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Science **with** pulsars

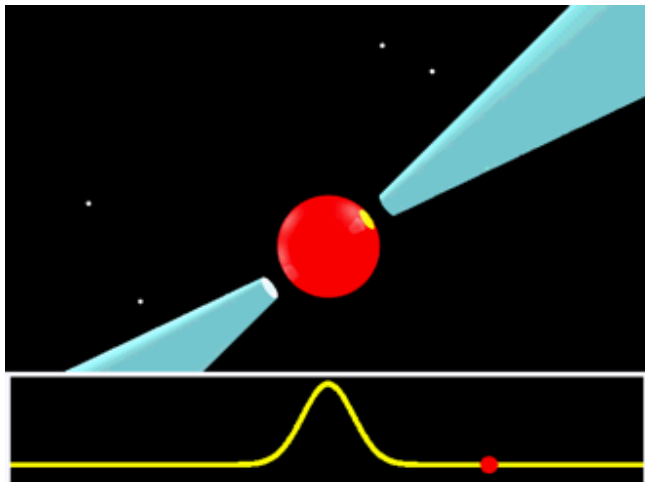
George Hobbs
CSIRO Australia Telescope National Facility
george.hobbs@csiro.au



Let's start at the beginning

08:35:20.61

-45:10:34.87



- 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

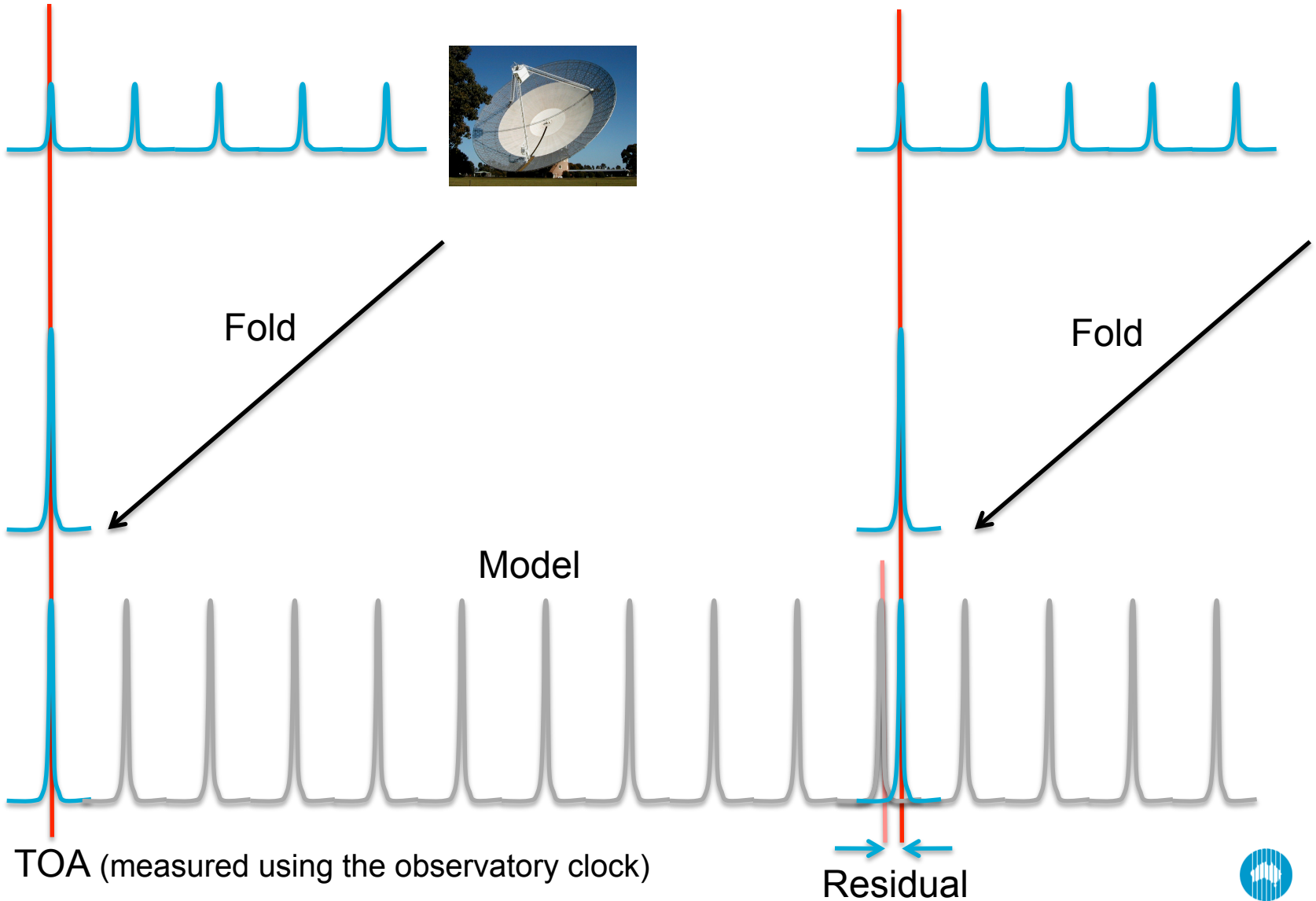
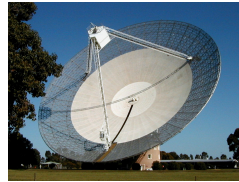
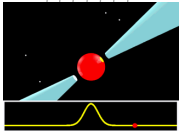
Animation: Michael Kramer

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
 - Part 6: Where is Parkes?
-
- (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

Obtain 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
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../archives/m2003-01-09-08:25:35.IFTp	1405.69000000	52648.36328904903029979	0.06000	7	-i	mCPSR2_20
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../archives/m2003-01-12-12:40:32.IFTp	1405.69000000	52651.50145000000000000	0.17000	7	-i	mCPSR2_20

$F0 = 245.4261197483027 \pm 0.000000000000005 \text{ Hz}$
 $F1 = -5.38188 \times 10^{-16} \pm 4 \times 10^{-21} \text{ Hz/s}$

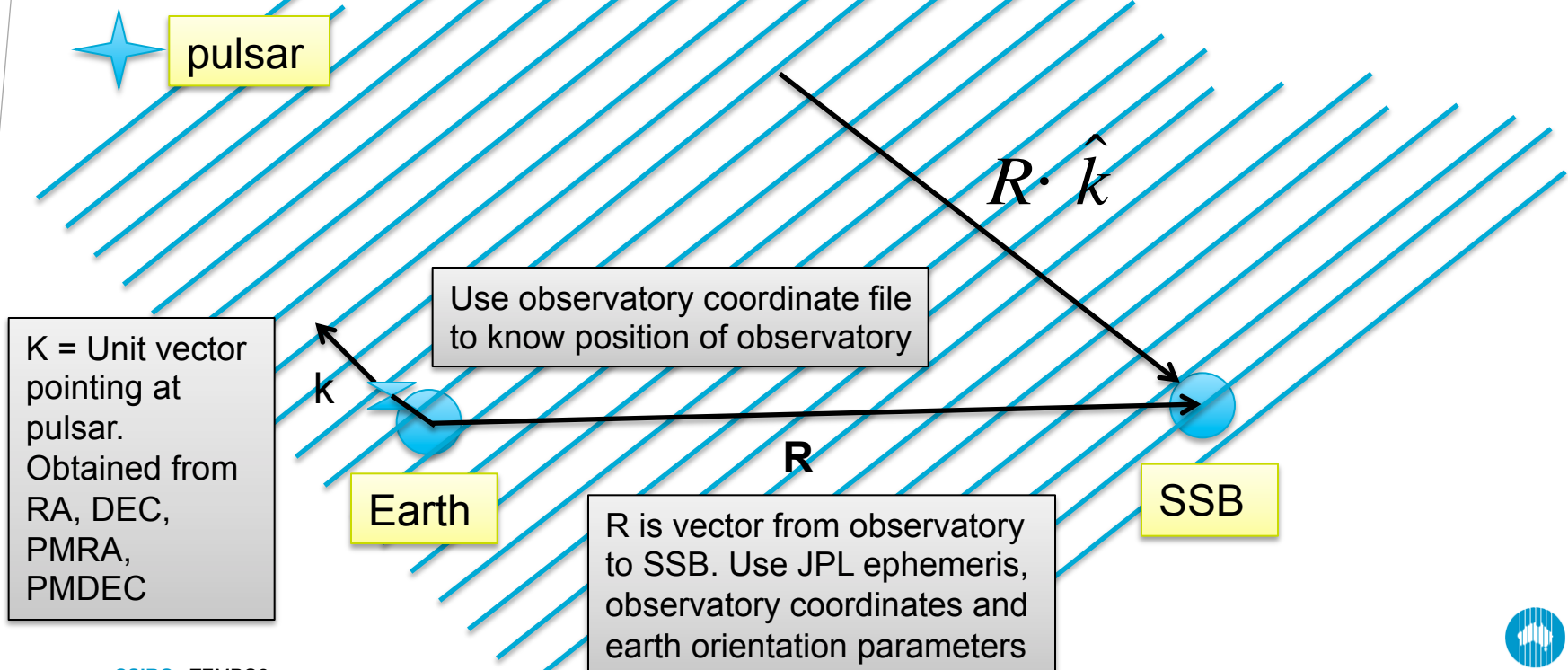
solar system
barycentre

solar system

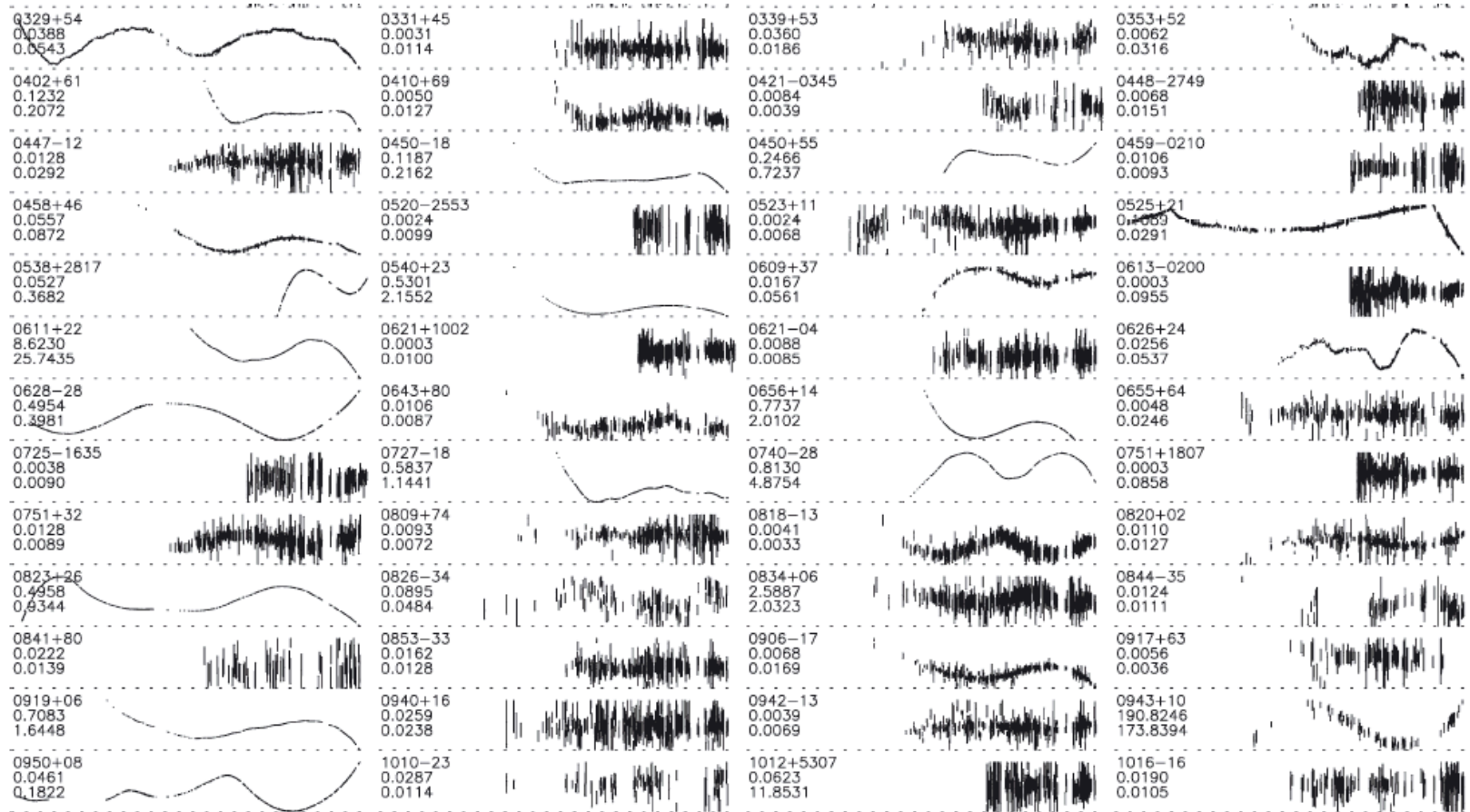
Details: Roemer delay

$$\Delta t = \Delta_C + \Delta_A + \Delta_{E\odot} + \Delta_{R\odot} + \Delta_{S\odot} - D/f^2 + \Delta_{VP} + \Delta_B$$

- The Roemer delay is the vacuum light travel time between the pulse arriving at the observatory and the equivalent arrival time at the SSB.



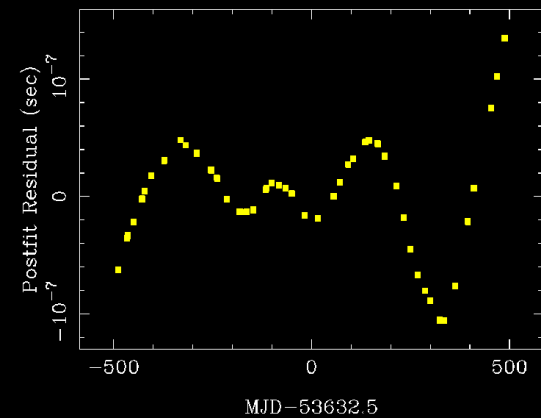
Example timing residuals Jodrell Bank Observatory data



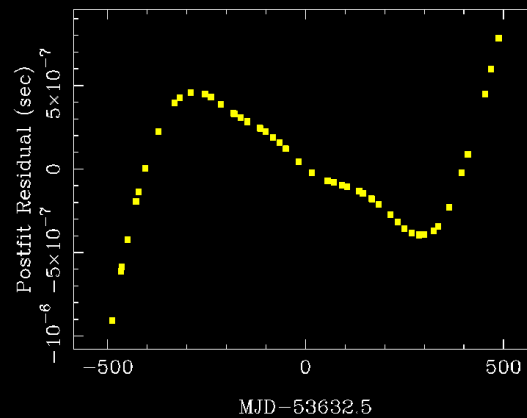
Hobbs et al. (2010), MNRAS

A few simulations

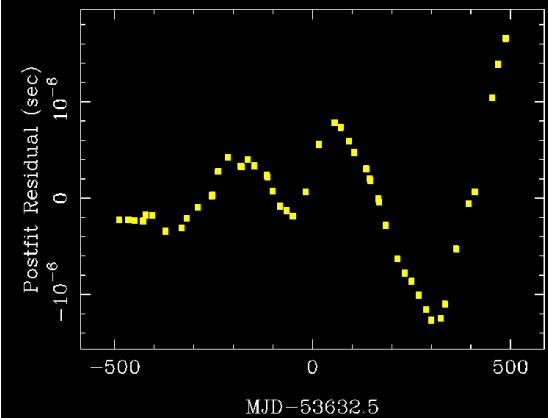
J1939+2134 (rms = 0.043 μs) post-fit



J1939+2134 (rms = 0.288 μs) post-fit



J1939+2134 (rms = 0.549 μs) post-fit



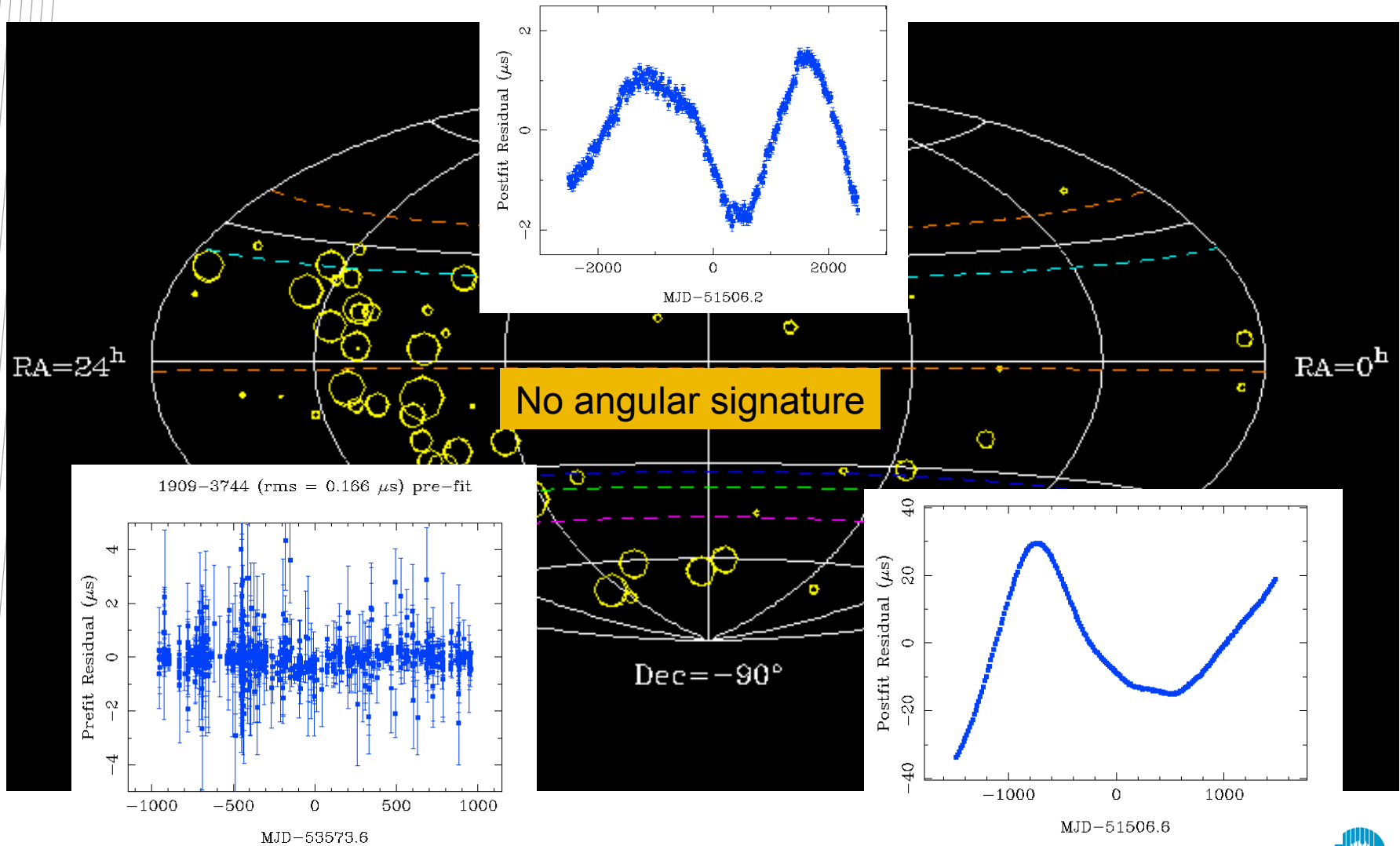
GW background

Spin-down irregularities

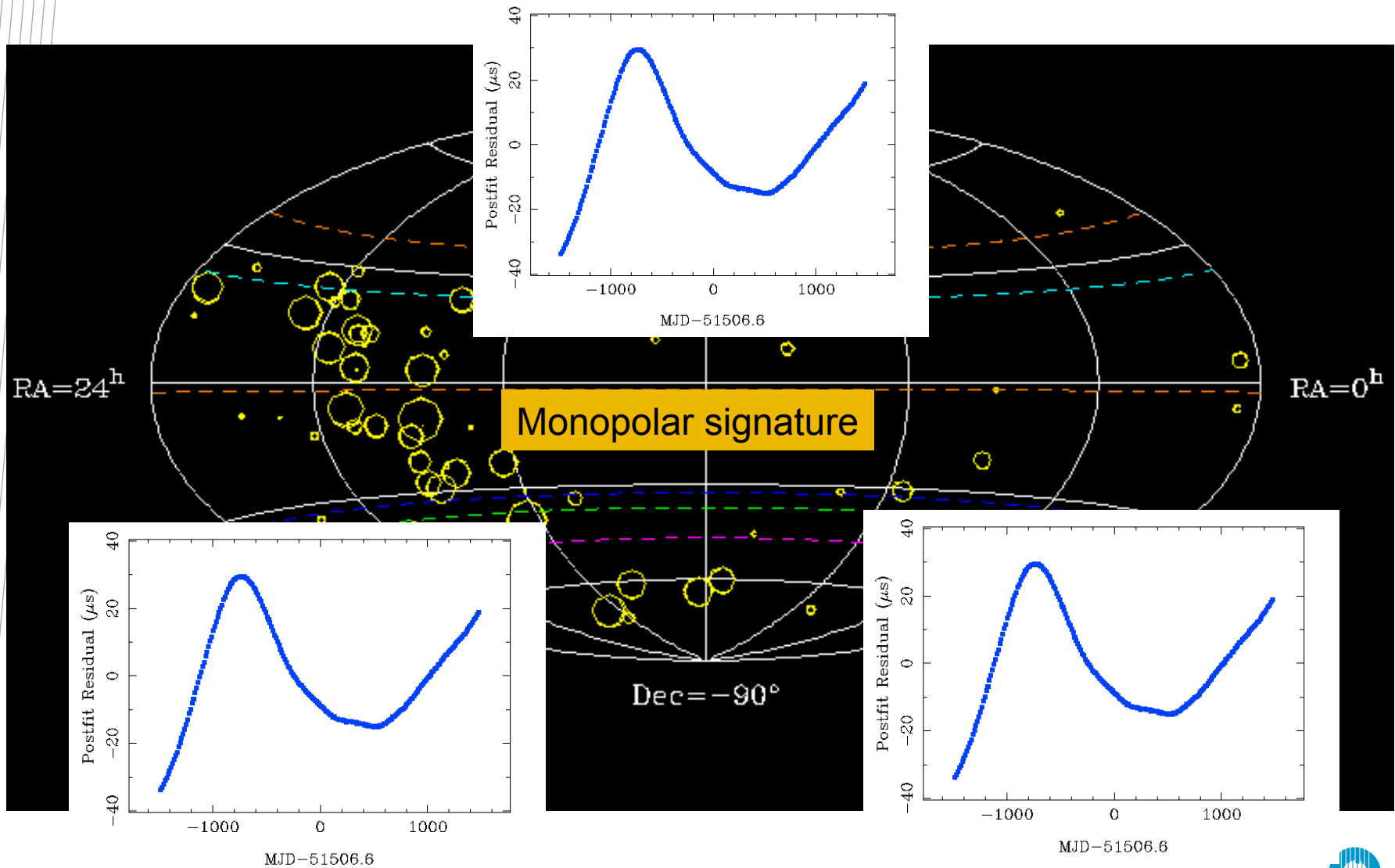
Clock noise

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

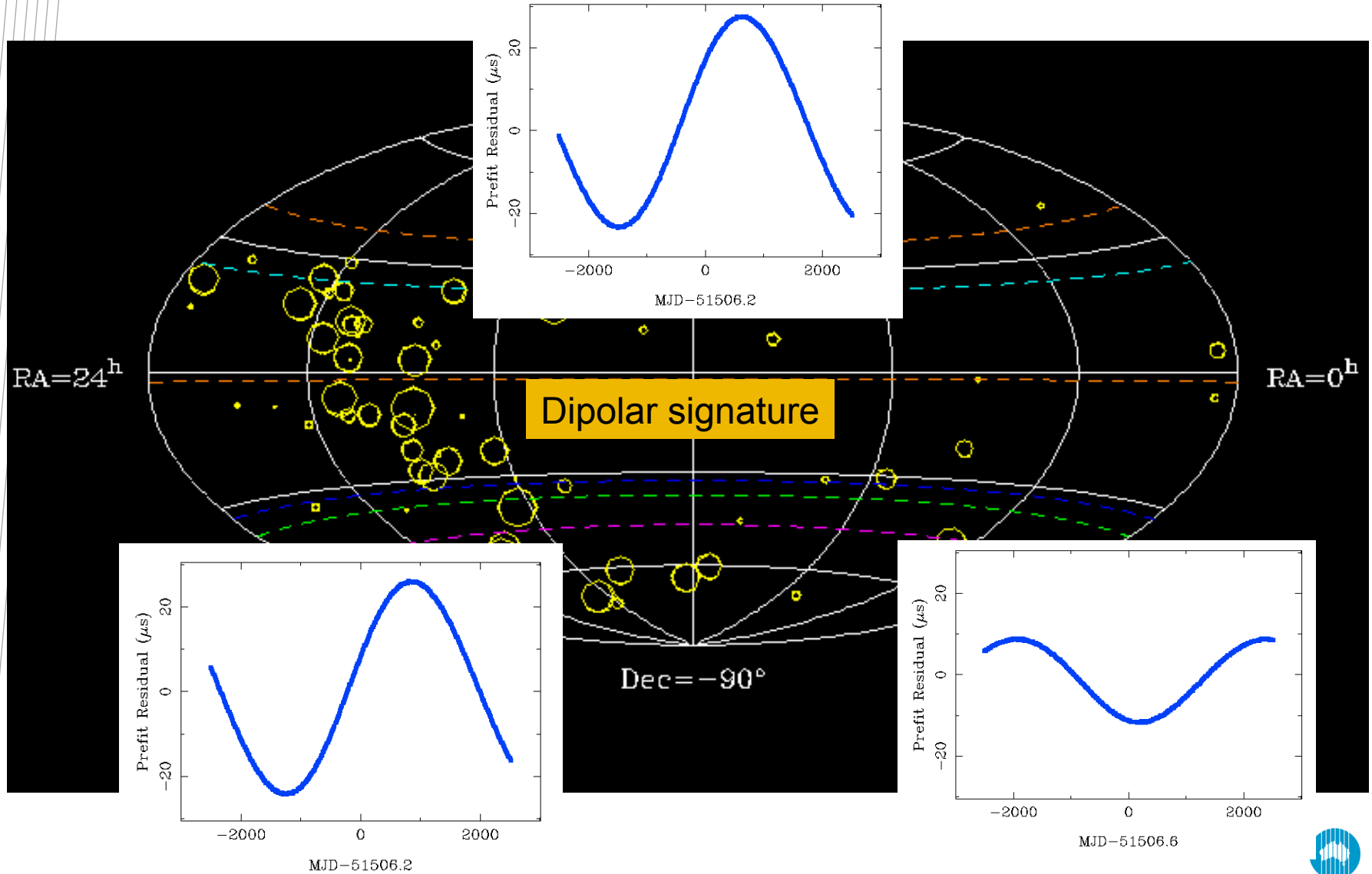
Spin-down irregularities



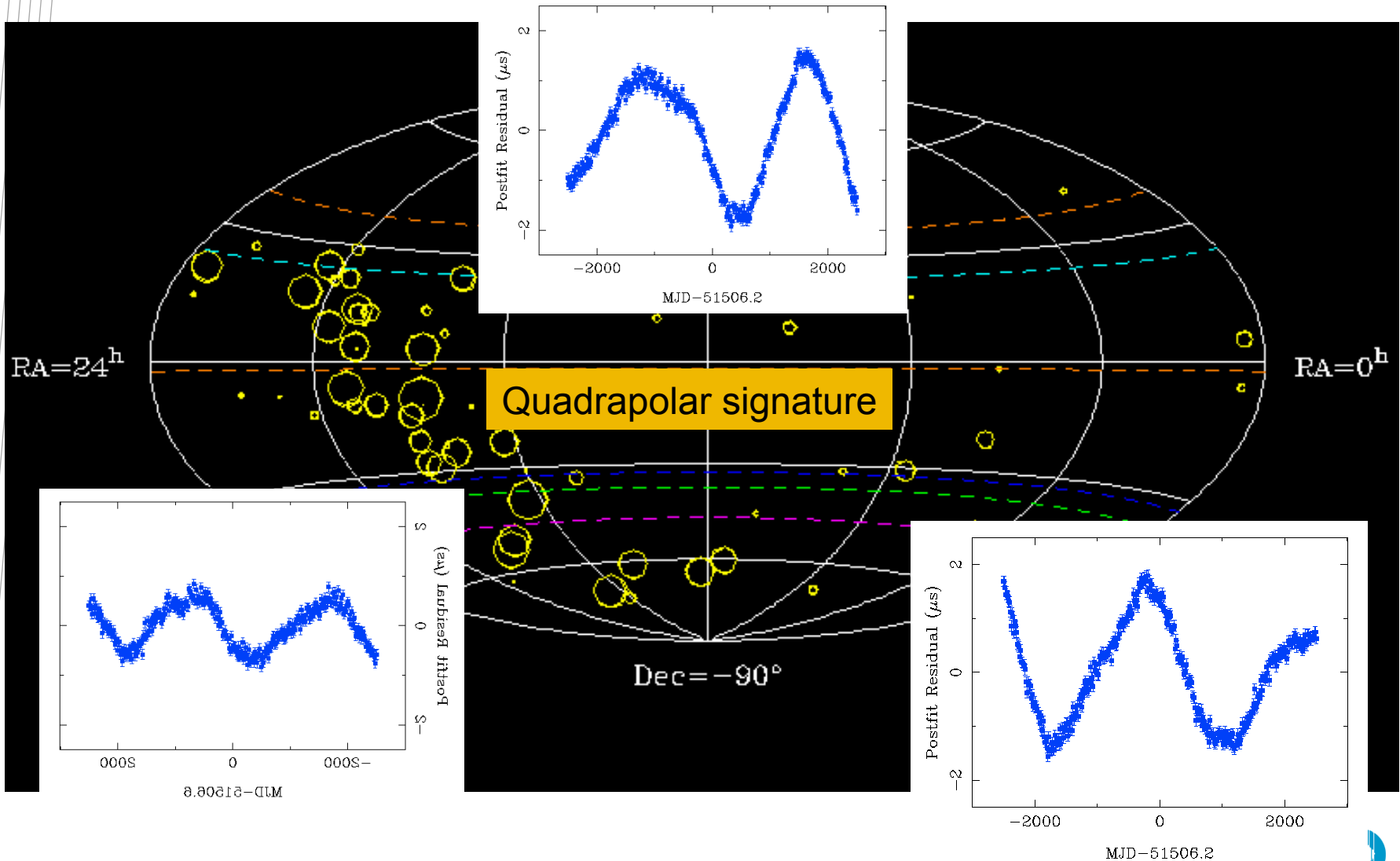
Terrestrial time standard irregularities



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



What if gravitational waves exist?

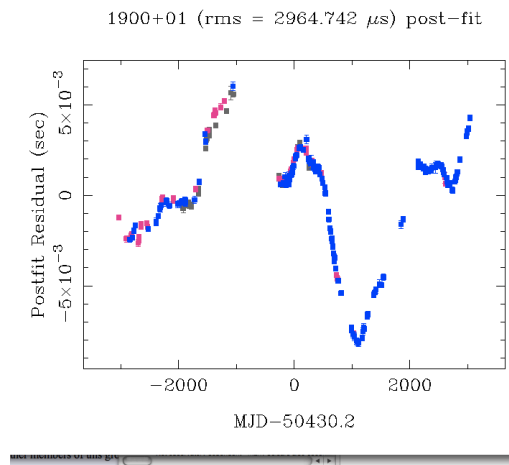
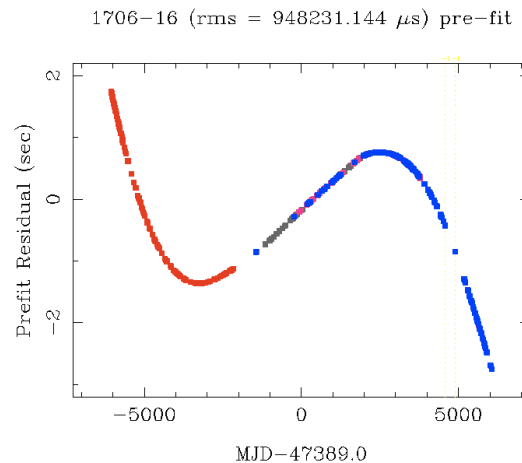
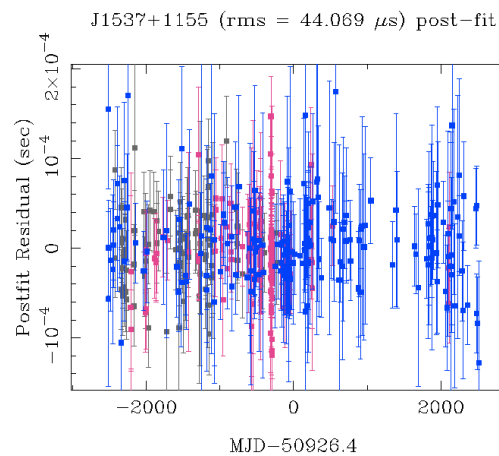


Part 2: Uncorrelated residuals

- Part 1: Introduction to pulsar timing
- Part 2: **Uncorrelated timing residuals**
- Part 3: Monopolar correlations
- Part 4: Dipolar correlations
- Part 5: Quadrupolar correlations
- Part 6: Where is Parkes?

Describing the spin-down of pulsars

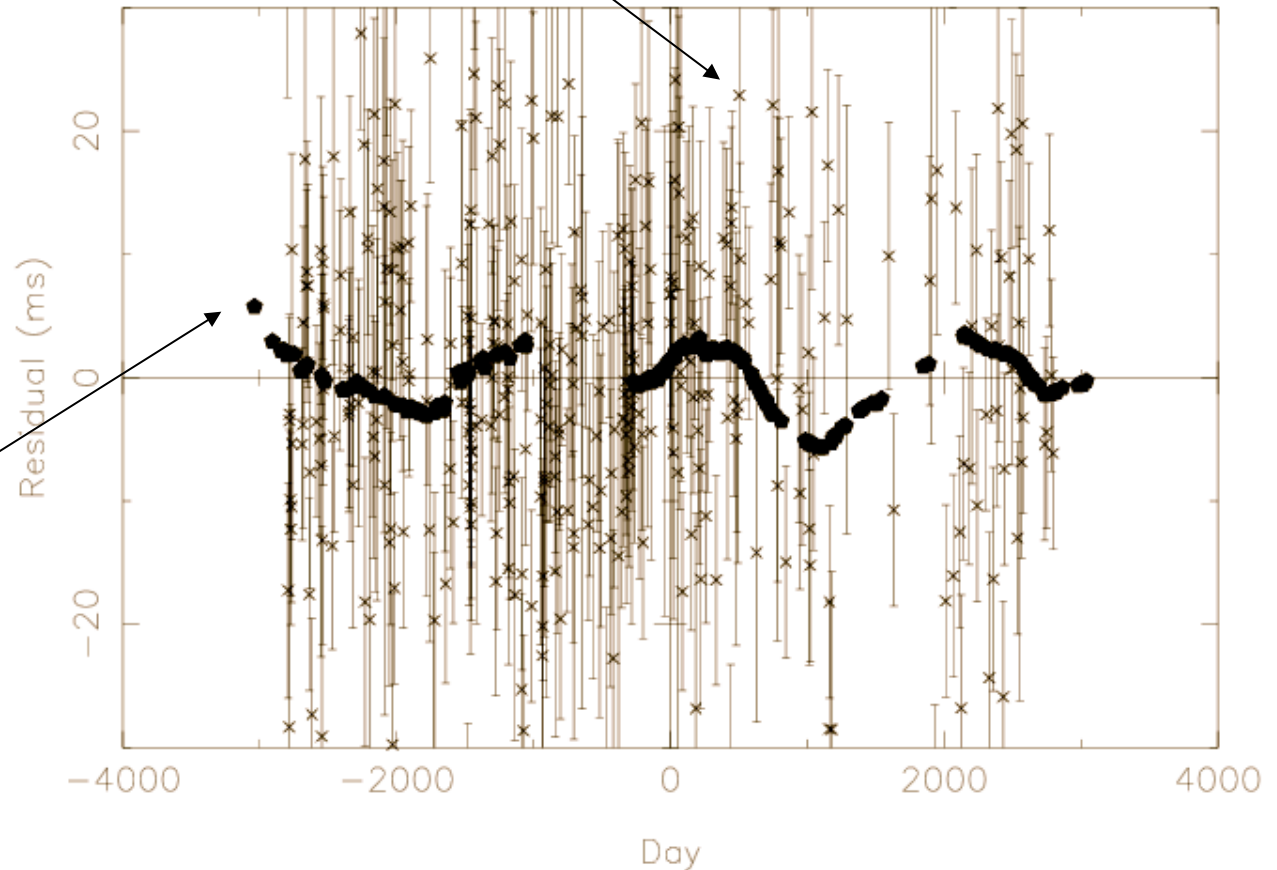
- Modelling the pulsar spin-down usually requires the pulse frequency, F and its first derivative, $F\dot{1}$.
- Residuals shown here have $F\ddot{2}$ (and higher derivatives) = 0.



Difficulties when categorising timing residuals

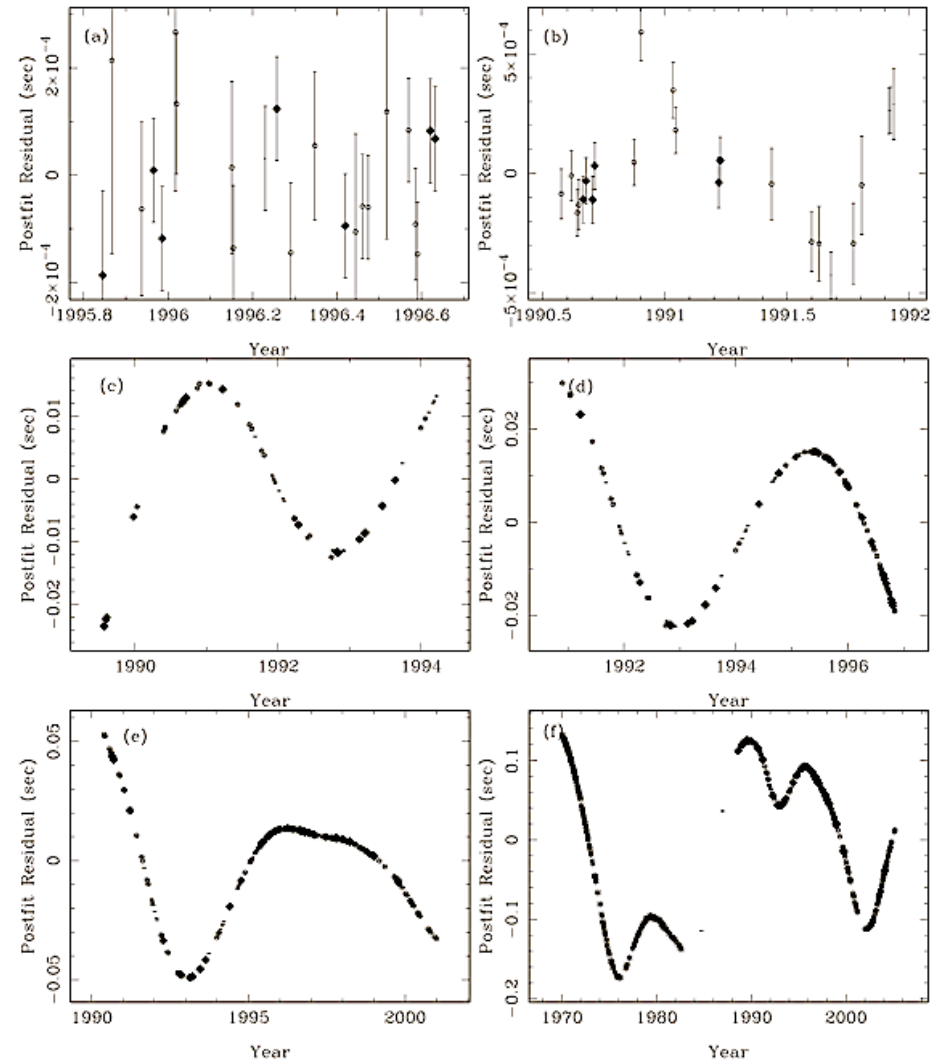
• B1746-20

• B1900+01



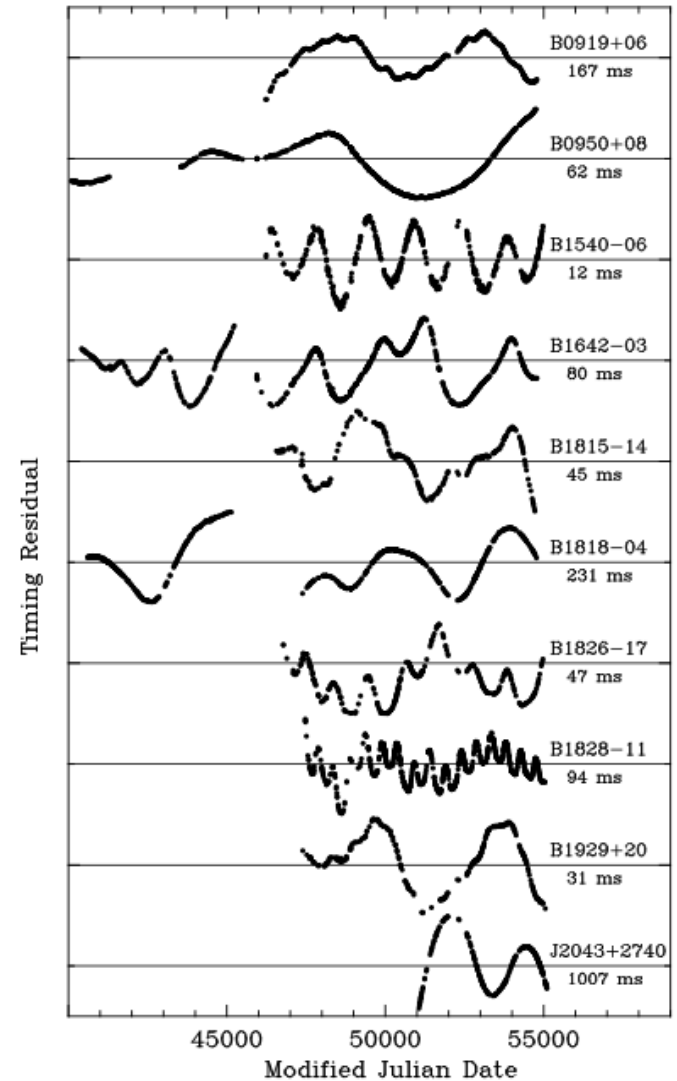
Difficulties when categorising timing noise: depends on data span

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



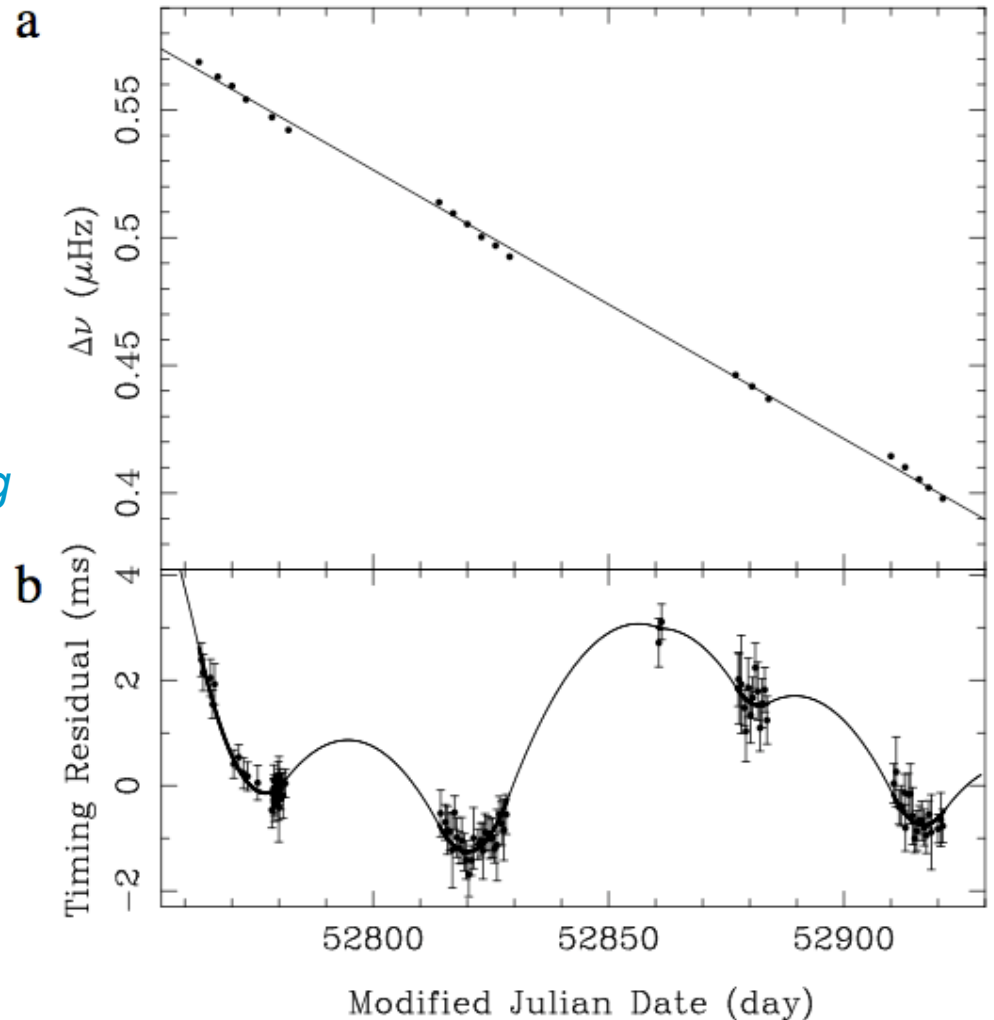
Typical pulsar timing residuals over many decades (Jodrell Bank Observatory data)

- 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)*

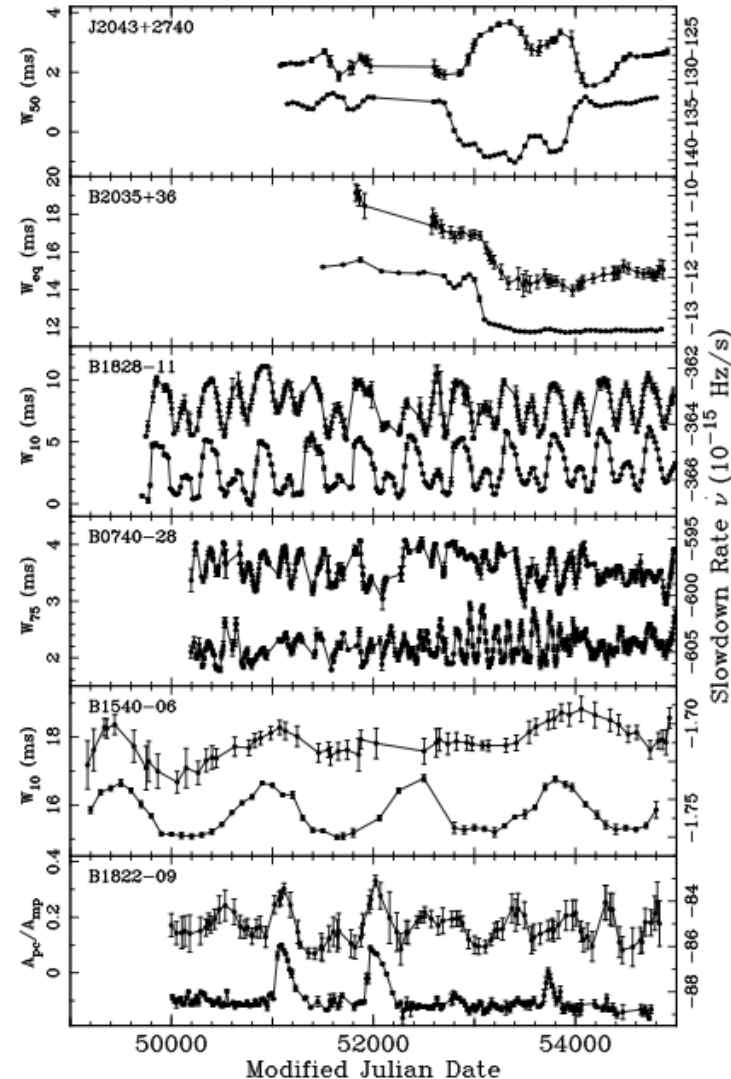


Discovery of a two state process in many pulsars

- 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: 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!
- => make the best use of future telescopes such as ASKAP, SKA ...

• **Unanswered questions:**

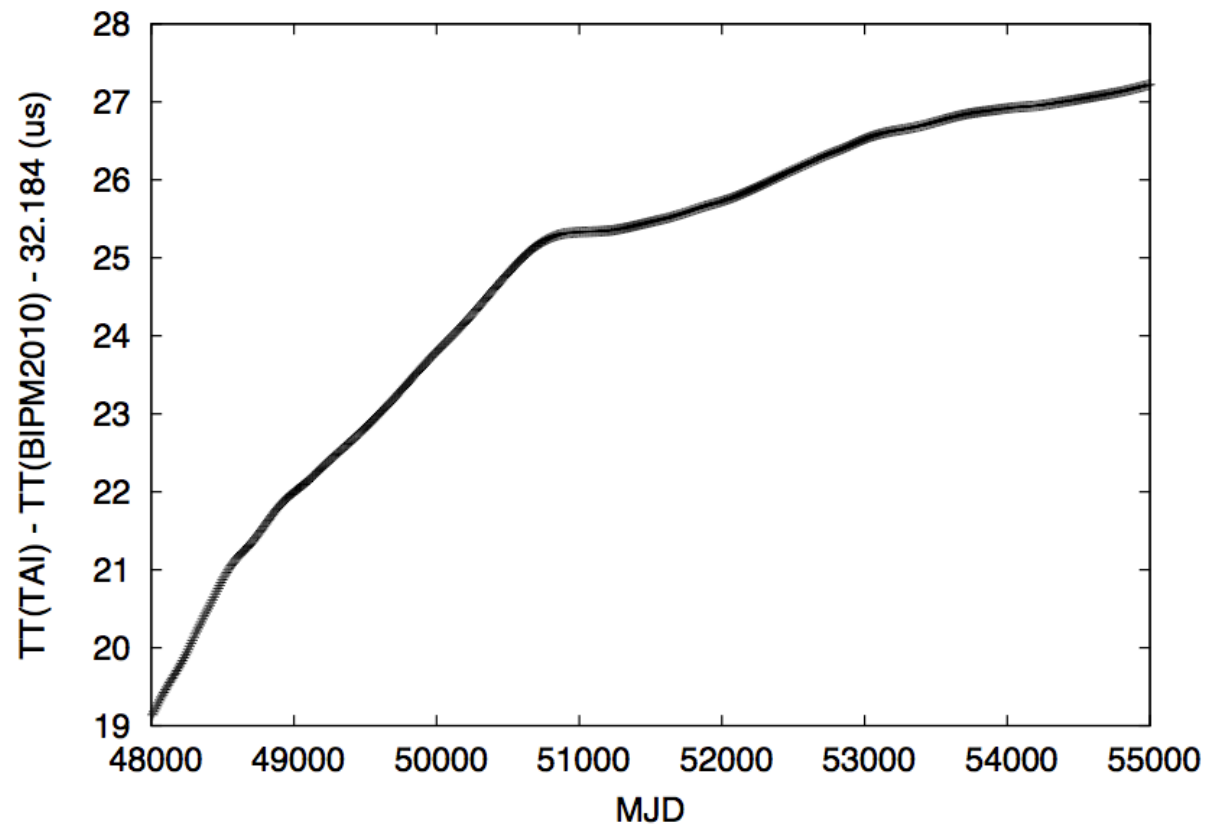
- *Why do the pulsars have this two state process?*
- *Are glitches and timing noise linked?*
- *Do all pulsars show this two state timing noise? Do millisecond pulsars exhibit different timing noise?*
- *How fast can the pulsar switch between the two modes?*

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 $<100\text{ns}$ (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

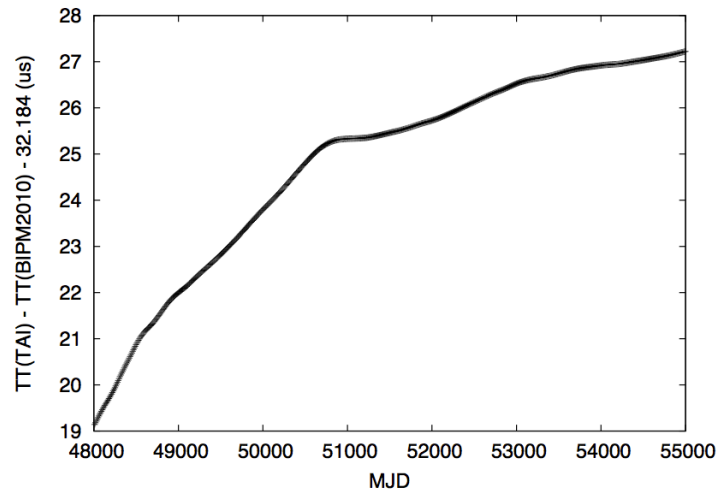
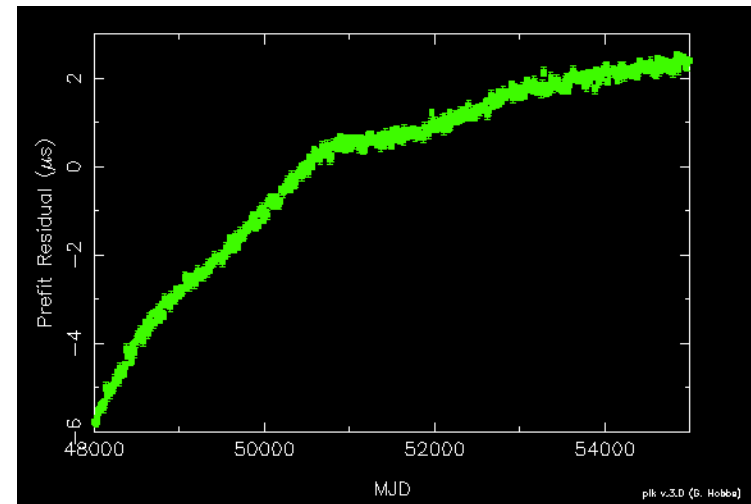
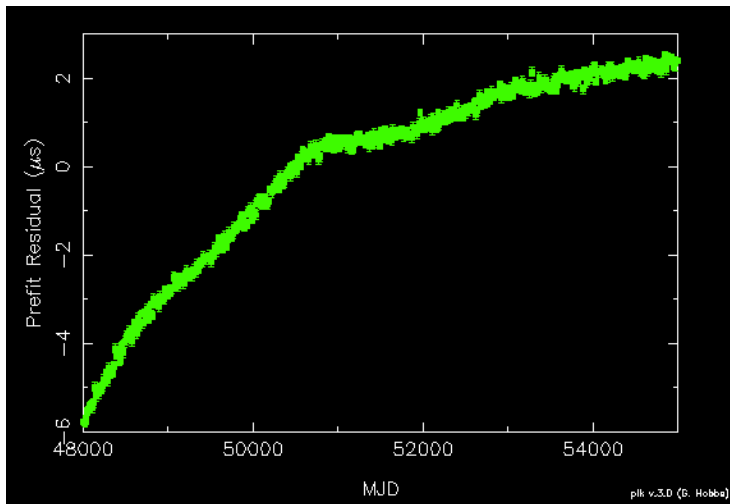


It's hard (page 11)

- **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)
 - ...

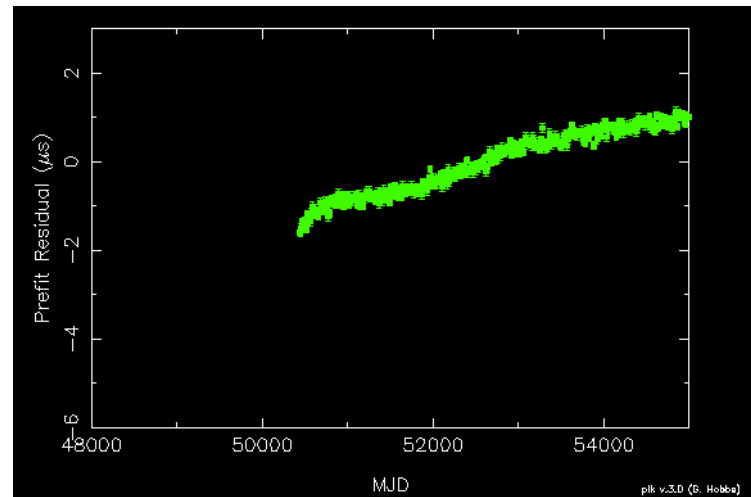
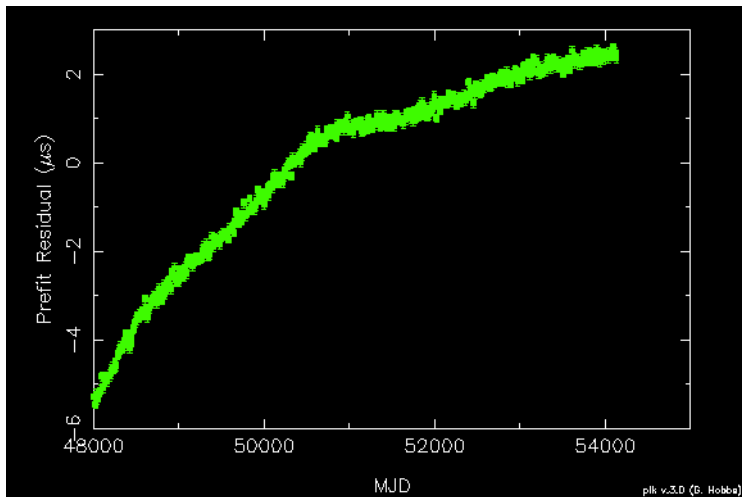
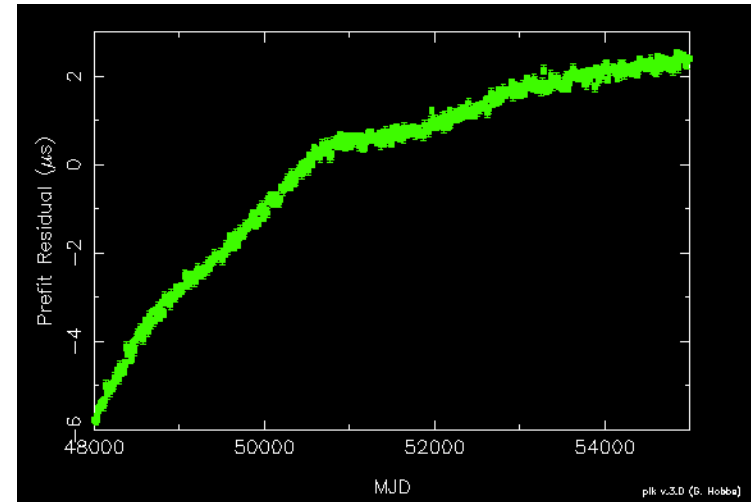
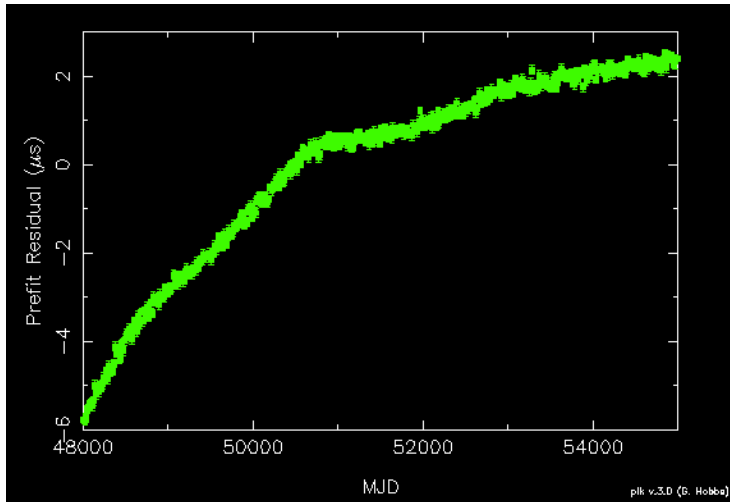
An example (page 12)

- Consider two pulsar data sets.



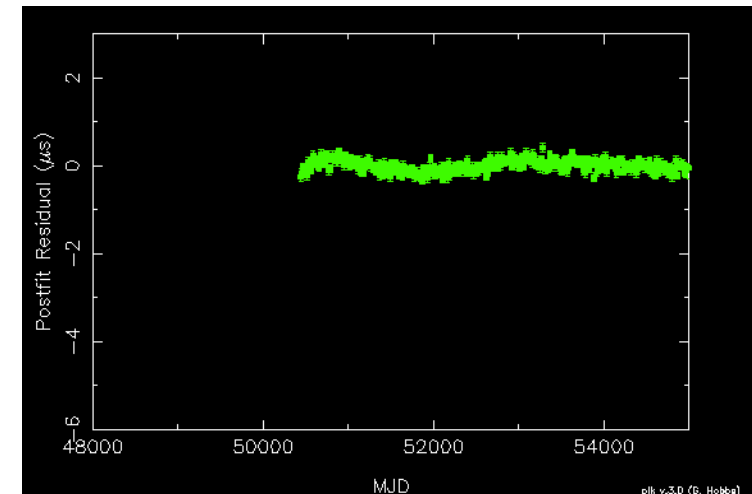
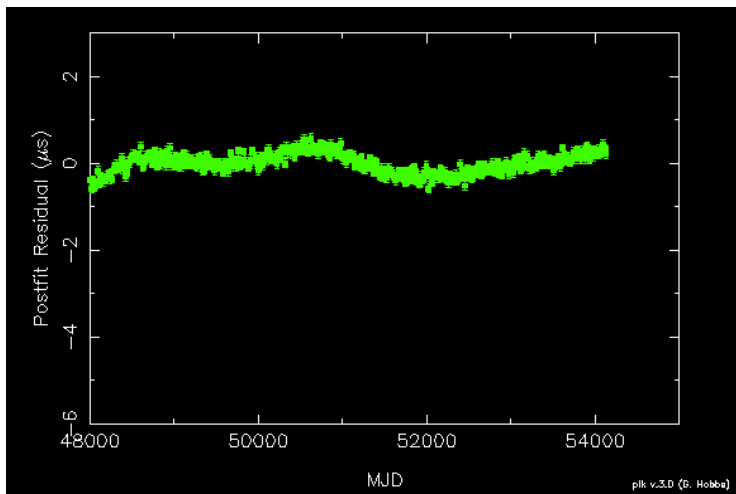
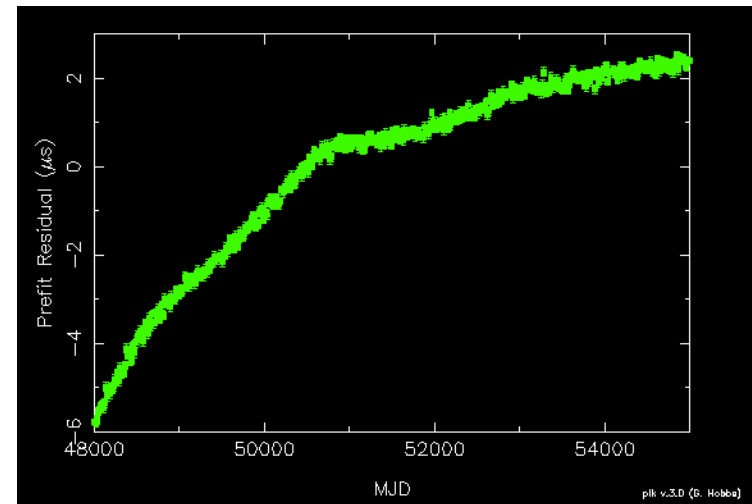
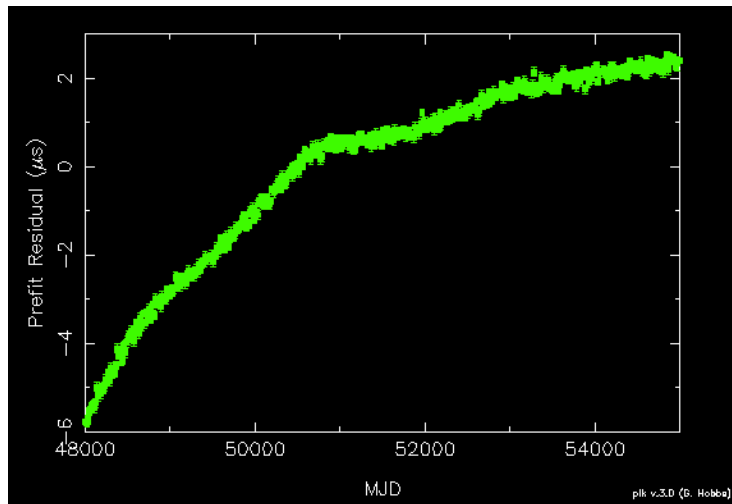
An example (page 13)

- Have different data spans



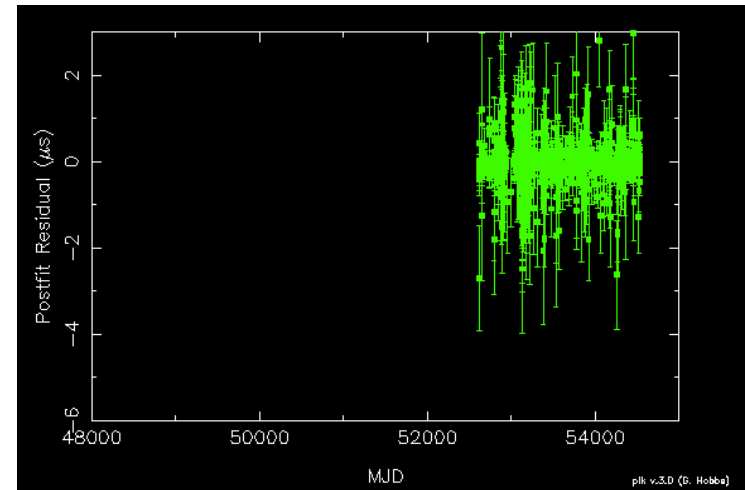
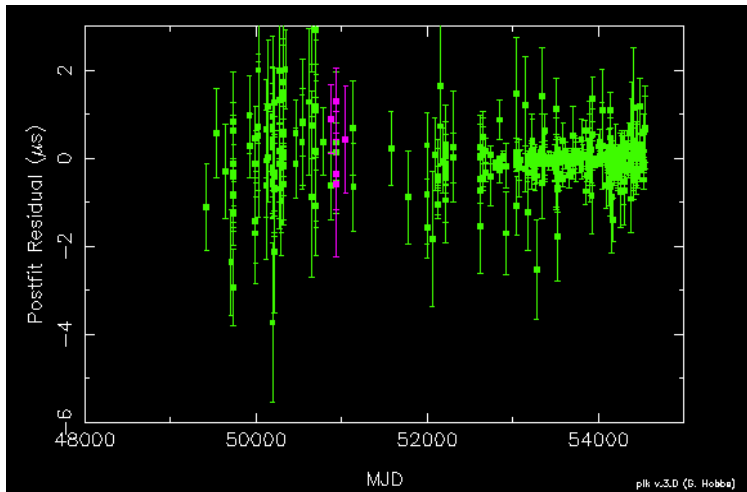
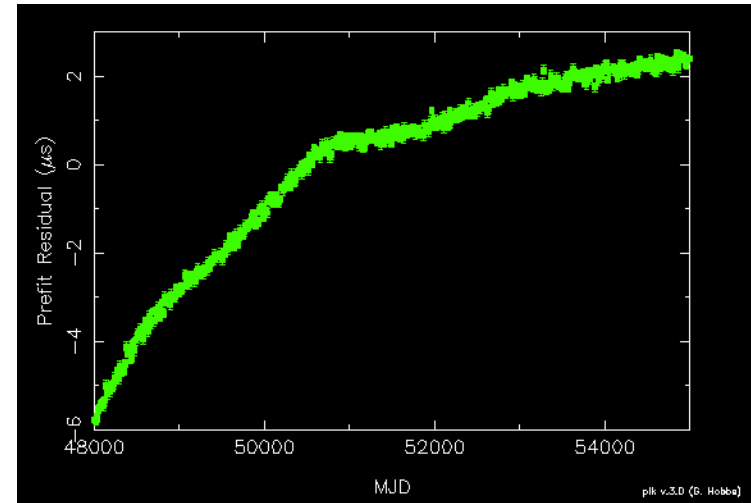
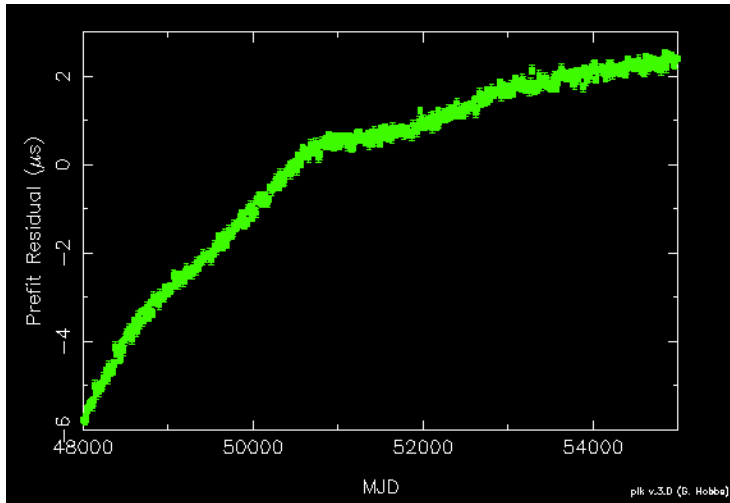
An example (page 14)

- Fit for the pulse frequency and its derivative



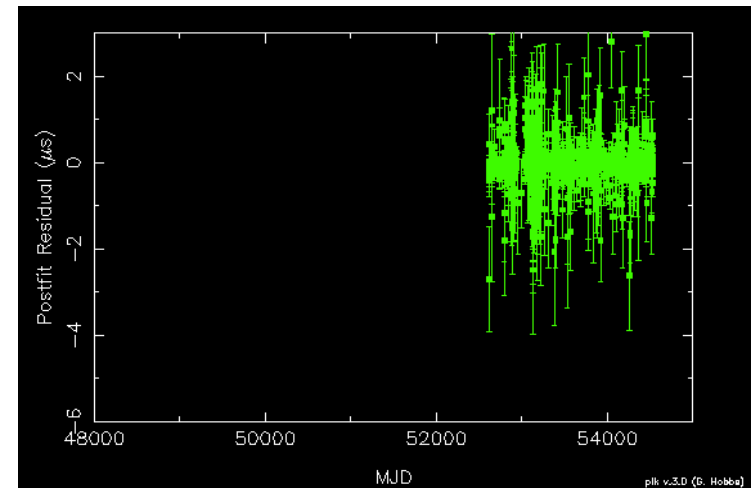
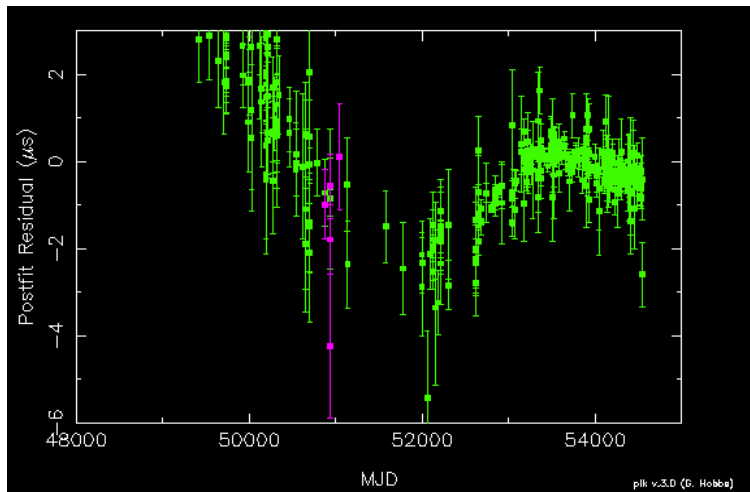
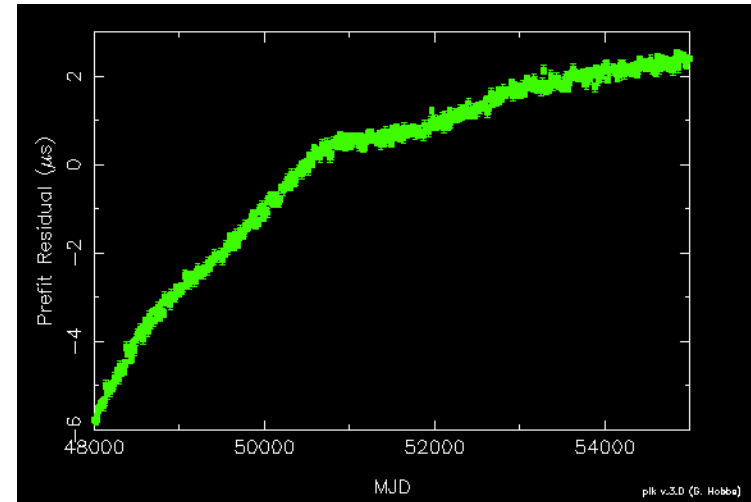
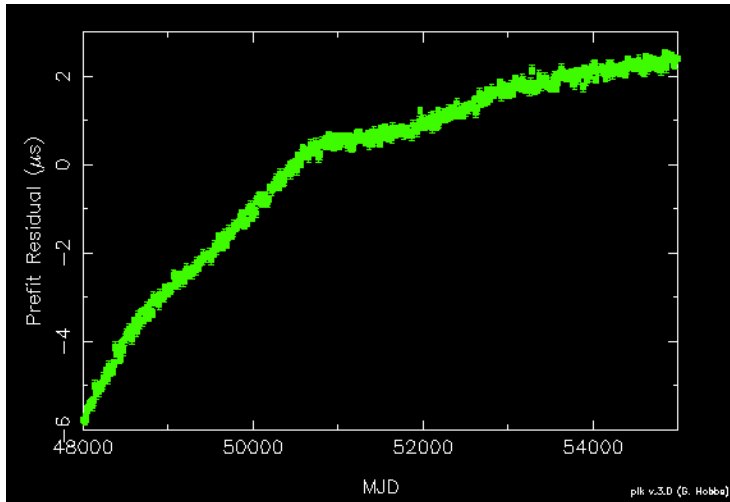
An example (page 15)

- Add in realistic amounts of noise



An example (page 16)

- Add in some unexplained timing irregularities



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)

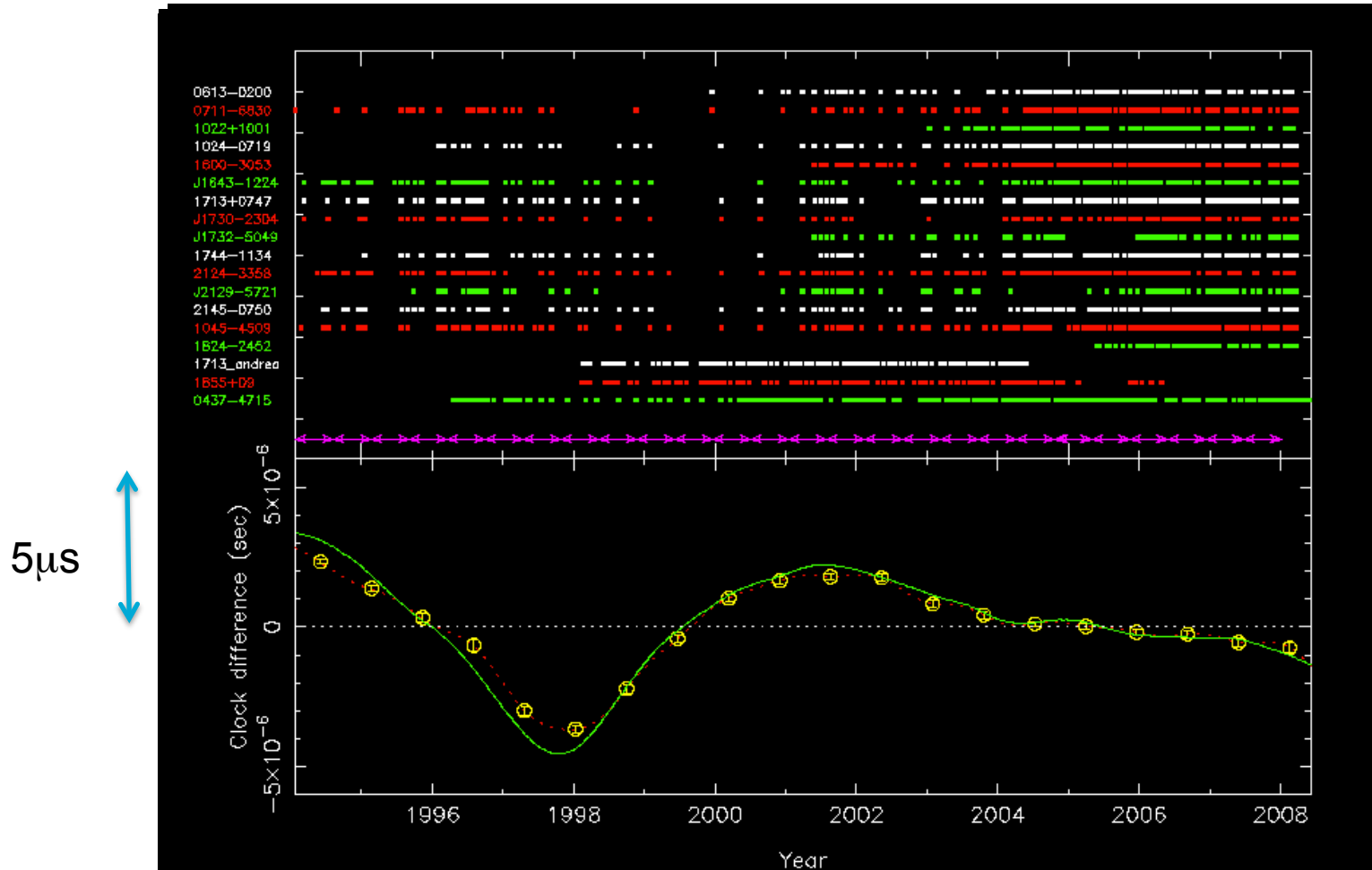
$$\vec{P}_{est} = (M^T C^{-1} M)^{-1} M^T C^{-1} \vec{R} \quad \leftarrow \text{Timing residuals}$$

Covariance matrix of the residuals

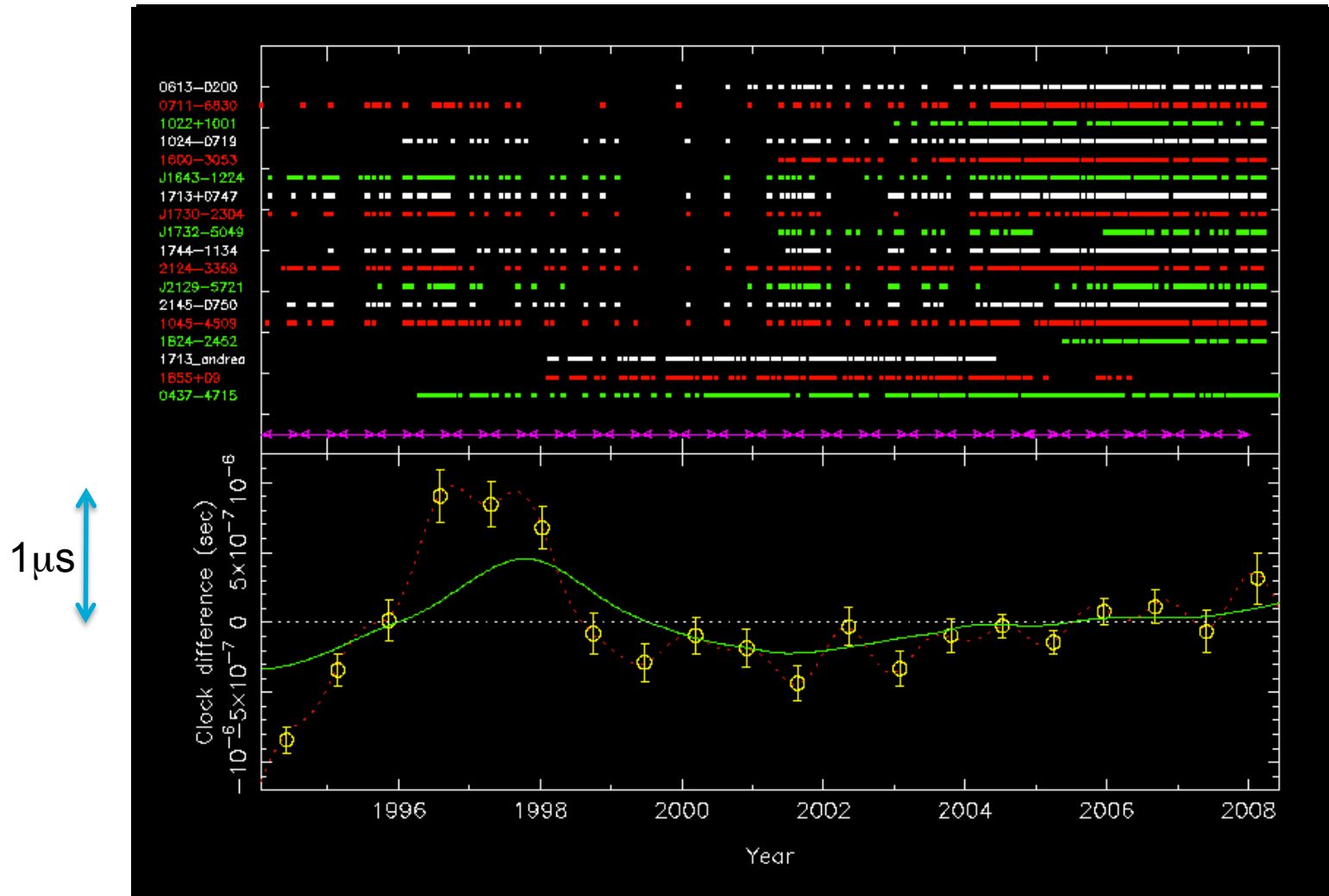
Pulsar timing model

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

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



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



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**
- Part 5: Quadrupolar correlations

Measuring planetary masses

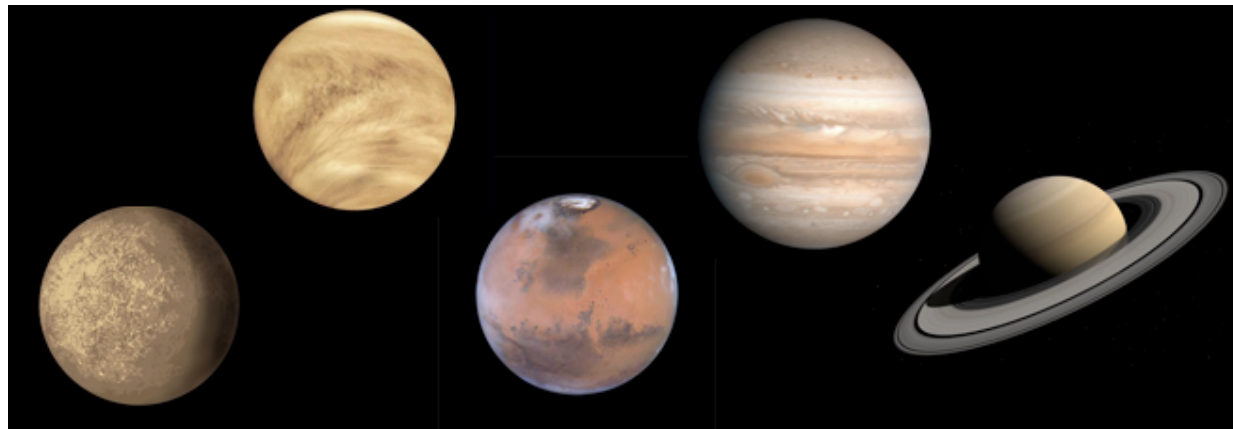
- Use International Pulsar Timing Array data from Parkes, Effelsberg, Nancay and Arecibo.
- Champion et al. 2010, ApJ.
- A planetary mass error will lead to incorrect determination of the Solar System barycentre => correlated pulsar timing residuals
- Can fit to multiple pulsars simultaneously to search 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	$1.66013(7) \times 10^{-7}$	$1.660(2) \times 10^{-7}$
Venus	$2.4478686(4) \times 10^{-6}$	$2.44782(10) \times 10^{-6}$
Mars	$3.227151(9) \times 10^{-7}$	$3.2277(8) \times 10^{-7}$
Jupiter*	$9.54791915(11) \times 10^{-4}$	$9.547916(4) \times 10^{-4}$
Saturn	$2.85885670(8) \times 10^{-4}$	$2.858858(14) \times 10^{-4}$



Summary of part 4

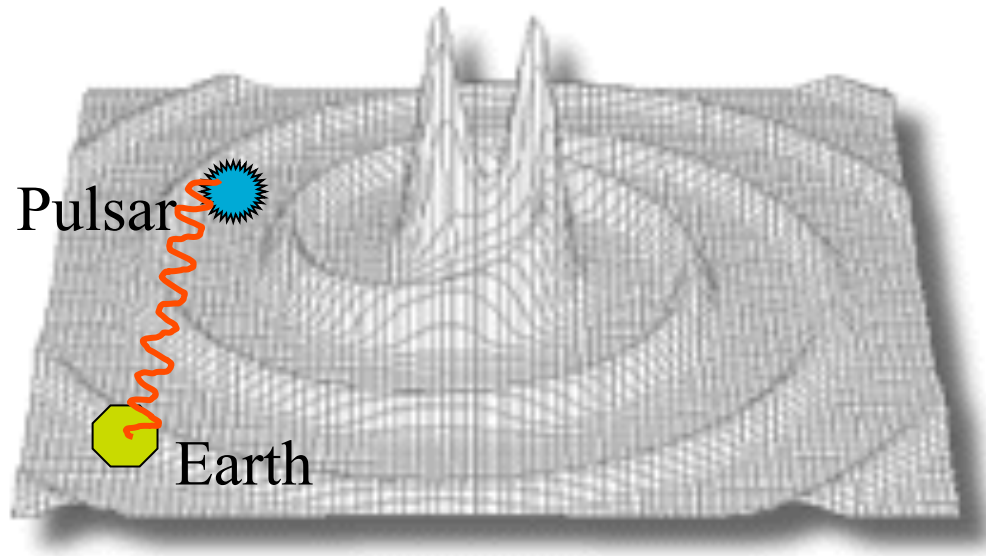
- Can measure planetary masses with pulsar timing
- New data sets will significantly improve the precision

- ***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 6: Where is Parkes?

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



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

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

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

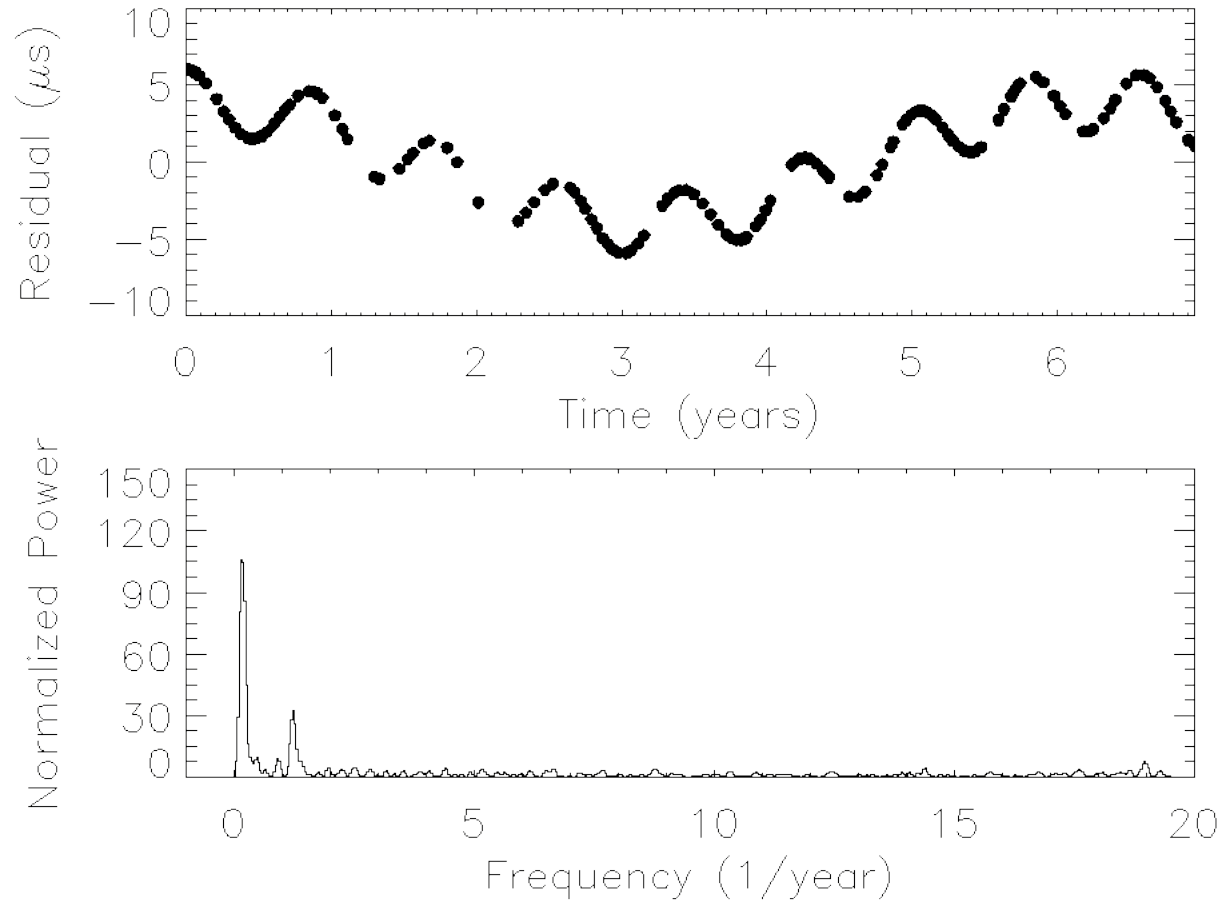
Orbital Motion in the Radio Galaxy 3C 66B: Evidence for a Supermassive Black Hole Binary

Hiroshi Sudou,^{1*} Satoru Iguchi,² Yasuhiro Murata,³ Yoshiaki Taniguchi¹

Science
magazine

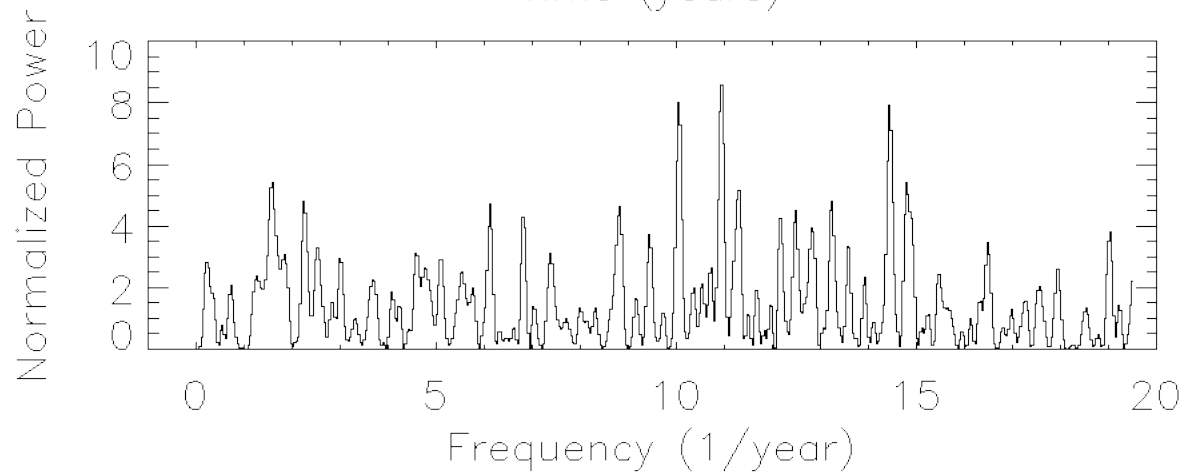
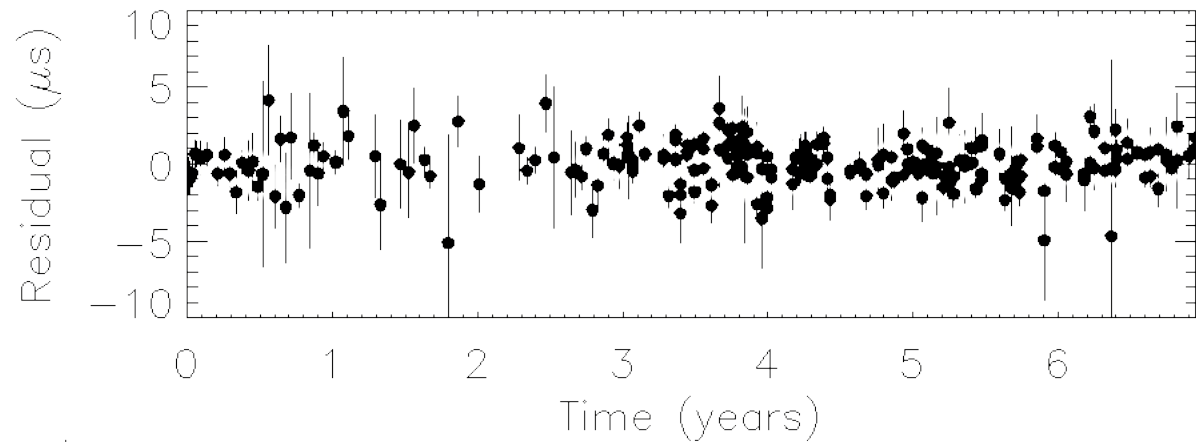
- $M_t = 5.4 \times 10^{10} M_{\text{solar}}$
- Mass ratio = .1
- $M_{\text{chirp}} = 1.3 \cdot 10^{10} M_{\text{solar}}$
- Orbital period = $1.05 \pm .03$ yrs
- Distance = 85 Mpc ($H=75$ km/s/Mpc)
- $h \approx M_{\text{chirp}}^{5/3} \Omega^{2/3} / D \approx 10^{-12}$
- $R = h/\Omega = 2 \mu\text{s}$

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



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

Application to 3C66B

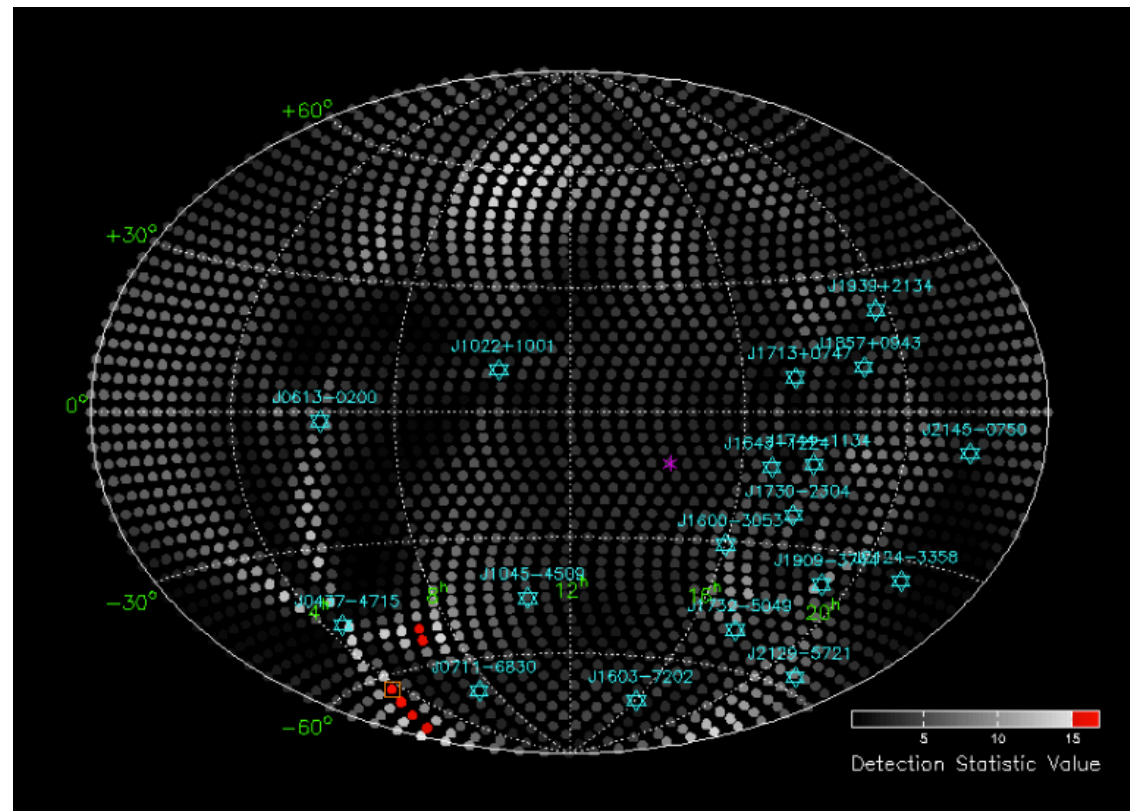


From Jenet, Lommen, Larson, & Wen, *ApJ*, 2004

Data from Kaspi et al. 1994

New technique – Our first “map of sky in GWs” - Hobbs et al. (in prep)

- Use same technique as the pulsar time scale, but search for a quadrupolar signal.



Detecting the stochastic background

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

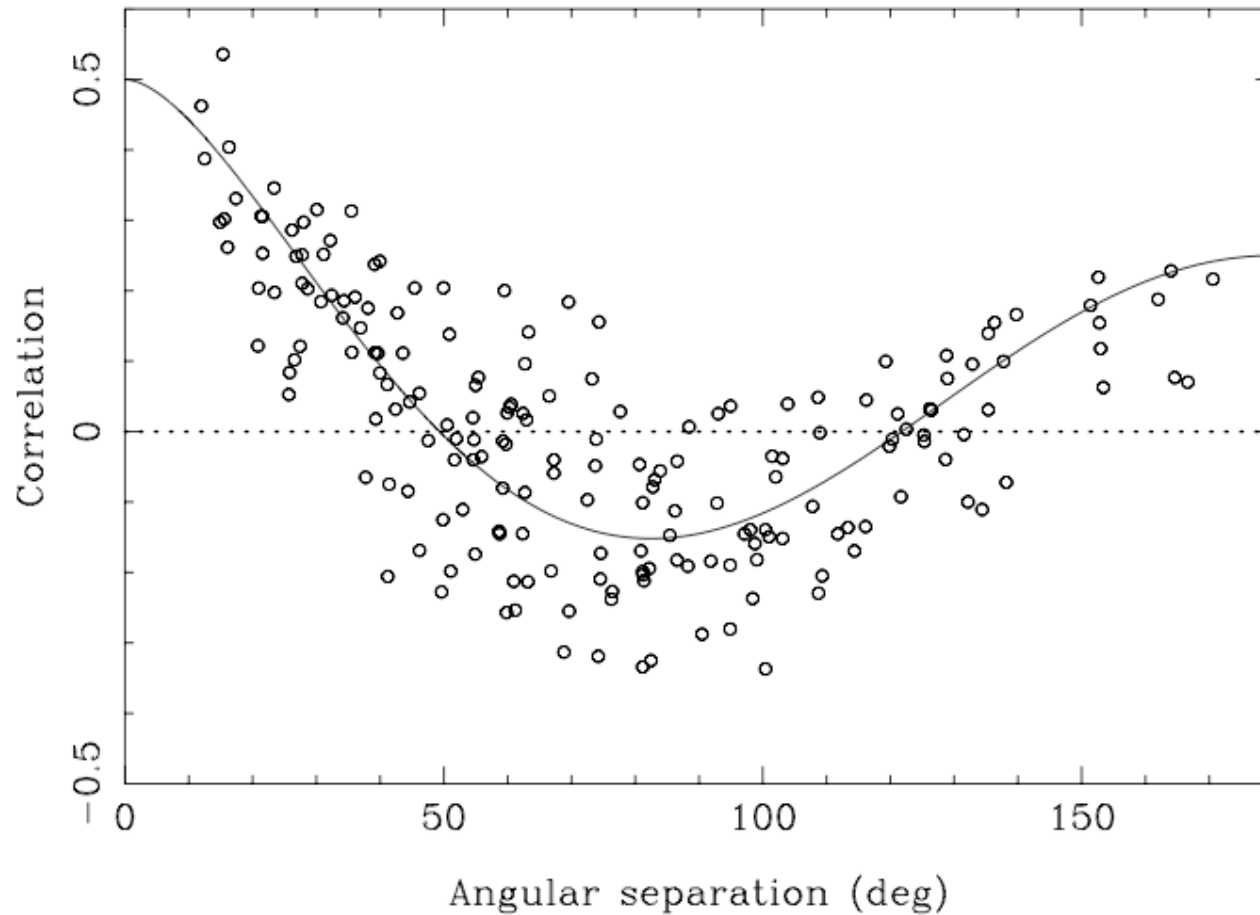
This is the same for all pulsars.

This depends on the pulsar.

- The induced timing residuals for different pulsars will be correlated

The expected correlation function

Simulated data

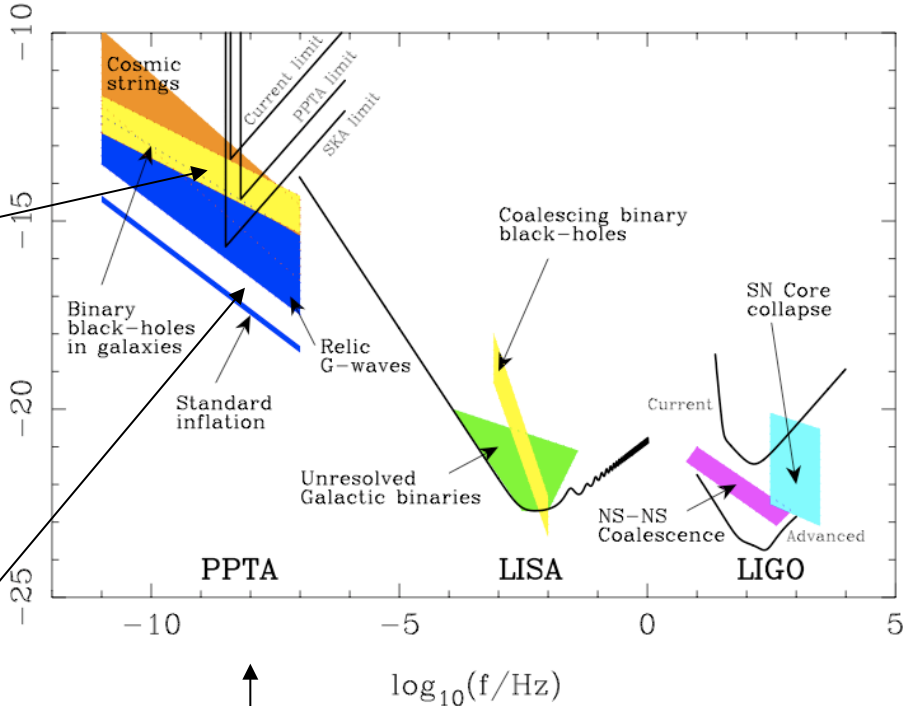


Detection/limits on the background

- 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

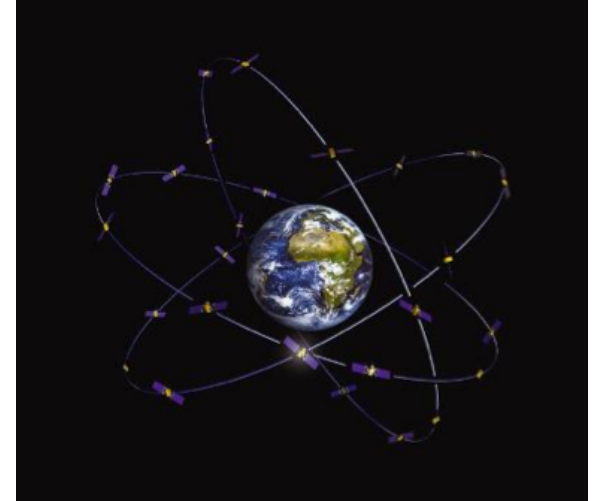
And now for something completely different ...

Pulsar navigation

- Normal pulsar timing:
 - set of pulse arrival times
 - initial model of pulsar
 - know telescope position
 - know clock

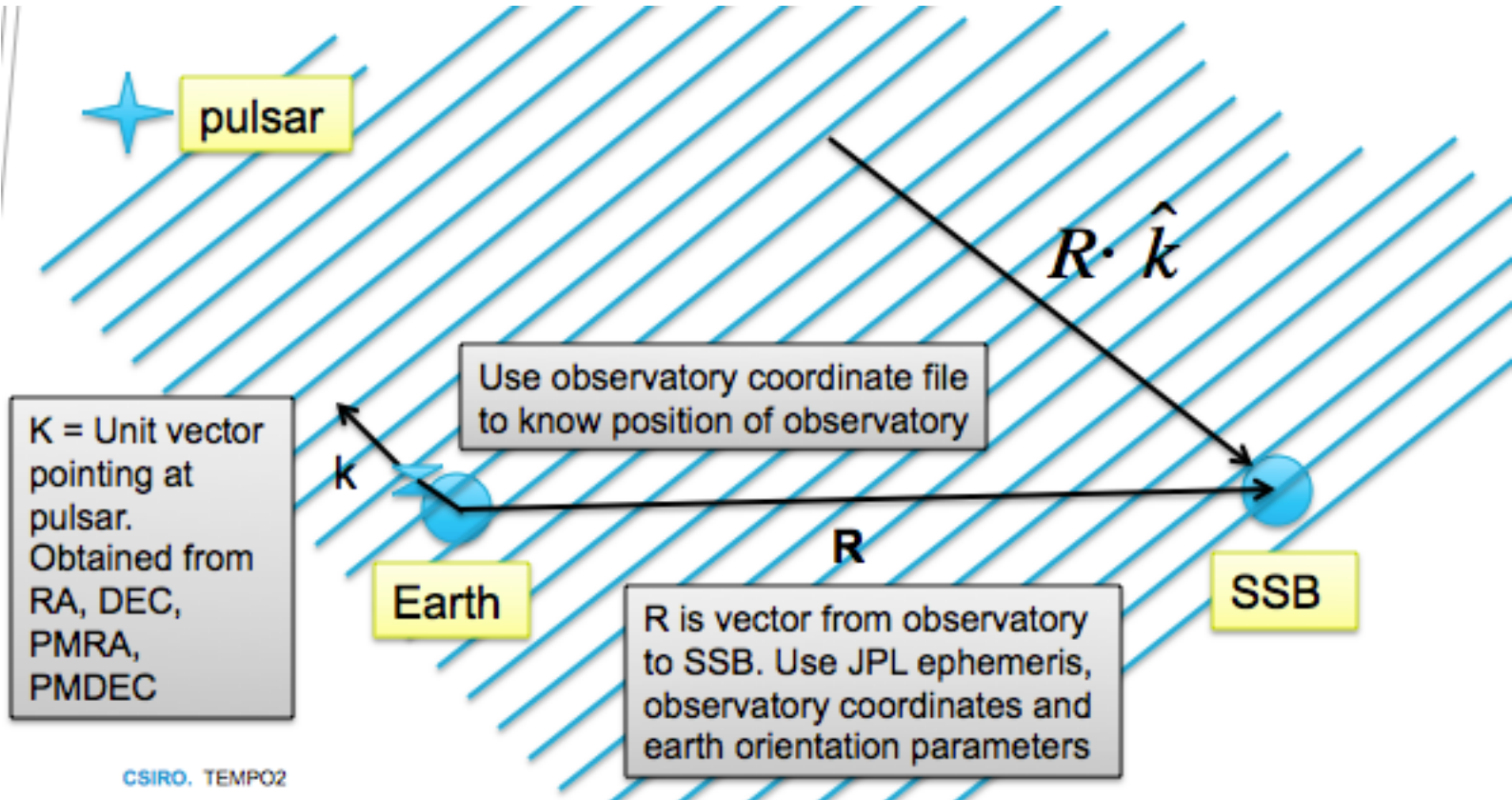
-> improved model of pulsar
-> timing residuals
- Do it backwards
 - set of pulse arrival times
 - “perfect” model of pulsar

-> get telescope position
-> determine time of observation



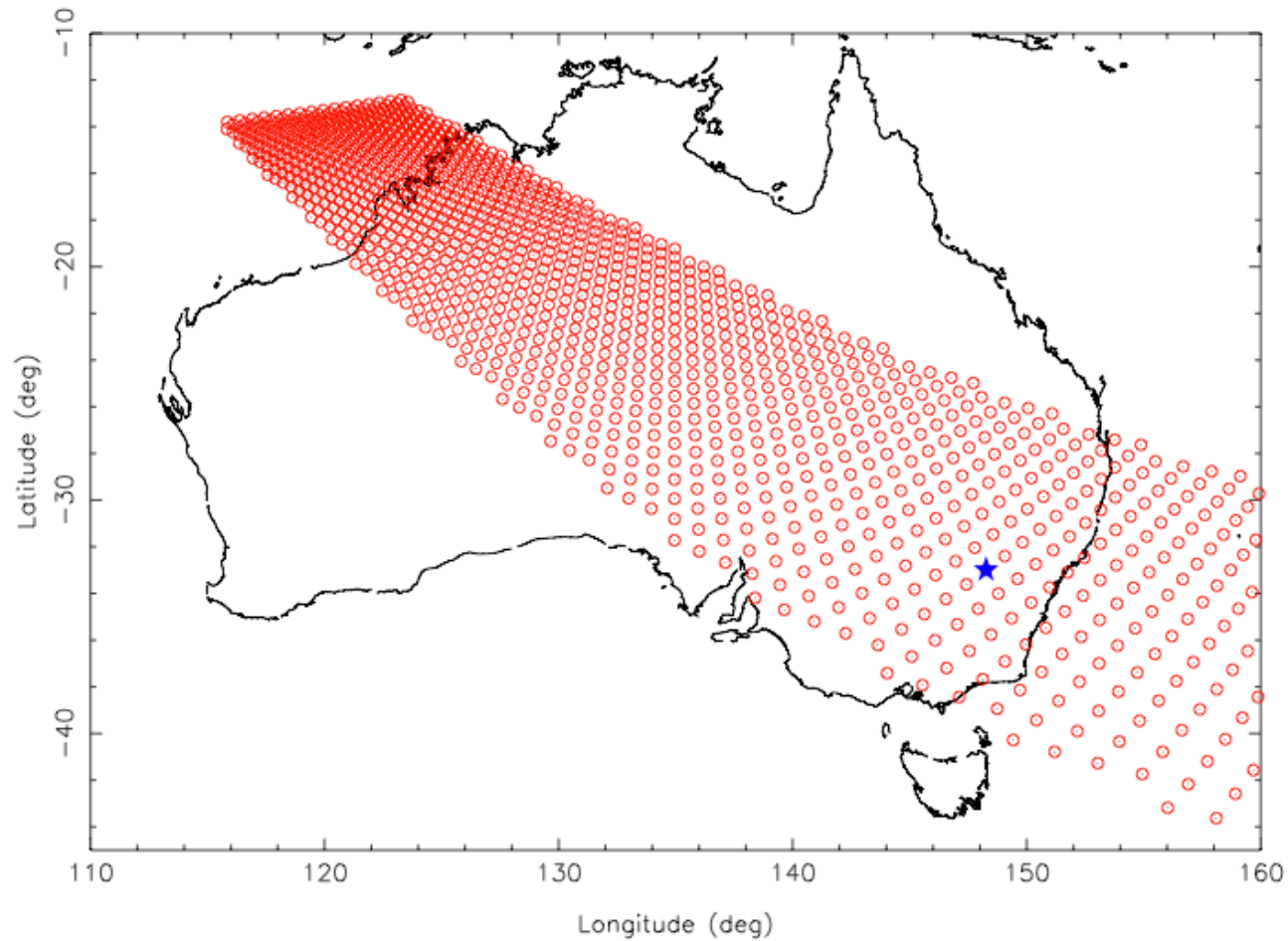
Can we create an astronomical “gps” system?

Pulsar navigation



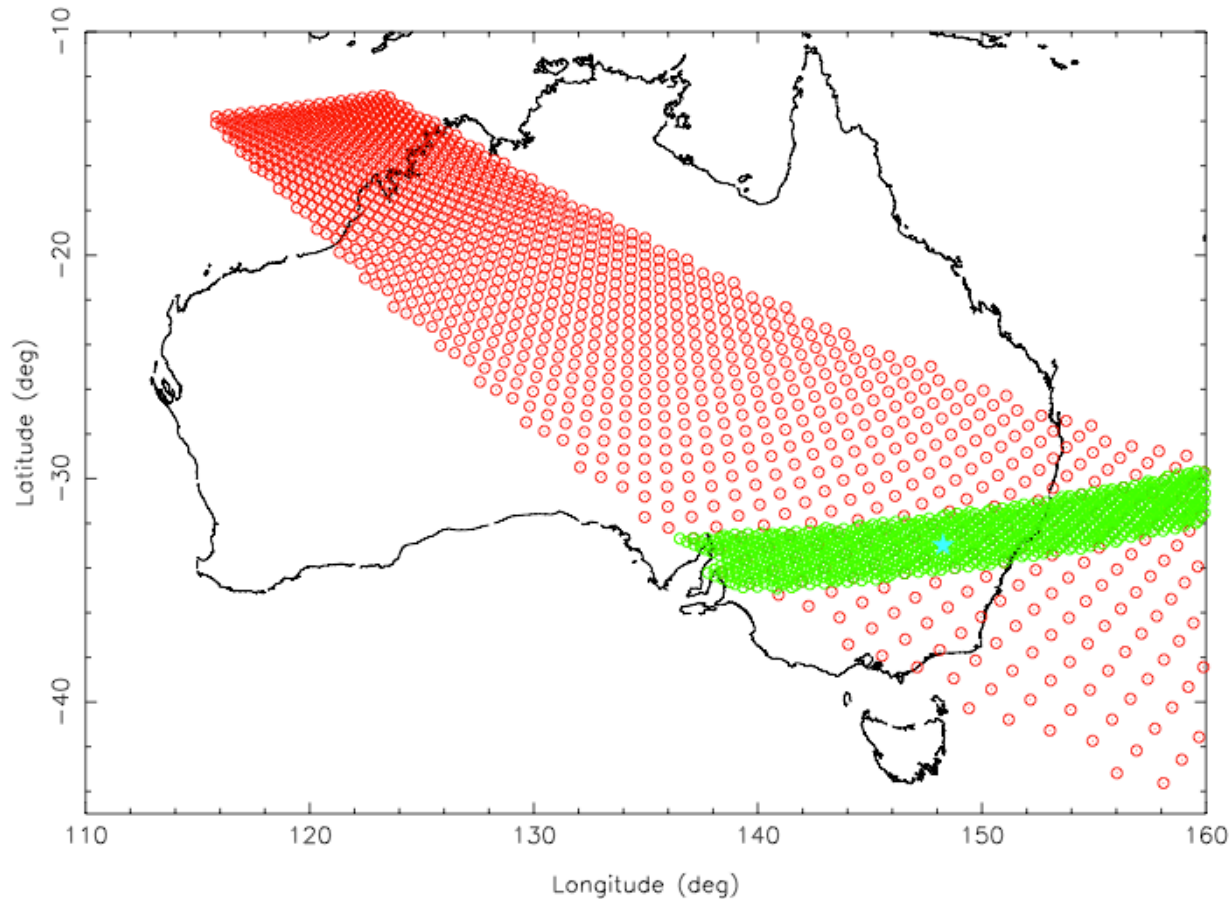
Pulsar navigation: assume that you are on the Earth's surface

- Parkes observations



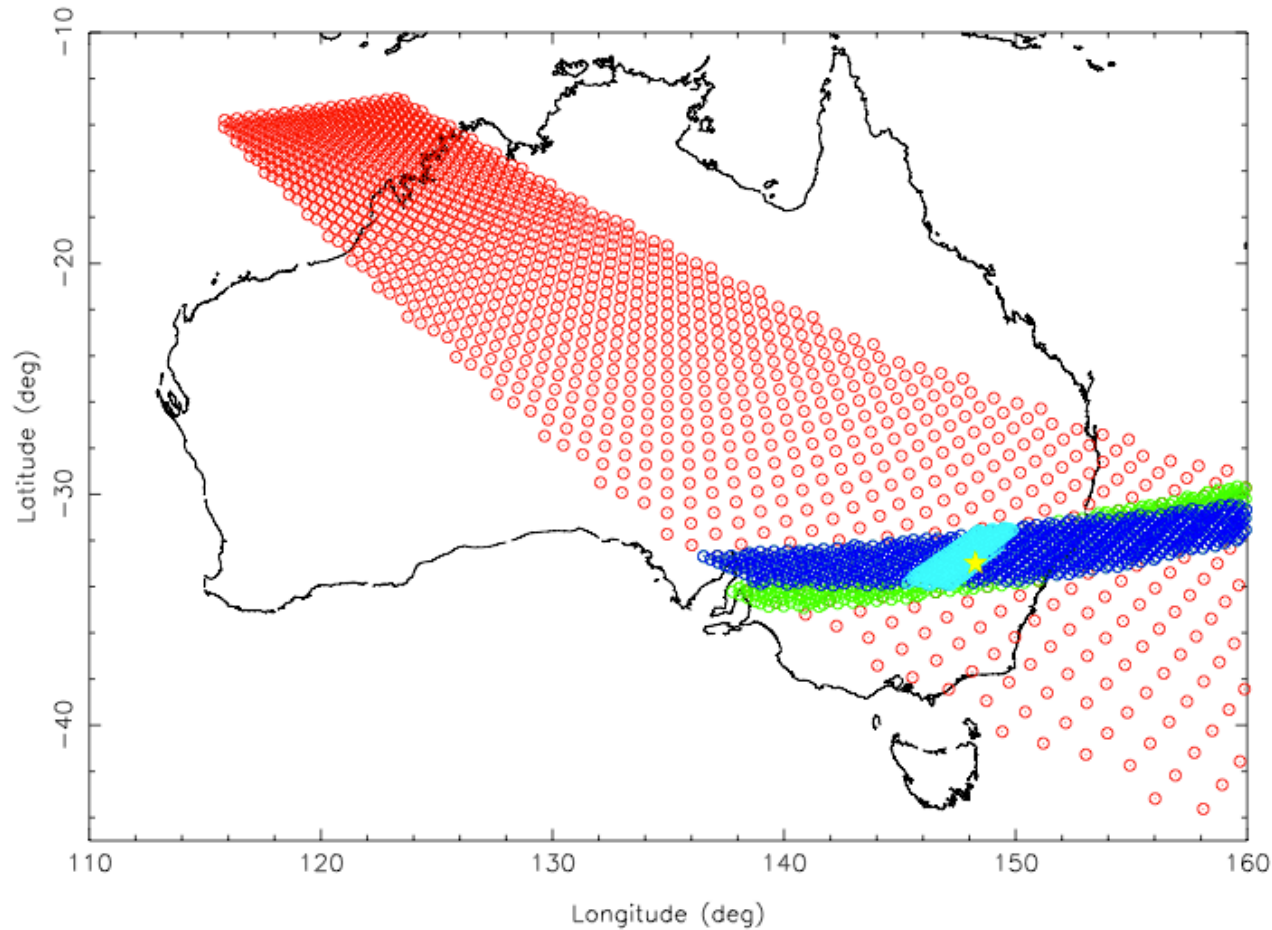
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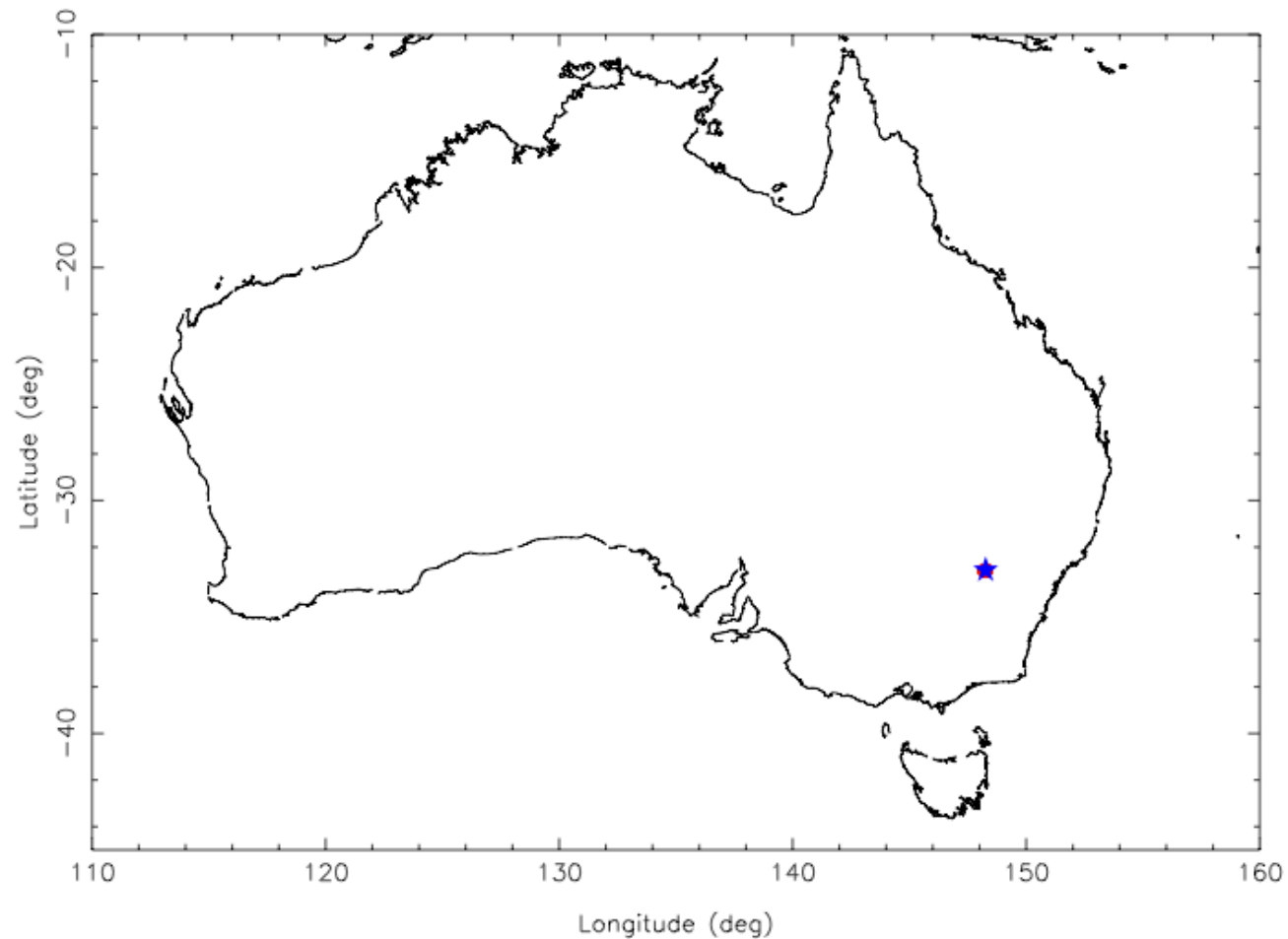
Pulsar navigation: assume that you are on the Earth's surface

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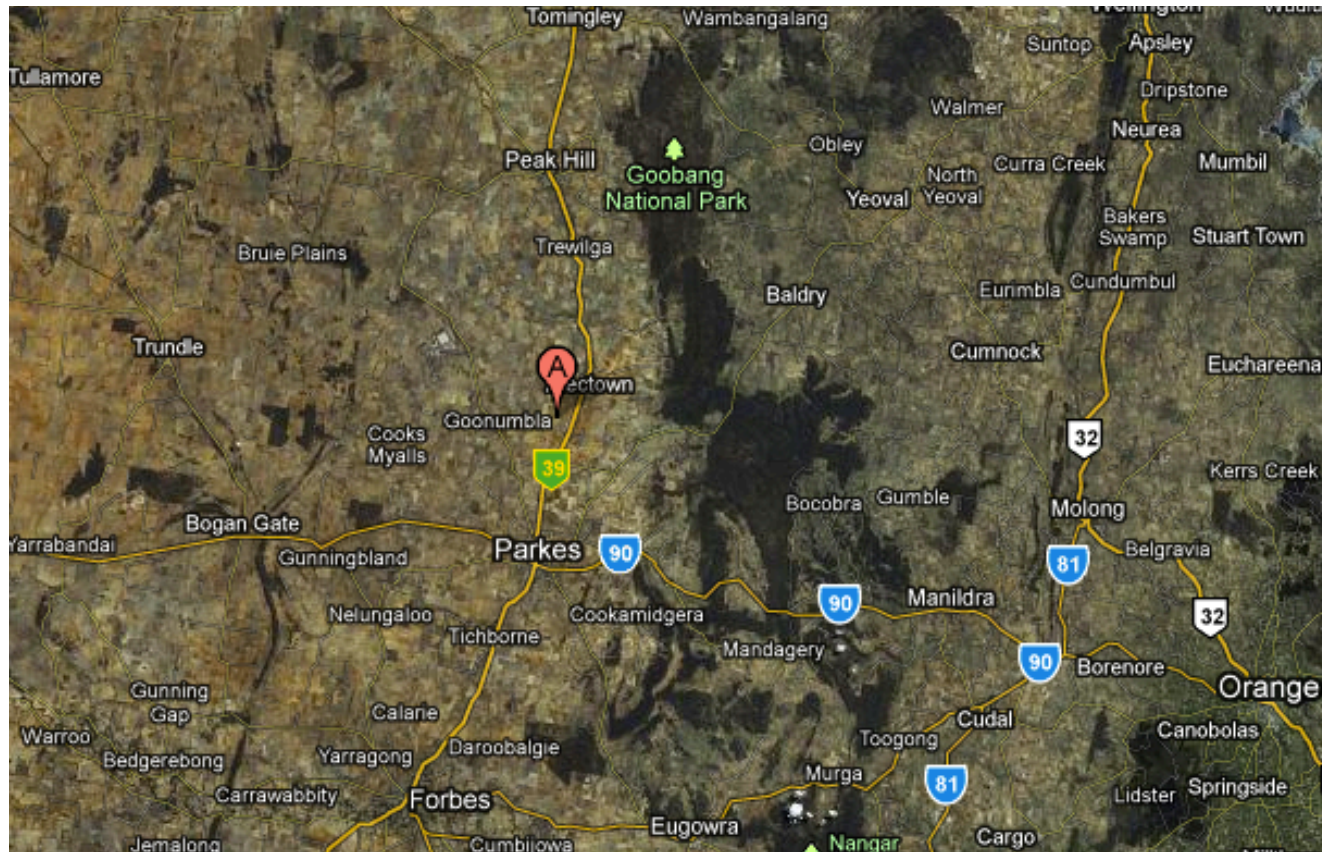
Pulsar navigation: assume that you are on the Earth's surface

- Parkes observations

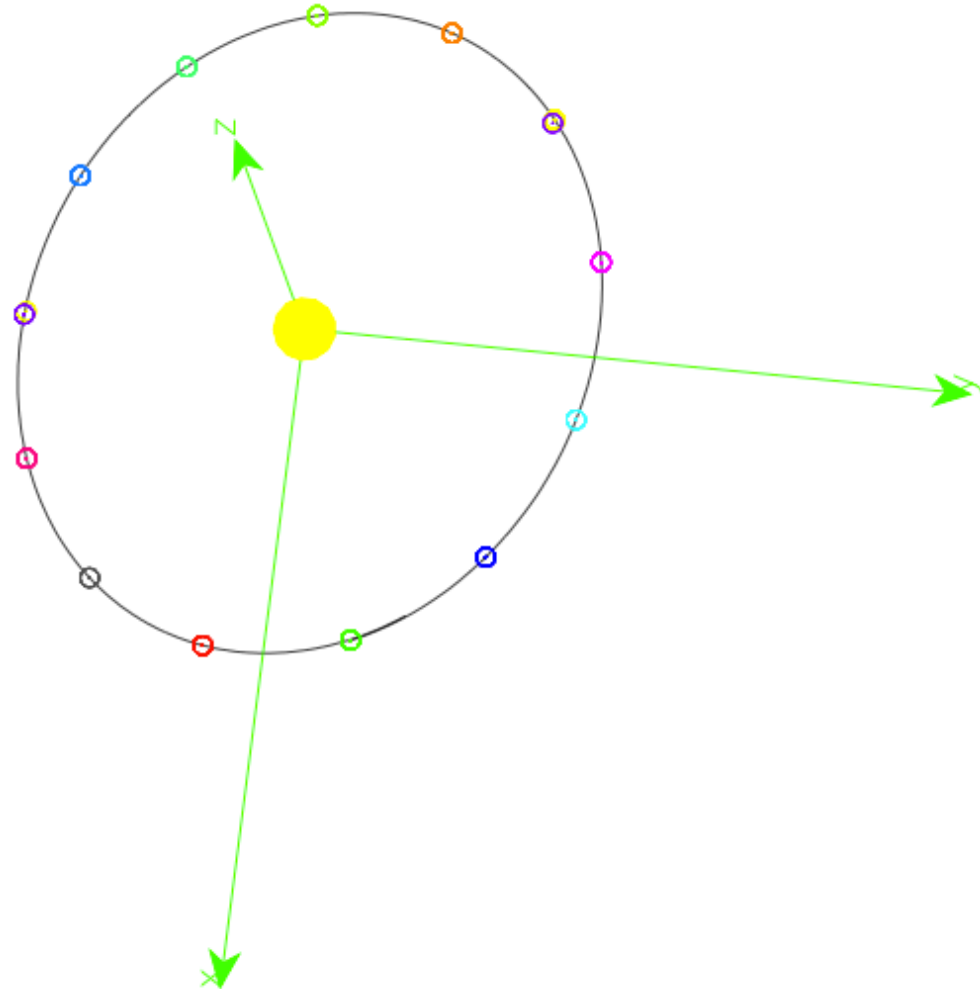


Pulsar navigation: assume that you are on the Earth's surface

- Parkes observations ... correct to within a few kilometres



Pulsar navigation: in 3D



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!

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?*