Noise in pulsar timing observations

PPTA

Ryan Shannon
(ARC Future Fellow/Swinburne/OzGrav)

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

SWINBURNE UNIVERSITY OF TECHNOLOGY
MONASH University
Australian National University
THE UNIVERSITY of ADELAIDE
THE UNIVERSITY OF MELBOURNE
THE UNIVERSITY OF WESTERN AUSTRALIA
AAO
CSIRO

Outline

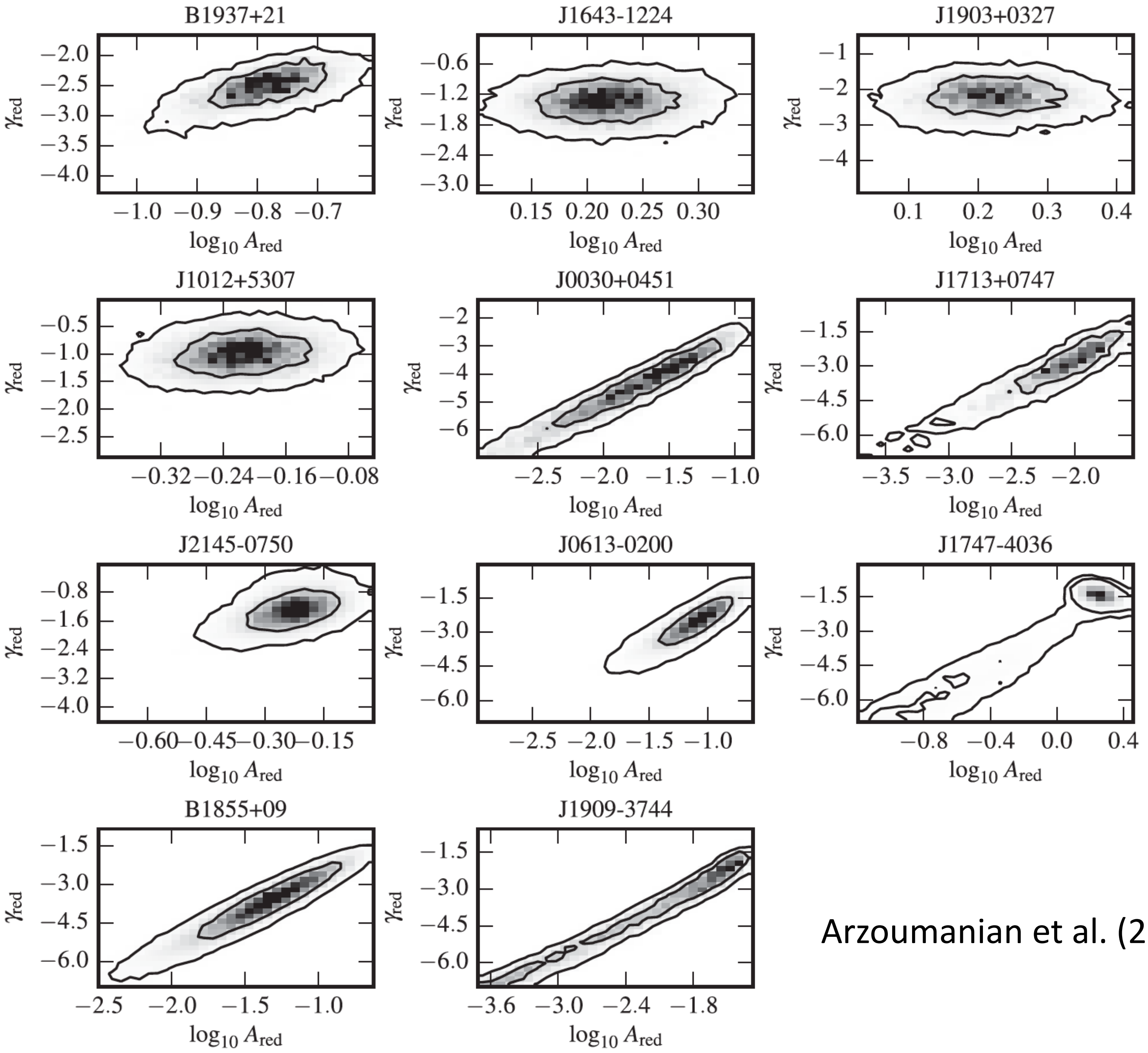


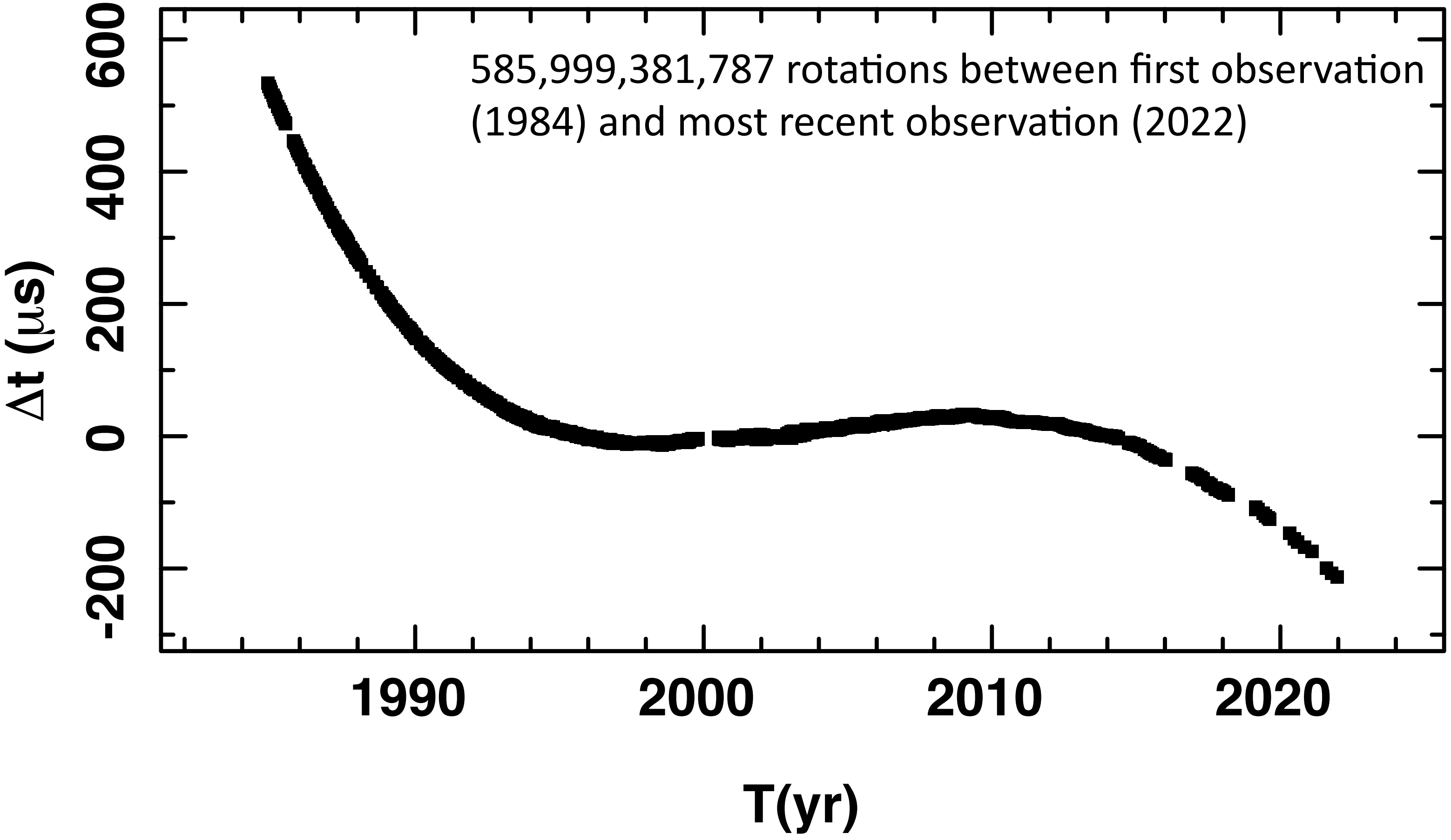
Figure 2. 2D posteriors of the amplitude and spectral index of the red-noise parameters for those pulsars with Bayes factors for red noise greater than 100, plus J1713+0747. The contours are the 50% and 90% credible regions.

- The joy of pulsar timing
- Noise in pulsar timing data sets
- Finding noise in pulsar timing data sets

Arzoumanian et al. (2018)

The joy of pulsar timing

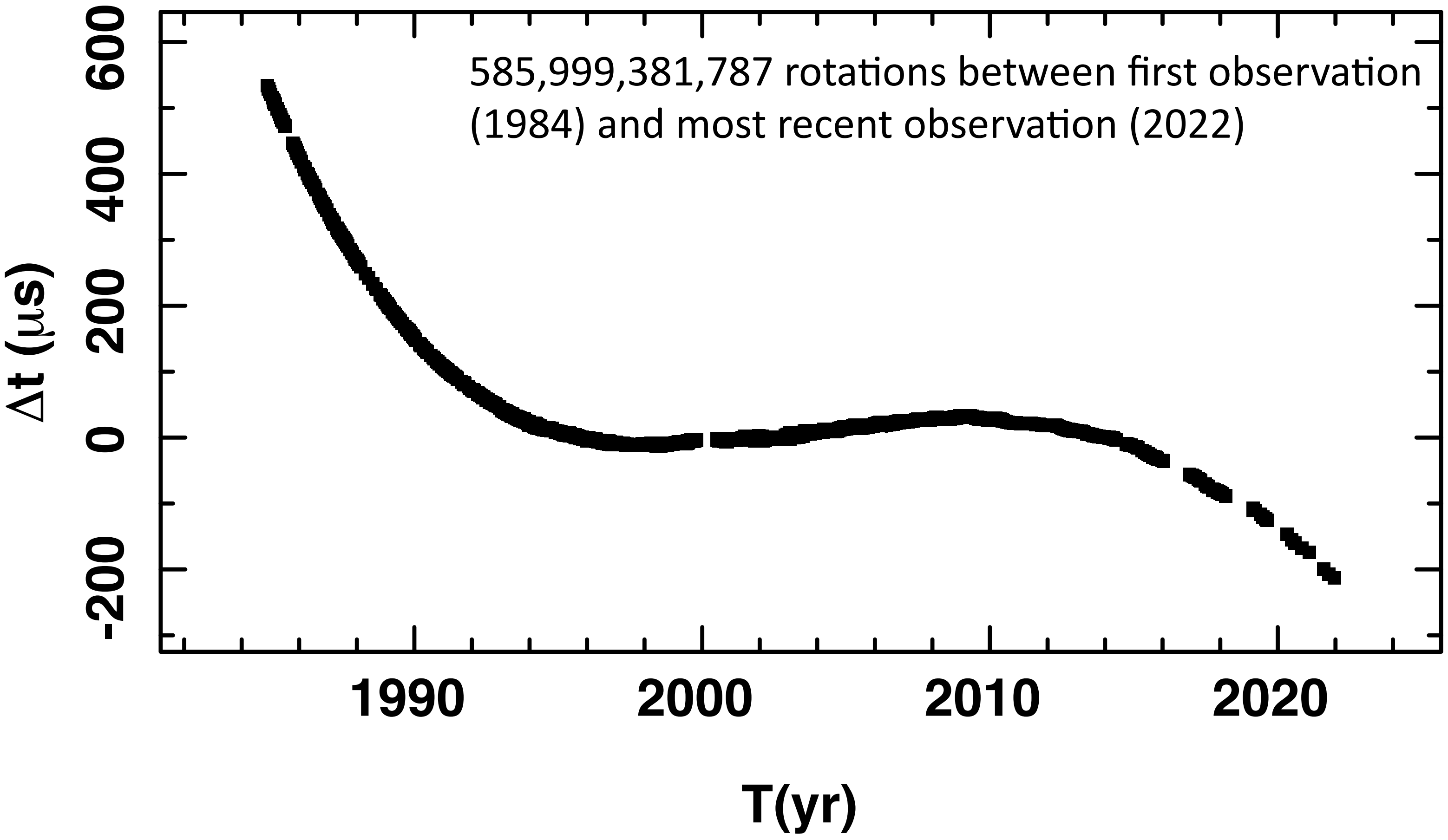
- **Phase coherent**: sensitive to effects that only manifest as small Doppler shifts
- **Millisecond pulsars** sensitive to the smallest of perturbations
- **Timing noise:** spin irregularities manifest as red noise in arrival times
- h~Δt/T ~ 10^{-3} s/10^{9} s= 10^{-12}



The joy of pulsar timing

- Enables effects that only cause weak doppler shifts of pulsar to be strongly studied
    - Search for gravitational waves
    - Tests of general relativity
    - Masses of neutron stars
    - Interiors and magnetsopheres as well (glitches/magnetospheric state changes, etc.)

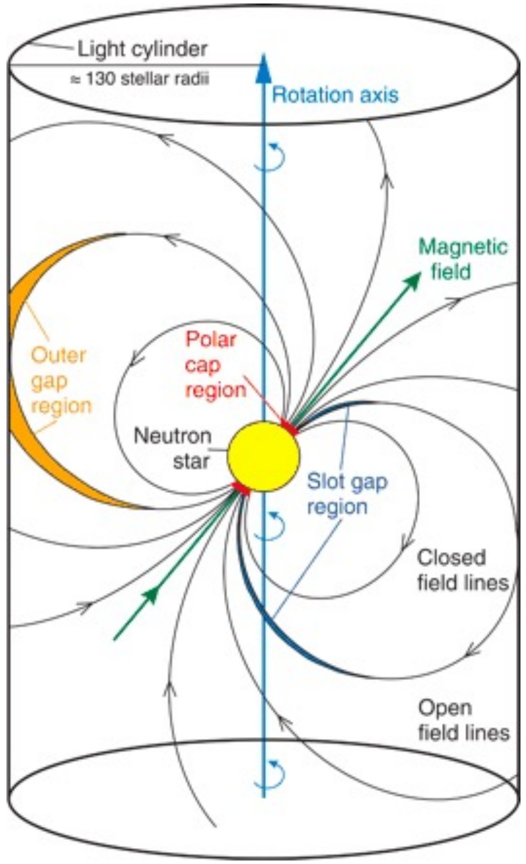
- Best timing: millisecond pulsars
    - Most stable rotation
    - Narrow pulse profiles – highest timing precision



585,999,381,787 rotations between first observation (1984) and most recent observation (2022)

Common assumptions in pulsar timing

- Radio emission is ”anchored” to neutron star
  - Measures rotational state of pulsar
- Radio emission is stable: emission will converge to same profile at each epoch
  - Notable exceptions precessing relativistic binaries
- Key point: signals of interest alter arrival times of pulses and don’t distort pulse shape



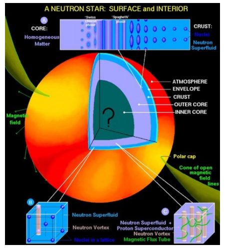
MAGIC collaboration

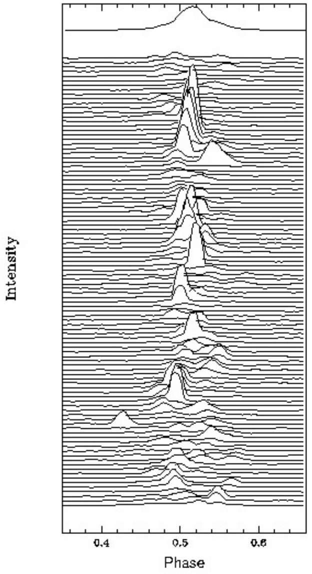
Contributions to Pulsar Arrival Times

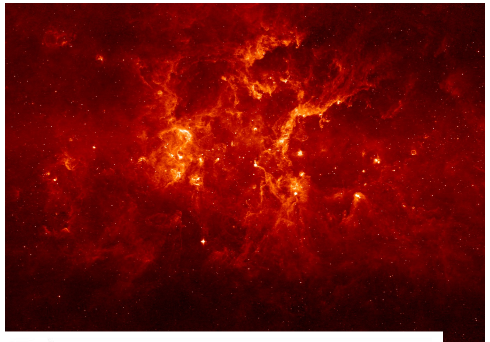
Pulsar

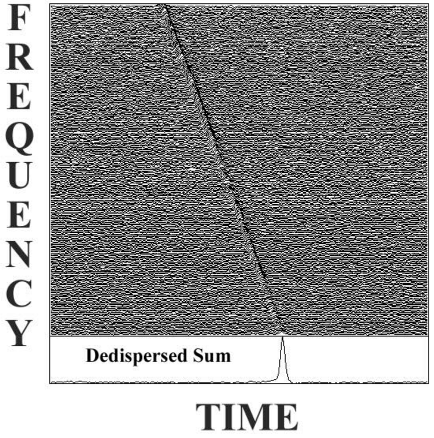
- Pulsar spindown
- Intrinsic variation in shape and/or phase of emitted pulse
- ***Reflex motion from companions.***
- Pulsar position, proper motion, distance
- ***Stochastic spindown variations***
- ***Gravitational Waves***
- ***Warm electrons in the ISM***
- Solar system

Earth

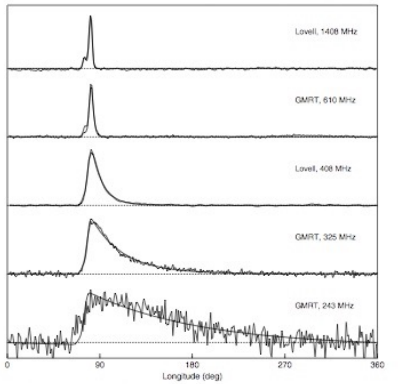








O. Löhmer et al.: Frequency evoluti



SWINBURNE UNIVERSITY OF TECHNOLOGY

OzGrav

Deterministic vs. Stochastic Process

- **Deterministic system:**
  - If initial state is known exactly, future state can be predicted
  - E.g. Pulsar, white dwarf system
- **Chaotic system (type of deterministic system)**
  - If deterministic system behavior is highly sensitive to initial condition, evolution will show apparent randomness
  - Example: Hyperion
- **Stochastic system:**
  - System evolution depends on random variables
  - Example CMB, Gravitational Wave Background
- A large portion of the rest of the talk will be devoted to identifying, assessing, and characterizing stochastic processes.

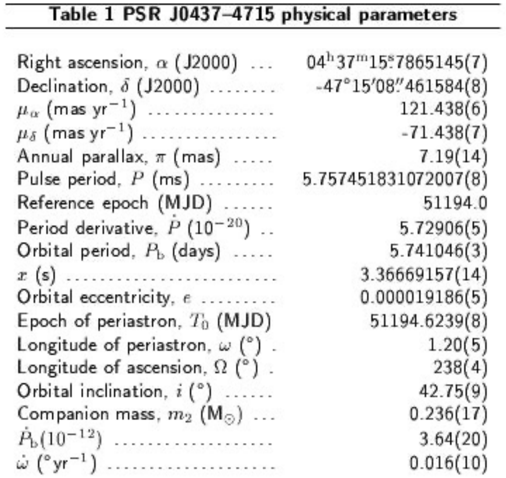
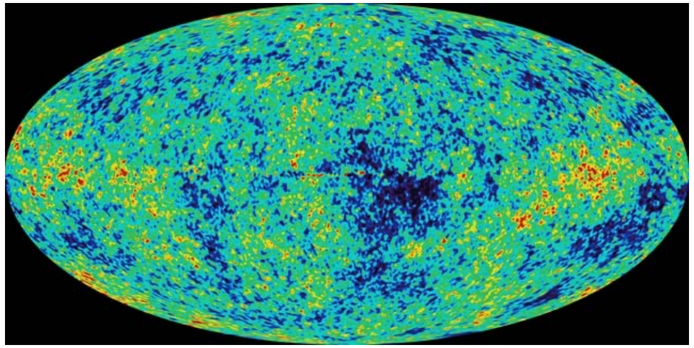


Table 1 PSR J0437–4715 physical parameters

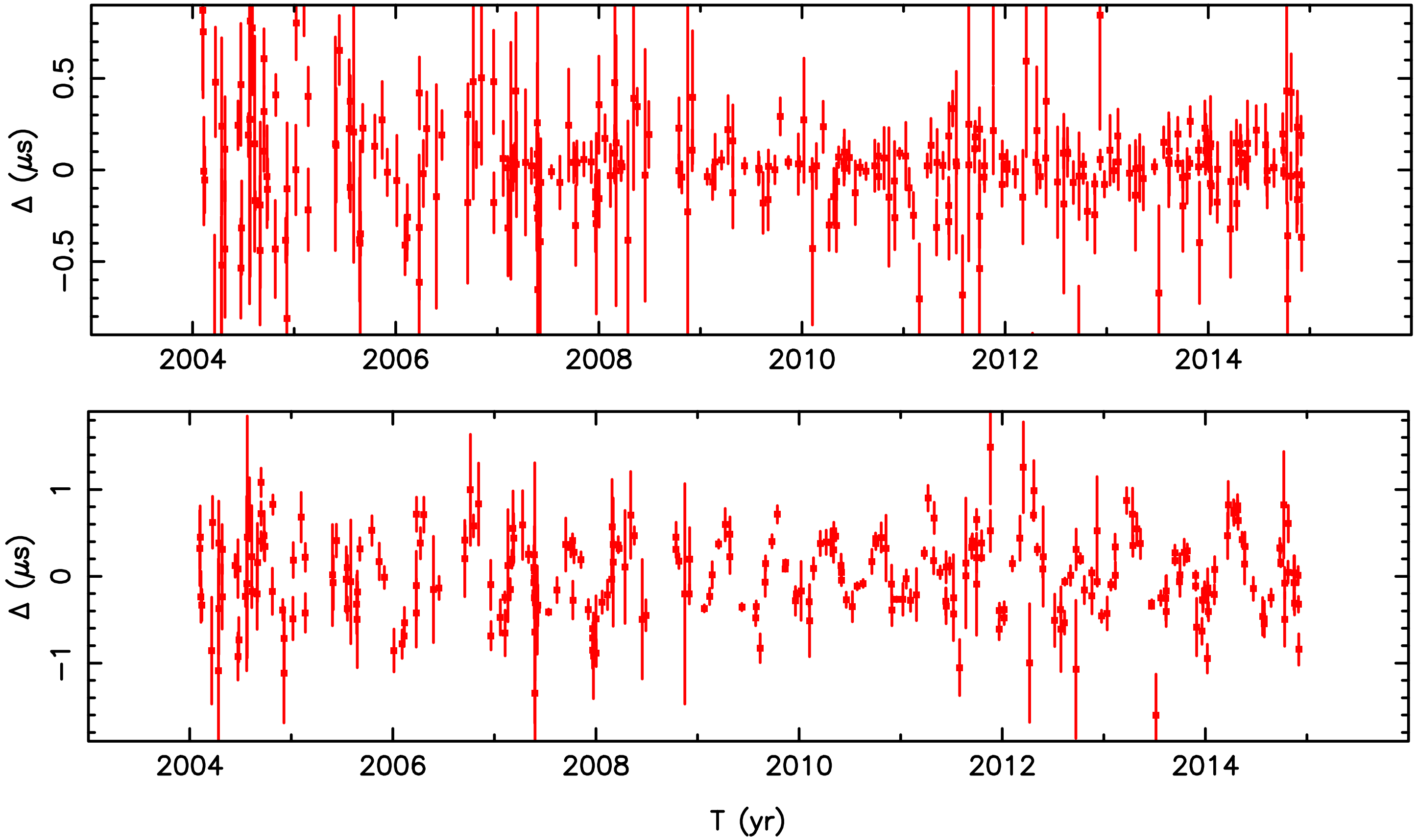
Right ascension, α (J2000) ...	$04^{h}37^{m}15^{s}.7865145(7)$
Declination, δ (J2000)	$-47^{\circ}15'08''.461584(8)$
μ_{α} (mas yr^{-1})	121.438(6)
μ_{δ} (mas yr^{-1})	-71.438(7)
Annual parallax, π (mas)	7.19(14)
Pulse period, P (ms)	5.757451831072007(8)
Reference epoch (MJD)	51194.0
Period derivative, $\dot{P}$ (10^{-20}) ..	5.72906(5)
Orbital period, P_{b} (days)	5.741046(3)
x (s)	3.36669157(14)
Orbital eccentricity, e	0.000019186(5)
Epoch of periastron, T_{0} (MJD)	51194.6239(8)
Longitude of periastron, ω (°) .	1.20(5)
Longitude of ascension, Ω (°) .	238(4)
Orbital inclination, i (°)	42.75(9)
Companion mass, m_{2} ($M_{\odot}$) ...	0.236(17)
$\dot{P}_{b}(10^{-12})$	3.64(20)
$\dot{\omega}$ (°yr^{-1})	0.016(10)



Example: Deterministic contributions

Timing residuals: Difference between maximum-likelihood model and residuals

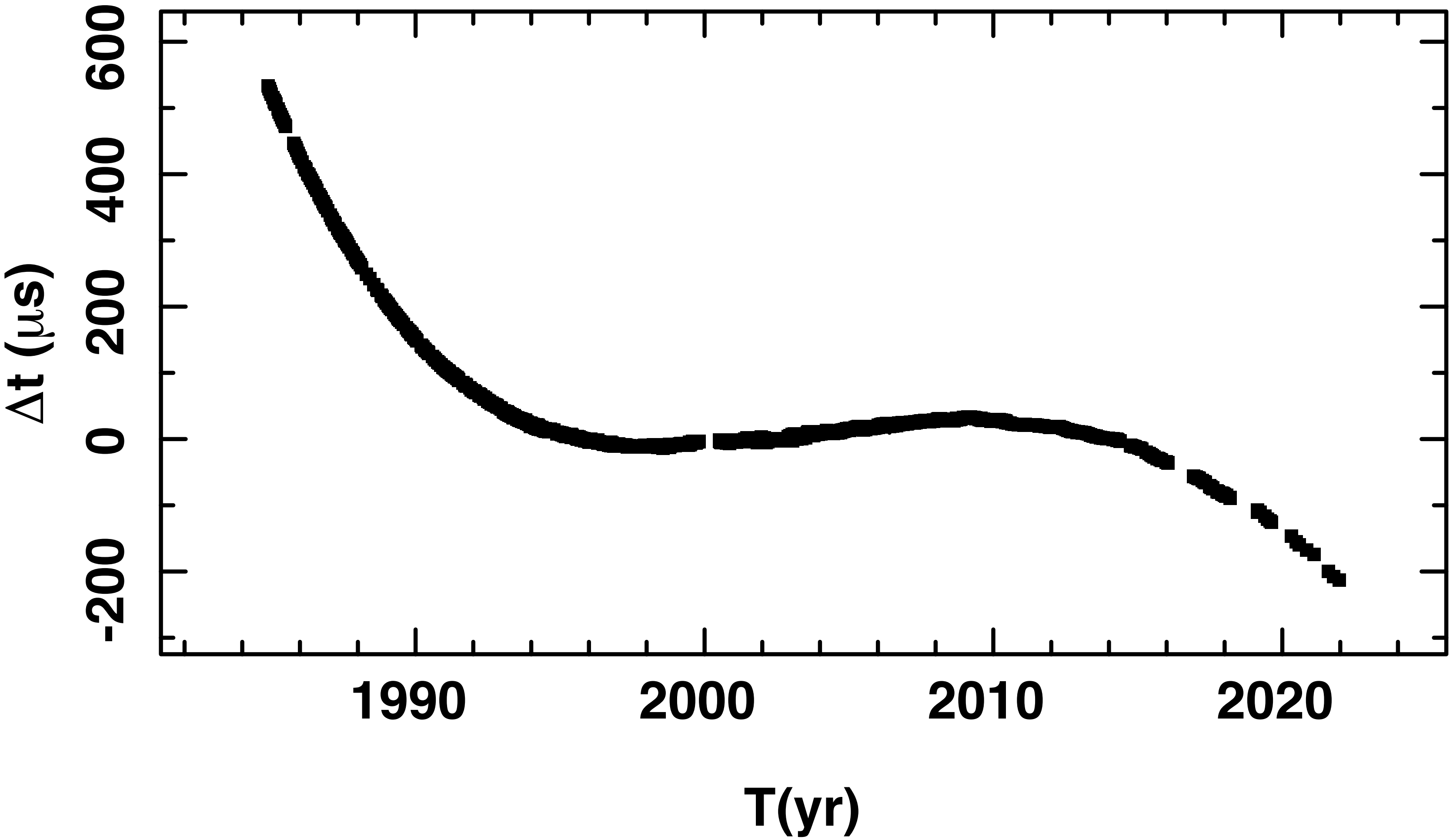
Need to refer arrival times to non-inertial frame: ***Solar System Barycentre.***



Best model

Timing parallax (curvature of radio waves as it passes solar system)

What about this?

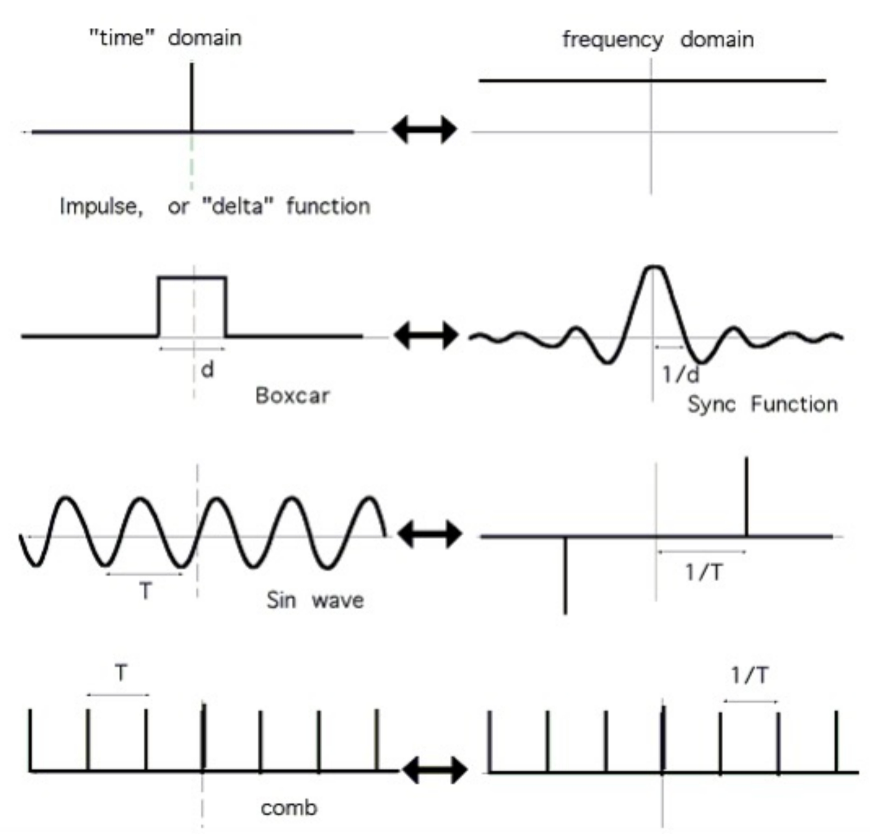


Power spectral density estimation in one slide

- Oftentimes signals are easier expressed in the “frequency domain” rather than the time domain
  - Sinusoid be expressed by three numbers:
    - Frequency
    - Amplitude
    - Phase
  - Or
    - Frequency
    - Amplitude (cosine)
    - Amplitude (sine)
- Fourier transform (FT):
  - Projection of time series onto harmonic of sinusoids
  - Fast Fourier transform (FFT): efficient algorithm of calculating FT
- Power spectrum
  - Square of Fourier transform
  - Useful if don’t care about phase of signals

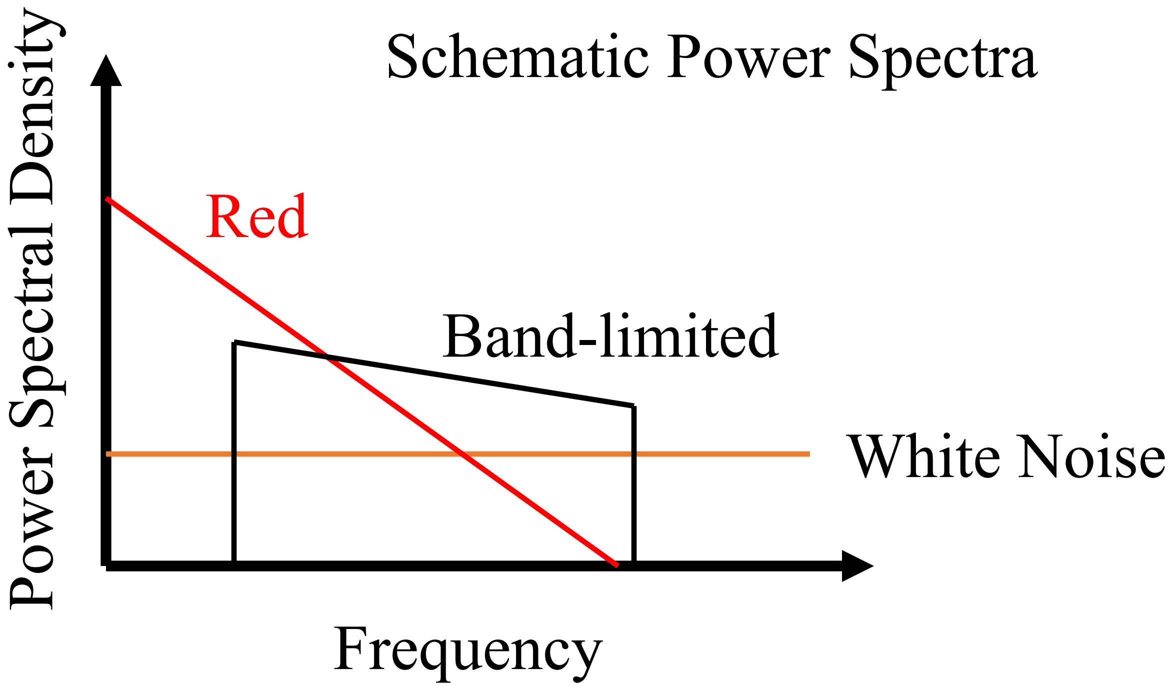
Time Series

Fourier transform



Classes of stochastic processes

- **White Noise (WN)**
  - Uncorrelated
  - Flat power spectrum
- **Red Noise (RN)**
  - Correlated noise
  - Wide-sense stationary
  - Random walks
  - "Red Power spectrum" (more power at lower frequency)
- **Band limited noise**
  - Red power spectrum with cut-offs
  - Excess power at certain frequencies

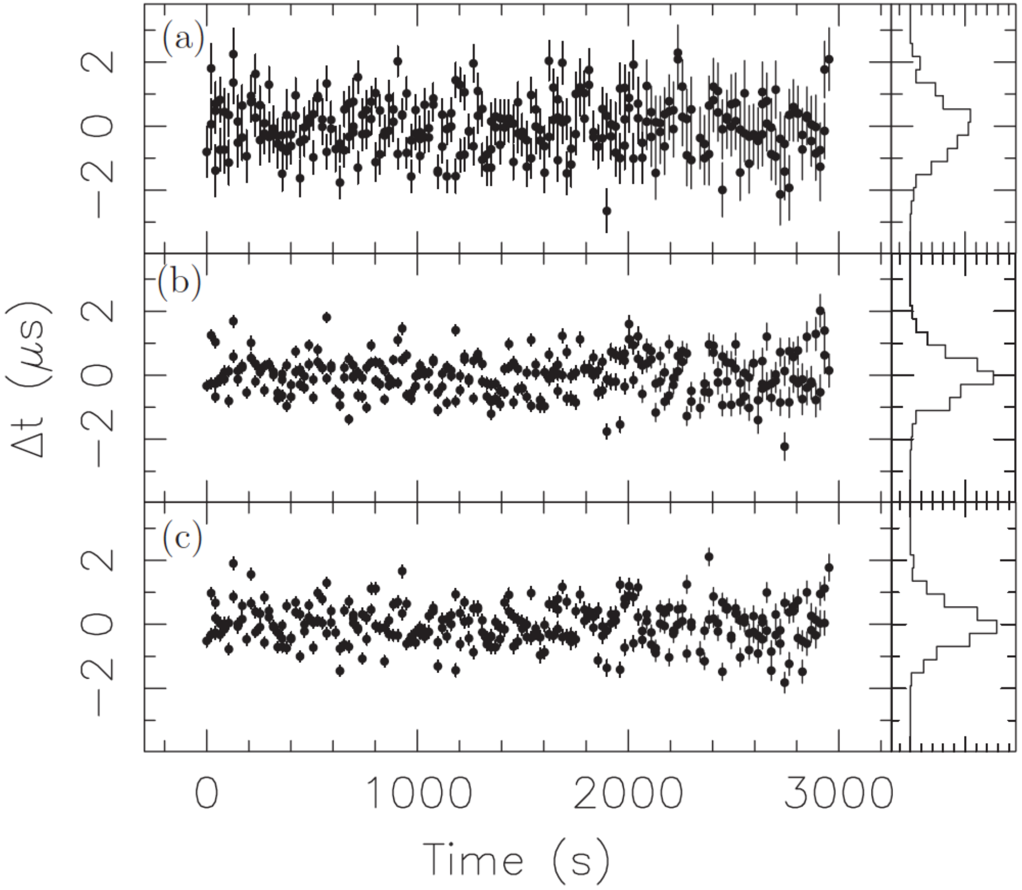


Power Law power spectral density:

$P(f) \propto f^{\alpha}$ $(\alpha < 0)$

White noise

- Noise that is uncorrelated on TOA-TOA time scales
- Radiometer (Receiver) noise
- Pulse-shape variations ("jitter")

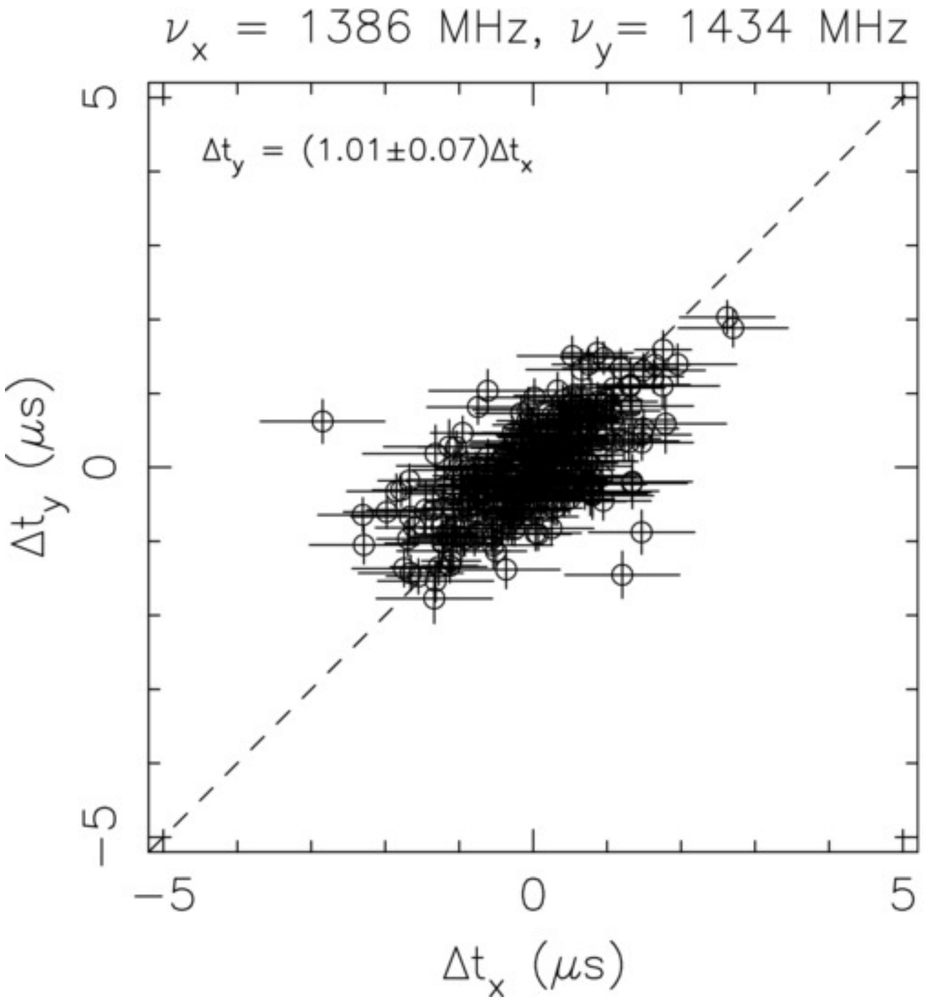


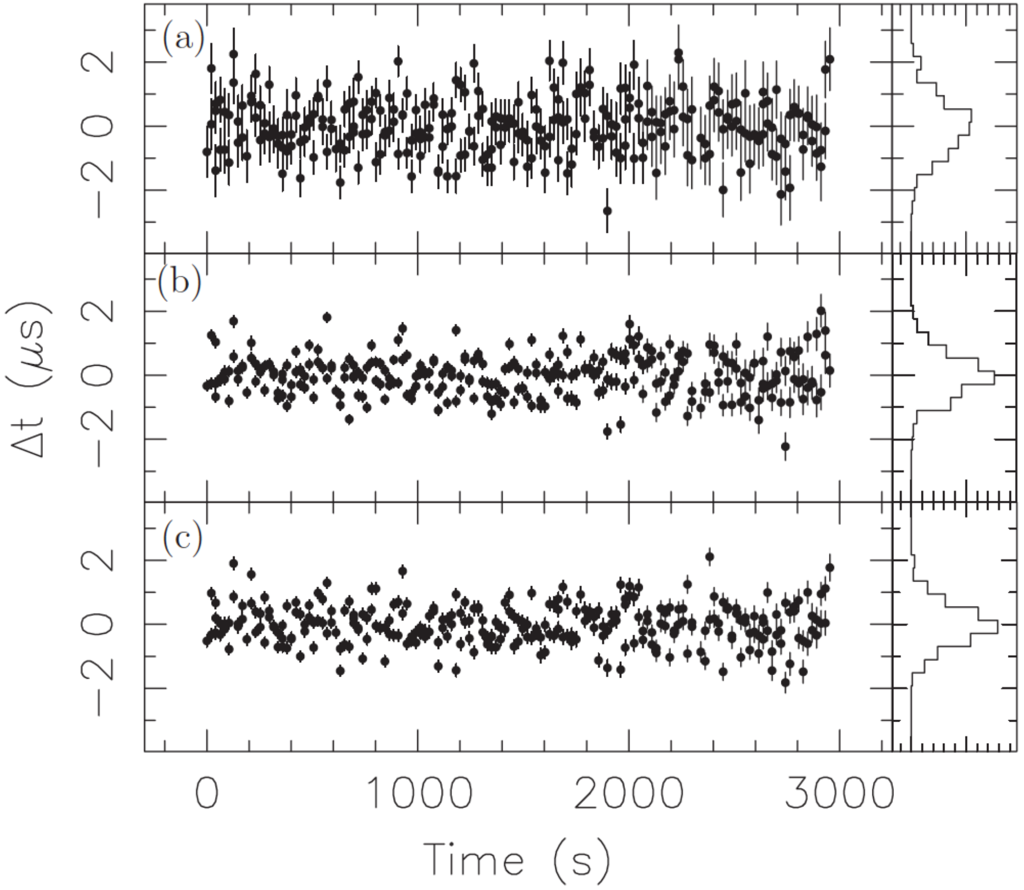
Short wavelength

Long wavelength

Pulse-shape variations in PSR J1713+0747
(Arecibo, Shannon & Cordes 2012)

Jitter Noise





Short
wavelength

Long
wavelength

Pulse-shape variations in PSR J1713+0747
(Arecibo, Shannon & Cordes 2012)

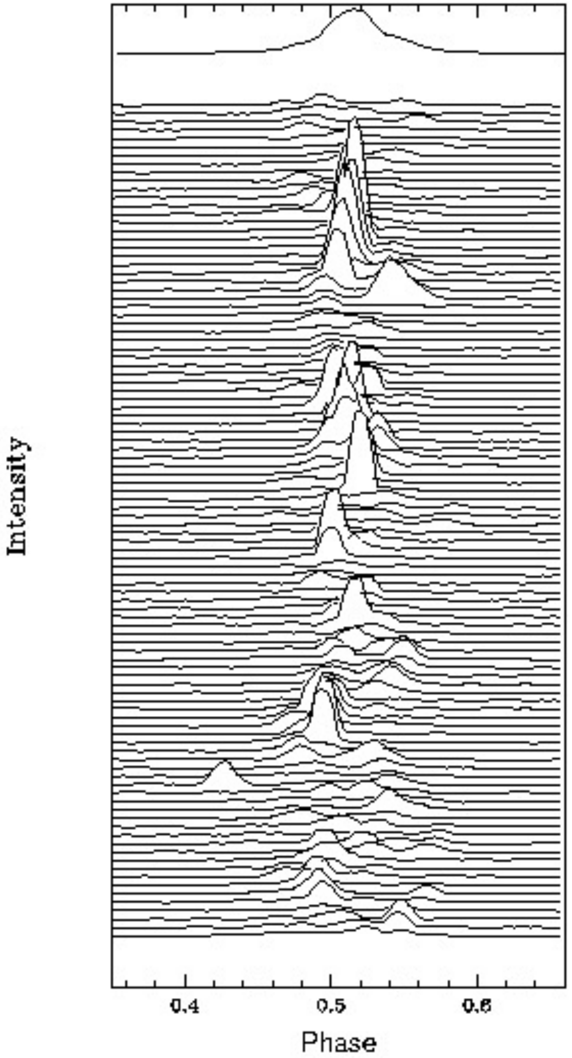
Timing Error from Pulse-Phase Jitter

$$U(\phi) \propto \int d\phi' \, f_\phi(\phi') a(\phi - \phi')$$

$$\Delta t_{\rm J} = N_i^{-1/2} (1 + m_I^2)^{1/2} \, P \langle \phi^2 \rangle^{1/2}$$

$$= N_i^{-1/2} (1 + m_I^2)^{1/2} \, P \left[\int d\phi \, \phi^2 f_\phi(\phi) \right]^{1/2}$$

- f_φ = PDF of phase variation
- $a(\varphi)$ = individual pulse shape
- N_i = number of independent pulses summed
- m_I = intensity modulation index ≈ 1
- f_J = fraction jitter parameter = ϕ_{rms} / W ≈ 1



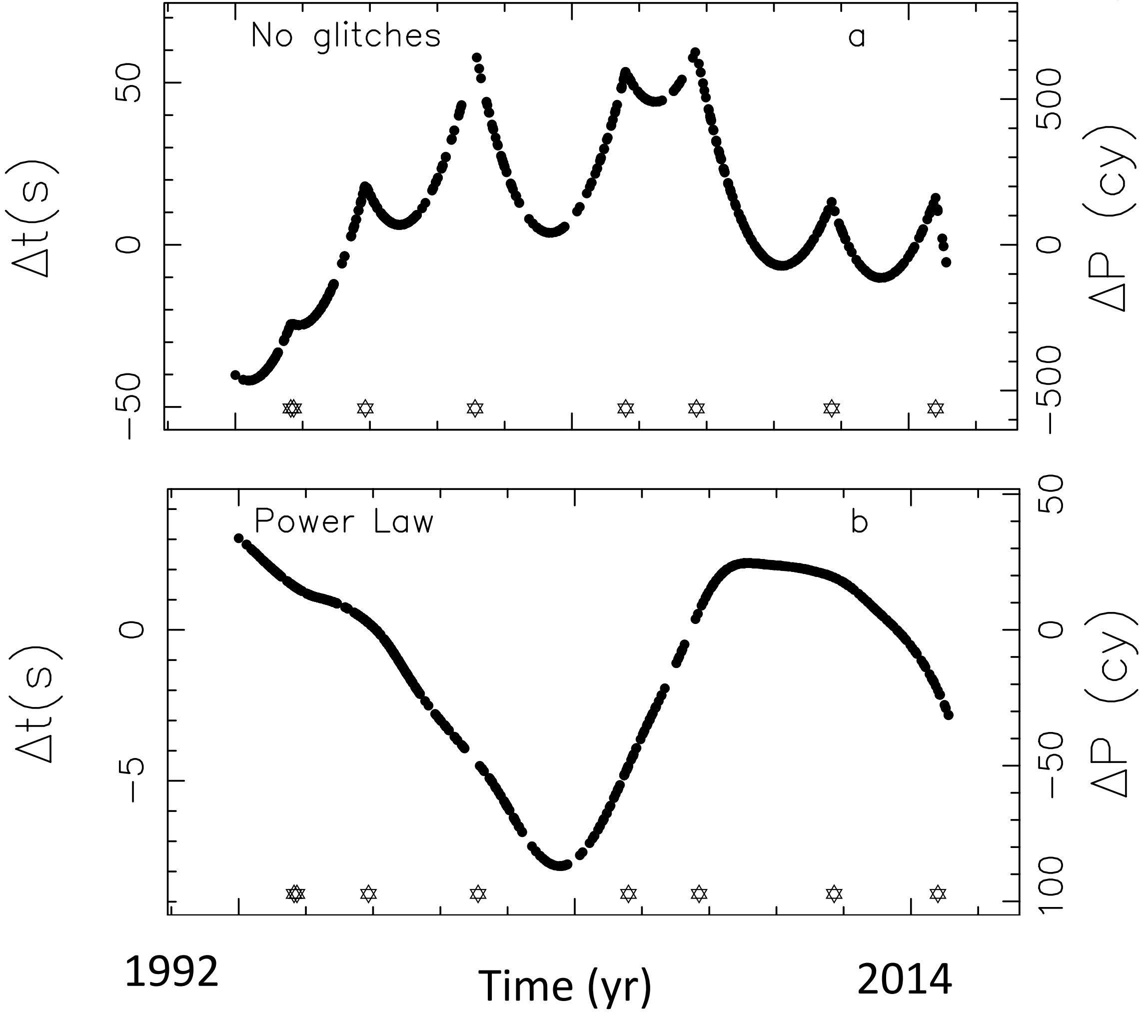
Gaussian shaped pulse:

$$\Delta t_{\rm J} = \frac{f_J W_i (1 + m_I^2)^{1/2}}{2 (2 N_i \ln 2)^{1/2}}$$

$$N_6 = N_i / 10^6$$

$$\boxed{\Delta t_{\rm J} = 0.28 \mu s \, W_{i,\rm ms} N_6^{-1/2} \left(\frac{f_J}{1/3} \right) \left(\frac{1 + m_I^2}{2} \right)^{1/2}}$$

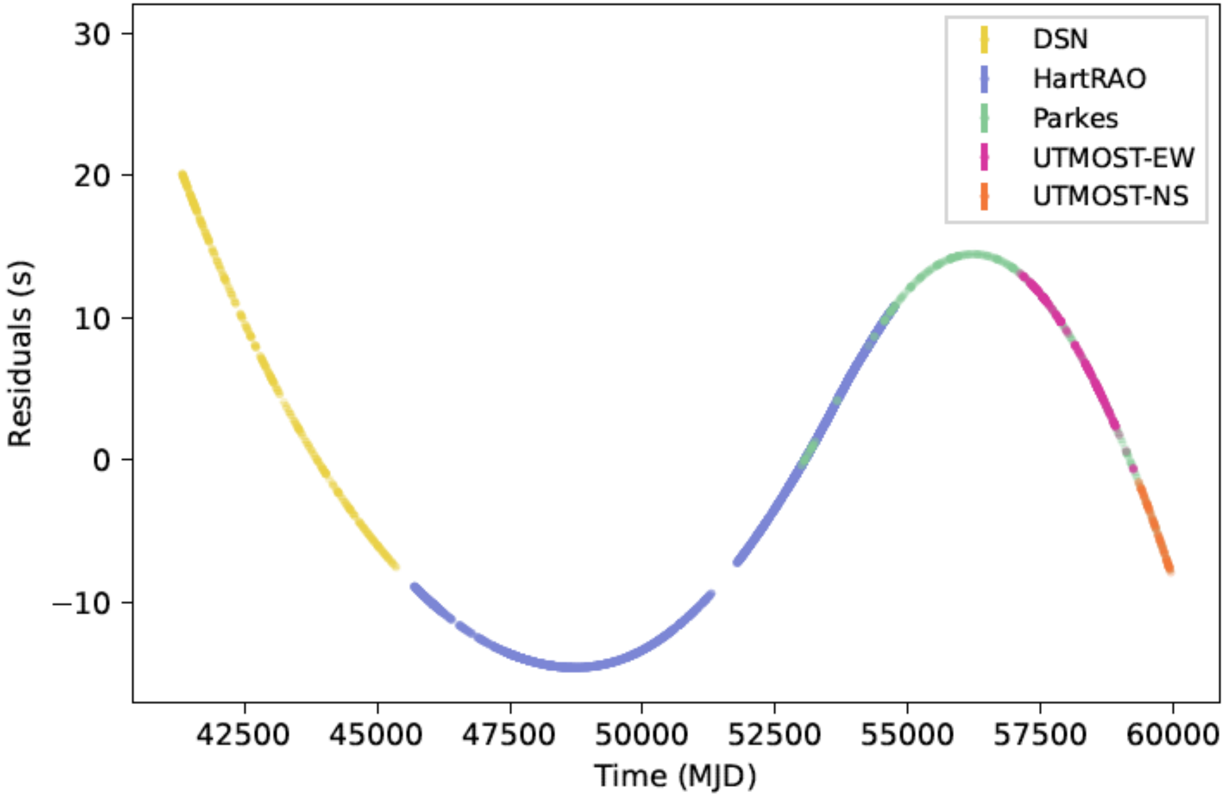
22 years of timing the Vela pulsar



Shannon et al. (2016)

Red noise

- For young pulsars, the residuals are attributed to spin noise in the pulsar
- Torque fluctuations crust quakes superfluid-crust interactions
- Other pulsars: excess residuals are caused by orbital motion (planets, WD, NS), ISM variations, gravitational waves

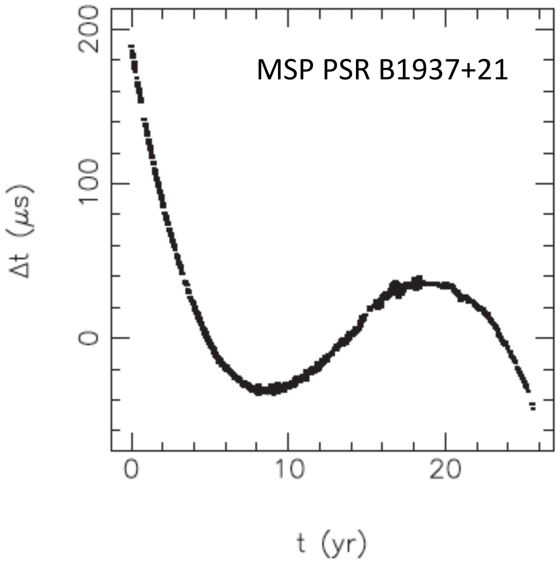


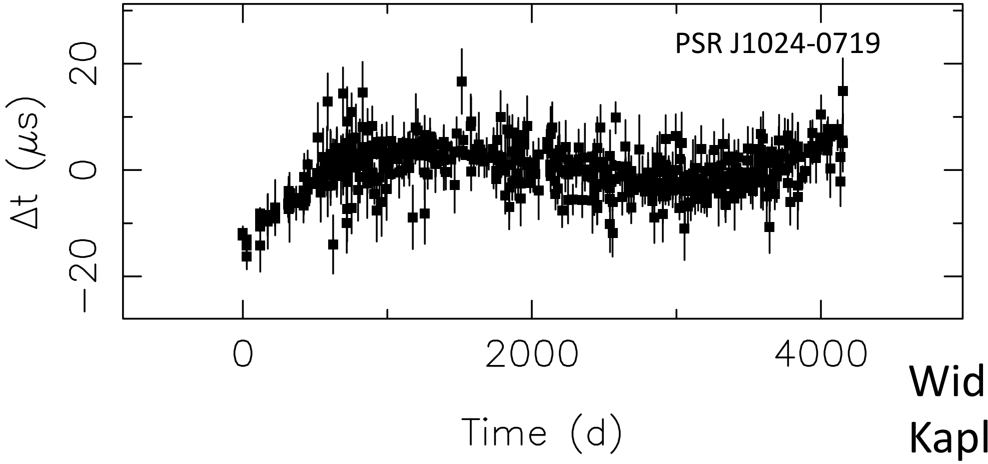
Lower et al. (2023)

Red noise

- Most young pulsars show red spin noise
  - Rotation instabilities?
  - Magnetospheric torque changes?
  - Open question: is this a generic property of MSPs too?
  - Can have similar spectral properties to GWB

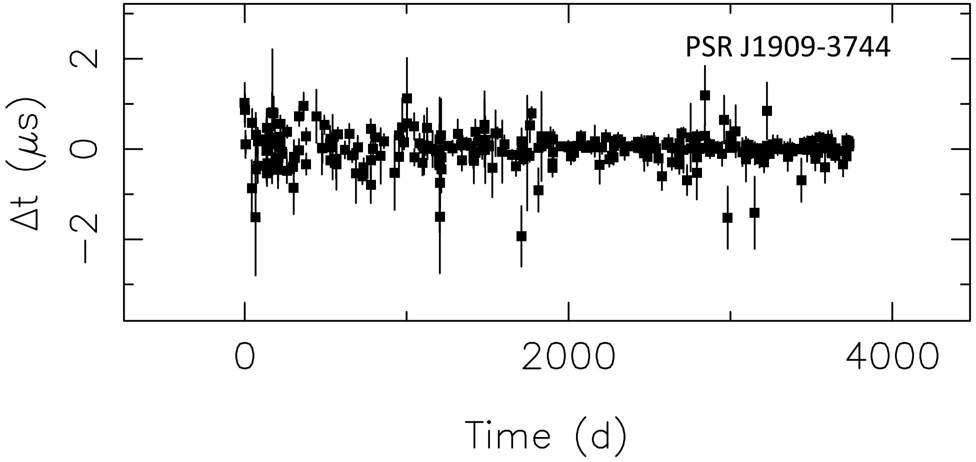
- Solution: need to (at least) model the presence of red noise in datasets
- Triage bad pulsars – kick them out of your PTA!





Wide companion
Kaplan et al (2015),
Bassa et al. (2015).

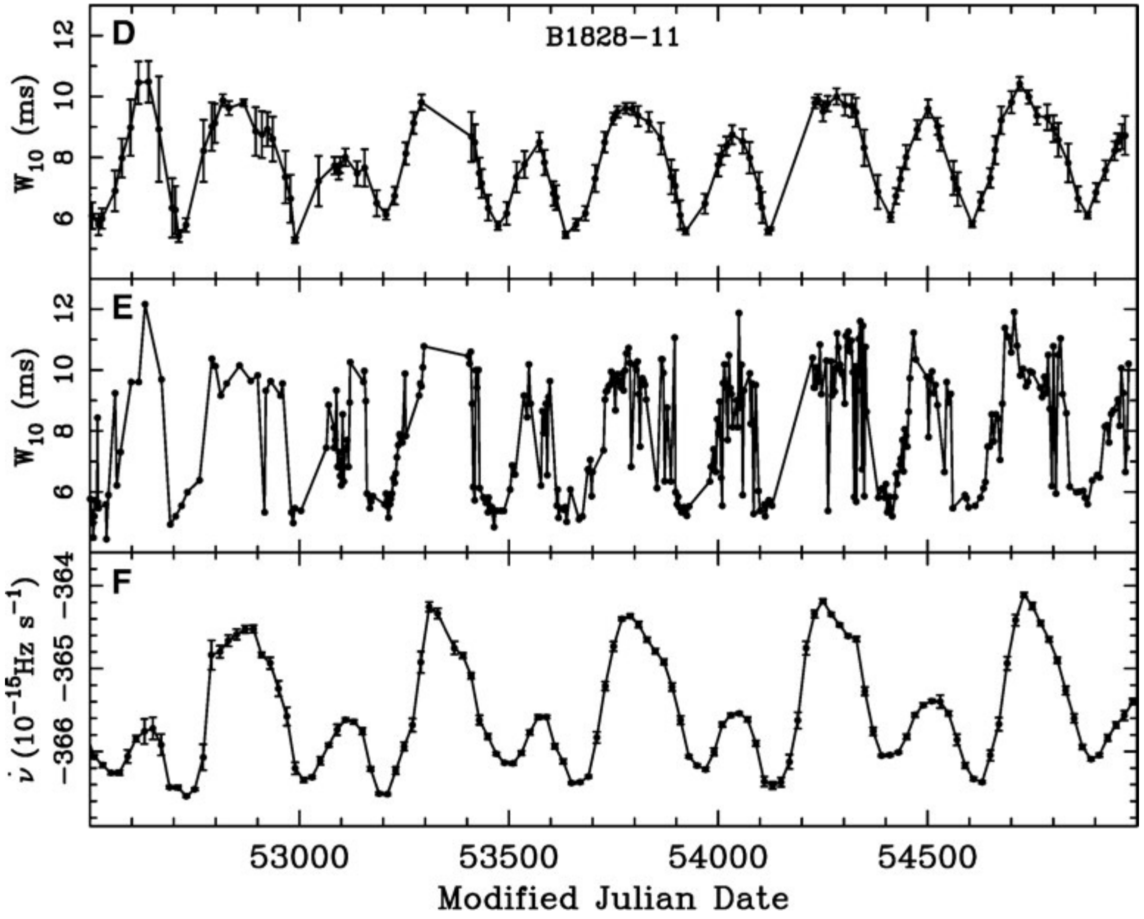
2003 **2014**



Quasiperiodic noise?

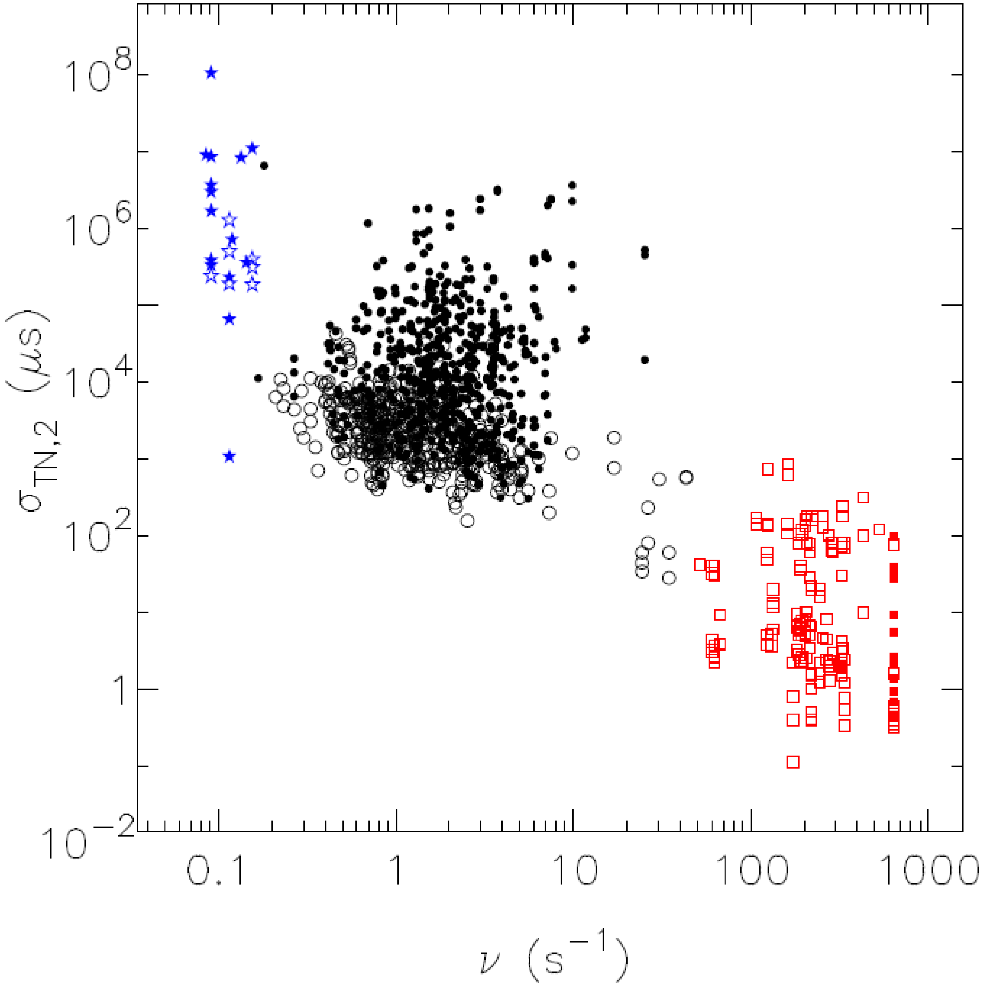
- Correlations between pulsar shape changes (effective width_ and pulse spin frequency derivative

- Magnetospheric origin for some pulsar timing noise?



Lyne et al. (2010)

Timing noise across the pulsar population



Shannon & Cordes (2010)

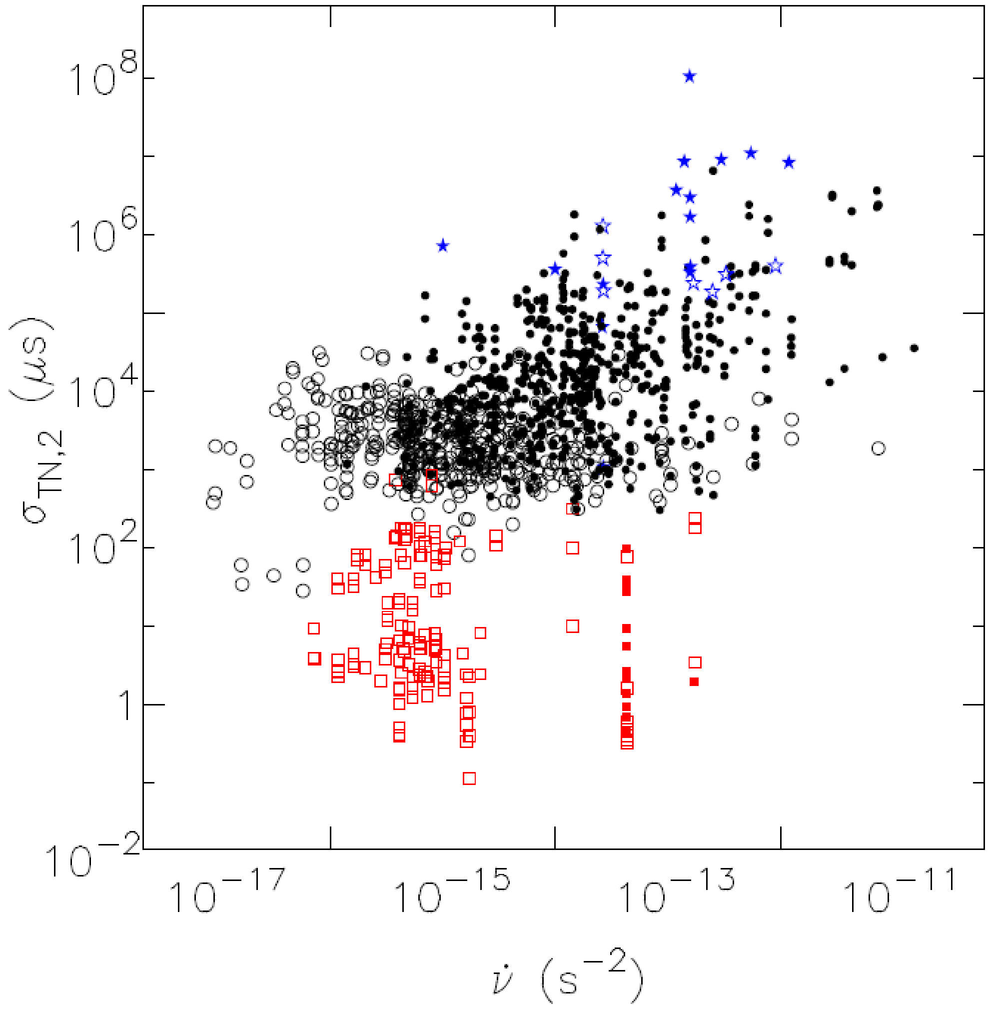
- Examined *every* report of TN in the literature 1980-2010

  Blue: Magnetars

  Black: Canonical (Normal) Pulsars (CPs)
- Red: MSPs
- Open symbols: upper limits
- Closed symbols: detections

- Implications: Spin noise will be present in MSPs if observed
- Over longer periods of time
- With higher timing precision

Timing noise across the pulsar population



Shannon & Cordes (2010)

- Examined *every* report of TN in the literature 1980-2010

Blue: Magnetars

Black: Canonical (Normal) Pulsars (CPs)

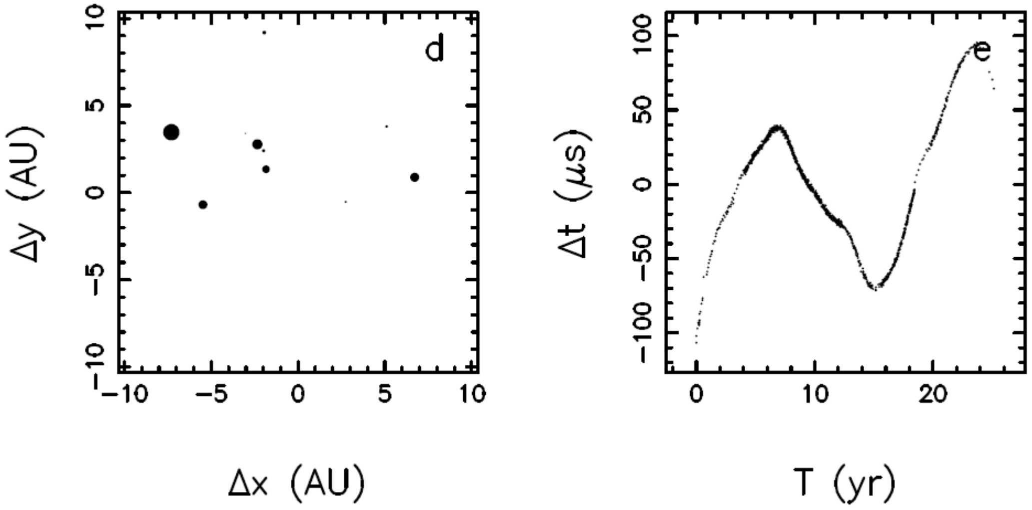
- Red: MSPs
- Open symbols: upper limits
- Closed symbols: detections

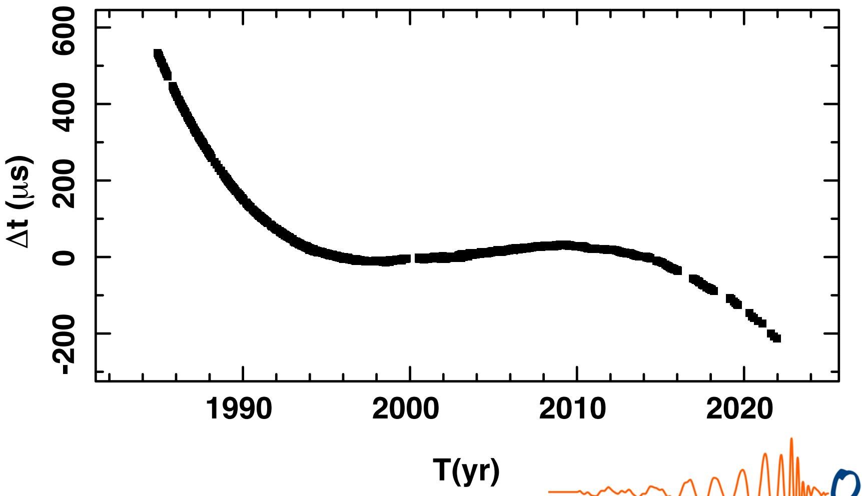
- Implications: Spin noise will be present in MSPs if observed
- Over longer periods of time
- With higher timing precision

Asteroid belt noise?

- Can an asteroid belt explain the noise in B1937+21?
- Low mass circumpulsar system (total mass ~ 0.05 Earth masses)
- 10 -200 objects: Cannot resolve periodicities of individual components.

(Shannon et al. 2013)



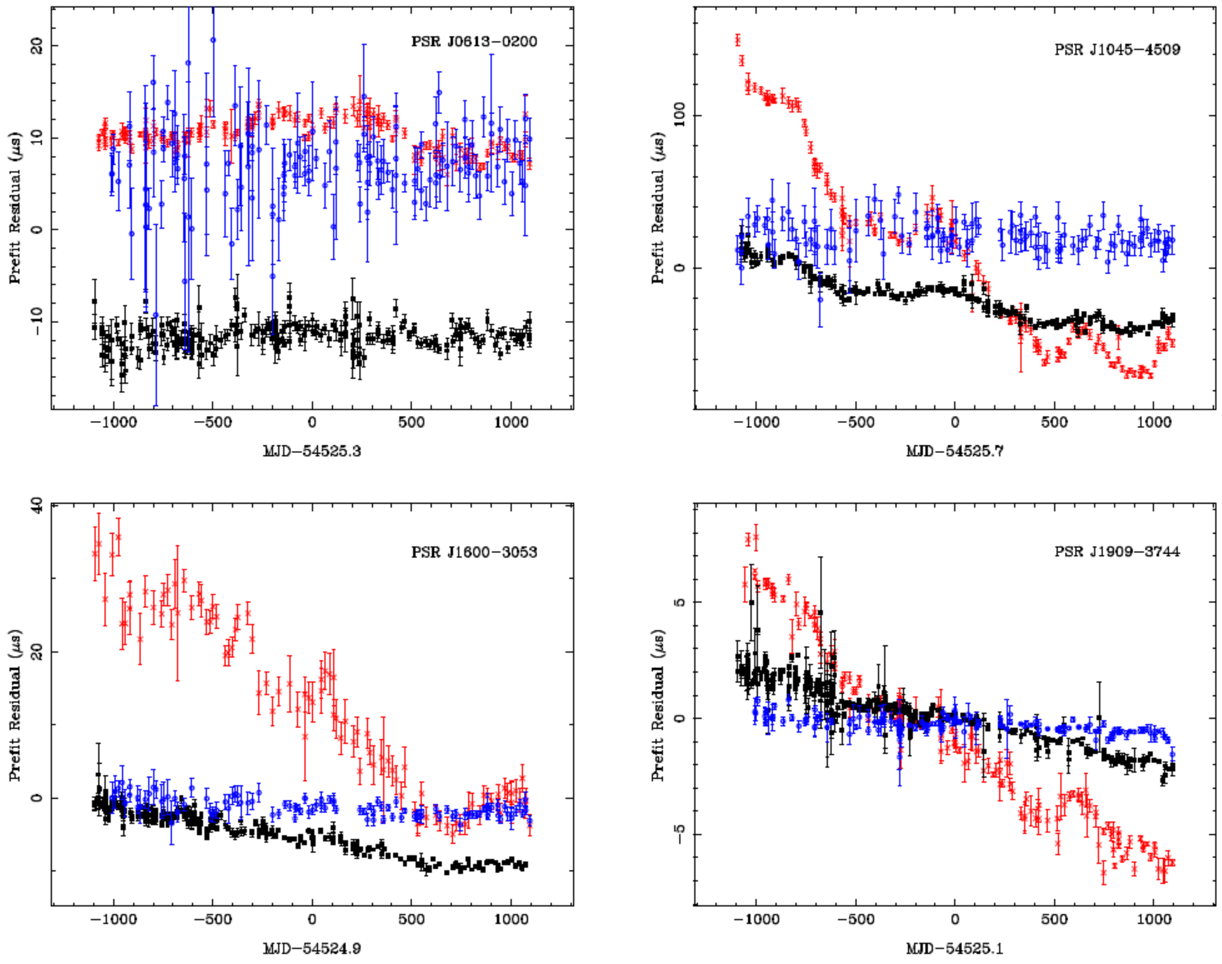


Red noise from the interstellar medium

Largest red signal in MSP data sets: Variations in dispersion measure (DM).
Proportional to λ^2.

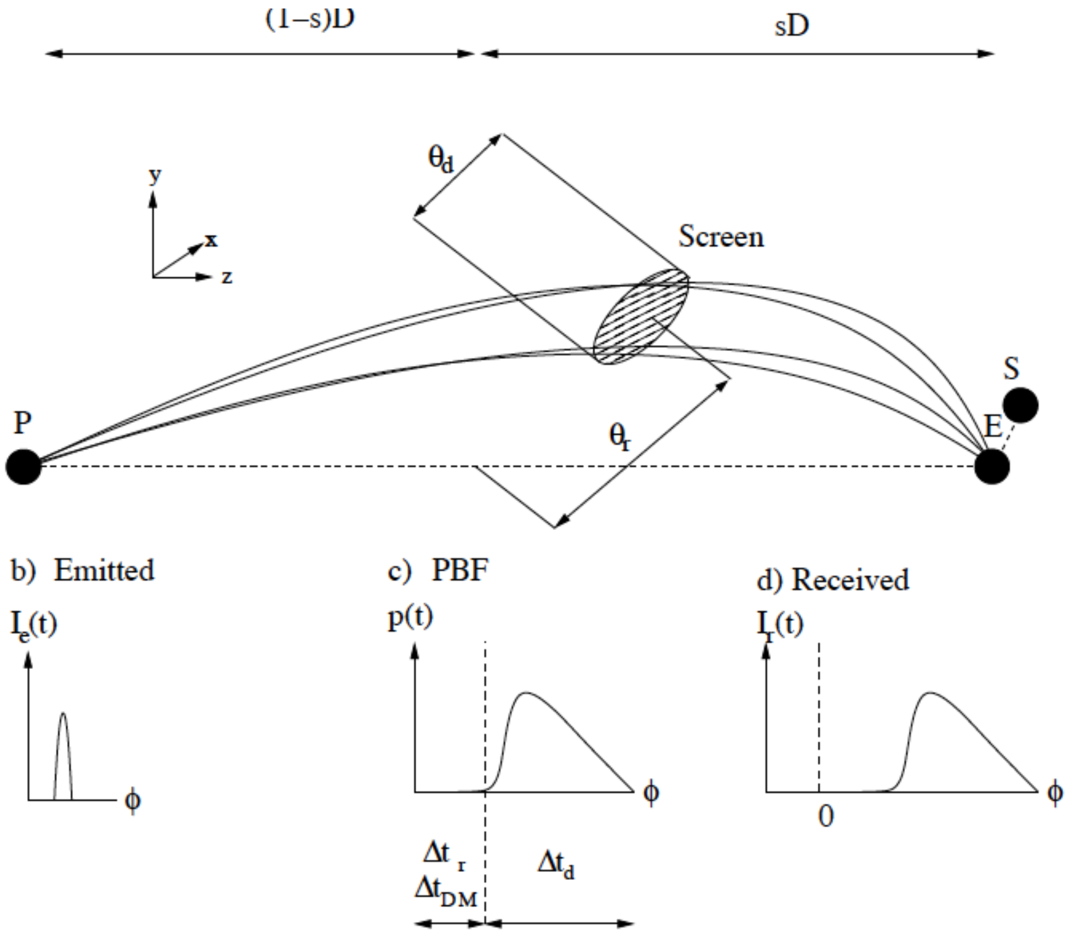
Need to remove **red signal** associated with DM variations without removing red signal associated with GWB

Include model of λ-independent noise in DM correction algorithm



Multi-path propagation

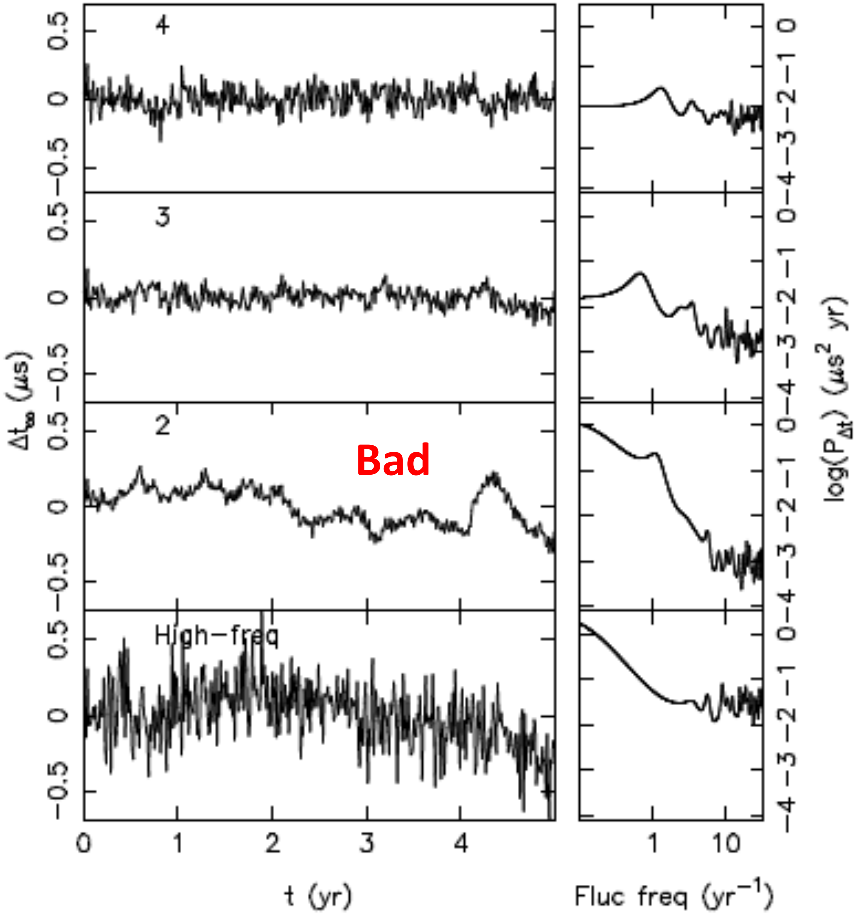
- Multi-path propagation causes broadening of pulse signal.
  - Proportional to λ^2 to $\lambda^{6.4}$
- Broadening is variable with time
- Strongest for distant pulsars observed at low frequencies
- Solution:
  - Observe at higher radio frequency
  - Explore mitigation methods like cyclic spectroscopy (Demorest 2012)



Shannon & Cordes (2017)

Biases in red-noise estimates

Assumption: observations contain only (instrumental) white noise and DM variations



Correct for DM + Scattering (2)

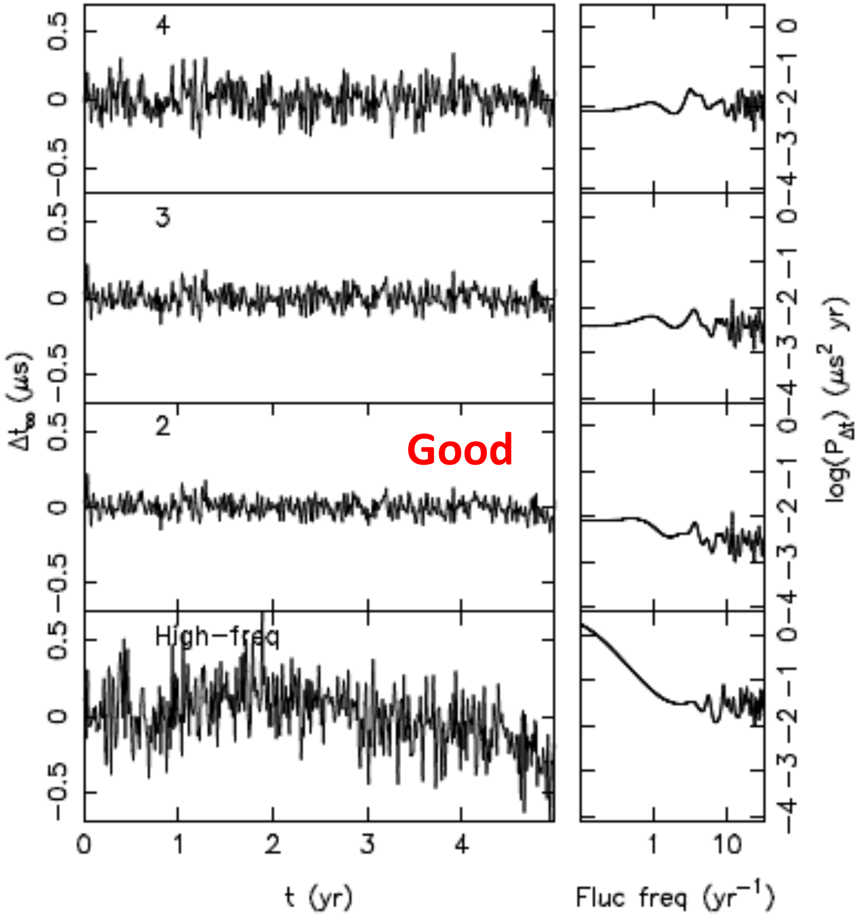
Correct for DM + Scattering

Correct for DM

Only observe at high frequency

Biases in red-noise estimates

Down-weight low frequency TOAs to account for scattering variations.



Correct for DM + Scattering (2)

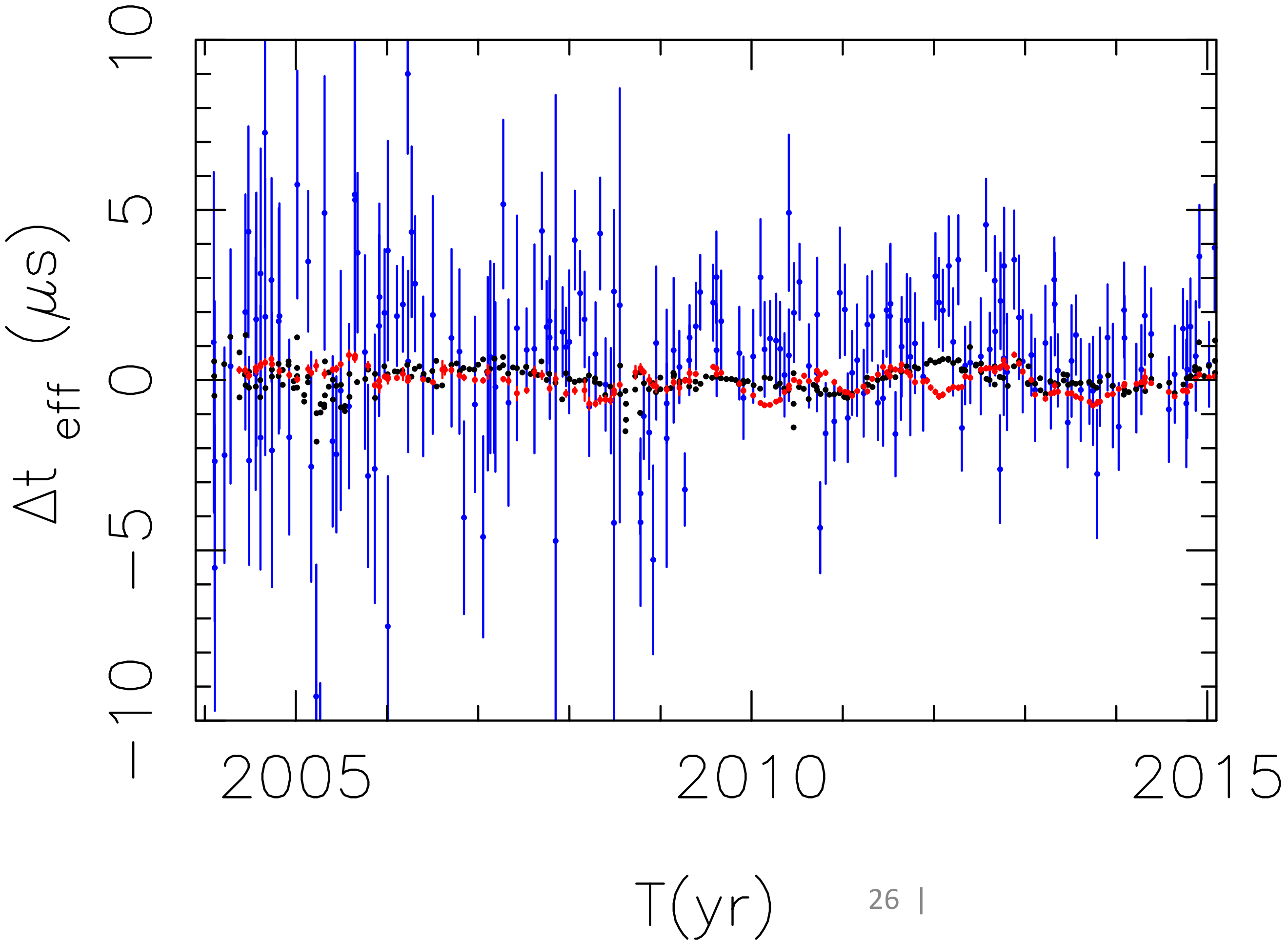
Correct for DM + Scattering

Correct for DM

Only observe at high frequency

Observations of scattering noise

- PSR J1643-1224
- See IPTA Noise paper (Lentati et al. 2016)!

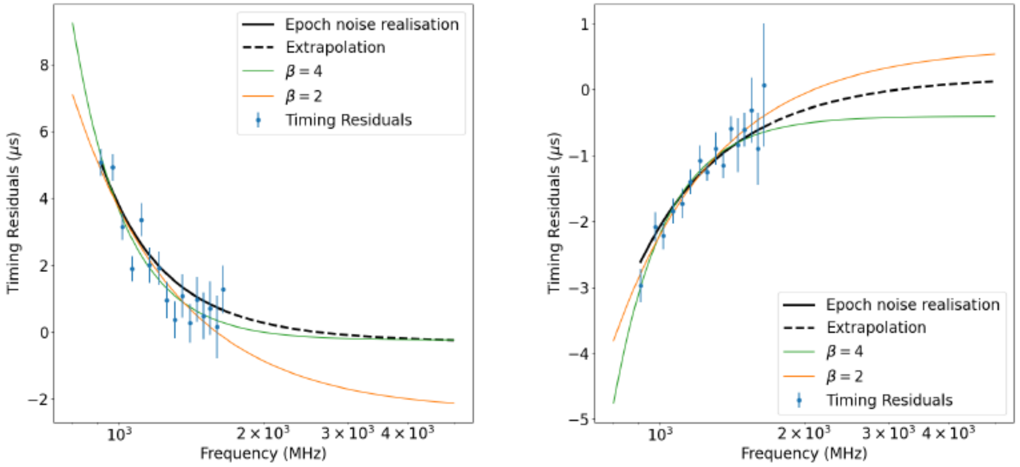


Parkes residuals corrected for DM variations and scaled to 3.1 GHz

Blue: 10cm
Black: 20cm
Red: 50cm

Scattering noise in the MPTA

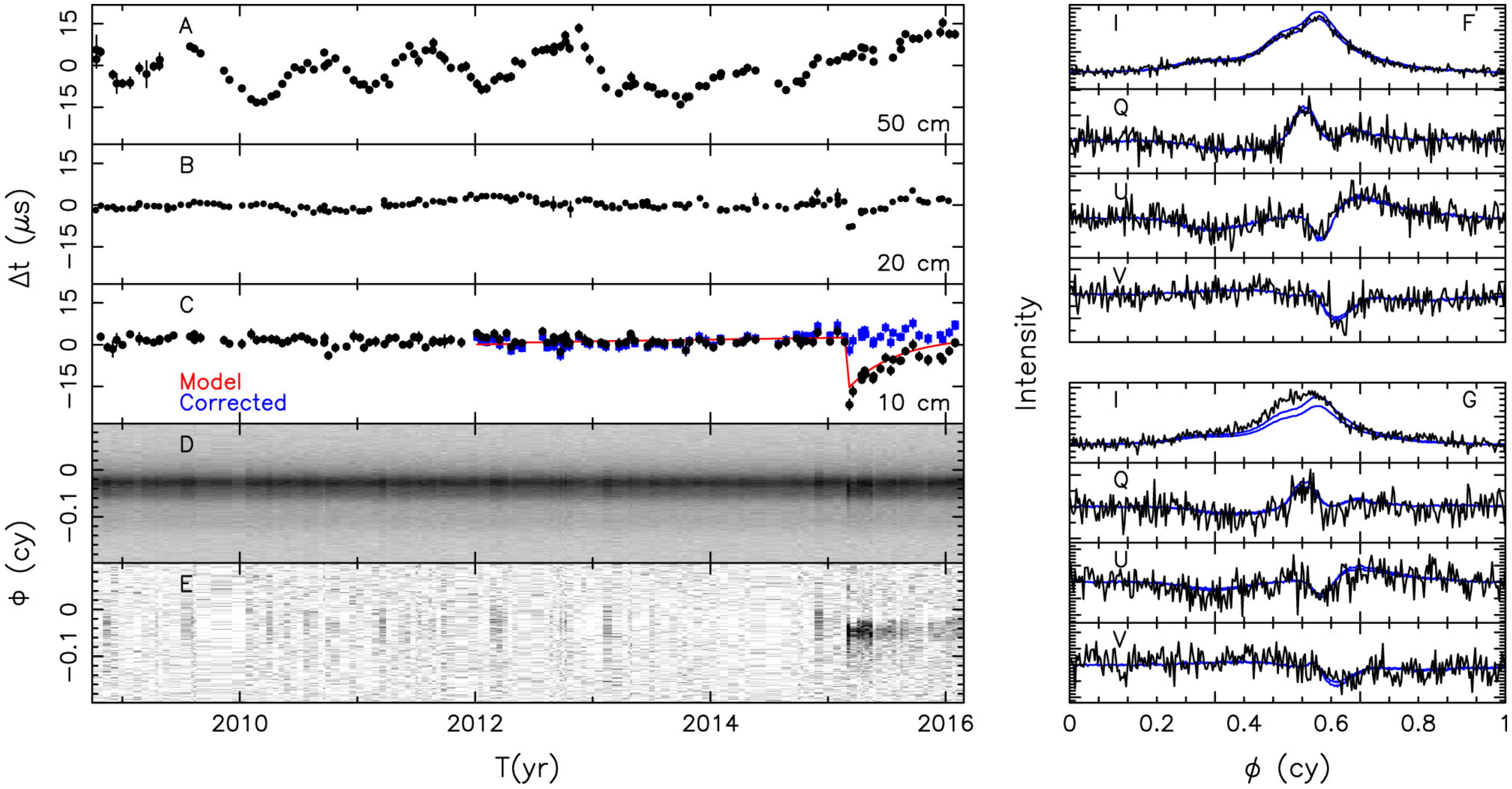
- Observe high DM pulsars
  - More likely subject to scattering effects
- Evidence for highly chromatic processes
  - ν^{-4} to $\nu^{<-6}$
- Can end up with achromatic red noise if don't search for chromatic noise



(a) Models fit to an observing epoch scattered primarily by a chromatic scattering process.

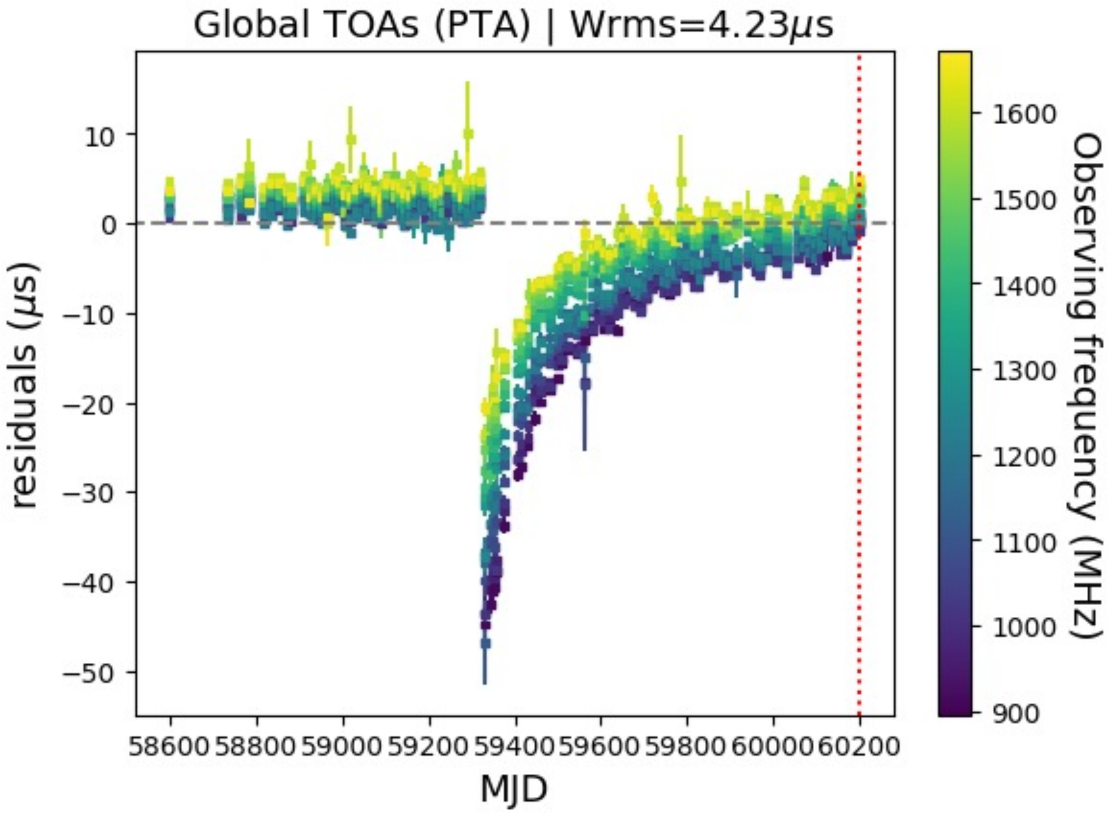
(b) Models fit to an observing epoch scattered primarily by a dispersion measure process.

Noise from pulse shape changes



- Assumption is that profile is not changing with time
- Need profile-domain timing methods

Profile distortions in J1713+0747



MeerKAT observations of J1713+0747

- What are the effects of smaller unmodelled distortions?

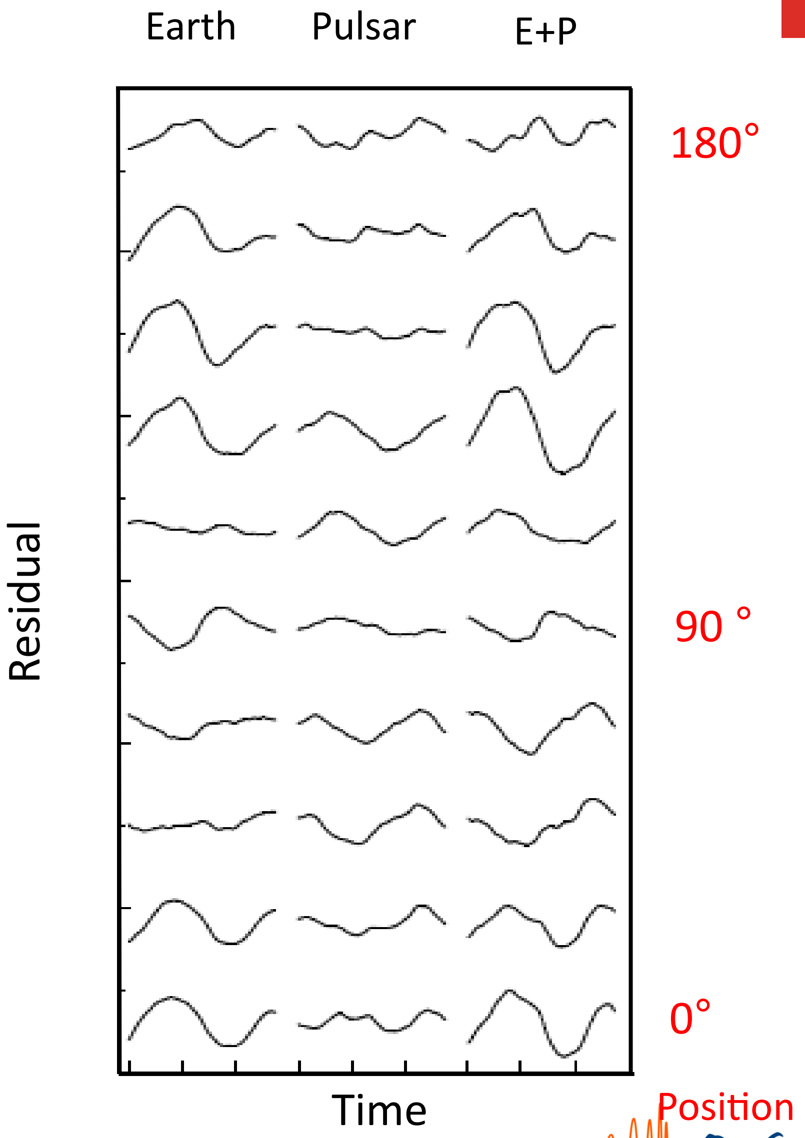
The stochastic background

Red power spectrum (more power at lowest frequency of GWs)

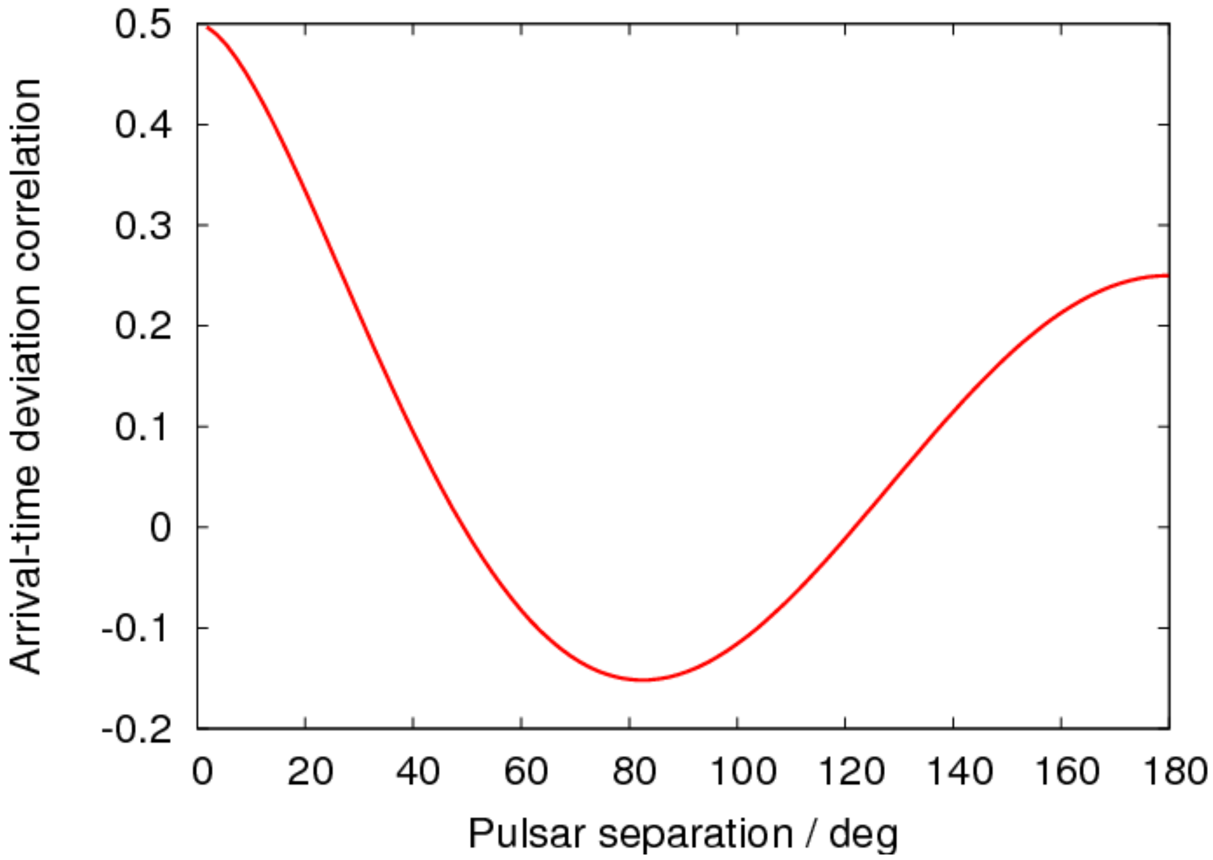
Characterised by a power-law amplitude *A* and a spectral index

Manifested in two ways:

- "Background noise" – sky temperature in GWs
- Spatial correlations



Detecting the GWB



Credit: P. Demorest

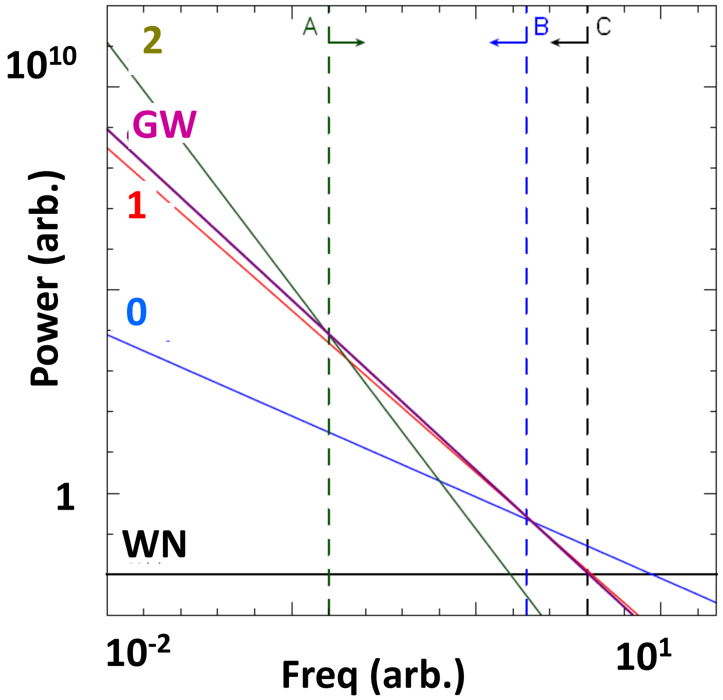
Other sources of noise can look like the background noise (e.g., pulsar spin noise)

Search for correlation in arrival times between multiple pulsars:
Pulsar Timing Array

Correlation between pulsars expected to follow Hellings-Downs (1983) function

Spin noise and gravitational waves

- Spin noise is present some MSPs
- Noise has time variability similar to that expected from GWB, making filtering difficult/impossible.
- For given spin properties, range of strengths of timing noise.
- Going to need to time a larger number of pulsars and then discard the ones that show timing noise.
- Don’t have good model for spin noise: possible that background noise is simply pulsar noise (Zic et al. 2022)



Summary: physical model for timing effects

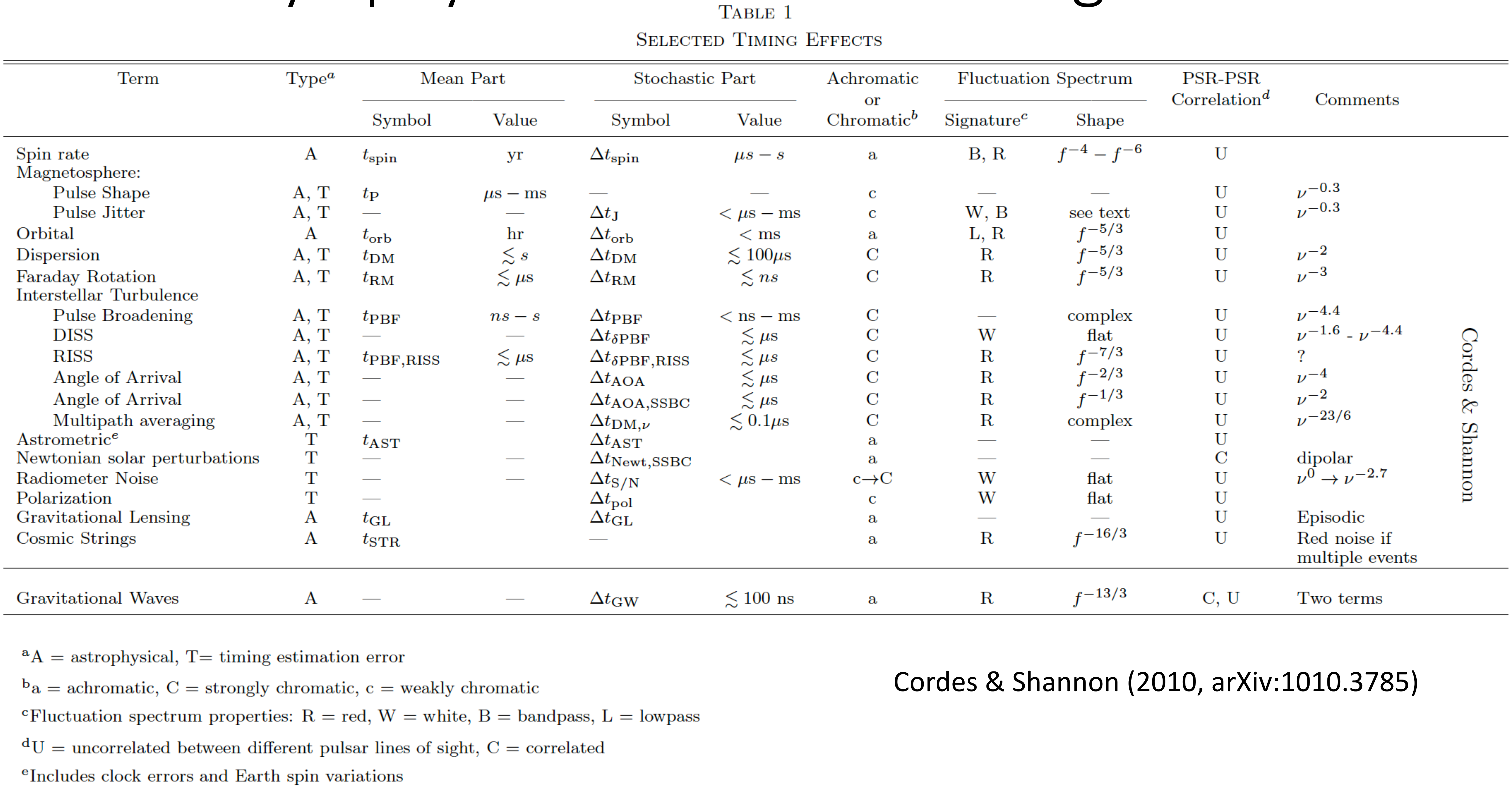


TABLE 1

SELECTED TIMING EFFECTS

Term	Type[a]	Mean Part		Stochastic Part		Achromatic or Chromatic[b]	Fluctuation Spectrum		PSR-PSR Correlation[d]	Comments
		Symbol	Value	Symbol	Value		Signature[c]	Shape		
Spin rate	A	$t_{\rm spin}$	yr	$\Delta t_{\rm spin}$	$\mu s - s$	a	B, R	$f^{-4} - f^{-6}$	U	
Magnetosphere:										
Pulse Shape	A, T	$t_{\rm P}$	μs − ms	—	—	c	—	—	U	$\nu^{-0.3}$
Pulse Jitter	A, T	—	—	$\Delta t_{\rm J}$	$< \mu$s − ms	c	W, B	see text	U	$\nu^{-0.3}$
Orbital	A	$t_{\rm orb}$	hr	$\Delta t_{\rm orb}$	$<$ ms	a	L, R	$f^{-5/3}$	U	
Dispersion	A, T	$t_{\rm DM}$	$\lesssim s$	$\Delta t_{\rm DM}$	$\lesssim 100\mu$s	C	R	$f^{-5/3}$	U	ν^{-2}
Faraday Rotation	A, T	$t_{\rm RM}$	$\lesssim \mu s$	$\Delta t_{\rm RM}$	$\lesssim ns$	C	R	$f^{-5/3}$	U	ν^{-3}
Interstellar Turbulence										
Pulse Broadening	A, T	$t_{\rm PBF}$	$ns - s$	$\Delta t_{\rm PBF}$	$<$ ns − ms	C	—	complex	U	$\nu^{-4.4}$
DISS	A, T	—	—	$\Delta t_{\delta \rm PBF}$	$\lesssim \mu s$	C	W	flat	U	$\nu^{-1.6}$ - $\nu^{-4.4}$
RISS	A, T	$t_{\rm PBF,RISS}$	$\lesssim \mu s$	$\Delta t_{\delta \rm PBF,RISS}$	$\lesssim \mu s$	C	R	$f^{-7/3}$	U	?
Angle of Arrival	A, T	—	—	$\Delta t_{\rm AOA}$	$\lesssim \mu s$	C	R	$f^{-2/3}$	U	ν^{-4}
Angle of Arrival	A, T	—	—	$\Delta t_{\rm AOA,SSBC}$	$\lesssim \mu s$	C	R	$f^{-1/3}$	U	ν^{-2}
Multipath averaging	A, T	—	—	$\Delta t_{{\rm DM},\nu}$	$\lesssim 0.1\mu$s	C	R	complex	U	$\nu^{-23/6}$
Astrometric[e]	T	$t_{\rm AST}$		$\Delta t_{\rm AST}$		a	—	—	U	
Newtonian solar perturbations	T	—	—	$\Delta t_{\rm Newt,SSBC}$		a	—	—	C	dipolar
Radiometer Noise	T	—	—	$\Delta t_{\rm S/N}$	$< \mu$s − ms	c→C	W	flat	U	$\nu^0 \rightarrow \nu^{-2.7}$
Polarization	T	—		$\Delta t_{\rm pol}$		c	W	flat	U	
Gravitational Lensing	A	$t_{\rm GL}$		$\Delta t_{\rm GL}$		a	—	—	U	Episodic
Cosmic Strings	A	$t_{\rm STR}$		—		a	R	$f^{-16/3}$	U	Red noise if multiple events
Gravitational Waves	A	—	—	$\Delta t_{\rm GW}$	$\lesssim 100$ ns	a	R	$f^{-13/3}$	C, U	Two terms

[a] A = astrophysical, T= timing estimation error

[b] a = achromatic, C = strongly chromatic, c = weakly chromatic

[c] Fluctuation spectrum properties: R = red, W = white, B = bandpass, L = lowpass

[d] U = uncorrelated between different pulsar lines of sight, C = correlated

[e] Includes clock errors and Earth spin variations

Cordes & Shannon

Cordes & Shannon (2010, arXiv:1010.3785)

Signal model for pulsar timing

- TOAs = timing model + white noise + red noise

- Timing model = deterministic terms

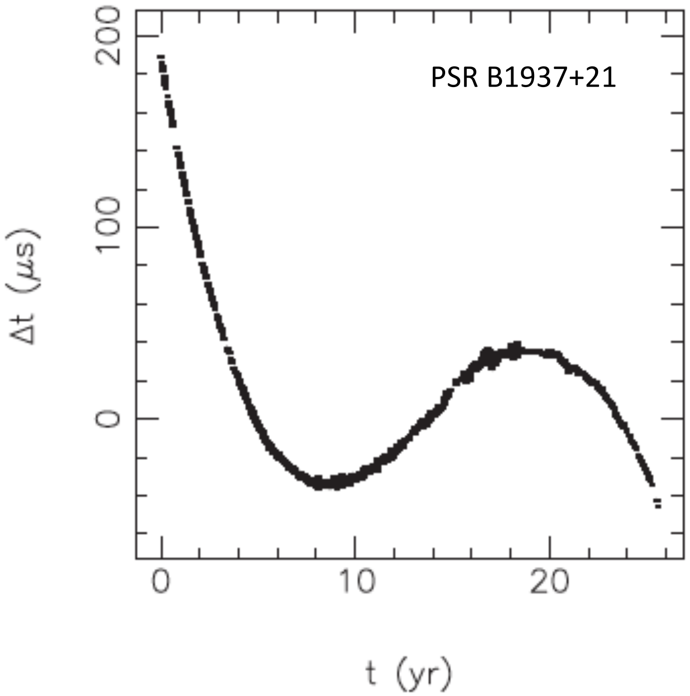
- Red noise = (**gravitational waves)** + spin noise + ISM noise + …

- White noise = radiometer noise + pulse jitter + instrumental effects

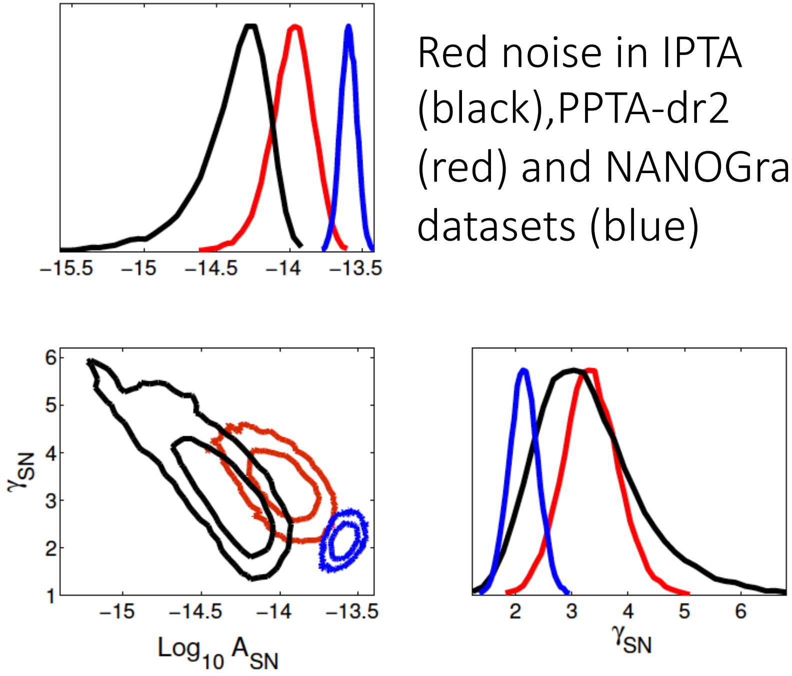
- Can fit/marginalize deterministic terms
- Want to minimize stochastic contributions relative to GWs
- Need to incorporate stochastic contributions into likelihood function

Example: characterizing red noise

Three data sets:
IPTA – first data release
NANOGrav 9 year data set
PPTA – same 9 year as NANOGrav



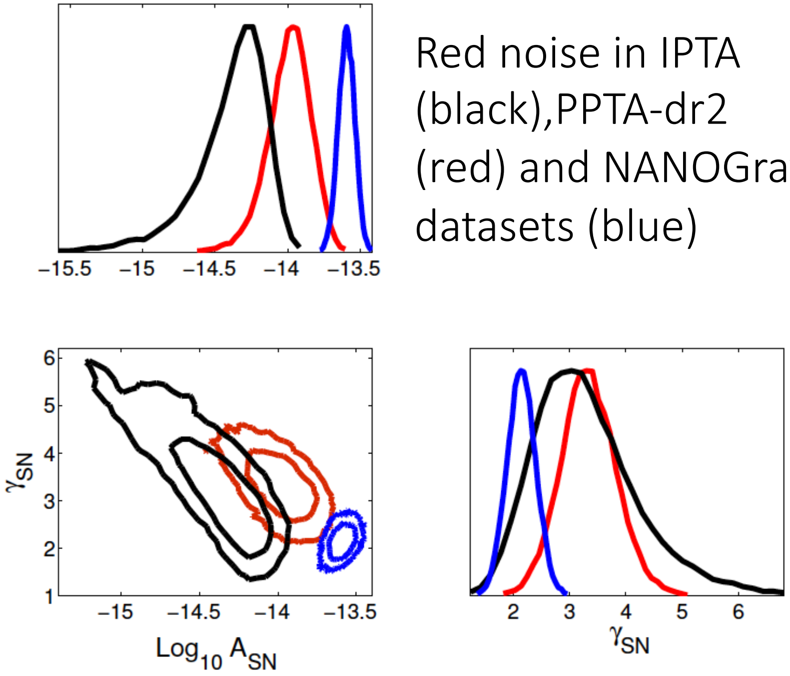
“Corner plots”



Red noise in IPTA (black),PPTA-dr2 (red) and NANOGrav datasets (blue)

Interpreting results of timing model

- Visual inspection?
    - Do the residuals look weird (sinusoidal trends vs time or orbital phase)
- How good is the fit? How good is the model?
- Are parameters significant? Do their values make sense?
- Do parameters improve the fit/increase the evidence?
- Are parameters consistent?
    - Geometric parallax / vs Change in orbital period
    - Consistent with other observatories, **IPTA**



Red noise in IPTA (black),PPTA-dr2 (red) and NANOGrav datasets (blue)

Ryan’s recipe for precision timing (2023)

- Use `tempo2` graphical plugin to inspect residuals
    - “Bailes Method” -> remove the low S/N TOAs and see what is left
    - Sort by frequency/flag by backend/serially/, etc.
    - Average data together in time/frequency to see what low structure exist

- Use maximum-likelihood methods to explore data
    - What are the important parameters?
    - What are the important noise sources?

- Use Bayesian methods to explore the models (temponest/enterprise)
    - How are parameters covariant?
    - Which parameters/models are supported?
    - Are parameters physics

- Test Bayesian models by subtracting maximum-likelihood noise models from data
    - Do residuals have Gaussian distribution?

Summary

- A variety of noise processes could be present in pulsar timing data sets
- Achromatic red noise could arise from the pulsar or from gravitational waves
- Chromatic red noise from the interstellar medium
- Having a good model for noise necessary for making the best use of pulsars as tools