An Introduction to Gravitational Wave Detection with Pulsar Timing Arrays

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GWPAW 2018
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Pulsar Timing Arrays

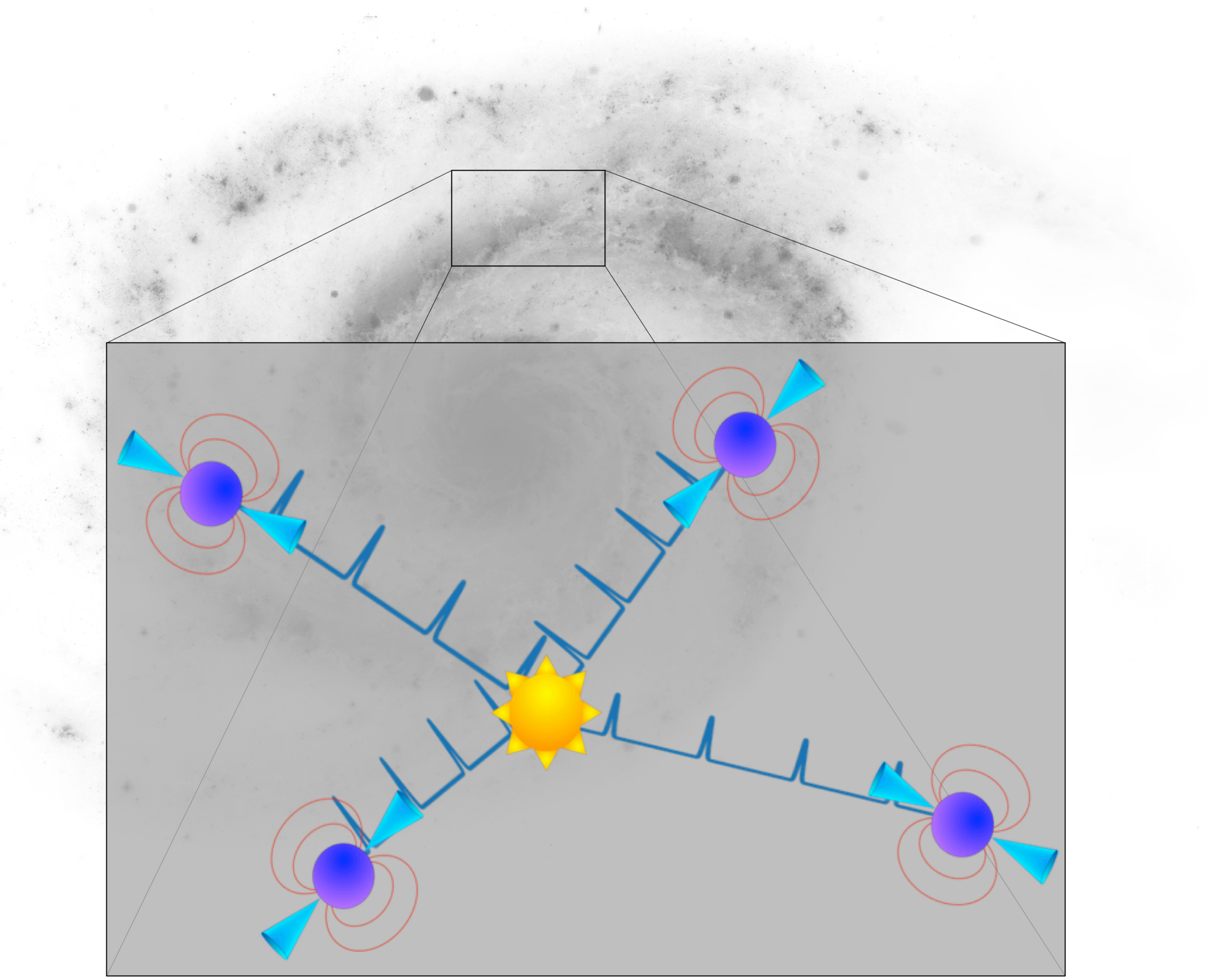


Image credit: J. Hazboun; NASA

Gravitational waves induce correlated changes in the pulse times of arrival.

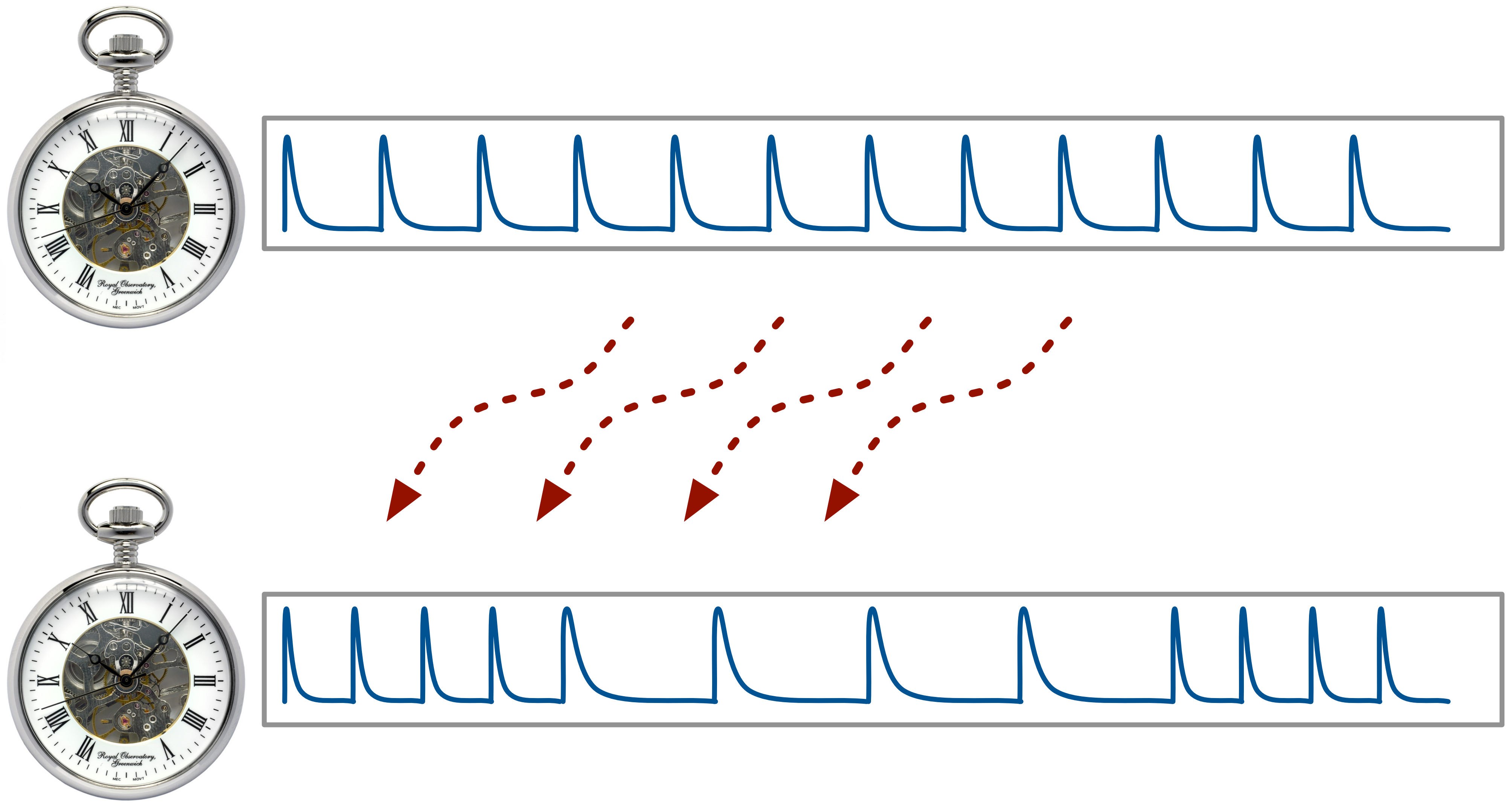


Image credit: S. Chatterjee

Pulsar Timing

Observed times of arrival are fit to a **timing model** to produce residuals.

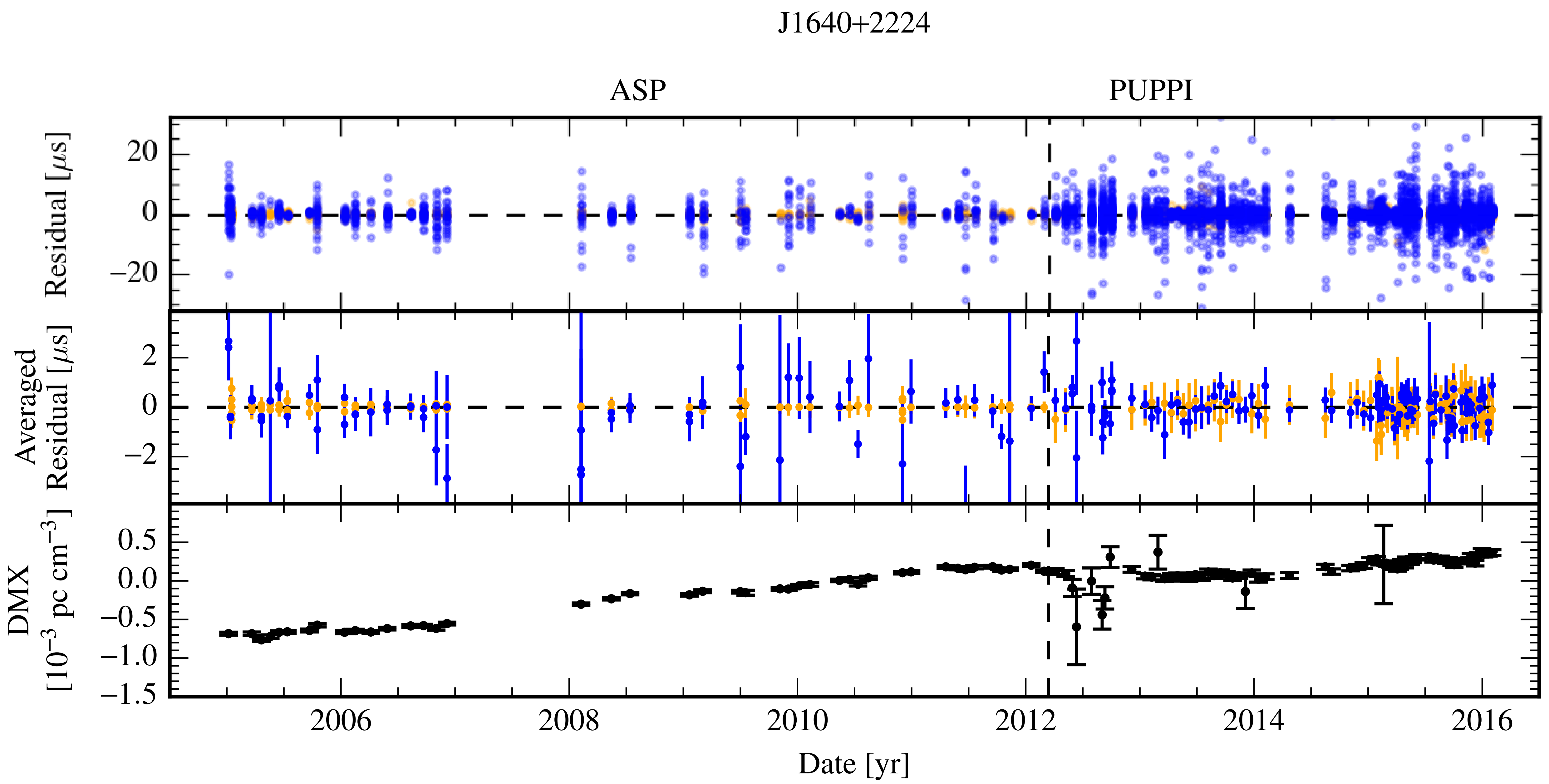


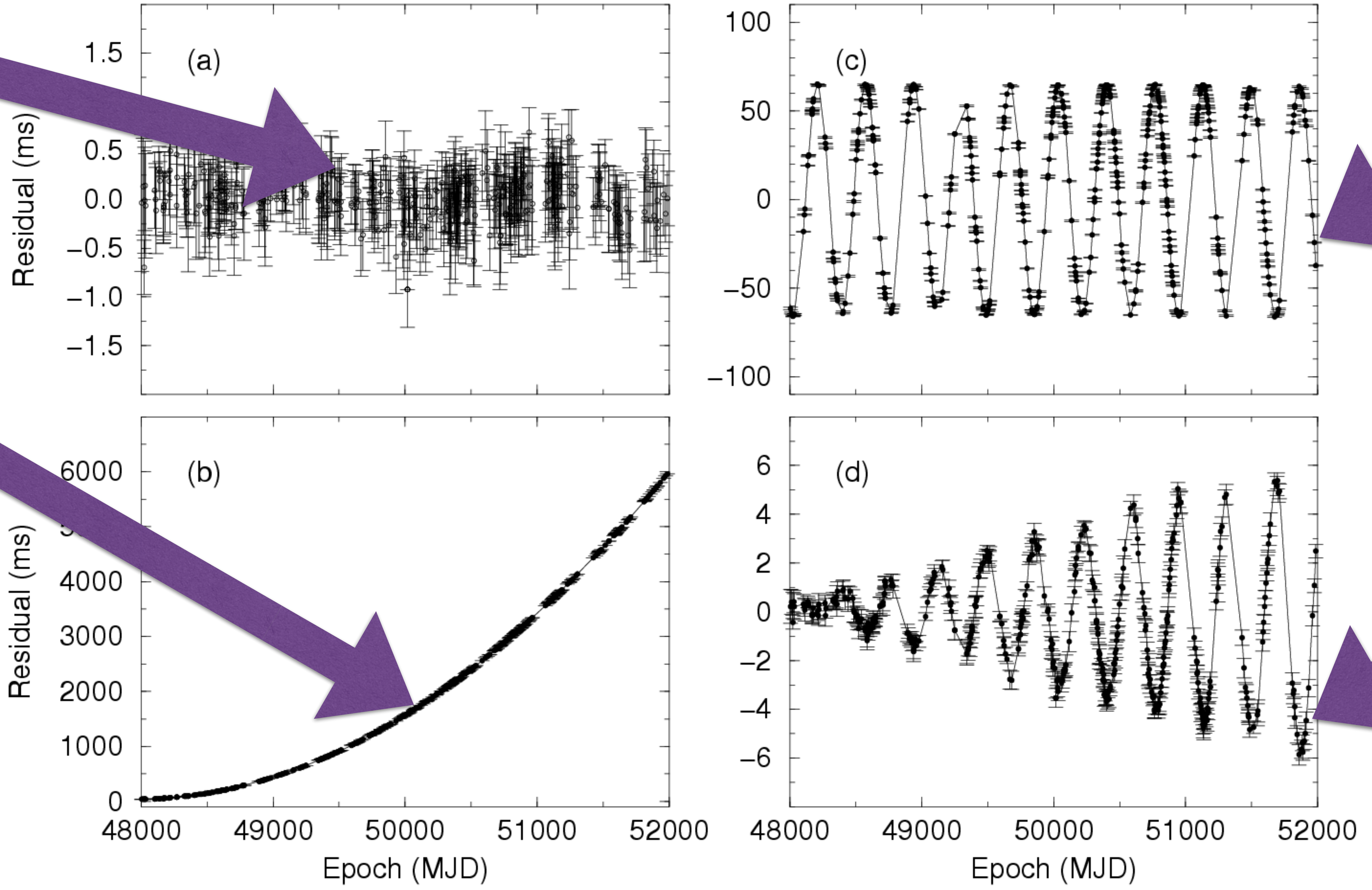
Figure credit: Z. Arzoumanian et al. (2018)

- Spin period and period derivative
- Position
- Proper motion
- Parallax
- Binary parameters
- Dispersion

Pulsar Timing

Good Timing Solution

Error in Pulsar Spin Frequency Derivative

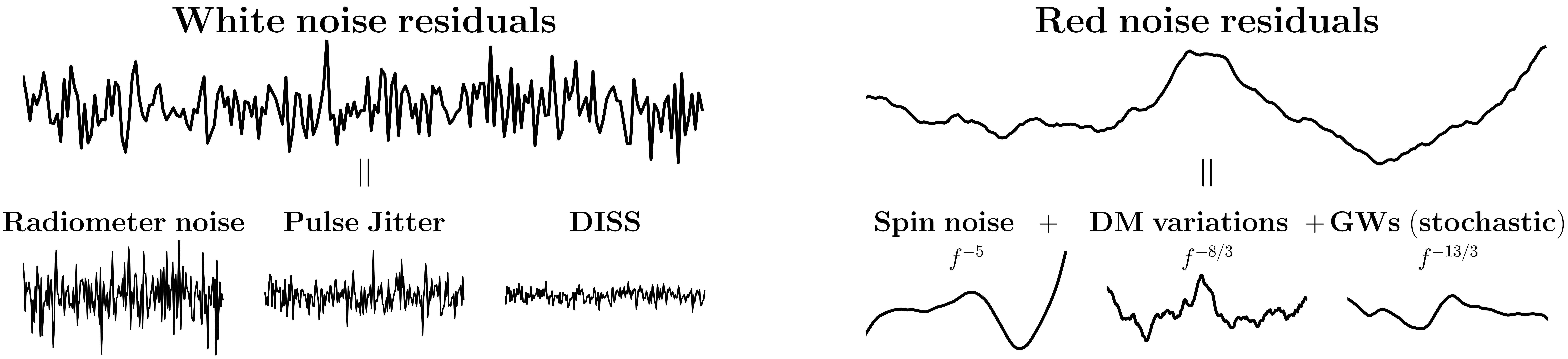


Position Error

Unmodeled Proper Motion

Image credit: Lorimer and Kramer, *The Handbook of Pulsar Astronomy*

Pulsar Noise



DISS = Diffractive
Interstellar Scintillation

Figures from James Cordes

Pulsar Residuals

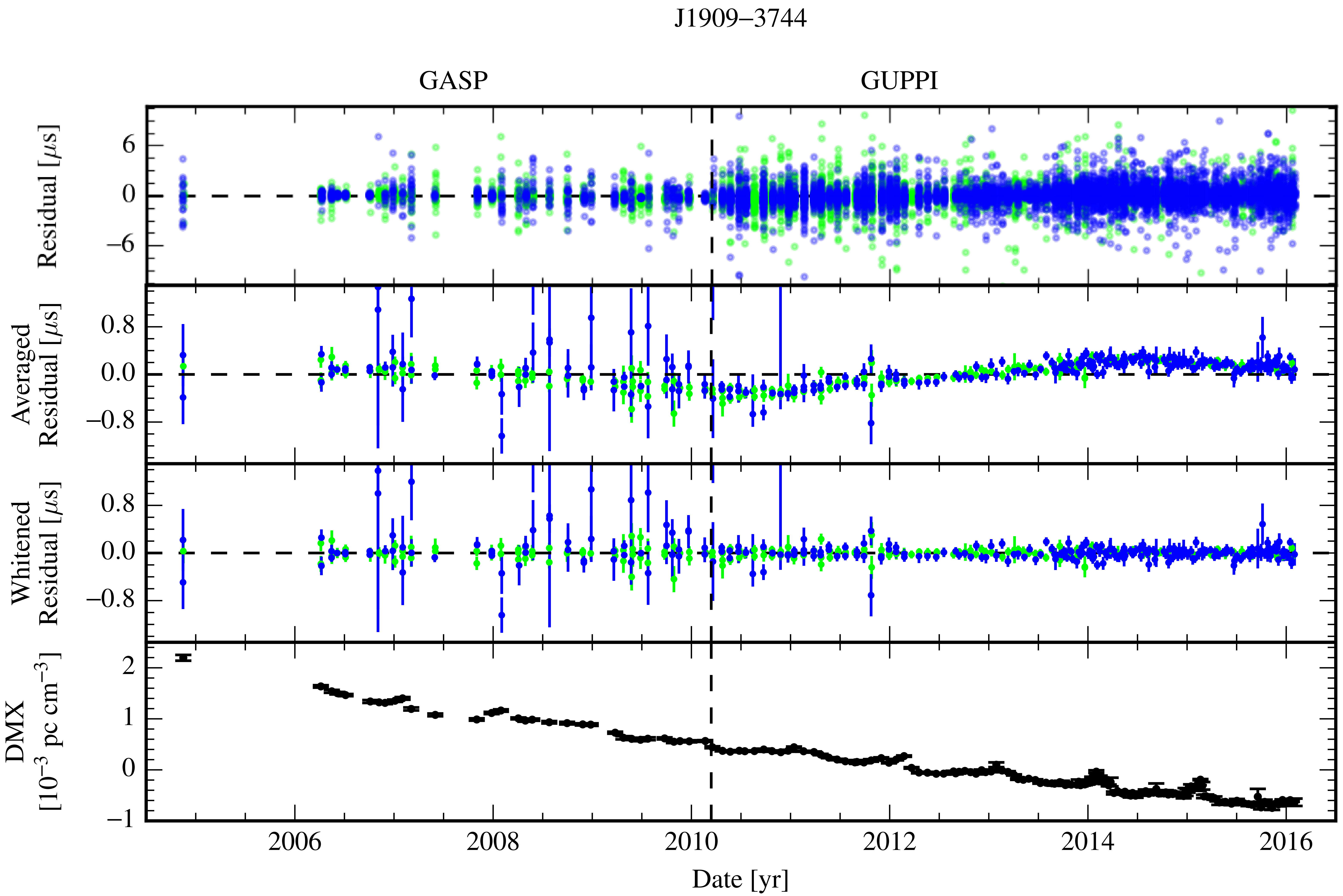
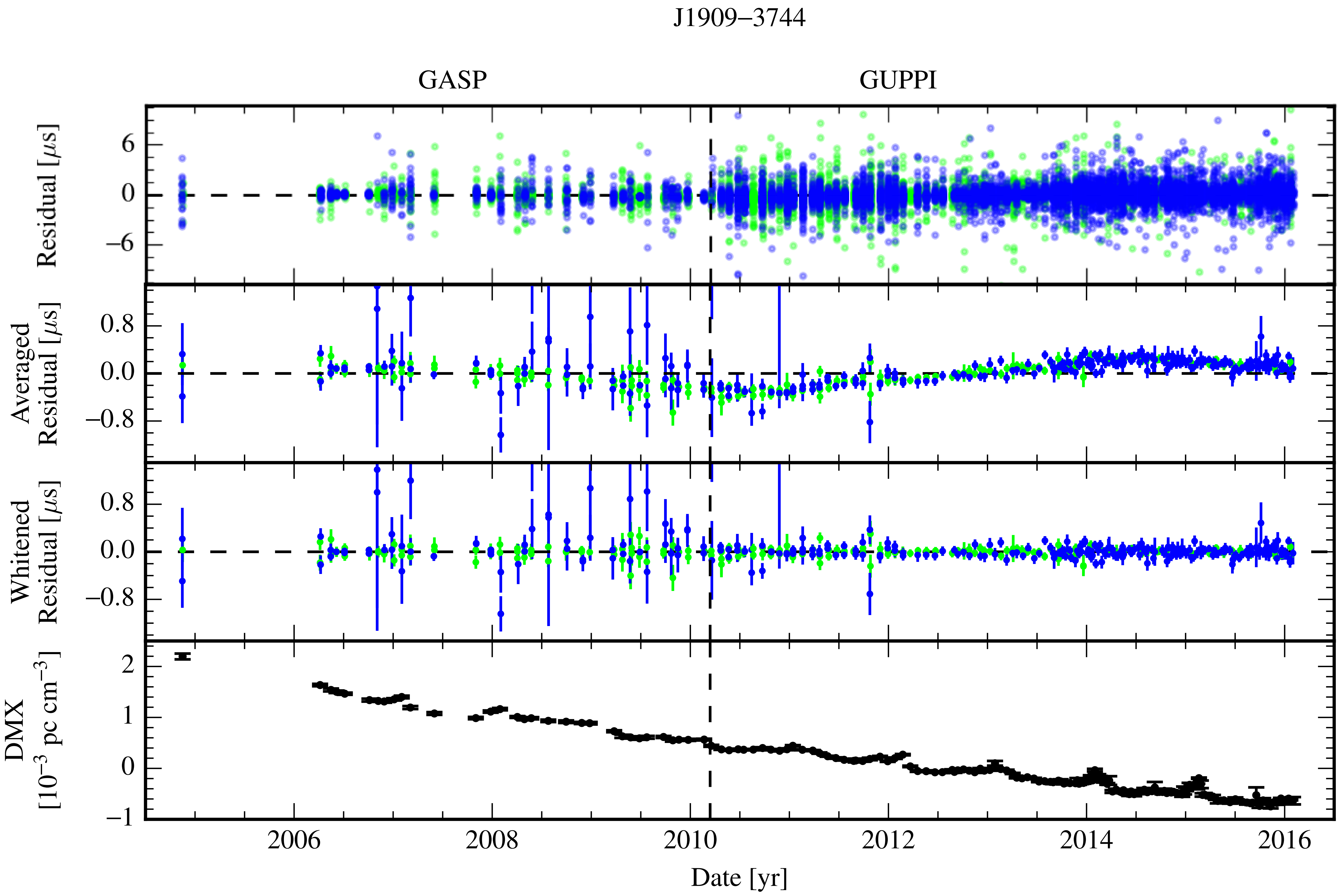


Figure credit: Z. Arzoumanian et al. (2018)

Pulsar Residuals

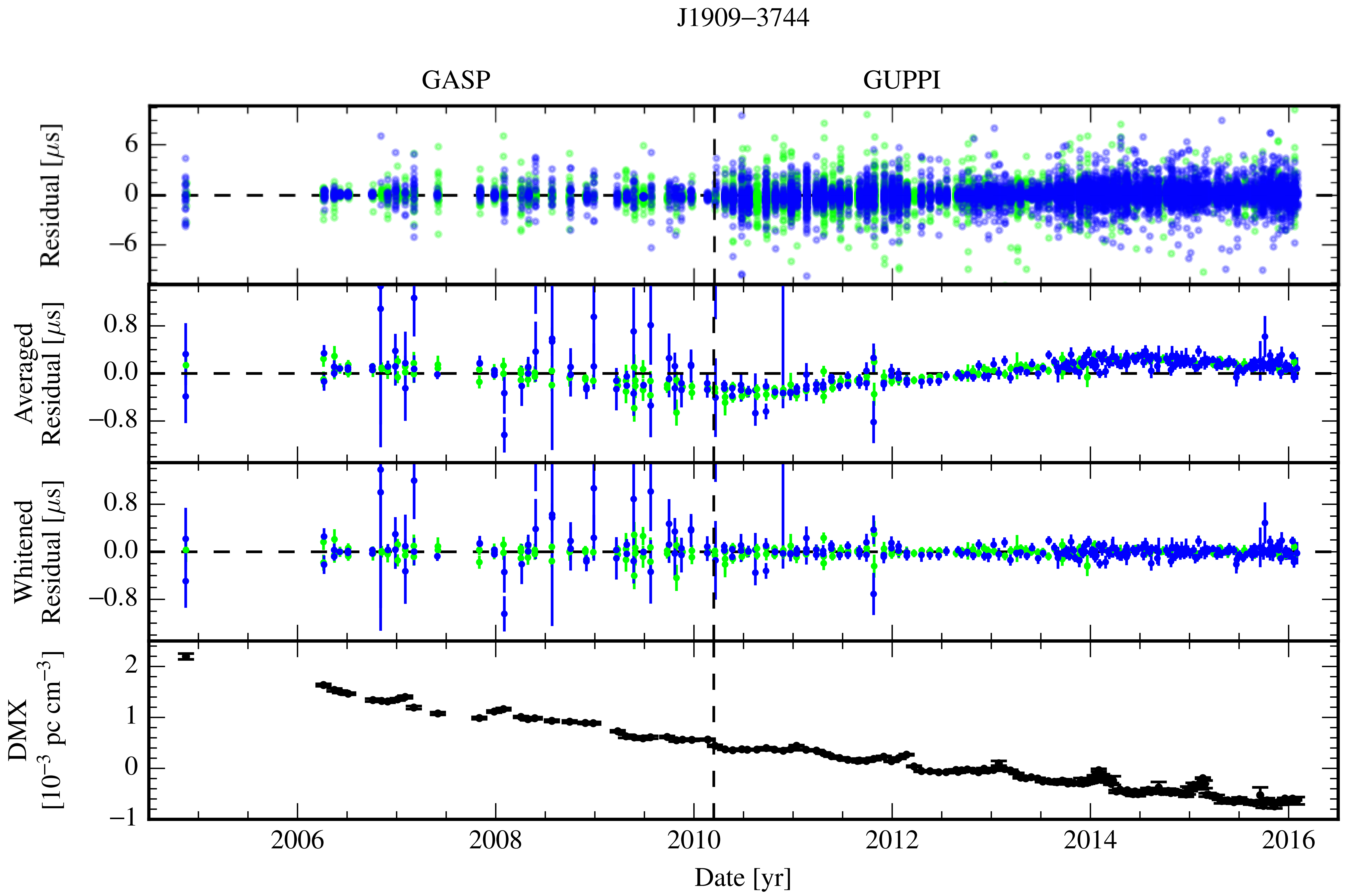


NANOGrav uses data taken with two generations of backends. The older generation is **ASP/GASP**. The current backends are **PUPPI/GUPPI**.

The backends record data over a range of frequencies. The newer backends have a wider bandwidth.

Figure credit: Z. Arzoumanian et al. (2018)

Pulsar Residuals



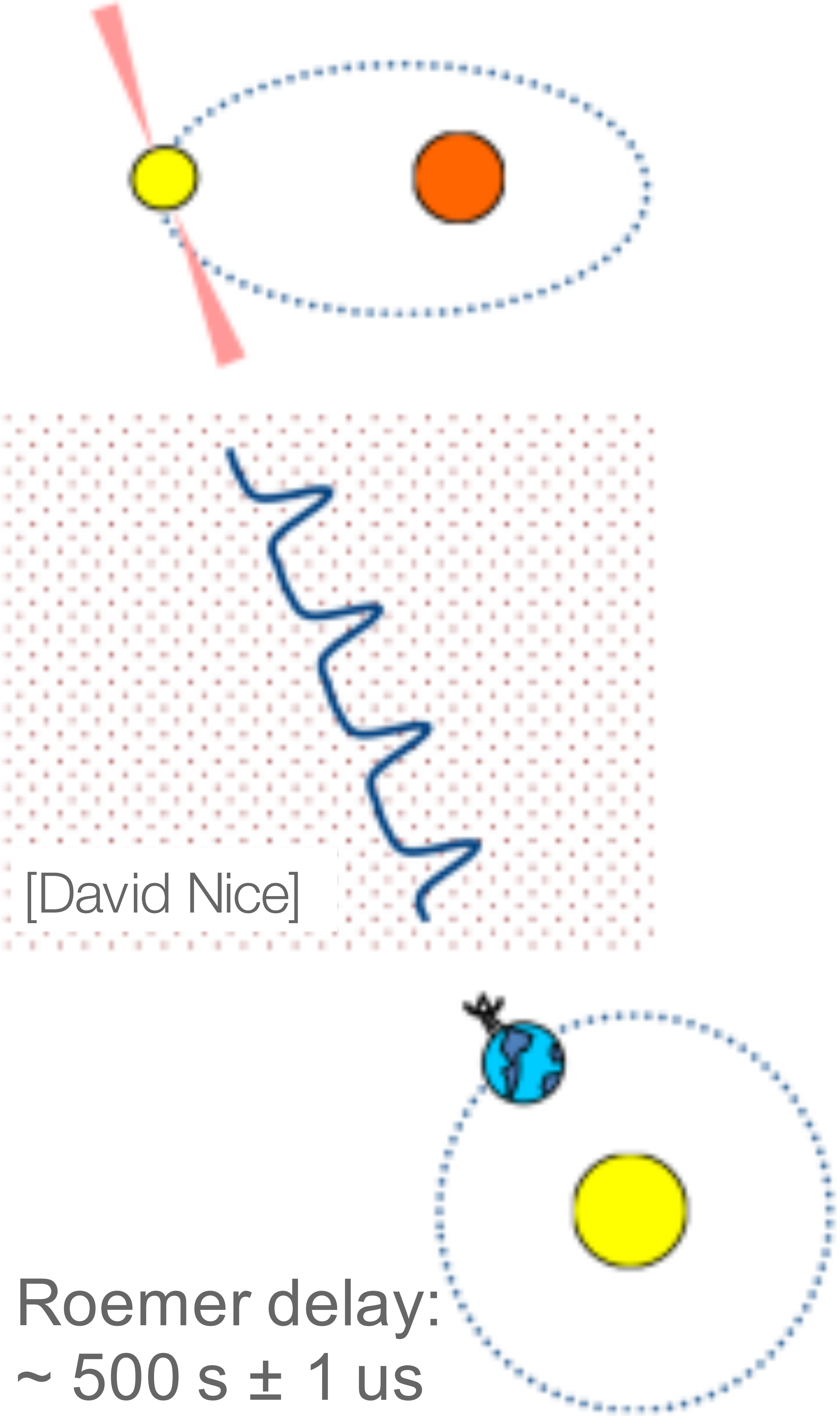
The **DMX parameters** describe changes in the dispersion due to the interstellar medium. There is one DMX parameter for each observation.

Figure credit: Z. Arzoumanian et al. (2018)

Signal Model

Pulsar 1		Pulsar 2		Pulsar 3
Timing Model White Noise Red Noise	+	Timing Model White Noise Red Noise	+	Timing Model White Noise Red Noise

The Solar System Ephemeris

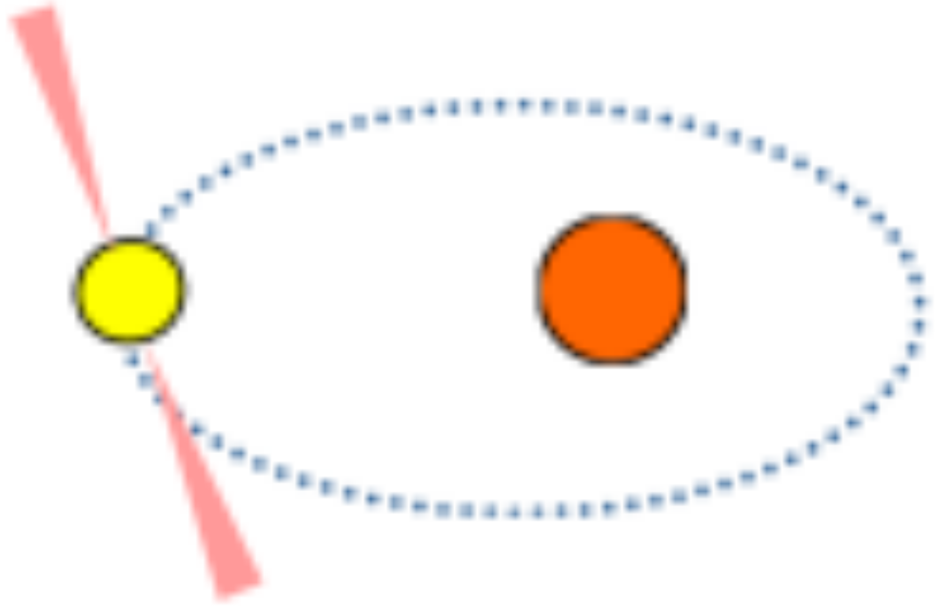


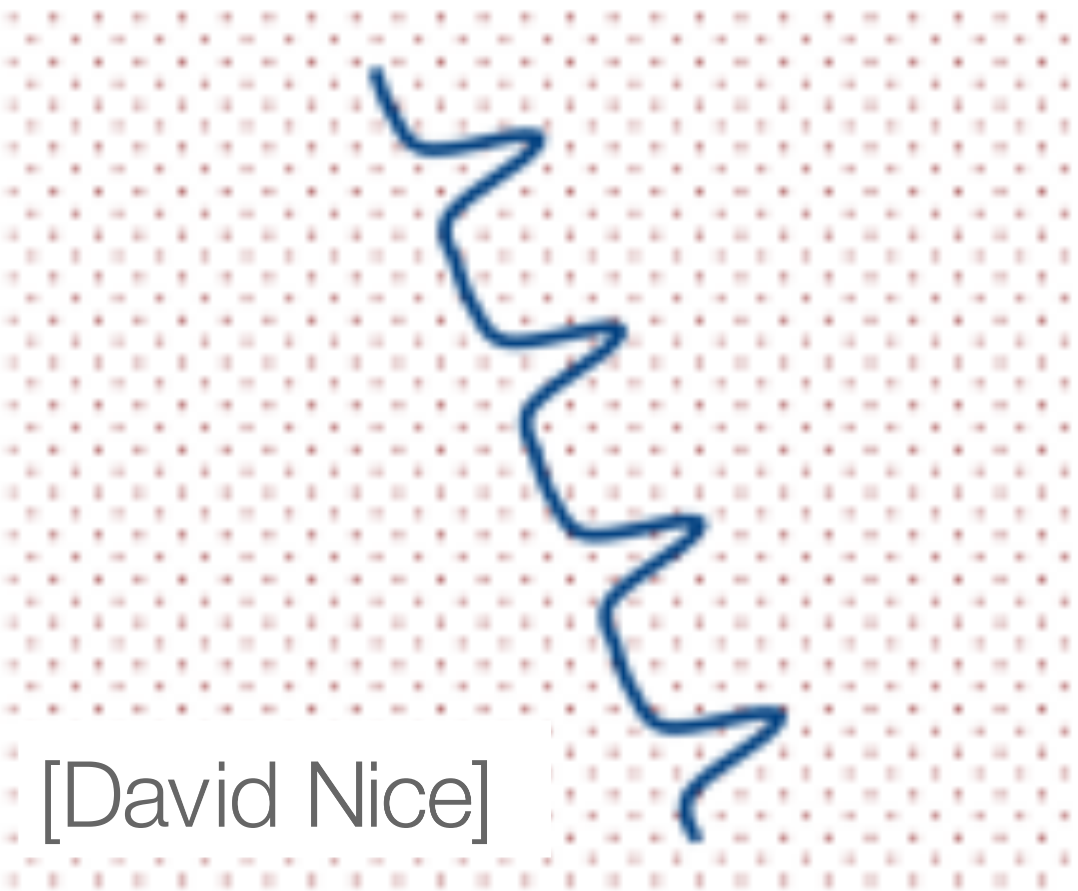
Pulse TOAs are referenced to the **Solar System barycenter (SSB)**. The **SSB** is the center of mass for the Solar System.

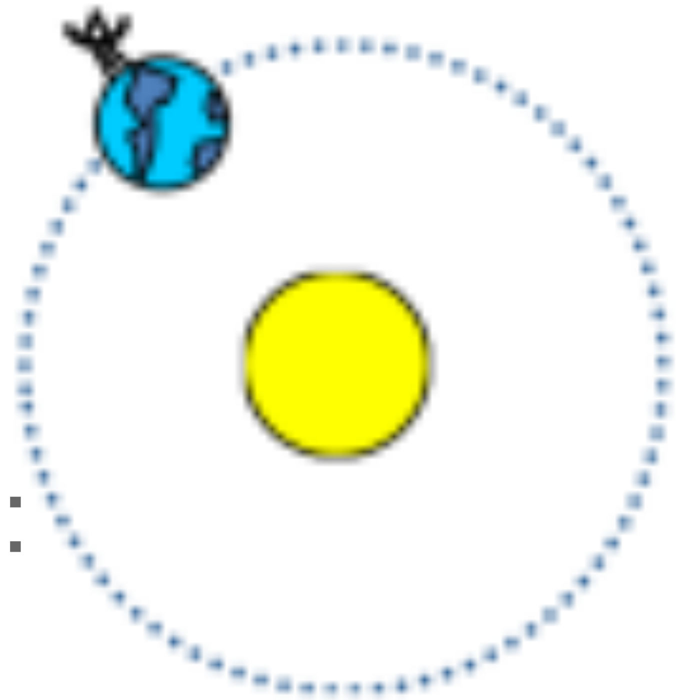
Pulse TOAs are recorded at particular observatories and then corrected to the SSB TOA.

The **Solar System ephemeris (SSE)** is a model for the position of the SSB. We primarily use the one produced by JPL. It uses data from spacecraft and lunar laser ranging.

The Solar System Ephemeris







Roemer delay:
~ 500 s ± 1 us

The **Roemer delay** is the time it takes the pulses to travel across the Earth's orbit:

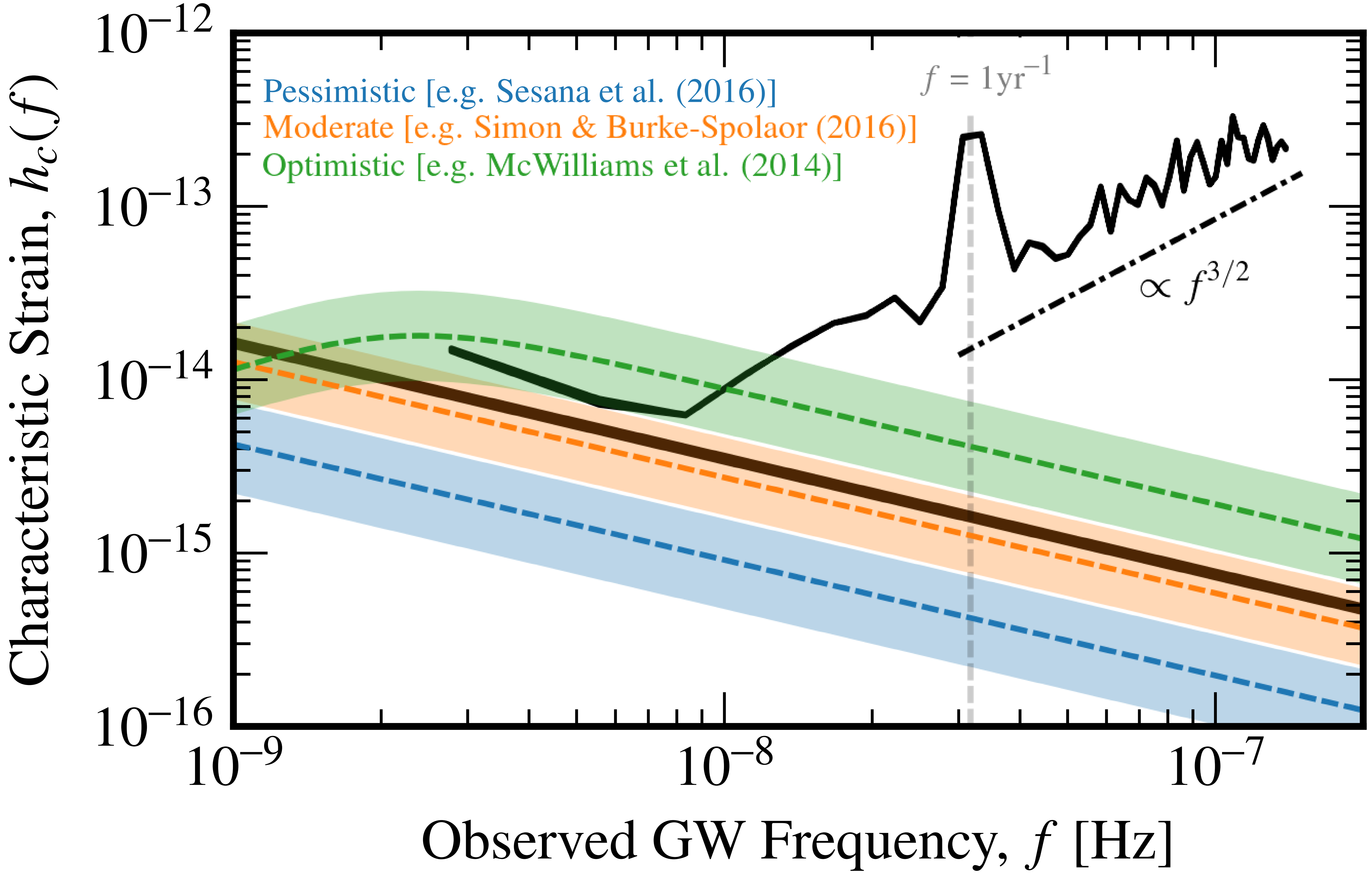
$$\tau \simeq 500\,\mathrm{s}\ \cos\beta\cos\left[\theta(\mathrm{t})+\lambda\right]$$

Ecliptic latitude

Orbital phase

Ecliptic longitude

GW Stochastic Background



We can place a limit on the GWB at each frequency, or model the GWB as a power law.

Assuming the GWB is made up of circular SMBHBs, and they evolve only due to GW emission,

$$h_c(f) = A_{gw} \left(\frac{f}{f_{yr}}\right)^{-2/3}$$

Figure credit: Z. Arzoumanian et al. (2018)

Signal Model

Pulsar 1

Timing Model
White Noise
Red Noise

+

Pulsar 2

Timing Model
White Noise
Red Noise

+

Pulsar 3

Timing Model
White Noise
Red Noise

+

Ephemeris Uncertainty

+

Gravitational Wave Signal

Software

- We use **tempo2** and **pint** to construct the residuals. **libstempo** is a python wrapper for tempo2.

- **ENTERPRISE** (Enhanced Numerical Toolbox Enabling a Robust PulsaR Inference SuitE) is a pulsar timing analysis code that can perform noise analyses and gravitational wave searches.

- **PTMCMCSampler** is the MCMC Sampler used by enterprise and previous pulsar timing software packages. It primarily uses Adaptive Metropolis sampling.

Data

- NANOGrav data is made publicly available when the data release papers are published.
- For more information about the 11-year GWB analysis, there is a summary here: https://nanograv.github.io/11yr_stochastic_analysis/
- You can download NANOGrav data here: https://data.nanograv.org/
- You can find the code used to do the GWB analysis here: https://github.com/nanograv/11yr_stochastic_analysis

Tutorial Exercise

The Jupyter notebook will walk you through running a GWB upper limit analysis on a single pulsar (J1713+0747).

The signal model is very modular, so you can easily modify the notebook to perform different types of analyses. You can also easily load up multiple pulsars and analyze them simultaneously.

IPTA Mock Data Challenge 2

If you want to try your hand at PTA data analysis, try the IPTA Mock Data Challenge 2: https://ipta.github.io/mock_data_challenge/

Entries are due **March 15, 2019**.

Questions? Contact Jeff Hazboun, hazboun@uw.edu.