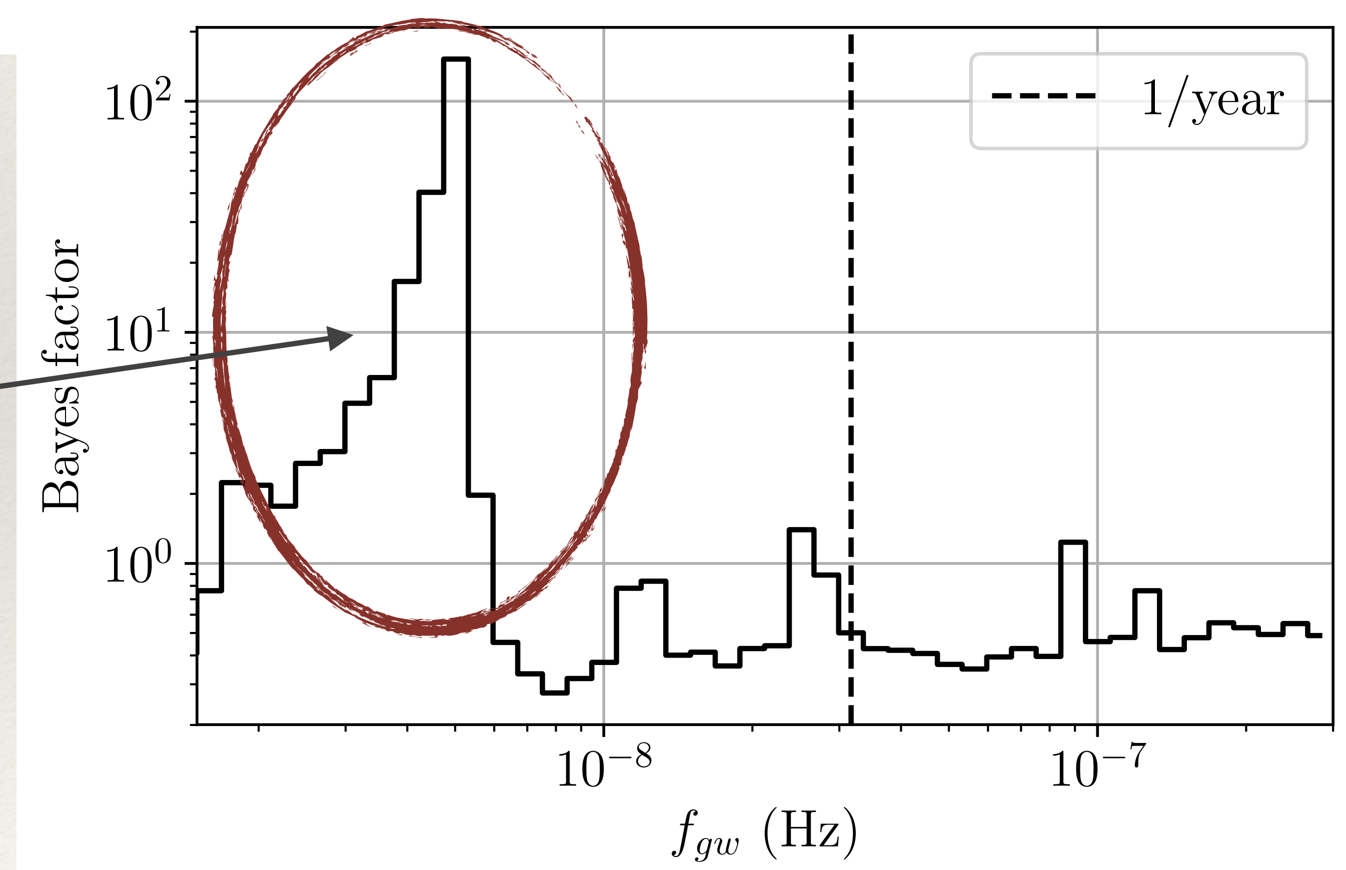
[EPTA+InPTA: 2306.16226]

Search for a circular SMBHB

[NG: 2306.16222]

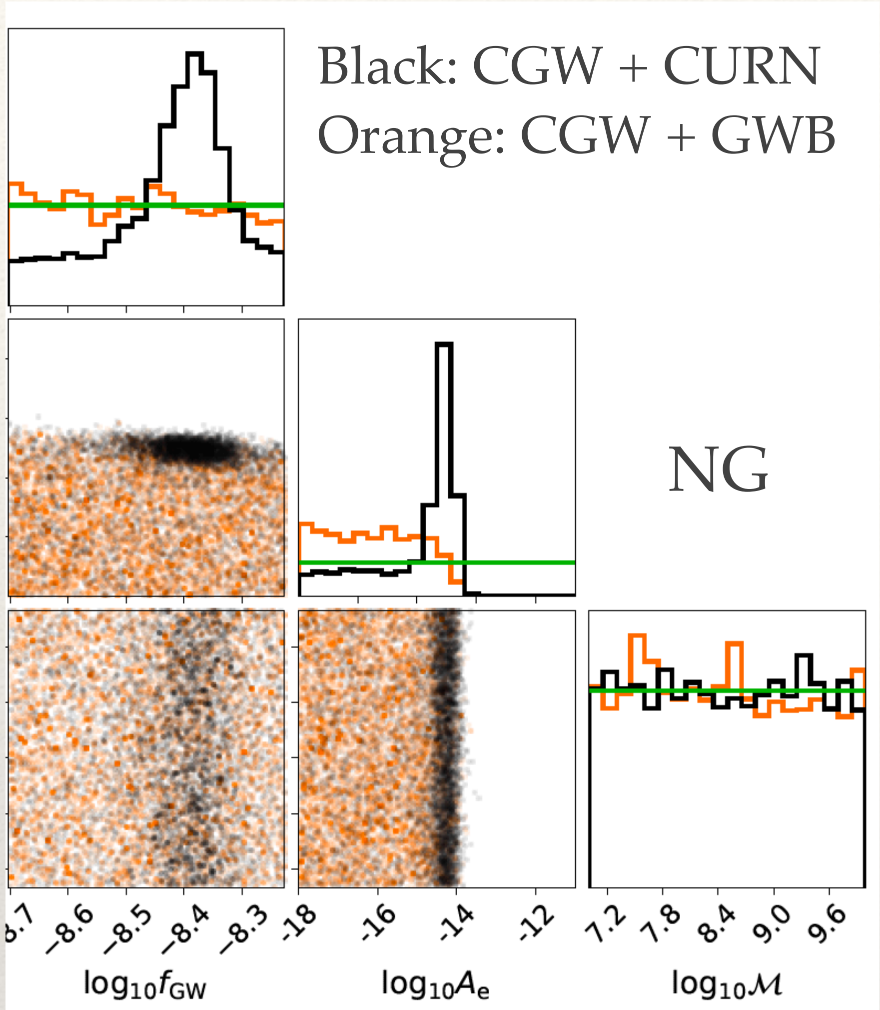


[EPTA+InPTA: 2306.16226]

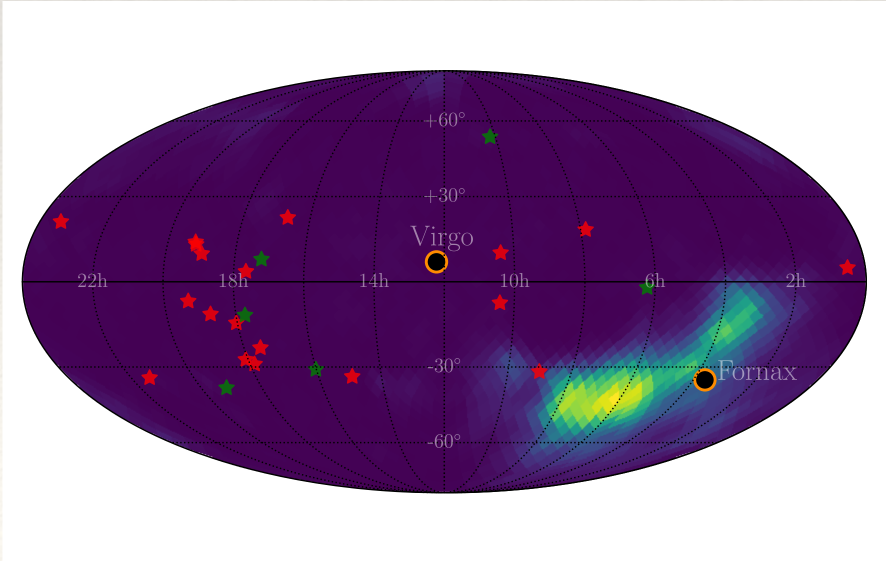


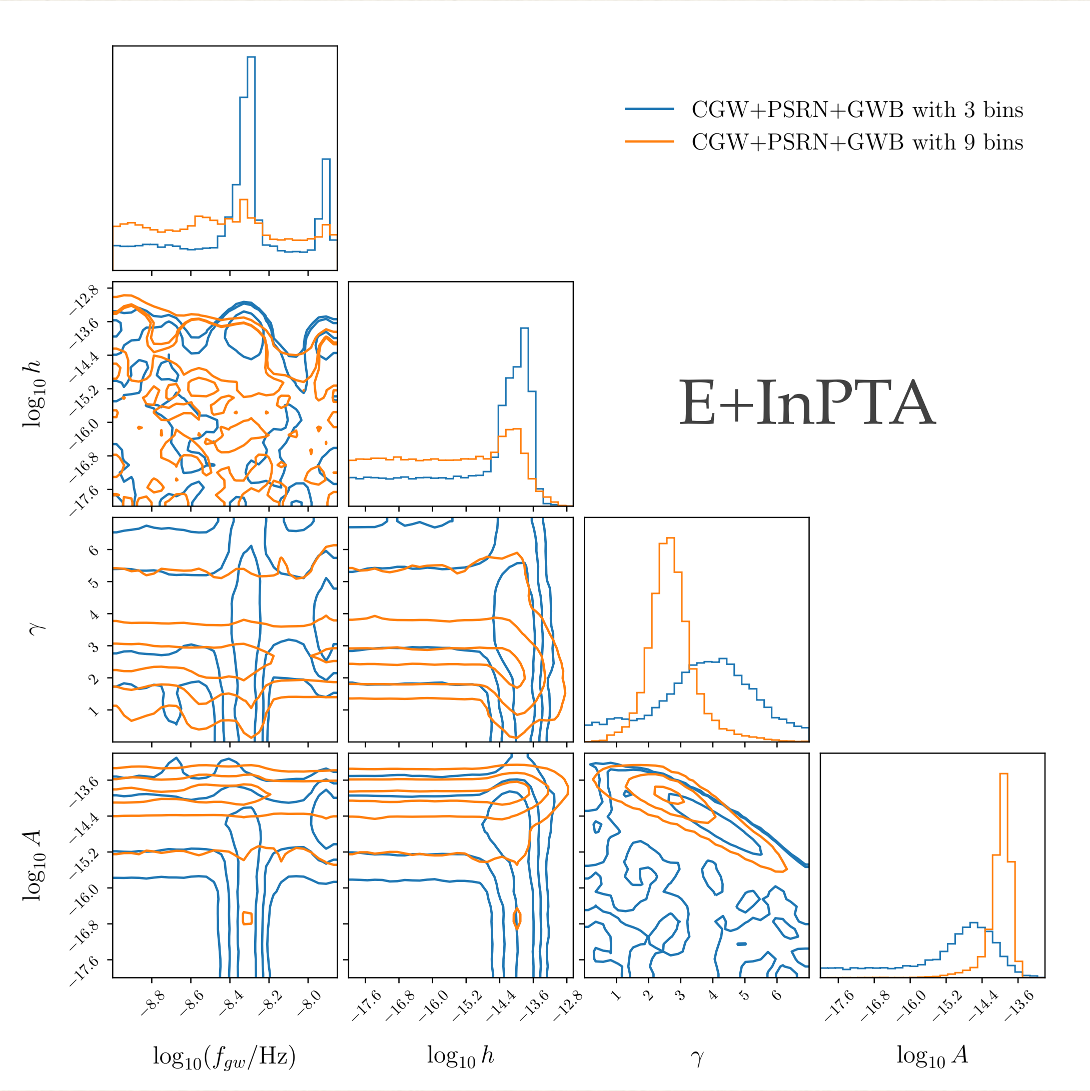
SMBHB candidate at low frequency (3-5nHz)

Covariance of CGW and GWB



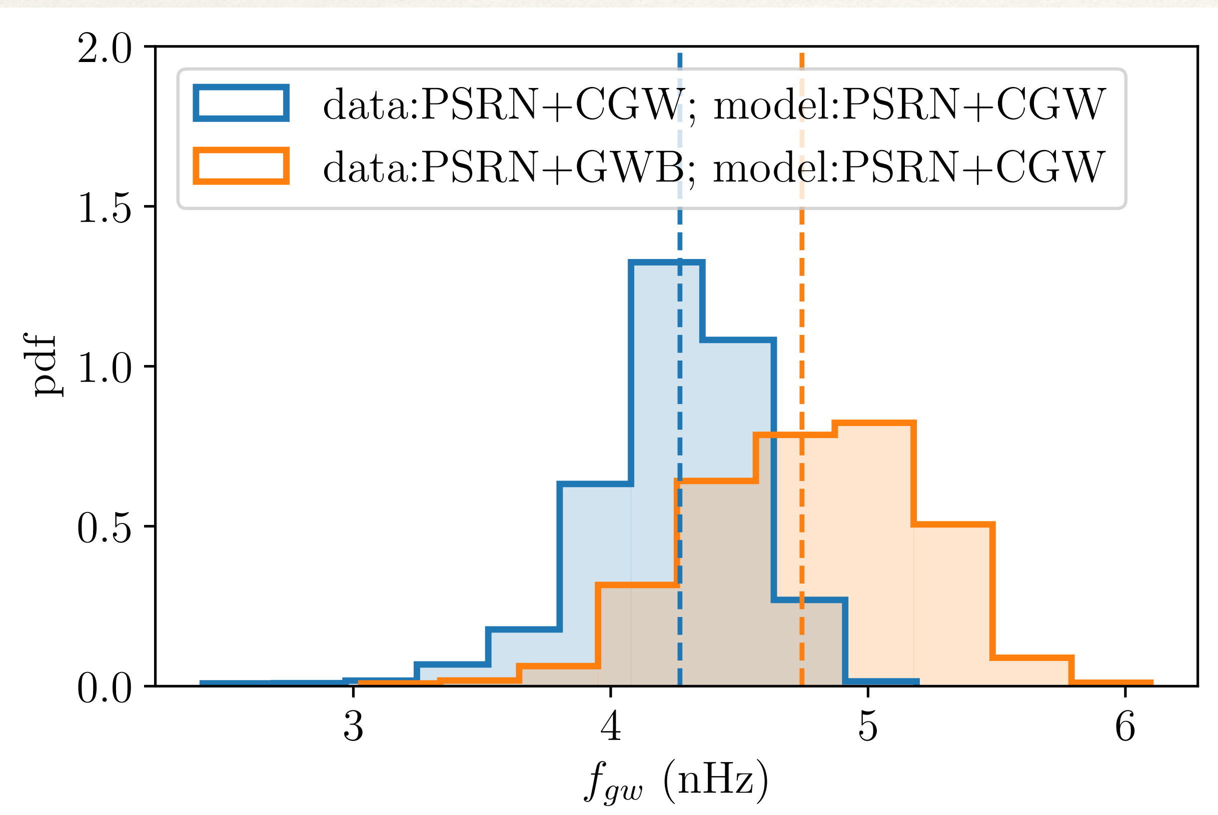
The significance of the candidate is reduced if we consider model GWB+CGW

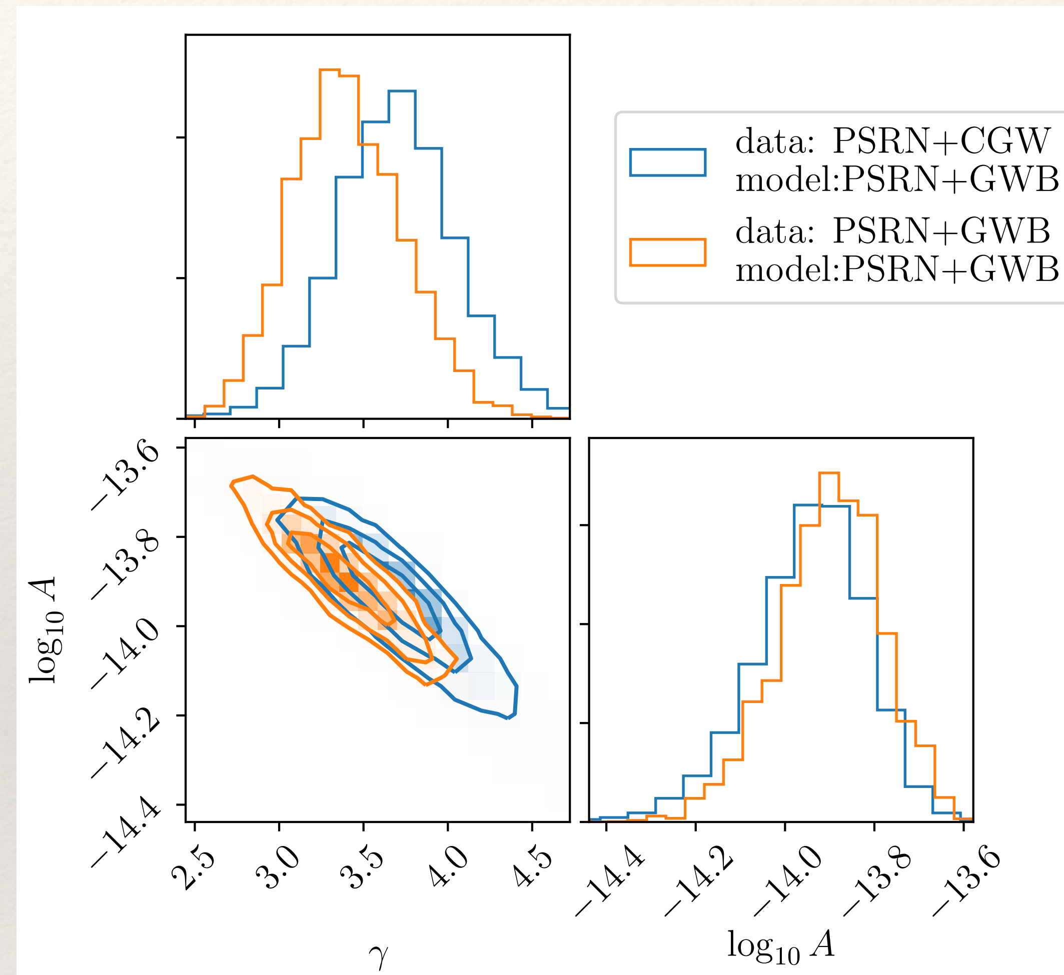




CGW signal in PTA?

Simulated data: PSRN + GWB only, Model_1: GWB, Model_2 CGW
Simulated data: PSRN + CGW only, Model_1: GWB, Model_2 CGW

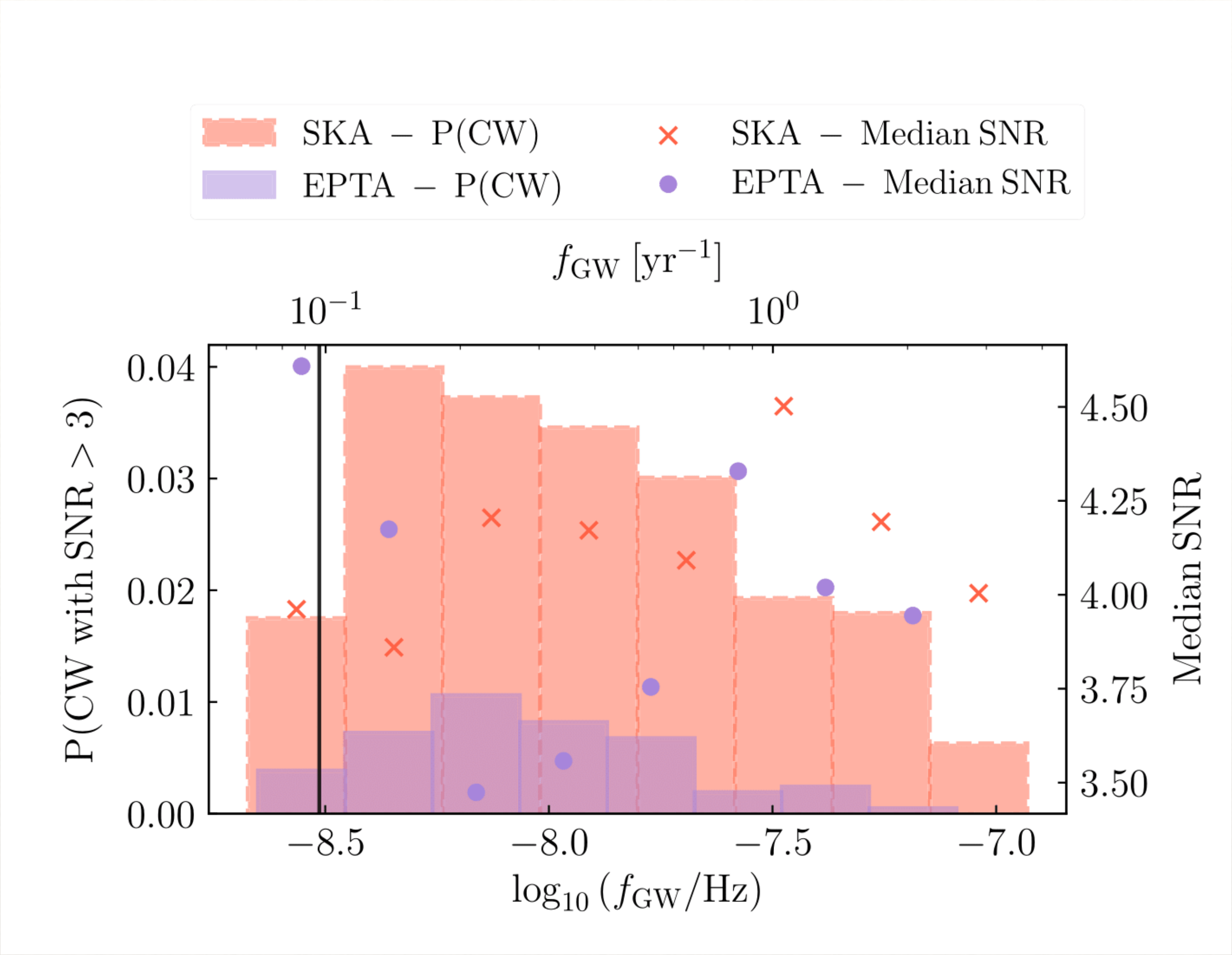




- It is easy to make mistake 
- However: GWB 2 parameters, CGW: Np+8 pars

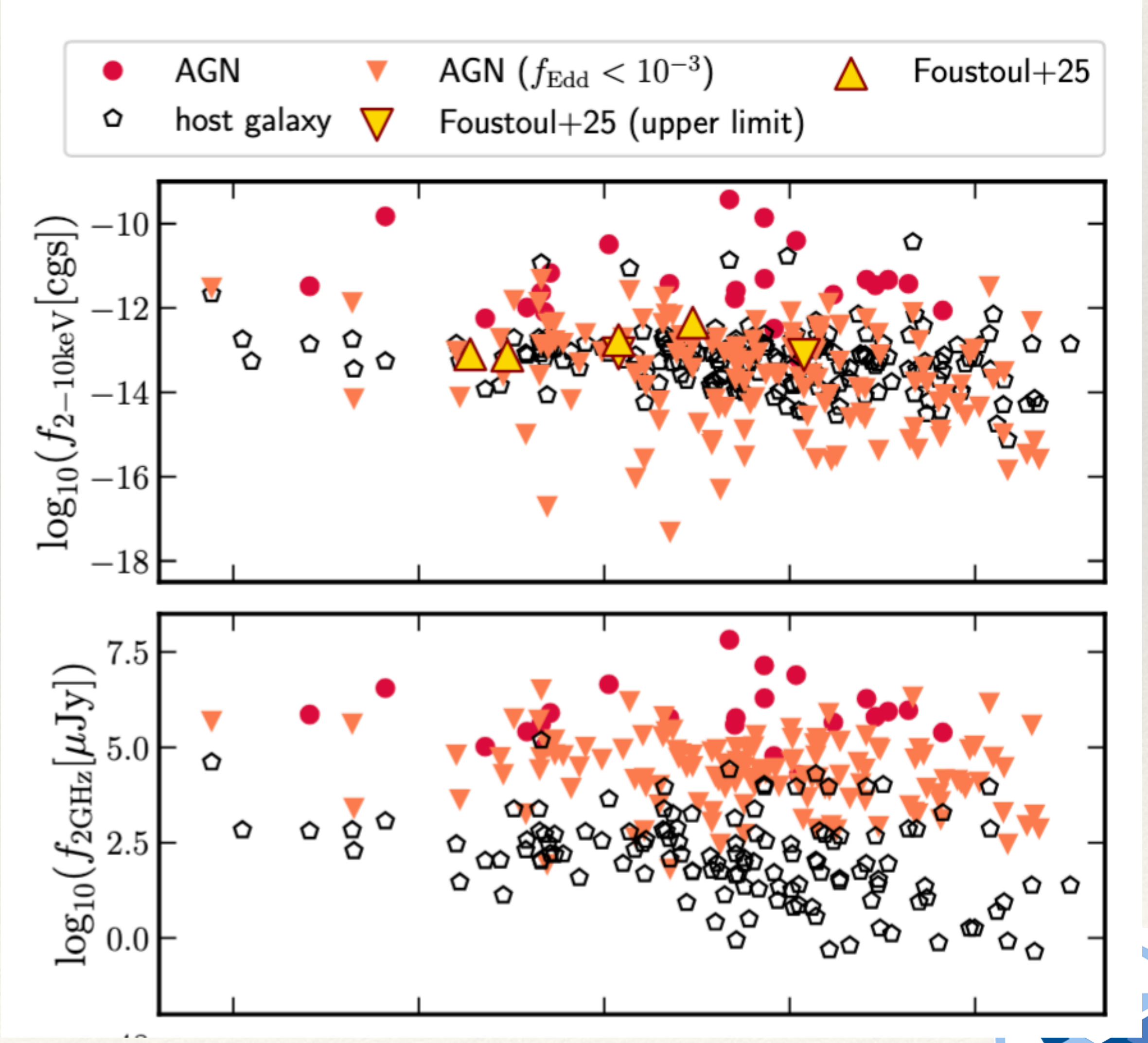
Expectations based on Horizon-AGN

[Quelquejay+ 2025]



Prospectives of e/m identification of SMBH

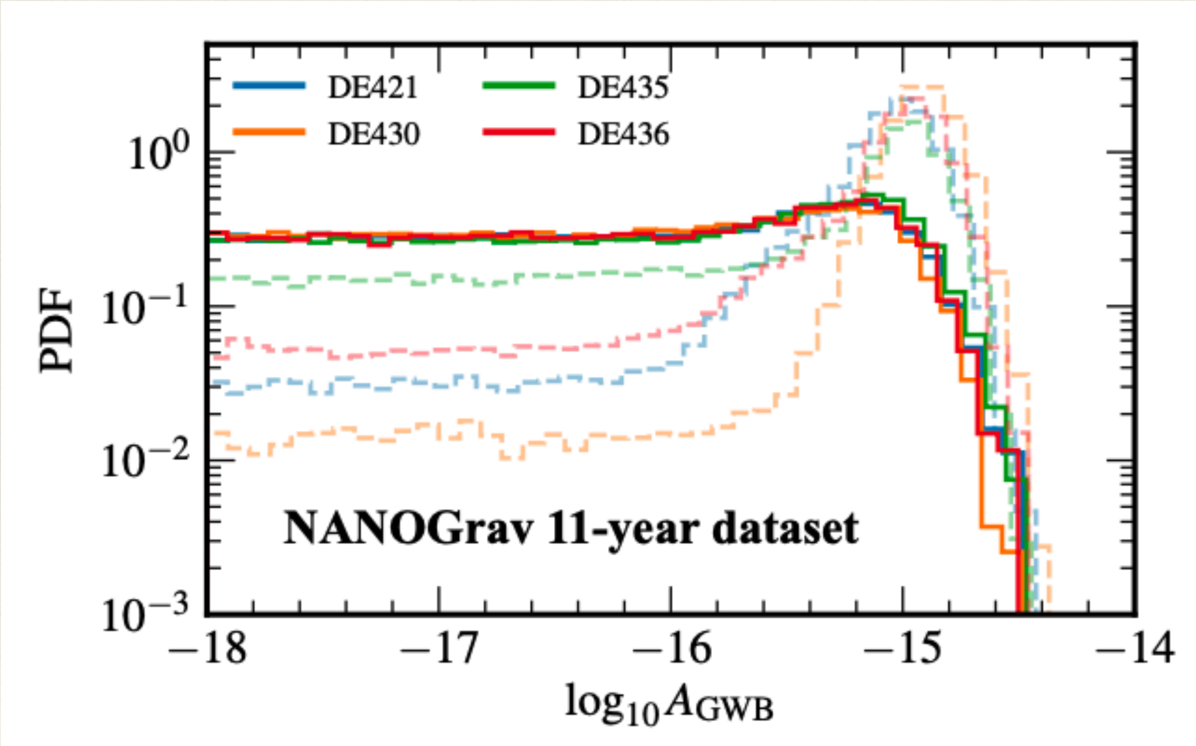
- If there is a gas: AGN (faint)
- Most likely to see (outshine the host galaxy) in radio(X-ray)



- Probability of finding at least one CGW
- Median SNR of CGW (in case of detection)

Is it really GW signal?

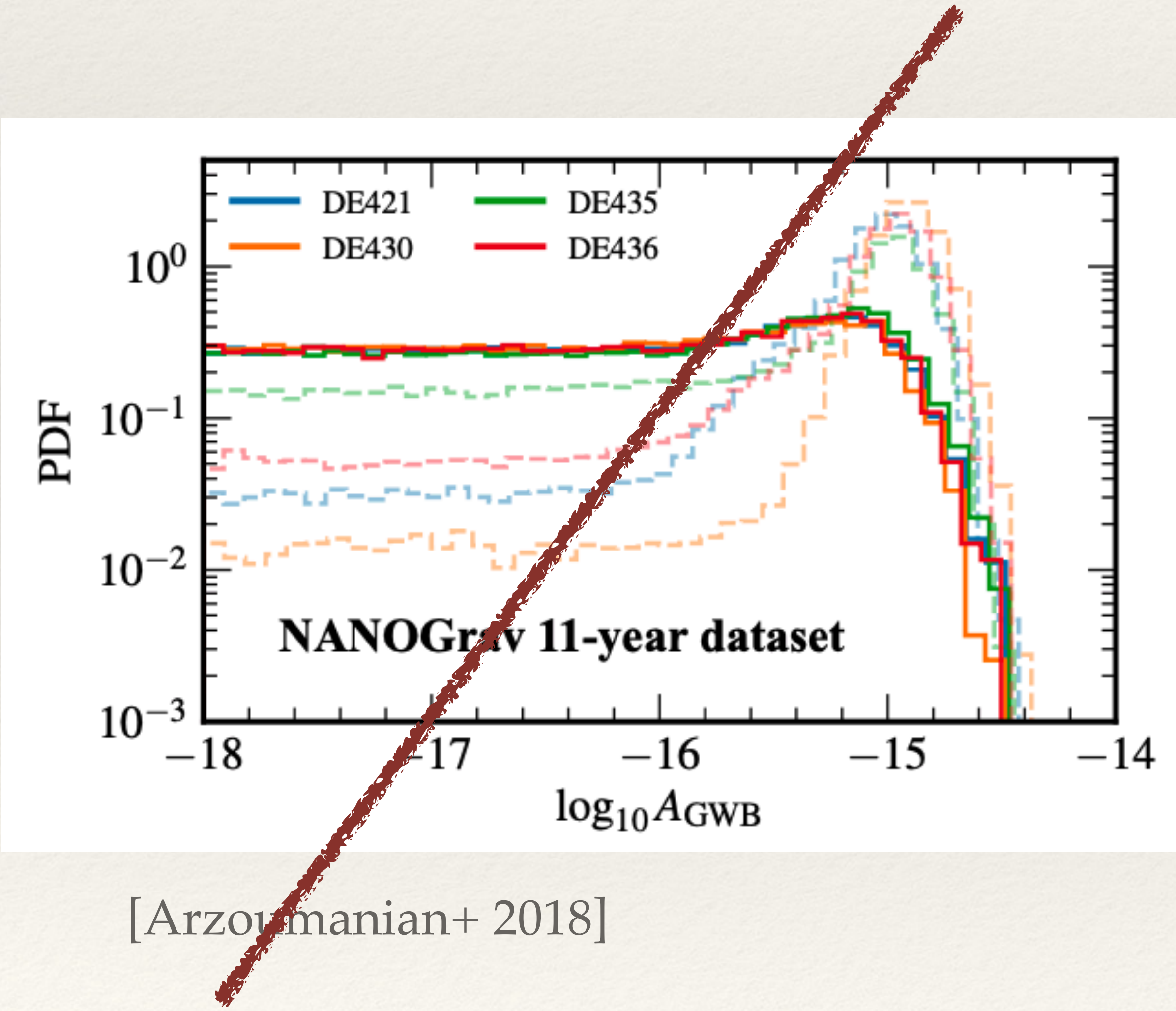
- Error in ephemerides: JPL ephemerides D440, good measurement of Jupyter



[Arzoumanian+ 2018]

Is it really GW signal?

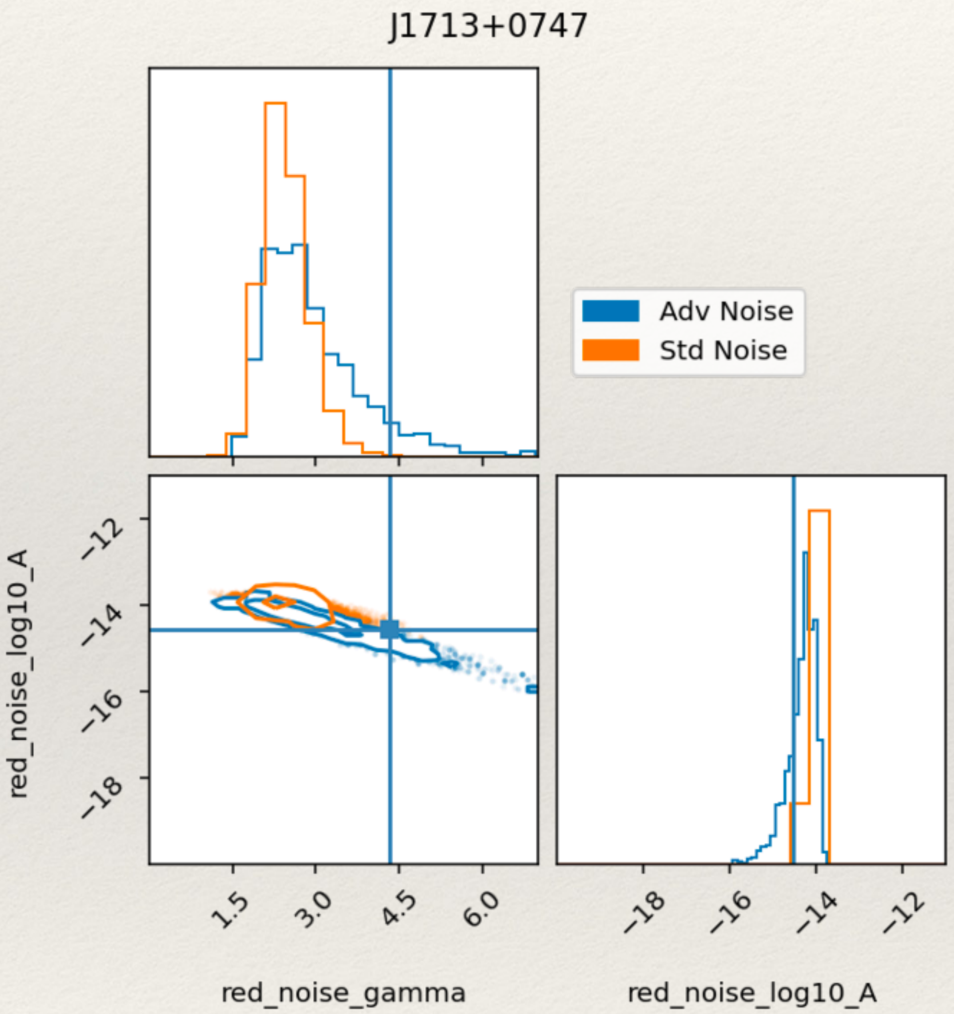
- Error in ephemerides: JPL ephemerides D440, good measurement of Jupyter

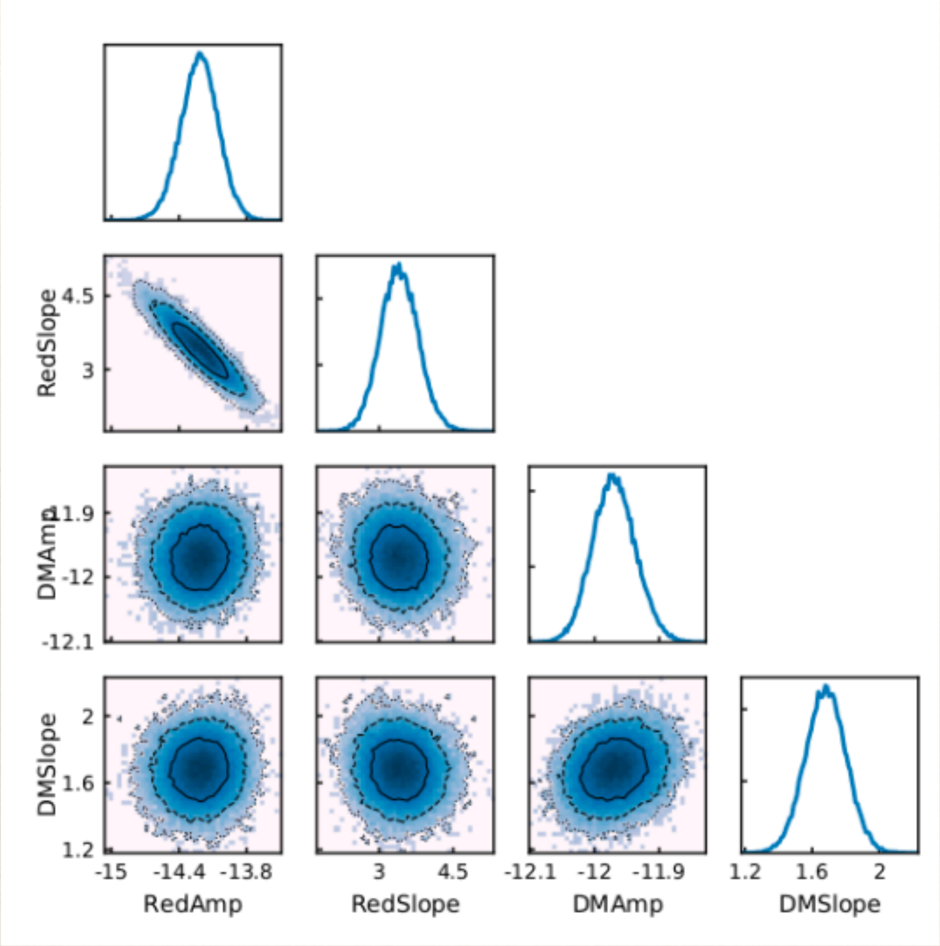


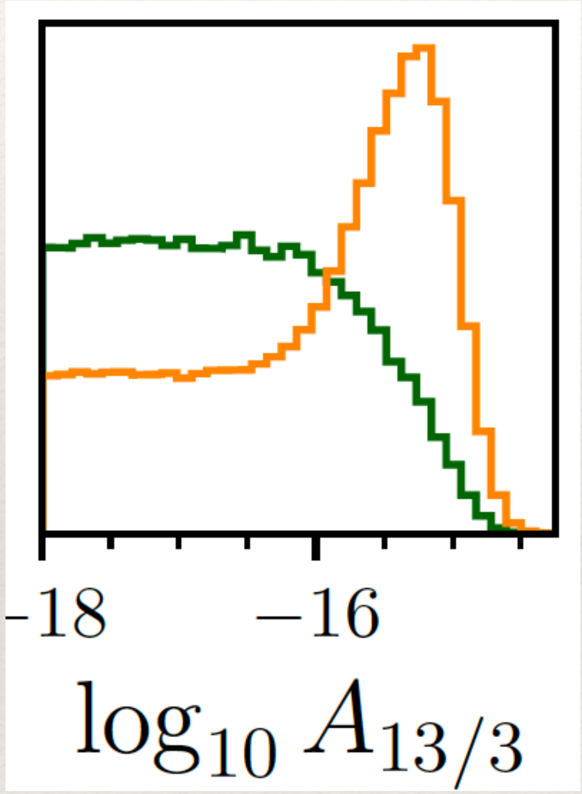
[Arzoumanian+ 2018]

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







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

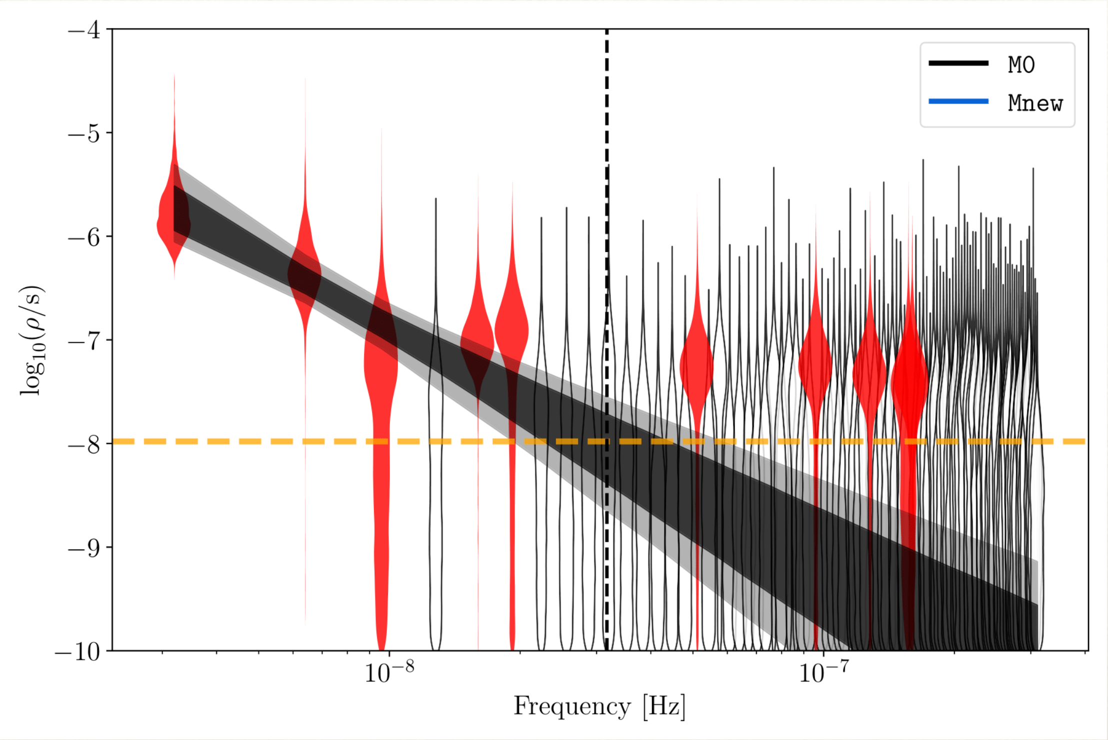
Pulsar	Sel. model
J0613-0200	*RN10 DMv30* *DMv-SN_NUP_1.4*
J1012+5307	*RN150 DMv30* *DMv-SN_NUP_1.4* *SN_NUP_2.5*
J1600-3053	*DMv30 Sv150* *SN_LEAP_1.4*
J1713+0747	*RN15 DMv150* *2 Exp. dips* *DMv-SN_NUP_1.4* *SN_JBO_1.5* *SN_LEAP_1.4* *SN_BON_2.0* *BN_Band.3*
J1744-1134	*RN10 DMv100* *DMv-SN_NUP_1.4* *BN_Band.2*
J1909-3744	*RN10 DMv100 Sv150*

EPTA 6 best pulsars, custom noise models

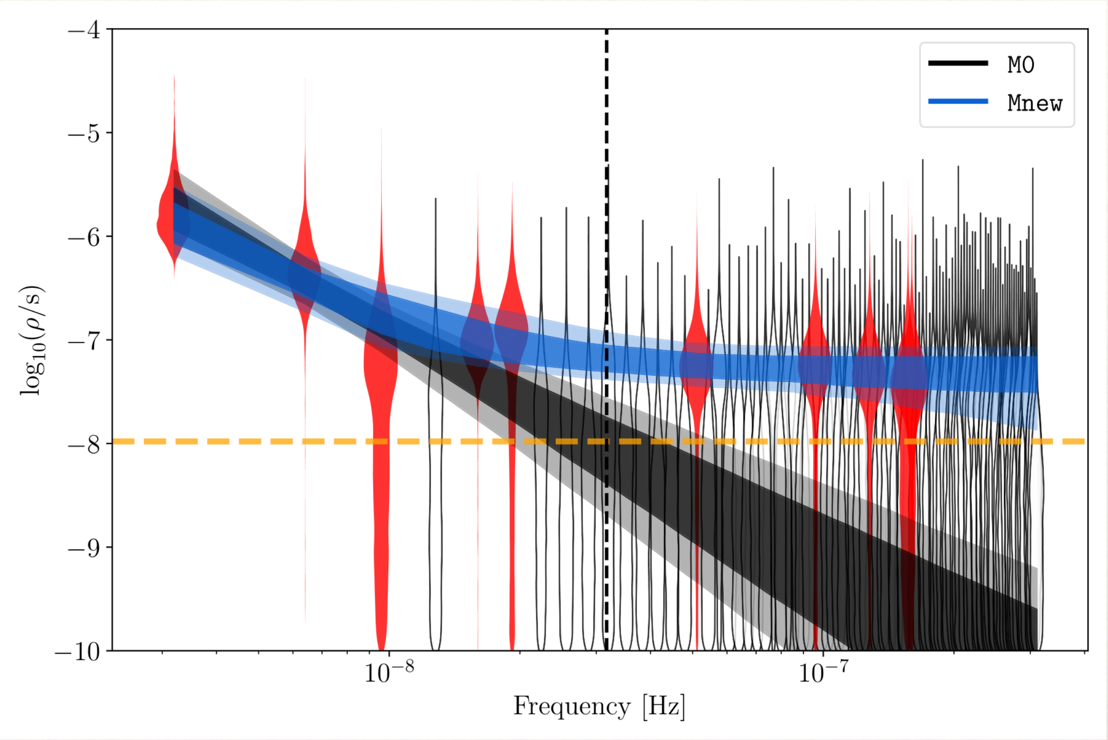
[Chalumeau+ 2021]

Noise model?

DMv noise PSR J1600-3053



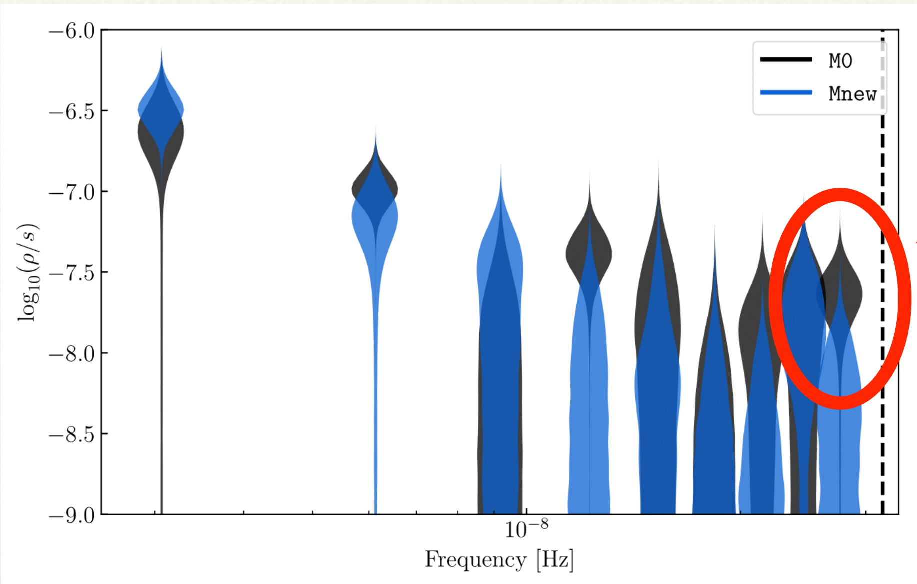
Doesn't look like power-law is a good model



Sign of a strong power leakage in DM estimation

[Quelquejay+ in prep.]

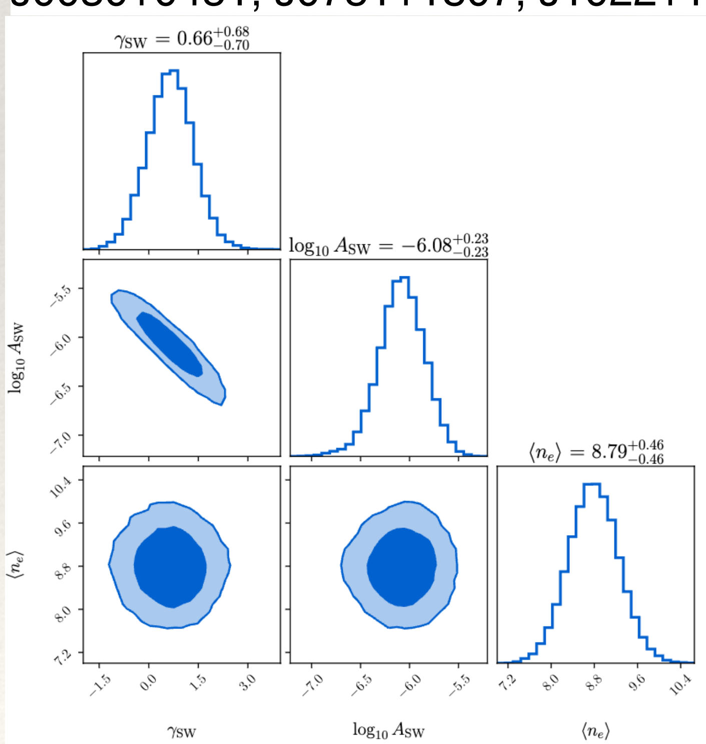
Noise model?



9-th bin close to 1/year frequency, sign of dipolar correlation
Might be chromatic: DM -> solar wind?

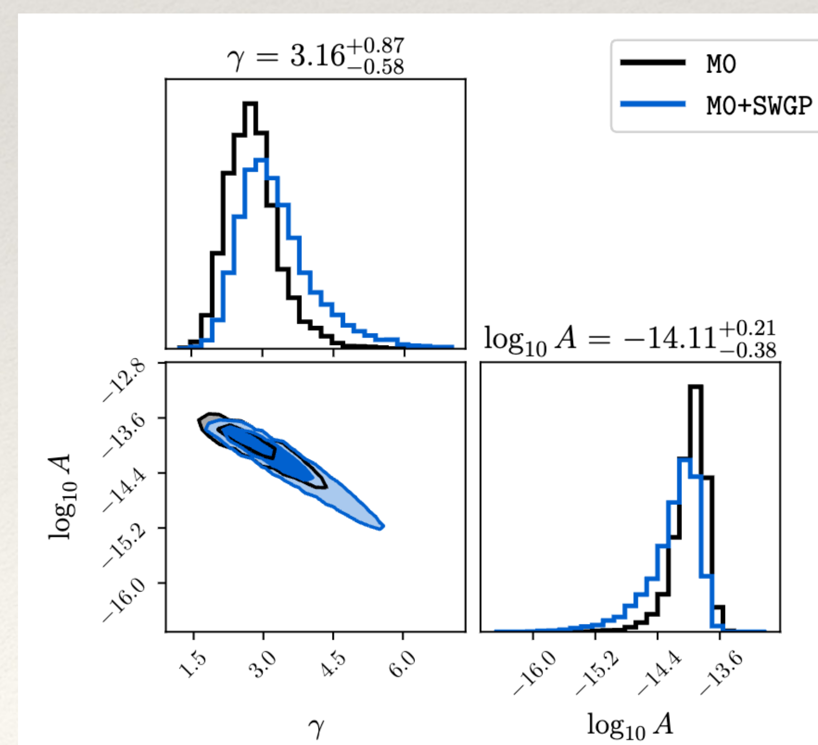
Some pulsar were previously identified to show annual DM variability

J0030+0451, J0751+1807, J1022+1001, J1730-2304



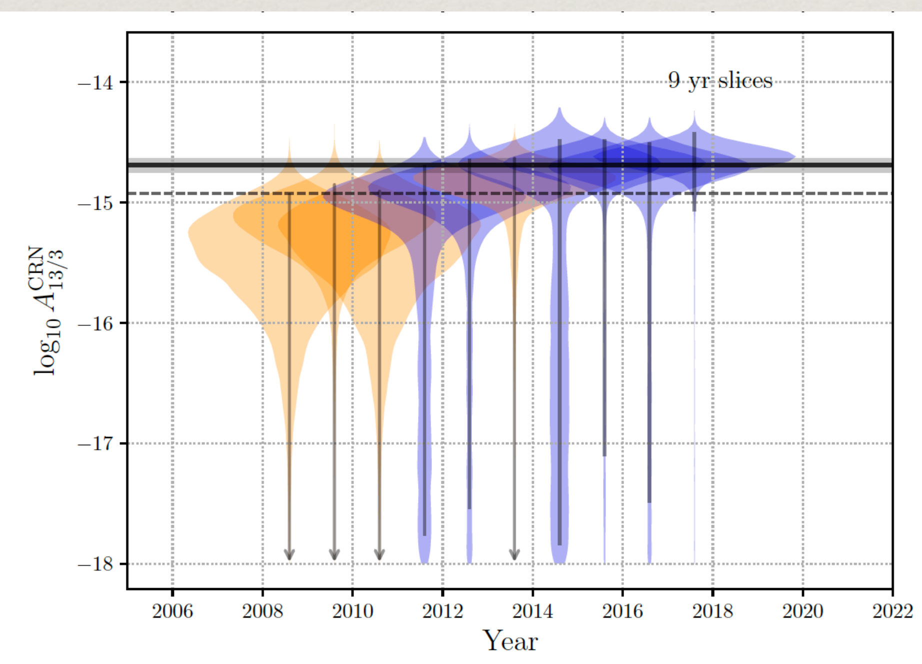
Show common solar wind (correlated DM variations with annual variability)

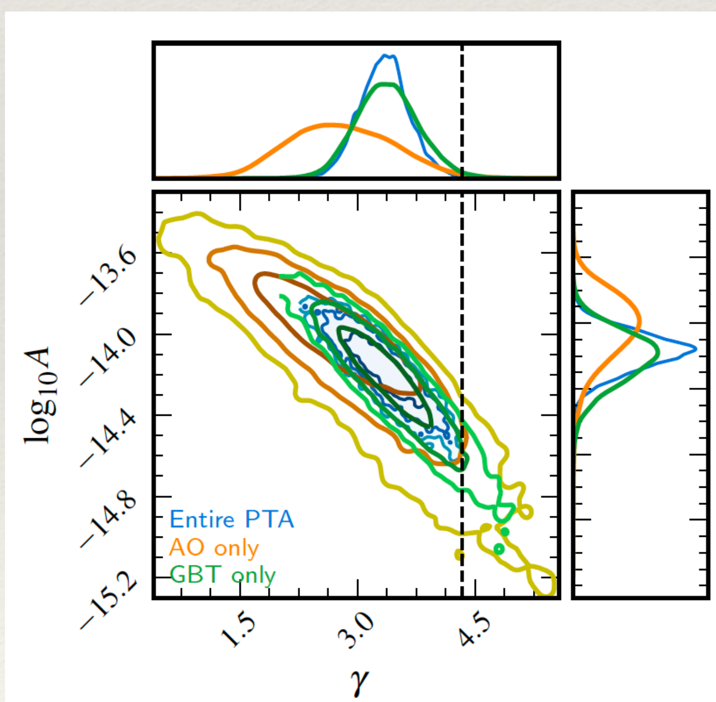
also affects HD (GW) spectrum



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 in reduction of radio observations?





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

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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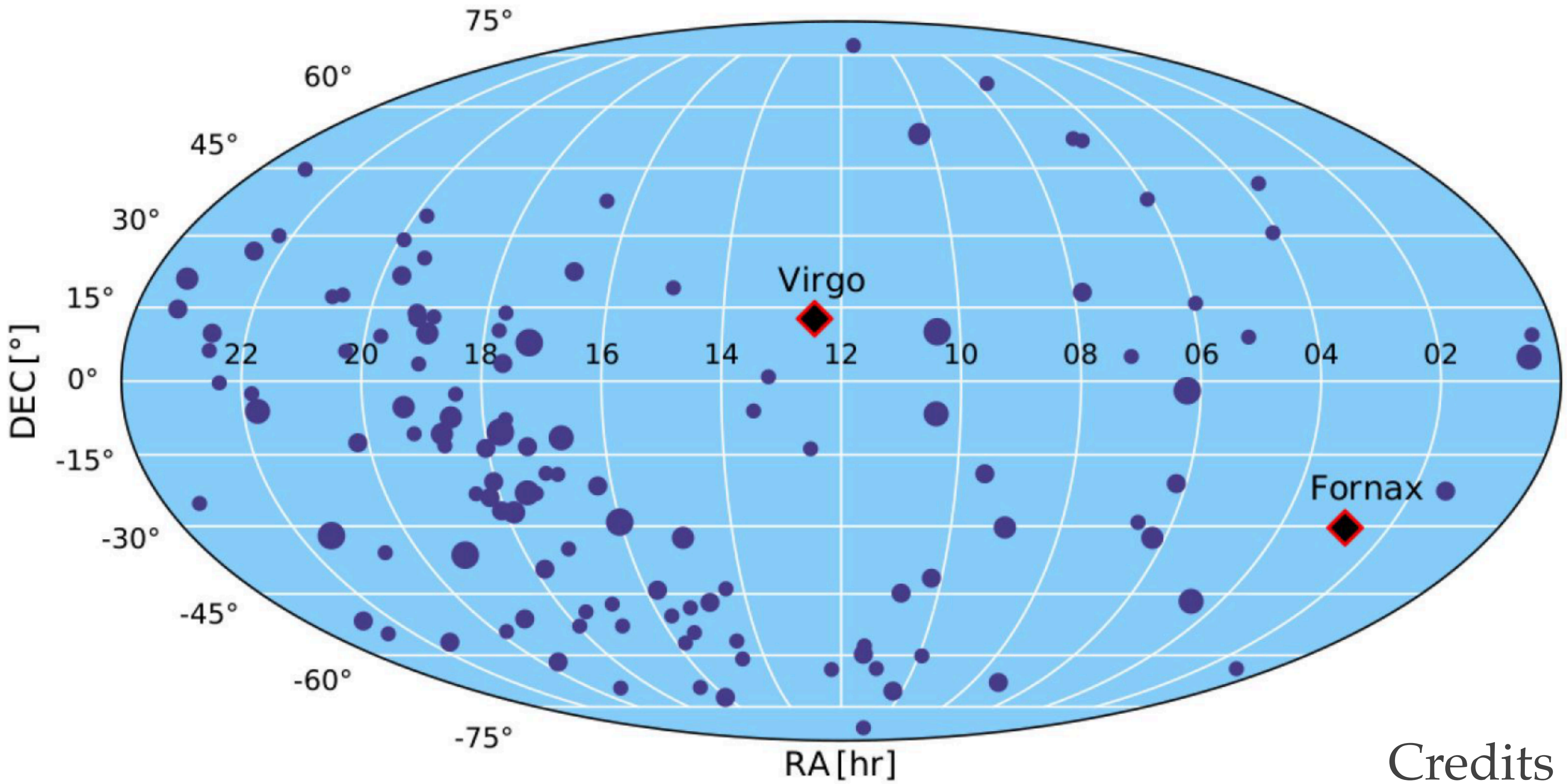

Credits Kuo Liu

4

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

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 reality we need to look at IPTA data, we need longer high quality data. It is "GW detection in slow motion"

Consistency?

IPTA ArXiv:2309.00693