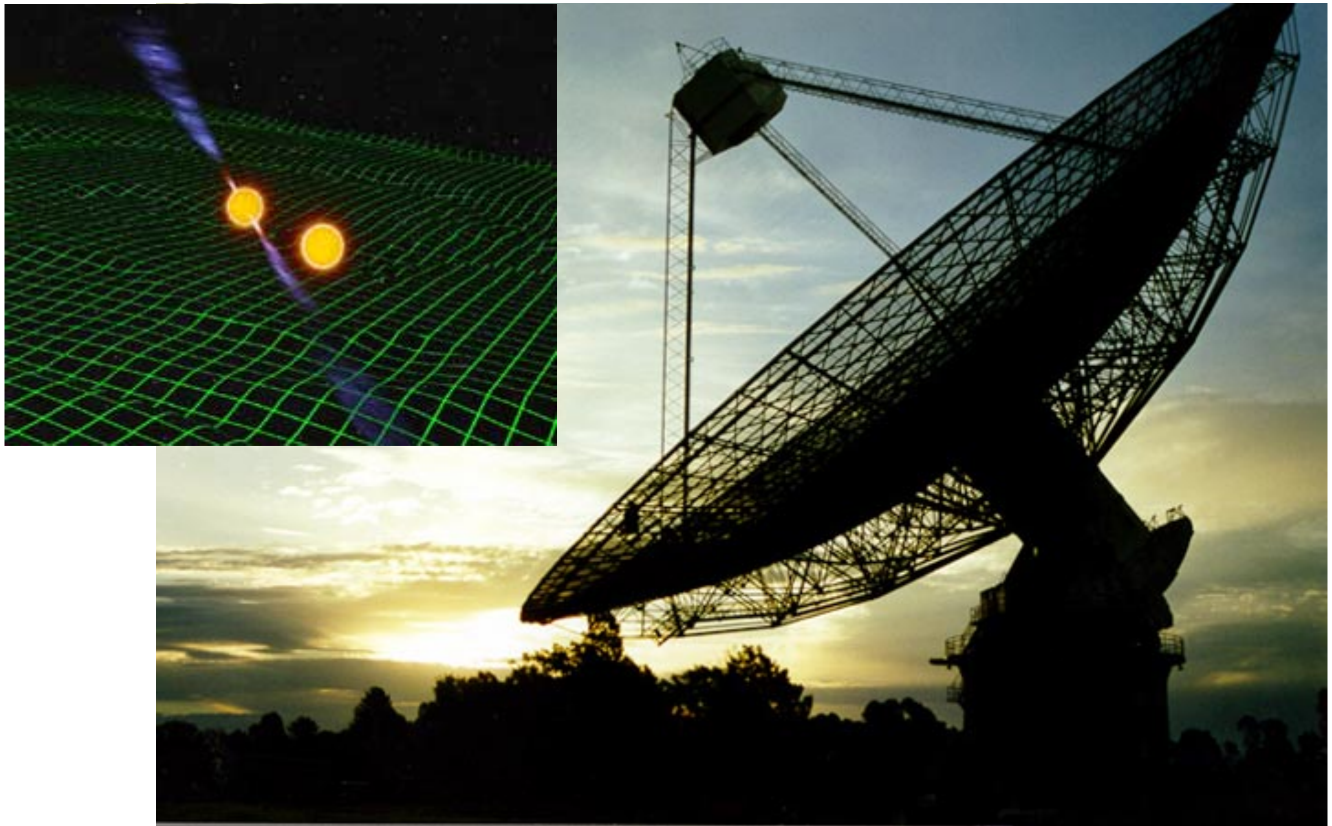

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Pulsars and gravitational waves: 1
An introduction

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Let's start at the beginning

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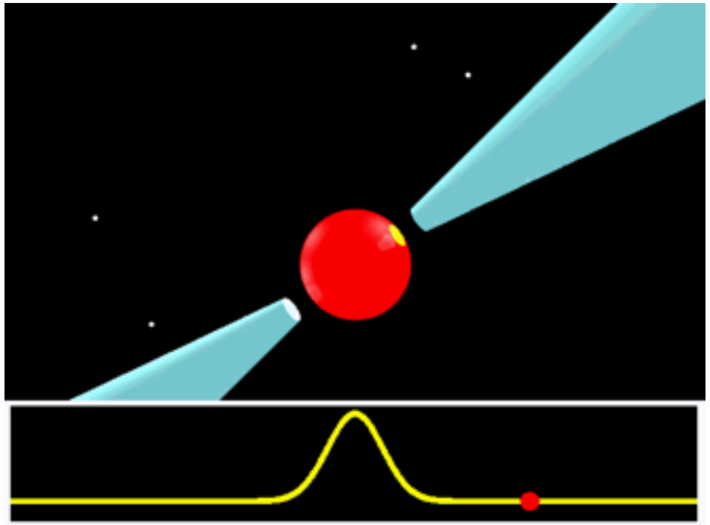


Animation: Michael Kramer

- Formation of the beam
- Propagation through the magnetosphere
- Propagation through the interstellar medium
- Propagation through the interplanetary medium
- The pulsar's astrometric, pulse and orbital parameters
- ...
- gravitational waves passing the Earth and/or the pulsar

Lecture series

- Lecture 1: overview (a bit of everything)
- Lecture 2: the pulsar timing method. How gravitational waves influence pulsar observations
- Lecture 3: Expected gravitational wave sources. Current data sets
- Lecture 4: Techniques to search for gravitational waves
- Lecture 5: a bit of fun and the future!

Purpose of this lecture series

- Provide an overview of pulsars
- Provide an overview of gravitational waves
- Show how, in theory, pulsar observations can be used to detect gravitational waves
- Describe issues with the current data sets
- Describe unsolved problems
- Provide enough information that you can process pulsar observations and develop tools to search for gravitational waves
- Understand the terminology used in the pulsar/gravitational wave literature
- Know what work has already been done
- Know what are the current problems that need to be solved
- Understand the future possibilities for this project

Purpose of lecture 1

- Provide an overview of pulsars, gravitational waves, pulsar timing and current results
- This is a general, colloquium-style talk to provide a basic overview
- A lot more details on all topics during the next four talks

- 1 goal: you should understand the phrase “pulsar timing residual”

- Please ask lots of questions during the talk

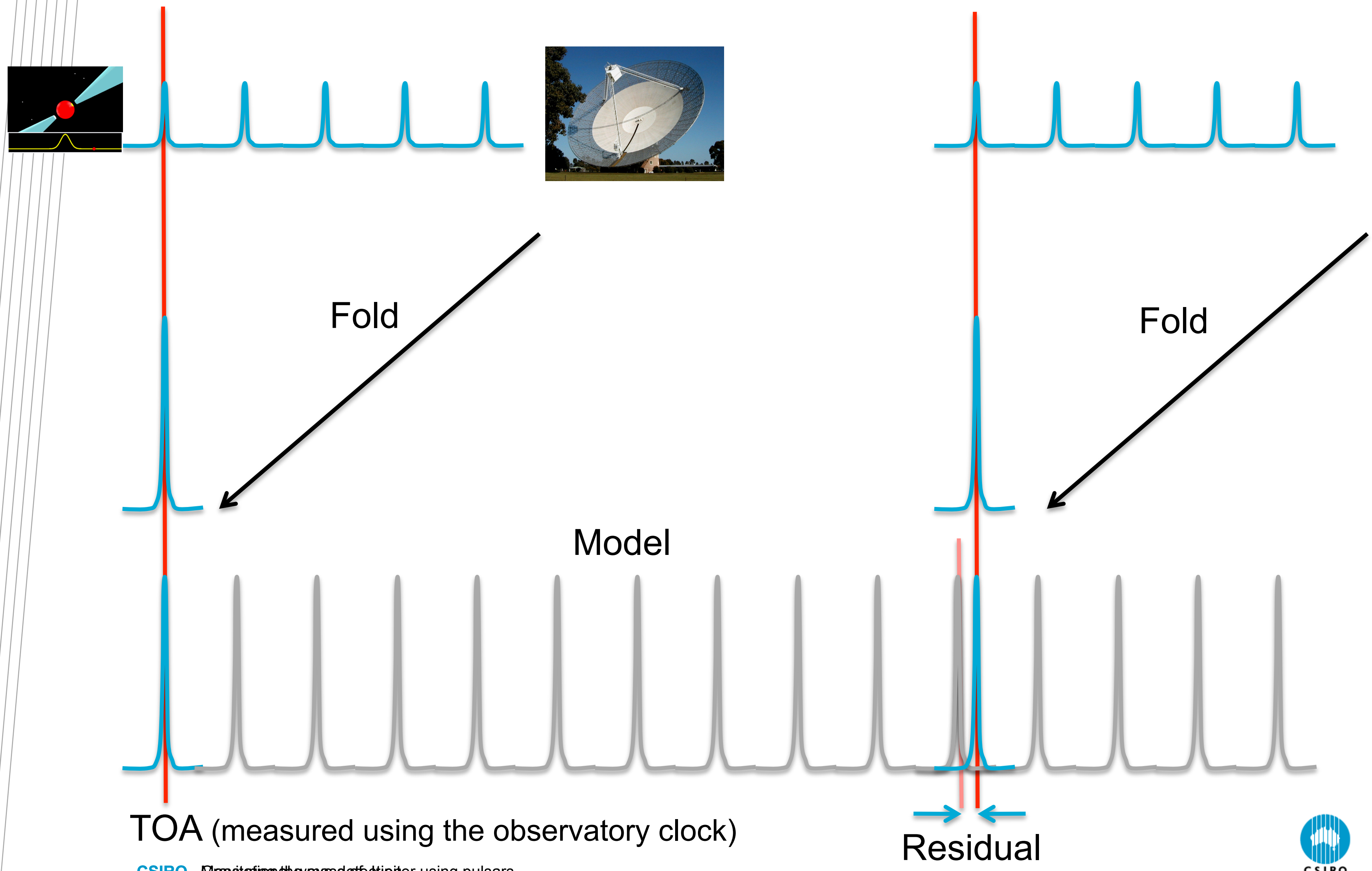
Structure of talk

- Part 1: Introduction to pulsar timing
- Part 2: Uncorrelated timing residuals
- Part 3: Monopolar correlations
- Part 4: Dipolar correlations
- Part 5: Quadrupolar correlations

- (Use data from the Jodrell Bank Observatory and Parkes Pulsar Timing Array project)

Pulsar timing

Slide from D. Champion



Pulsar timing (details in Edwards, Hobbs & Manchester, MNRAS, 2006)

Model for pulsar spin down

Improve

Obta

times

```
../archives/m2003-01-04-09:28:46.IFTp 1405.69000000 52643.43167667956360134 0.05000 7 -i mCPSR2_20
../archives/m2003-01-05-07:47:36.IFTp 1405.69000000 52644.32508854790199848 0.50000 7 -i mCPSR2_20
../archives/m2003-01-05-08:02:11.IFTp 1405.69000000 52644.35381661670970033 0.06000 7 -i mCPSR2_20
../archives/m2003-01-06-10:09:56.IFTp 1405.69000000 52645.44665465660590087 0.07000 7 -i mCPSR2_20
../archives/m2003-01                                                          15000 7 -i mCPSR2_20
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../archives/m2003-01-12-12:18:06.IFTp 1405.69000000 52651.51479977265690025 0.20000 7 -i mCPSR2_20
../archives/m2003-01-12-12:25:10.I
../archives/m2003-01-12-12:33:50.I
../archives/m2003-01-12-12:40:32.I
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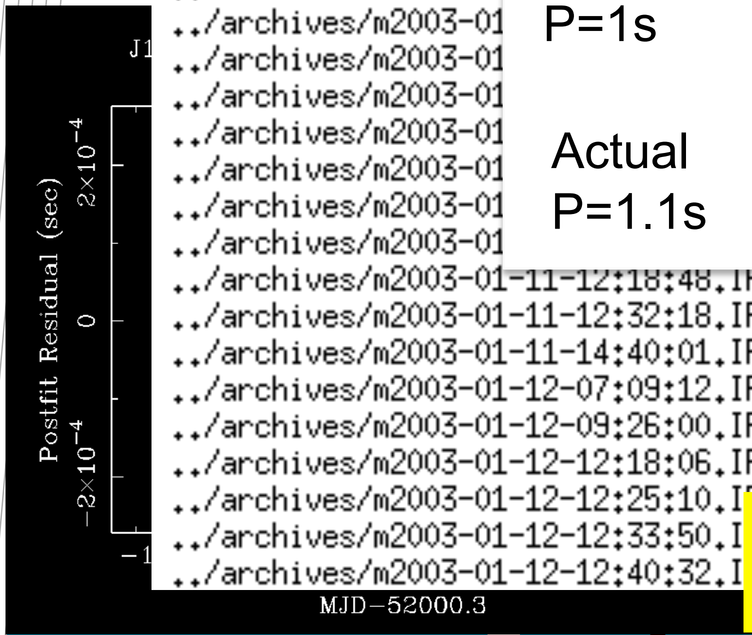
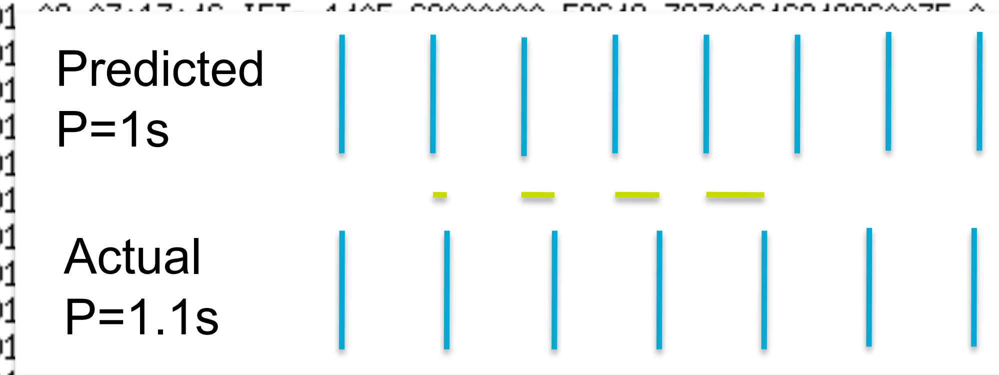


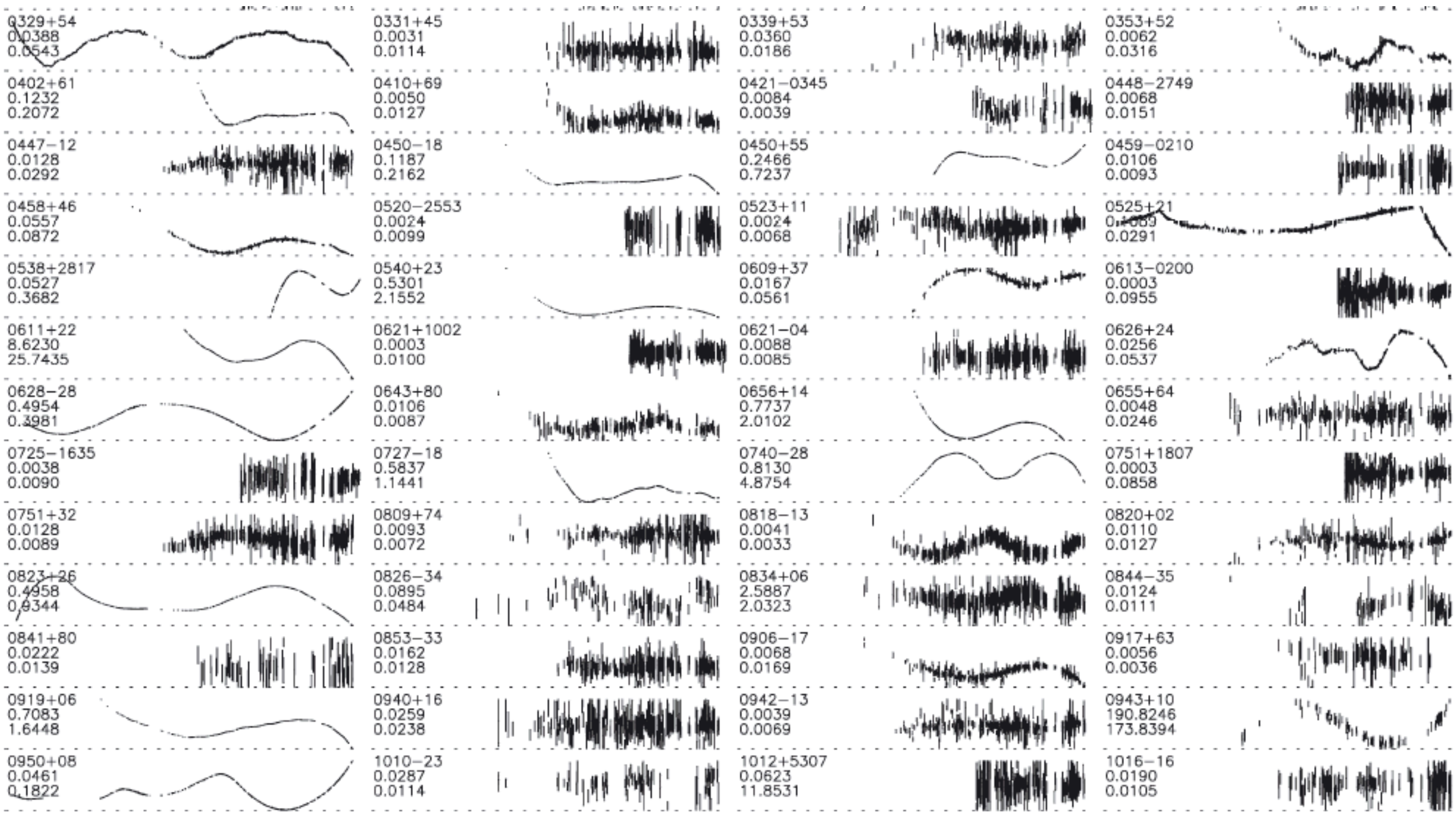


F0 = 245.4261197483027 +/- 0.0000000000005 Hz
F1 = -5.38188×10^{-16} +/- 4×10^{-21} Hz/s

solar system barycentre

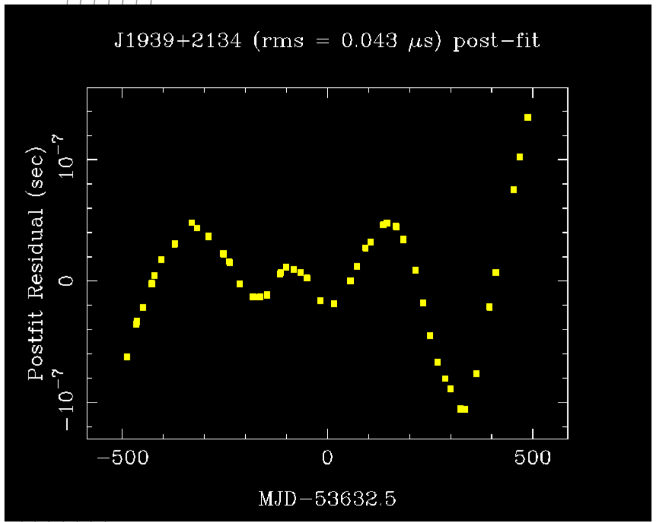
solar system

Example timing residuals
Jodrell Bank Observatory data

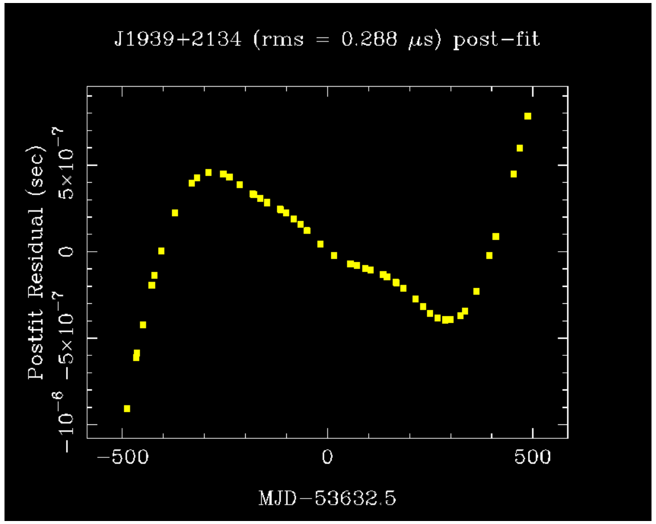


Hobbs et al. (2010), MNRAS

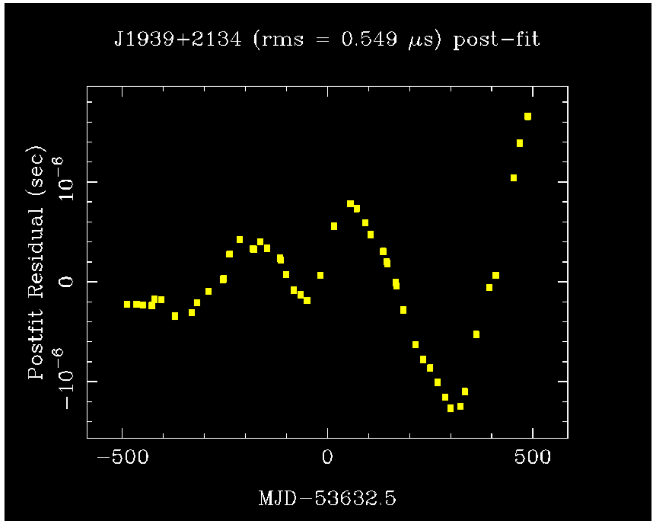
A few simulations



GW background



Spin-down irregularities

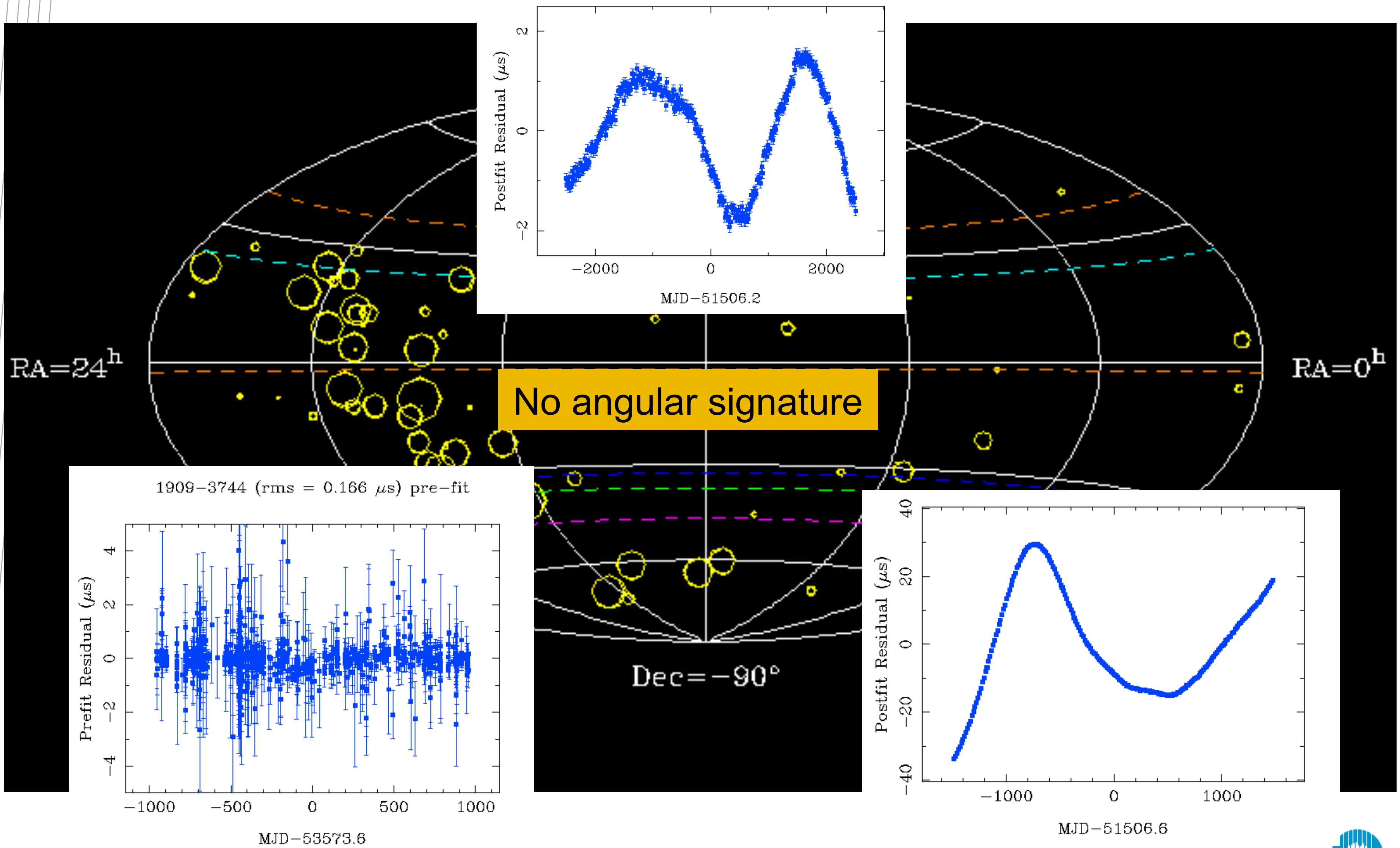


Clock noise

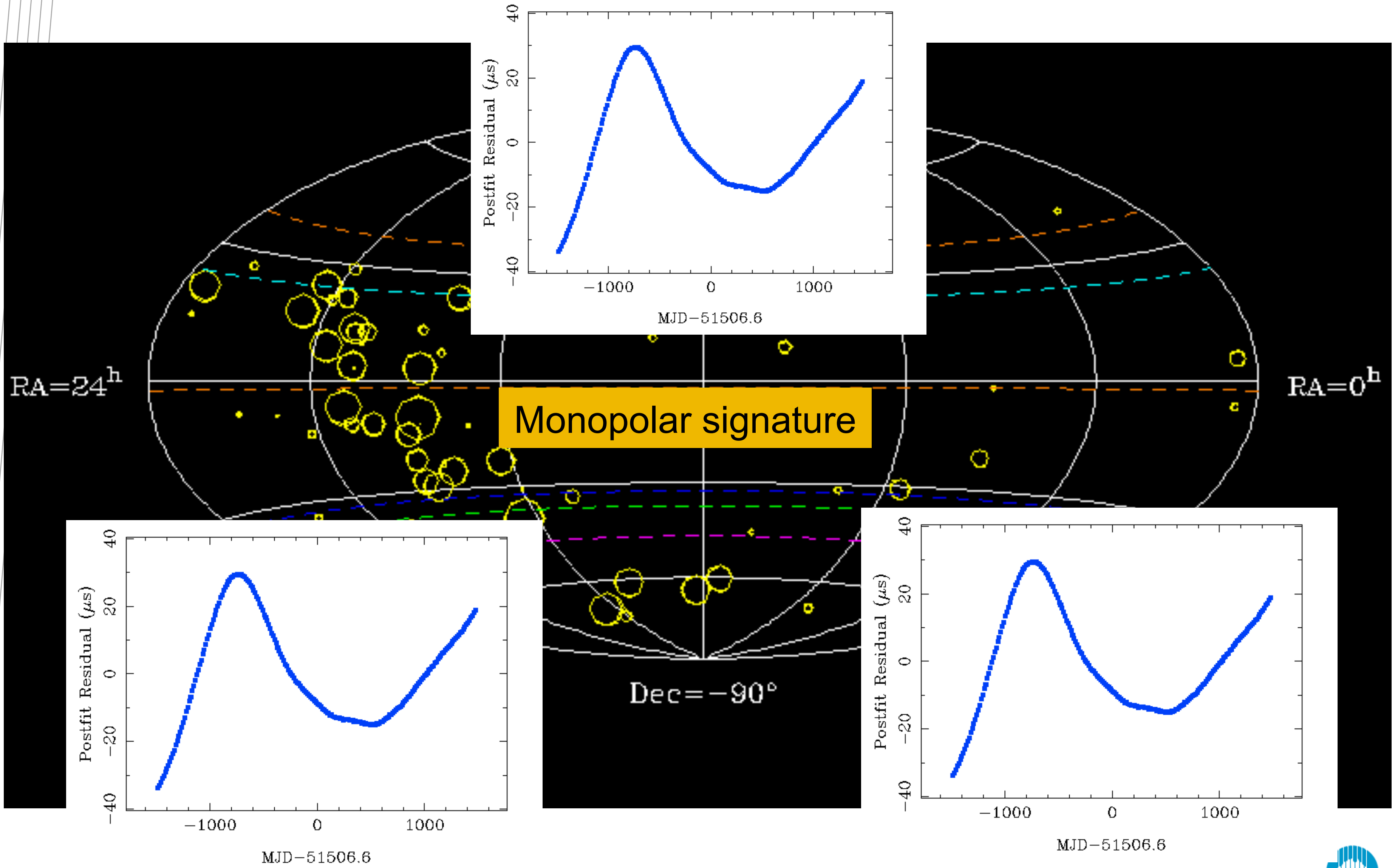
- With one pulsar you cannot (normally) tell what unmodelled physical effect is causing the residuals

Simulated data

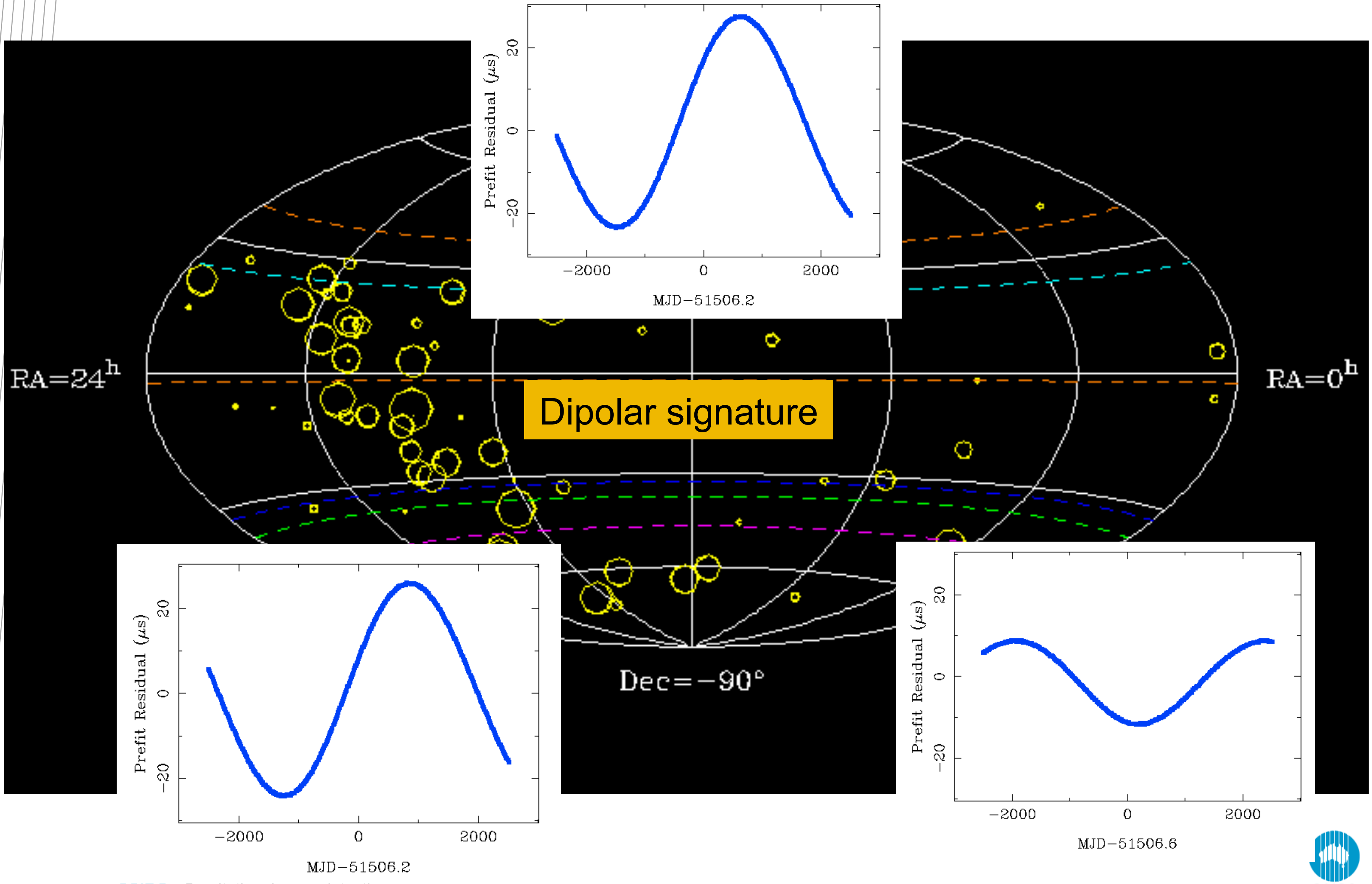
Spin-down irregularities



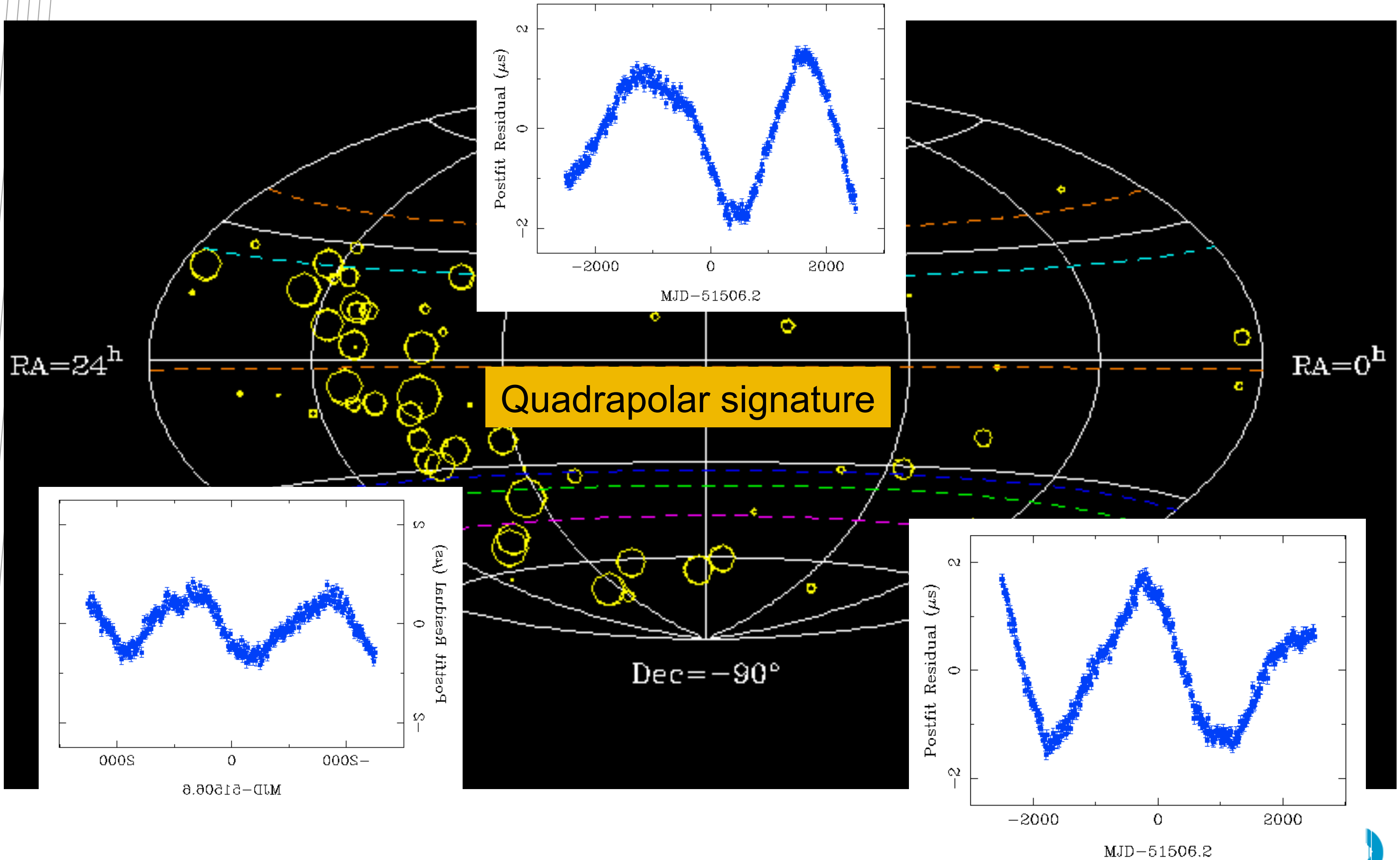
Terrestrial time standard irregularities



Errors in the planetary ephemerides - e.g. error in the mass of Jupiter



What if gravitational waves exist?

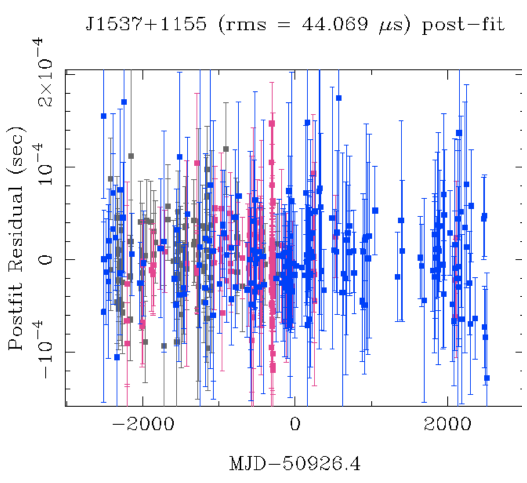


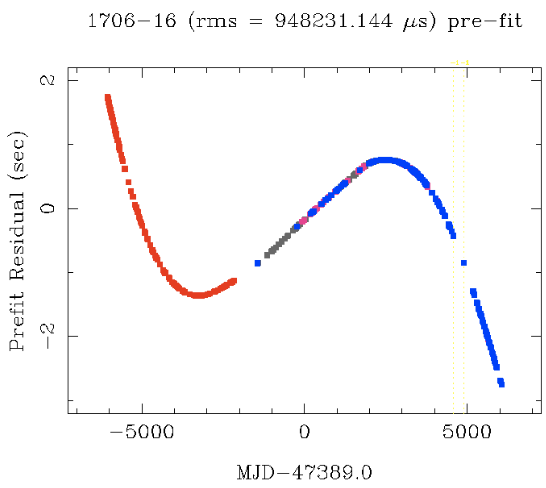
Part 2: Uncorrelated residuals

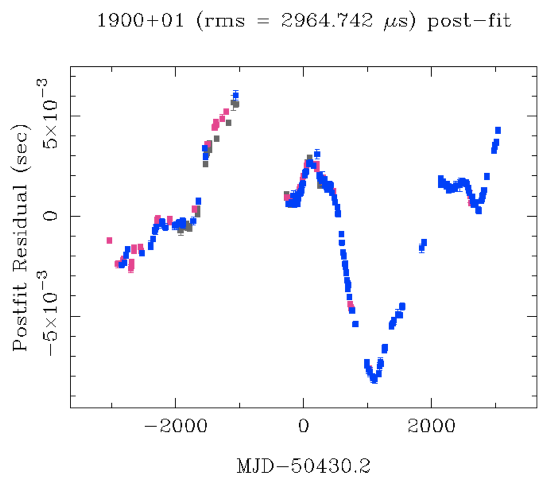
- Part 1: Introduction to pulsar timing
- Part 2: **Uncorrelated timing residuals**
- Part 3: Monopolar correlations
- Part 4: Dipolar correlations
- Part 5: Quadrupolar correlations

Describing the spin-down of pulsars

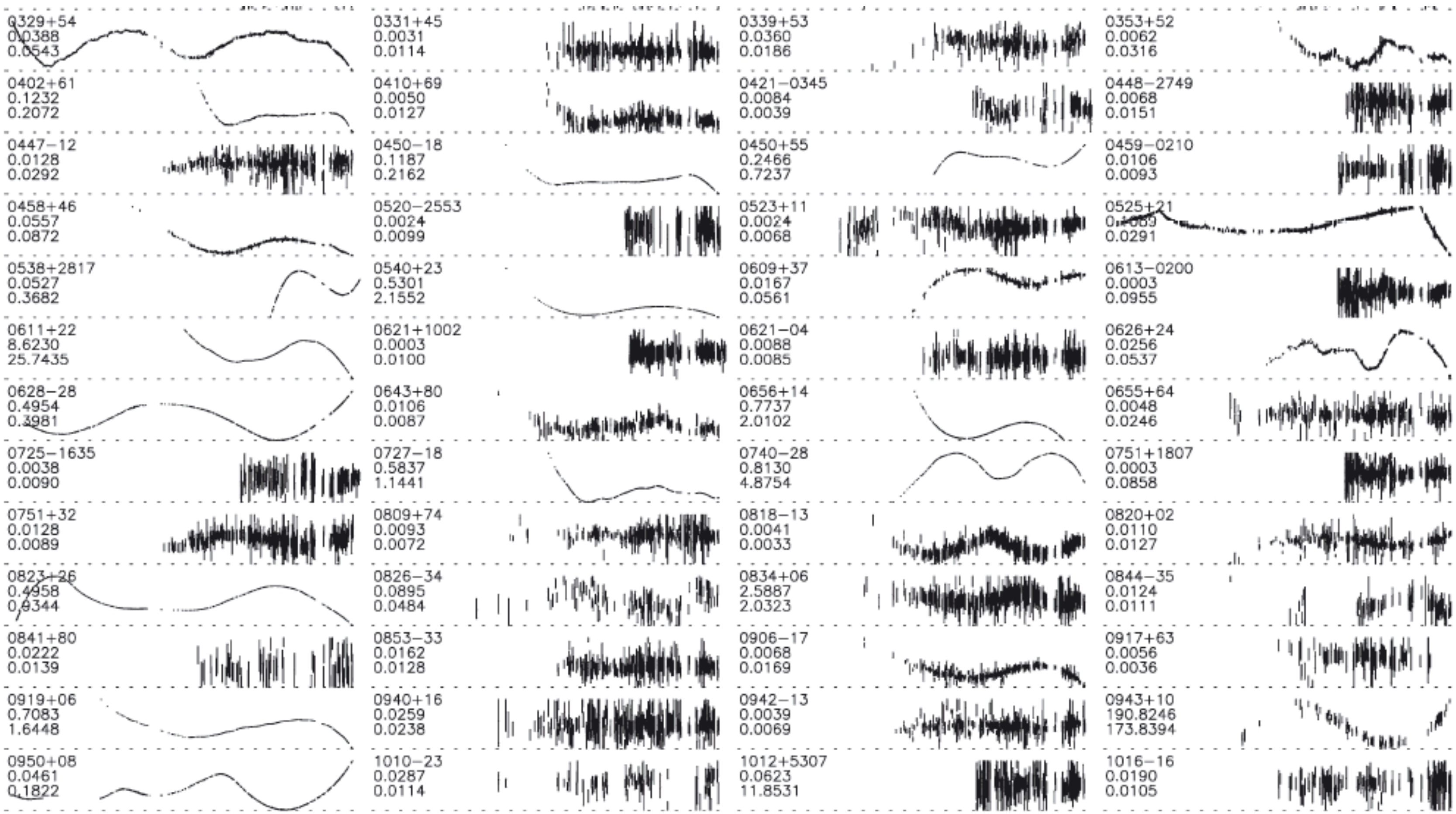
- Modelling the pulsar spin-down usually requires the pulse frequency, F and its first derivative, F1.
- Residuals shown here have F2 (and higher derivatives) = 0.







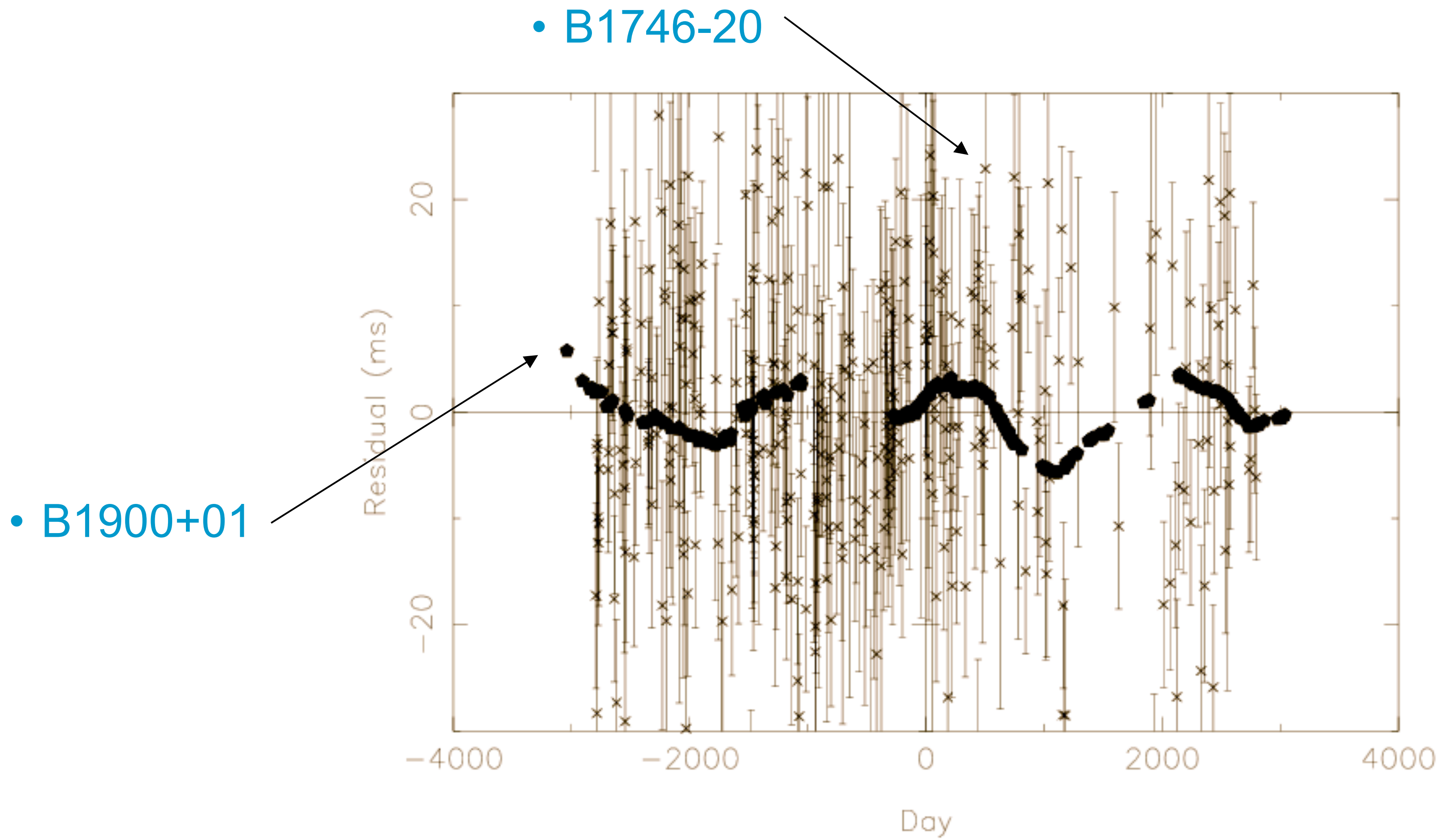
Example timing residuals
Jodrell Bank Observatory data



Hobbs et al. (2010), MNRAS

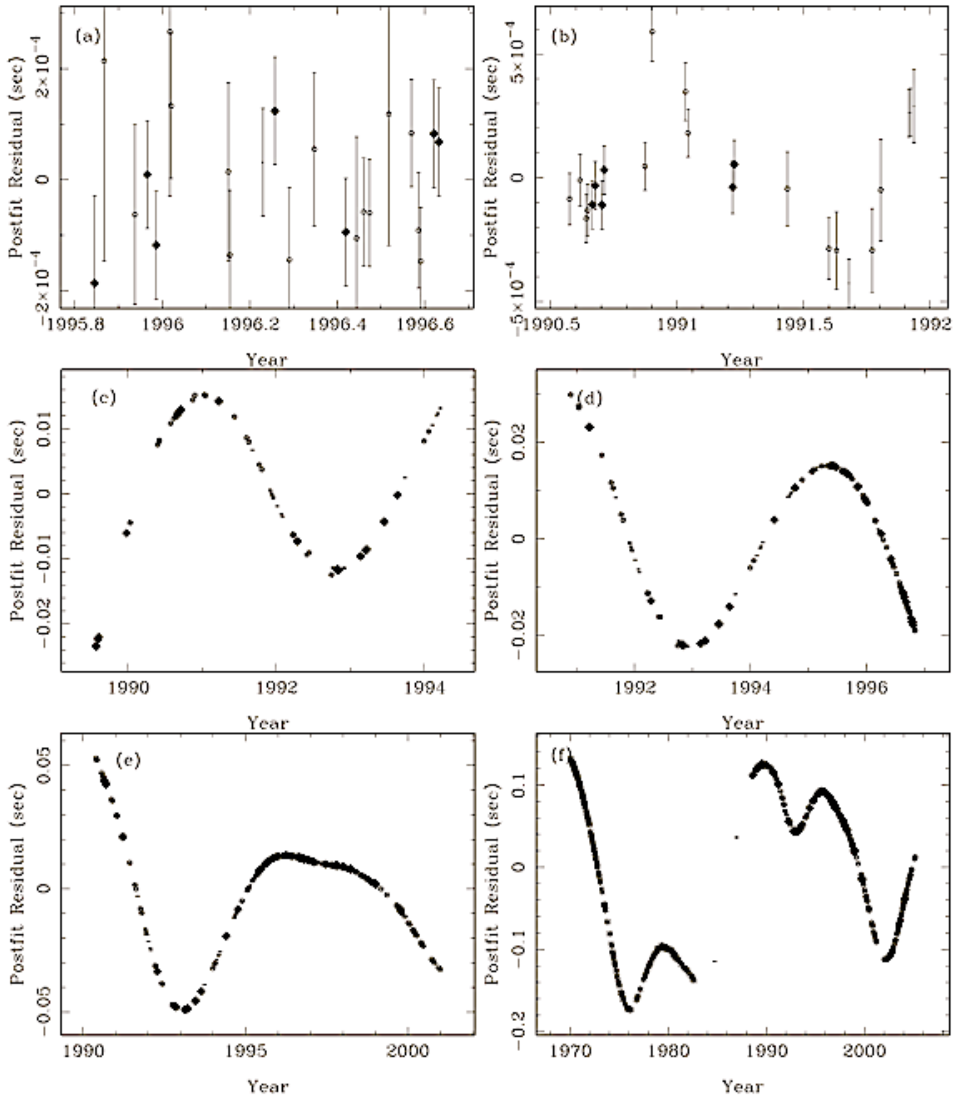
How do you work out what is causing these residuals?

Difficulties when categorising timing residuals



Difficulties when categorising timing noise: depends on data span

- PSR B1818-04
- Any simple classification scheme would change with data span.
- Most previous large-scale analyses of timing noise used ~3 yr of data.



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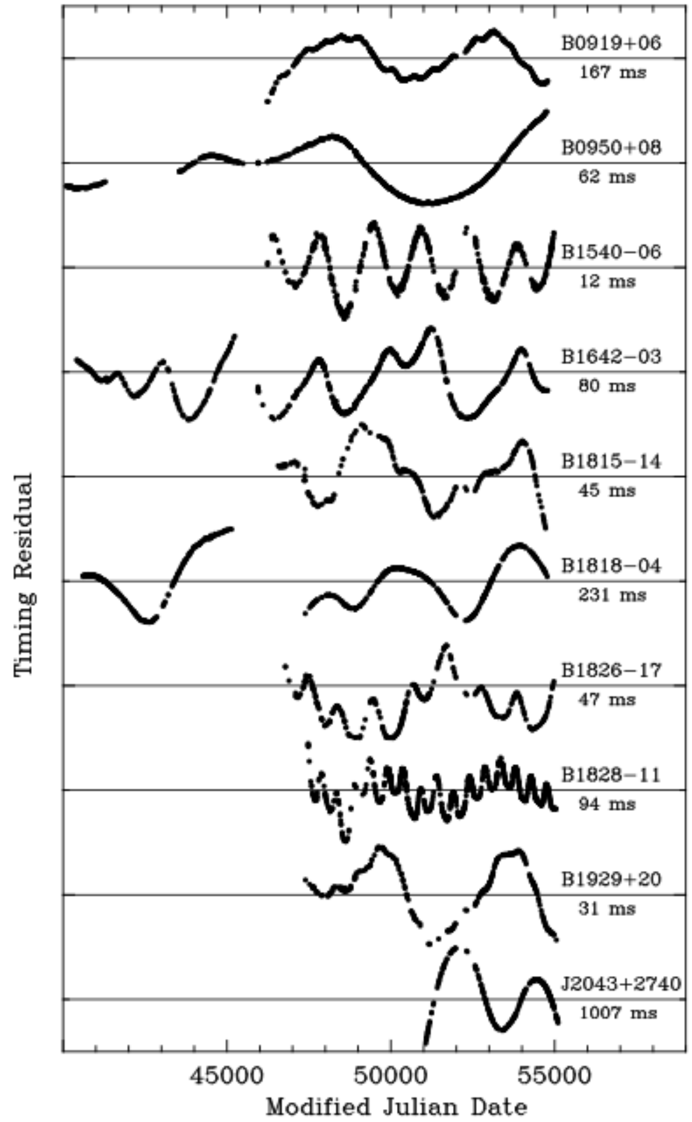
Typical pulsar timing residuals over many decades (Jodrell Bank Observatory data)

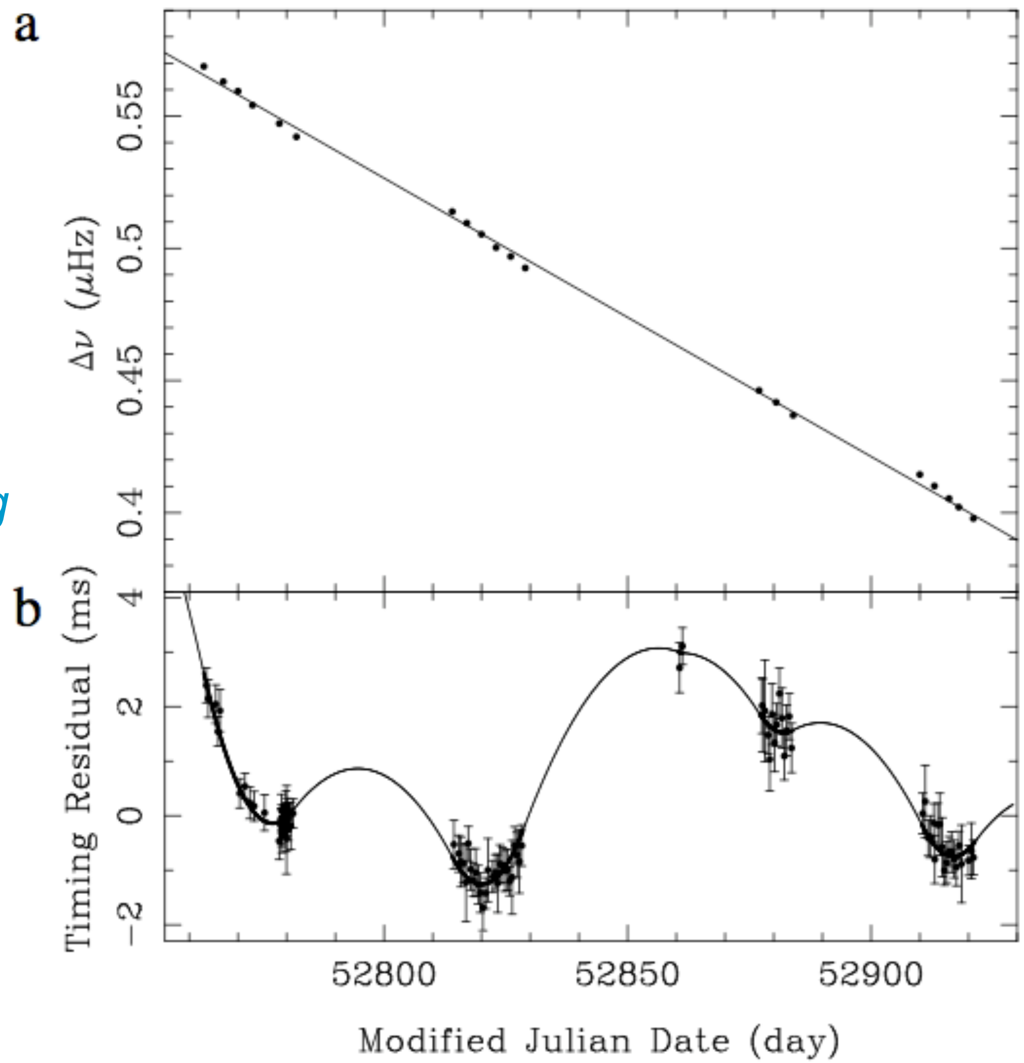
- Hobbs et al. 2010, MNRAS
- Studied 366 pulsars with data spanning 10->40 years
- Found quasi-periodicities
- Need long datasets to see the oscillations clearly!
- The irregularities in the pulsar spin are not completely “random”!

- Could this be caused by planets, free-precession, asteroid belts, … ???



An interlude: B1931+24

- PSR B1931+24 has been reported to undergo "extreme nulling" events (Kramer et al. 2006)
- Normal pulsar for 5 to 10 days
- Switches off for up to 35 days
- *The pulsar spin-down rate changes by ~50% between the on and off states (pulsar spinning down faster when "on")*



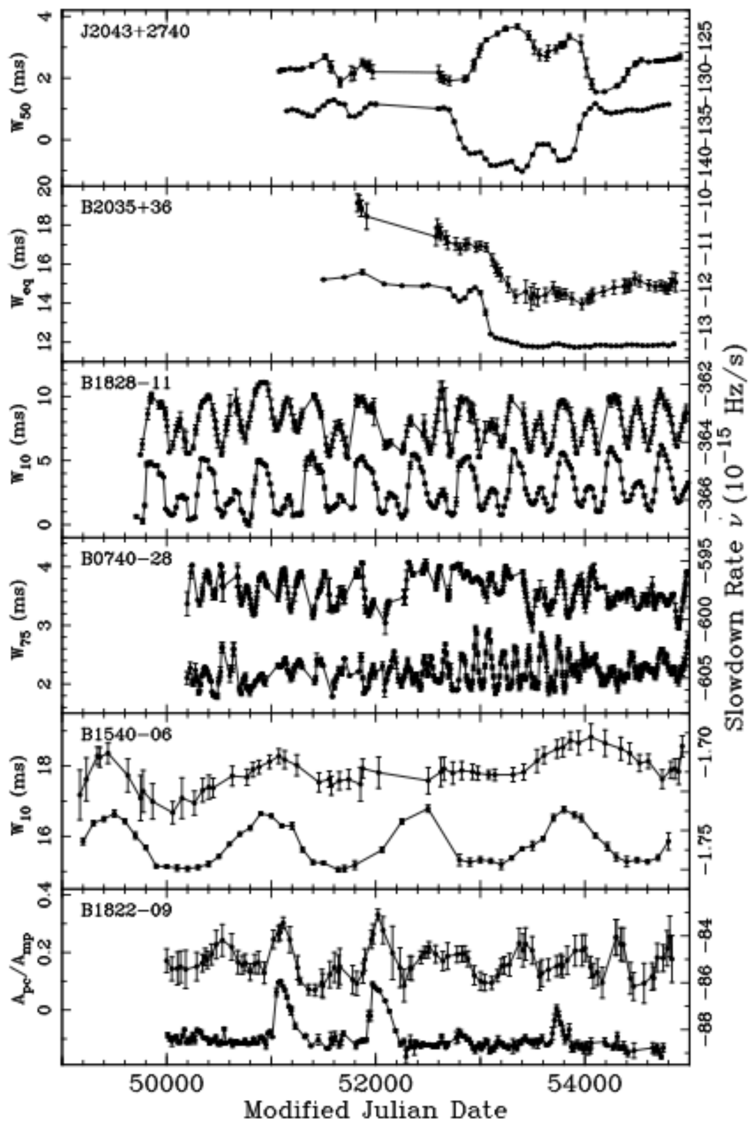
- *(Note: PSR J1832+0029 has recently been discovered - "on" for approx 1 year and then "off" for approx 2 years)*

Discovery of a two state process in many pulsars

- Lyne, Hobbs, Kramer, Stairs, Stappers, Science 24 June 2010
- We show that timing behaviour often results from typically two different spin-down rates.
- Show correlated pulse shape variations => magnetospheric origin

- In theory can use the observed pulse shape to correct the “pulsar clock”

Pulse shape



Spindown rate

Why is this important?

- Conclusion: (some/all) pulsar timing noise is magnetospheric in origin – get correlated spin down changes with pulse profile. Timing noise is a two-state process

- *"Mankind's best clocks all need corrections, perhaps for the effects of changing temperature, atmospheric pressure, humidity or local magnetic field. Here, we have found a potential means of correcting an astrophysical clock". – Andrew Lyne*

- => reduce the time taken to detect gravitational waves!

- ***Unanswered questions:***

- *Why do the pulsars have this two state process?*
- *Are glitches and timing noise linked?*
- *Do all pulsars show this two state timing noise? Do millisecond pulsars exhibit different timing noise?*
- *How fast can the pulsar switch between the two modes?*

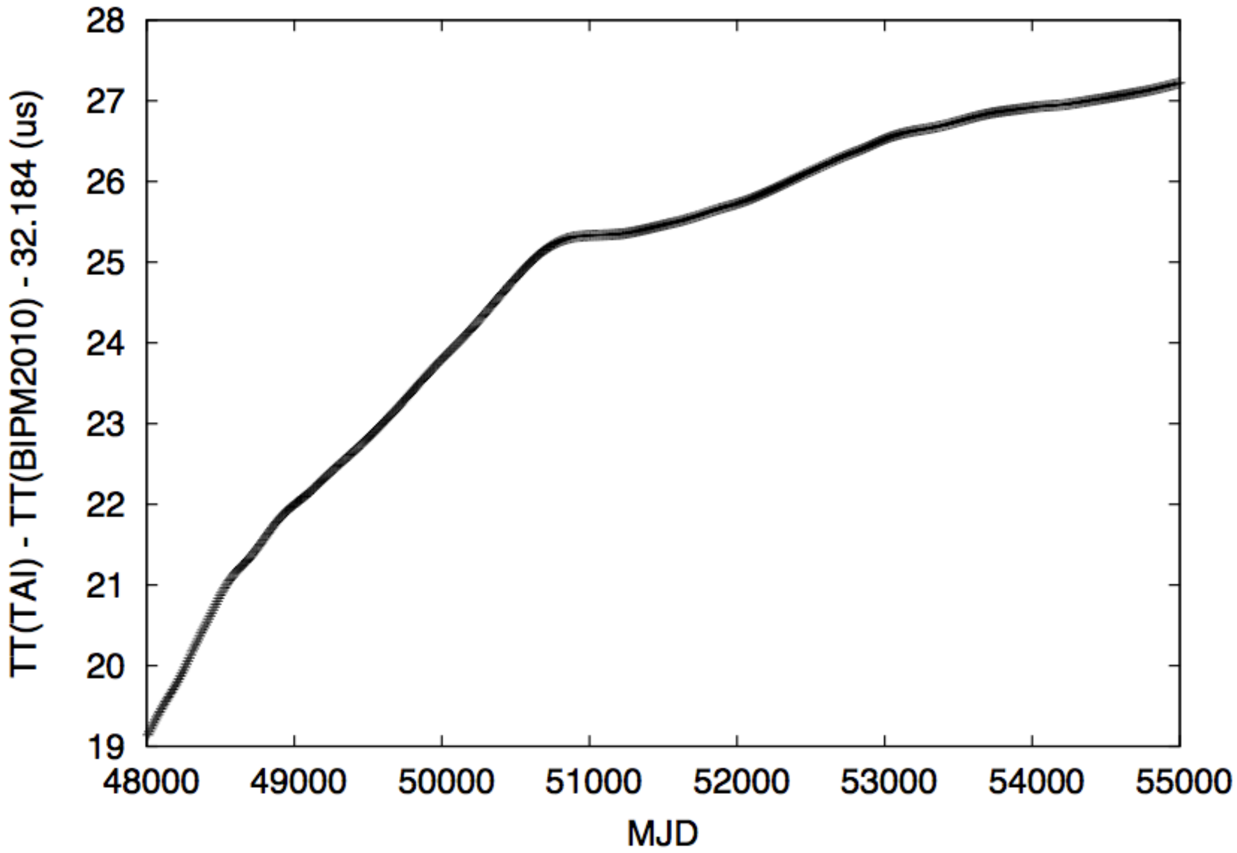
Part 3: Correlated timing residuals: monopole

- Part 1: Introduction to pulsar timing
- Part 2: Uncorrelated timing residuals
- Part 3: **Monopolar correlations**
- Part 4: Dipolar correlations
- Part 5: Quadrupolar correlations

- Now using observations of millisecond pulsars obtained as part of the Parkes Pulsar Timing Array project … timing precisions of <100ns (equiv 30m) are obtained for some pulsars.

Time standards

- Pulsar observations referred to a realisation of terrestrial time: TT(TAI)
- Post-corrected time standard TT(BIPM2010) can be used



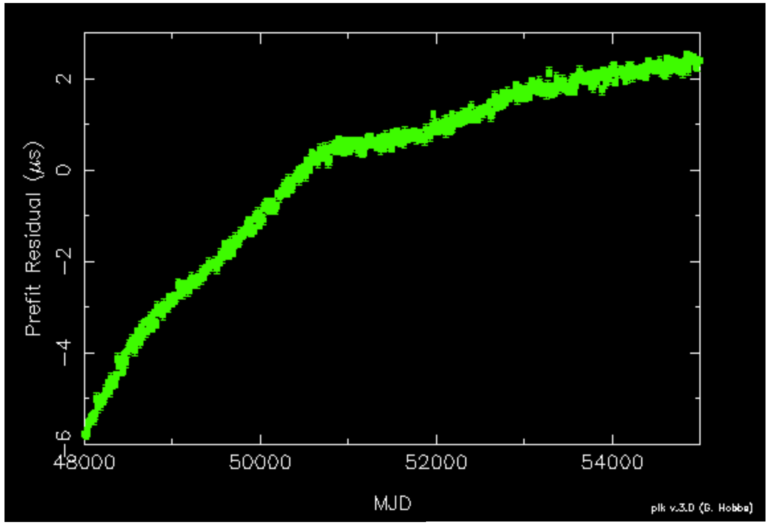
It’s hard

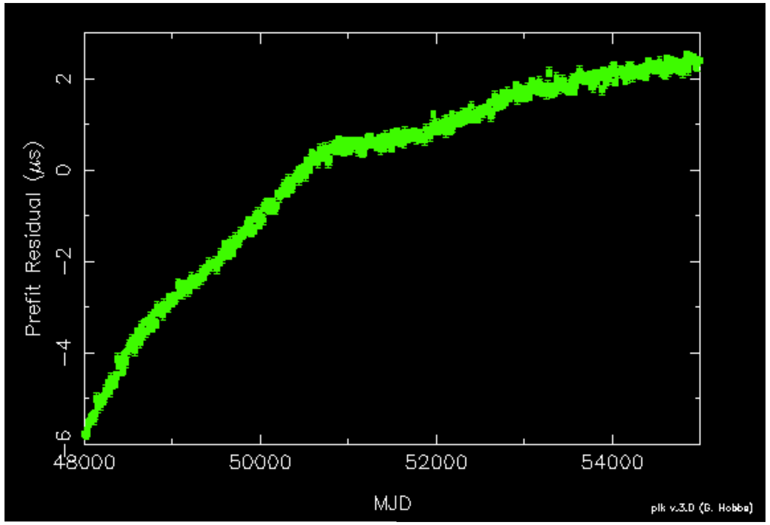
- Must deal with:
  - Different data spans for different pulsars
  - Different timing model fits being applied
  - Different sampling for different pulsars (and all sampling is irregular)
  - Variable error bars (between pulsars and within a given pulsar data set)
  - Unexplained pulsar timing irregularities
  - Other phenomena that may cause correlated signals (i.e., a gravitational wave background signal has a correlated component)
  - …

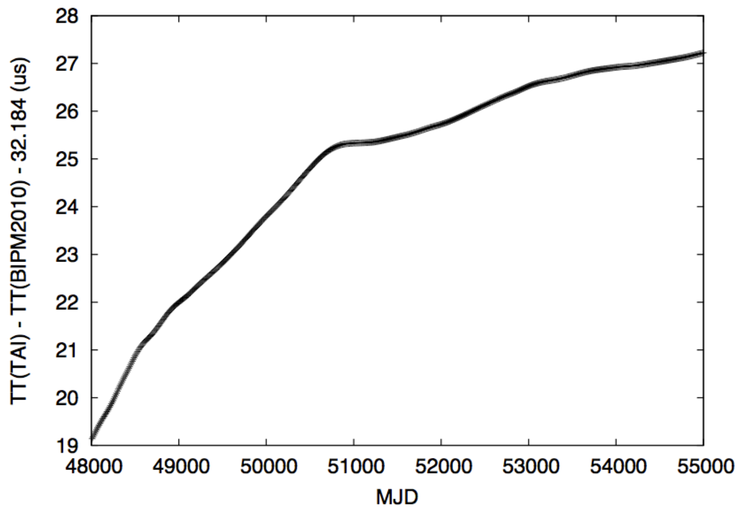
This is also important for gravitational wave detection

An example

- Consider two pulsar data sets.







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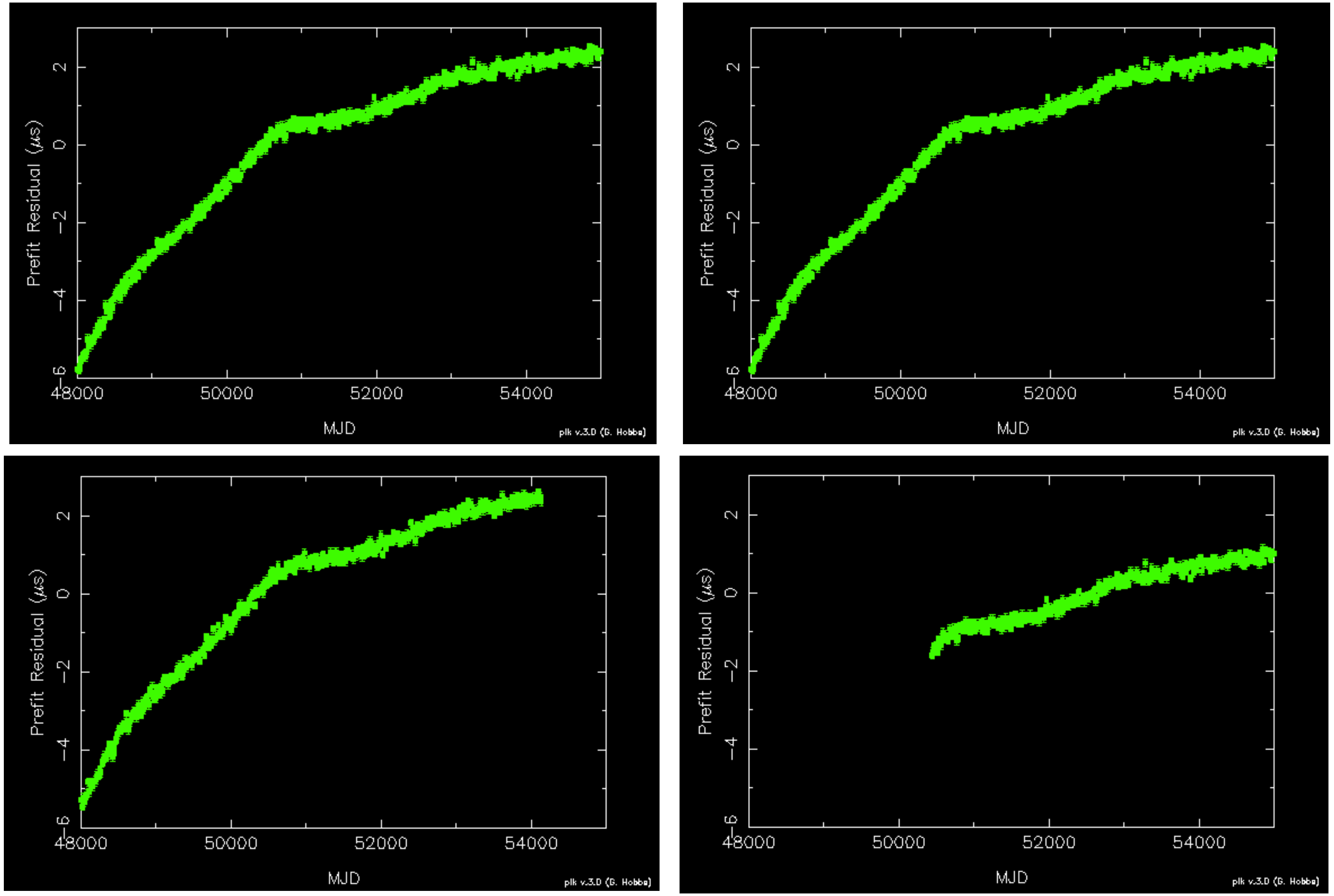
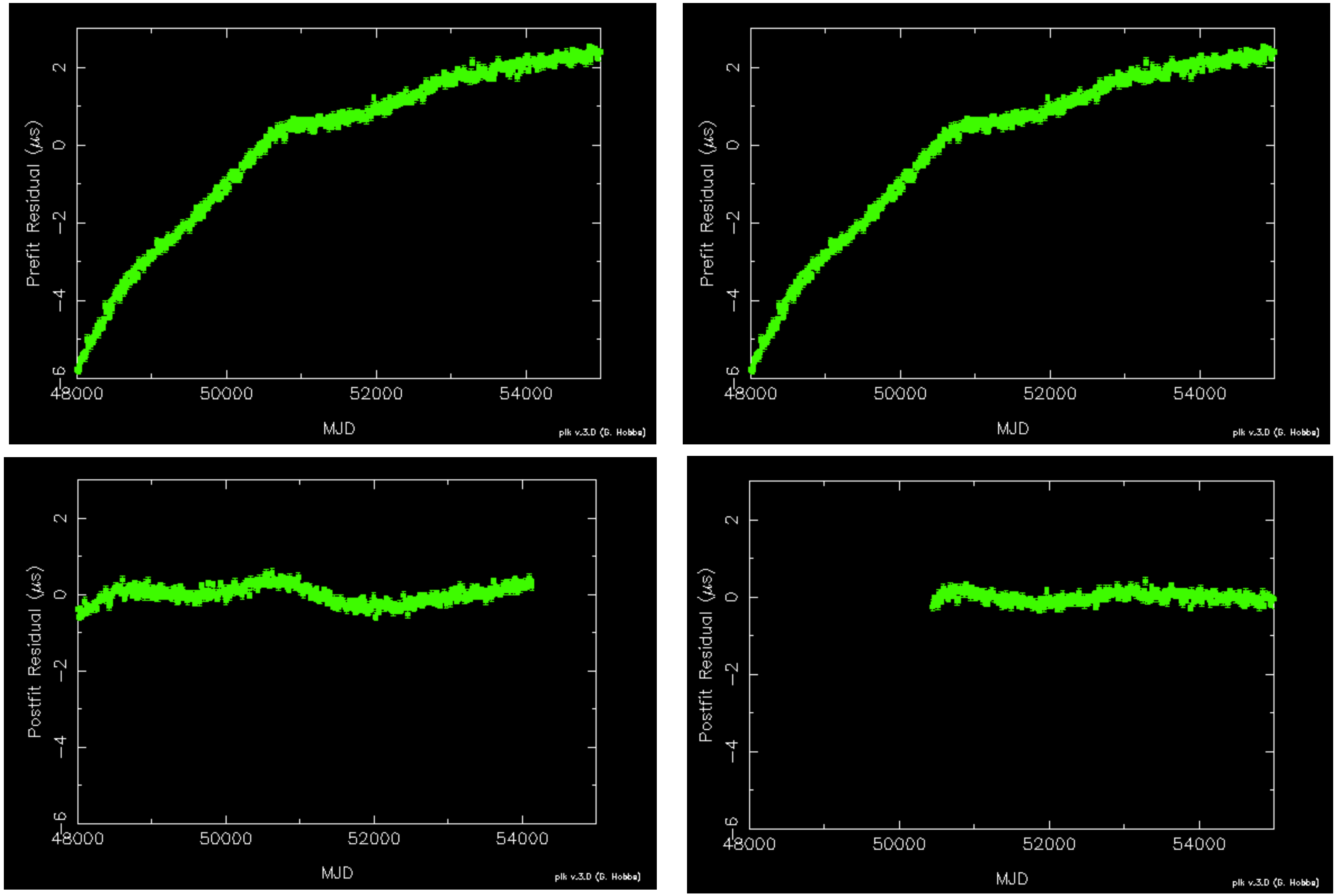
An example

- Have different data spans



An example

- Fit for the pulse frequency and its derivative



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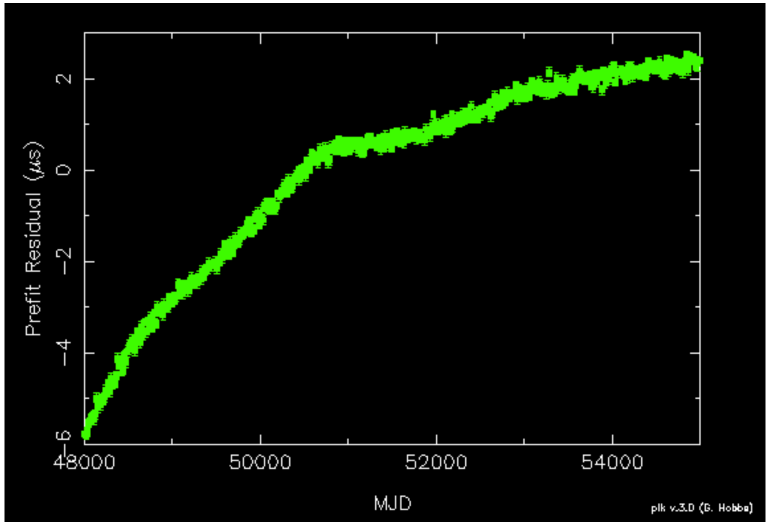
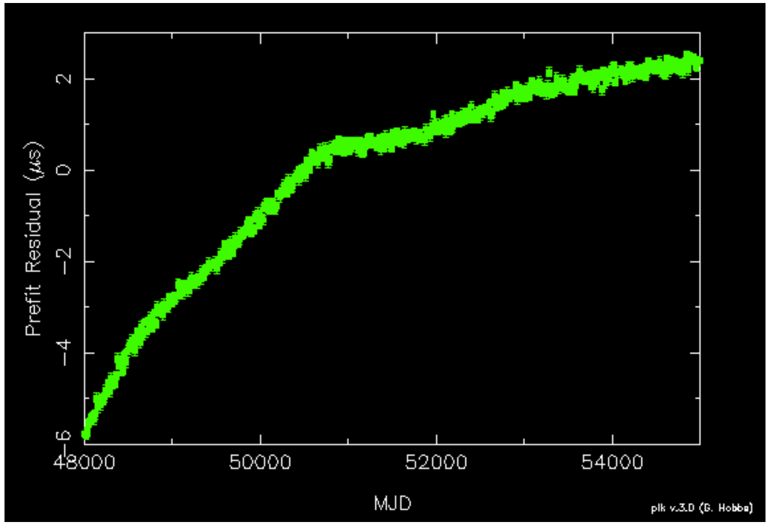
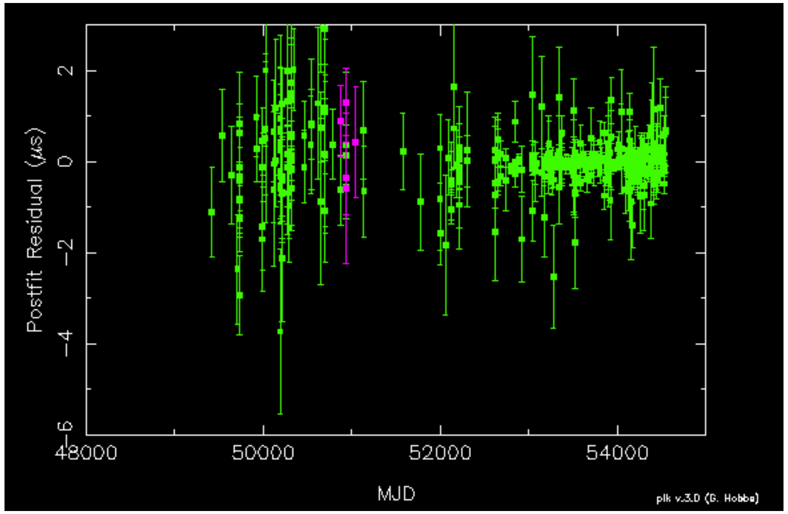
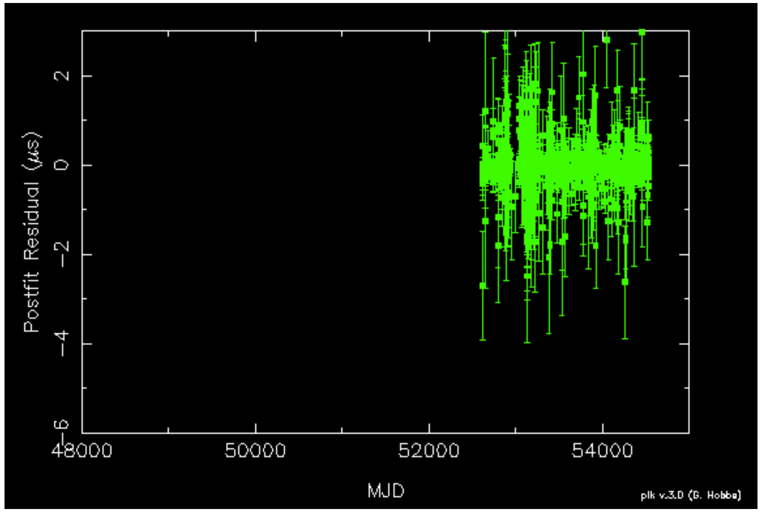
An example

- Add in realistic amounts of noise



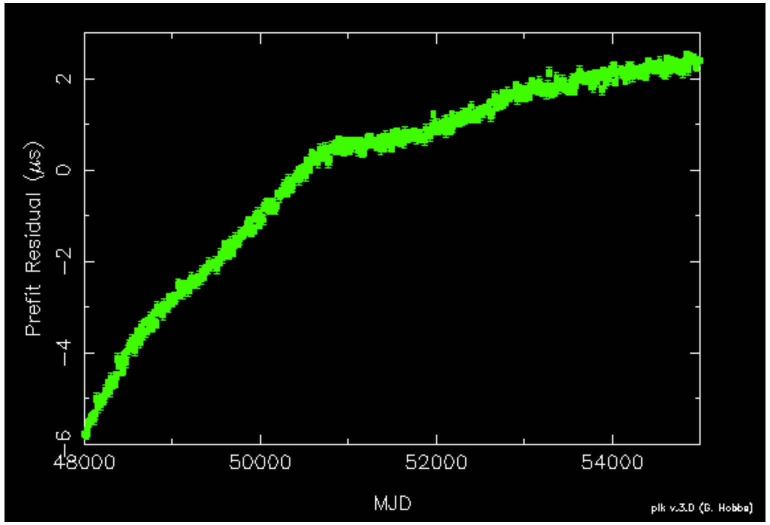


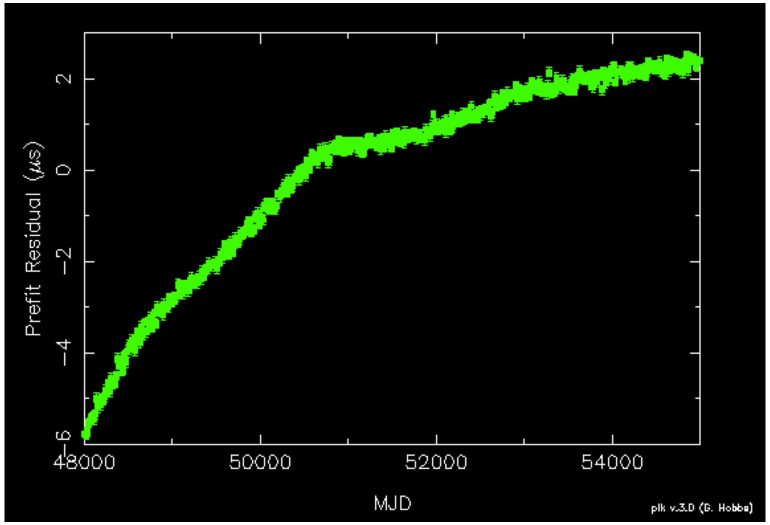


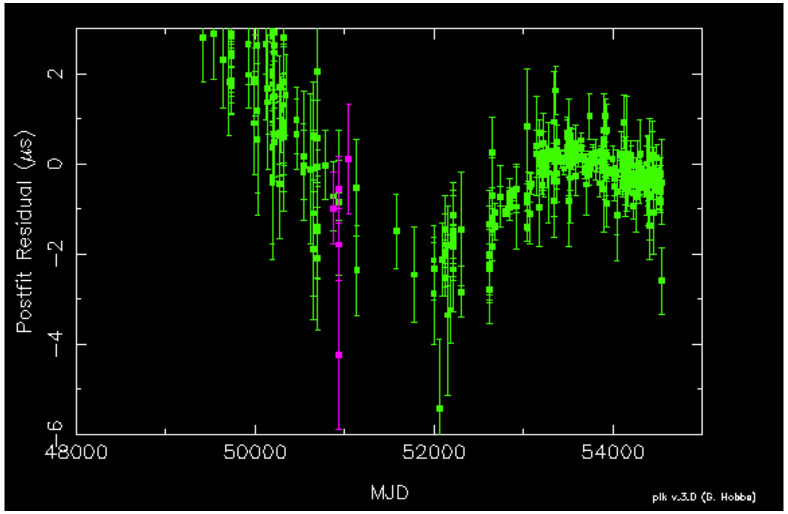


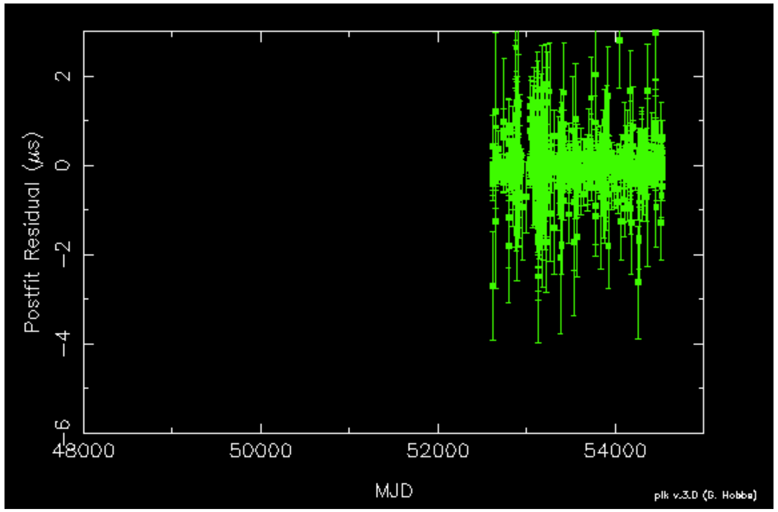
An example

- Add in some unexplained timing irregularities









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Important notes

- We can never recover the linear and quadratic irregularities in a time standard (or in, e.g., a gravitational wave signal)
- For data sets with different data spans, it is not possible to use a simple “weighted-average” method to determine the ensemble pulsar time standard (the pulsar timing fits significantly affect the timing residuals)

Technique:
(Hobbs et al., in preparation)

- Define clock function to be simple Fourier expansion:

$$f(t) = \sum A_k \cos(k\omega_0 t) + B_k \sin(k\omega_0 t)$$

(note: can use other functional forms if needed)

- Carry out a standard least-squares fit of pulsar timing model parameters + f(t) as usual, except:
- simultaneously fit to multiple pulsars
- use measurement of the covariance in the residuals for a given pulsar as part of the least-squares-fit fit (to deal with timing noise)

$$\vec{P}_{est} = (M^T C^{-1} M)^{-1} M^T C^{-1} \vec{R}$$

Timing residuals

Pulsar timing model

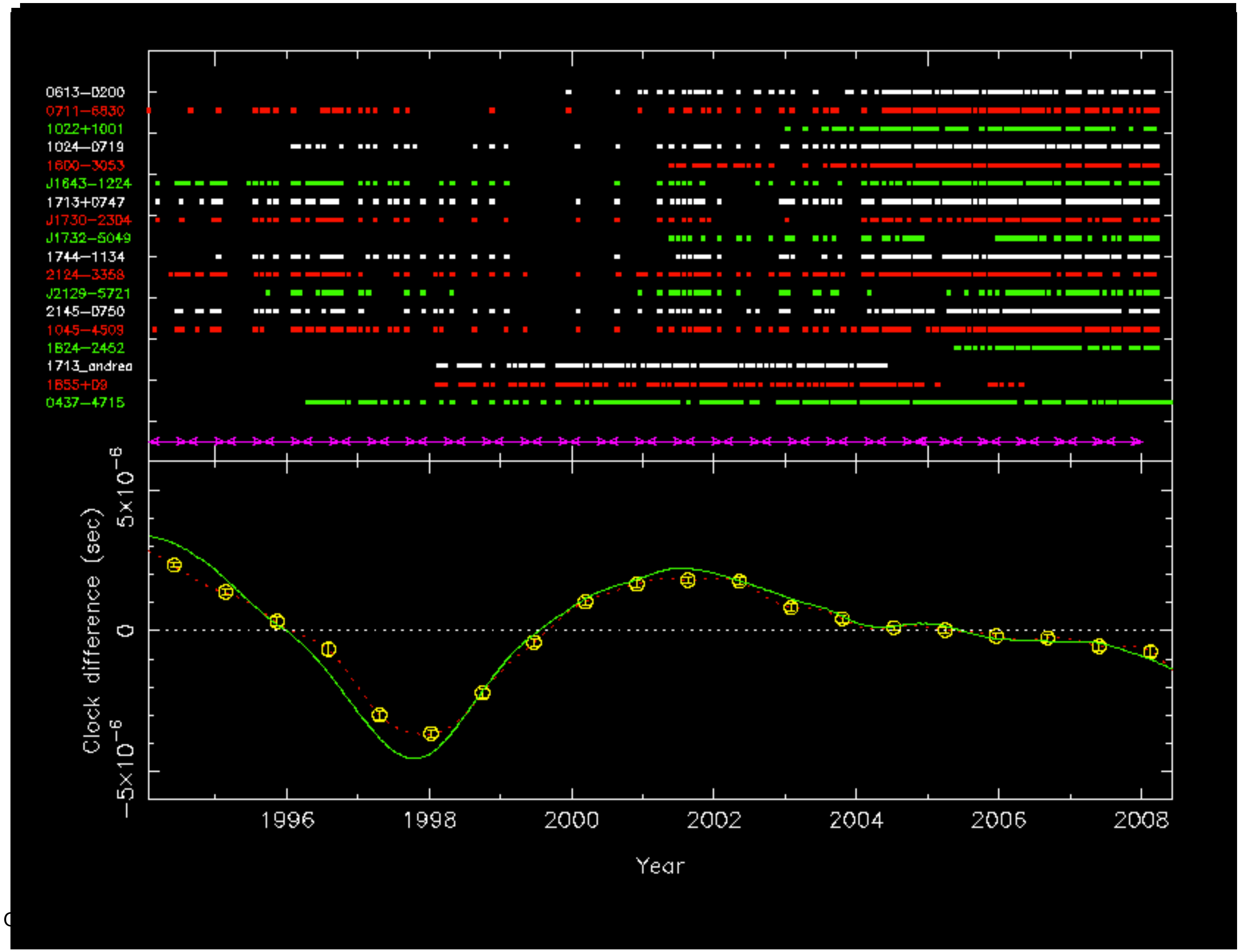
Covariance matrix of the residuals

Now using same technique to search for gravitational waves

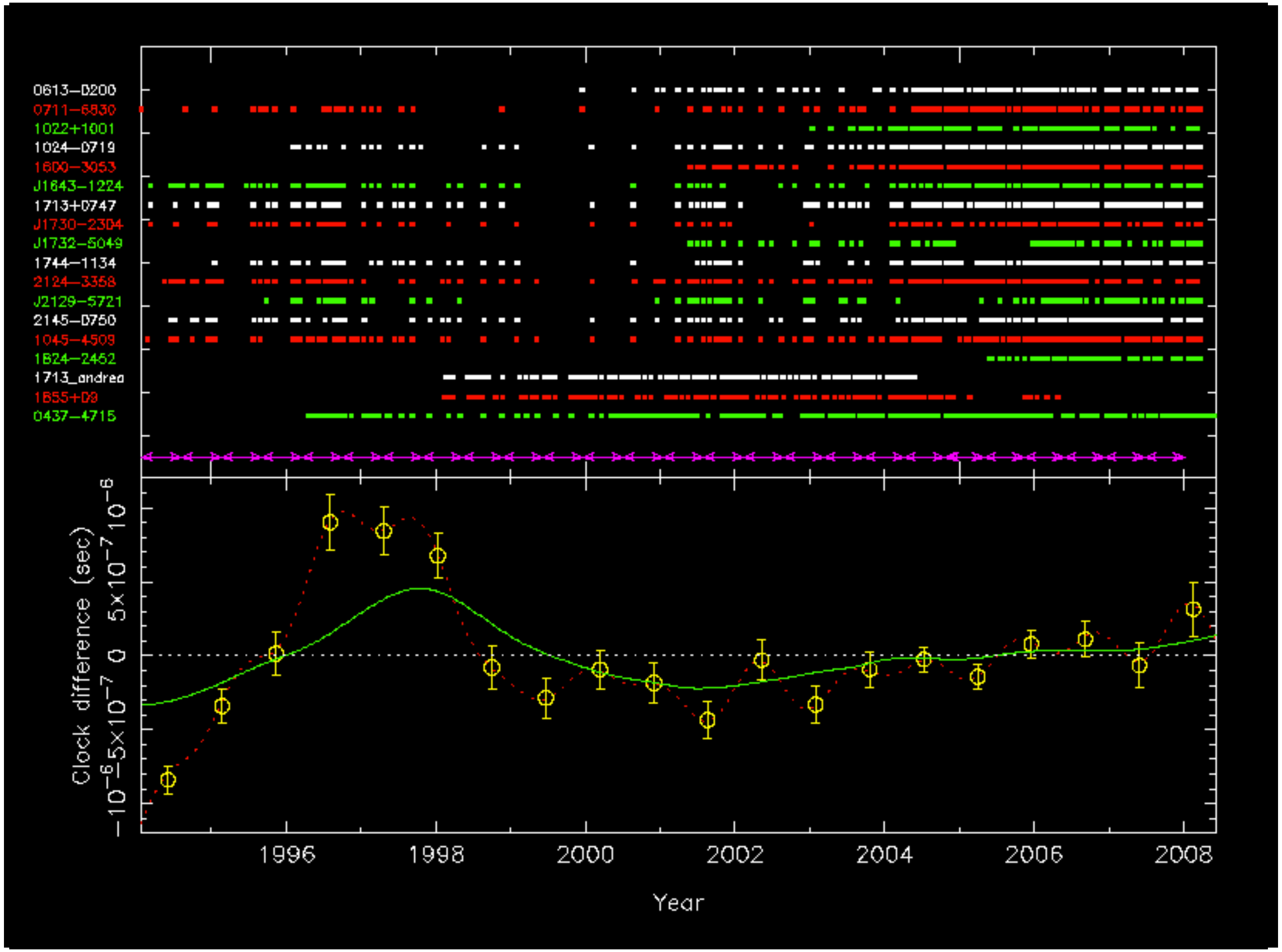
Testing: can we recover TAI-TT(BIPM2010) x 10?

- Simulate 10x expected TAI-TT(BIPM2010) in real pulsar data

5μs



Final result (no simulations)
EPT-TT(TAI) and TT(BIPM2010)-TT(TAI)



1μs

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Summary of part 3:

- Can recover recent deviations between TT(BIPM2010) and TT(TAI) using pulsar observations
- Have significant deviation from TT (BIPM2010) prior to the year 1999
- Can not (currently) distinguish between errors in TT(BIPM2010) and errors in the time transfer from the Parkes observatory
- New data sets should significantly improve the results
- New pulsar discoveries and improved observing techniques are significantly improving the precision with which pulsars can be timed.
- Pulsars may be able to provide confirmation/addition to Earth-based timestandards on timescales of years and decades.

- ***Unanswered questions:***

- *Can we prove that the deviation from TT prior to 1999 is caused by errors in TT(BIPM2010)?*
- *Can we use the pulsar timescale to improve our timing precision?*
- *Can we include pulsar data in the creation of TT(BIPM2010) to improve terrestrial time.*
- *Can any other affects mimic clock errors?*

Part 4: Correlated timing residuals: dipole

- Part 1: Introduction to pulsar timing
- Part 2: Uncorrelated timing residuals
- Part 3: Monopolar correlations
- Part 4: **Dipolar correlations** **(very short section!)**
- Part 5: Quadrupolar correlations

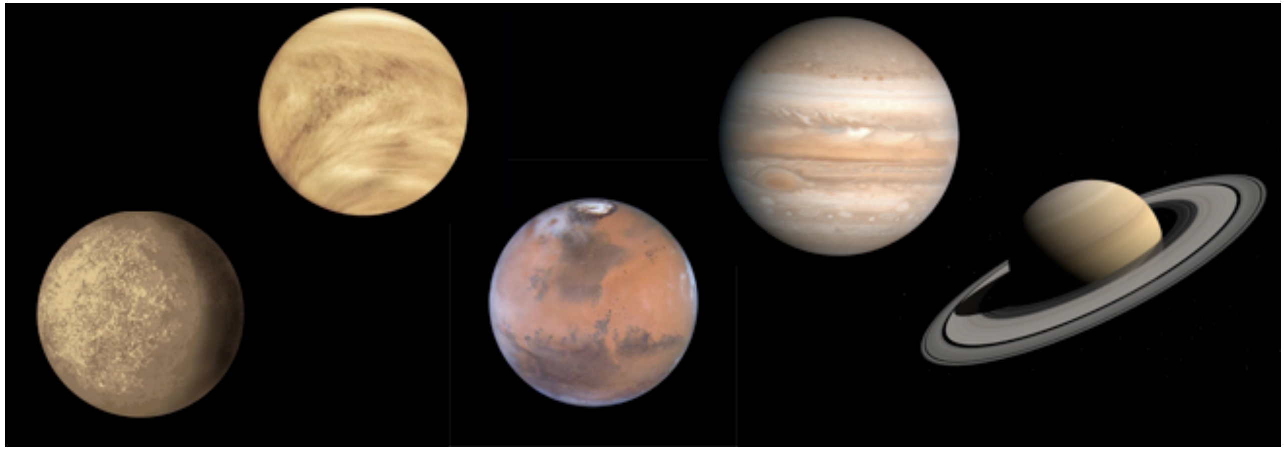
Measuring planetary masses

- Use International Pulsar Timing Array data from Parkes, Effelsberg, Nancay and Arecibo.
- Champion et al. 2010, ApJ.
- A planetary mass error will lead to incorrect determination of the Solar System barycentre => correlated pulsar timing residuals
- Can fit to multiple pulsars simultaneously to search for such a signal

Measuring planetary mass

- Champion, Hobbs, Manchester et al. (2010), ApJ, 720, 201
- Use data from Parkes, Arecibo, Effelsberg and Nancay

M_{Sun}	Best Published	This work
Mercury	$1.66013(7)\times10^{-7}$	$1.660(2)\times10^{-7}$
Venus	$2.4478686(4)\times10^{-6}$	$2.44782(10)\times10^{-6}$
Mars	$3.227151(9)\times10^{-7}$	$3.2277(8)\times10^{-7}$
Jupiter*	$9.54791915(11)\times10^{-4}$	$9.547916(4)\times10^{-4}$
Saturn	$2.85885670(8)\times10^{-4}$	$2.858858(14)\times10^{-4}$



Summary of part 4

- Can measure planetary masses with pulsar timing
- New data sets will significantly improve the precision

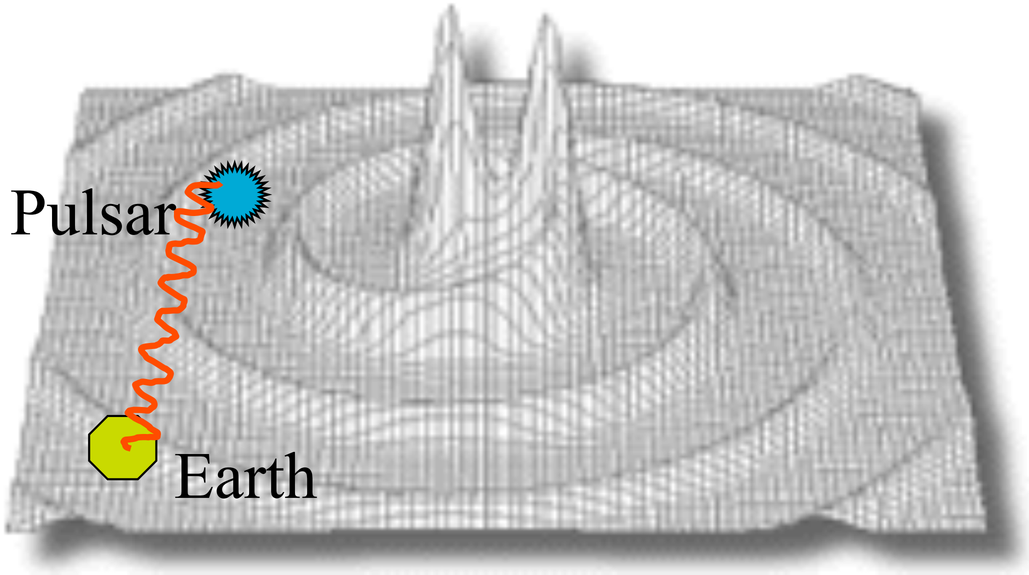
- ***Unanswered questions:***

- *Can we identify an unknown TNO? (Have a summer student this year trying to rule out "nemesis" – a postulated large mass in our solar system)*
- *Can we realistically simulate the effects of perturbing a planetary mass?*
- *Can we search for unknown planets/asteroids around the pulsars?*

Part 5: Correlated timing residuals: quadrupole

- Part 1: Introduction to pulsar timing
- Part 2: Uncorrelated timing residuals
- Part 3: Monopolar correlations
- Part 4: Dipolar correlations
- Part 5: **Quadrupolar correlations**

Part 2: Details of the detection method. Single GW sources



Lots more detail tomorrow!

$$\frac{\delta\nu}{\nu} = -\mathcal{H}^{ij}(h_{ij}(t_e, x_e^i) - h_{ij}(t_e - d, x_p^i))$$

$$R(t) = -\int_0^t \frac{\delta\nu(t)}{\nu} dt$$

Application to 3C66B: Jenet et al. (2004)

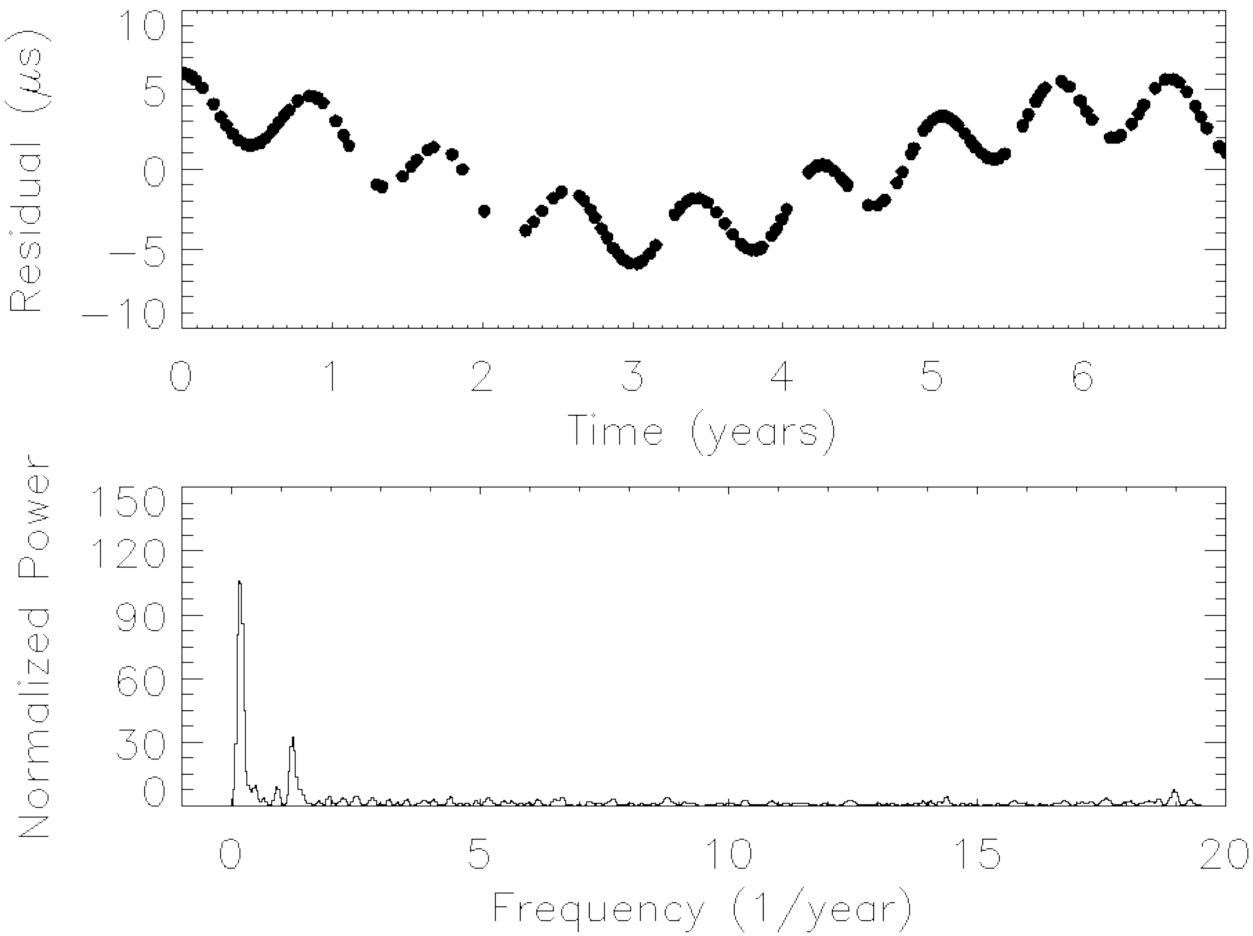
Orbital Motion in the Radio Galaxy 3C 66B: Evidence for a Supermassive Black Hole Binary

Hiroshi Sudou,[1*] Satoru Iguchi,[2] Yasuhiro Murata,[3] Yoshiaki Taniguchi[1]

Science magazine

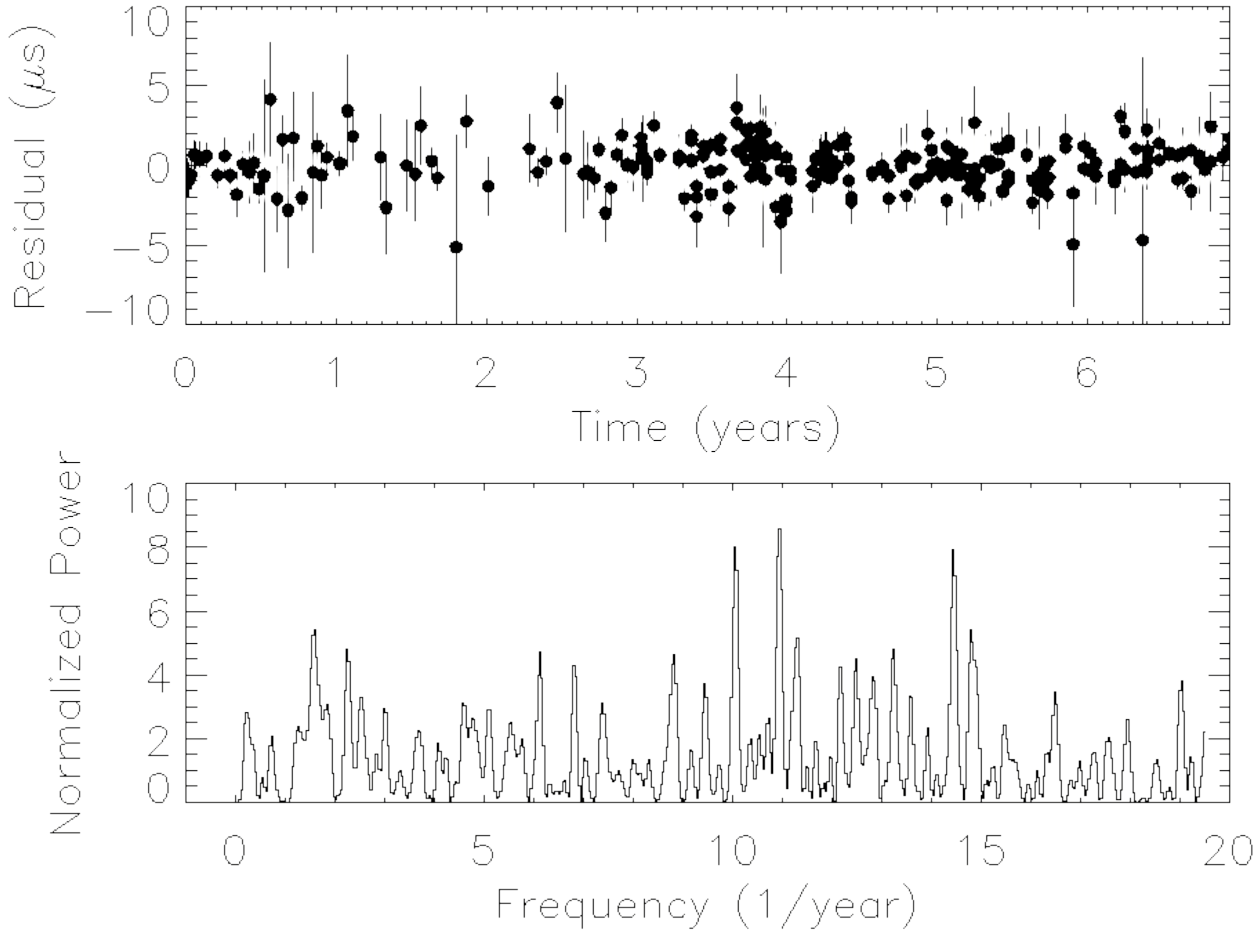
- $M_t = 5.4 \times 10^{10}\ M_{solar}$
- Mass ratio = .1
- $M_{chirp} = 1.3\ 10^{10}\ M_{solar}$
- Orbital period = 1.05 ± .03 yrs
- Distance = 85 Mpc (H=75 km/s/Mpc)
- $h \approx M_{chirp}^{5/3}\ \Omega^{2/3} / D \approx 10^{-12}$
- $R = h/\Omega = 2\ \mu$ s

Application to 3C66B: Jenet et al. (2004)



From Jenet, Lommen, Larson, & Wen, ApJ, 2004

Application to 3C66B

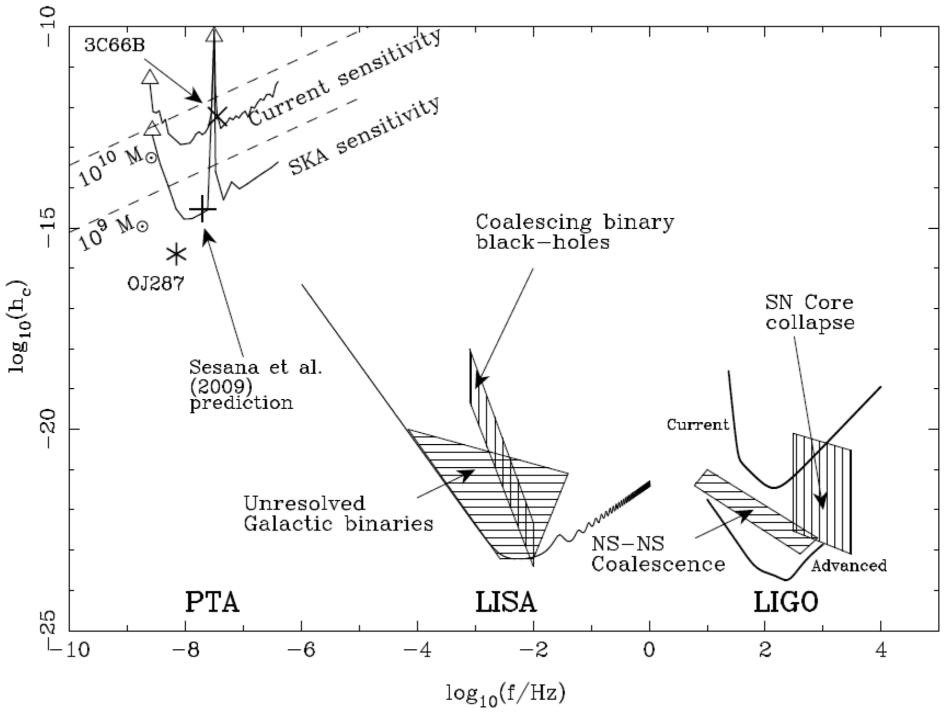


From Jenet, Lommen, Larson, & Wen, ApJ, 2004

Data from Kaspi et al. 1994

The sensitivity of the Parkes pulsar timing array to individual sources: Yardley et al. (2010)

- Non-detection => sky-averaged constraint on the merger rate of nearby (z < 0.6) black hole binaries in the early phases of coalescence with a chirp mass of 10^{10} solar mass of less than one merger every 7yr.
- Much more sensitive if you know the direction of sky the GWs are likely to come from



A stochastic background of GW sources

Expect backgrounds from:

1. Supermassive black-hole binaries
2. Relic GWs from the early universe
3. Cosmic strings

Details in Lecture 3

The stochastic background is made up of a sum of a large number of plane gravitational waves.

$$h_{\mu\nu} = \mathrm{Re}\left[\sum_j A_{\mu\nu_j} e^{i\vec{k}_j\cdot\vec{x} - i\omega_j t}\right]$$

Detecting the stochastic background

$$R(t,\hat{k}) \;=\; -\int_0^t \sum_{s=0}^{N-1} \mathcal{H}(\hat{k},\hat{\eta_s})^{ij}(h_{ij}(t_e,x_e,\hat{\eta_s}) - h_{ij}(t_e-d,x_p,\hat{\eta_s}))dt_e$$

This is the same for all pulsars.

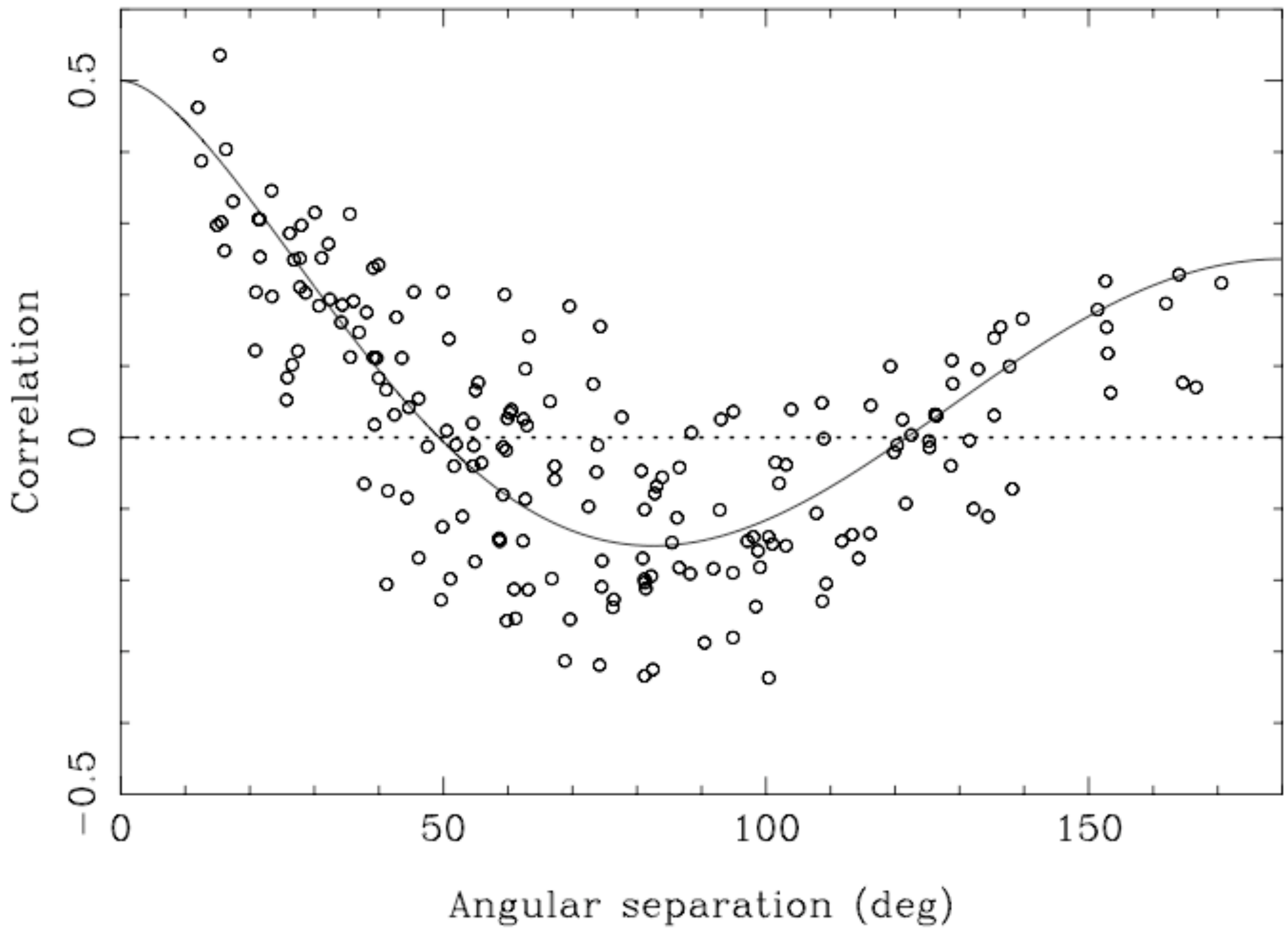
This depends on the pulsar.

- The induced timing residuals for different pulsars will be correlated

CSIRO

The expected correlation function

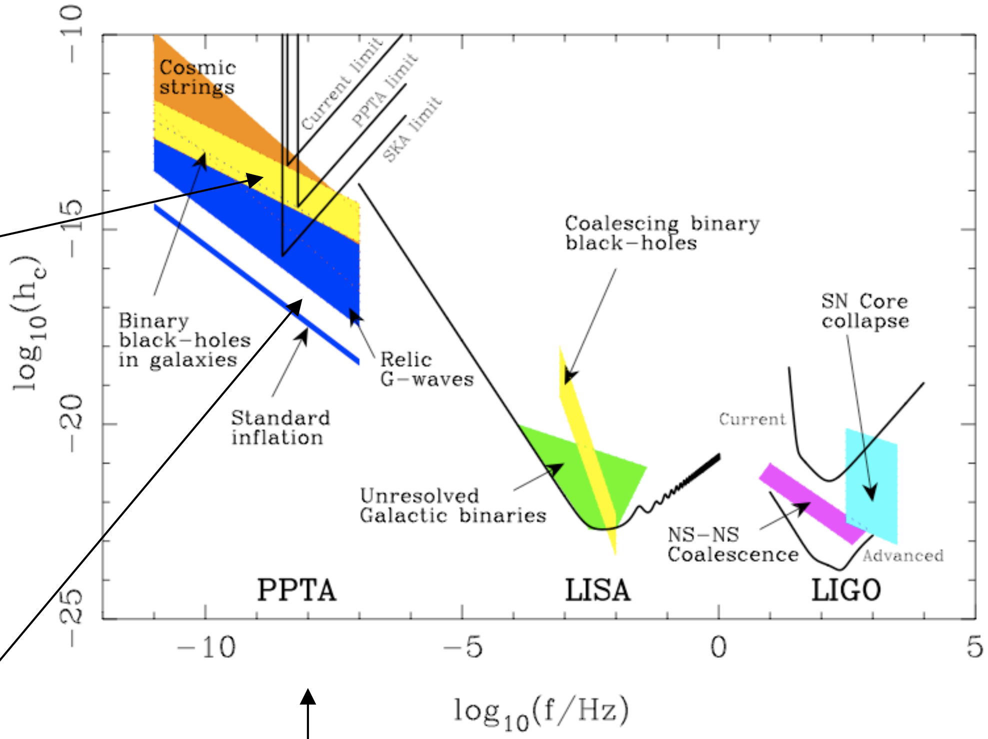
Simulated data



See Hellings & Downs 1983, ApJ, 265, L39

Detection/limits on the background

- Yardley et al. (2011) providing details on detecting the background
- No detection yet made



Current data sets are ruling out a few cosmic string models

The square kilometre array should detect GWs or rule out most models

GW frequencies between 10^{-9} and 10^{-8} Hz - complementary to LIGO and LISA

Conclusion

- Pulsars can be used to study many different aspects of astronomy and astrophysics
- The pulsar timing array projects are providing high quality data sets on large numbers of pulsars
- We have a better understanding of pulsar timing irregularities
- We have found errors in the terrestrial time standards
- The International Pulsar Timing Array has the best published mass of the Jovian system
- We have techniques developed and ready that should be able to detect GWs.
- However, we need some confidence that merging supermassive black holes actually exist!

Next lectures will detail the pulsar timing method and the gravitational wave experiment in detail!

Unanswered questions

- ***Timing irregularities:***
- *Why do the pulsars have this two state process?*
- *Are glitches and timing noise linked?*
- *Do all pulsars show this two state timing noise? Do millisecond pulsars exhibit different timing noise?*
- *How fast can the pulsar switch between the two modes?*
- ***Planets:***
- *Can we identify an unknown TNO?*
- *Can we realistically simulate the effects of perturbing a planetary mass?*
- *Can we search for unknown planets/ asteroids around the pulsars?*
- ***Clocks:***
- *Can we prove that the deviation from TT prior to 1999 is caused by errors in TT (BIPM2010)?*
- *Can we use the pulsar timescale to improve our timing precision?*
- *Can we include pulsar data in the creation of TT(BIPM2010) to improve terrestrial time.*
- *Can anything else mimic clock errors?*
- ***Gravitational waves/galaxies***
- *What do our upper bounds on GW emission imply for e.g. galaxy merger rates, the rate of expansion in the inflationary era and cosmic strings?*
- *Can we find a black hole binary system with ~1 pc separation?*
- *Can we undertake a coherent search to identify single source of GWs?*
- *Can we find burst GW sources?*

03:32:59.368 +54:35:43.57

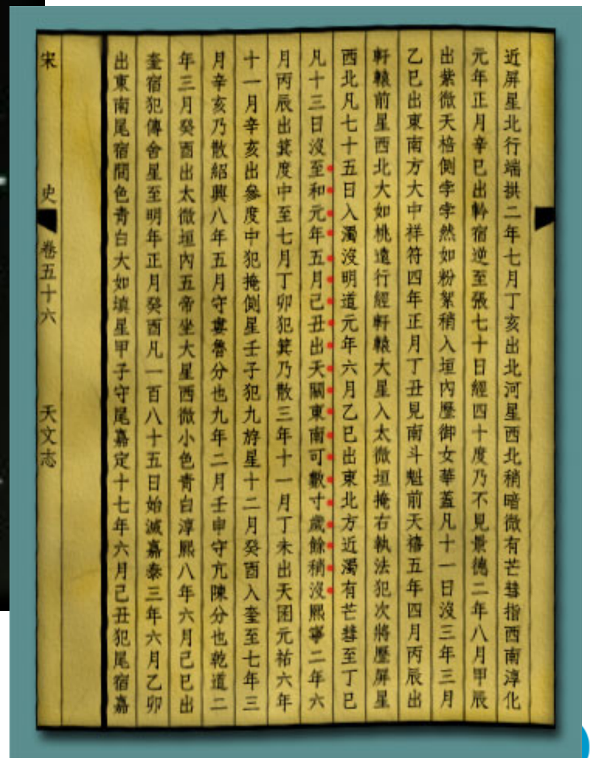
08:35:20.61 -45:10:34.87

05:34:31.973 +22:00:52.06

04:37:15.815 -47:15:08.624

The Crab supernova

An ancient Chinese Astronomer in AD1054



宋史　卷五十六　天文志

近屛星北行端拱二年七月丁亥出北河星西北稍暗微有芒彗指西南淳化
元年正月辛巳出軫宿逆至張七十日經四十度乃不見景德二年八月甲辰
出紫微天棓側孛孛然如粉絮稍入垣內歷御女華蓋凡十一日沒三年三月
乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出
軒轅前星西北大如桃遶行經軒轅大星入太微垣掩右執法犯次將歷屛星
西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳
凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六
月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年
十一月辛亥出參度中犯掩側星壬子犯九斿星十二月癸酉入奎至七年三
月辛亥乃散紹興八年五月守婁魯分也九年二月壬申守亢陳分也乾道二
年三月癸酉出太微垣內五帝坐大星西微小色青白淳熙八年六月己巳出
奎宿犯傳舍星至明年正月癸酉凡一百八十五日始滅嘉泰三年六月乙卯
出東南尾宿間色青白大如填星甲子守尾嘉定十七年六月己丑犯尾宿嘉

So what happened?

http://www.spacetelescope.org/videos/html/heic0609b.html