The Parkes Pulsar Timing Array

R. N. Manchester

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Sydney Australia

Summary

- The PPTA – what is it?
- Processing pipeline
- PPTA data sets
- The extended PPTA data set

• The Parkes Pulsar Timing Array Collaboration

- CSIRO Astronomy and Space Science, Sydney
  Dick Manchester, George Hobbs, Ryan Shannon, Mike Keith, Sarah Burke-Spolaor, Aidan Hotan, John Sarkissian, John Reynolds, Mike Kesteven, Warwick Wilson, Grant Hampson, Andrew Brown, Ankur Chaudhary, (Russell Edwards), (Jonathan Khoo), (Daniel Yardley)
- Swinburne University of Technology, Melbourne
  Matthew Bailes, Willem van Straten, Stefan Oslowski, Andrew Jameson, (Ramesh Bhat), (Jonathon Kocz)
- Monash Universit
  Yuri Levin
- University of M
  Vikram Ravi (Stuart Wyithe)
- University of Califo
  Bill Coles
- University of Texa
  (Rick Jenet)
- MPIfR, B
  (David Champion), (Joris Verbiest), (KJ Lee)
- Southwest Universi
  Xiaopeng You
- Xinjiang Astronomical O
  (Wenming Yan), Jingbo Wang
- National Space Science Center, Beijing
  Xinping Deng

•The PPTA Project

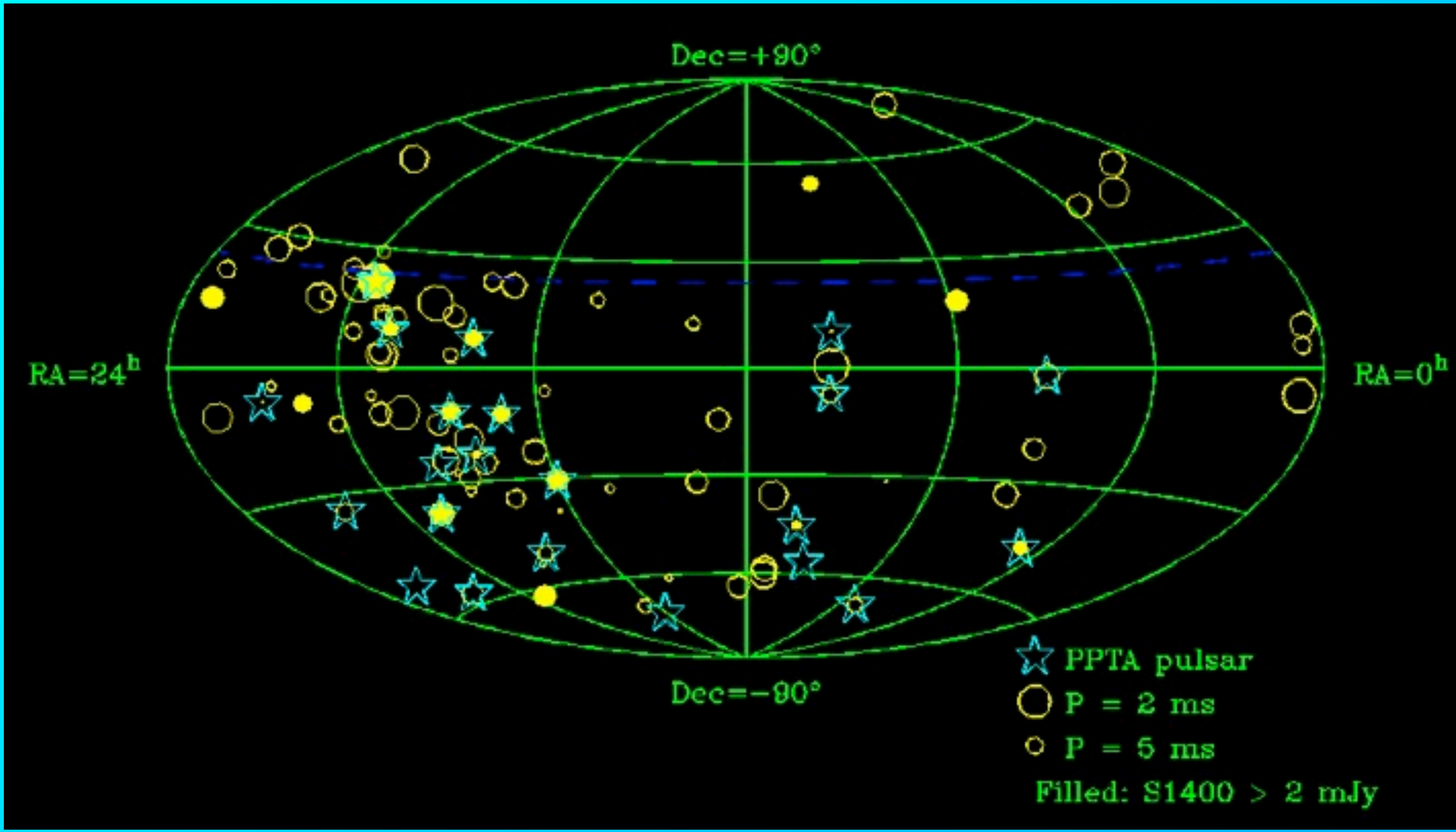
- Using the Parkes 64-m radio telescope in three bands, 50cm (700 MHz), 20cm (1400 MHz) and 10cm (3100 MHz) to observe 21 MSPs
- Observations at 2 - 3 week intervals
- Regular good-quality observations since 2005 March
- Digital filterbanks and baseband recording systems used
- Database and processing pipeline –

• Website: www.atnf.csiro.au/research/

•PPTA-related papers in the last year

- **Keith, M. et al., 2012**, "*Measurement and correction of variations in interstellar dispersion in high precision pulsar timing*" MNRAS, submitted
- **Manchester, R. N. et al. 2012**, "*The Parkes Pulsar Timing Array Project*", PASA, submitted
- **Hobbs, G. et al. 2012**, "*Developing a pulsar-based timescale*" MNRAS, submitted
- **Deng, X. P., et al. 2012**, "*Optimal interpolation, prediction in pulsar timing*", MNRAS, in press
- **You, X. P., Coles, W. A., Hobbs, G. B., Manchester, R. N. 2012**, "*Measurement of the electron density, magnetic field of the solar wind using millisecond pulsars*", MNRAS, 422, 1160-1165
- **Coles, W., Hobbs, G., Champion, D. J., Manchester, R. N., Verbiest, J. P. W. 2011**, "*Pulsar timing analysis in the presence of correlated noise*", MNRAS, 418, 561-570
- **Oslowski, S., van Straten, W., Hobbs, G. B., Bailes, M., Demorest P. 2011**, "High signal-to-noise ratio observations and the ultimate limits of precision pulsar timing", MNRAS, 418, 1258-1271
- **van Straten, W. and Bailes, M. 2011**, "*DSPSR: Digital signal processing software for pulsar astronomy*", PASA, 28, 1-14
- **Hobbs, G. et al. 2011**, "*The Parkes Observatory Data Archive*", PASA, 28, 202-214
- **Yan, W. M. et al. 2011**, "*Rotation measure variations for 20 millisecond pulsars*", ApSS, 335, 485-498
- **Yardley, D. R. B. et al. 2011**, "*On detection of the stochastic gravitational-wave background using the Parkes Pulsar Timing Array*", MNRAS, 414, 1777-1787
- **Yan, W. M. et al. 2011**, "*Polarization observations of 20 millisecond pulsars*", MNRAS, 414, 2087-2100

• The PPTA Pulsars



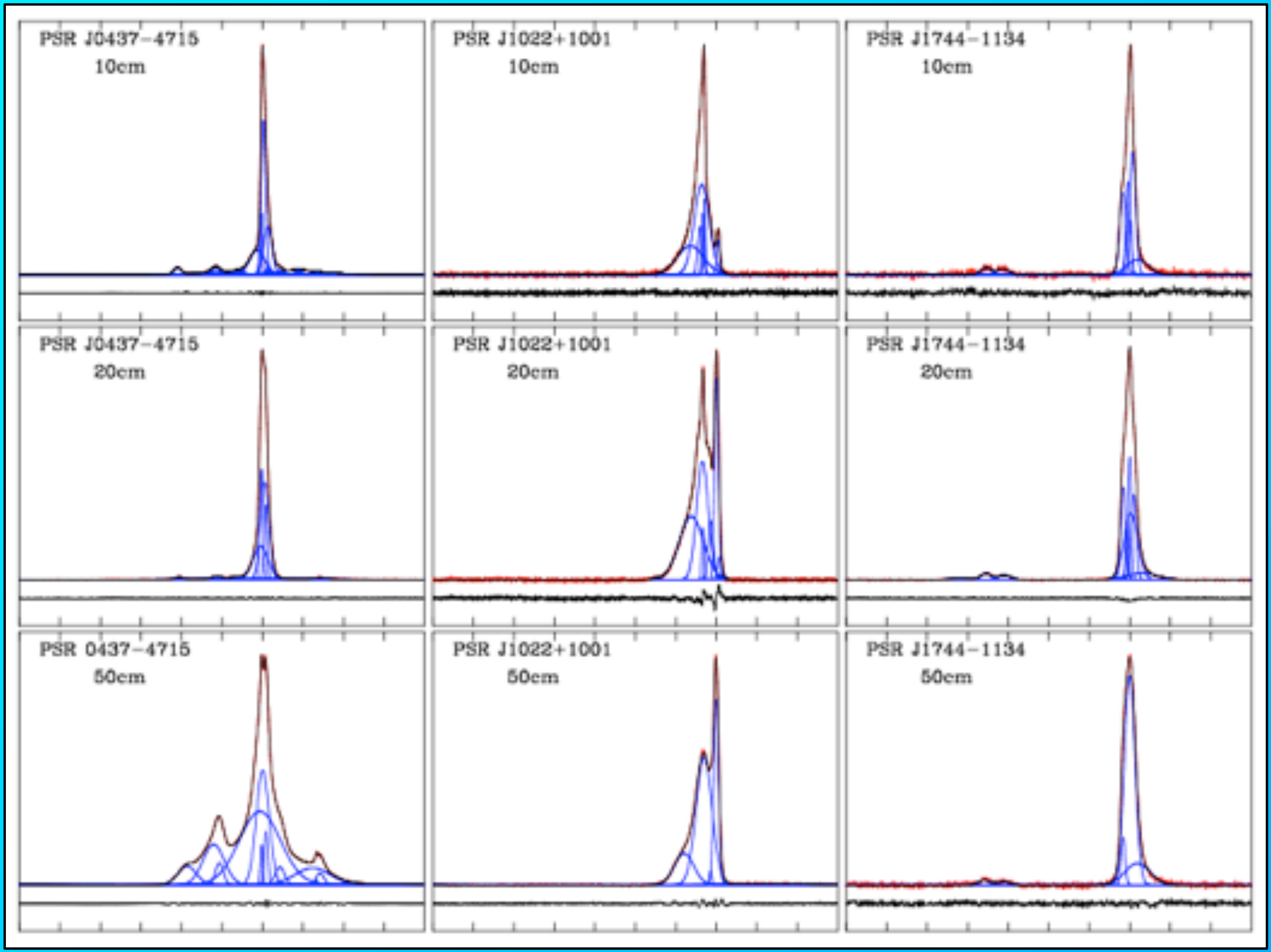
• All (published) MSPs not in globular clusters

•PPTA Data Processing Pipeline

- Band edges (5%) and known RFI zapped
- Data files summed in time to give 8 sub-integrations
- Start times adjusted for instrumental delays
- Data calibrated for instrumental gain and phase, feed cross-coupling (20cm) and placed on flux density scale **(Willem's talk)**
- Data summed in time, frequency and polarisation to give Stokes I (invariant interval for J0437-4715) profile for each observation (typically 1 hr duration) and each band
- Profiles cross-correlated with noise-free template to give ToAs
- Three-band data sets analysed using TEMPO2, fitting for DM offsets and pulsar parameters (spin freq. just F0, F1) using Cholesky method
- "Best" single-band data set chosen (selecting DM correction or not and optimal calibration method) to give lowest rms timing residuals
- Final fit with all parameters except F0 and F1 held fixed at values from three-band solution

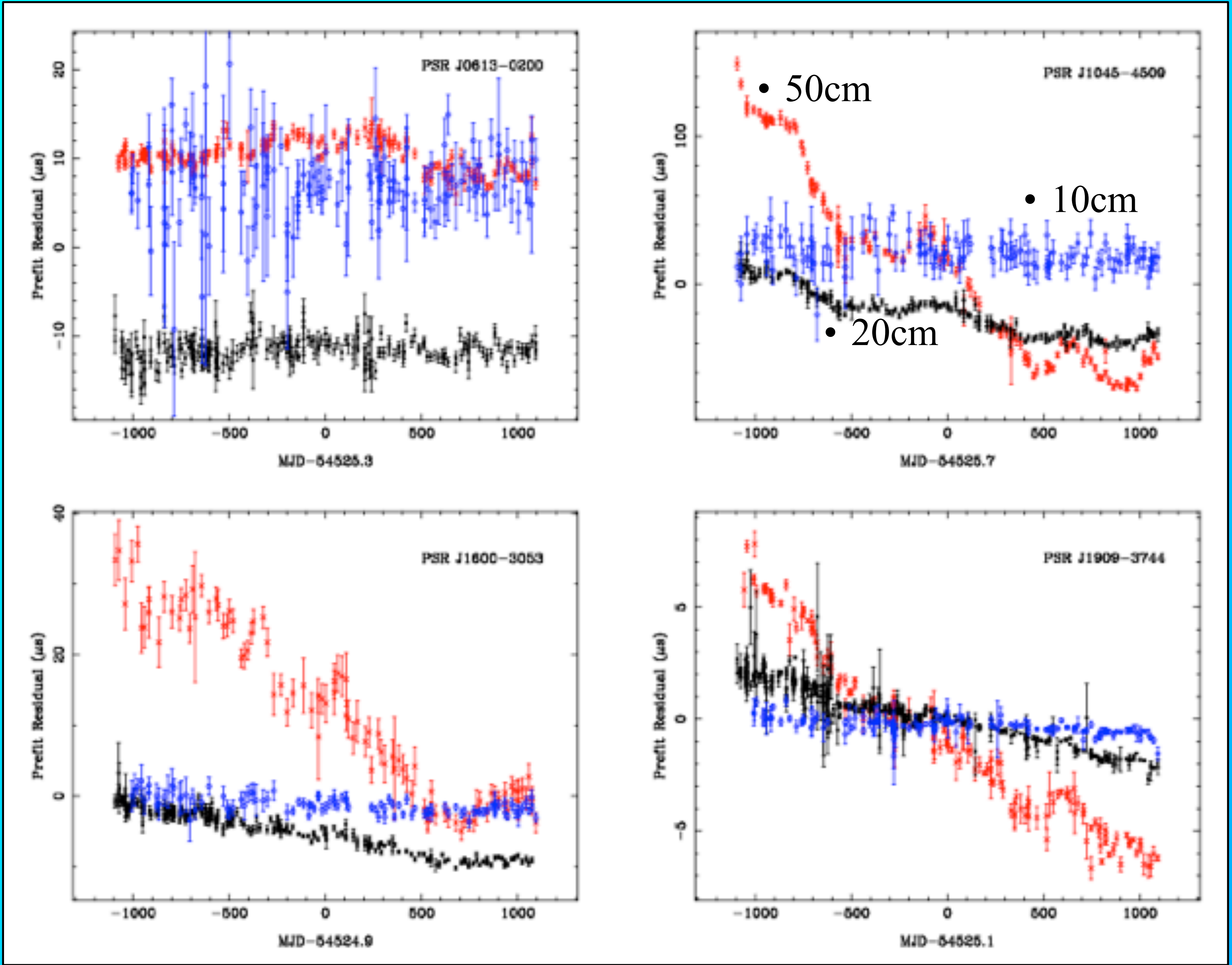
•PPTA Profile Templates

- von Mises functions fitted to high S/N profiles using PSRCHIVE program PAAS
- Up to 17 components fitted per profile
- 10cm and 50cm profiles aligned with 20cm profiles for maximum correlation



- (Manchester et al. 2012)

•Three-Band Timing Residuals



•DM Variations and Correction

- DM offsets solved for along with pulsar parameters and frequency-independent (“common-mode”) signal using Cholesky algorithm in Tempo2 on PPTA three-band data sets

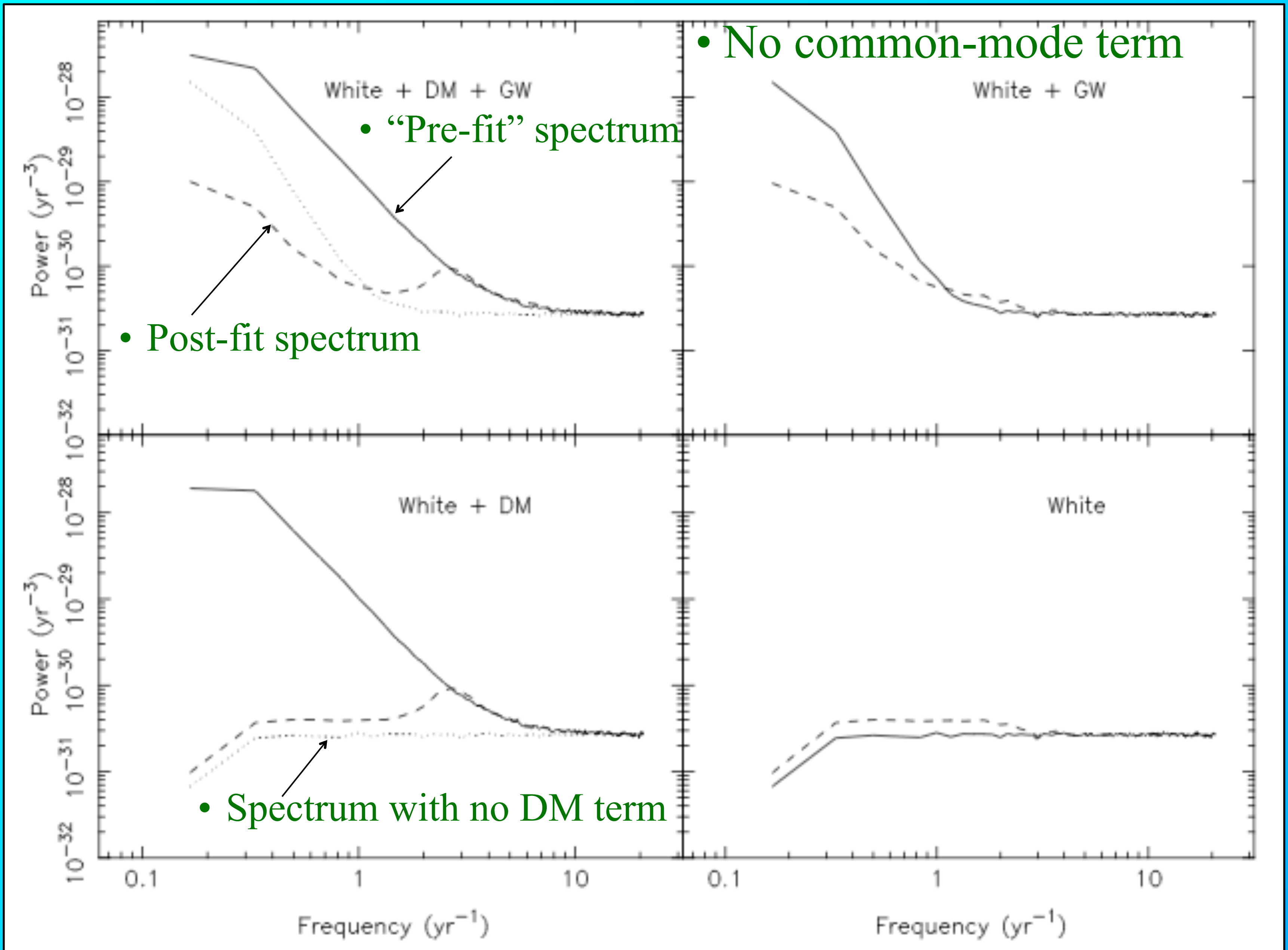
$$\boxed{t_{o,i} = t_c + t_d(\lambda_i/\lambda_r)^2 + t_{w,i}}$$

- DM offsets measured at intervals through data sets with linear interpolation between values
- Interval size taken to be inverse of modulation frequency where red (DM) signal is same power as white noise
- Mean DM offset constrained to be zero
- Effectiveness of algorithm tested using simulations

- (Keith et al. 2012)

- **(Also Xiaopeng’s talk tomorrow)**

• Simulated Modulation Power Spectra



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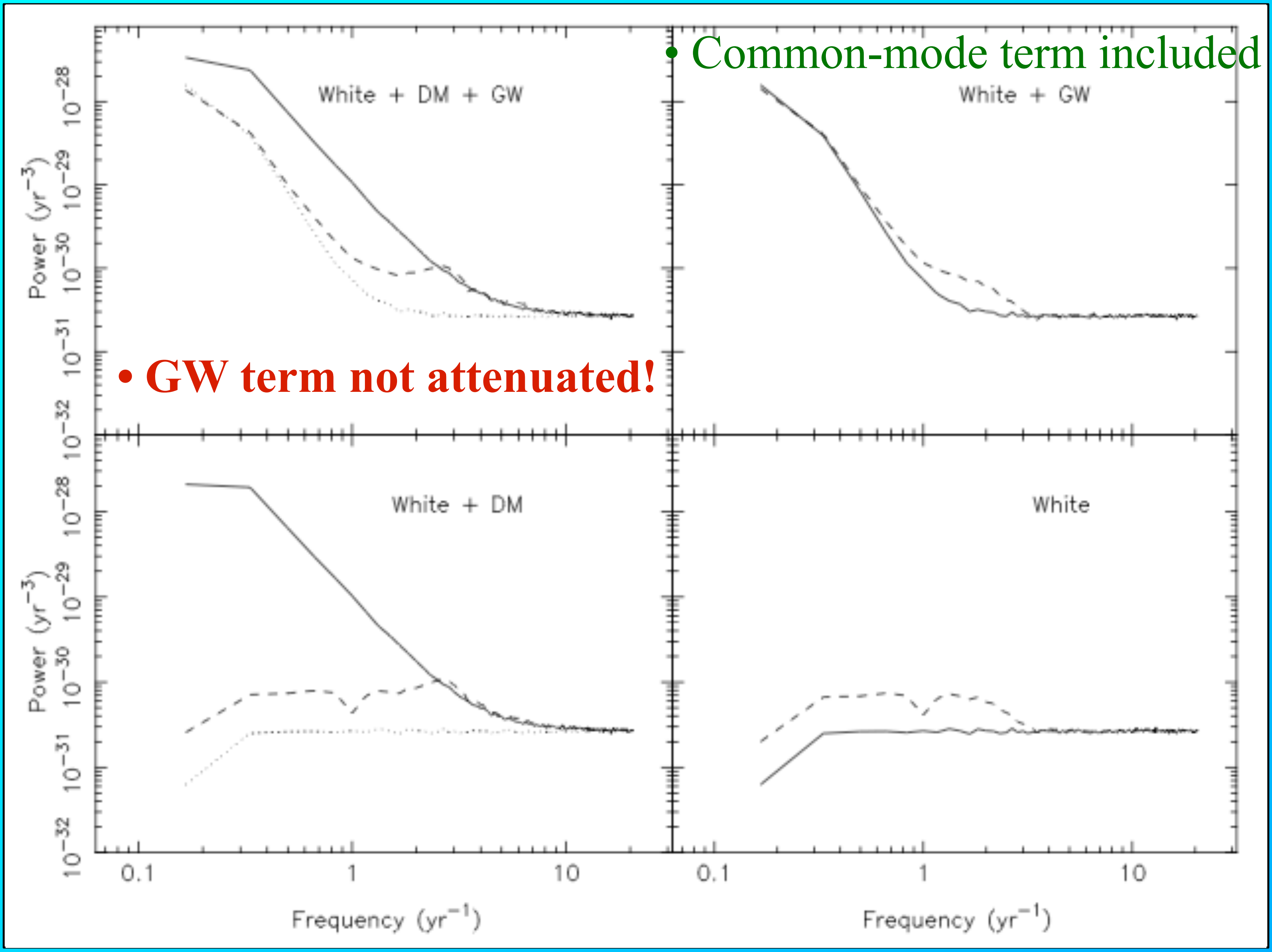
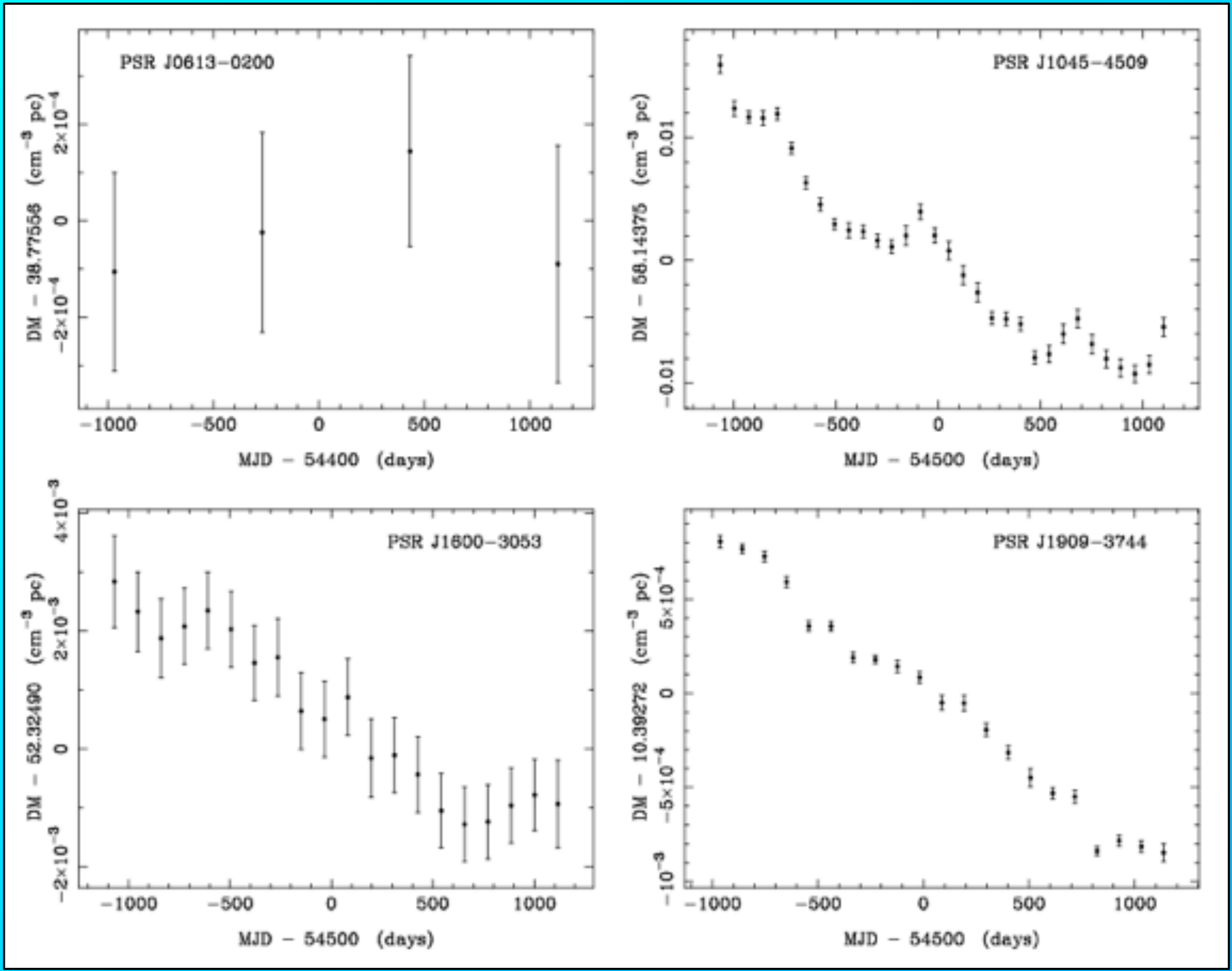


•DM Variations

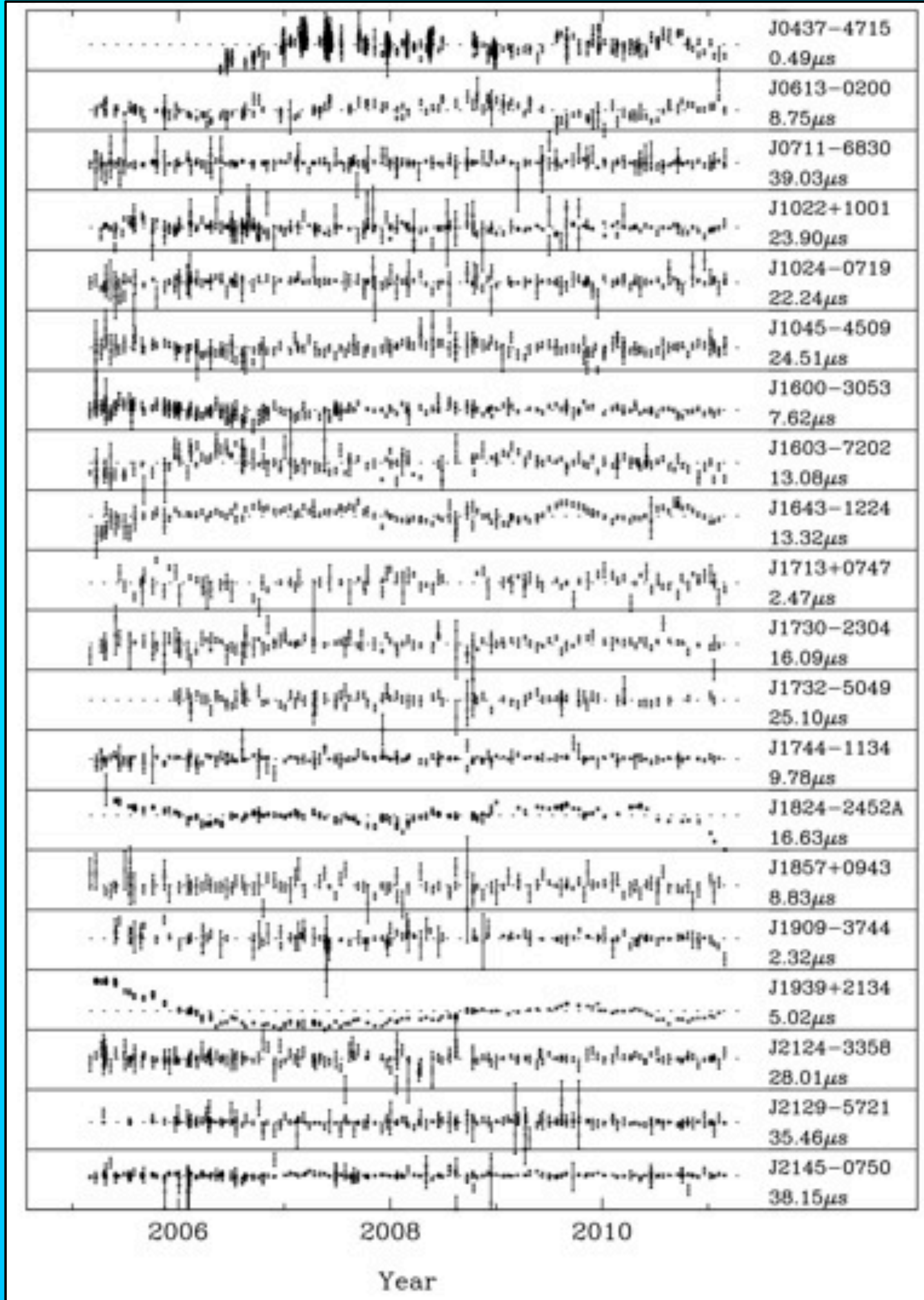


• (NANOGrav and EPTA DM talks later this morning)

- **“Best” Band Timing Parameters**

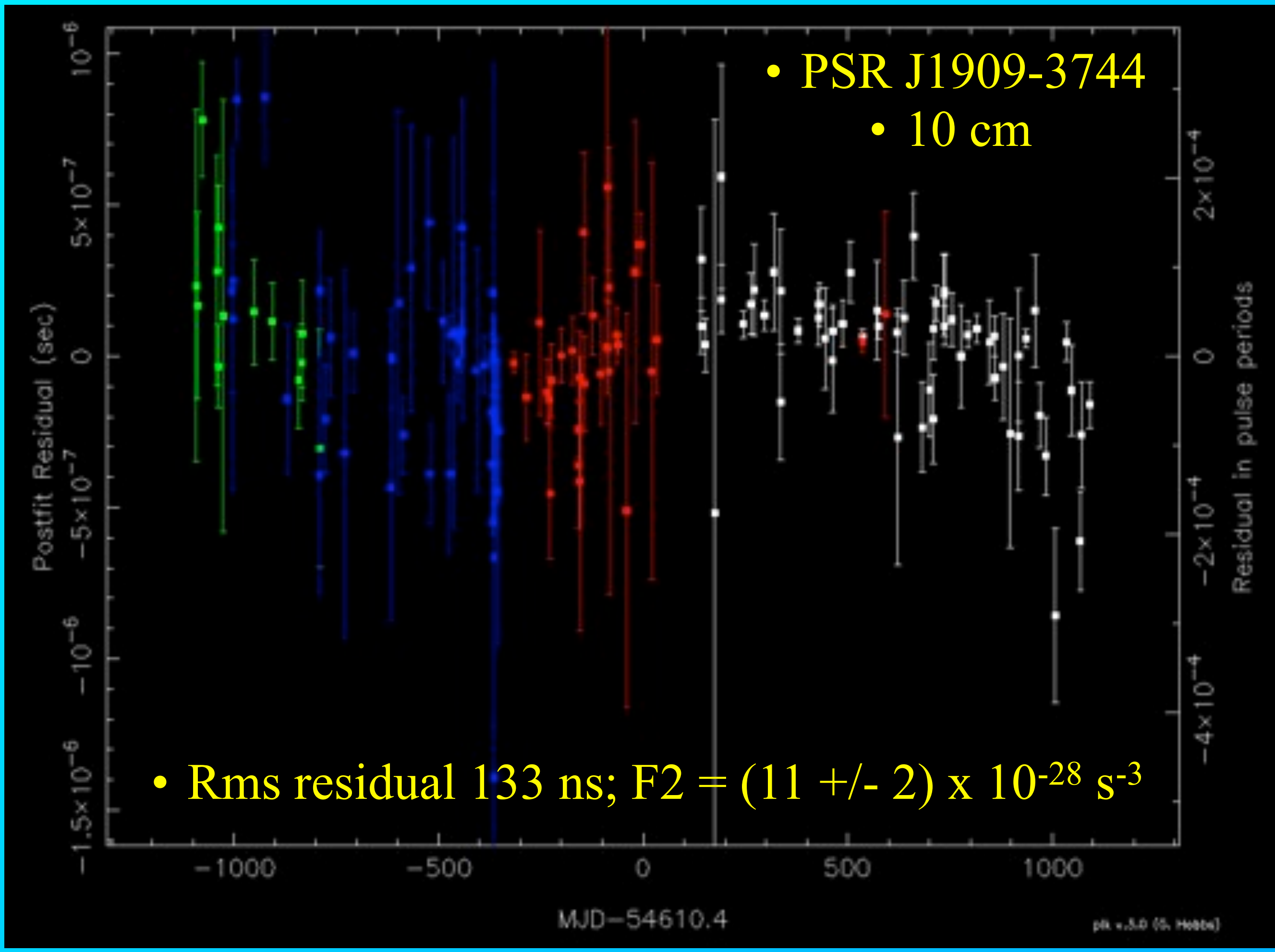
PSR	N_{par}	Band	Corr.	Data span (yr)	Rms Res. (μs)	χ_r^2
J0437−4715	18	10cm	IVI+DMC	4.76	0.075	5.50
J0613−0200	13	20cm	DMC	6.00	1.07	1.76
J0711−6830	7	20cm	...	6.00	0.89	1.66
J1022+1001	12	20cm	MEM	5.89	1.72	9.27
J1024−0719	8	20cm	MEM	6.00	1.13	1.40
J1045−4509	13	20cm	MEM+DMC	5.94	2.77	1.80
J1600−3053	13	20cm	MEM+DMC	5.94	0.68	2.78
J1603−7202	12	20cm	MEM	6.00	2.14	7.93
J1643−1224	14	20cm	...	5.88	1.64	5.46
J1713+0747	16	10cm	...	5.71	0.31	4.00
J1730−2304	7	20cm	DMC	5.94	1.47	2.90
J1732−5049	12	20cm	DMC	5.09	2.22	1.34
J1744−1134	8	20cm	MEM+DMC	5.88	0.32	4.77
J1824−2452A	7	20cm	DMC	5.76	2.44	30.22
J1857+0943	12	20cm	MEM+DMC	5.94	0.84	1.16
J1909−3744	17	10cm	DMC	5.76	0.133	2.21
J1939+2134	7	20cm	DMC	5.88	0.68	141.63
J2124−3358	8	20cm	DMC	6.00	1.90	1.38
J2129−5721	12	20cm	MEM+DMC	5.87	0.80	1.00
J2145−0750	14	20cm	MEM	6.00	0.78	3.18

- **PPTA "Best" Data Sets**
  - 6-year data span
  - Lowest rms residuals for:
    - J0437-4715 – 75 ns
    - J1909-3744 – 133 ns
    - (both at 10cm)
  - Significant "red" noise
  - "White" rms residuals:
    - J0437-4715 – 46 ns
    - J1909-3744 – 61 ns



•Red Timing Noise

- Half of the PPTA pulsars have > 3σ values for F2
- Largest value is for PSR J1939+2134
- Strongest observed F2s can’t be GW since not seen in other pulsars
- Can’t be DM variations since these corrected for where necessary

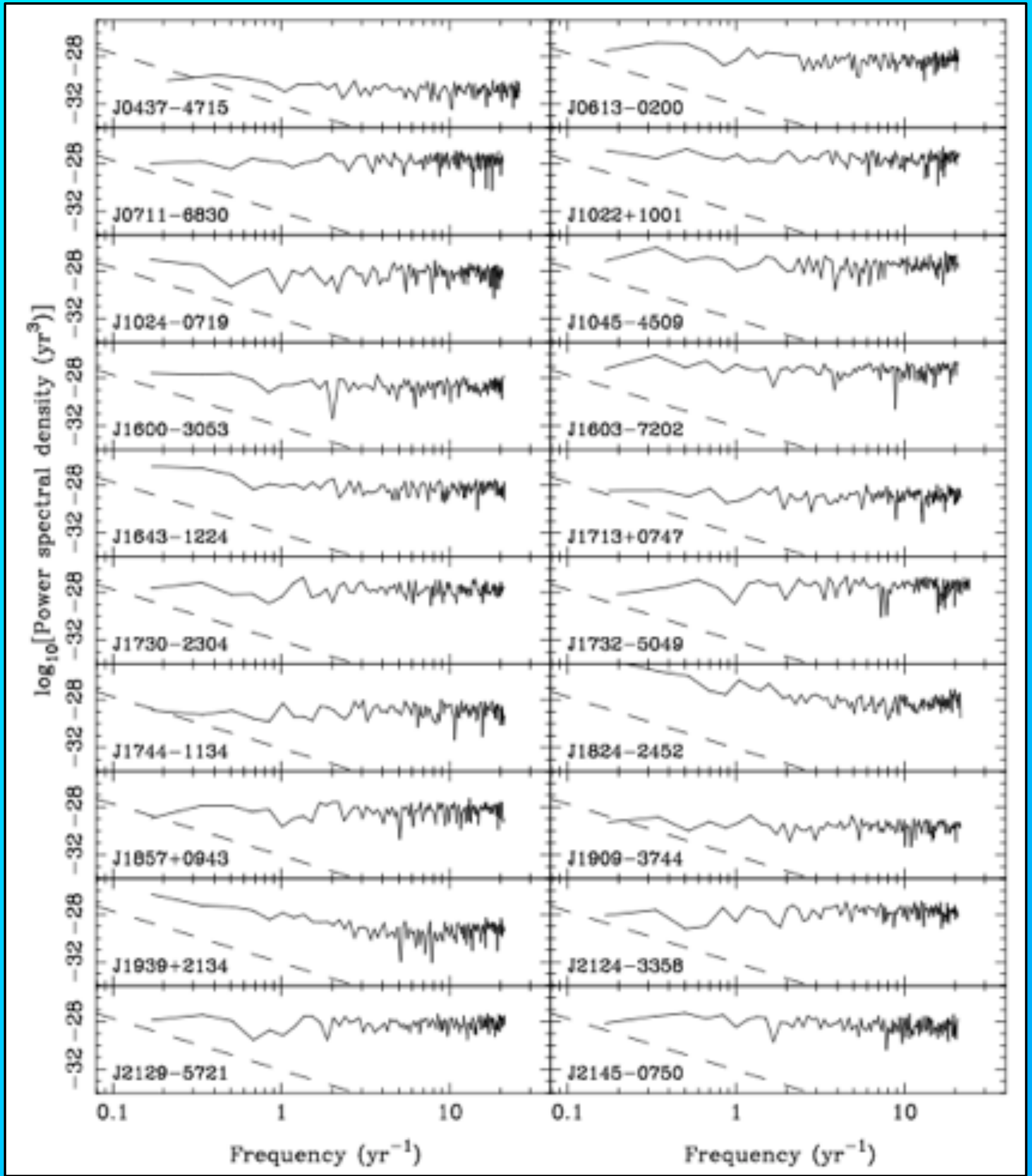


•Most likely intrinsic spin noise – a significant problem for PTA projects

• Modulation Spectra

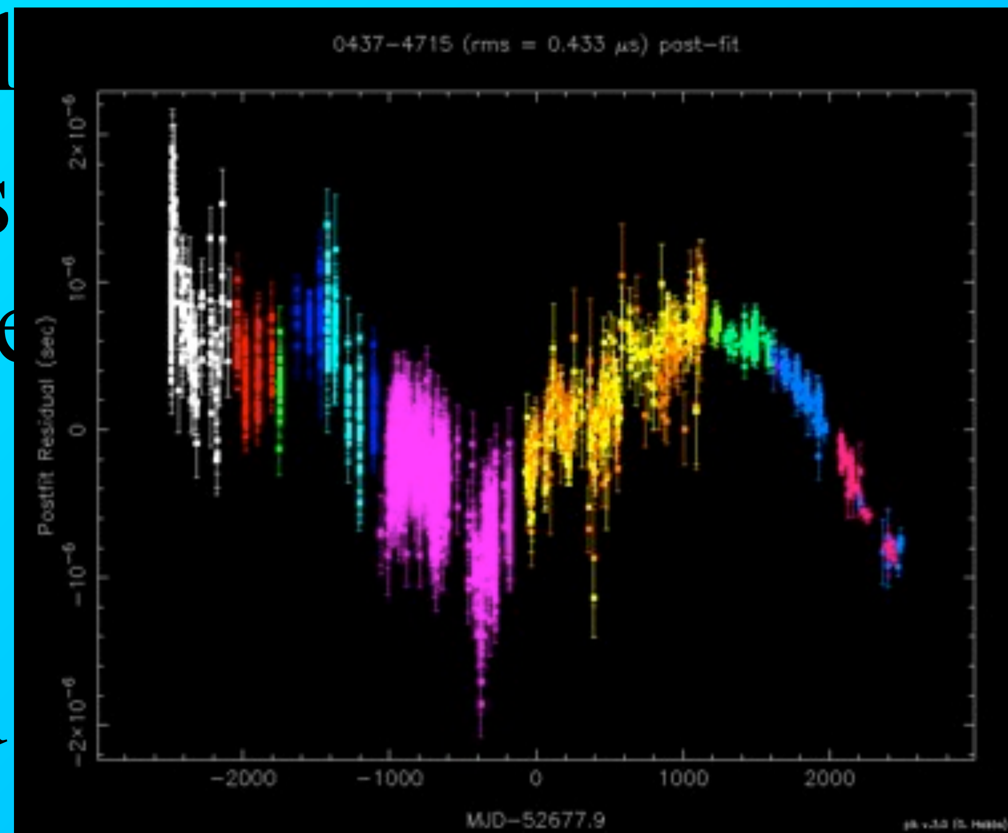
- Power spectra of residual time series after Cholesky fit
- Wide variation in levels of both white and red noise
- Dashed line is expected spectrum of GW background of amplitude $A_g = 10^{-15}$
- Already some pulsars at or below GW line at low freq.
- GW bkgnd has steeper spectrum than pulsar red noise – should eventually win out

- **(Talks by Ryan Shannon and Mike Keith)**



•Extended PPTA Data Sets

- Parkes data from Swinburne timing program for 1994 – 2006 (Verbiest et al. 2008, 2009), added to PPTA
- Most instrumental offsets measured from overlapping data and fixed
- Extended data s... ge...
- DM offsets included and held fixed
- Fit with Cholesky



• PPTA Extended data sets – Timing parameters

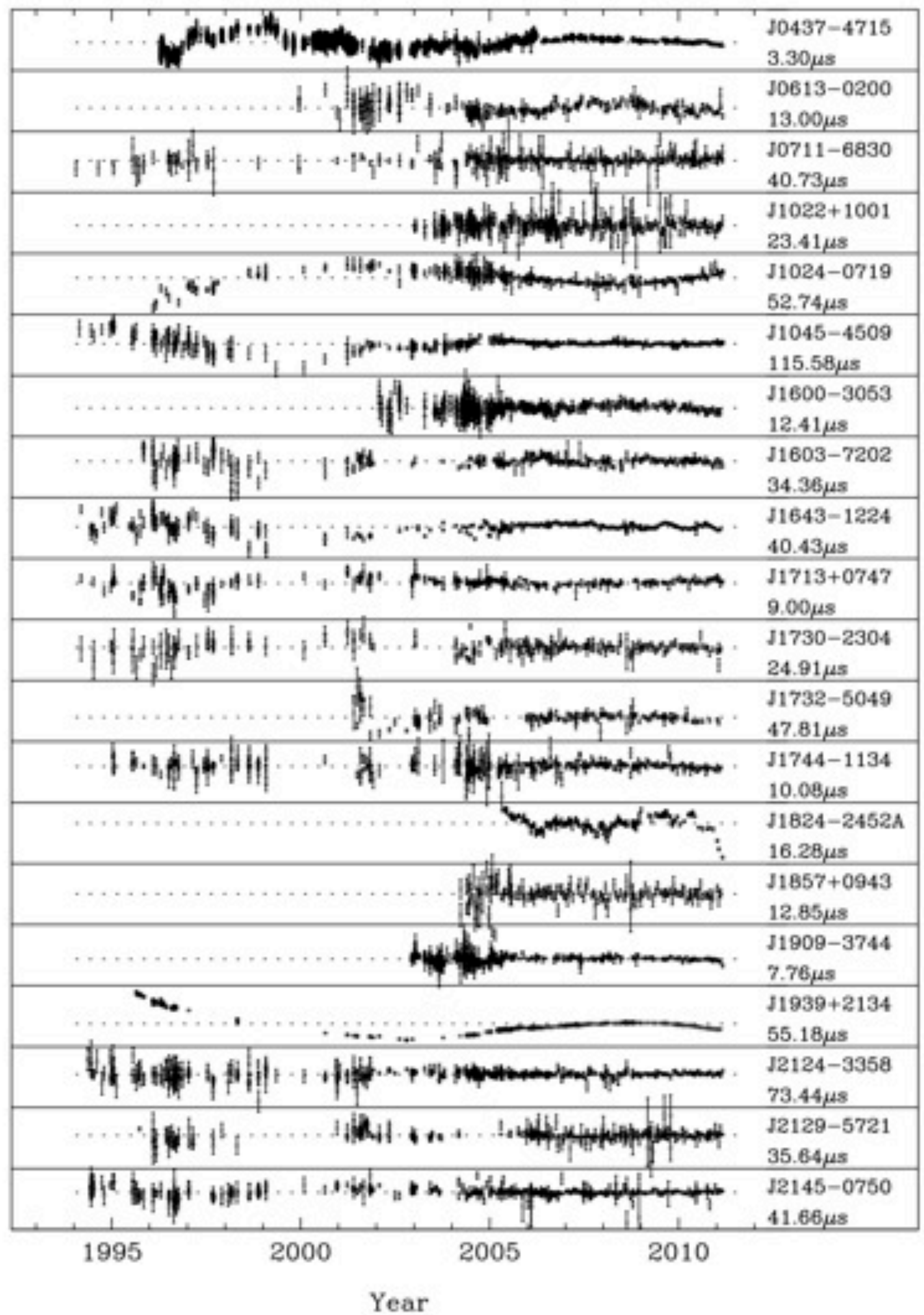
PSR	Data Span (MJD)	$N_{ToA,3B}$	N_p	N_{j0}	N_{j1}	N_{ToA}	Rms Res. (μs)	χ^2_r	$\ddot{\nu}$ (10^{-28} s^{-3})
J0437−4715	50190 – 55619	5055	15	7	9	3508	0.21	7.17	1.26 ± 0.03
J0613−0200	51526 – 55619	629	12	6	0	341	1.11	1.24	7.2 ± 2.1
J0711−6830	49373 – 55620	555	6	10	1	319	1.54	1.54	-0.8 ± 0.7
J1022+1001	52649 – 55619	624	12	7	0	378	1.82	8.14	-0.4 ± 1.6
J1024−0719	50117 – 55620	493	6	10	0	309	4.38	12.57	-38.6 ± 0.8
J1045−4509	49405 – 55620	635	10	10	0	393	5.05	3.18	9.3 ± 1.2
J1600−3053	52301 – 55598	704	12	7	1	503	0.98	1.21	8.6 ± 2.2
J1603−7202	50026 – 55619	483	12	7	3	290	2.12	3.08	1.2 ± 0.4
J1643−1224	49421 – 55598	477	11	7	3	288	2.30	5.90	6.0 ± 1.0
J1713+0747	49421 – 55619	612	15	10	0	334	0.46	7.75	-2.60 ± 0.16
J1730−2304	49421 – 55598	390	7	10	0	223	2.59	3.25	-0.8 ± 0.8
J1732−5049	52647 – 55582	244	11	9	0	149	2.47	1.17	28 ± 7
J1744−1134	49729 – 55599	534	7	9	3	368	0.65	3.27	1.9 ± 0.3
J1824−2452A	53518 – 55620	302	6	3	0	178	2.02	14.50	241 ± 22
J1857+0943	53086 – 55599	291	15	7	0	152	0.96	1.18	7.1 ± 5.2
J1909−3744	52618 – 55619	1245	14	7	0	724	0.19	5.06	3.54 ± 0.44
J1939+2134	49956 – 55599	386	7	9	3	237	4.27	3664	127.8 ± 1.4
J2124−3358	49489 – 55619	652	7	11	0	473	2.92	1.85	-6.1 ± 0.8
J2129−5721	49987 – 55619	448	11	10	0	285	1.41	2.21	6.3 ± 0.8
J2145−0750	49517 – 55618	972	13	10	0	696	1.06	2.81	-1.38 ± 0.12

- “Red” signal significant for most pulsars

• Extended PPTA Best-band Data Sets

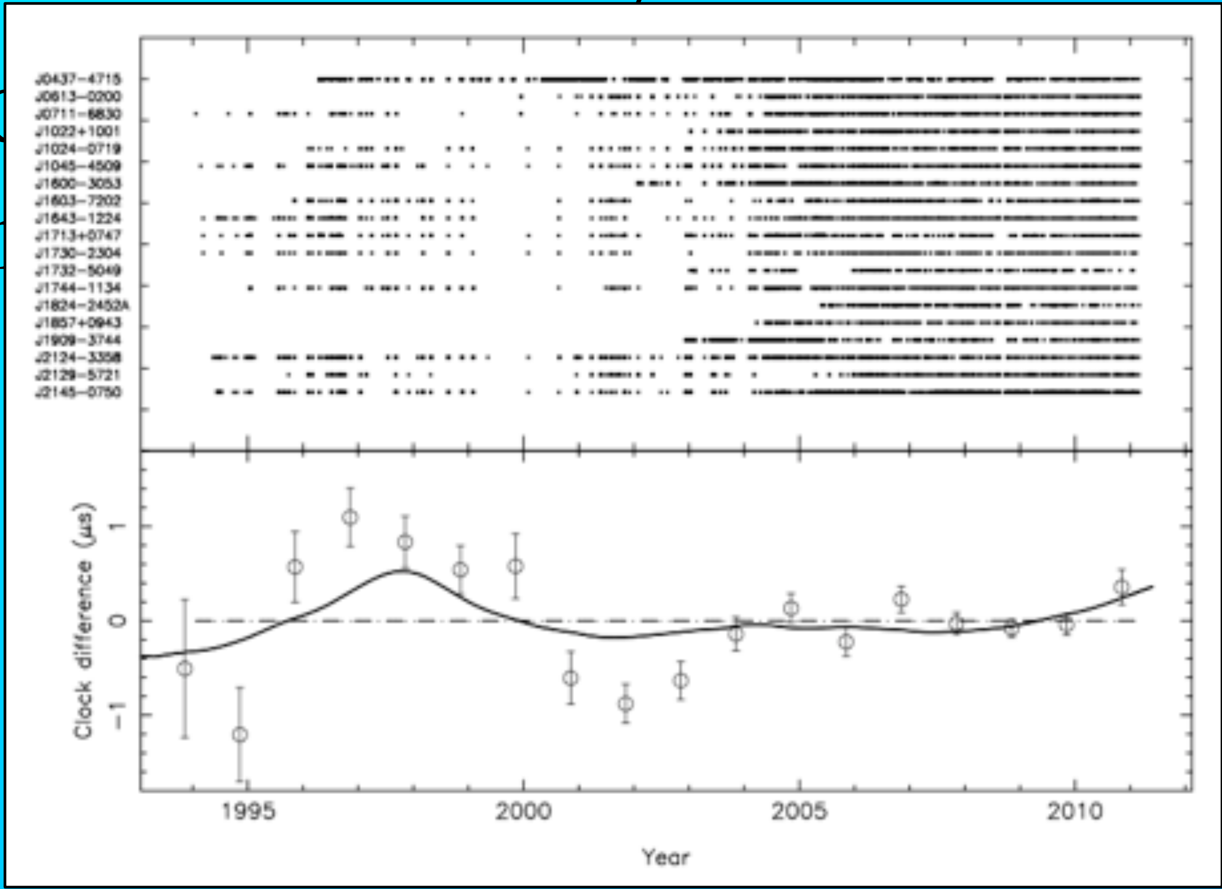
- DM and PCM corrected where necessary
- Residuals after fitting for astrometric parameters and F0, F1
- Best rms residuals for:

  J0437-4715 (190 ns)
  J1909-3744 (260 ns)
- Clear “red” signal for most pulsars



• Applications of PPTA Extended Data Sets

- Increased data span is very valuable for detection or limiting the GW background – sensitivity ~ $T^{13/6}$
- Vital to establishment of a pulsar-based based timescale – stability of atomic
- Important also – identificati
- **George's talk on Thursday**



•Recent Tempo2 Updates (from George)

- Significant updates to clock plugin (George's talk)
- Ability to simulate the GW memory effect (Jingbo's talk)
- Ability to simulate realistic-looking data sets with correct sampling, red noise etc. (Mike's talk)
- Update to Yardley algorithm for detecting a GW background (using the Cholesky spectral analysis routines) (Mike's talk)
- Development of the "interpolate" plugin (Xinping's talk)
- Ability to carry out a constrained least-squares fit (Mike's paper)
- Simulate individual, non-evolving sources of GWs (George, Ryan, Sarah Burke-Spolaor, Vikram)
- Fit for offset in observatory position with respect to the planetary ephemeris (George, Ryan)
- Updates to the "fixData" plugin enabling the user to search for EFACs and EQUADs
- Various plugins to predict the covariance function for use with the Cholesky algorithm (e.g., analytic Cholesky and autoSpectralFit - George, Mike, Ryan)
- Complete update of the glitch plugin (George, Dick, Meng Yu)

•Data Release

- Both PPTA and extended PPTA data sets are available on the www.ipta4gw.org/wiki website
- PPTA project paper (Manchester et al. 2012) describing data sets is also available on website
- README file giving processing details in tar file
- Extended Tempo2 format ToAs with

•The Future

- PPTA data sets provide the raw material for many investigations as well as inspiration for numerous theoretical studies
- Continuation of timing observations with improved instrumentation and signal processing algorithms vital to achieving PPTA goals
- Realisation of PTA goals will be aided combining PPTA data sets with those

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- Realisation of PTA goals will be aided combining PPTA data sets with those

- ***Finally, George is taking over the leadership of the PPTA project – thereby ensuring that the PPTA and IPTA have a bright future***

•Thank you all!

•The Gravitational Wave Spectrum