Sensitivity of Pulsar Timing Arrays to Individual Sources of Gravitational Waves

Southern Cross Astrophysics Meeting

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Collaborators

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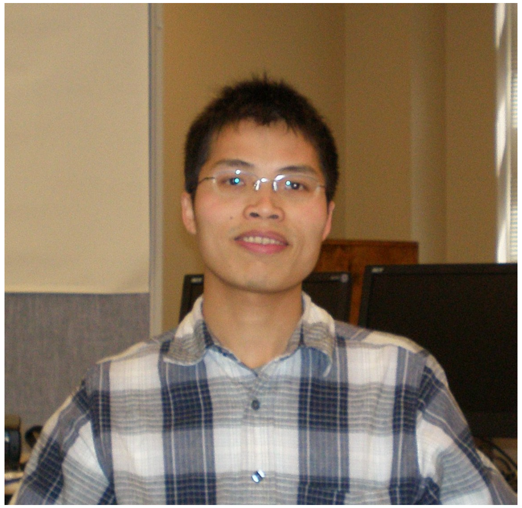
  

Talk Outline

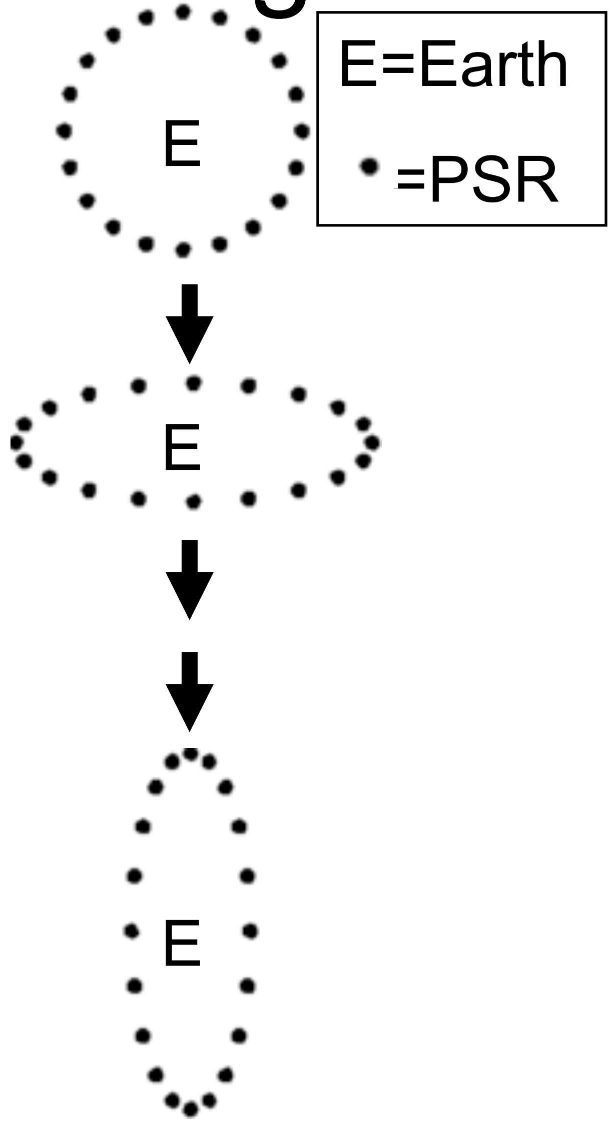
- Crash course in GWs and pulsar timing
- The project I’m involved in
- Detection algorithm & sensitivity curves for some different observing scenarios
- Sensitivity of PPTA data collected up to 2006

Brief intro: Gravitational Waves and Pulsar Timing

- A GW is a periodic distortion of space-time; stretching / compressing

- Pulsar timing compares observations of a pulsar to a model for its behaviour

- The model does not include GWs, hence we observe GWs in the timing residuals



The Project

- Use simulated & real data to constrain rate of coalescence of supermassive black hole binaries (SMBHBs)

- Non-detection

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  place a limit

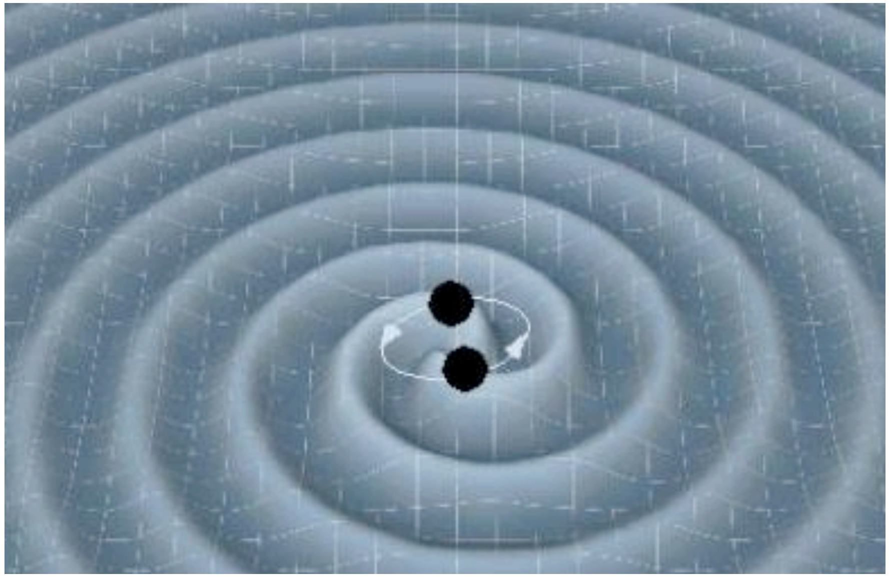


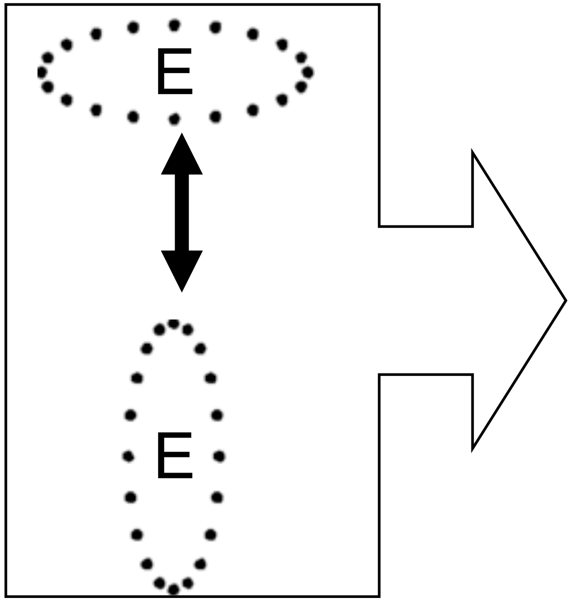
Image source: http://www.srl.caltech.edu /lisa/graphics/lisa_black_hole_binary.jpg

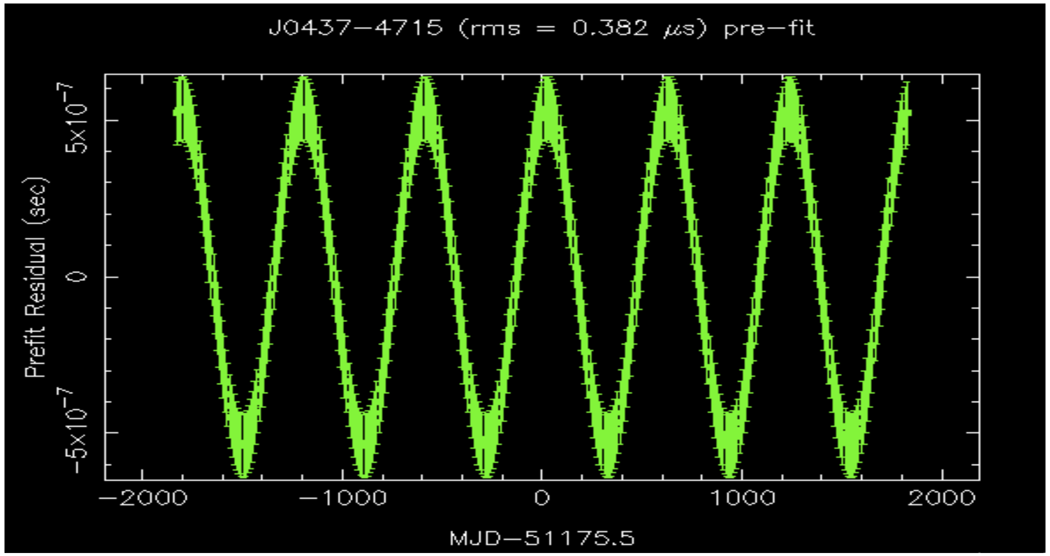
Science background

- Timing residuals induced by GWs from black hole binaries:

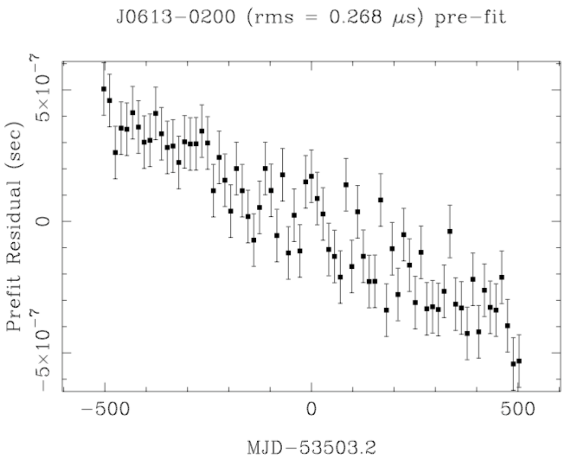
$$A_{res} = \frac{h_s}{\omega} \times geometrical\ terms \times polarization$$

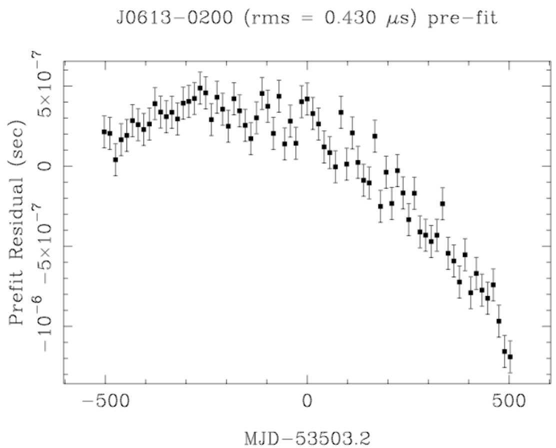
where ω is GW frequency, h_s is GW strain from a single SMBHB, A_{res} is amplitude of pulsar timing residual

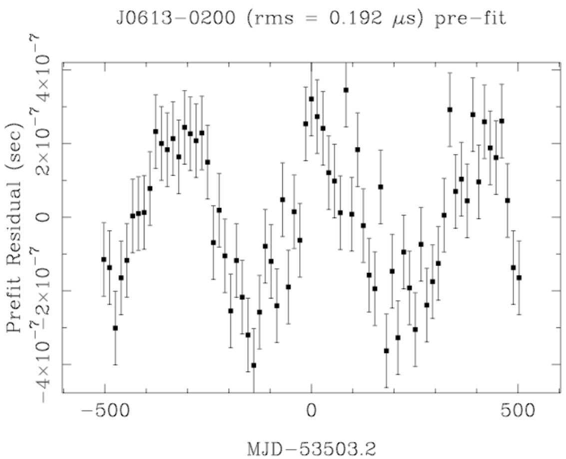


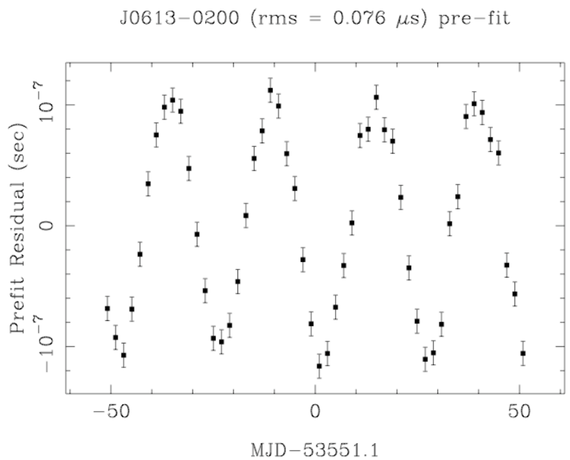


GW Signals Removed by Fitting









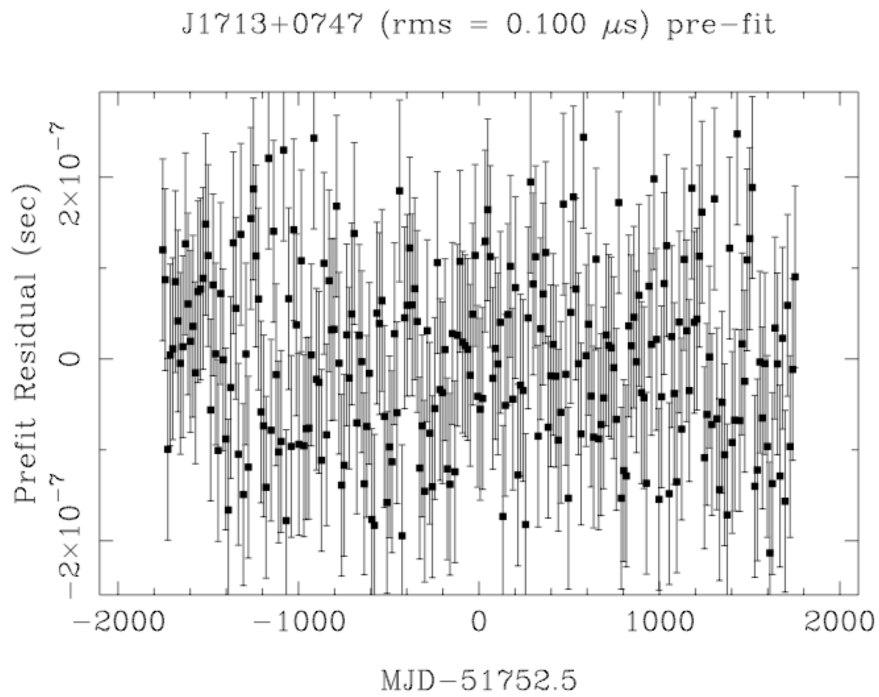
Detection Algorithm (1 of 4)

- Simulate TOAs for each pulsar using "fake" plugin, TEMPO2

- Residuals have flat power spectrum

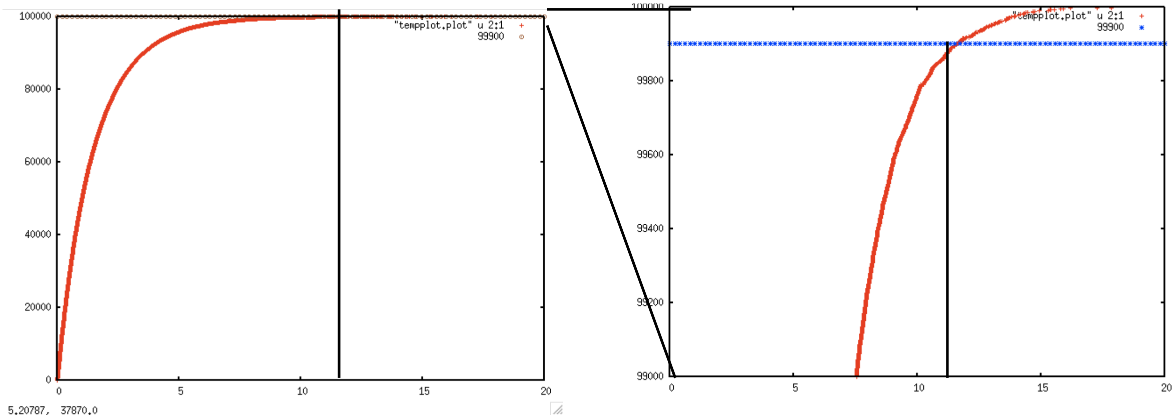
  ⬇

  shuffling residuals produces statistically equivalent data sets



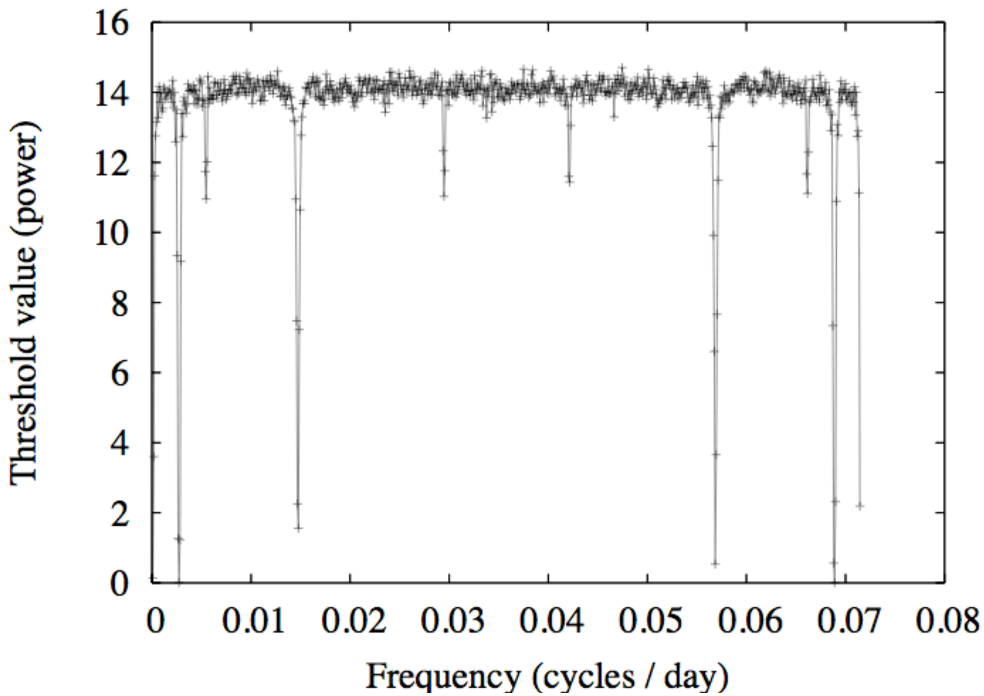
Detection Algorithm (2 of 4)

- Use shuffling technique to produce 100,000 stat'ly equiv. data sets.



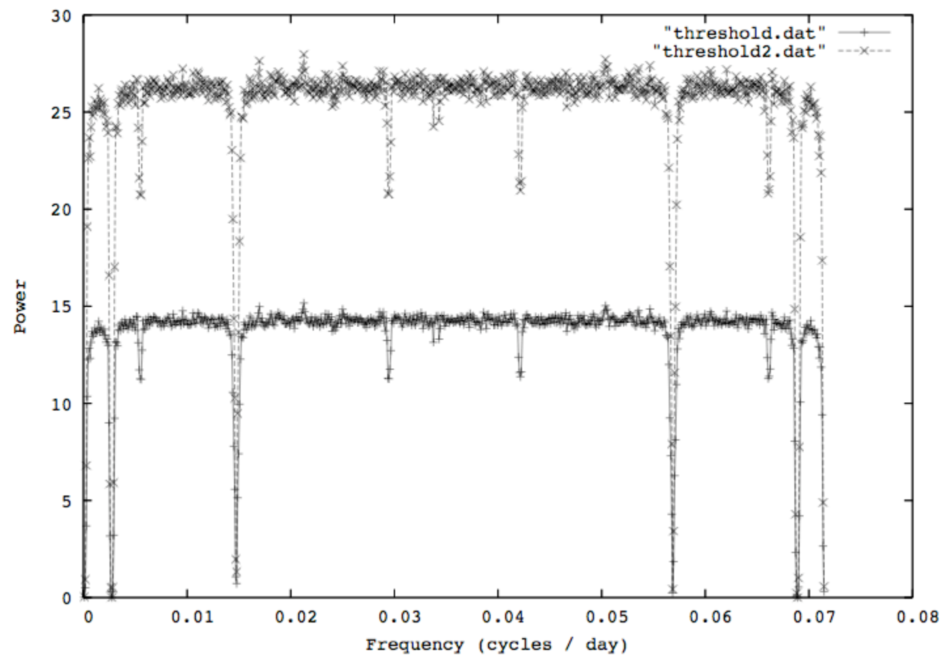
- Take Lomb periodogram of each

- Set power threshold in <u>each</u> frequency channel at 100th highest power (i.e. 0.1% false alarm probability)



Detection Algorithm (3 of 4)

- Now find factor "α" such that "$\alpha \times$ thresholds" gives 0.1% probability for no measured power above threshold in <u>any</u> channel



- Create 1,000 new data shuffles, add in GW at particular ω and h_s

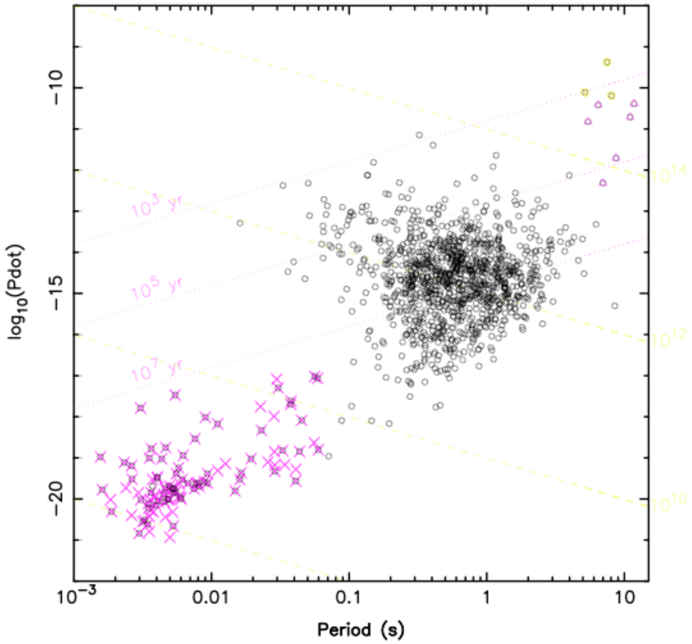
Detection Algorithm (4 of 4)

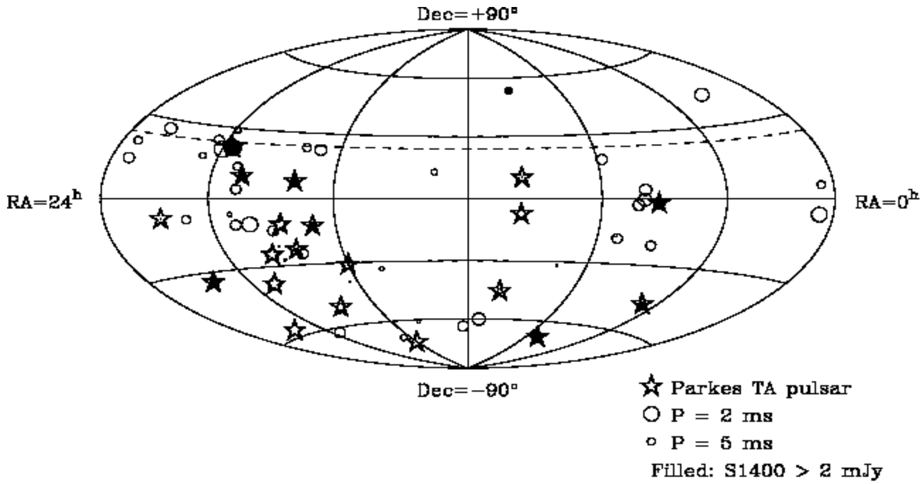
- If measured power is above (second, higher) threshold - detection is made
- Look at (ω, h_s) combinations that give a detection 95% of the time (so 950 / 1000)
- Run simulations on Swinburne Supercomputer

Simulation Results (1 of 6): Scenarios Chosen

Scenario	NumPsrs	RMS (ns)	Timespan
Arecibo I	1	10	5 / 10 / 15
Arecibo II	5	10	5 / 10 / 15
PPTA	20	100	5 / 10 / 15
NANOGrav	40	100 / 500	5 / 10 / 15
SKA I	100	100	5 / 10 / 15
SKA II	100	10	5 / 10 / 15

Simulation Results (2 of 6): Pulsars chosen





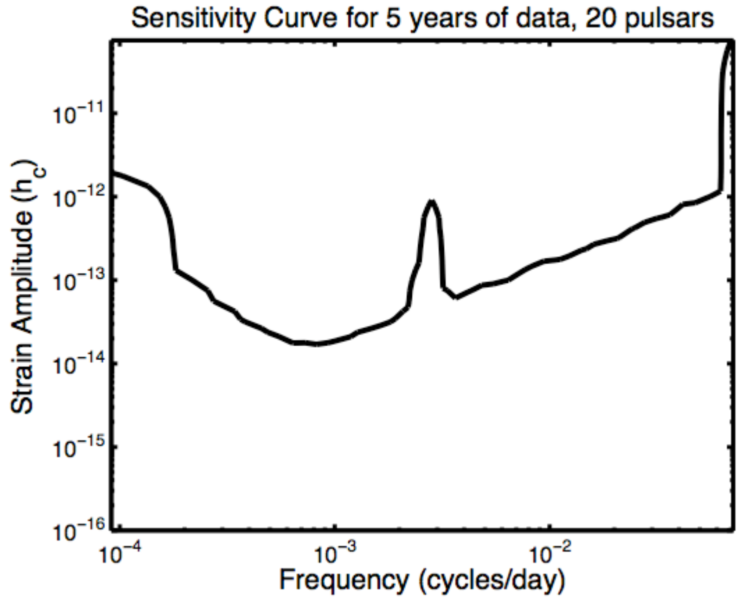
Subset of the 100 pulsars on the sky.

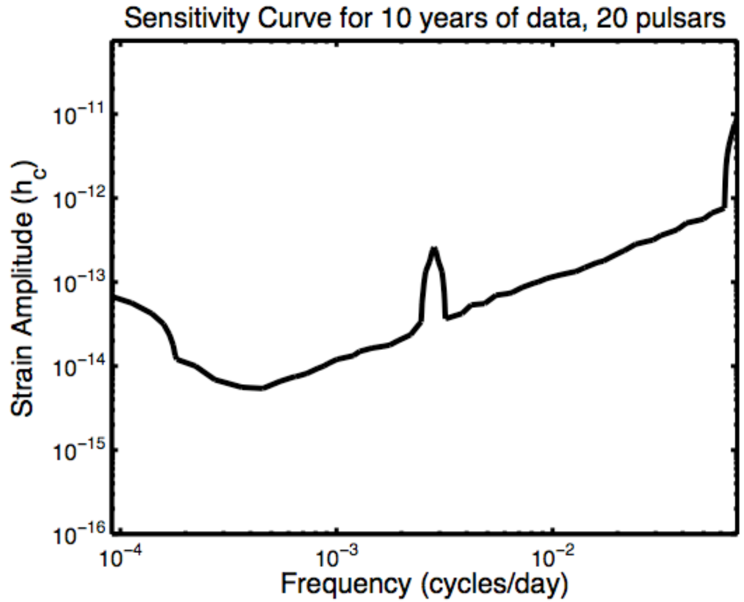
Purple crosses show pulsars used in SKA simulation.

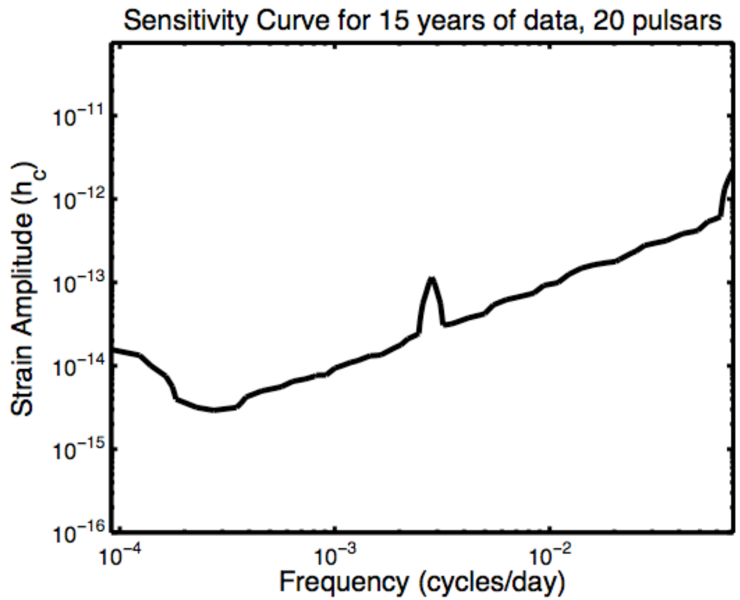
Chose pulsars with period < 60ms, period deriv. < 1e-17

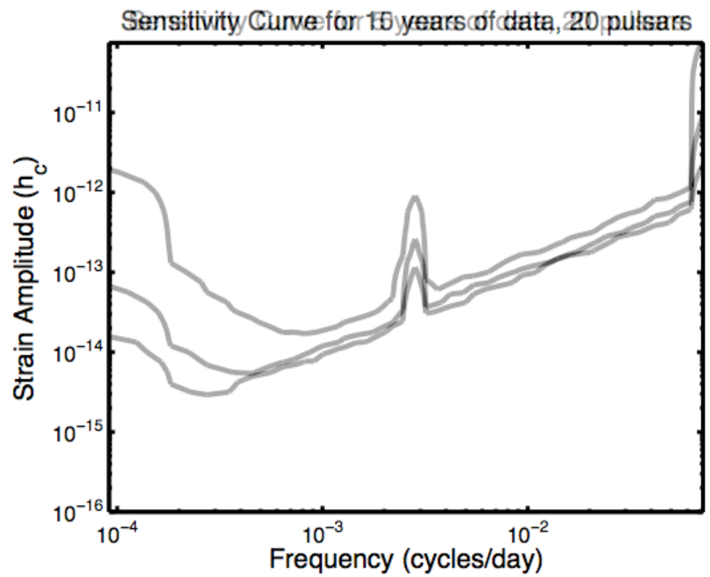
(Perhaps not for a timing array)

Simulation Results (3 of 6): PPTA Sensitivity Curves



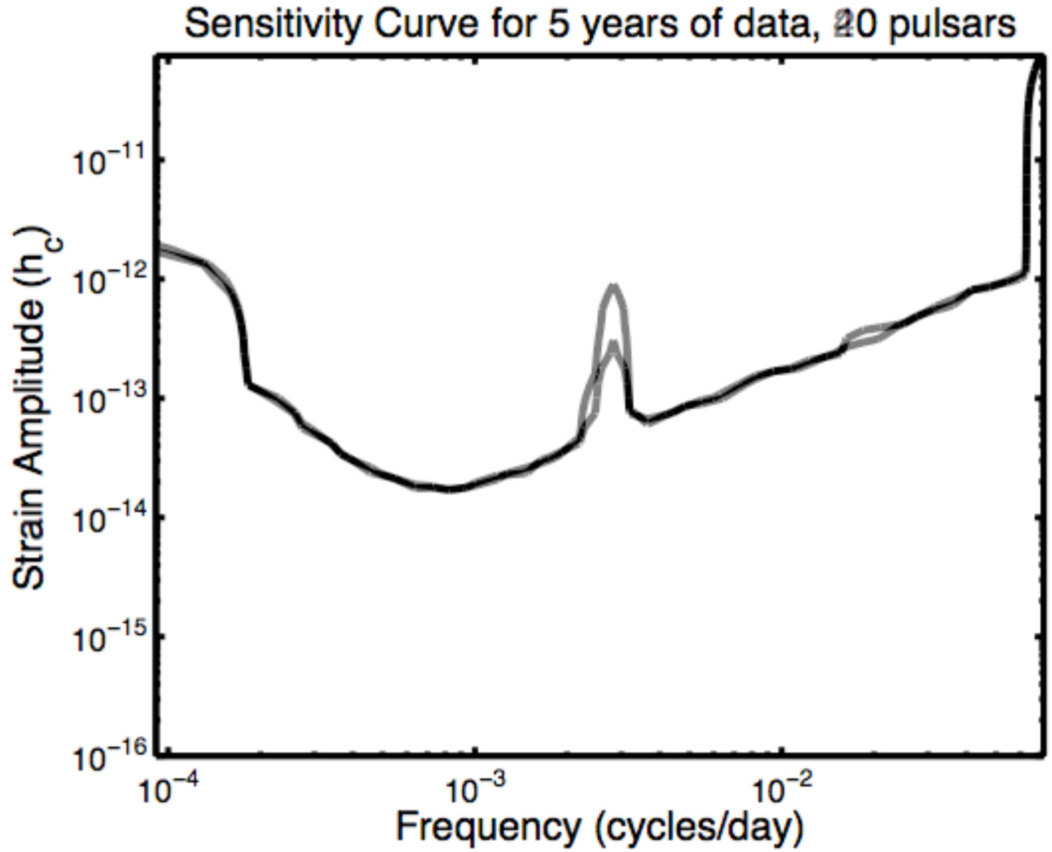




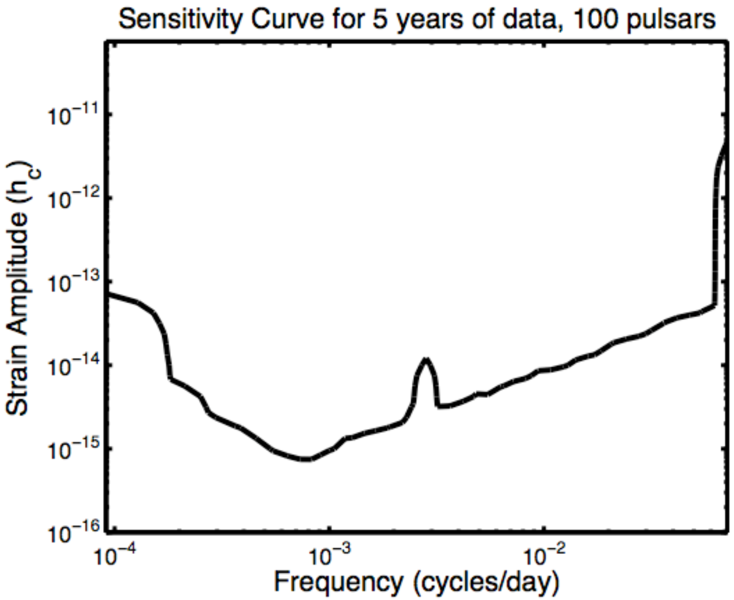


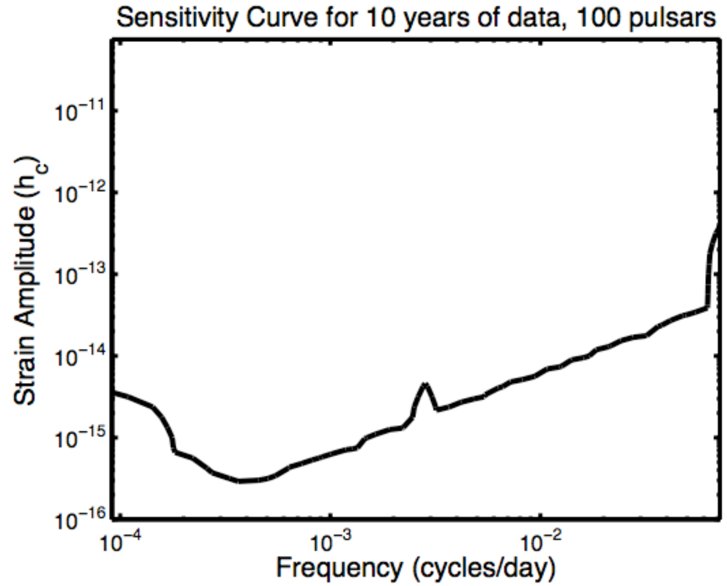
Simulation Results (4 of 6)
PPTA vs. NANOGrav

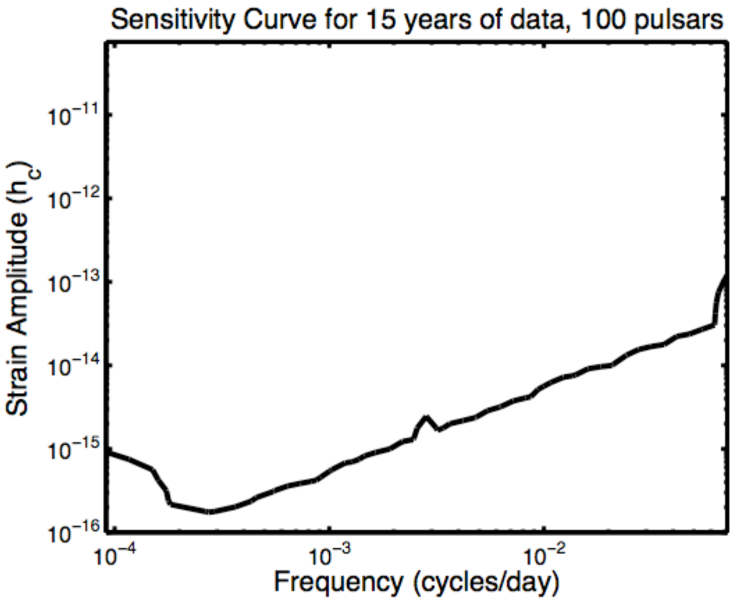
Extra 20 pulsars with 500ns timing residuals do not increase the sensitivity to individual sources!

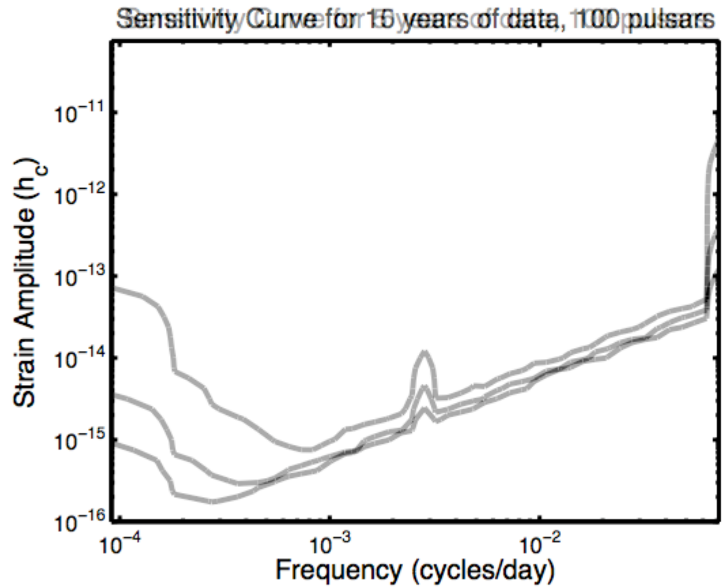


Simulation Results (5 of 6) SKA 10ns Sensitivity Curves









Simulation Results (6 of 6): Comments

Sensitivity ↑ as observing timespan ↑
Sensitivity ↑ as number of pulsars ↑
Sensitivity ↑ as rms residual ↓
all as expected

- Greatest sensitivity is very near $\frac{1}{T_{obs}}$ in case of white residuals
- In detection regime, $h \propto \omega$ due to amplitude of residual being frequency-dependent

Results for PPTA (up to 2006) (1 of 3)

- White datasets from 7 pulsars used
- Still use shuffling technique

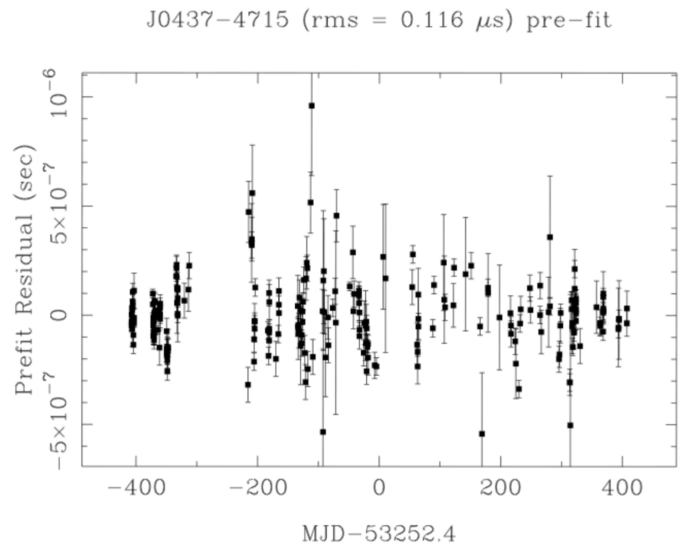


TABLE 2

PULSAR OBSERVATIONS USED FOR THIS ANALYSIS

Pulsar	Telescope	Span (days)	N	rms Residual (μs)
J0437−4715.........	Parkes	815	233	0.12
J1024−0719.........	Parkes	861	92	1.10
J1713+0747..........	Parkes	1156	168	0.23
J1744−1134.........	Parkes	1198	101	0.52
J1857+0943..........	Arecibo/Parkes	7410	398	1.12
J1909−3744.........	Parkes	866	2859	0.29
J1939+2134..........	Parkes	862	231	0.21

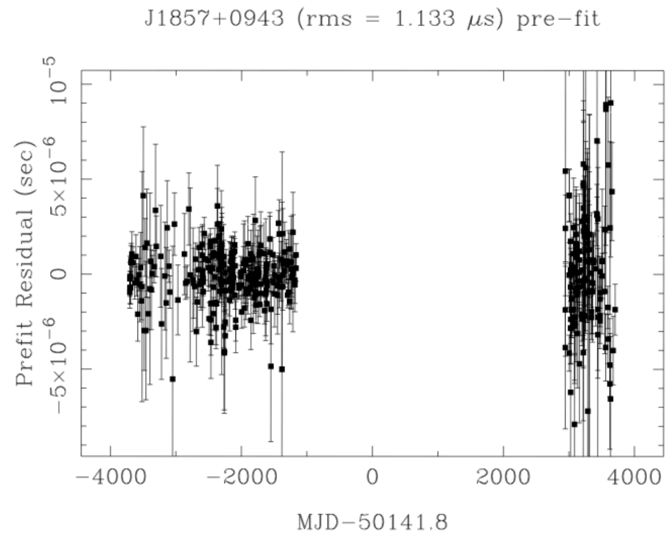
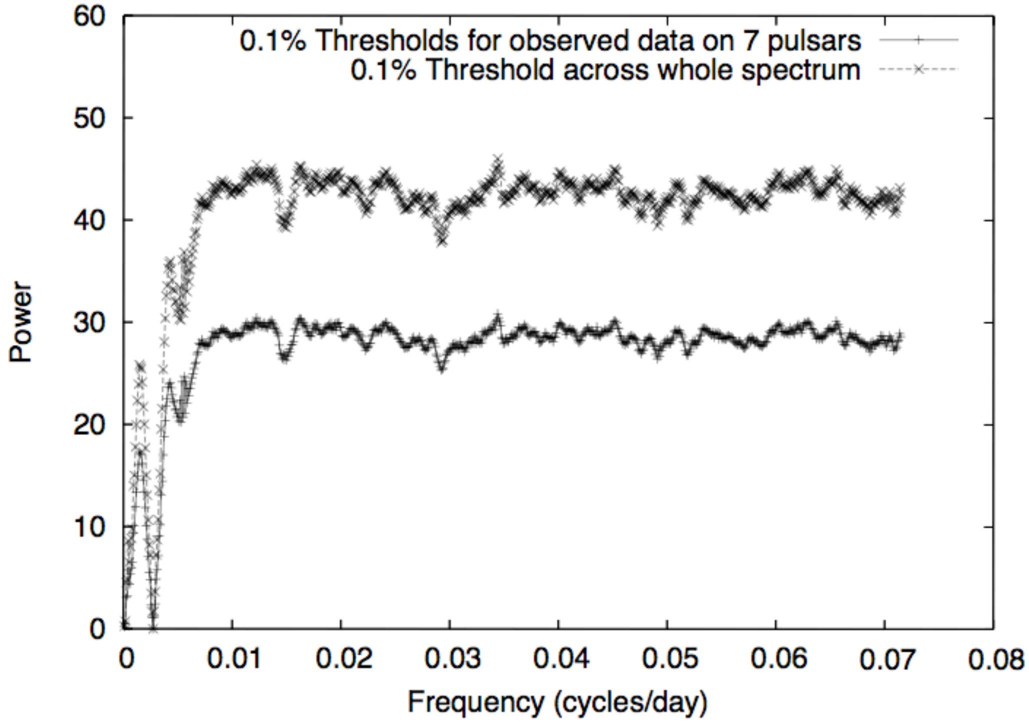


Table from Jenet, F.A. et al., 2006, ApJ, 653, 1571-6

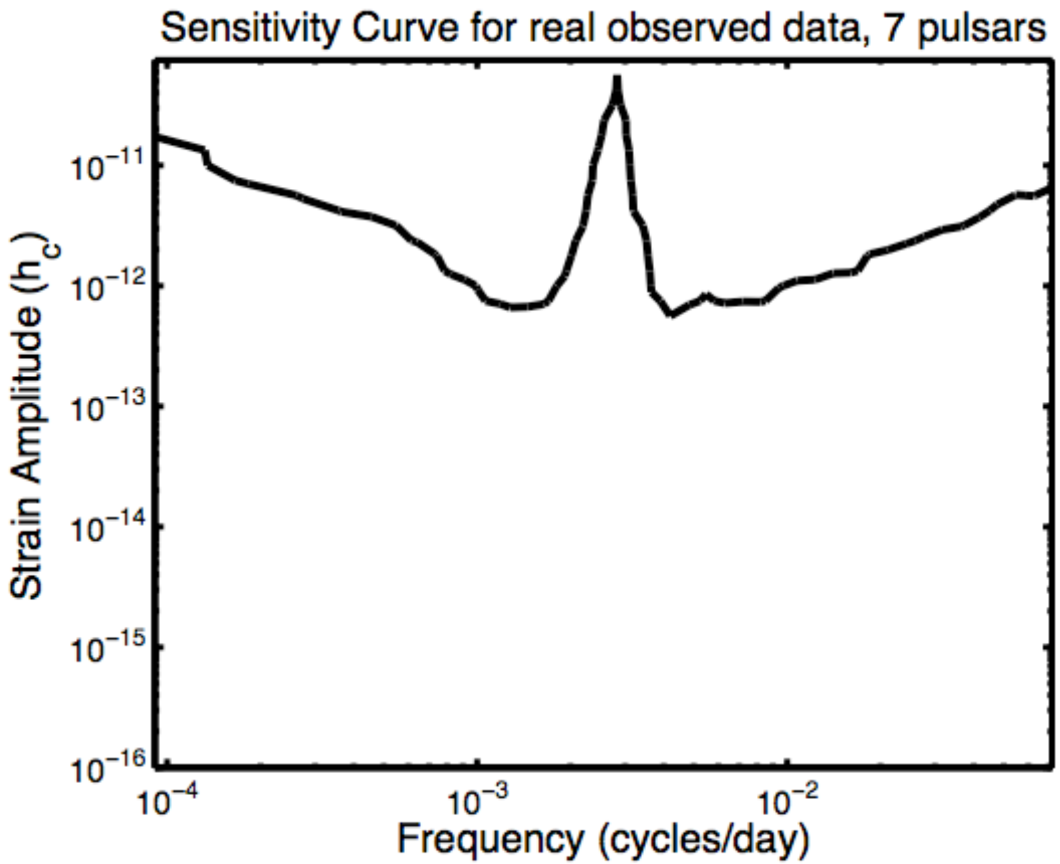
Results for PPTA (up to 2006) (2 of 3)

- Thresholds for detection using real data
- Note lack of aliasing due to irregular sampling



Results for PPTA (up to 2006) (3 of 3)

- Sensitivity curve for real data (7 pulsars)
- Shortest data span = 815 d = (1/1.2e-3) d
- Breadth of 1yr peak probably due to oversampling.



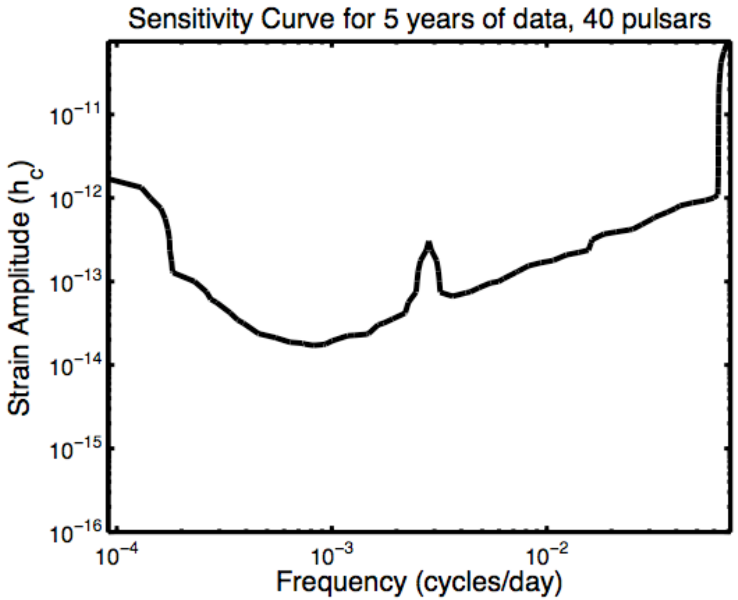
Next Steps…

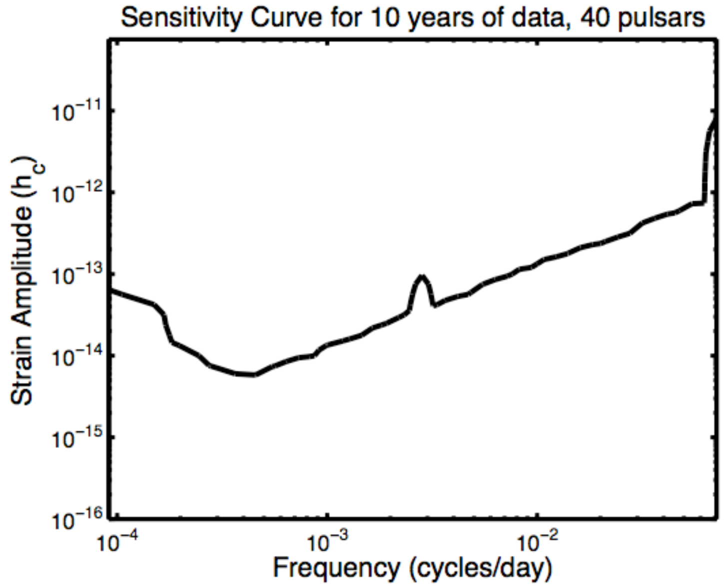
- Do simulations including stochastic background (so far have used unrealistic assumption of whiteness)

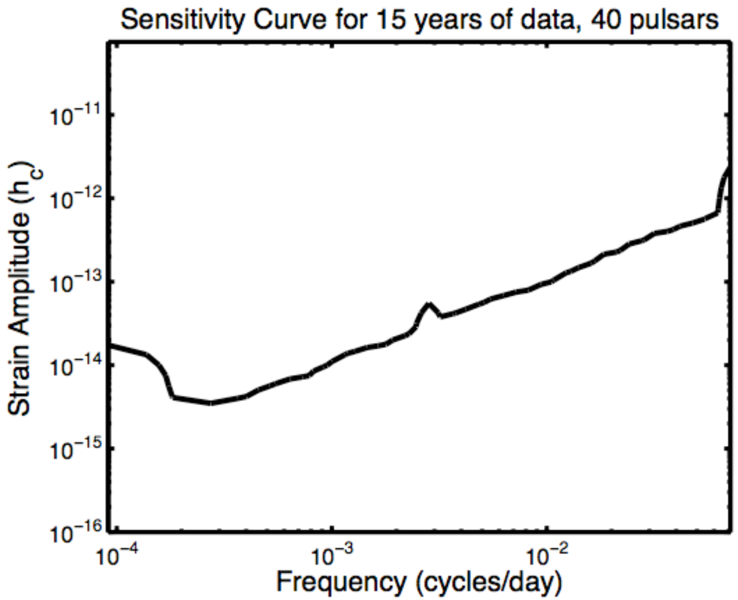
- Use fully updated PPTA datasets (~600 more days on each pulsar)

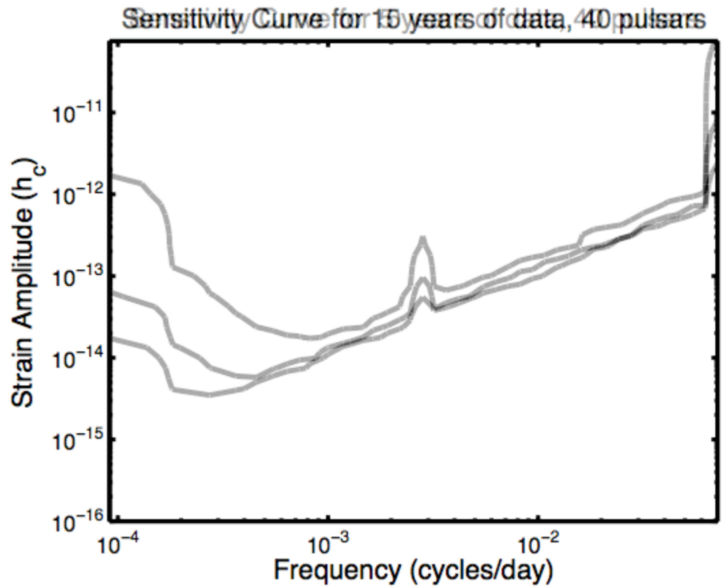
THE END

Simulation Results (of): NANOGrav Sensitivity

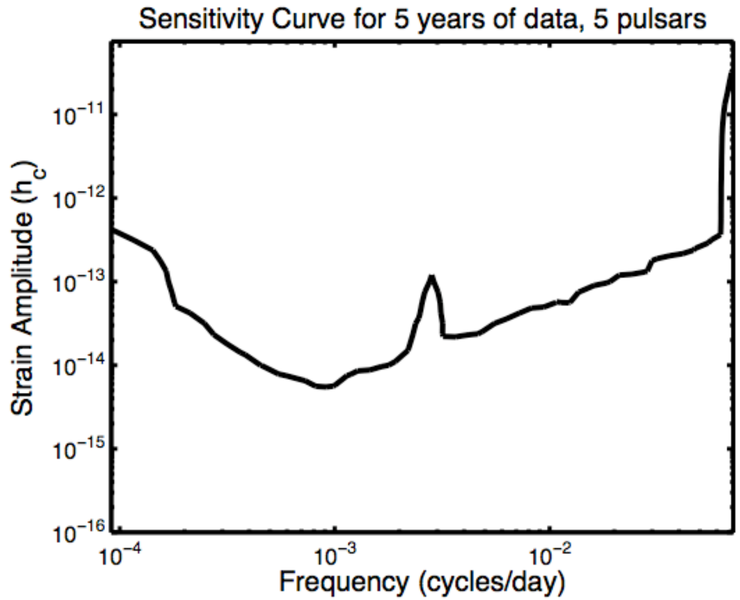


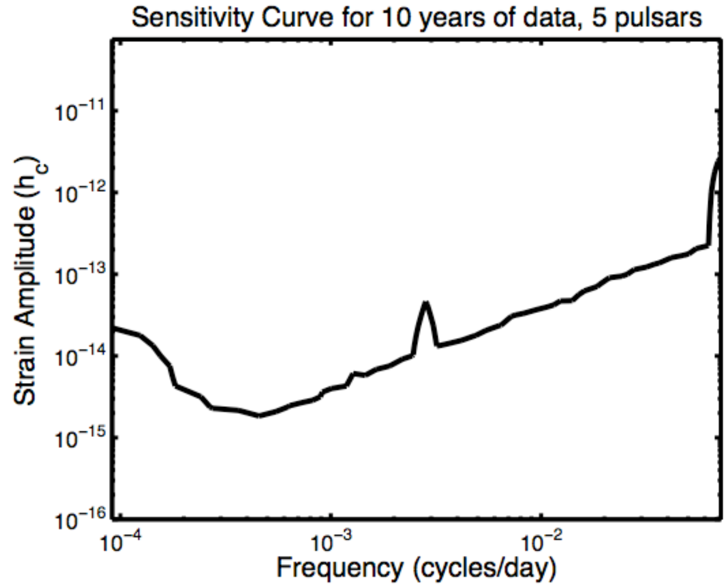


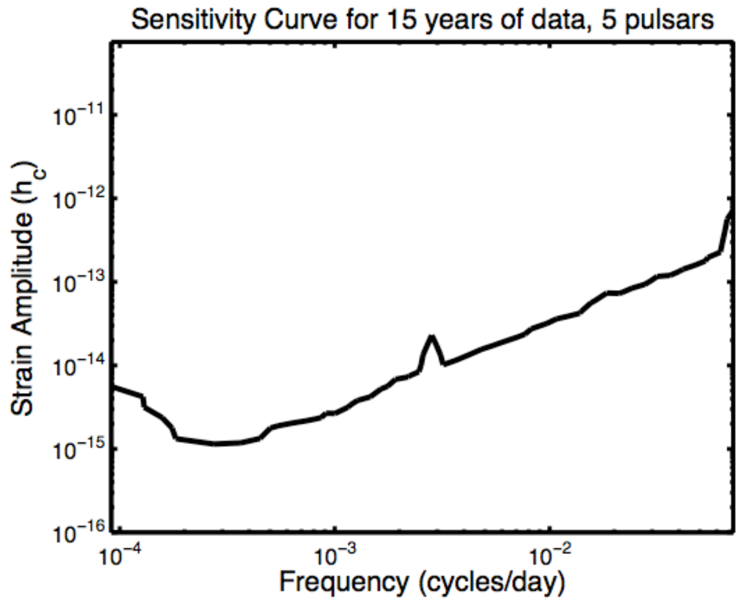


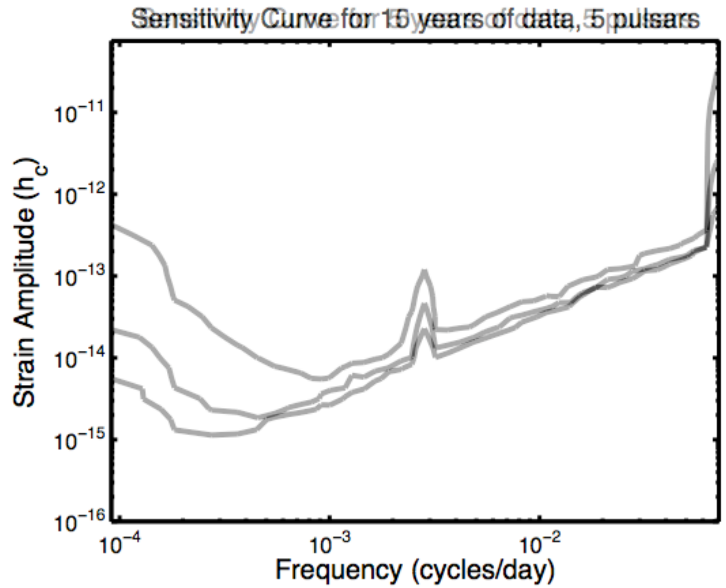


Arecibo 5 psr Sensitivity Curves





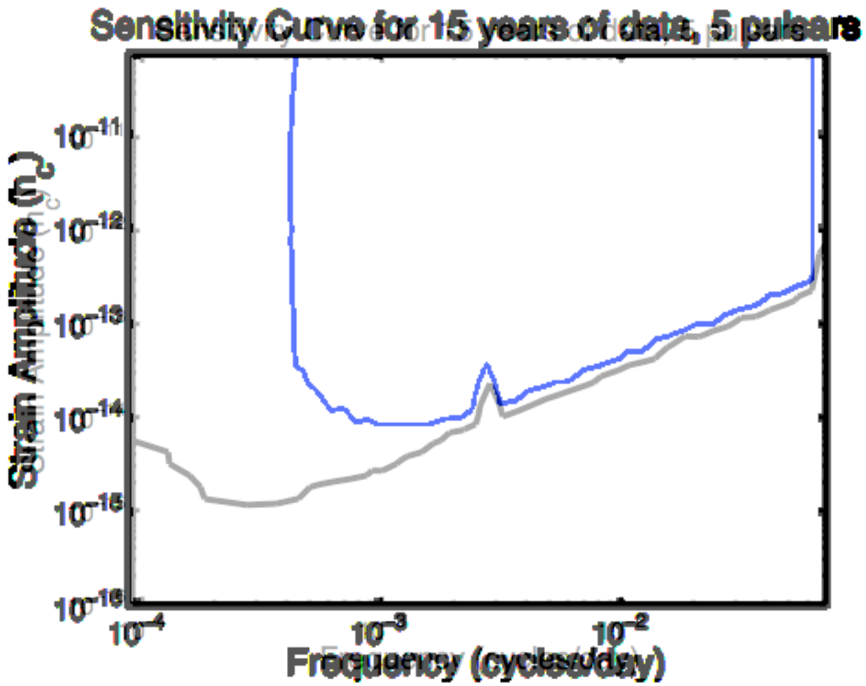




Simulation Results (5 of 6)

- Can include a stochastic background also. Shown here -

$$h_c(f) = 10^{-16} f^{-2/3}$$



- Had a few issues with this…

$$h_s = 4\sqrt{\frac{2}{5}}\frac{(GM_c)^{5/3}}{c^4 D(z)}\left(\pi f(1+z)\right)^{2/3}$$