Dispersion Variations: Impact and Analysis

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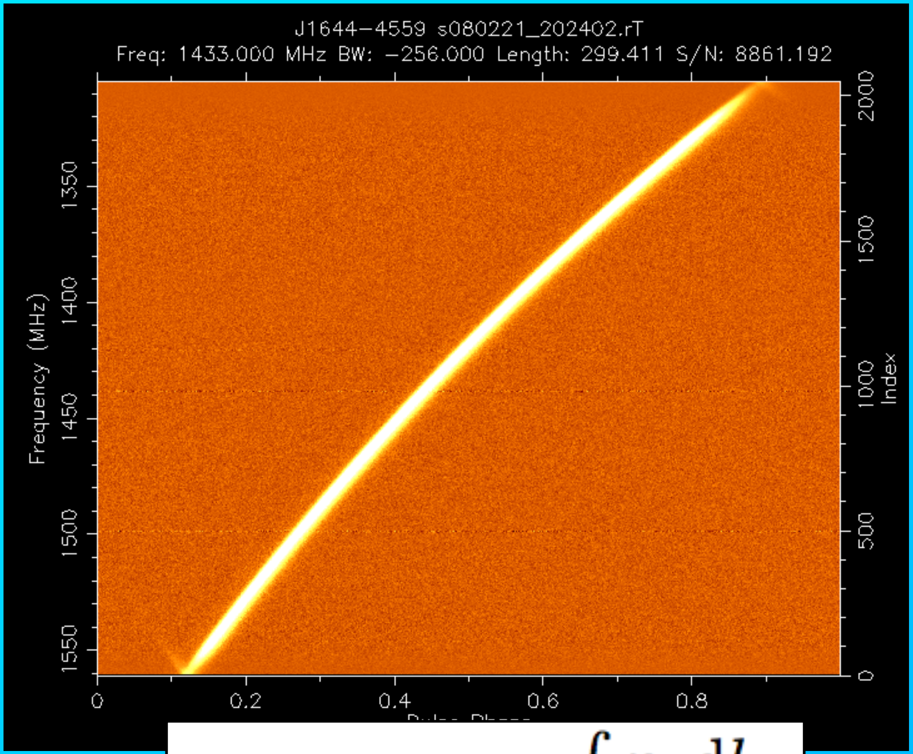
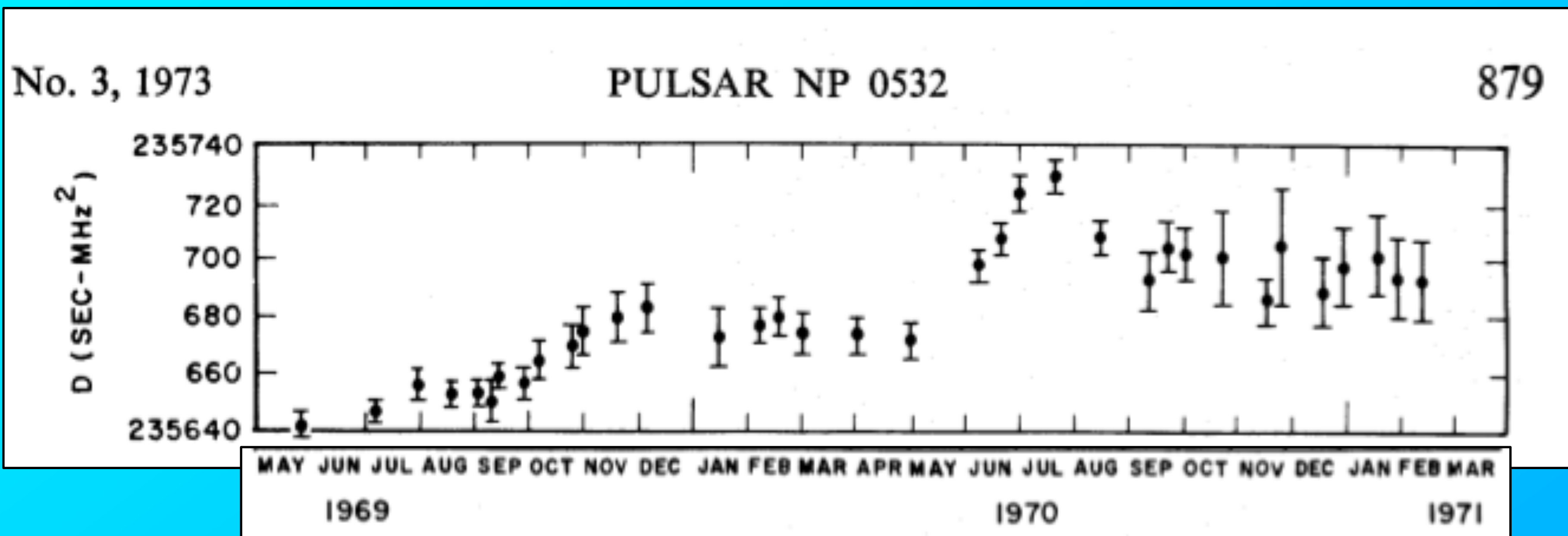


$$\Delta t_{\rm DM} \sim \frac{\int n_e \mathrm{d}l}{\nu^2}$$

Dispersion Variations

- Variations first detected in Crab and Vela pulsars
  - Rankin & Counselman (1973)
  - Hamilton, Hall & Costa (1985)



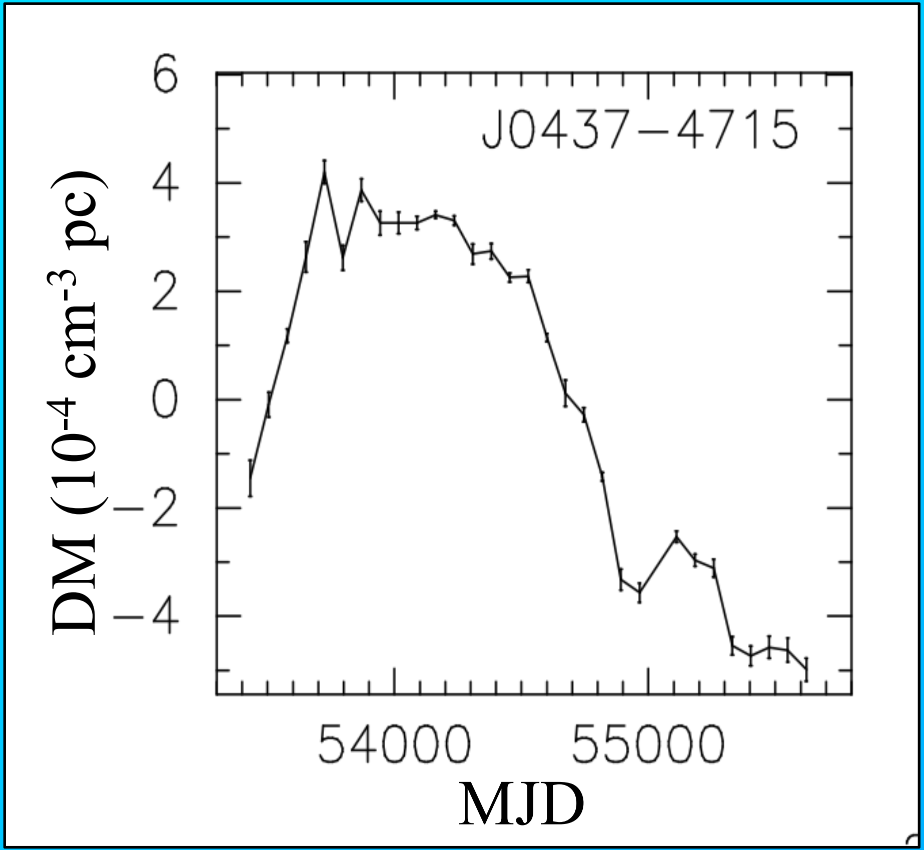
For Vela, rate ~ 0.04 cm^{-3} pc yr^{-1}

- Uncorrected DM variations add noise to timing data
- Spectrum is red but often contains significant power at frequencies ~ 1 yr^{-1}
- Uncorrected DM variations will bias fitted pulsar parameters, e.g. parallax
- Will also contribute power to unmodelled signals, e.g. from gravitational waves

$\Delta DM = 10^{-4}\ cm^{-3}\ pc$

→

Δt_{DM} = 212 ns at 1.4 GHz



(Keith et al. 2013)

DM Correction

- Observed ToAs are sum of frequency-independent "common-mode" terms t_{CM} (e.g., clock errors, GW, etc) and interstellar delays t_{DM} – assume ~ λ^2

$$t_{\mathrm{OBS}} = t_{\mathrm{CM}} + t_{\mathrm{DM}}(\lambda/\lambda_{\mathrm{REF}})^2$$

- The interstellar term t_{DM} is noise – want to minimise it
  - ➢ Observe at ~zero wavelength, i.e., X-ray or γ-ray
  - ➢ Observe at two or more wavelengths, λ_1 and λ_2 (with $\lambda_1 > \lambda_2$)
- Can then solve for t_{DM} and t_{CM}:

$$\tilde{t}_{\mathrm{DM}} = (t_{\mathrm{OBS},1} - t_{\mathrm{OBS},2})\lambda_{\mathrm{REF}}^2/(\lambda_1^2 - \lambda_2^2),$$

$$\tilde{t}_{\mathrm{CM}} = (t_{\mathrm{OBS},2}\lambda_1^2 - t_{\mathrm{OBS},1}\lambda_2^2)/(\lambda_1^2 - \lambda_2^2).$$

- t_{DM} is proportional to the DM variation
- t_{CM} is what we really want!
- We need to minimise the uncertainty in t_{CM}:

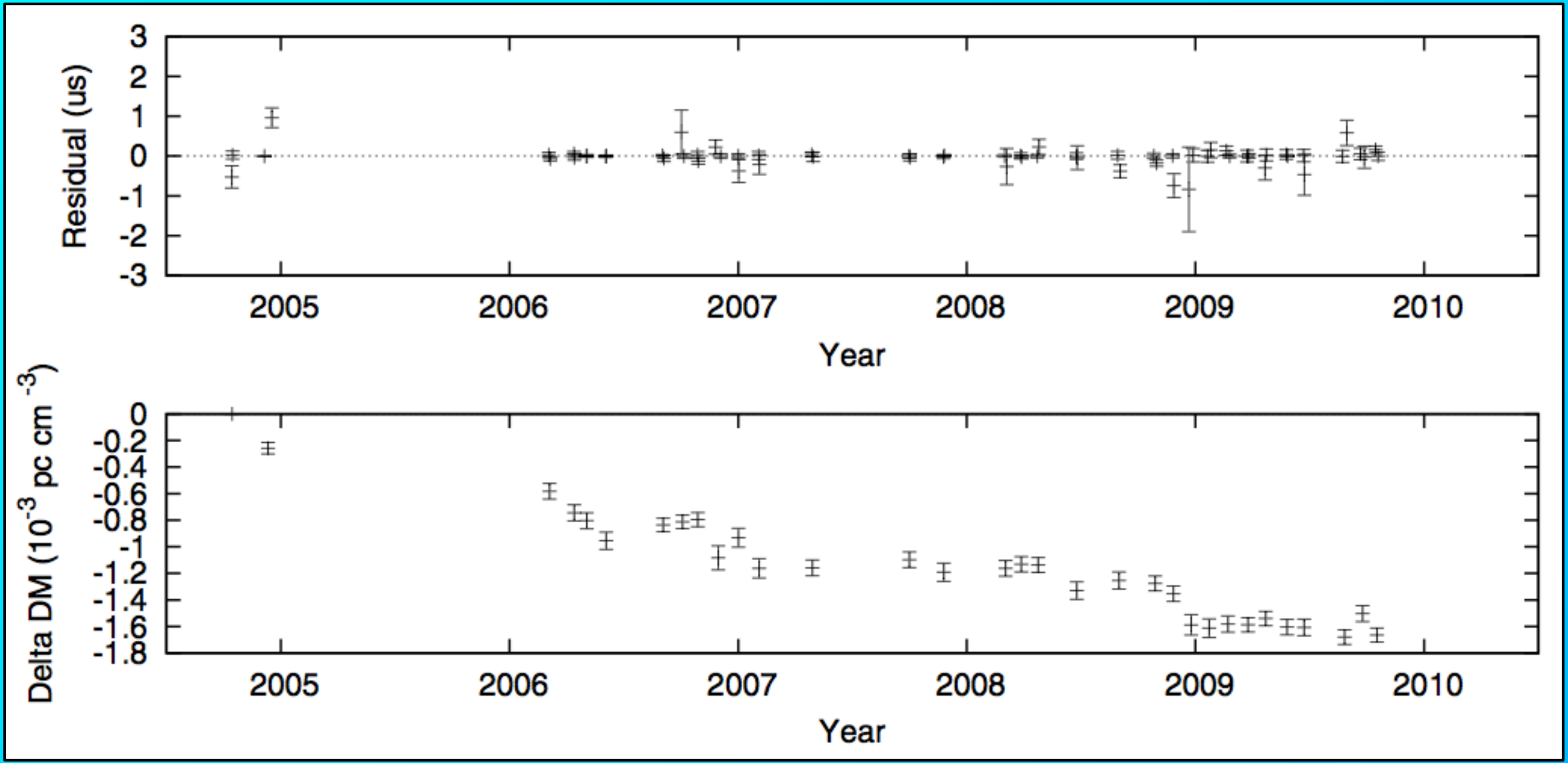
$$\sigma_{t_{\rm CM}} = \left[\sigma^2_{t_{\rm OBS,2}} + \left(\frac{\lambda_2^2}{\lambda_1^2}\sigma_{t_{\rm OBS,1}}\right)^2\right]^{1/2}\left(\frac{\lambda_1^2}{\lambda_1^2-\lambda_2^2}\right)$$

i.e., need $\lambda_2 << \lambda_1$ and small σ_t

– note that σ_{t1} can be larger than σ_{t2} by a factor $\sim(\lambda_1/\lambda_2)^2$

- Sum of DM corrections is constrained to zero
- Also, need to ensure that t_{CM} is not covariant with timing model terms, e.g., ν, $\dot{\nu}$, etc.

DM Variations - PSR J1909-3744 NANOGrav



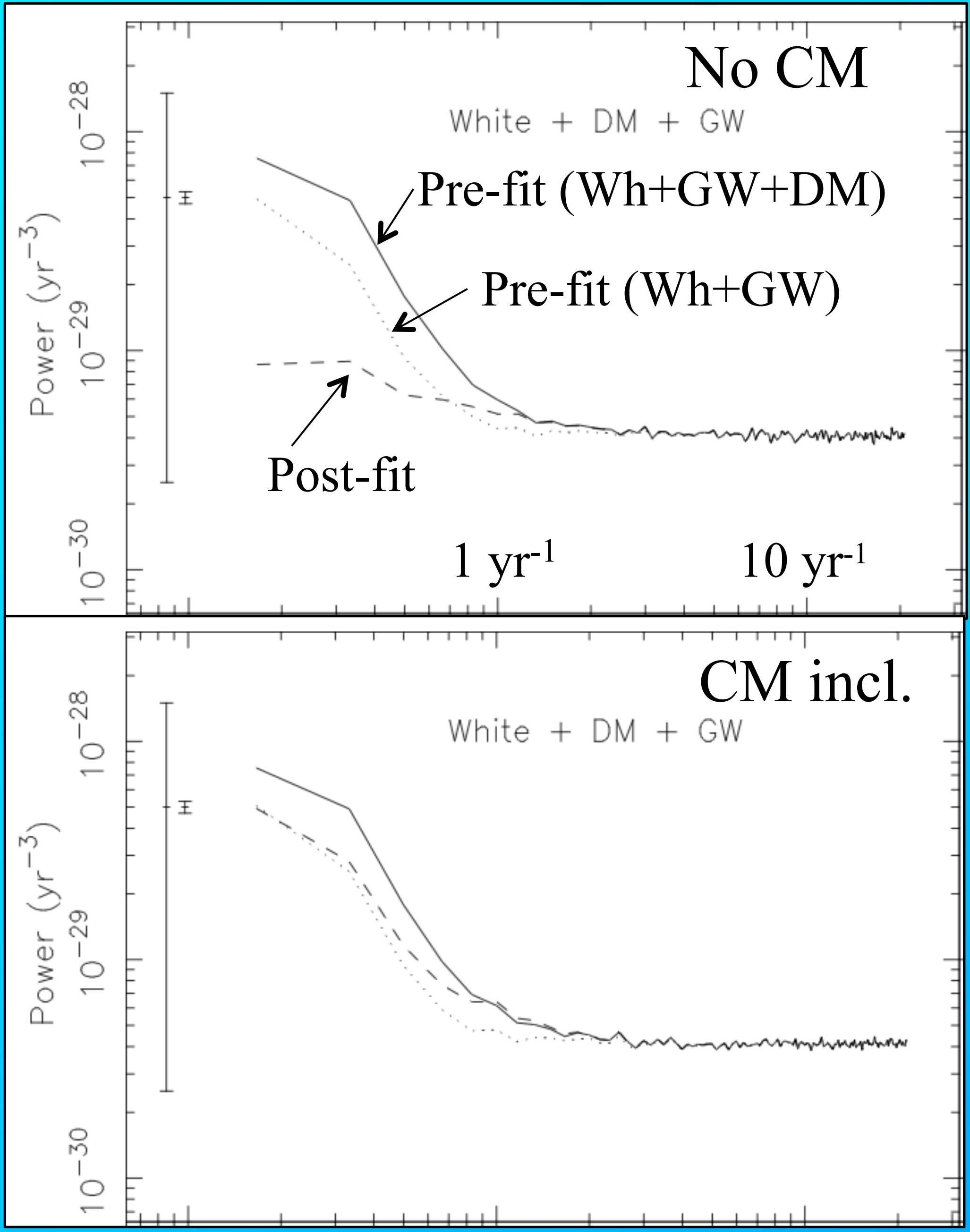
- GBT: 820 and 1400 MHz
- ΔDM from dual-band observations within 15-day span

(Demorest et al. 2013)

Effect of CM Term

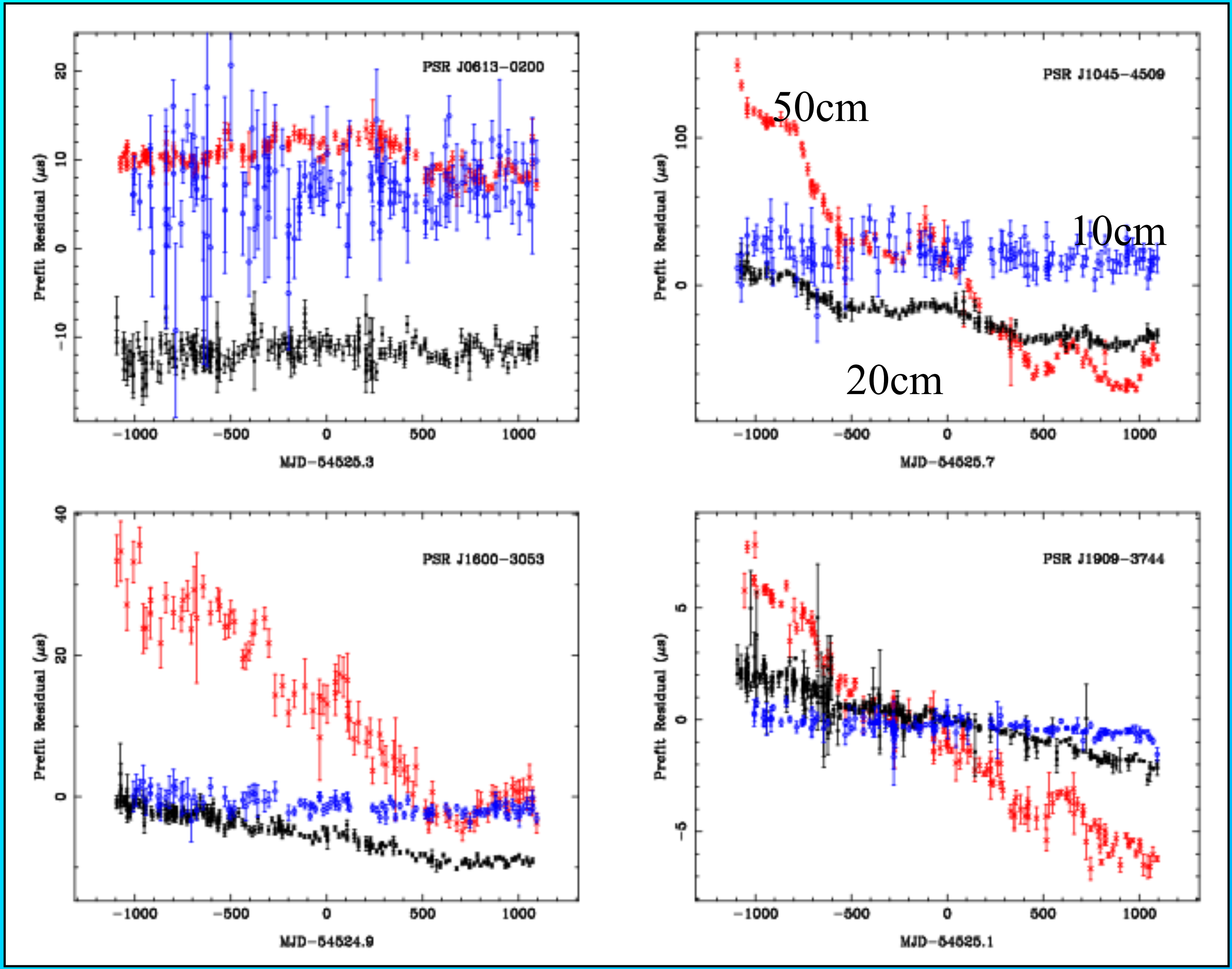
- If CM term not included in fit, power is extracted from freq-independent variations and coupled into DM variations
- With CM term included, all freq-independent power (e.g., GW signal, clock errors) is contained in CM values

(Keith et al. 2013)



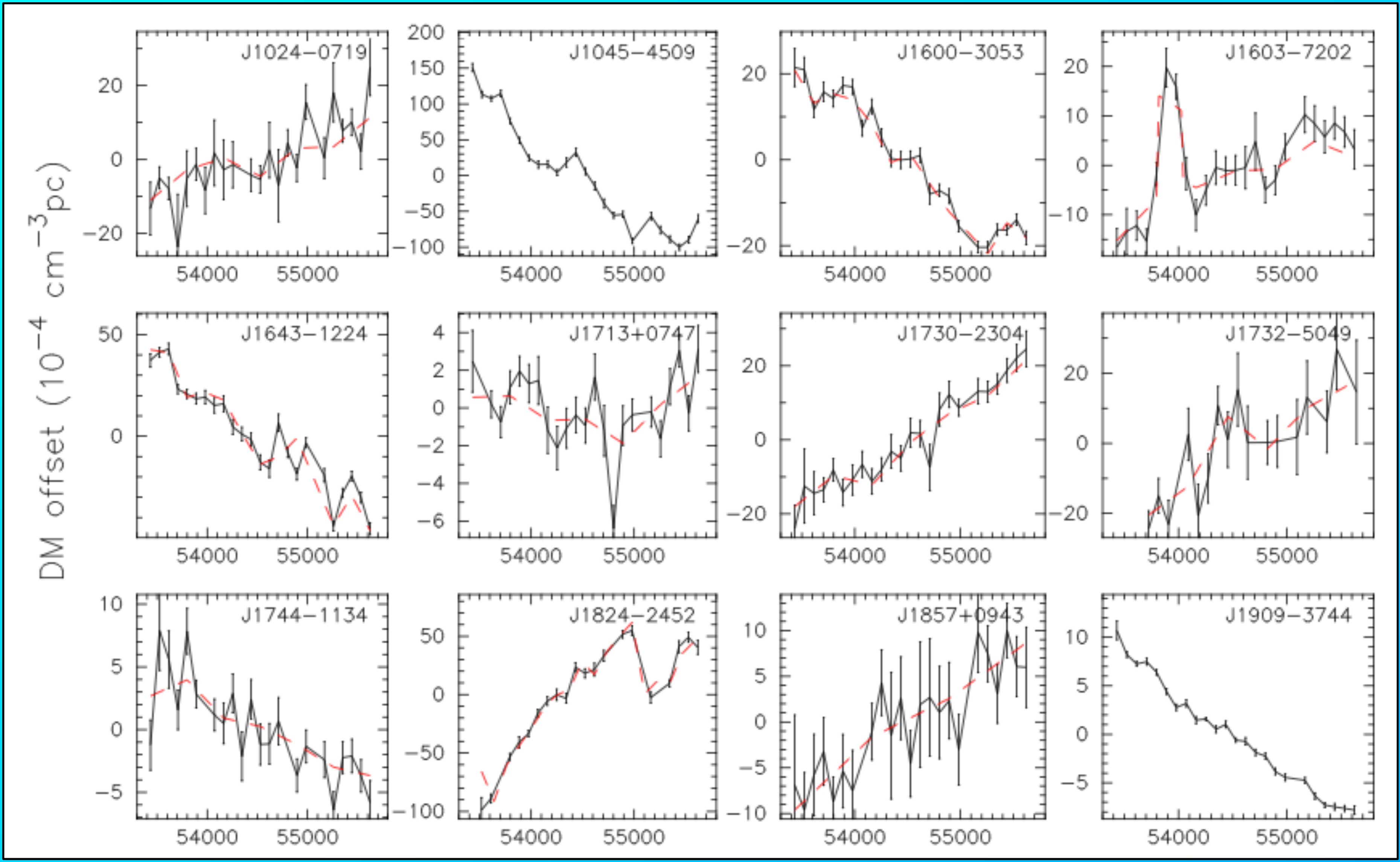
Power spectra of timing residuals

PPTA Three-Band Timing Residuals



(Manchester et al. 2013)

DM Variations for PPTA pulsars



(Keith et al. 2013)

DM Smoothing

- For PPTA, data are better sampled – obs every 2-3 weeks
- Benefit in averaging multi-band data over a longer span – reduces effective σ_t
- Uniform sampling at T_s with linear interpolation
- $T_\mathrm{s} = 1/f_\mathrm{c}$, where f_c is frequency where DM-fluctuation and white-noise powers are equal
- Little effect of sensitivity of GW detection since expected $A^2_{GW} \sim f^{-13/3}$ – steeper than spectrum of DM fluctuations
- Improves precision of model terms with spectral power at $f \sim f_\mathrm{c}$, e.g., parallax

Effect of DM Corrections: PPTA Psrs

- Nine psrs where DM correction clearly beneficial
- For six more, some benefit
- For others, added noise outweighs benefit or non-ν^2 variations

PSR	$\frac{\lvert\Delta\nu\rvert}{\sigma_\nu}$	$\frac{\lvert\Delta\dot{\nu}\rvert}{\sigma_{\dot{\nu}}}$	$\frac{\Sigma_{\rm post}}{\Sigma_{\rm pre}}$	$\frac{\bar{P}_{\rm post}}{\bar{P}_{\rm pre}}$	Imp.
J0437−4715	92	48	0.6	0.15-0.25	Y
J0613−0200	0.16	2.9	1.1	0.3-1.2	y
J0711−6830	3.9	5.5	1.0	0.4-1.6	y
J1022+1001	1.4	0.3	1.0	0.6-2.6	n
J1024−0719	1	0.91	1.0	0.2-0.7	Y
J1045−4509	28	11	0.7	0.22-0.39	Y
J1600−3053	35	0.51	1.0	0.4-0.8	Y
J1603−7202	2.4	2.5	1.0	0.2-0.9	Y
J1643−1224	11	0.73	1.7	1.3-3.1	N
J1713+0747	3.2	6.2	1.0	0.2-0.7	Y
J1730−2304	6.5	1.8	1.1	0.9-3.2	n
J1732−5049	2.6	2.8	1.0	0.4-1.4	y
J1744−1134	5.4	0.48	1.0	0.5-2.0	n
J1824−2452A	24	31	0.7	0.29-0.56	Y
J1857+0943	4.3	1	1.0	0.2-1.0	y
J1909−3744	28	5	1.0	0.44-0.79	Y
J1939+2134	13	1.7	0.7	0.34-0.67	Y
J2124−3358	0.25	0.056	1.0	0.5-1.9	y
J2129−5721	3	2.1	1.1	0.7-2.8	n
J2145−0750	0.22	0.18	1.0	0.2-1.0	y

(Keith et al. 2013)

Scattering and non-ν^2 Delays

- Scattering delays scale roughly as λ^4
- If not separately solved for, will bias DM corrections and contribute excess noise to high-frequency ToAs
- Observed in PSR J1939+2134 and J1643-1224
- For J1643-1224, DM correction increases the white timing noise at 20cm by more than a factor of three
- Will limit use of very low frequencies for DM correction unless scattering delay is separately measured

J1643-1224 Residuals - PPTA

Summary

- DM variations are a major contributor to timing noise for MSPs at GHz frequencies
- Best solution is to avoid them by timing X-ray, γ-ray, or at least relatively high radio frequencies >~ 3 GHz
- Observations at frequencies <~ 2 GHz must be corrected using observations at lower frequencies
- Frequencies <~ 400 MHz problematic for all but low-DM pulsars because scattering delays are starting to dominate
- With current systems, timing precision is generally limited by precision and accuracy of DM corrections – main motivation for development of ultra-wide-band receivers