NANOGrav Timing and GW Limits

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Talk outline:

1. NANOGrav 5-year timing and stochastic GWB limits (Demorest et al 2012).

2. Some thoughts about DM(t) fitting.

3. Short updates on ongoing/future work:

    a. Red timing noise analysis (Ellis et al).

    b. Instrumentation updates (GUPPI/PUPPI, receiver development).

    c. Long-term (~20 year) timing of J1713+0747 (Zhu et al).

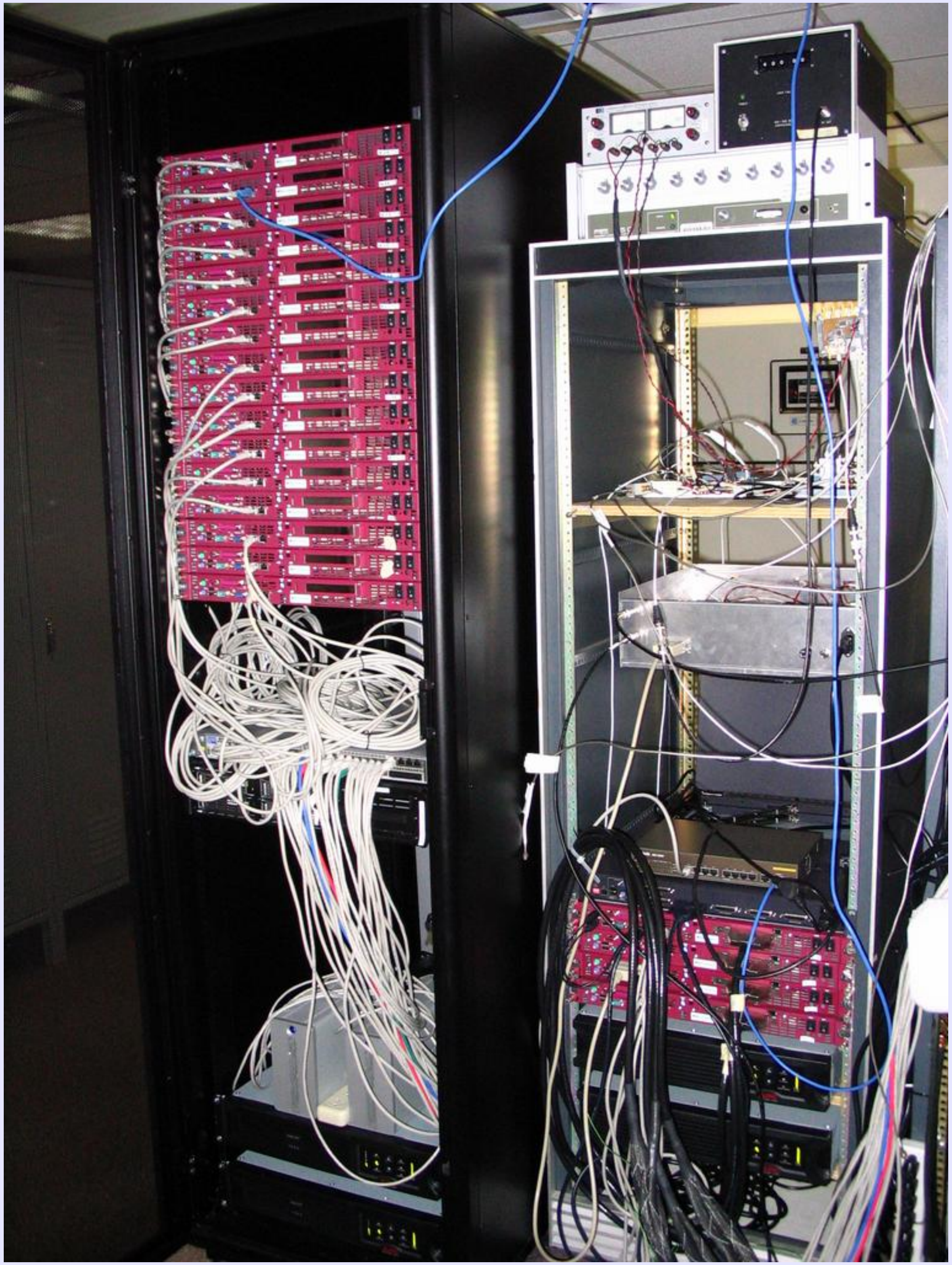
NANOGrav observing:

Monitor ~20 pulsars (now ~30) monthly, starting in 2005. 5-yr data analysis uses 17 pulsars.

Dual-freq: 820, 1400 MHz (GBT); 327, 430, 1400, 2300 MHz (AO).

Typically ~30 min per source per band each epoch.

Uses ASP pulsar backends; ~64 MHz coherent dedisp.



Arecibo observatory: 305-m fixed reflector

Pointing restricted to ~20 deg zenith angle.

Green Bank Telescope: 100-m, fully steerable

Minimum declination -45 degrees.

Basic processing, timing strategy:

(PD, M. Gonzalez, D. Nice, I. Stairs, S. Ransom, R. Ferdman)

ASP/GASP backends record coherent-dedisp folded profiles (~1 minute, 4 MHz channels, 2048 bins).

Calibrate using injected noise diode signal and flux cal.

“T-scrunch” data within an observing epoch.

Generate TOAs using standard “FFT-fit” approach on total intensity.

Fit to timing model, including shifts for profile evolution with frequency and DM variation with time.

Processing pipeline software:

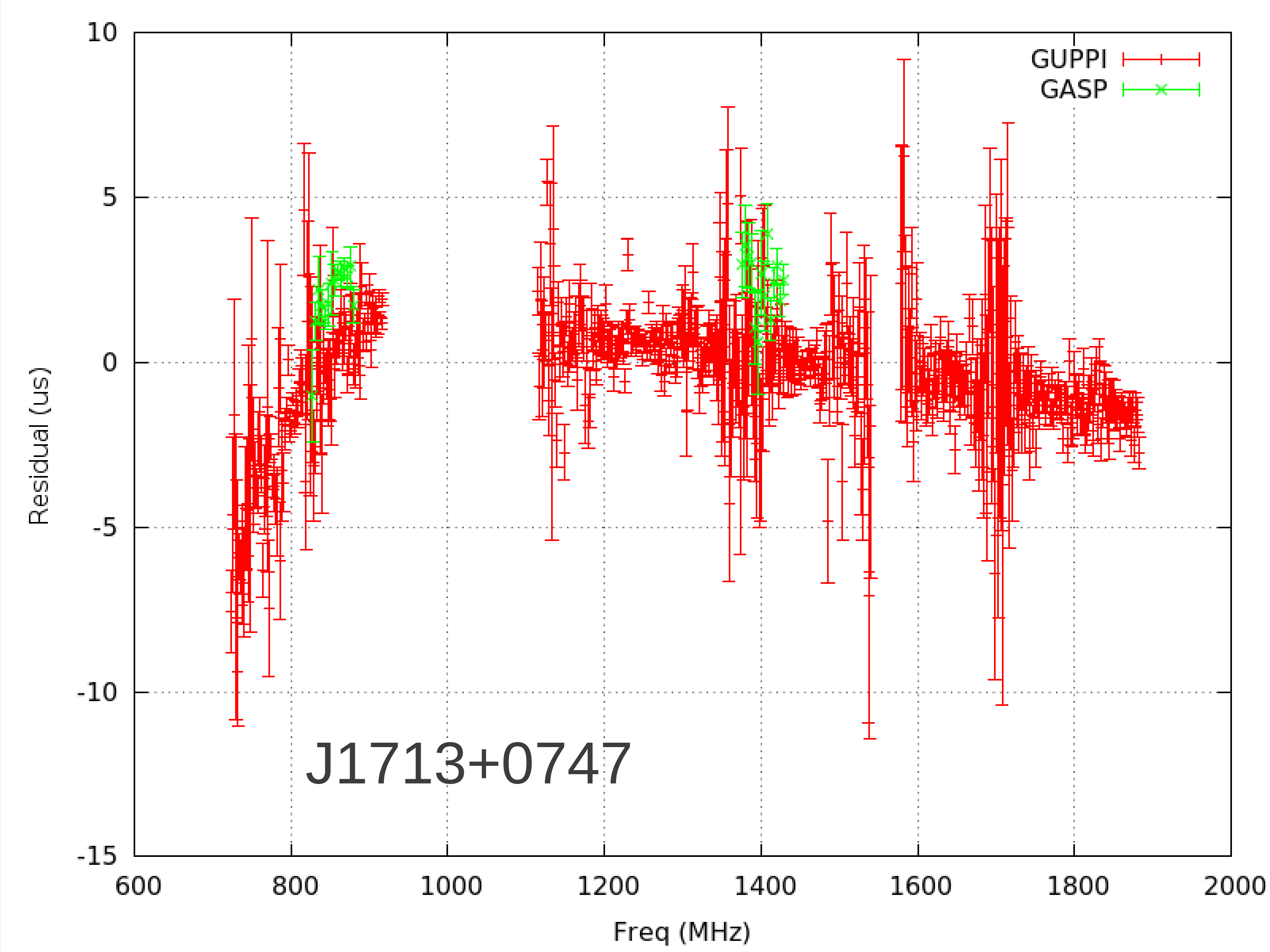
- Calibration and TOA generation:

  - PSRCHIVE-based pipeline
    - Standard programs: pac, pam, pat, etc.
    - Improvements (eg, reading ASP files, psrsmooth, etc) contributed back to main PSRCHIVE.

  - ASPFitsReader-based pipeline
    - Independent calibration, “scrunching”, TOA-generation.
    - Designed for ASP files (now extended to PSRFITS).

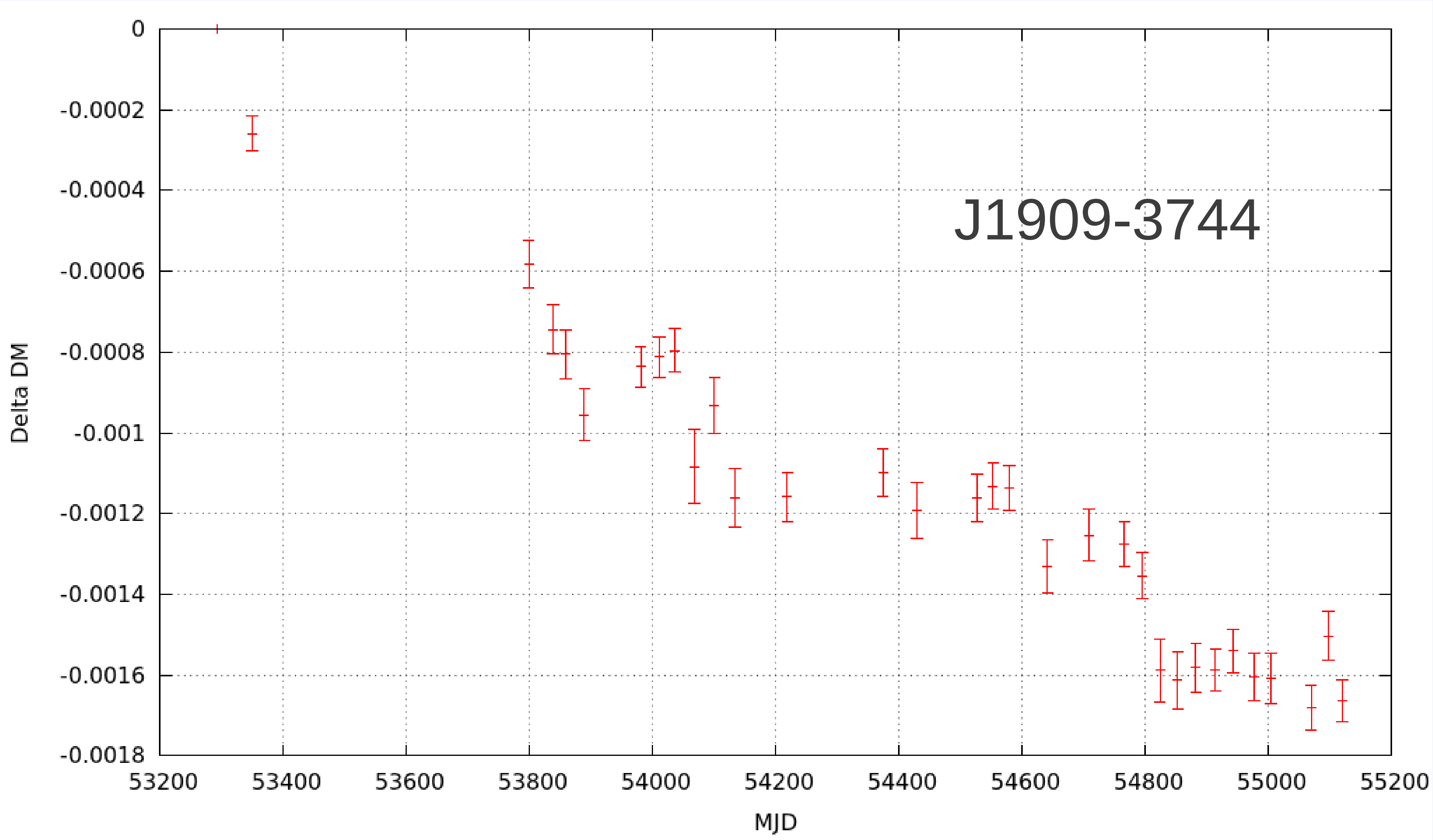
- Both pipelines used same template profiles.
- Final analysis in paper uses PSRCHIVE TOAs.
- Main timing analysis uses “classic” TEMPO
  - Several ongoing comparison with TEMPO2.

Profile evolution with freq:



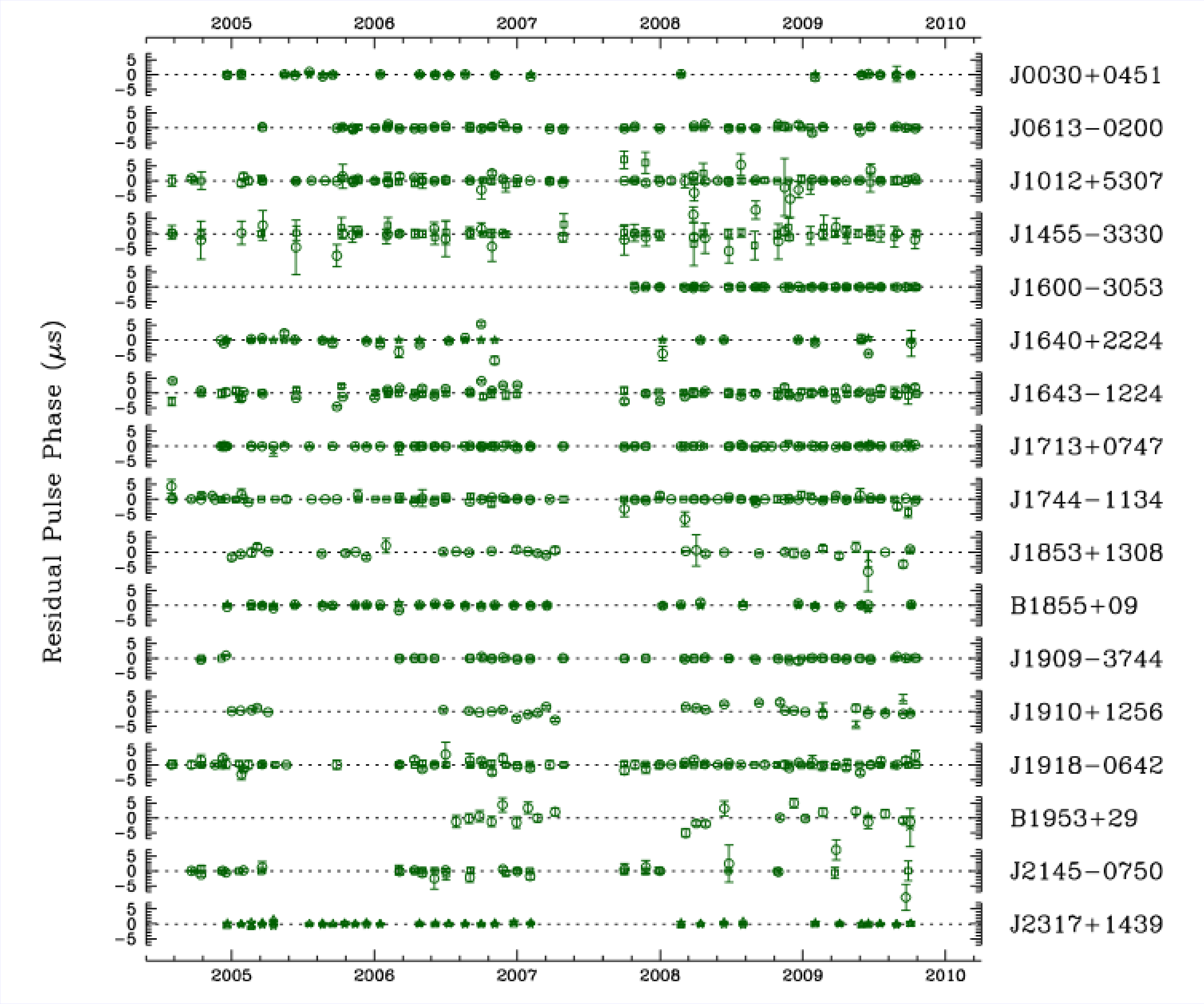
Solution: Fit constant (in time) shift per each channel.

DM variation with time:



Independent DM measurement per epoch in timing model fit. Points without dual-freq data (within 15 days) are dropped.

NANOGrav 5-year timing results overview:



(plot: D. Nice)

NANOGrav 5-year timing results summary

TABLE 2
OVERVIEW AND RESULTS FROM TIMING MODEL FITS.

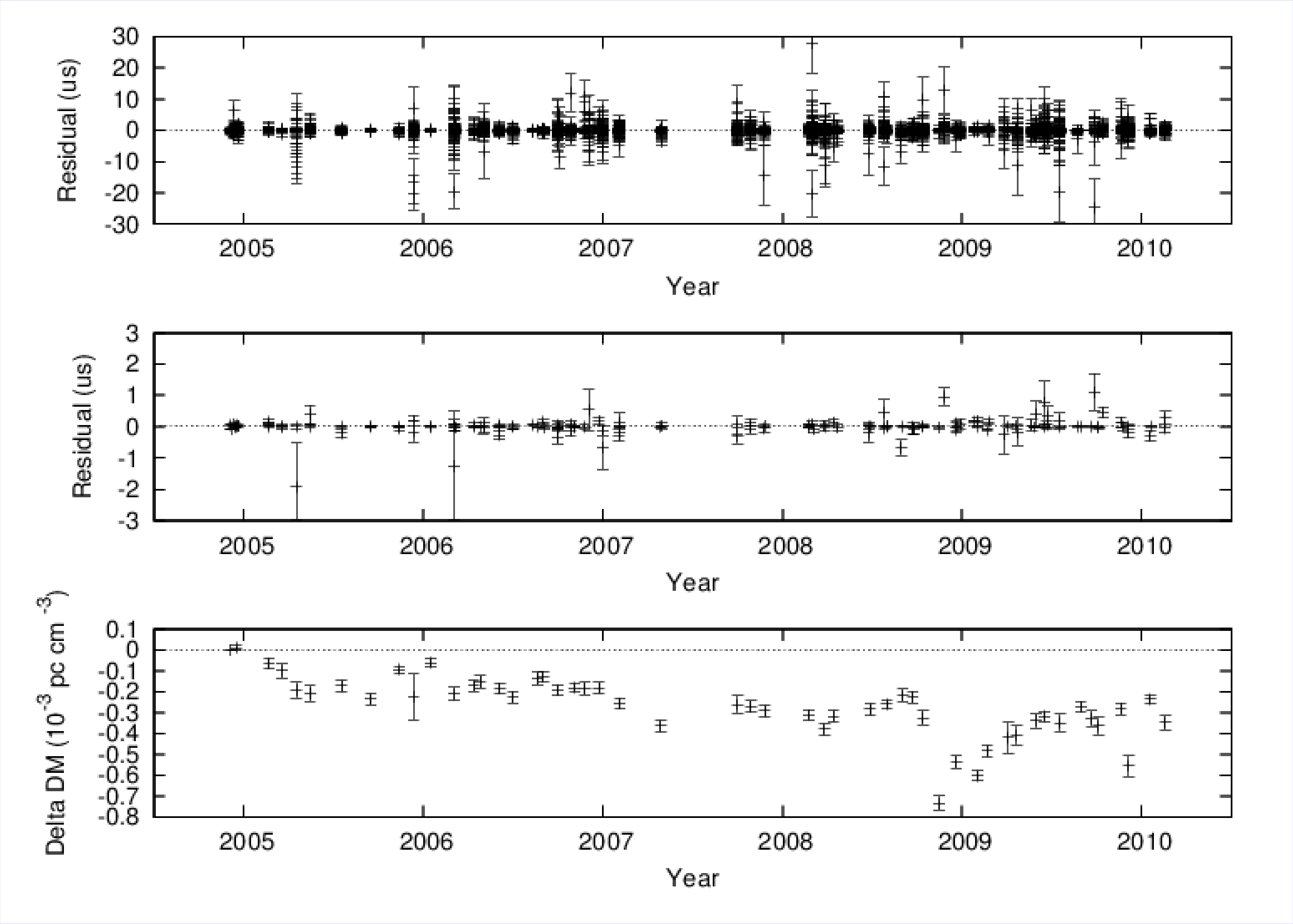
Source	# of TOAs[a]	# of parameters DM	Profile	Other[b]	RMS (μs)	Fit χ^2	Epoch-averaged RMS (μs)[c] Low-band[d]	High-band	Combined
J0030+0451	545	20	26	7	0.604	1.44	0.019	0.328	0.148
J0613–0200	1113	34	45	12	0.781	1.21	0.021	0.519	0.178
J1012+5307	1678	52	53	14	1.327	1.40	0.192	0.345	0.276
J1455–3330	1100	37	53	12	4.010	1.01	0.363	1.080	0.787
J1600–3053	625	21	31	14	1.293	1.45	0.233	0.141	0.163
J1640+2224	631	23	26	12	0.562	4.36	0.057	0.601	0.409
J1643–1224	1266	40	48	13	2.892	2.78	0.589	1.880	1.467
J1713+0747	2368	50	111	15	0.106	1.48	0.092	0.025	0.030
J1744–1134	1617	54	49	7	0.617	3.58	0.139	0.229	0.198
J1853+1308	497	0	34	12	1.028	1.16	0.271	0.096	0.255
B1855+09	702	29	21	14	0.395	2.19	0.277	0.101	0.111
J1909–3744	1001	31	37	14	0.181	1.95	0.011	0.047	0.038
J1910+1256	525	0	34	14	1.394	2.09	0.712	0.684	0.708
J1918–0642	1306	49	37	12	1.271	1.21	0.129	0.211	0.203
B1953+29	208	0	27	12	3.981	0.98	1.879	0.543	1.437
J2145–0750	675	20	37	12	1.252	1.97	0.068	0.494	0.202
J2317+1439	458	30	12	15	0.496	3.03	0.373	0.150	0.251

[a] One TOA per frequency channel per epoch.
[b] "Other" parameters are all spin, astrometric and binary parameters as described in §3.2.
[c] RMS computed from residuals averaged down to one point per receiver per epoch. See text for details.
[d] Note that in these results, the low-frequency RMS tends to be suppressed due to the DM(t) fit.

Data publicly available online:
http://www.cv.nrao.edu/~pdemores/nanograv_data/

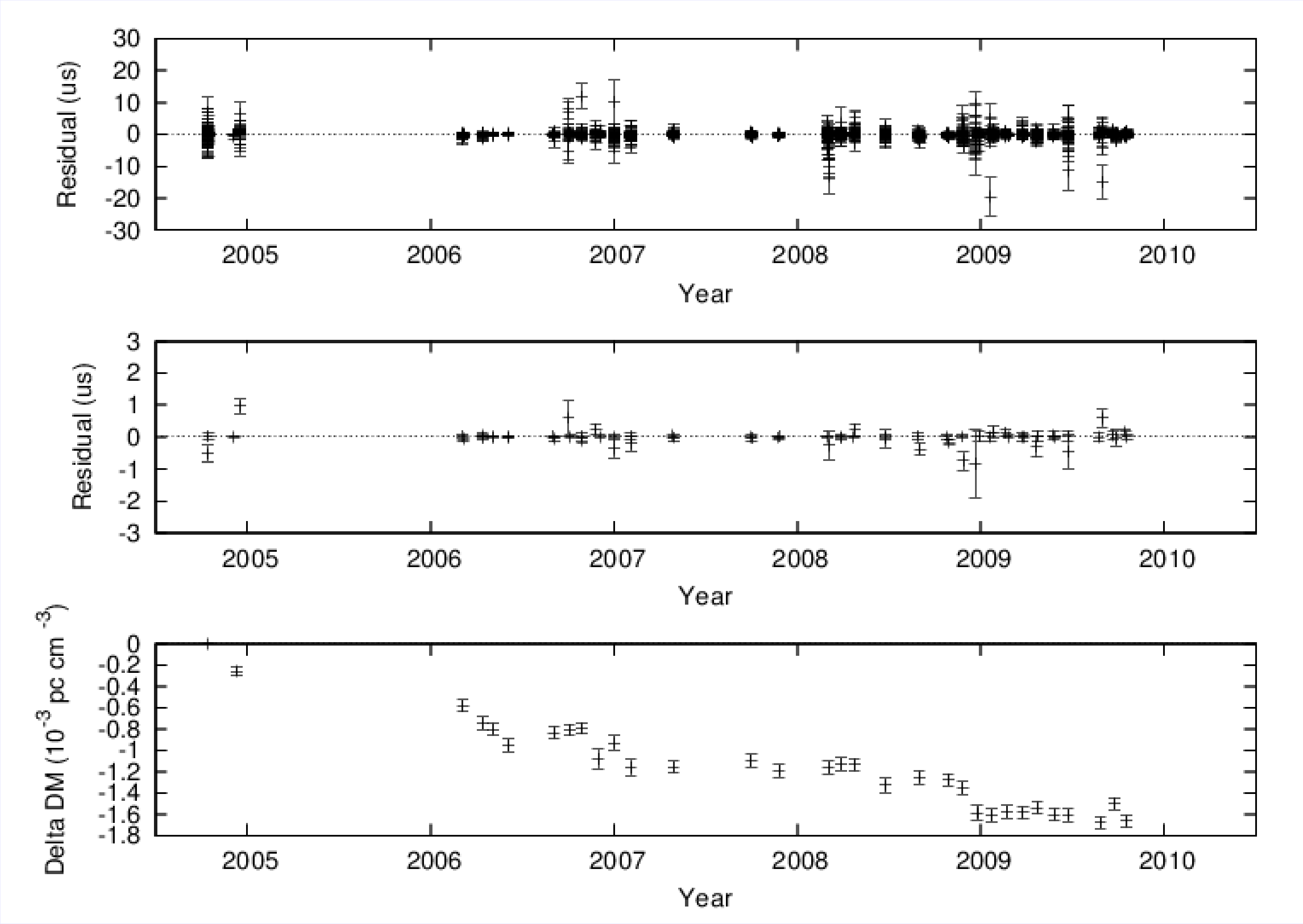
Best timing residuals versus time:

J1713+0747



Best timing residuals versus time:

J1909-3744



Characterizing noise in the residuals

Basic idea: Analyze the residuals, accounting for signal power removed by the timing model fit, to look for red noise of known spectral shape (eg, a stochastic GWB).

Analysis in time domain, starts with analytic pre-fit cov matrices for power-law spectra; same as van Haasteren et al (2009, 2011).

Initial algorithm development in Demorest PhD (2007); lots of recent work by Ellis, Siemens, et al takes this method and extends/improves it!

For more details see Demorest et al (2012), and Ellis et al (2012; in prep). Also Xavi's talk and Justin's poster from this meeting.

Accounting for the timing model fit

Weighted least-squares fit, solved via the normal equations:

$$\mathbf{A}^T\mathbf{W}\mathbf{A}\mathbf{a} = \mathbf{A}^T\mathbf{W}\mathbf{y}$$

Residuals (data – model) are calculated via application of the "R-matrix":

$$\mathbf{r} = \mathbf{y} - \mathbf{A}\mathbf{a} = \mathbf{R}\mathbf{y}$$

$$\mathbf{R} = \mathbf{I} - \mathbf{A}\left(\mathbf{A}^T\mathbf{W}\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{W}$$

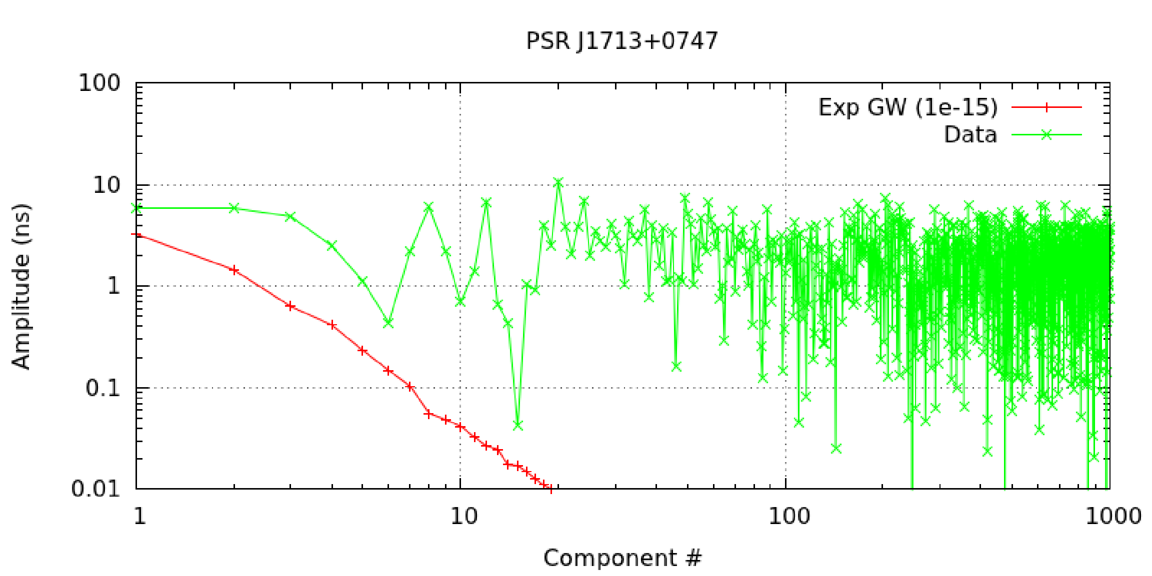
The R-matrix can be used to calculate cov matrix of the residuals, given cov matrix of the pre-fit data:

$$\mathbf{C}_{\mathbf{r}} = E\left\{\mathbf{r}\mathbf{r}^T\right\} = \mathbf{R}E\left\{\mathbf{y}\mathbf{y}^T\right\}\mathbf{R}^T = \mathbf{R}\mathbf{C}_{\mathbf{y}}\mathbf{R}^T$$

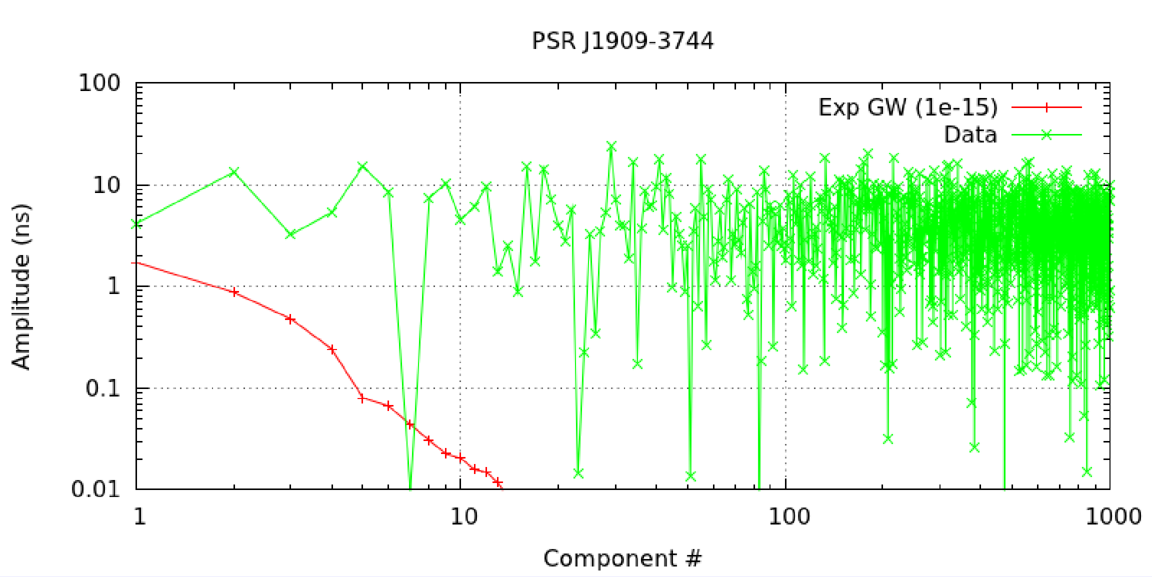
Note, R accounts for everything that was fit (including DM, etc). This approach also works for cross-cov matrices.

Eigenvalue spectra

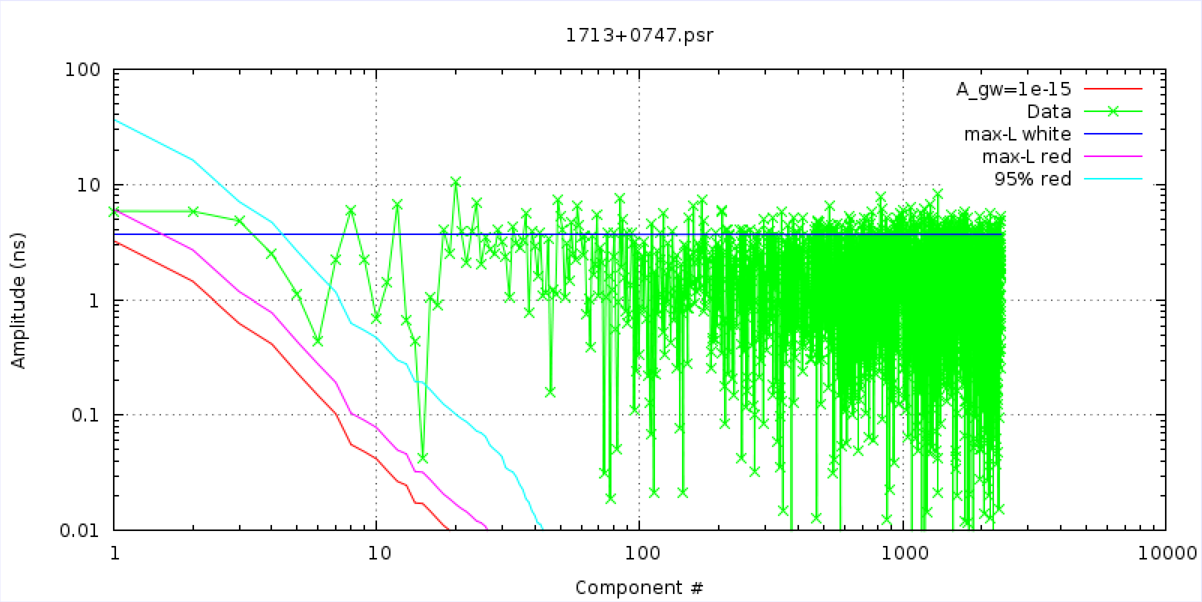
For a fixed GW spectral index, diagonalizing the residual cov matrix C_r^{GW} provides a useful basis for analyzing the residuals.



Eigenvalues quantify amount of GW power transmitted through fit, and comparing with data lets us put limits on GW amplitude.



Eigenvalue spectra and noise likelihood



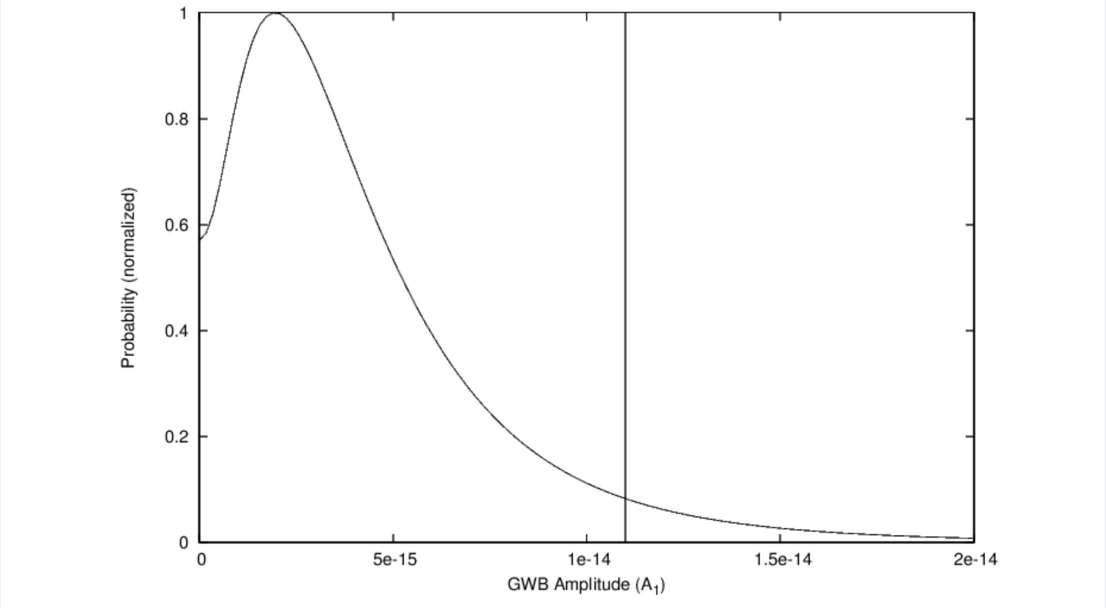


FIG. 5.— Probability distribution for the GWB amplitude A_1 based on J1713+0747 timing, and assuming $\alpha = -2/3$. 95% of the distribution is contained in $A_1 < 1.1 \times 10^{-14}$ (vertical line), the maximum-likelihood value $\hat{A_1} = 1.9 \times 10^{-15}$, and the likelihood ratio between this point and $A_1 = 0$ is $R = 0.6$. In this case, a non-zero value of A_1 provides the best fit to the data, but without much statstical significance over a white noise only model. These statistics for all sources, considering several different values of α, are presented in Table 3.

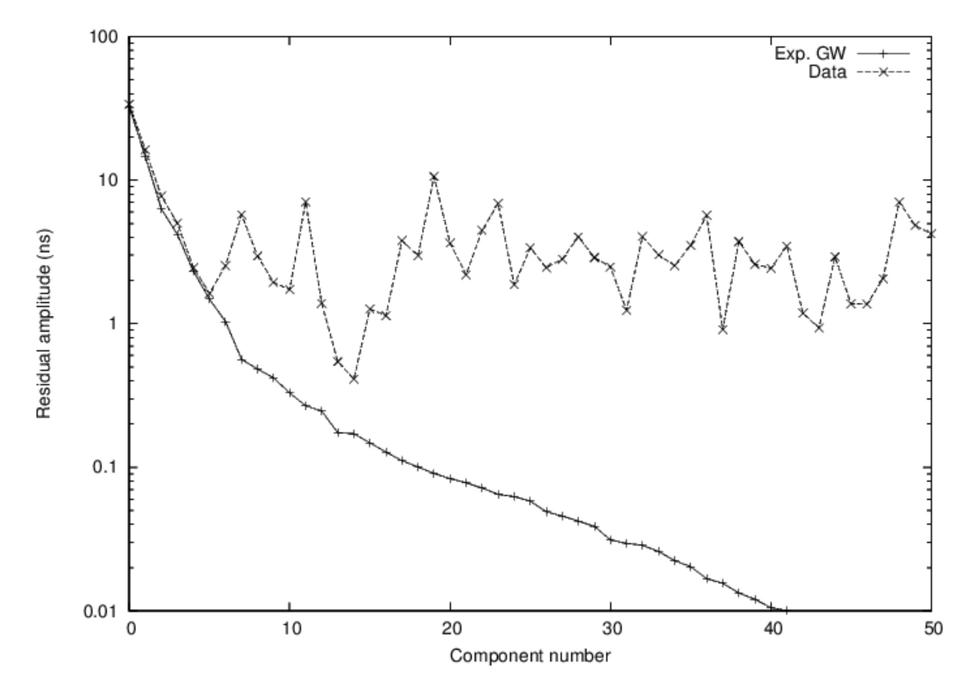
In the diagonal basis, the likelihood function for GW amplitude is easy to evaluate.

Based on likelihood ratios, probable "non-white" results are seen in:

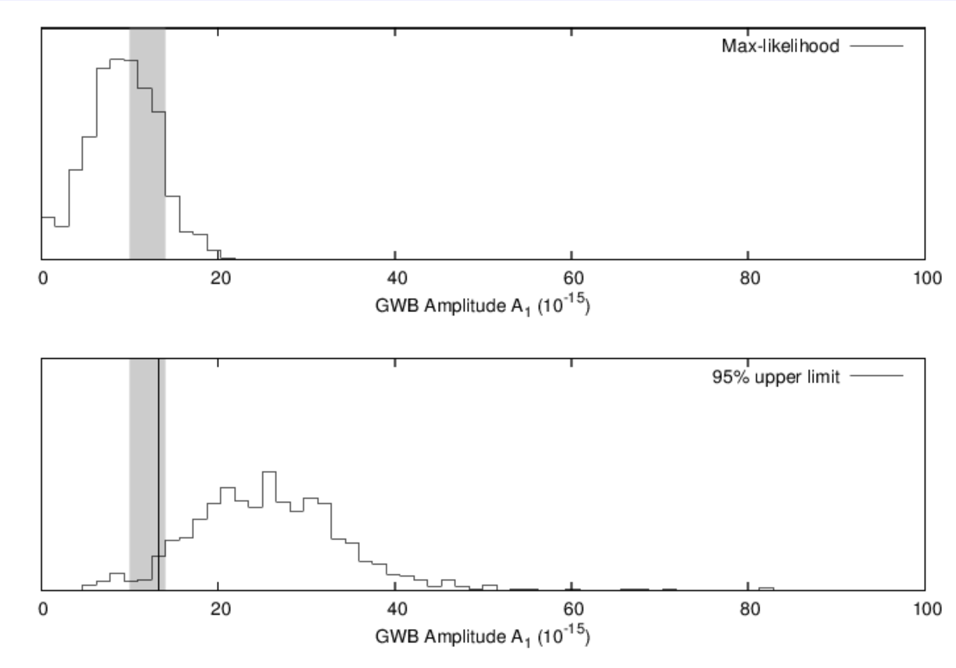
J1643-1224
J1910+1256
J1640+2224
B1953+29

Testing with simulated signals

Inject a simulated $A=10^{-14}$ signal into J1713+0747 TOAs using tempo2.



Noise analysis detects and recovers expected amplitude.



Cross-correlation between pulsars

Use max-likelihood red noise params and expected residual cross-cov matrix to measure correlation between residuals for each pulsar pair:

$$\rho_{ab} = \frac{\sum_{ijkl} r_i^{(a)} \left(C^{tot(a)}\right)^{-1}_{ij} C^{GW(a,b)}_{jk} \left(C^{tot(b)}\right)^{-1}_{kl} r_l^{(b)}}{\sum_{ijkl} \left(C^{tot(a)}\right)^{-1}_{ij} C^{GW(a,b)}_{jk} \left(C^{tot(b)}\right)^{-1}_{kl} C^{GW(a,b)}_{il}}.$$

$$\sigma_{\rho_{ab}} = \left(\sum_{ijkl} \left(C^{tot(a)}\right)^{-1}_{ij} C^{GW(a,b)}_{jk} \left(C^{tot(b)}\right)^{-1}_{kl} C^{GW(a,b)}_{il} \right)^{-1/2}$$

Then fit set of measured correlations to Hellings-Downs function for isotropic GWB to get GWB amplitude.

Cross-correlations vs angle for MBH GWB spectrum

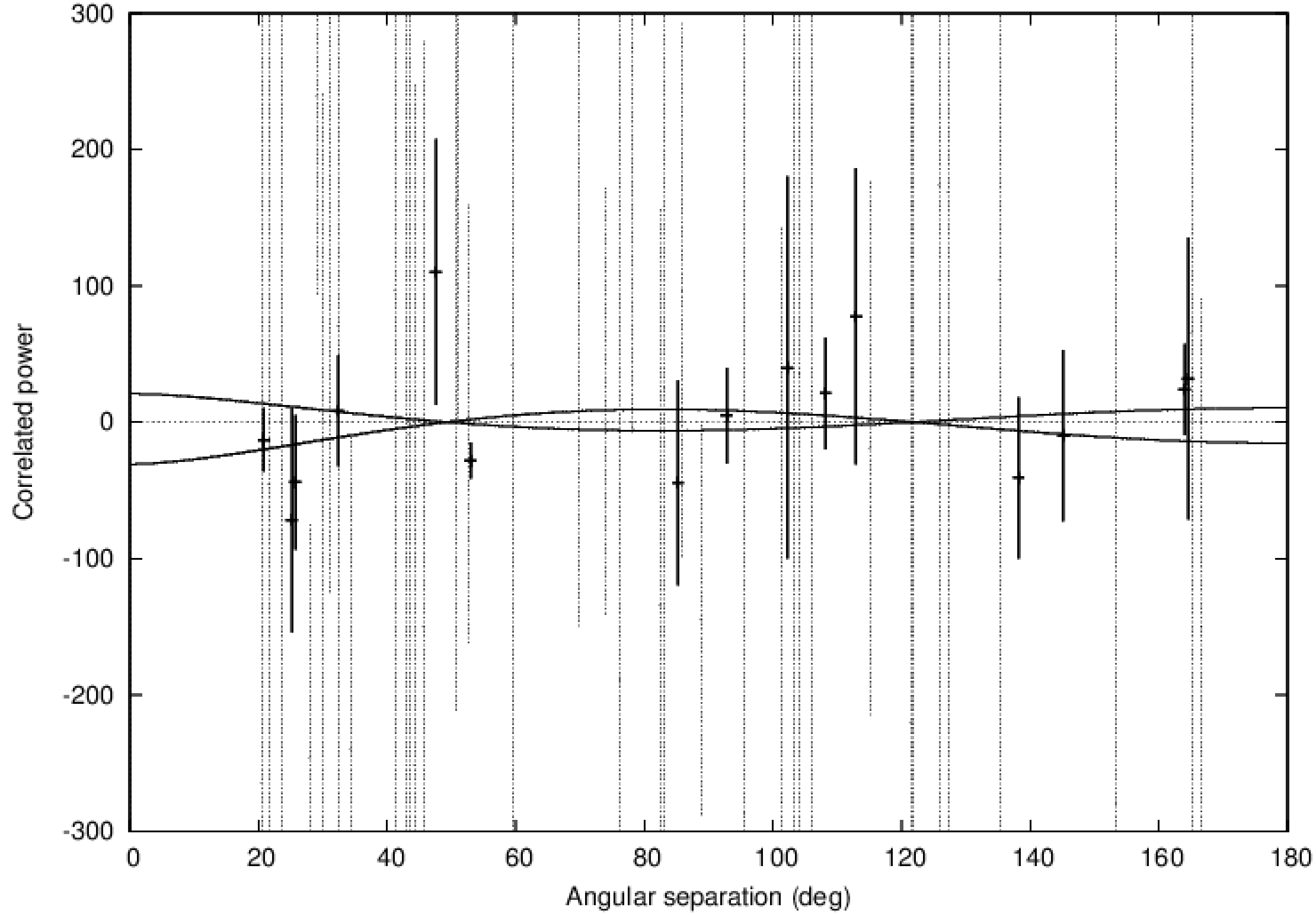


FIG. 8.— Measured cross-correlated power ρ_{ab} as a function of separation angle θ_{ab} for pairs of pulsars in our set, with error bars showing 1-σ uncertainty. Power is normalized relative to an $A_1^2 = 10^{-30}$, $\alpha = -2/3$ GWB. The lines show the $\pm 2\ \sigma$ fit to the amplitude of the Hellings-Downs function $\zeta(\theta)$. All 136 cross-correlation points were used for the fit, however for clarity the 15 lowest-uncertainty values are denoted with solid/bold symbols.

Best-fit A^2 = (-10 +/- 26) x 10^{-30}; GW amplitude < 7×10^{-15}

Other GW spectral indices

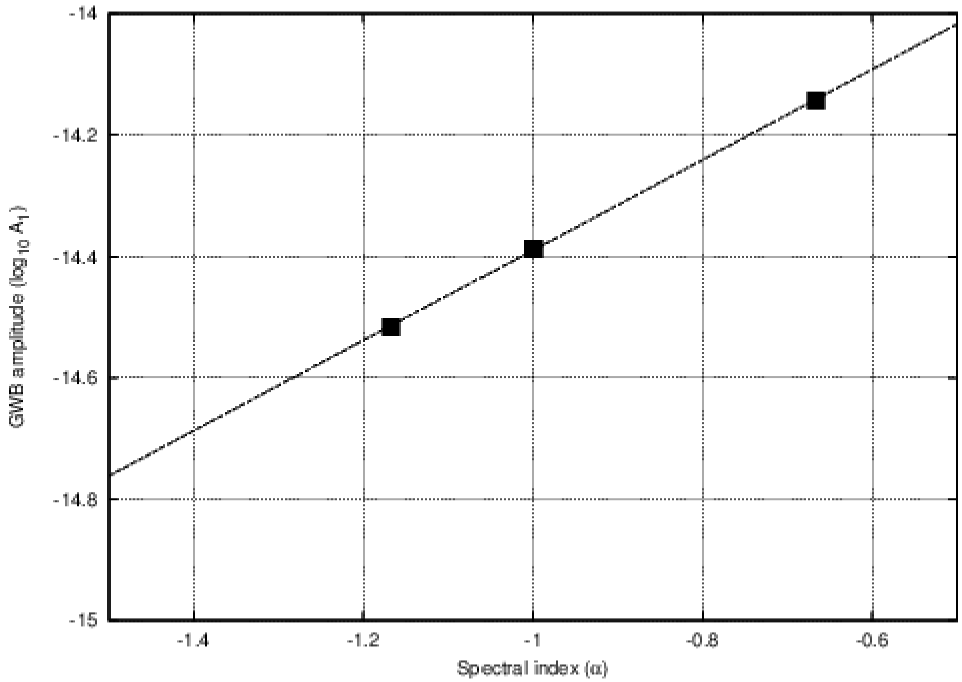


FIG. 9.— Measured 2-σ upper limits on A_1 as a function of GW spectral index α (squares). The values are consistent with a simple scaling based on $A_T = 2.26 \times 10^{-14}$ at $T = 5.54$ years and Eqn. 12 (line). This relationship can be used to convert these results to equivalent limits for other values of α.

Some thoughts on DM(t) fitting

In the white-noise-dominated regime, the model we're applying here is appropriate. Some recent questions:

Does fitting DM(t) reduce GW (and/or other non-DM) sensitivity? YES!

- IMO, this is fundamental and can not be worked around. Ignoring DM(t) is not a viable option.

Does fitting DM(t) make the residuals “look whiter”? YES!

- But “by eye” is *not* a good analysis technique!

Does fitting DM(t) remove all the red noise power? NO!

- The analysis I just presented shows that it doesn't, and furthermore lets us quantify exactly how much is/isn't removed by the fit.

Some thoughts on DM(t) fitting

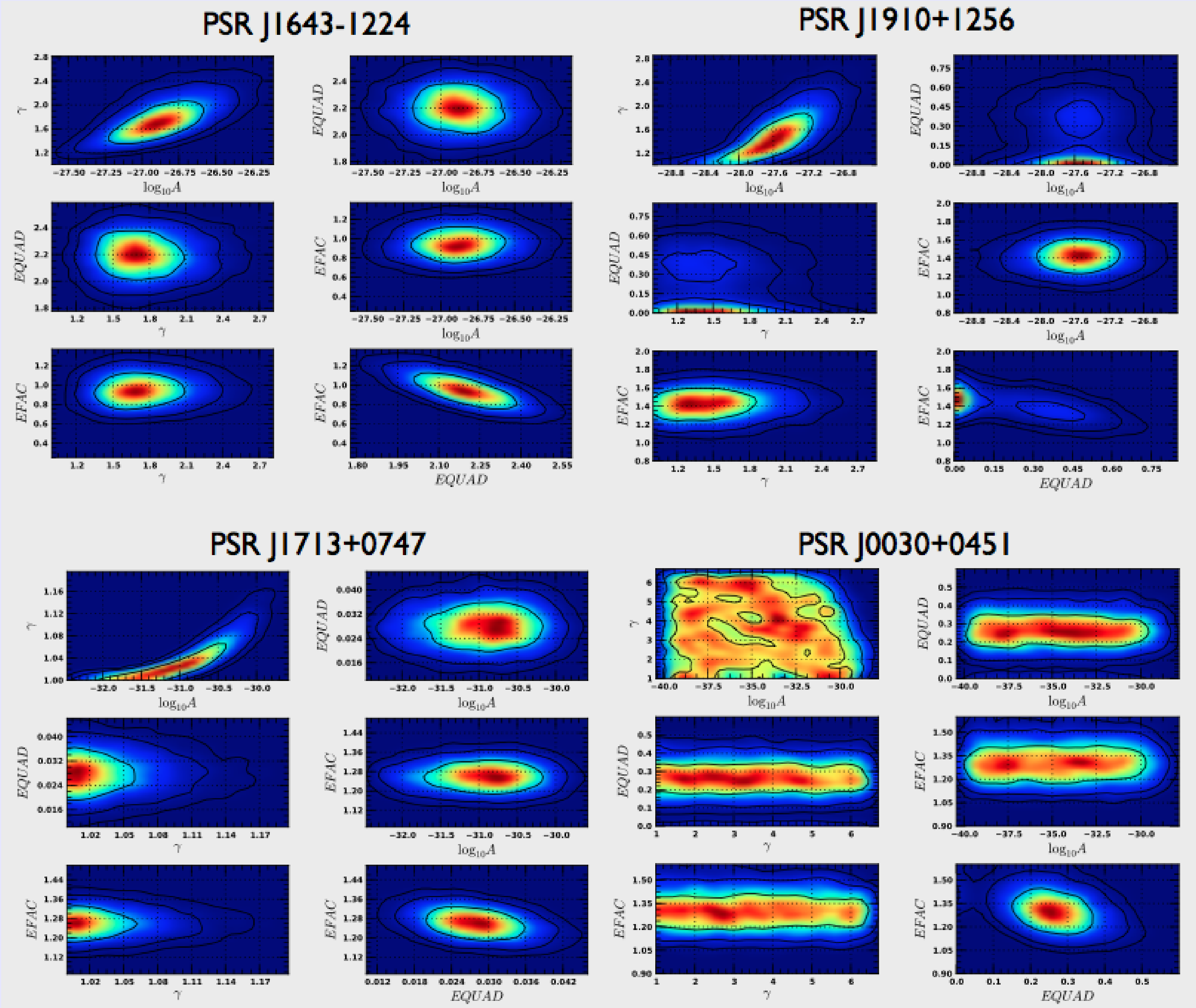
The real question is: Does the strategy we've presented here do a better/worse job than others at characterizing the noise in the data? I don't know!

Method 1 (this talk): Fit for normal timing model and DM(t); "Residuals" are the actual fit residuals.

Method 2 (G. Hobbs, lunch, yesterday): Fit for normal timing model, DM(t), and common mode signal; "Residuals" are fit residuals with CM added back in.

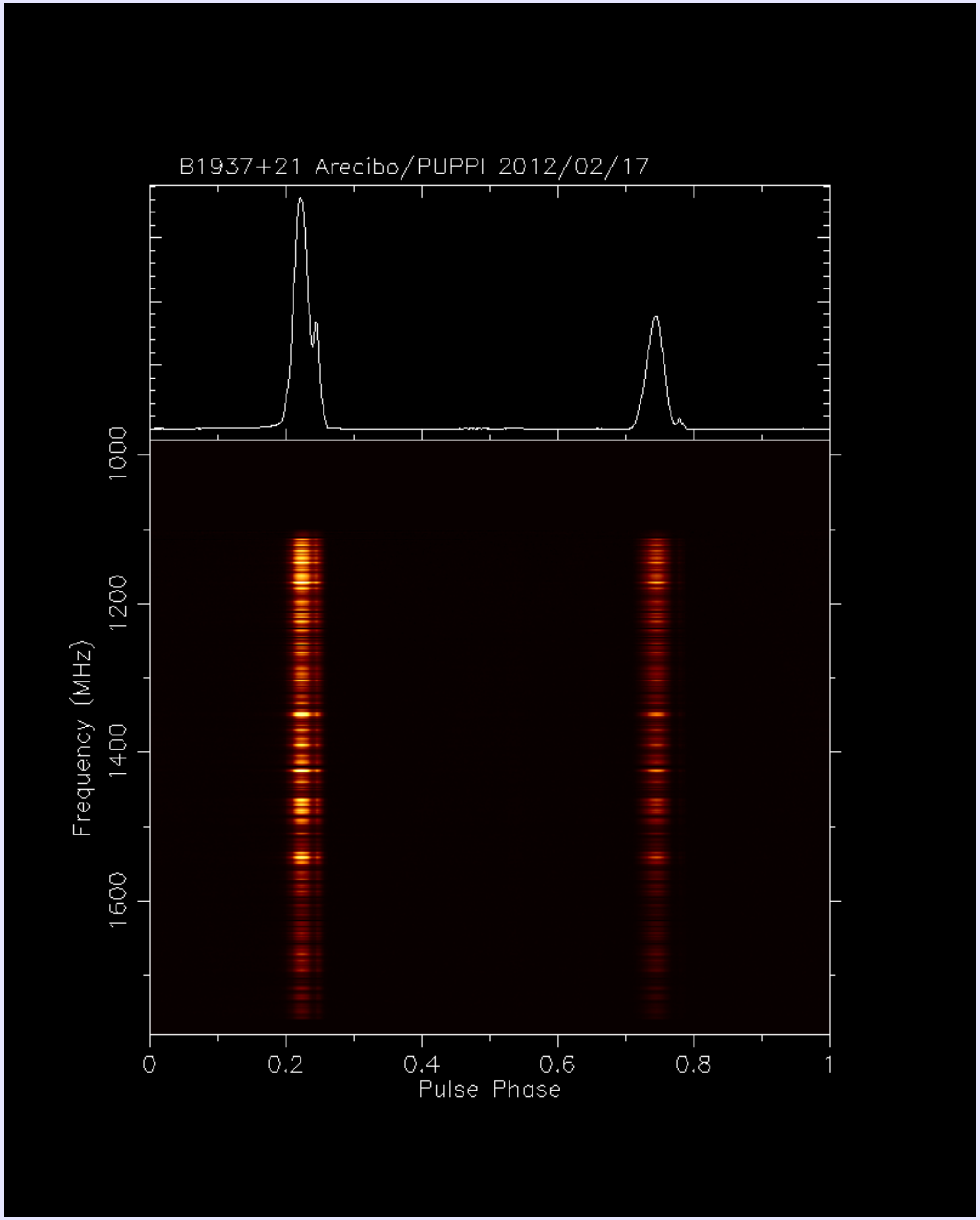
The two types of "residuals" require different analyses. While #2 will most likely "look redder" it is not obvious (to me) if they actually contain more information than #1, when each is analyzed in the appropriate way.

Extended red noise analysis (J. Ellis)



See poster for more details!

Instrumentation: Coherent GUPPI/PUPPI
Order-of-magnitude improvement in radio BW



800 MHz total BW (usually limited by receiver BW).

PUPPI first light at Arecibo Feb 2012.

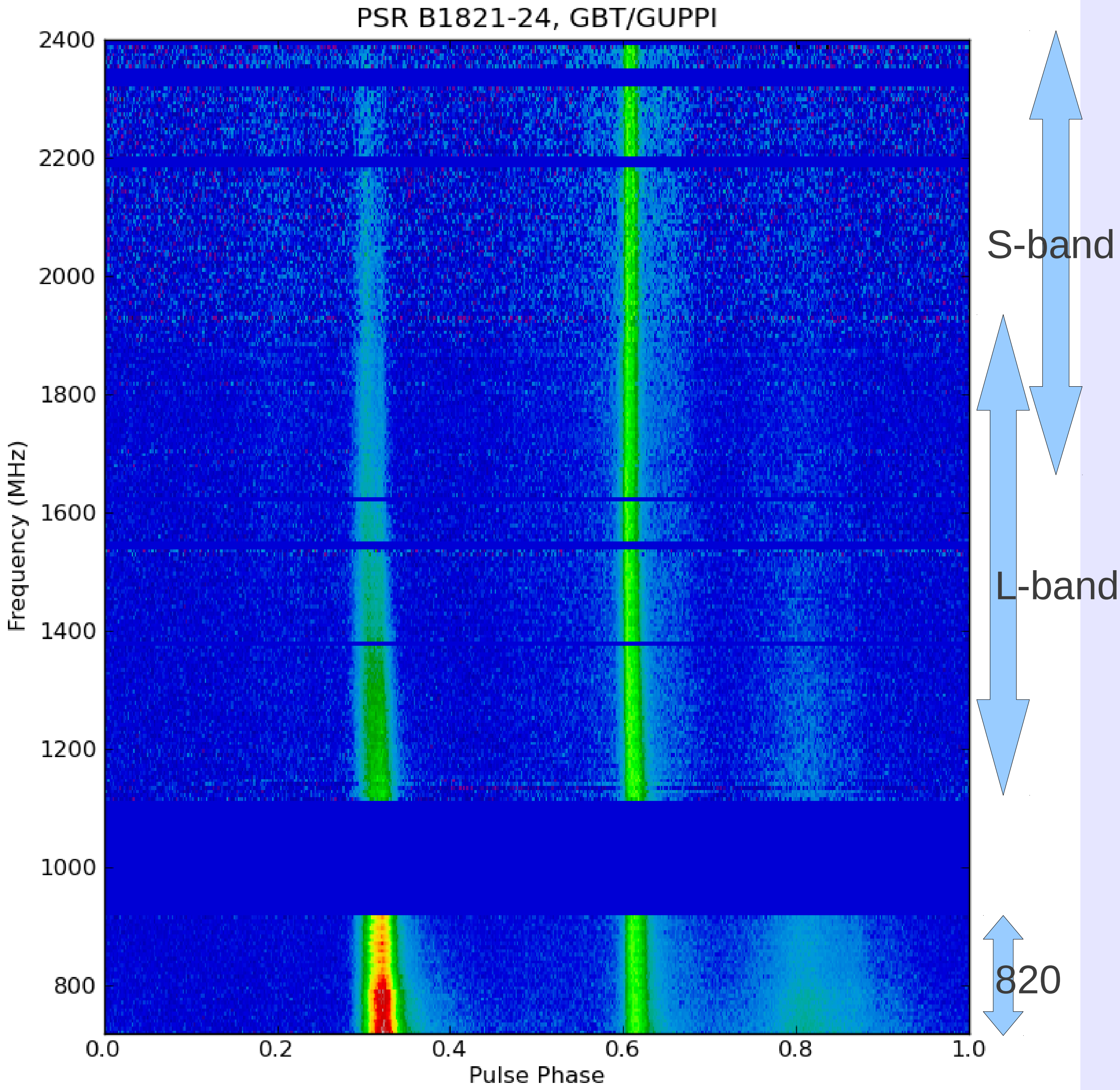
GUPPI in regular use for GBT NANOGrav timing for ~2 years.

Instrumentation: Coherent GUPPI/PUPPI

Very preliminary analysis of GUPPI timing shows improvement versus GASP of ~1-3x:

Source	# of TOAs	# of fit parameters	RMS (μs)	Fit χ^2	Epoch-averaged RMS (μs) Low-band	High-band	Combined	GUPPI timing RMS (μs)	Ratio
J0030+0451	545	53	0.604	1.44	0.019	0.328	0.148	-	-
J0613–0200	1113	91	0.781	1.21	0.021	0.519	0.178	0.120	1.5
J1012+5307	1678	119	1.327	1.40	0.192	0.345	0.276	0.094	2.9
J1024–0719	-	-	-	-	-	-	-	0.101	-
J1455–3330	1100	102	4.010	1.01	0.363	1.080	0.787	0.223	3.5
J1600–3053	625	66	1.293	1.45	0.233	0.141	0.163	0.119	1.4
J1614–2230	-	-	-	-	-	-	-	0.106	-
J1640+2224	631	61	0.562	4.36	0.057	0.601	0.409	-	-
J1643–1224	1266	101	2.892	2.78	0.589	1.880	1.467	0.697	2.1
J1713+0747	2368	176	0.106	1.48	0.092	0.025	0.030	0.033	1.4
J1744–1134	1617	103	0.617	3.58	0.139	0.229	0.198	0.151	1.3
J1853+1308	497	46	1.028	1.16	0.271	0.096	0.255	-	-
B1855+09	702	64	0.395	2.19	0.277	0.101	0.111	-	-
J1909–3744	1001	72	0.181	1.95	0.011	0.047	0.038	0.021	1.8
J1910+1256	525	48	1.394	2.09	0.712	0.684	0.708	-	-
J1918–0642	1306	98	1.271	1.21	0.129	0.211	0.203	0.204	1.0
B1937+21	-	-	-	-	-	-	-	0.162	-
B1953+29	208	39	3.981	0.98	1.879	0.543	1.437	-	-
J2010–1323	-	-	-	-	-	-	-	0.337	-
J2145–0750	675	69	1.252	1.97	0.068	0.494	0.202	0.134	1.5
J2317+1439	458	57	0.496	3.03	0.373	0.150	0.251	-	-

Encouraging, but still lots more work to be done: Full poln calibration, timing offsets, RFI cleaning, ...



Pulsar receiver development at GBT:

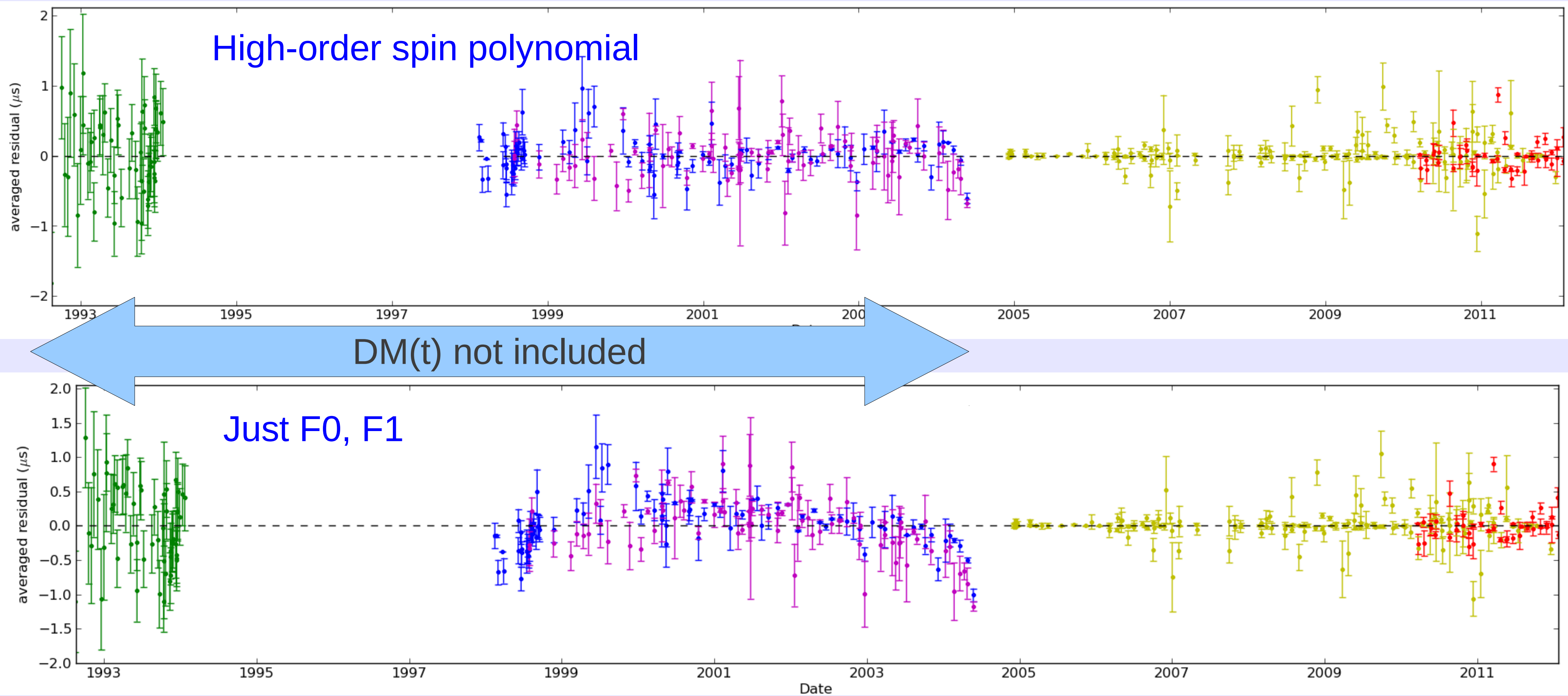
Potential super-wide-band receiver to cover ~0.5 to 3.0 GHz. Will need new 'GUPPI++' backend to process this whole bandwidth.

Tradeoff: Worse T_{sys} than current receivers.

Benefit: Better DM measurement for high-precision timing.

S. Weinreb feed will be ordered/tested this year.

Long-term timing of J1713+0747 (W. Zhu)



Preliminary results, and analysis is ongoing! Some evidence for red noise above but it needs more study/characterization. Full-poln calibration in progress for recent data (red=GUPPI). Careful tempo vs tempo2 investigation with these data.

Summary

1. NANOGrav timing: 17 pulsars over 5 years with two telescopes.

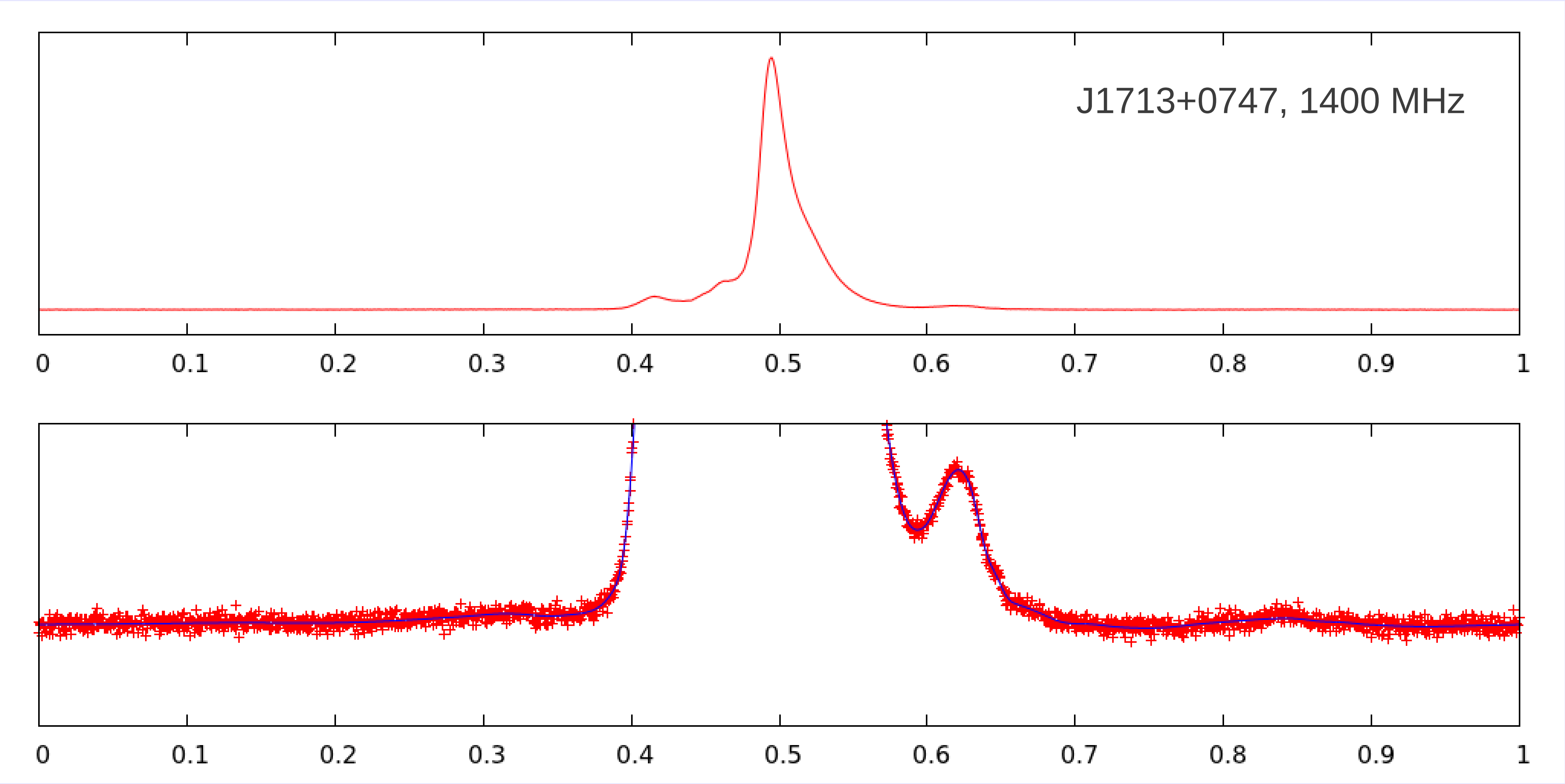
2. No GWB detected; 7×10^{-15} upper limit on MBH stochastic GWB.

3. Mild non-white noise detected in a small number of sources.

4. Careful comparison of DM(t) fit methods is needed.

5. Analysis of long-term (20 year +) “historical” data sets ongoing. Increasing data span is very important!

Template profiles:



One template per receiver. Generated from full S/N-weighted sum of all data, then de-noised (using "psrsmooth").

Receiver optimization for pulsar timing

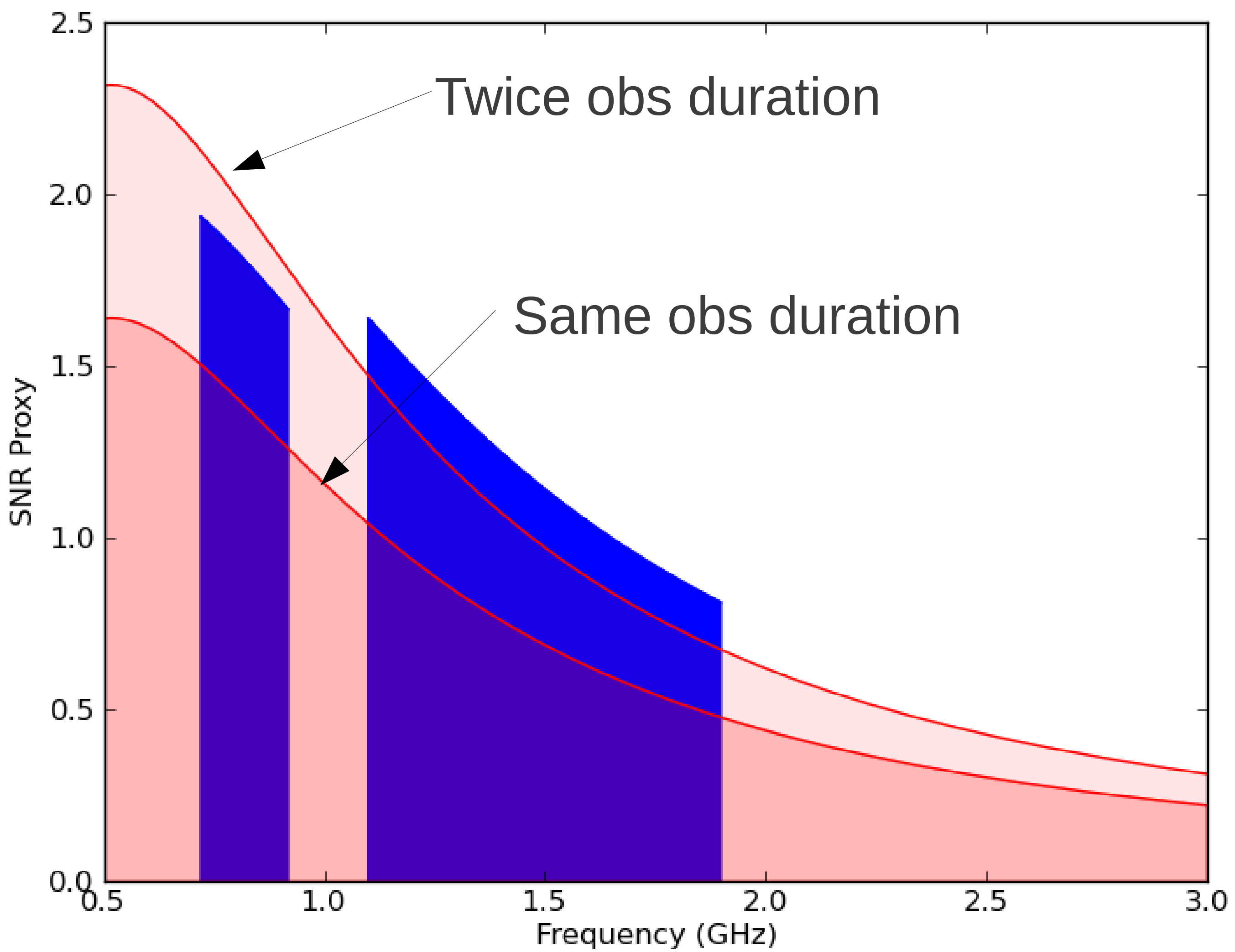
Basic conclusions:

Wide-band integrated S/N ratio will be ~10% to 50% better than existing GBT L-band or L-band+820 receivers.

DM-corrected timing will be ~30% to 2x better than existing receivers. Additional improvement from reduced systematics (but harder to quantify).

These results are mostly insensitive to pulsar parameters. Main factor is Tsys of new receiver: For GBT, break-even at ~50K, but probably not worth it unless <40K is possible.

Receiver optimization for pulsar timing



Plot: S. Ransom

Factors include: Receiver params, pulsar spectral index, galactic BG flux, scatter-broadening.