Have we seen all glitches?

Meng Yu

National Astronomical Observatories of China

Co-worker: Qinjian Liu

Department of Astronomy, Peking University

Acknowledgement: Prof. R. N. Manchester (Australia Telescope National Facility, ATNF), **Prof. G. Hobbs** (ATNF), **Dr. L. Lentati** (Cambridge University), **Prof. K. J. Lee** (Kavli Institute, Peking University) and **Dr. J. B. Wang** (Xinjiang Astronomical Observatory, China)

Outline

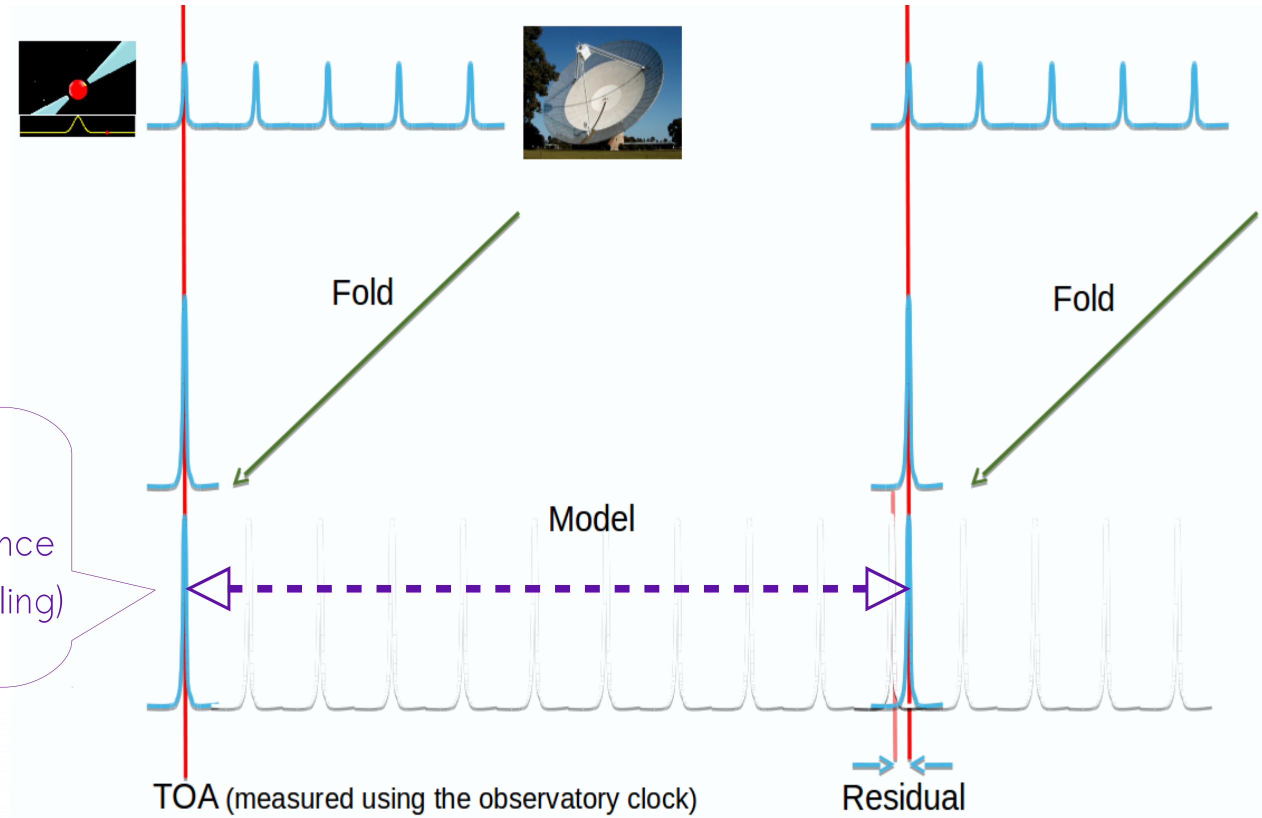
1. Glitch and its identification
   - Timing observation
   - Glitch, identification and measurement
2. Constraints on detecting glitch
   - Glitch epoch relative to observing span and observing cadences
   - Epoch of another glitch relative to observing cadences
   - Strength of timing noise
3. Solving the complete probability formula
4. Inferring distribution embedded in data
5. Conclusion

1. Glitch and its identification

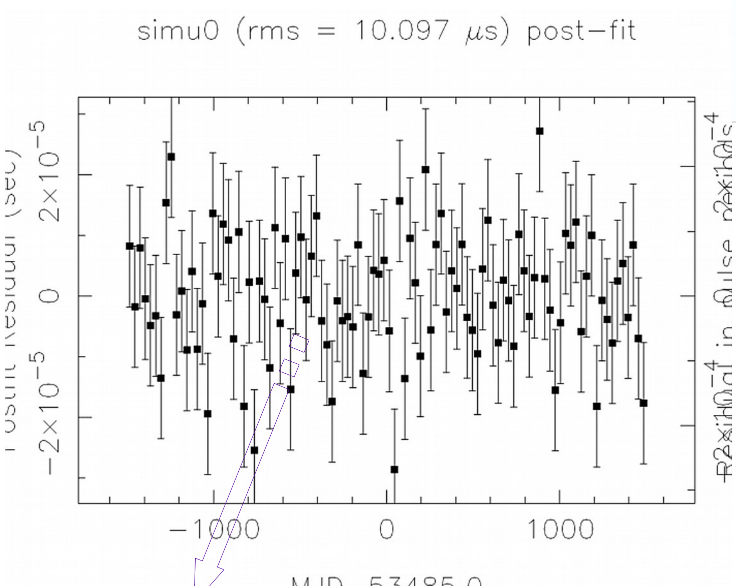
1.1 Timing observation

Pulsar timing observations 'sample' neutron star rotation phases discretely and unevenly.

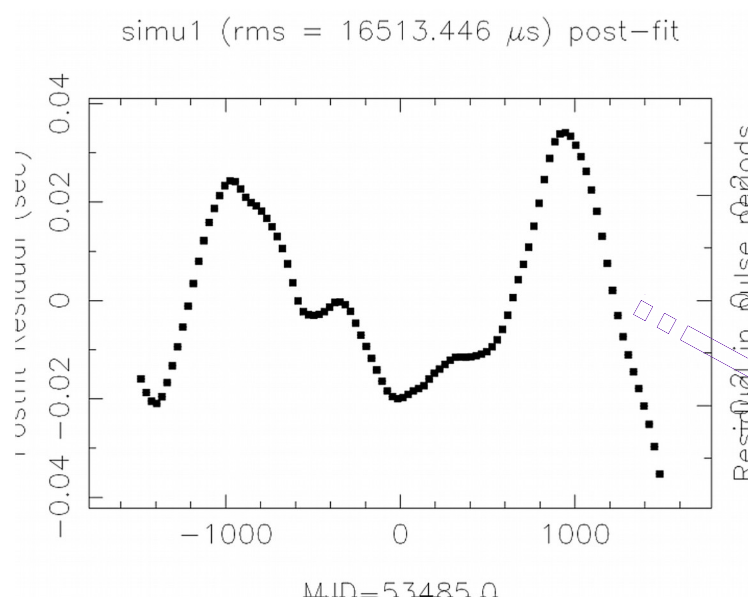
- TOA interval
- Observing cadence (observing sampling)



Courtesy D. Champion



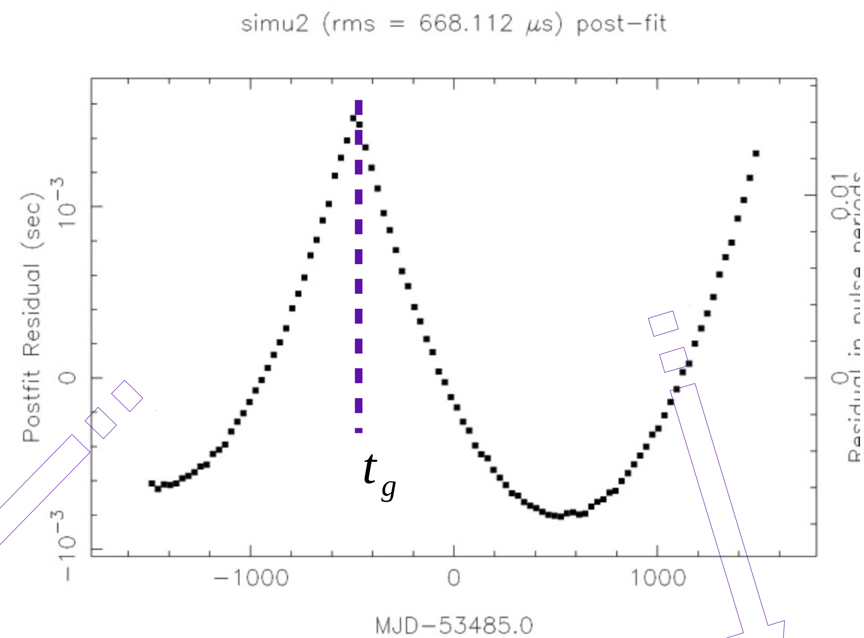
white noise



timing noise

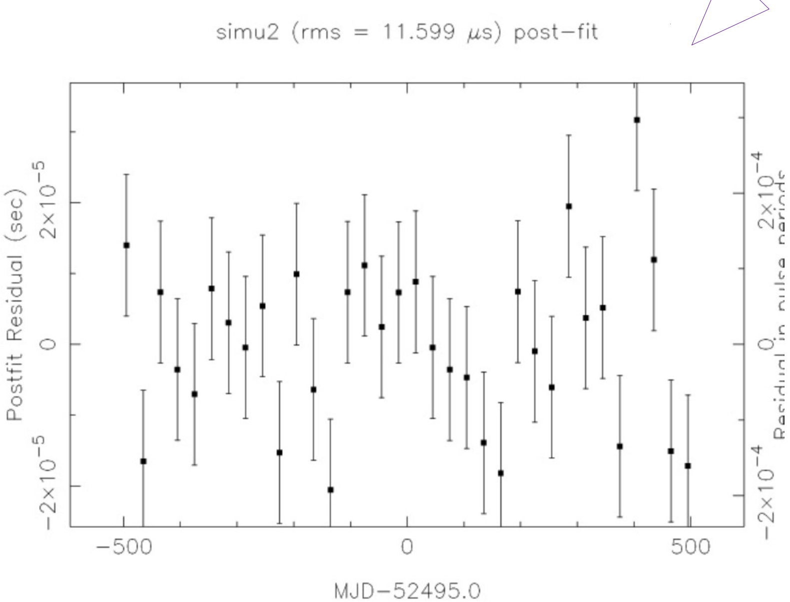
1.2 Glitch, identification and measurement

Glitch is unexpected, 'instantaneous' increase in pulse frequency.



Simulation of a ToA set:

- MJD 52000 - MJD 55000
- 1400MHz
- 30d cadence
- 10us ToA error
- Dv = 10^-9 Hz glitch at t_g = MJD 53000



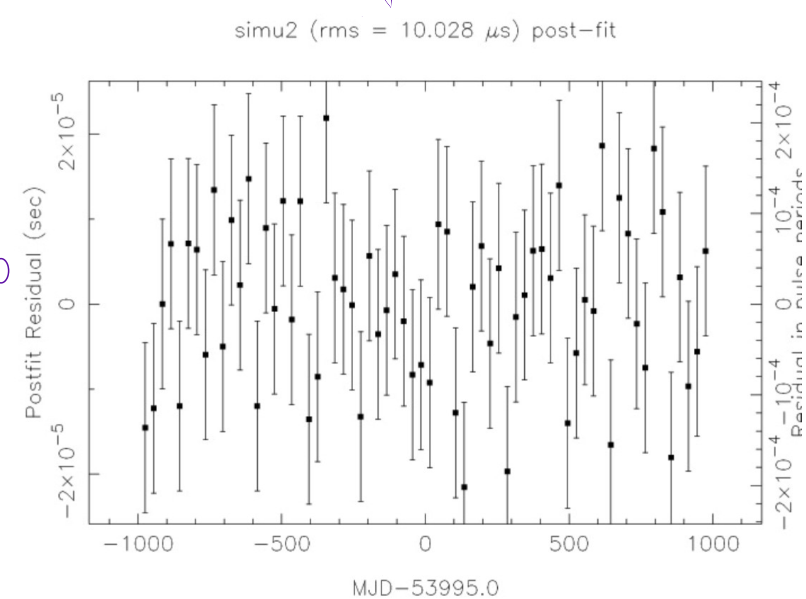
pre-glitch v at MJD 53000
= 9.36653721085499 Hz

-

post-glitch v at MJD 53000
= 9.36653721185579 Hz

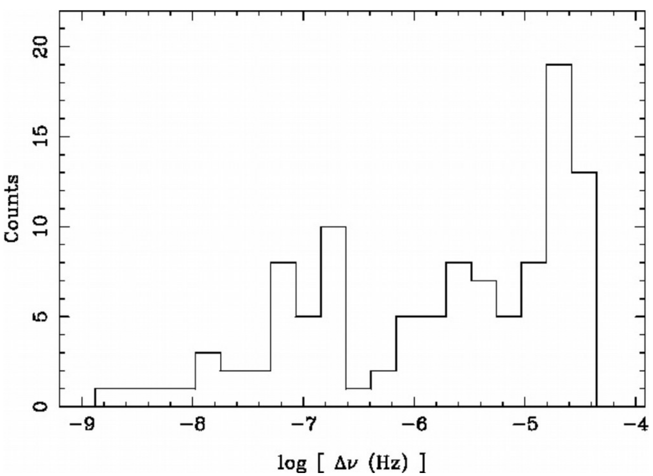
=

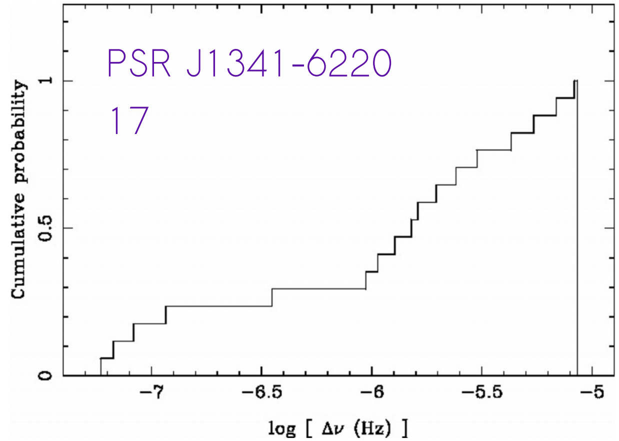
-1.0008 x 10^-9 Hz

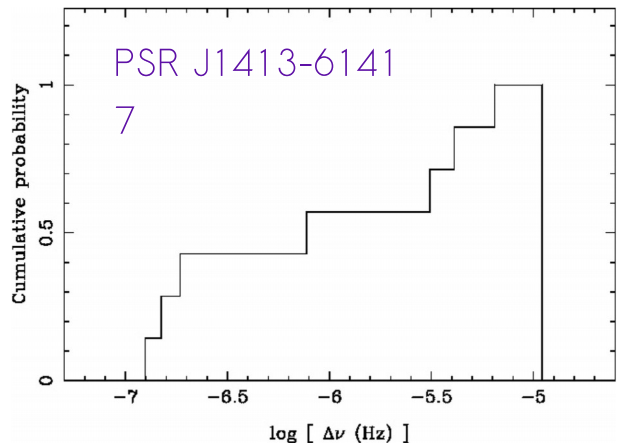


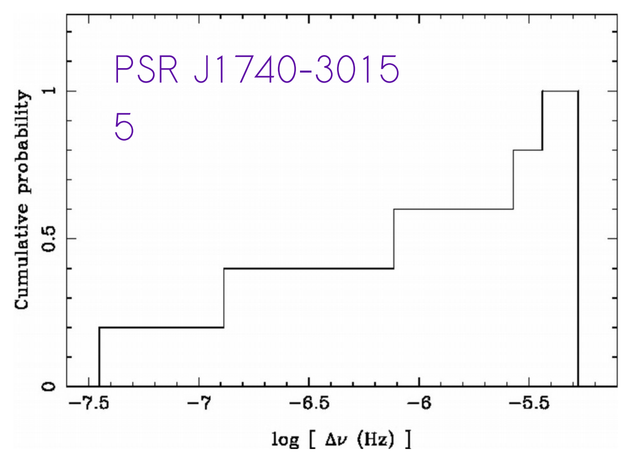
1.3 What can we draw from Yu et al. (2013)

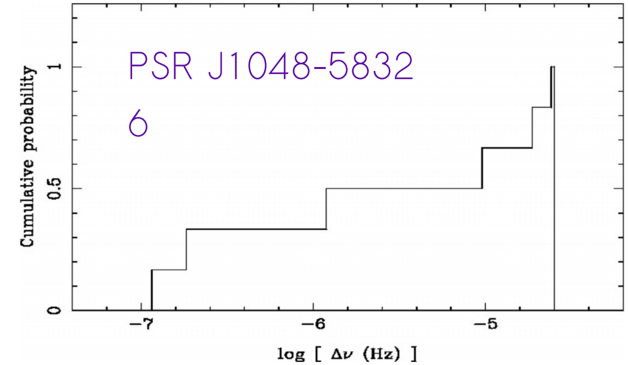
- 165 pulsars
- Parkes observed
- Cadences 2 -- 4 weeks
- Data range 5.3 -- 20.8 yr
- 36 glitching pulsars
- 107 glitches
- 7 pulsars with gl. no. >= 5

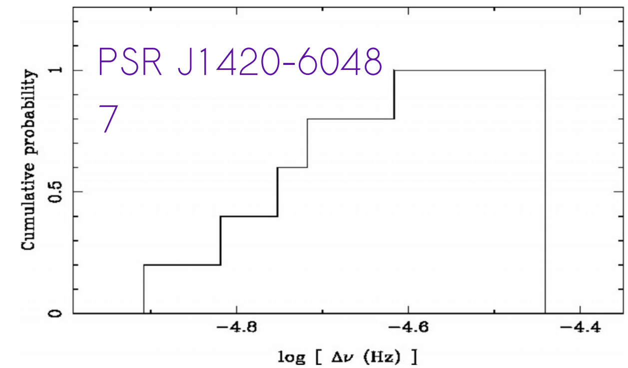


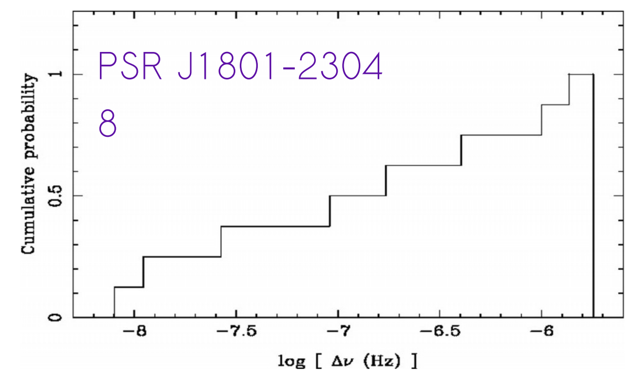


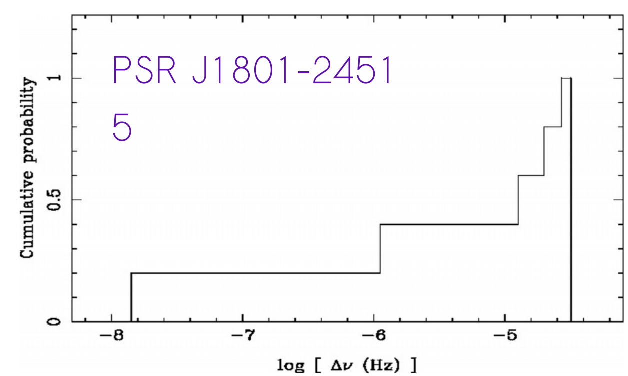








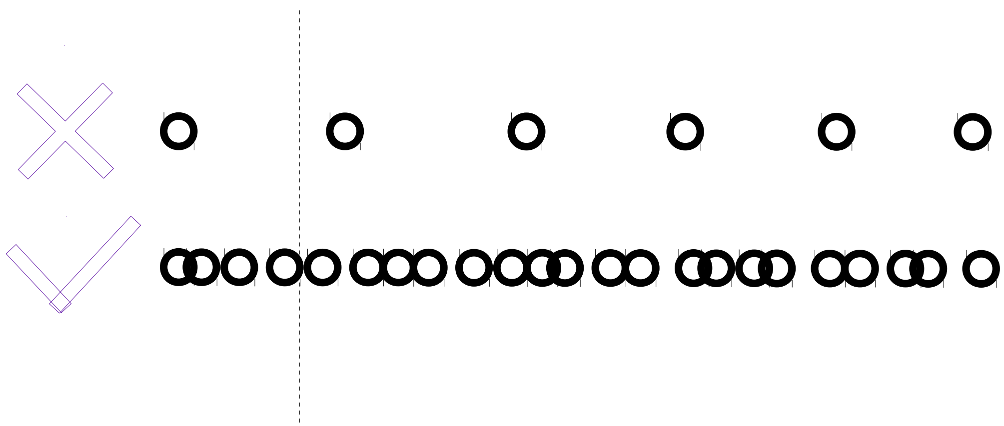




Figs. Observed aggregated / individual Dv distributions.

2. Constraints on detecting glitch

2.1 Glitch epoch relative to observing span and observing cadences

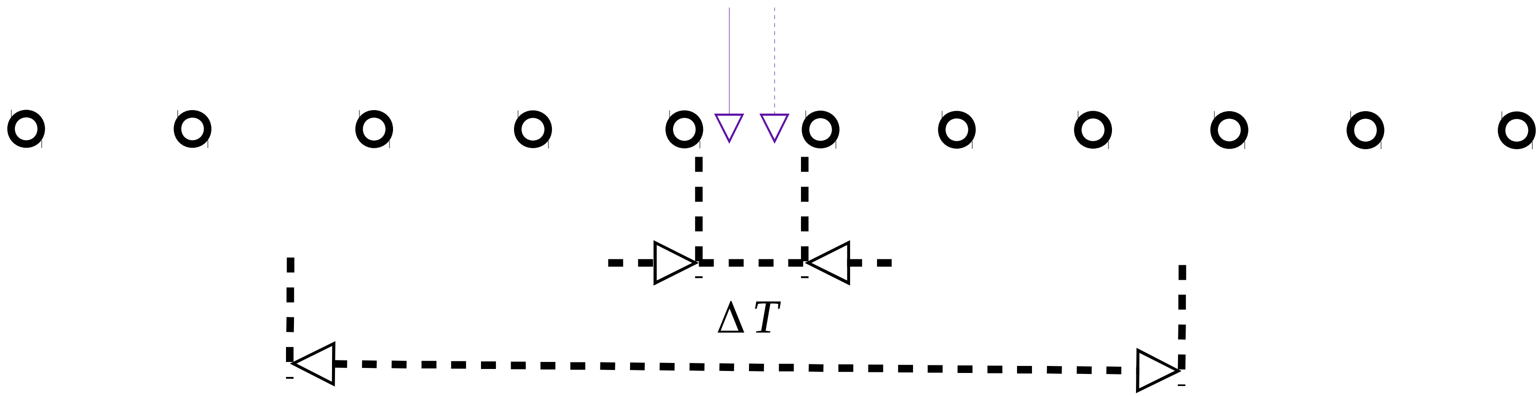


'epoch term' : P{D(dv) | C_e}P{C_e}

$$P\{C_e\} = \frac{\textit{Entire time span but the first two plus last two TOA intervals}}{\textit{Entire time span}}$$

$$P\{D(\Delta\nu)|C_e\} = 1$$

2.2 Epoch of another glitch relative to observing cadences



'multiglitch term' : P{D(dv) | C_m}P{C_m}

$$P\{C_m\}=\begin{cases}\dfrac{\Delta T}{T} & \textit{if coincidence}\\ 1-\dfrac{\Delta T}{T} & \textit{otherwise}\end{cases}$$

$$P\{D(\Delta\nu)|C_m\}=\begin{cases}0.5 & \textit{if coincidence}\\ 1.0 & \textit{otherwise}\end{cases}$$

where T is the length of detection window

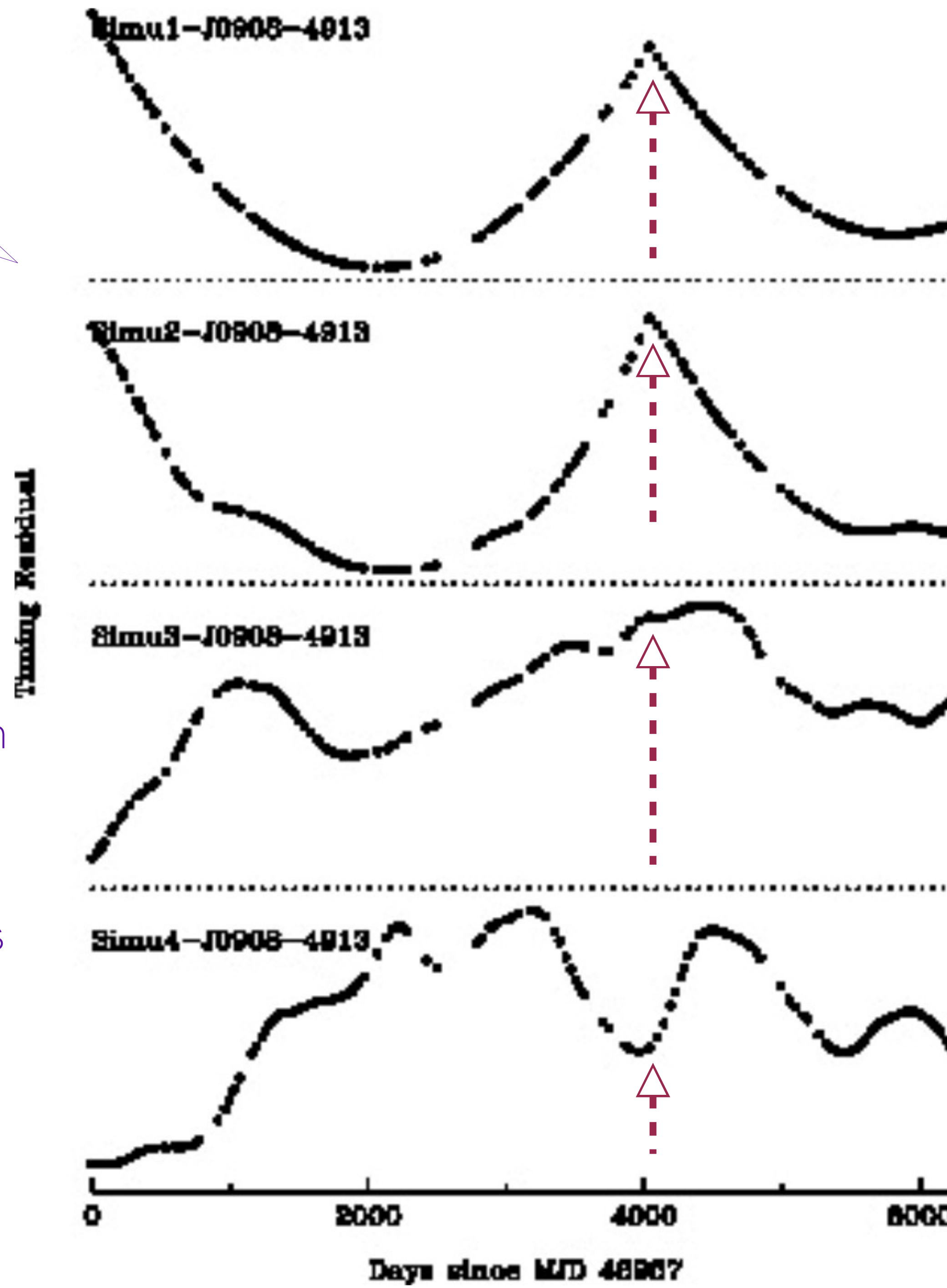
For typical Parkes obs.,

T ~ 4000 d (10 yr)   dT ~ 6 x 20 d ~ 120 d   dT / T ~ 3%

another 3% will be multiplied for a third glitch to coincide with the two and so negligible.

2.3 Strength of timing noise

- Simulated sets of timing residuals
- A Dv = 10^-7 Hz glitch added
- From top panel to bottom, timing noise grows



'noise' term : P{D(dv) | C_n} P{C_n}

- Group case:

P{C_n} is a one dimensional array indicating distribution of timing noise strength. P{D(dv)| C_n} forms a two dimensional array, each element indicates the probability for detecting glitch with certain size occurred in certain strength of timing noise.

- Individual case:

P{C_n} is an arbitrary number. P{D(dv)|C_n} is a one dimensional array, each element indicates the probability for detecting glitch with certain size.

- For an element, P{D(dv)|C_n} = no. of detectable gl. / total gl. no.

3. Solving the complete probability formula

3.1 The formula

$$P\{D(\Delta\nu)\} = \begin{cases} P\{D(\Delta\nu|C_e)P\{C_e\} \\ +P\{D(\Delta\nu|C_m)\}P\{C_m\} \\ +P\{D(\Delta\nu|C_n)\}P\{C_n\} & within\,detection\,window \\ 0 & otherwise \end{cases}$$

3.2 Solution

- Group case
  We modelled timing noise of 157 Yu et al. (2013) pulsars with power-law model using the numerical Bayesian inference approach TempoNest to derive P{C_n}.

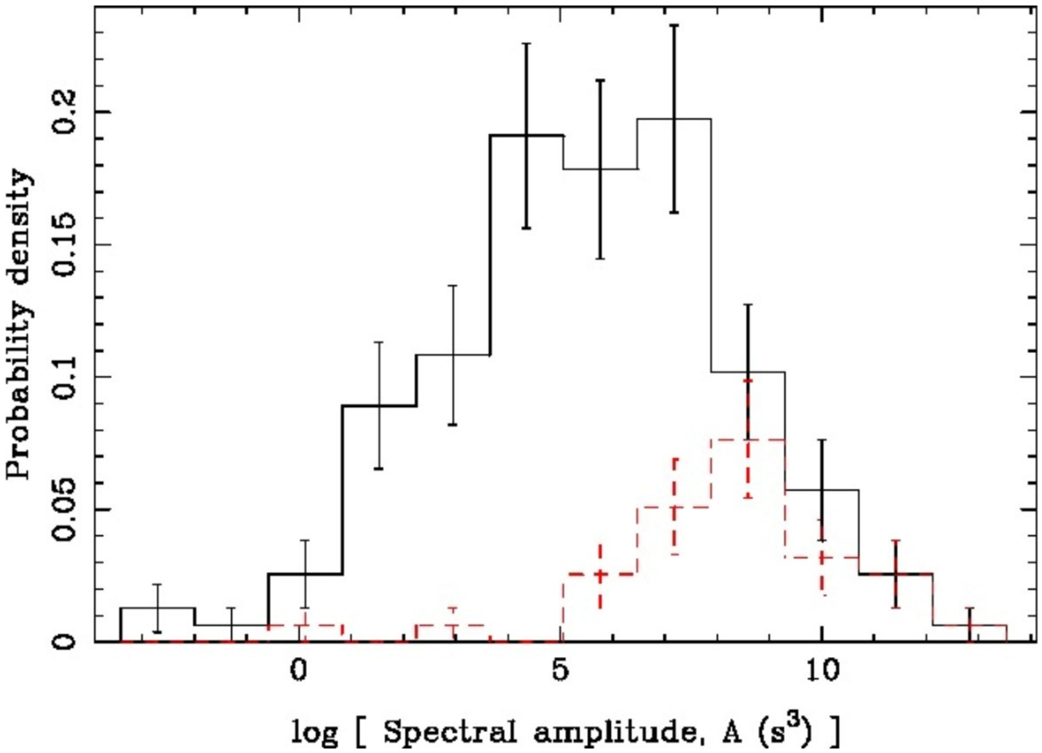


Fig. P{C_n}, distribution of timing noise strength (12 bins). Contribution of the 36 observed glitching pulsars is indicated by the red dashed bars.

We introduced the Monte Carlo simulation to derive the P{D(dv)| C_n}. In each realisation, for any pulsar out of the 157, real pulsar ephemeris, observing sampling, TOA error bars and the measured timing noise parameters were used to produce timing noise. A glitch with size uniformly distributed between 1.65e-9 and 3.52e-5 Hz (the min and max glitch found in the Yu et al. data) was uniformly distributed into the specific detection window. TempoNest, was used to model data with searching for glitch. One hundred realisations were made for each pulsar.

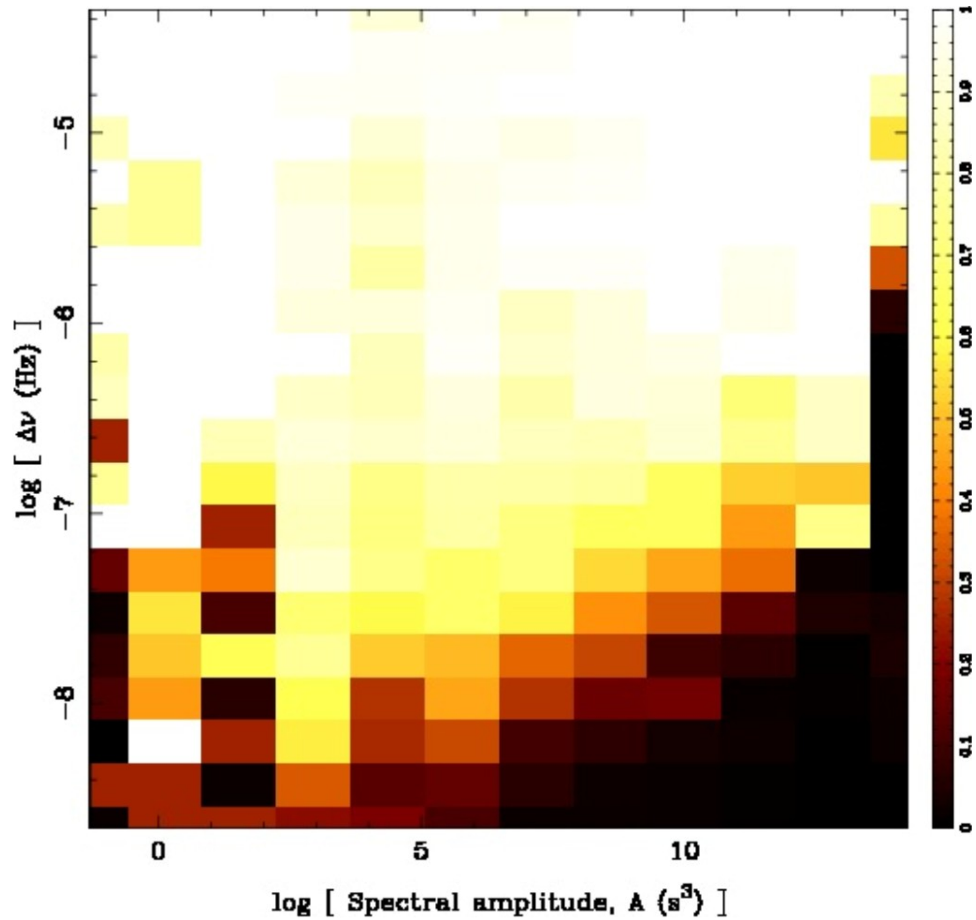


Fig. The derived P{D(dv)|C_n} matrix (12 x 20 elements). Value of each element indicates the ratio of positive detections to the total number of glitches distributed into the particular size and amplitude interval. To better present the image, element values are squared.

We calculate the product between the matrix P{D(dv)|C_n} and the array P{C_n} to derive solution for the noise term.

For each simulated glitch, we calculate P{D(dv)|C_e}P{C_e} + P{D(dv)|C_m}P{C_m} value with the given definitions. Then we distribute all values into the 20 size bins, make sum in each bin followed by a normalisation to derive solution for the epoch and the multiglitch term.

For each bin, we make sum over the terms followed by a normalisation to derive solution for the complete probability formula, P{D(dv)}.

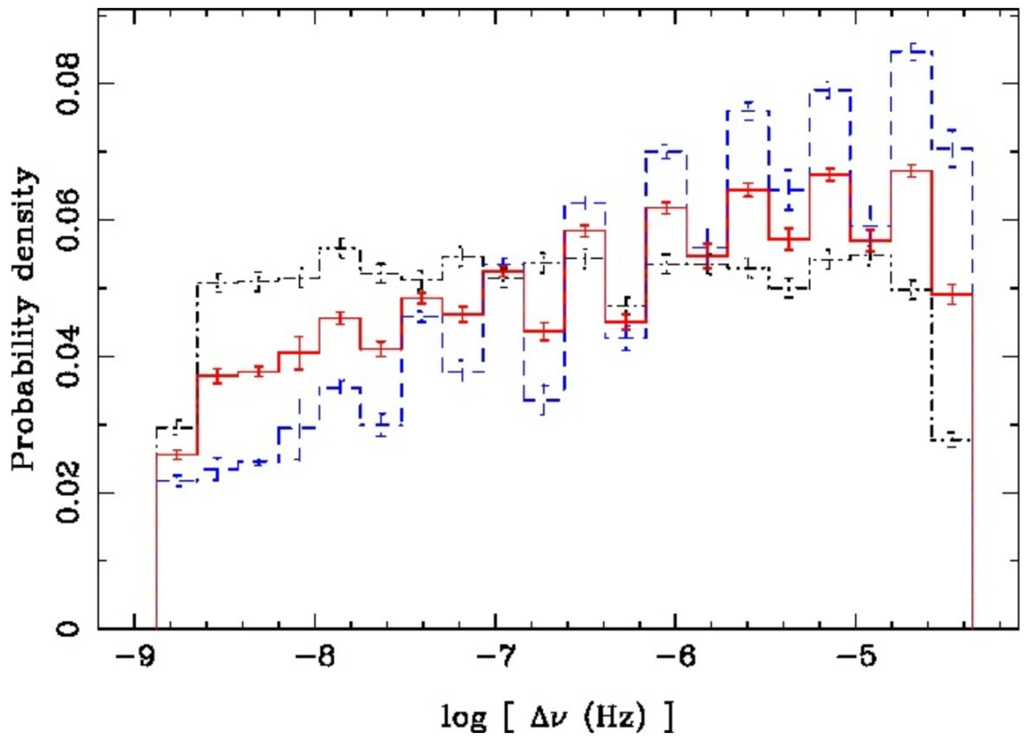
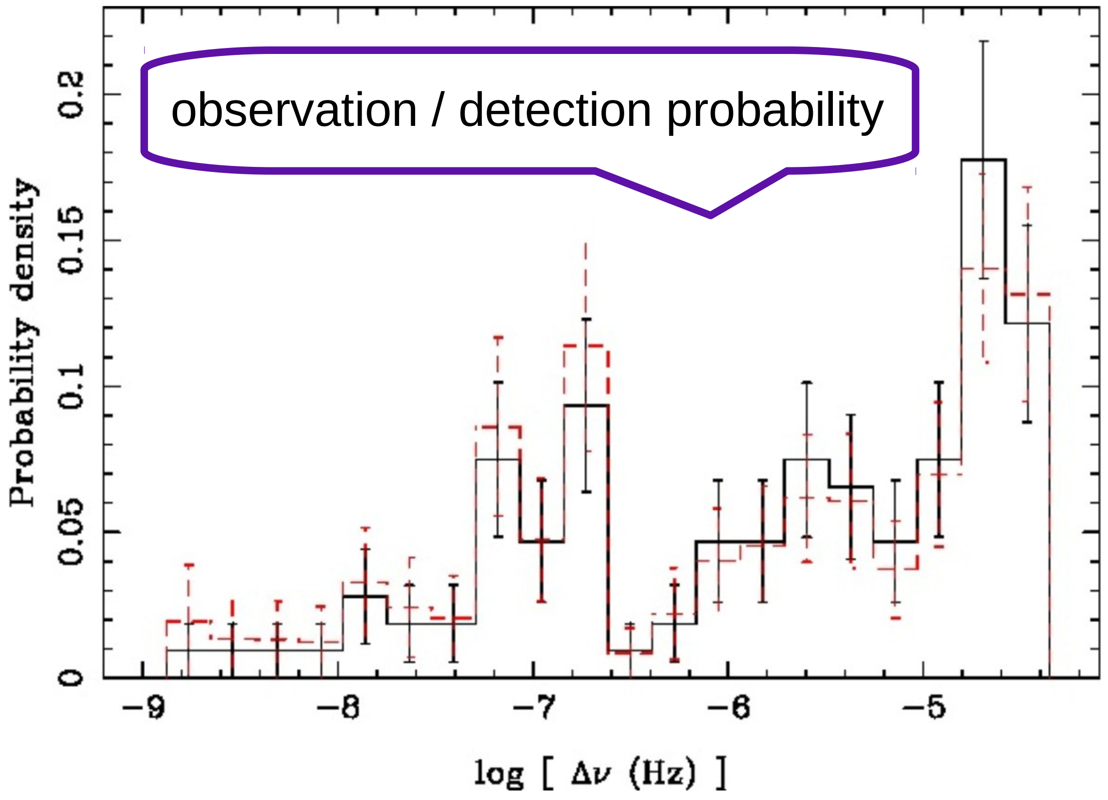


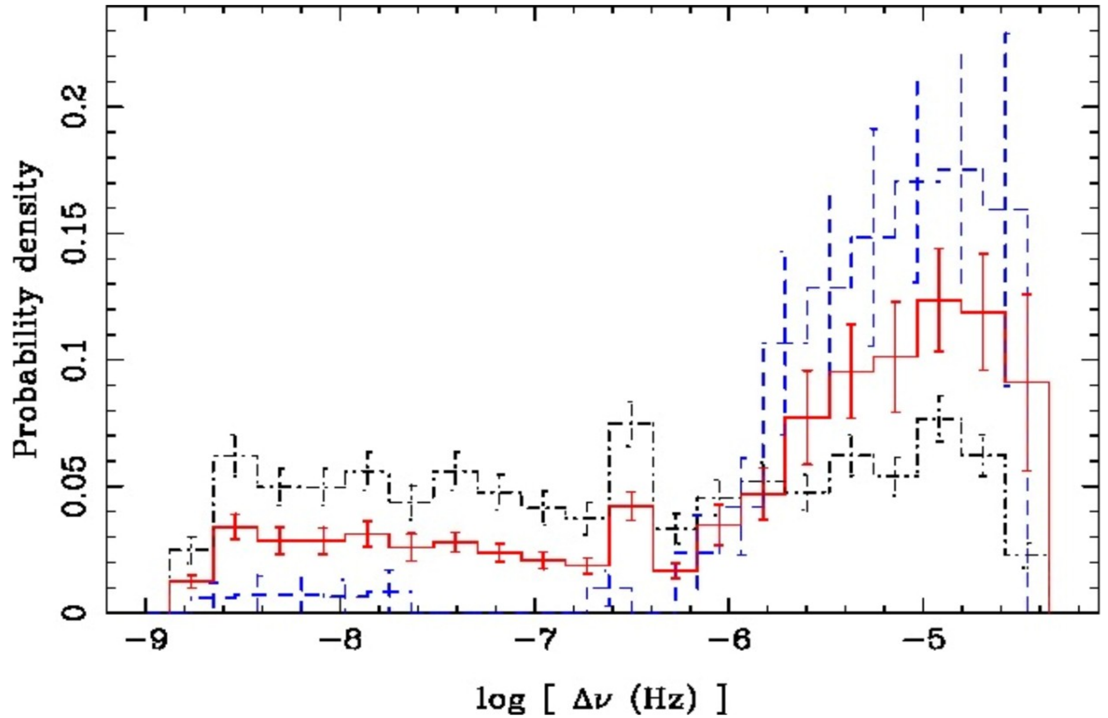
Fig. Derived glitch detection probability density (red filled bars) of the Yu et al. (2013) data sets. The partial components, noise term and the epoch term plus multiglitch term are indicated by blue dashed and black dashed-dotted bars.

4. Inferring distribution embedded in data



4.1 Group case

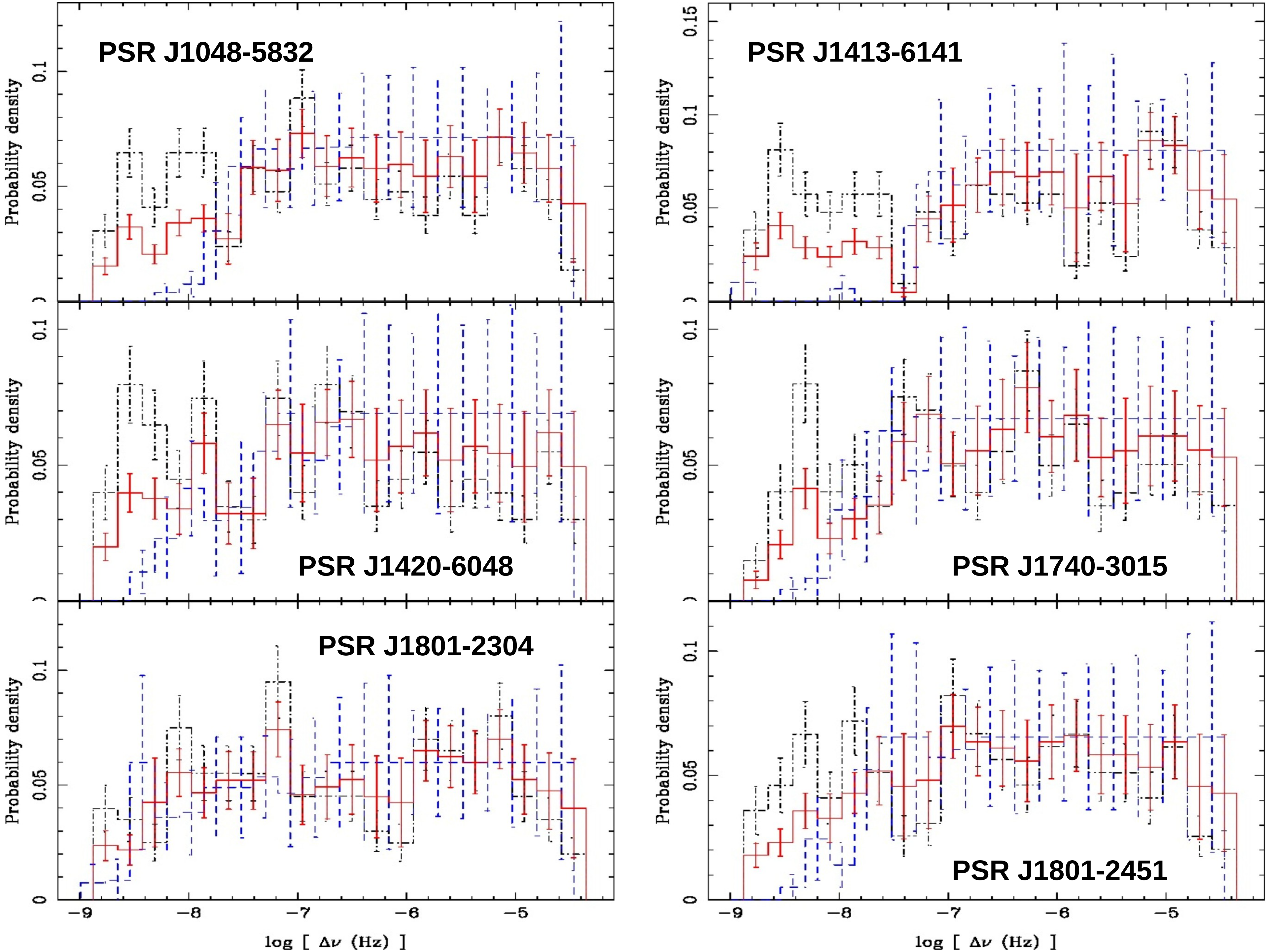
The similarity between the observed and inferred distributions implies Yu et al. (2013) have detected all detectable glitches.



4.2 Individual case

Similar approach was used to solve the complete probability formula for the seven individual pulsars which have been observed to glitch for five or more times.

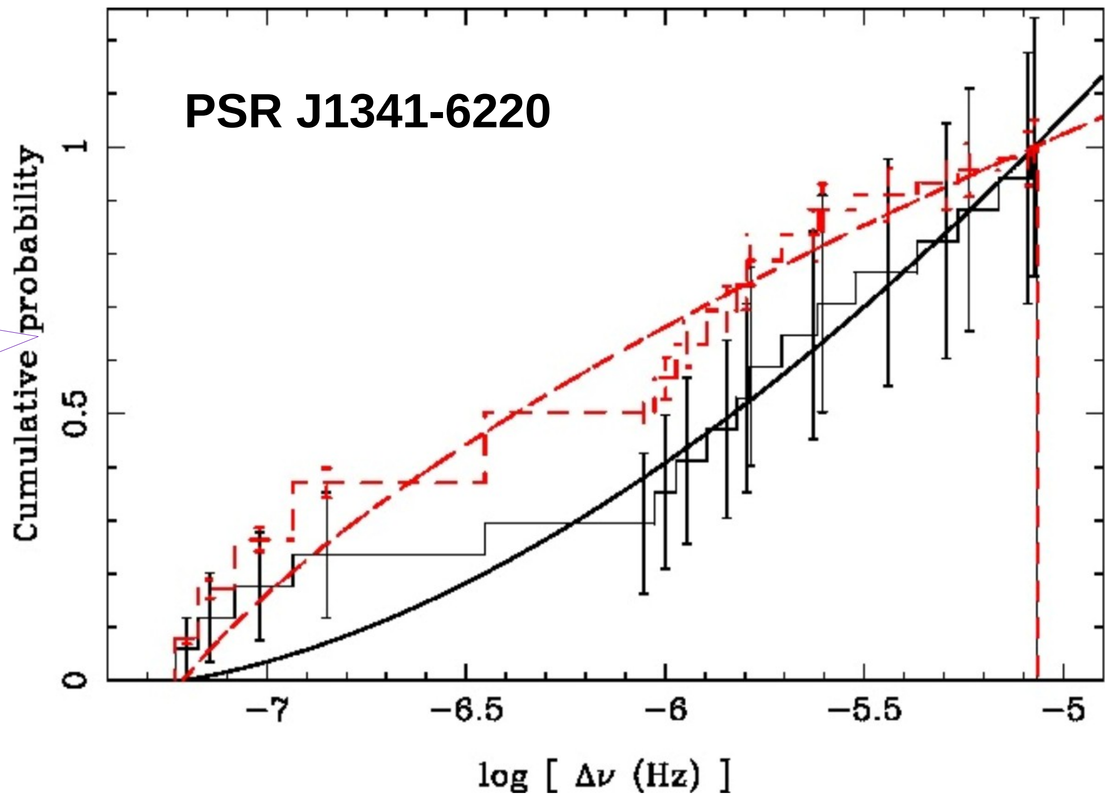
Figure to the right shows glitch detection probability density of PSR J1341-6220. The other six are shown on next page.

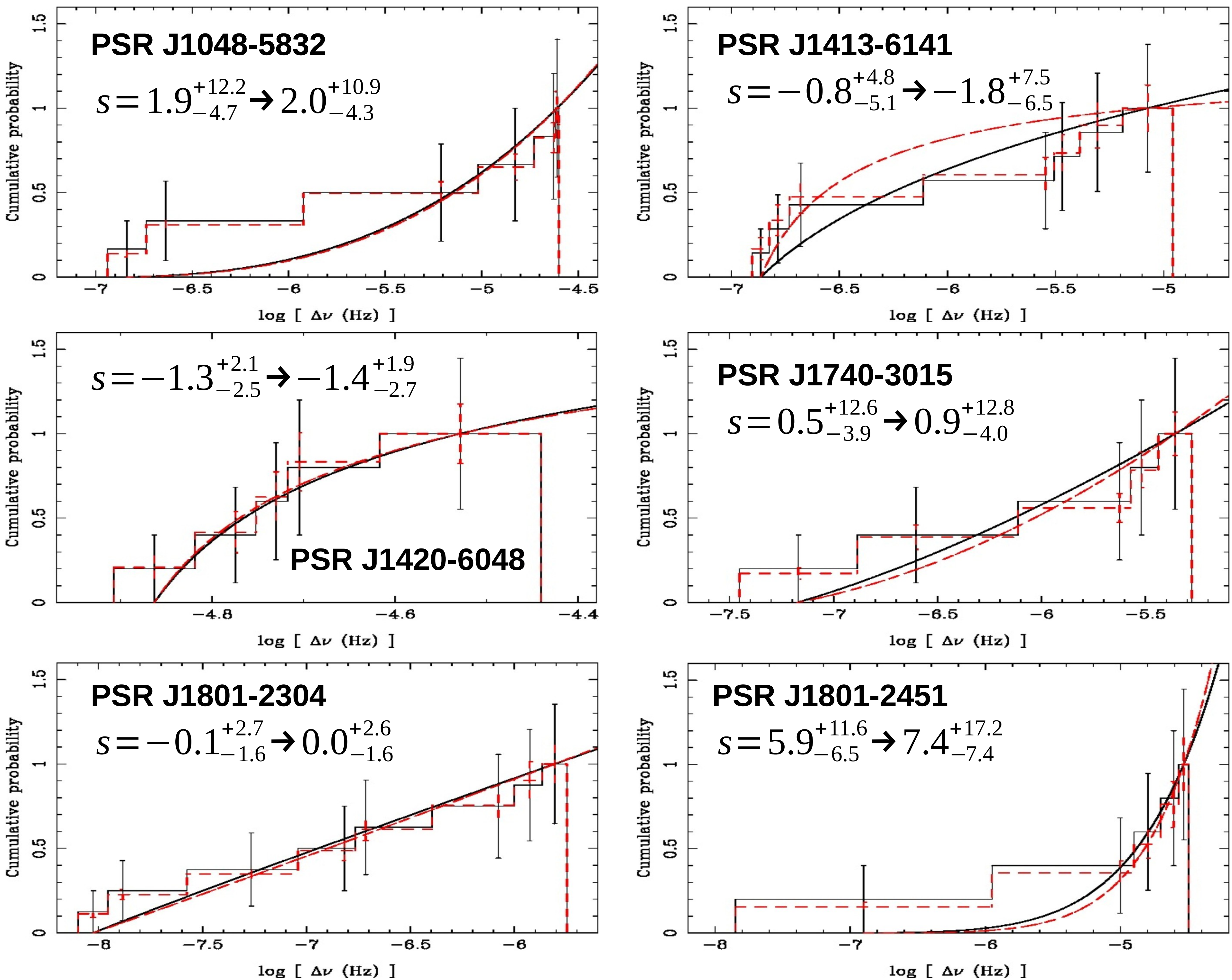

PSR J1048-5832
PSR J1413-6141
PSR J1420-6048
PSR J1740-3015
PSR J1801-2304
PSR J1801-2451
Probability density
log [Δν (Hz)]
0
0.05
0.1
0.15
−9
−8
−7
−6
−5

To derive distribution embedded in data for each of the seven pulsars, we first scatter observed glitch sizes into the 20 size bins, count of bin i is denoted n_i. Secondly, for the bins with nonzero n_i, we divide the count by the density value, the nearest integer is denoted m_i. Thirdly, when forming CDF of the sizes, we used the m_i values as the step (instead of one) at each size value. Finally, we least-squares fit the CDF with power-law model

$$P(<\Delta\nu) = \frac{\Delta\nu^{1+s} - \Delta\nu_{min}^{1+s}}{\Delta\nu_{max}^{1+s} - \Delta\nu_{min}^{1+s}}$$

$$s = 0.7^{+1.4}_{-0.7} \rightarrow -0.4^{+1.0}_{-0.4}$$

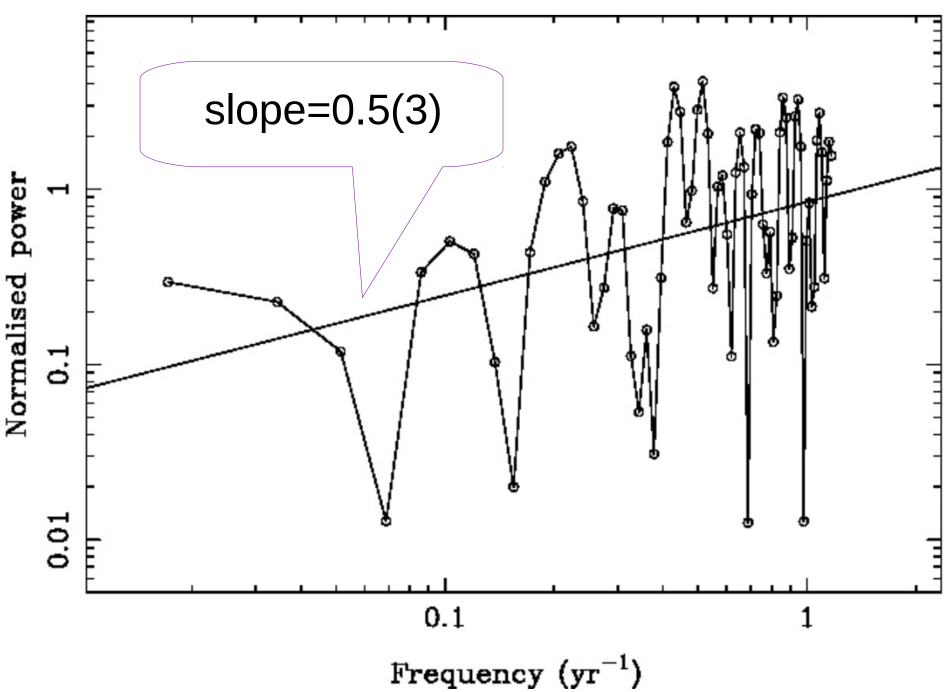




PSR J1048-5832
$s = 1.9^{+12.2}_{-4.7} \rightarrow 2.0^{+10.9}_{-4.3}$
PSR J1413-6141
$s = -0.8^{+4.8}_{-5.1} \rightarrow -1.8^{+7.5}_{-6.5}$
$s = -1.3^{+2.1}_{-2.5} \rightarrow -1.4^{+1.9}_{-2.7}$
PSR J1420-6048
PSR J1740-3015
$s = 0.5^{+12.6}_{-3.9} \rightarrow 0.9^{+12.8}_{-4.0}$
PSR J1801-2304
$s = -0.1^{+2.7}_{-1.6} \rightarrow 0.0^{+2.6}_{-1.6}$
PSR J1801-2451
$s = 5.9^{+11.6}_{-6.5} \rightarrow 7.4^{+17.2}_{-7.4}$
Cumulative probability
log [Δν (Hz)]

5. Conclusion

- By comparing the inferred and observed distributions, we found Yu et al. (2013) have detected all detectable glitches with the manual method described therein.
- In this work, we have established a good model for the detectability to glitches of the data set.
- Among the individual distributions, the most evident correction occurred for PSR J1341-6220, this pulsar is observed to show the strongest timing noise in the sample; the evident correction manifests timing noise absorbs glitches.
- PSR J1341-6220 shows 17 glitches in our data. The Lomb periodogram is derived for the time series of variation of glitch size as a function of glitch epoch. Straight-line fit to the periodogram results in a slope that violates prediction (-1) of the self-organised criticality.



Thank you

For details, please refer to Yu M., Liu Q.-J., 2017, MNRAS, 468, 3031