Trans-dimensional signal modeling in PTA data

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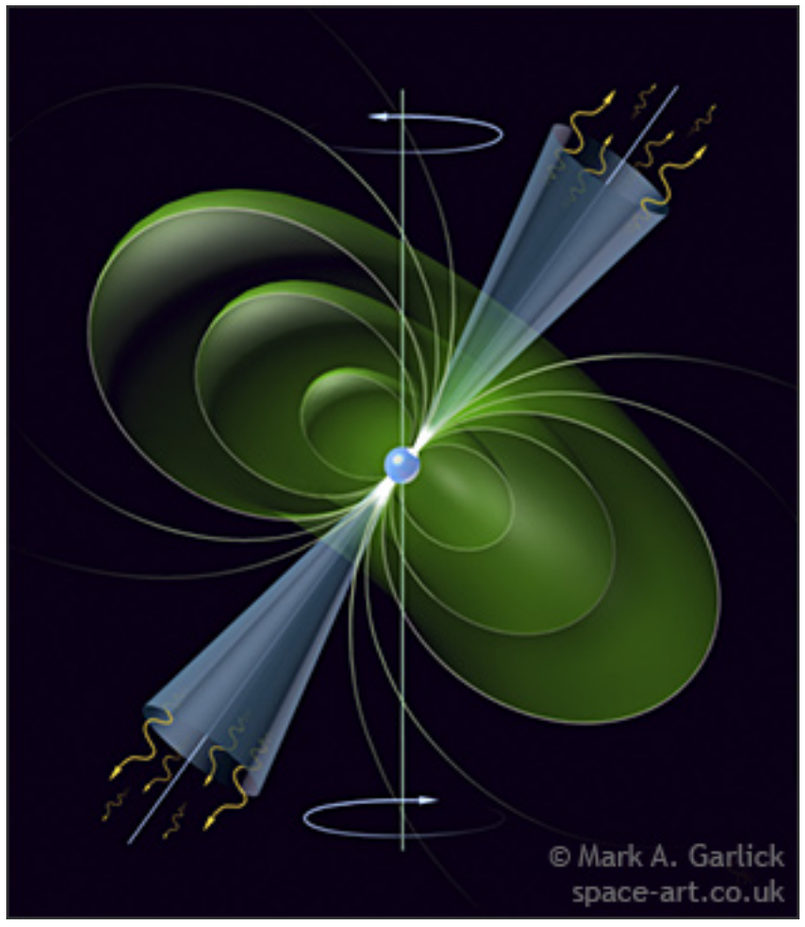
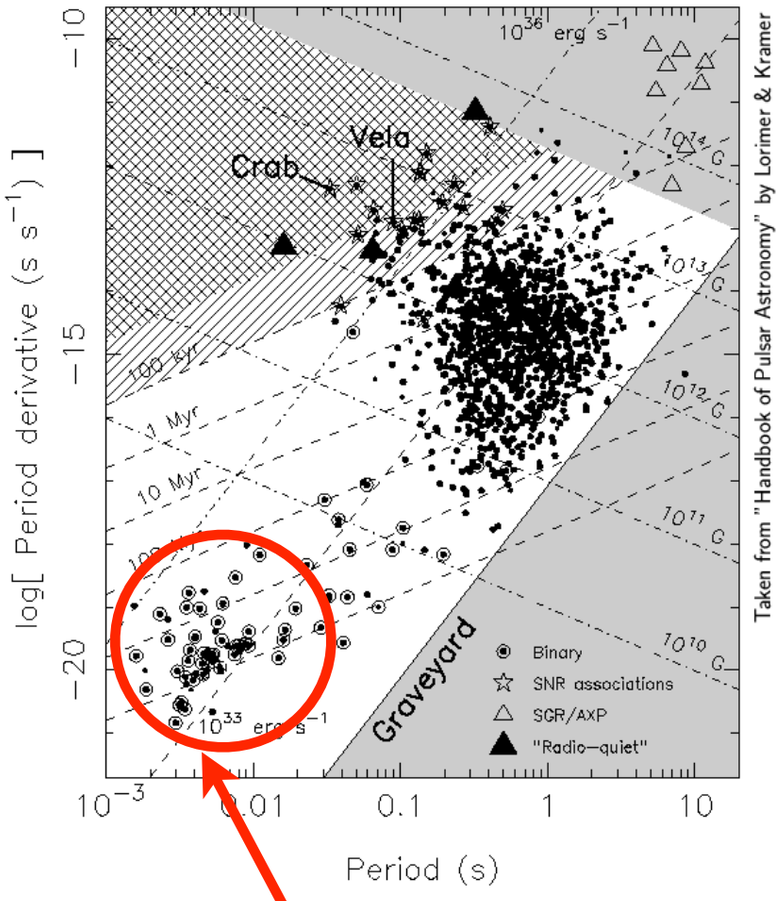
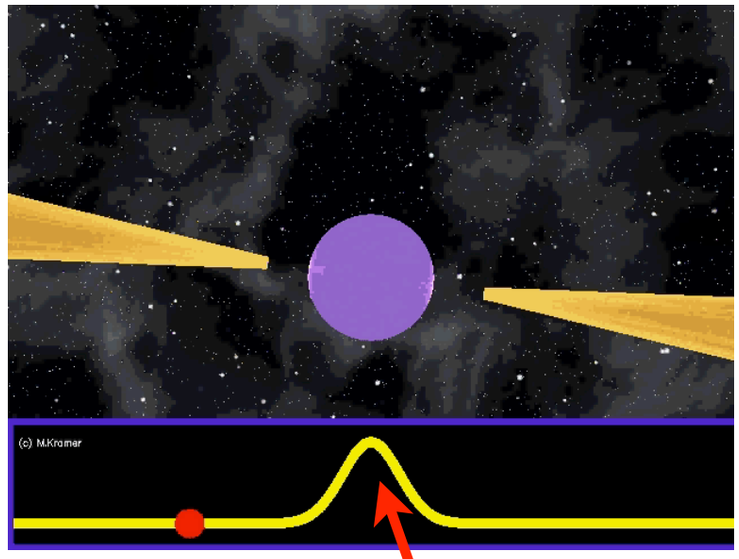
Pulsar Timing Preliminaries



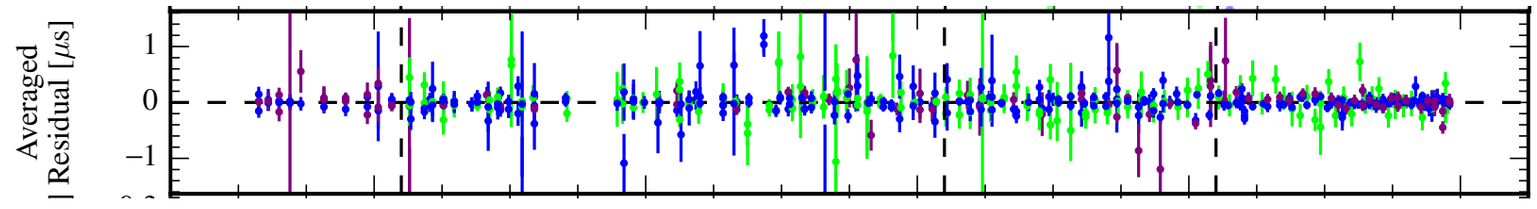
Highly magnetized rotating neutron star





time-of-arrival (TOA)

Extremely stable clocks



$$\delta t = t_{\mathrm{measured}} - t_{\mathrm{model}}$$

Pulsar Timing "Residual"

Measured Pulse time-of-arrival (TOA)

Model that accounts for many delay factors but not GWs

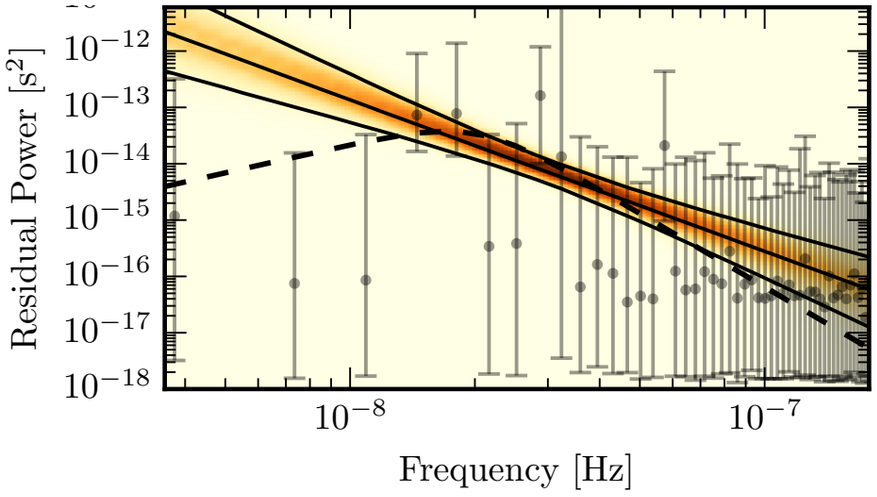
Motivation

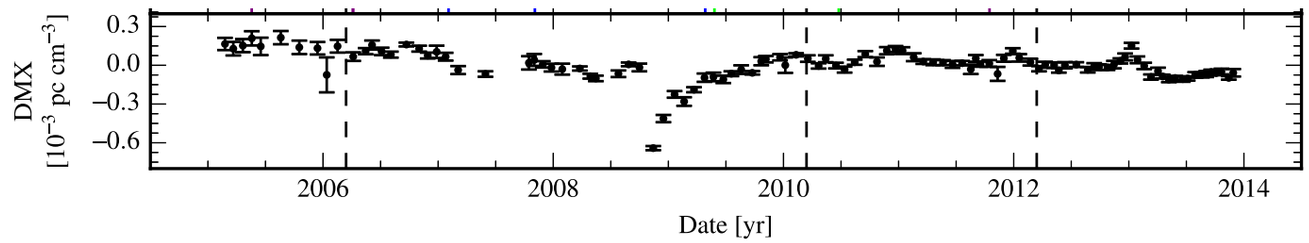
- Spectral modeling of red noise. Power-law = 2 parameters. Free spectrum > 30 parameters. Which is “better”?

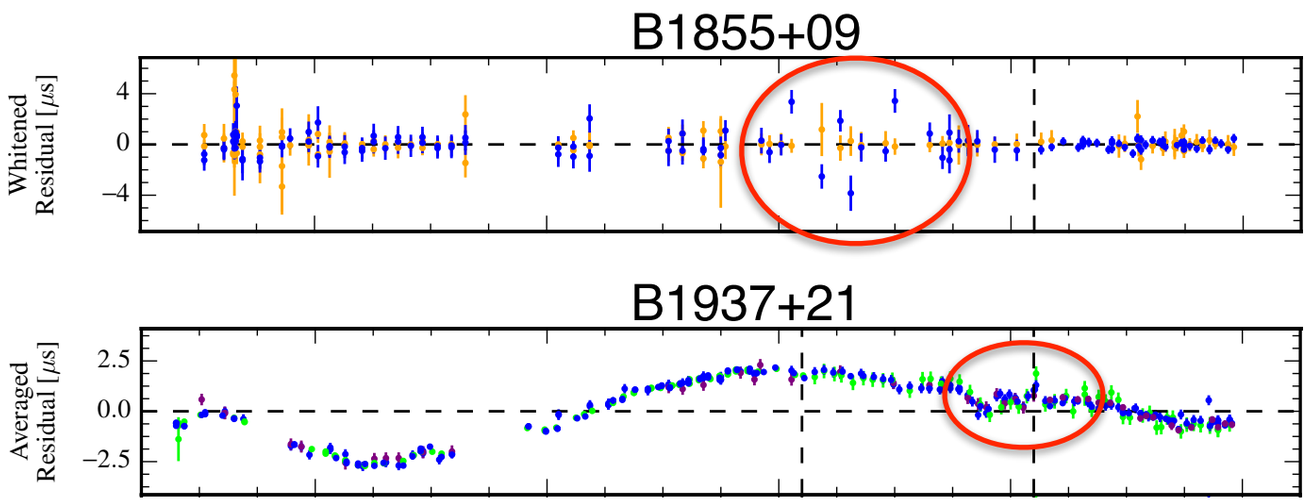
- Would like a way to use free parameters where they are needed.

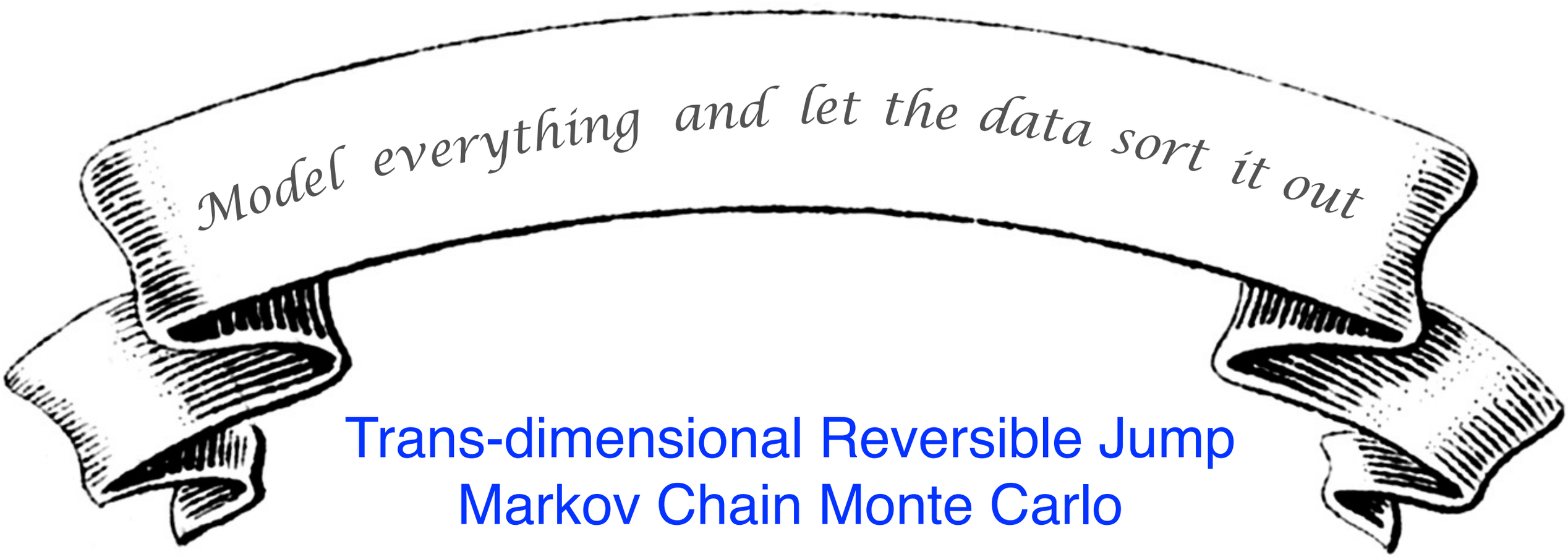
- Some pulsars show transient noise events. How do we model them?

- Would like a way to model them without a-priori choosing number of basis functions.







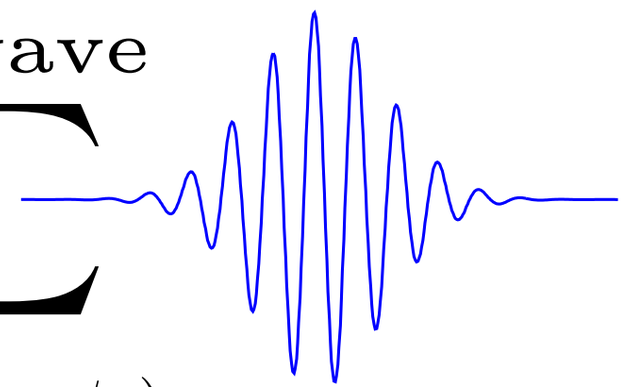


Trans-dimensional Reversible Jump Markov Chain Monte Carlo

- Similar to standard MCMC but now the model is another parameter
- Let the data pick the best model.
- Marginalize over models and their parameters.

BayesWave: Cornish & Littenberg, CQG 32, 135012 (2015)
BayesLine: Littenberg and Cornish, PRD 91, 084034 (2015)
PTA Noise: Ellis & Cornish, PRD 93, 084048 (2016)
PTA GW Burst: Ellis & Cornish in prep

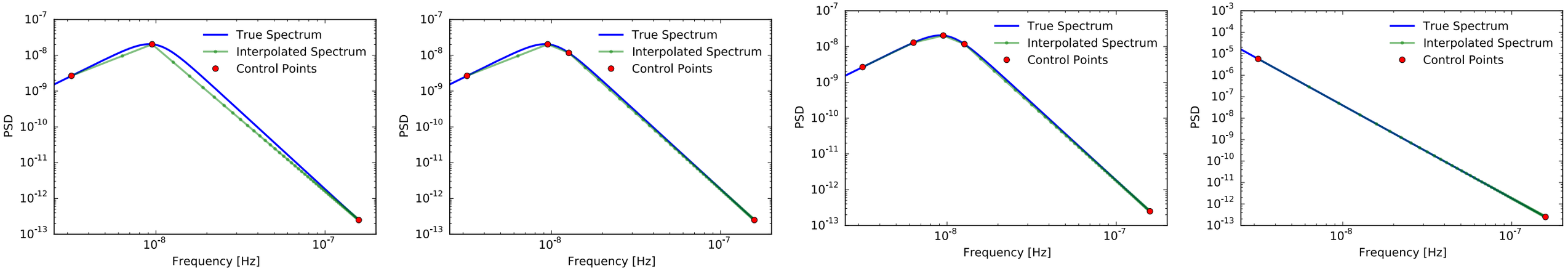
Modeling

Model Transient signals with sum of Morlet-Gabor Wavelets $\sum^{N_{\mathrm{wave}}}$ 

$$\Psi(t; A, f_0, Q, t_0, \phi_0) = Ae^{-(t-t_0)^2/\tau^2} \cos(2\pi f_0(t - t_0) + \phi_0)$$

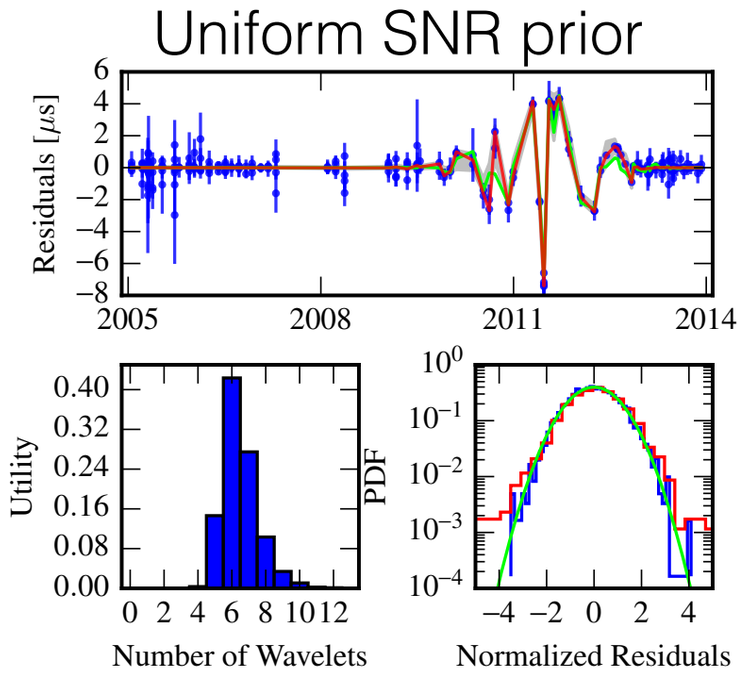
$$s_+(t) = F_+(\theta, \varphi, \psi) \sum_{i=1}^{N_+} \Psi_i(t) \qquad s_\times(t) = F_\times(\theta, \varphi, \psi) \sum_{i=1}^{N_\times} \Psi_i(t)$$

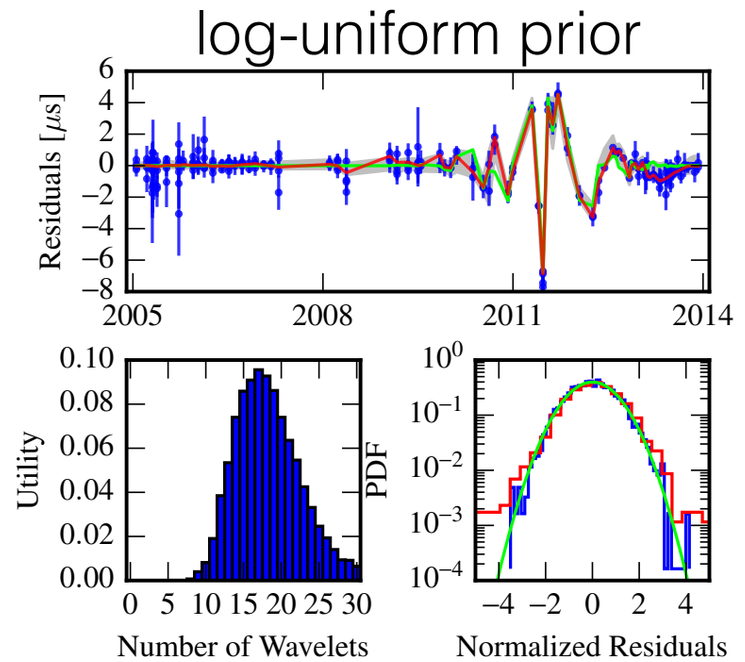
Model red spectrum with free control points and linear interpolation in log-space.



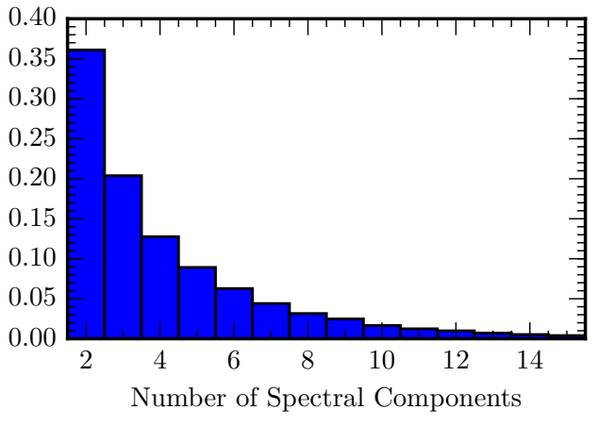
Transient Noise Event Simulation.

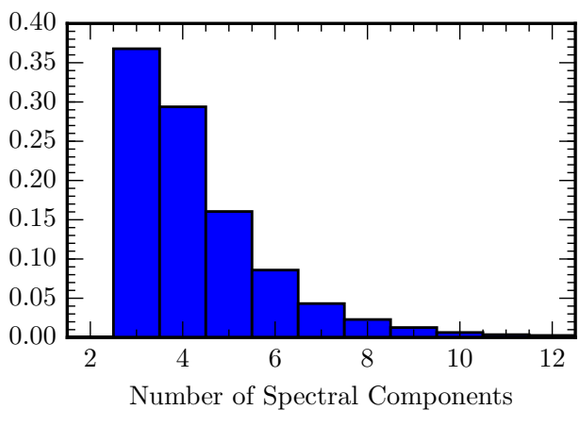
- B1855+09 TOAs with simulated white noise burst.
- Test model with uniform SNR prior and log-uniform amplitude prior
- Signal recovered well in both cases.
- Model much simpler with uniform SNR prior.

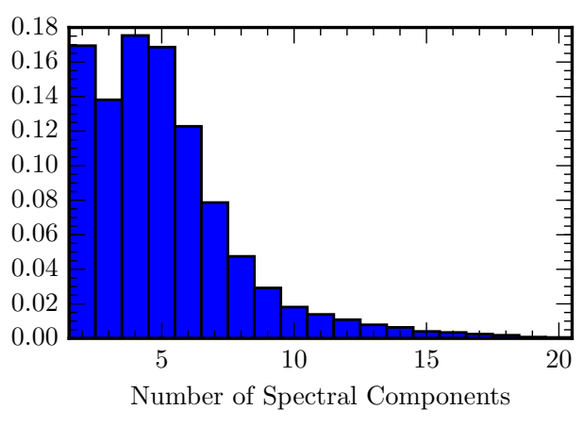


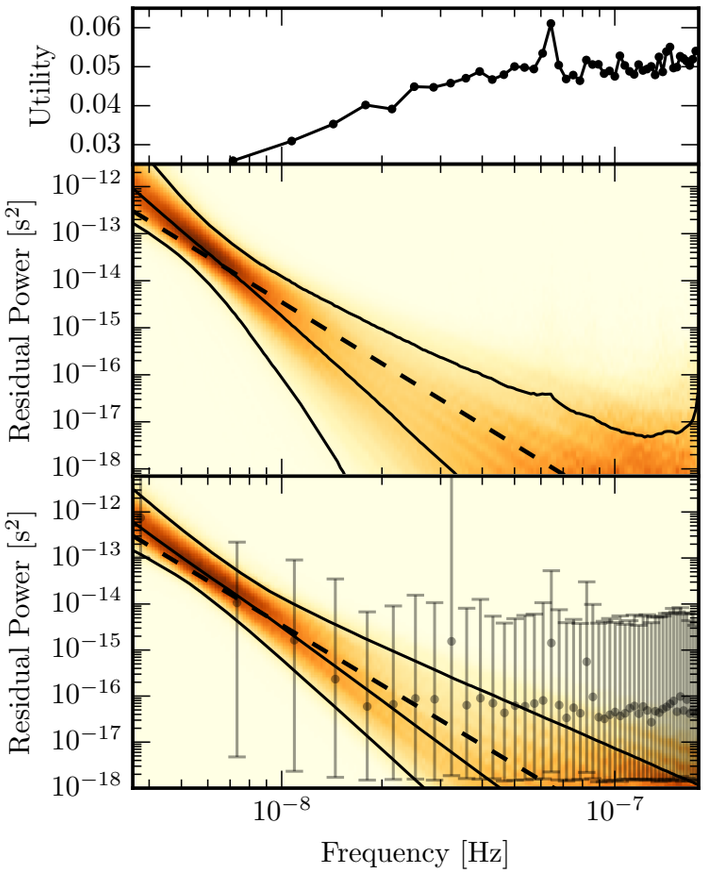


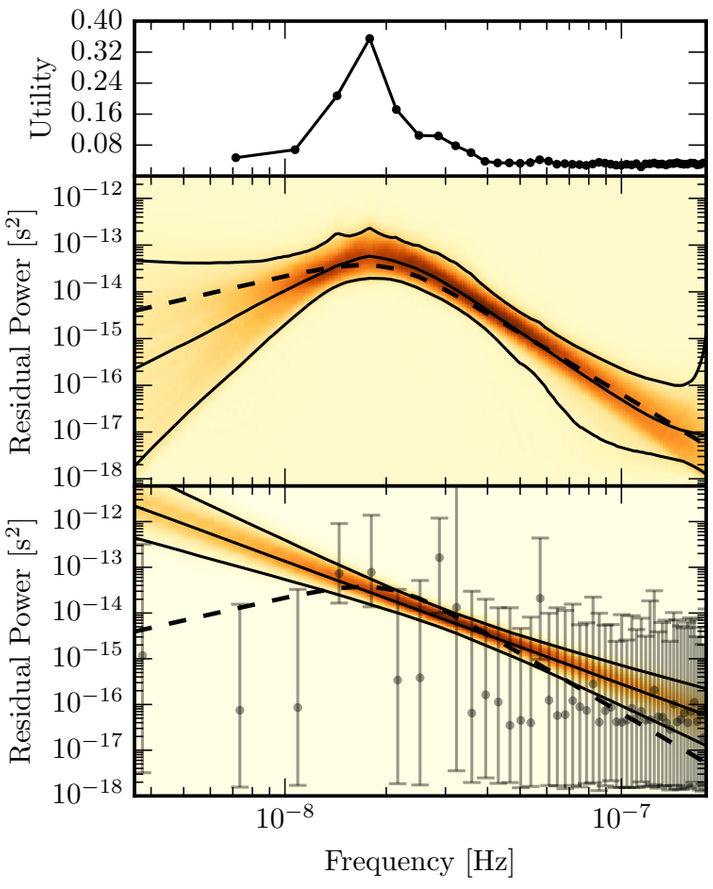
Adaptive PSD estimation

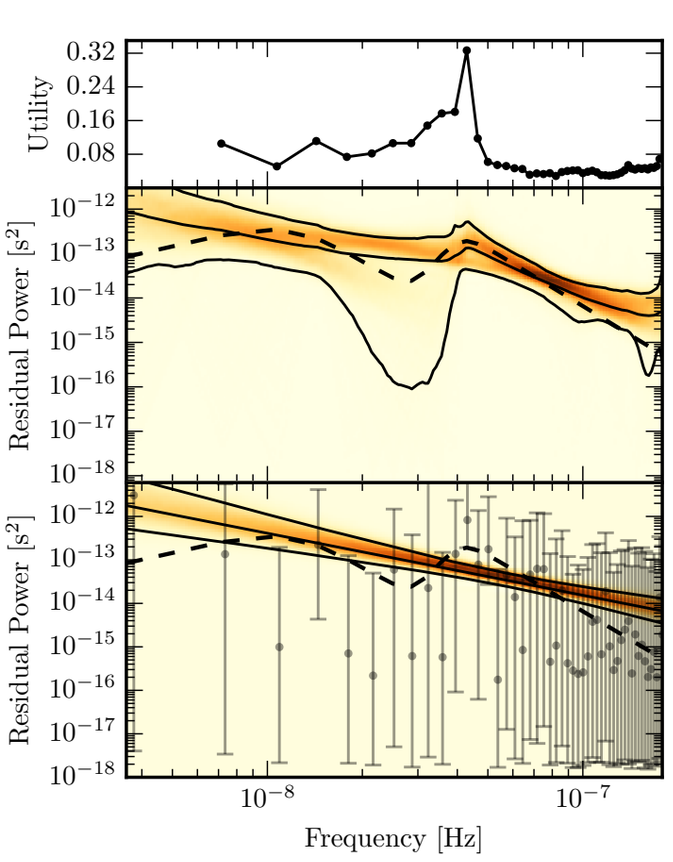










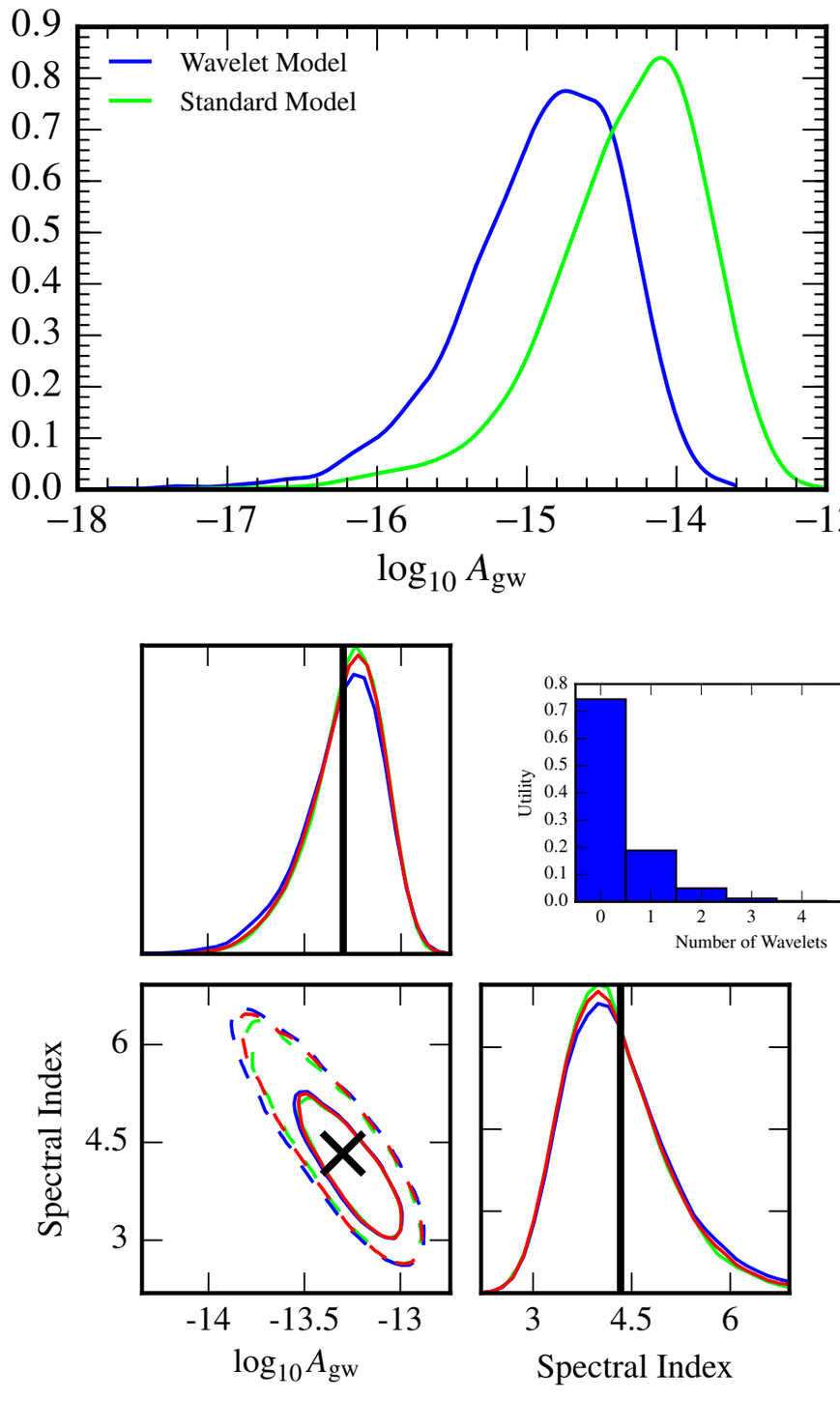


Improvement of GW limits

- If transient noise event is present and not modeled, GW limits could suffer severely

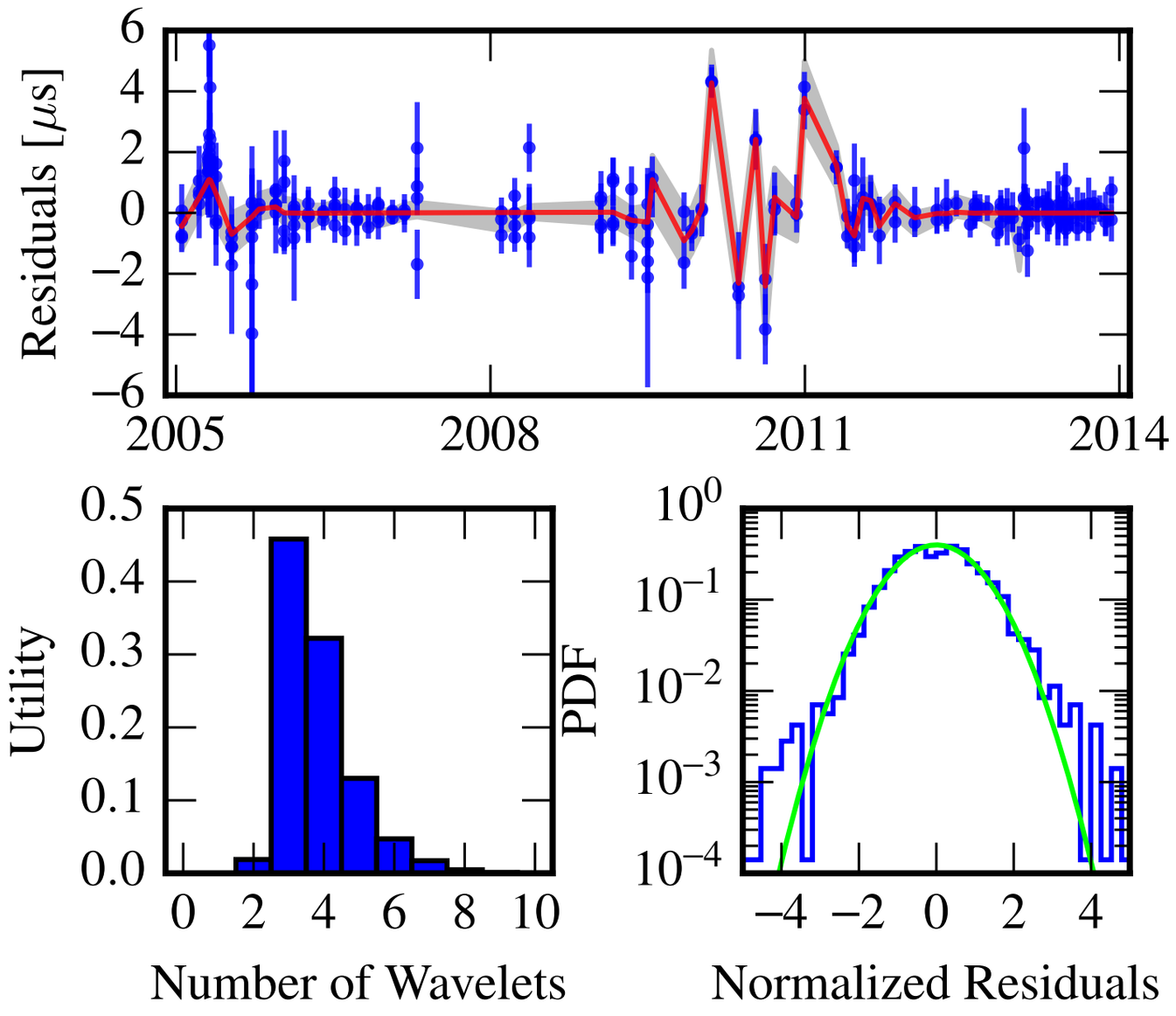
- Wavelet model does not absorb GW power in the absence of a transient signal

- Plan to use this method for upcoming GW limits.



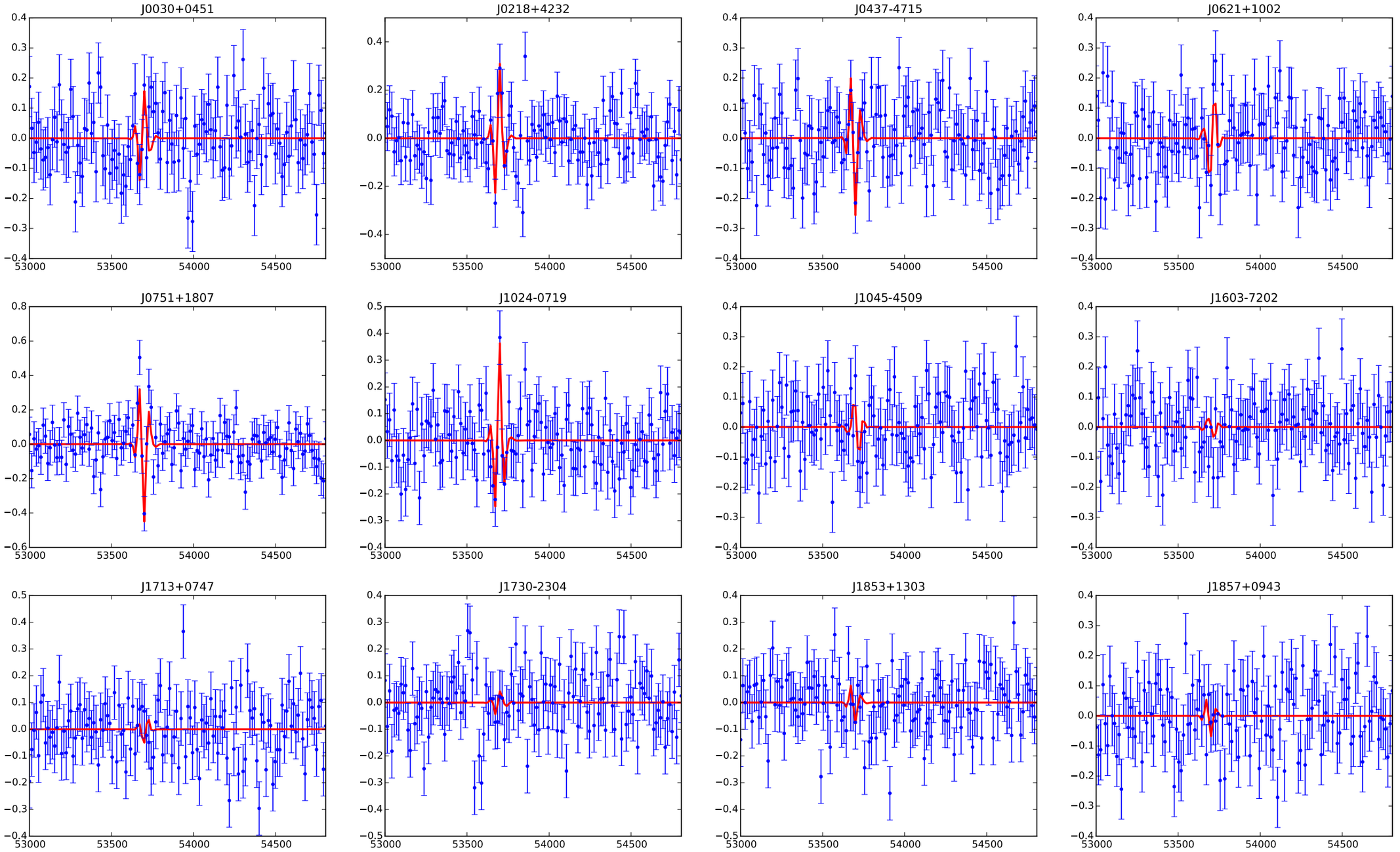
Analysis on B1855+09

Bayes factor for > 0 wavelets is ~exp(13)



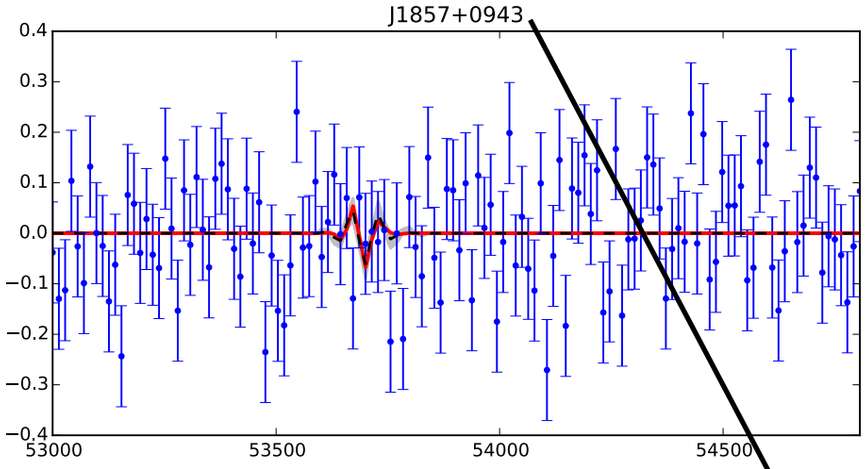
- Real B1855+09 data shows a very significant transient noise event
- Corresponds to observation run in which half of observing bandwidth data was corrupted
- Plan to carry out this analysis on all NANOGrav pulsars in the future

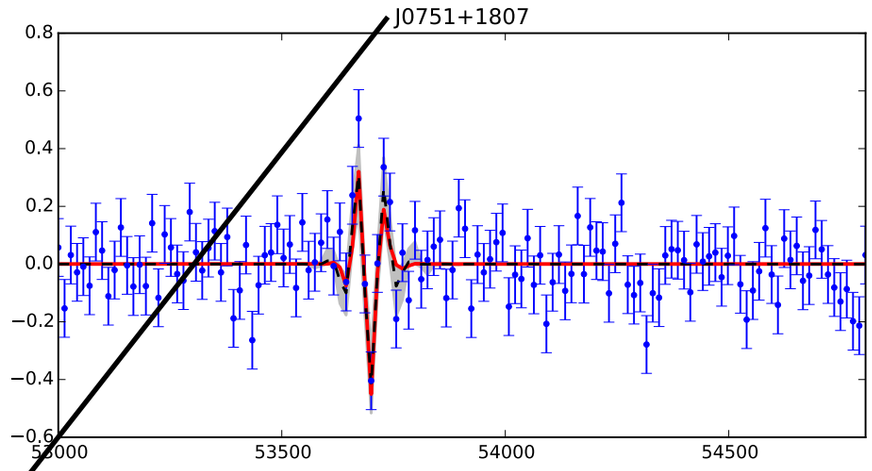
Simulated data: SNR=10, 12 pulsars, 5 years

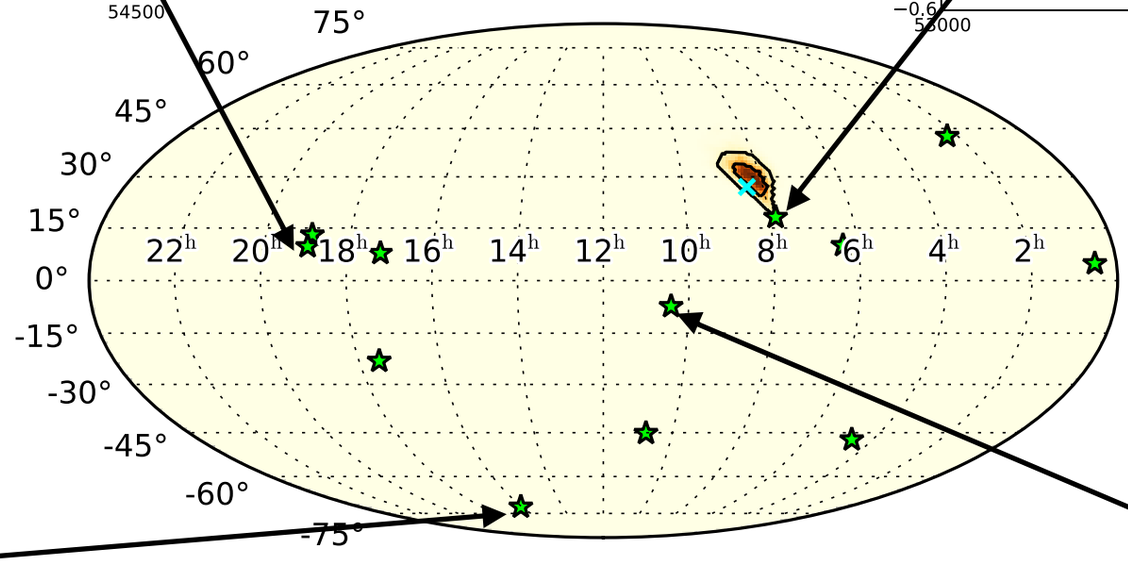


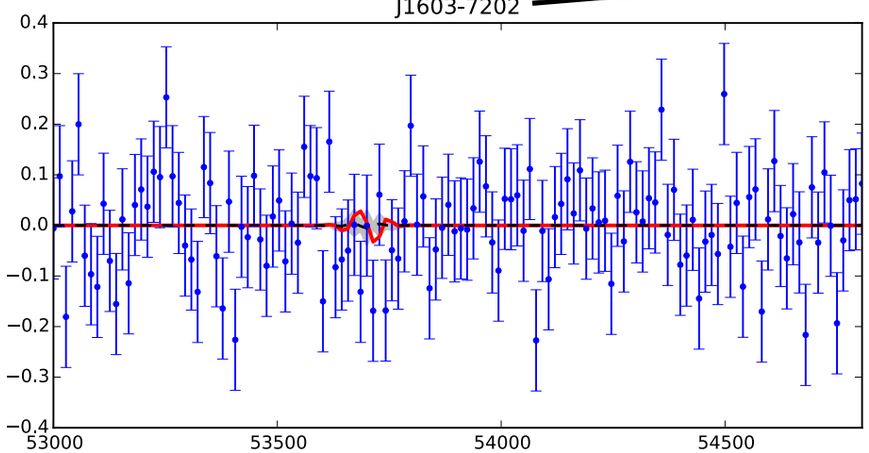
Simulated stochastic burst with duration 30 days and bandwidth 3.2e-8 Hz

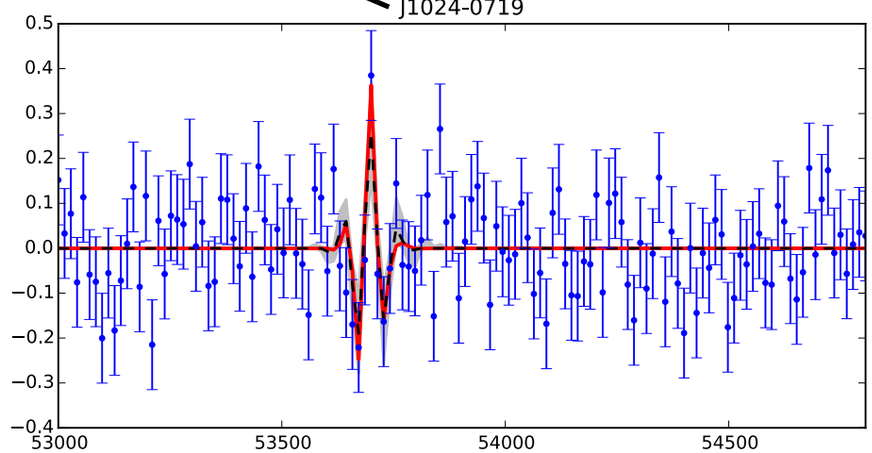
Recovered signals: SNR=10, 12 pulsars, 5 years











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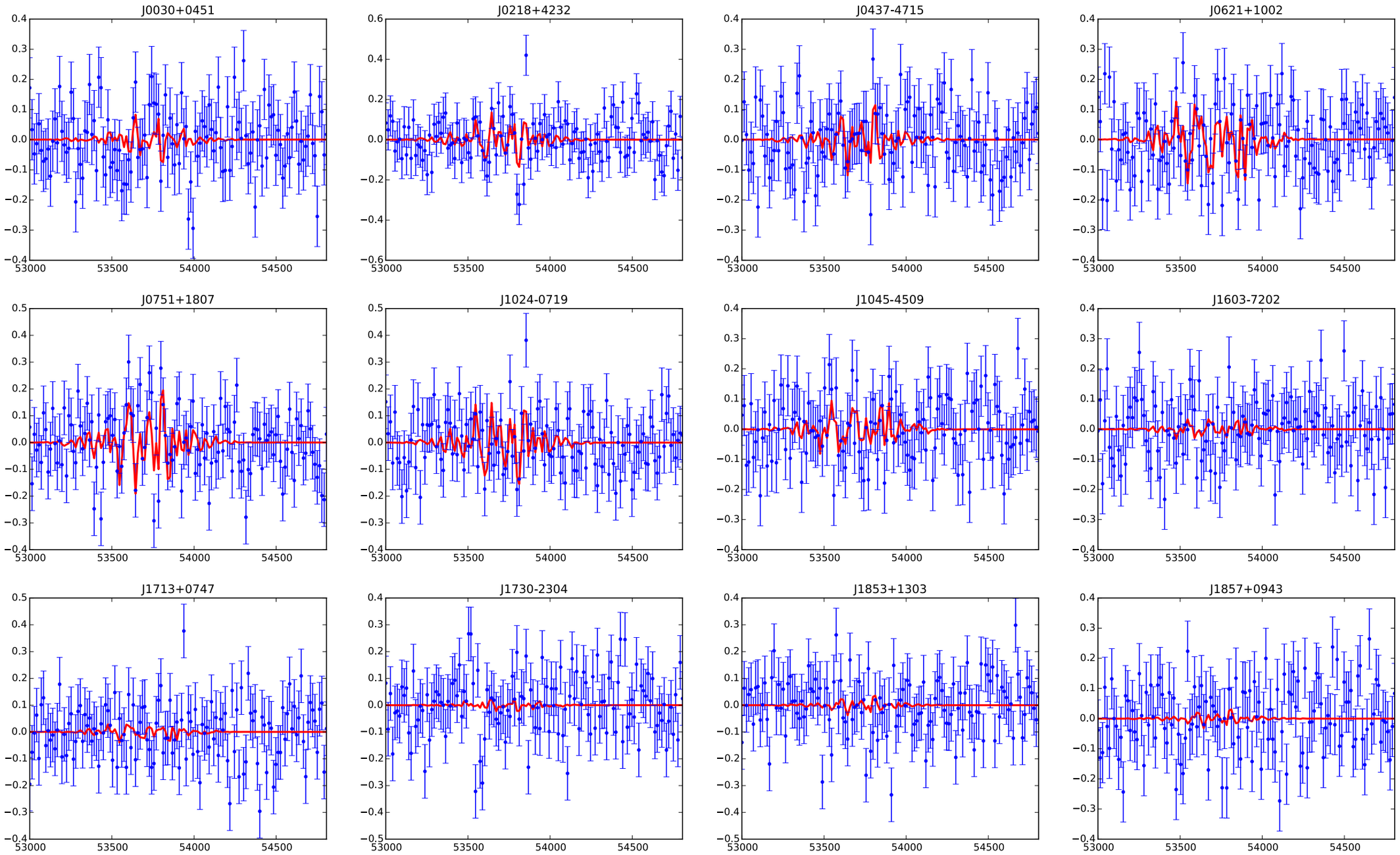
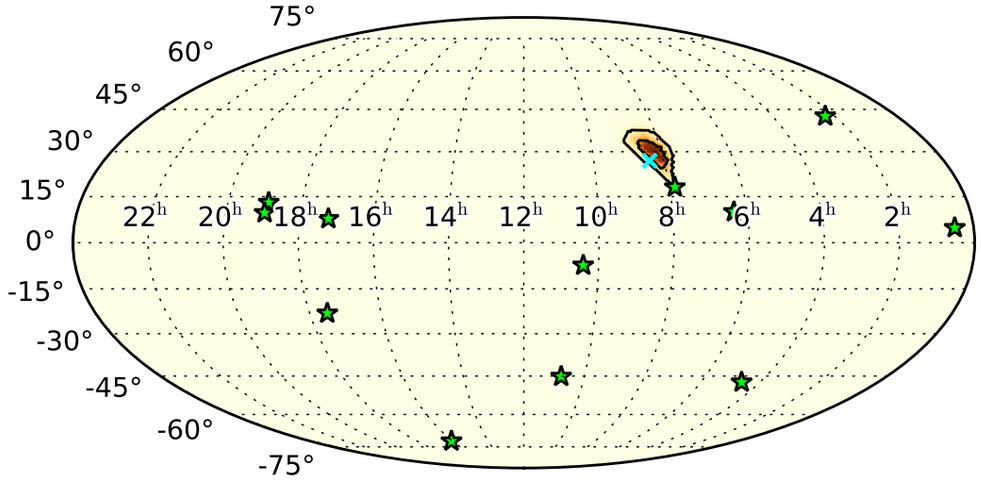
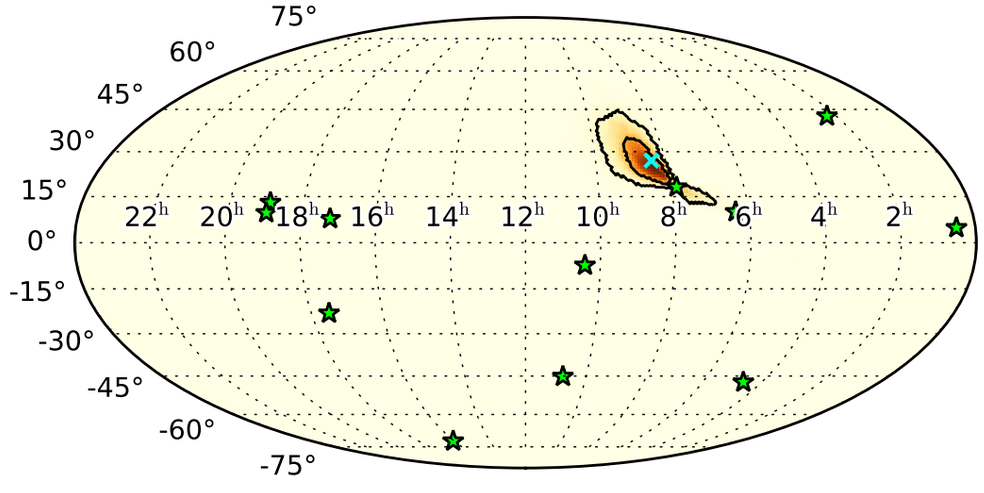


Simulated stochastic burst with duration 200 days and bandwidth 1.3e-7 Hz

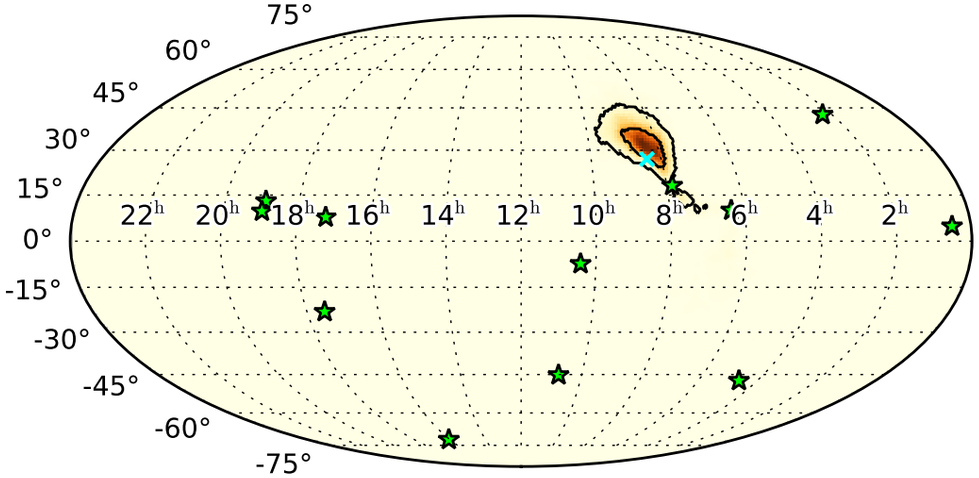
Recovered signals: SNR=10, 12 pulsars, 5 years



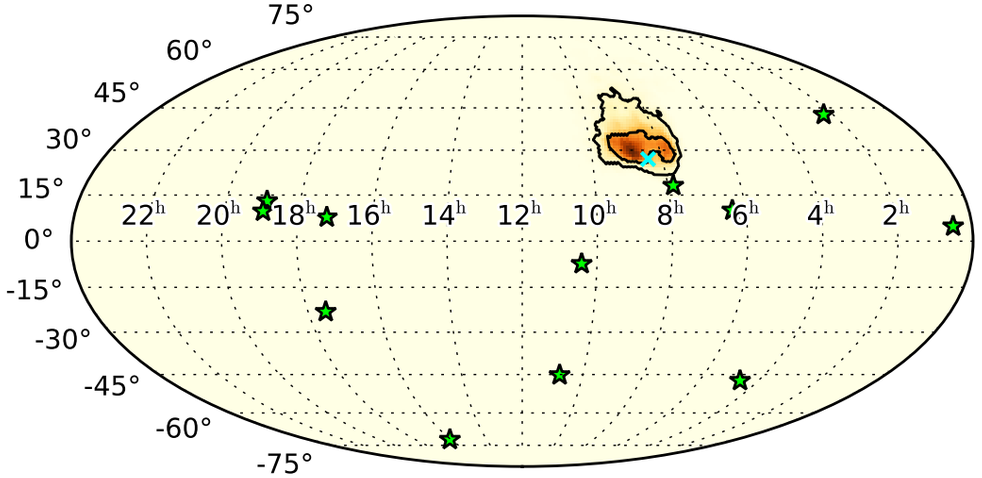
Duration 30 days. Bandwidth 3.2e-8 Hz



Duration 30 days. Bandwidth 1.3e-7 Hz



Duration 200 days. Bandwidth 3.2e-8 Hz

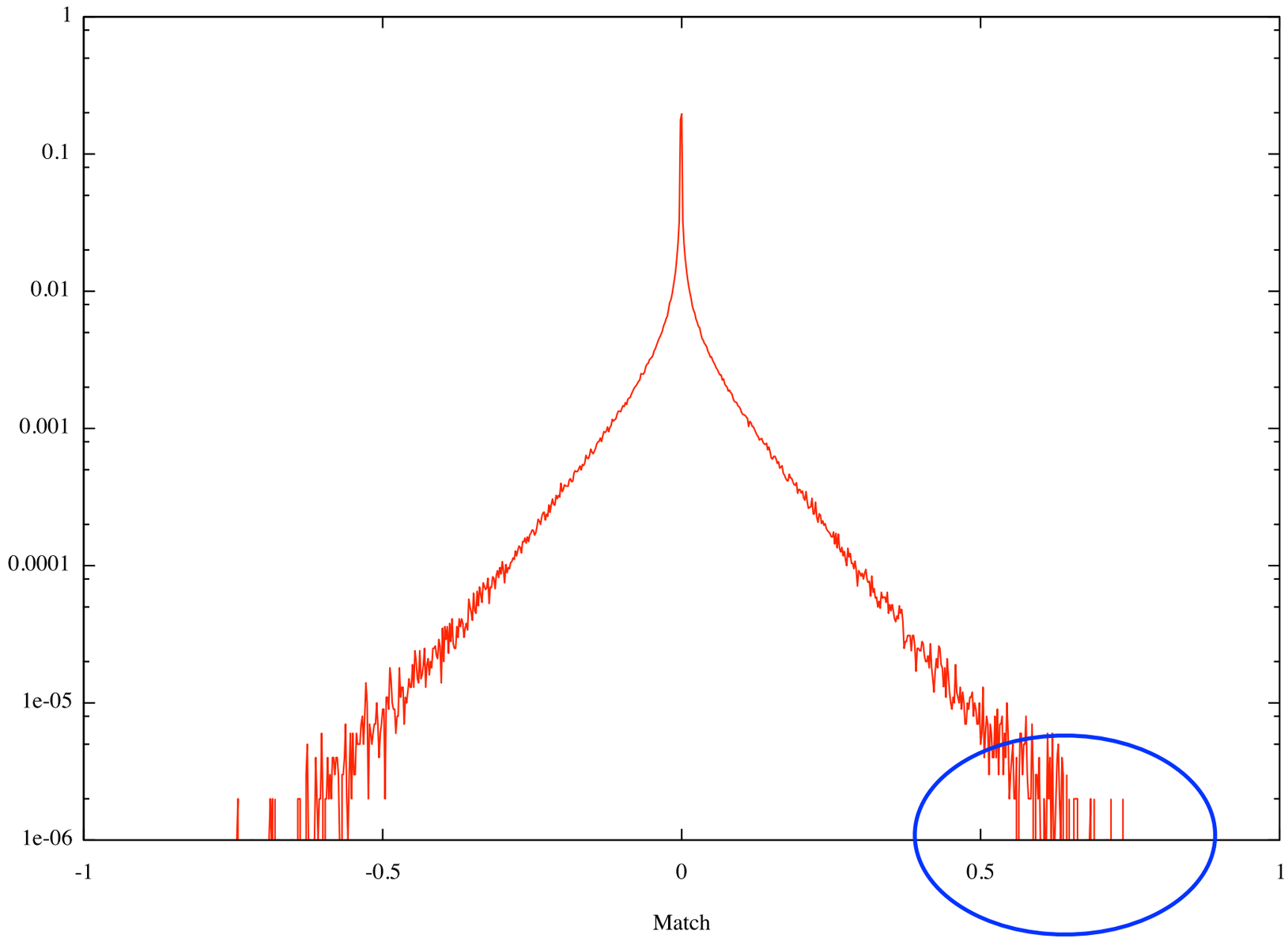


Duration 200 days. Bandwidth 1.3e-7 Hz

Performance degrades for signals with larger TF volume (fixed SNR)

Distinguishing between GW bursts from glitches

On average, for every Earth term burst signal, there will be an equal number of uncorrelated pulsar term burst from different sources. These are effectively glitches.

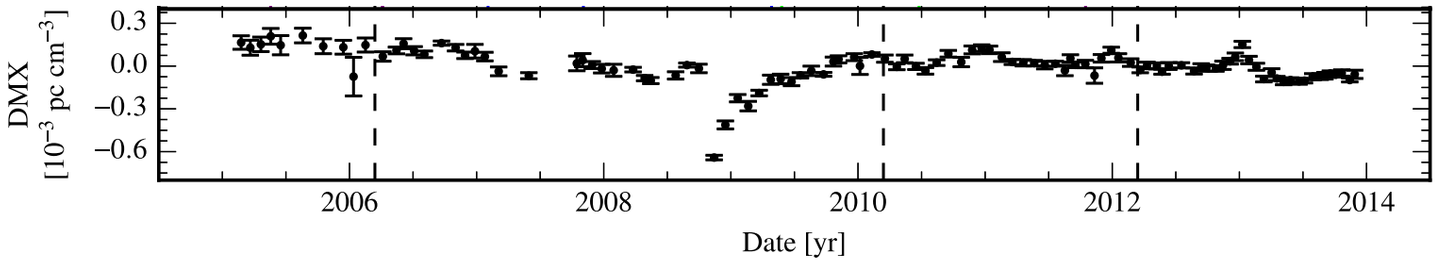


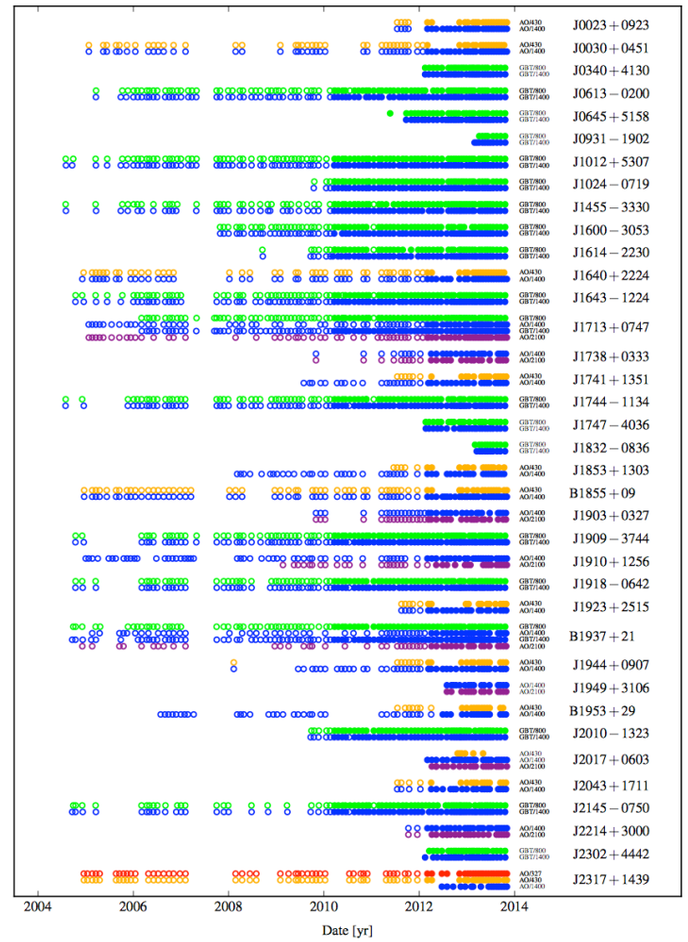
Probability of two stochastic glitches matching in two pulsars is tiny

Probability of a match in N>>1 pulsars is essentially zero

Future Directions

- Apply to Dispersion Measure as well as TOAs





- Use wavelets per observing backend to model systematics
- Quite a difficult sampling problem

- NANOGrav generic burst search