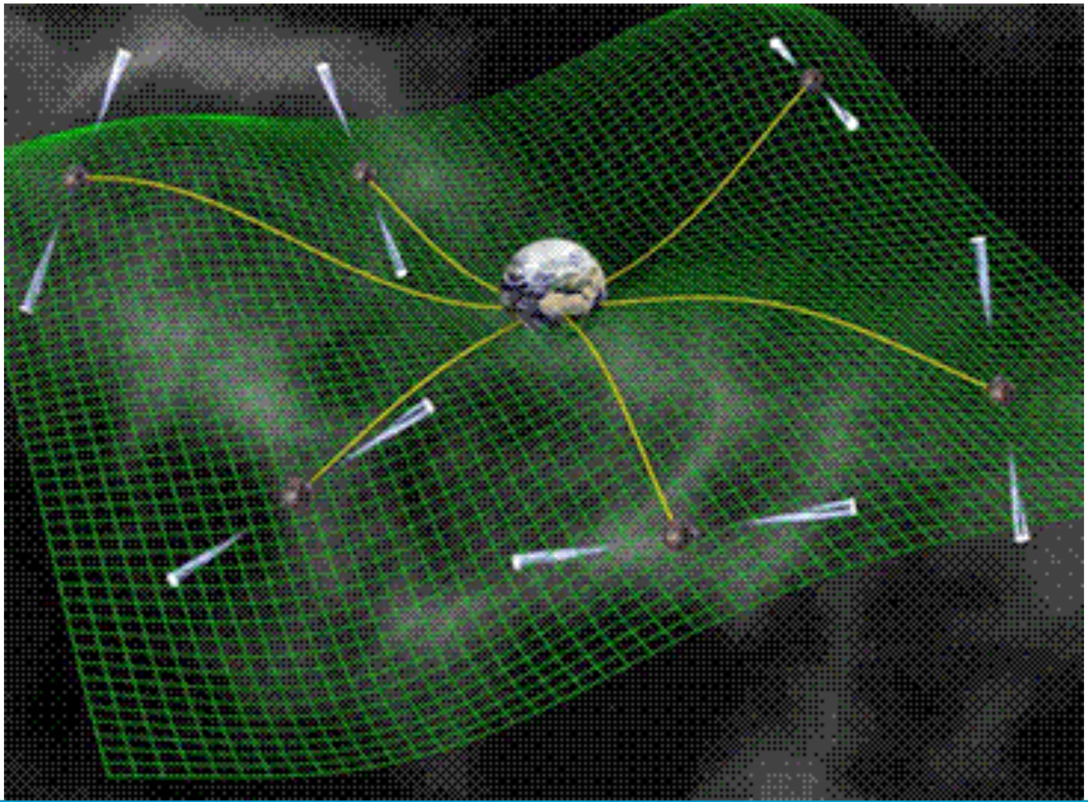
Image credit:
David Champion



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Gravitational-Wave Detection With Pulsars.

Daniel Yardley;

PhD student @ The University of Sydney /
CSIRO Astronomy & Space Science (ATNF);

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Talk outline

- Introduction to gravitational waves (GWs);
- Effect of GWs on pulsar timing observations;
- Sources of GWs that affect pulsar timing observations;
- Detecting an individual GW source;
- Detecting a stochastic background of many GW sources;
- The next steps toward detecting GWs with pulsar timing.

What is a gravitational wave?

- A GW is a travelling disturbance in the “fabric” of space-time.
- A GW changes the space-time metric:

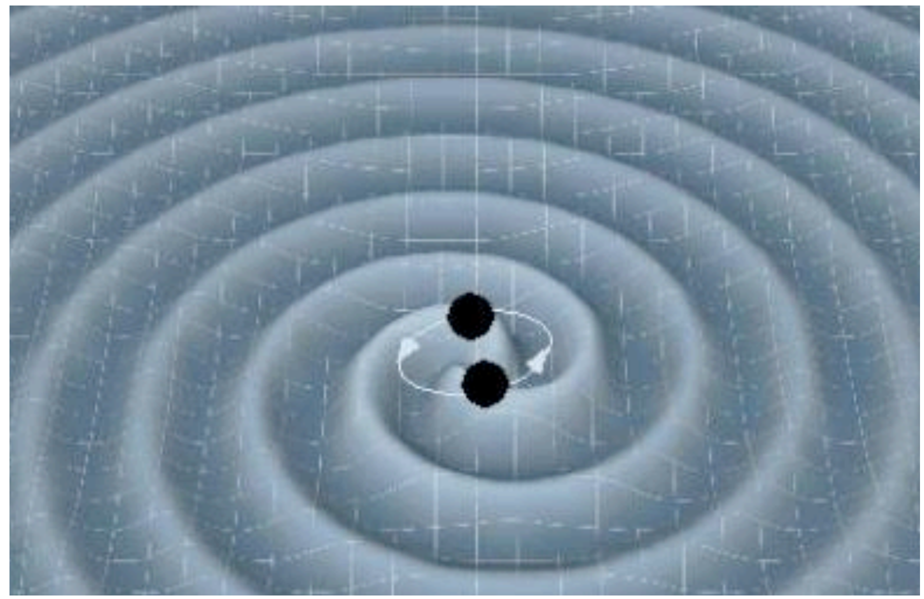
h_{ab}

add GWs

$h_{ab} + \Delta h(\mathbf{x},t)$

GW perturbation

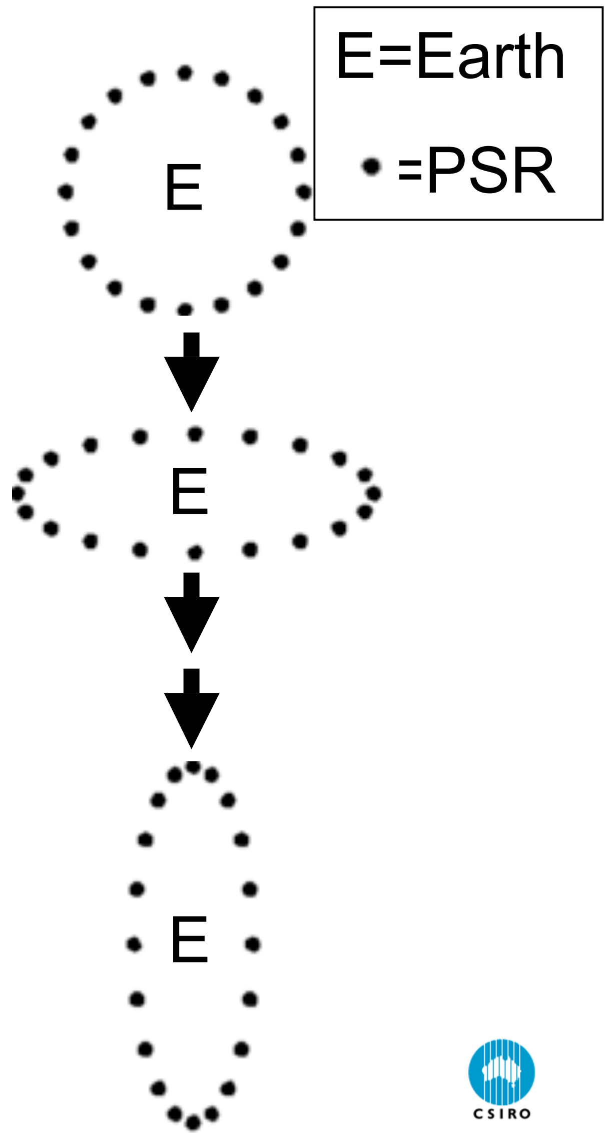
Image source: http://www.srl.caltech.edu/lisa/graphics/lisa_black_hole_binary.jpg



GWs are emitted by many different sources, including orbiting objects.

How do GWs affect pulsars? (Slide 1 of 2)

- A GW will distort space-time between the Earth and the pulsar. This affects the distance travelled by each pulse.
- Therefore, some pulse times-of-arrival (ToAs) will arrive earlier or later than expected.
- Pulsar timing compares the observed ToAs from a pulsar to a <u>model</u> for its behaviour.
- Model does not include GWs, hence a typical GW will induce <u>timing residuals</u>.

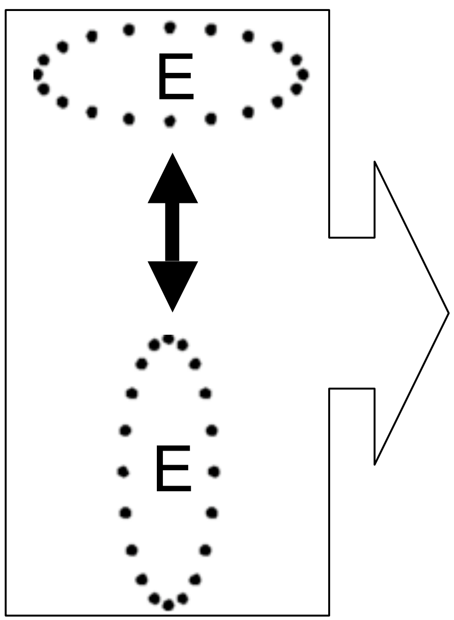


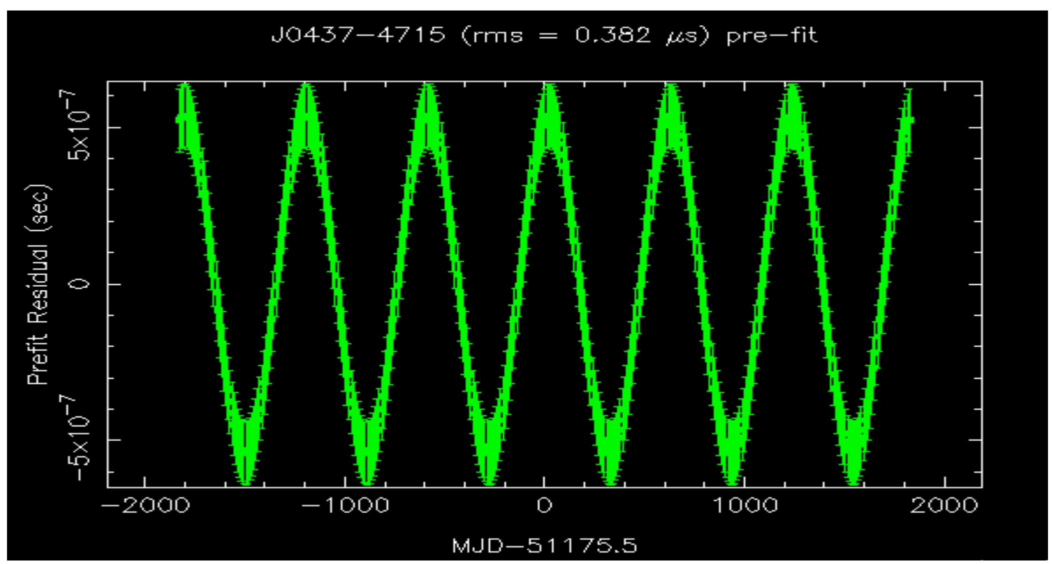
How do GWs affect pulsars? (Slide 2 of 2)

- GWs from a non-evolving binary induce a sinusoid.
- Amplitude of ToA perturbations induced by GWs from binary systems is:

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

ω: GW frequency ; h_s: GW strain.





Simulated timing residuals with a time-span of 3500 days

Which GW sources will affect ToAs? (1 of 2)

- ToAs are typically observed once every few weeks over a time-span of between 5 and 15 years.
- Thus, if the period of a continuous GW is less than a few days, it is difficult to detect in the residuals. Also, if the GW period is much larger than the time-span, then it is difficult to detect.
- Large amplitude GWs with periods T_{gw} in the range

$$15 \text{ years} < T_{gw} < \text{few days}$$

are emitted by supermassive black-hole binaries, cosmic superstrings, relic GWs from the Big Bang and quantum phase transitions in the early universe.

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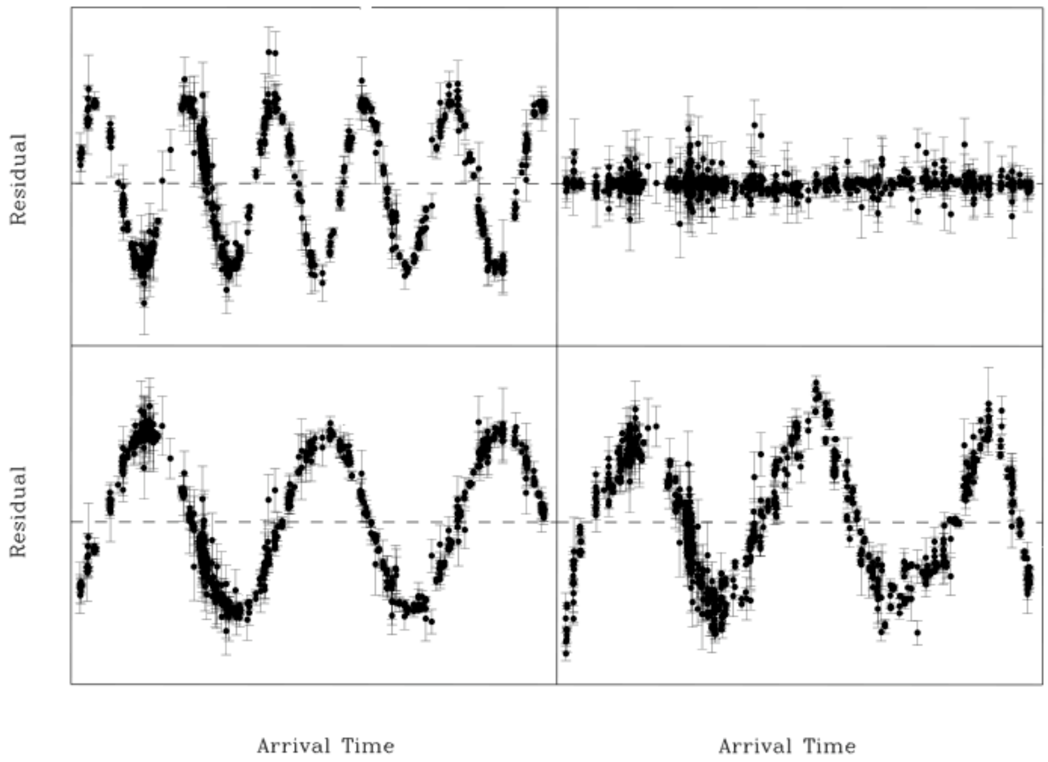
Which GW sources will affect ToAs? (2 of 2)

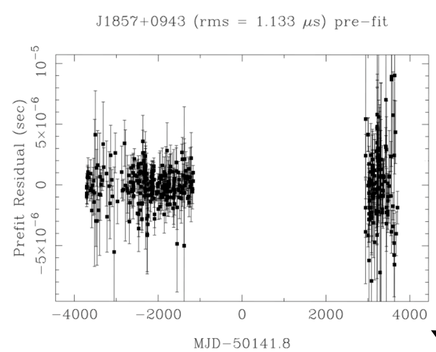
- If the ToA perturbations induced by a continuous GW have a period of 1 year, they cannot be detected in the timing residuals. They will be removed when estimating the pulsar position.

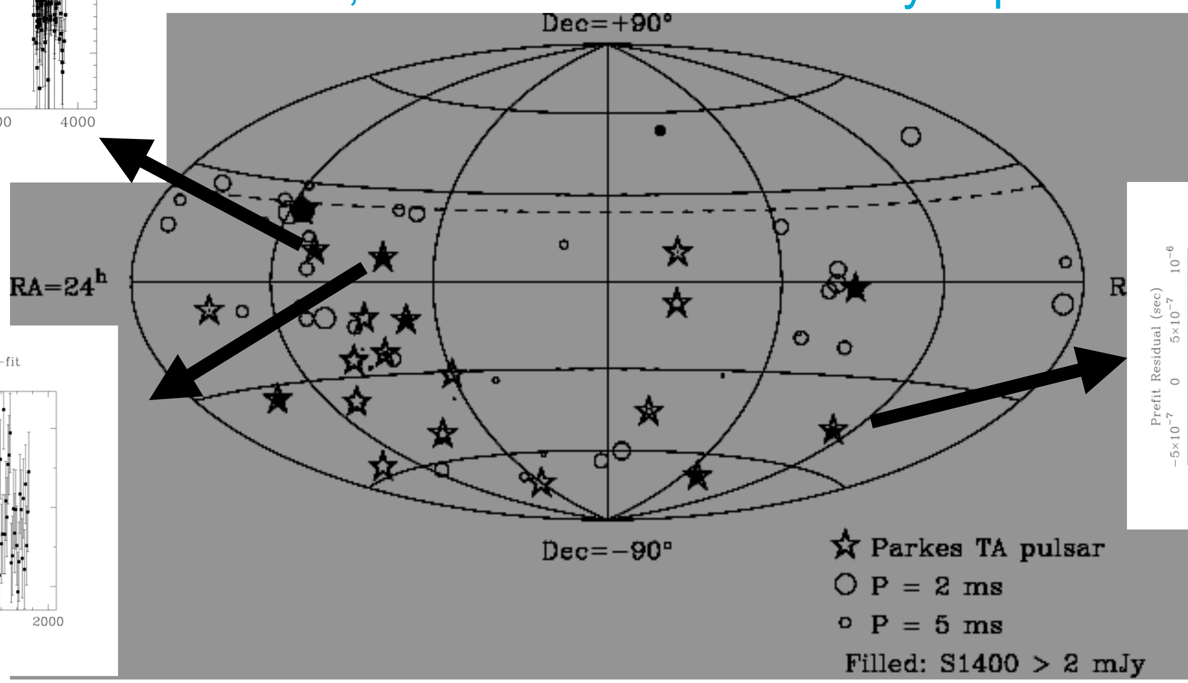


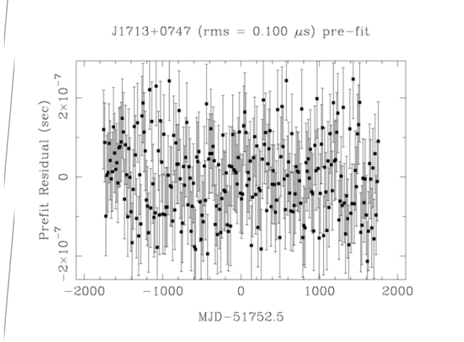
Yardley et al. (2010)

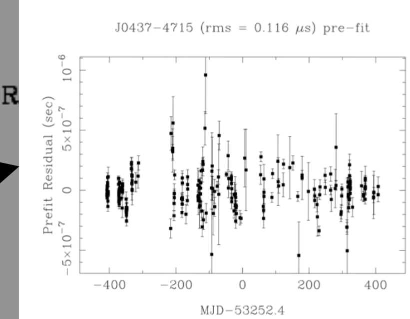
How do we know a sinusoid is caused by GWs?

- A GW will induce a signal in the ToAs that is correlated between pulsars spread across the sky.
- Thus, to confirm that a signal in the timing residuals is caused by a GW source, we must observe the expected signal in the residuals of other pulsars.
- Thus, we must observe an array of pulsars to detect GWs.



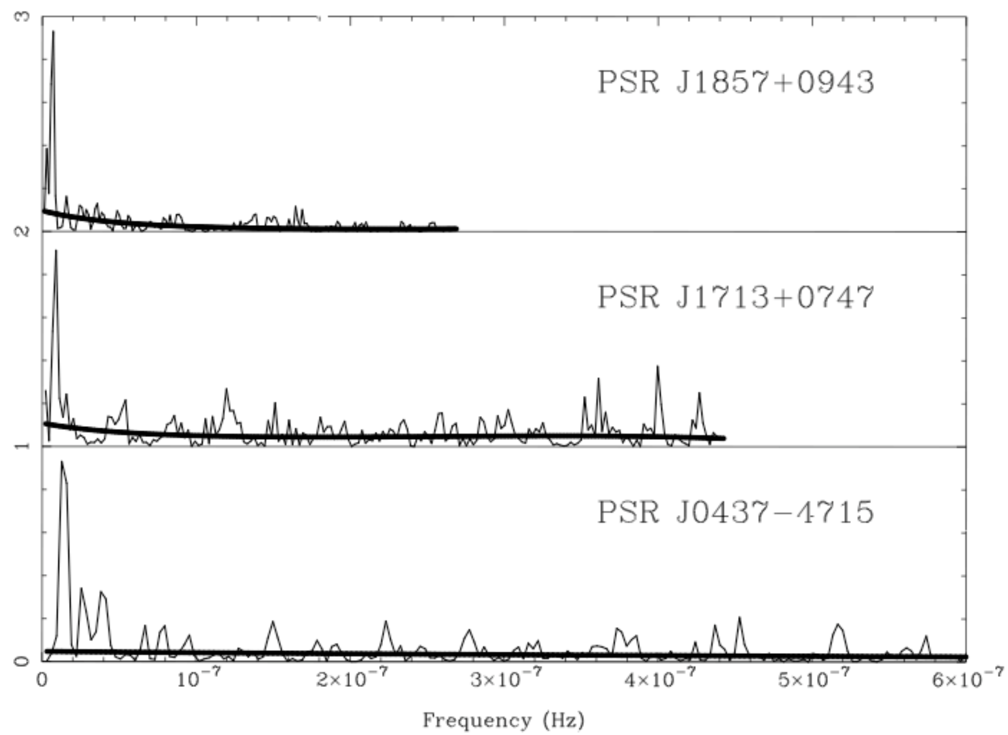






Detecting a simulated single source of GWs

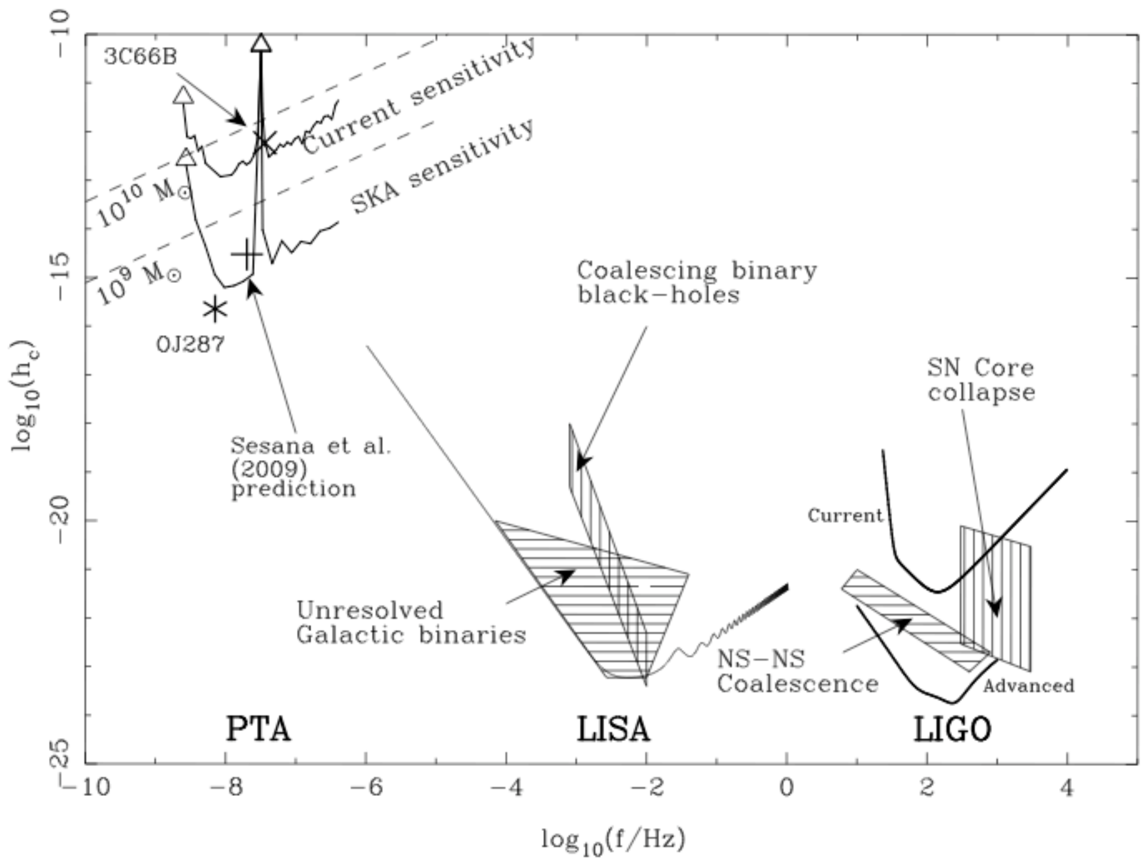
- One method for detecting sinusoidal GW sources is to estimate the power spectrum of each set of timing residuals.
- Sum these estimates. If the power in one frequency bin is much higher than an estimate of the noise, then we have detected the signal.



Yardley et al. (2010)

The sensitivity of pulsar timing to individual GW sources

- Using this straightforward detection technique, we can compare the sensitivity of pulsar timing arrays to other experiments that aim to detect GWs, such as LIGO and LISA.

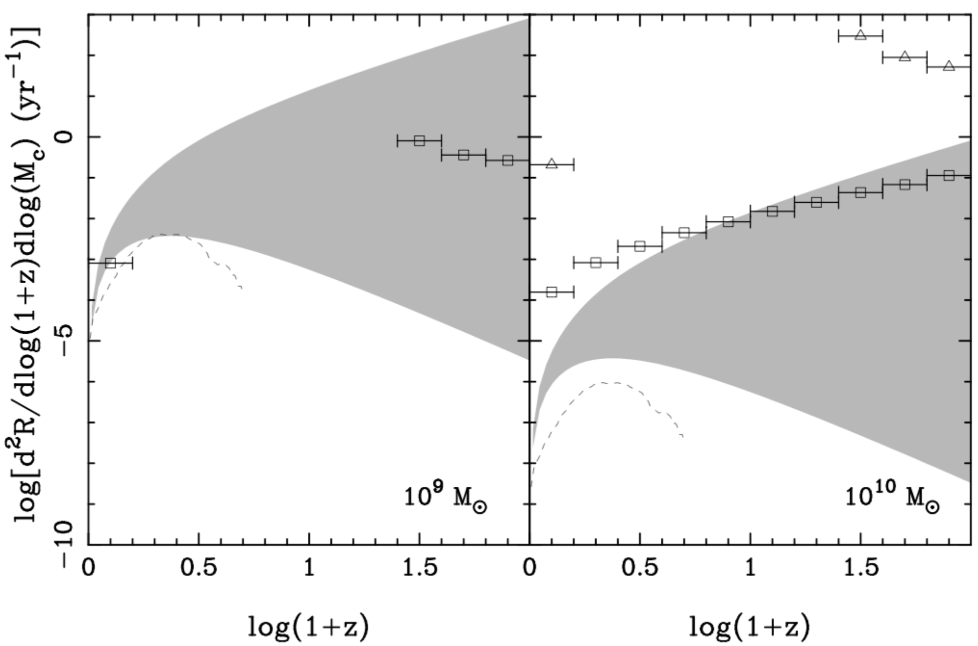


Yardley et al. (2010)

Result of making (or not making) a detection

- If we DO detect a single source of GWs, we can:
  - search for an electromagnetic counterpart (e.g. Sesana and Vecchio, 2010);
  - probe regions of space that are opaque to electromagnetic radiation (see, e.g., Sathyaprakash and Schutz, 2009).

- If we DO NOT detect a single source of GWs, we can, for example, place a limit on the coalescence rate of black hole binaries (Wen et al., 2011).



Yardley et al. (2010), Wen et al. (2011)

What is a Gravitational-Wave Background (GWB)?

- If there are many GW sources affecting pulse ToAs, the total GW signal will form a gravitational-wave background (GWB).
- The GWB is assumed to be:
  - ❖ isotropic (same in every direction in space)
  - ❖ stochastic (every source of GWs out of phase with every other source)
- GWBs can be caused by: binary supermassive black holes (this talk); cosmic strings; relic GWs from Big Bang.

The "amplitude" of the GWB

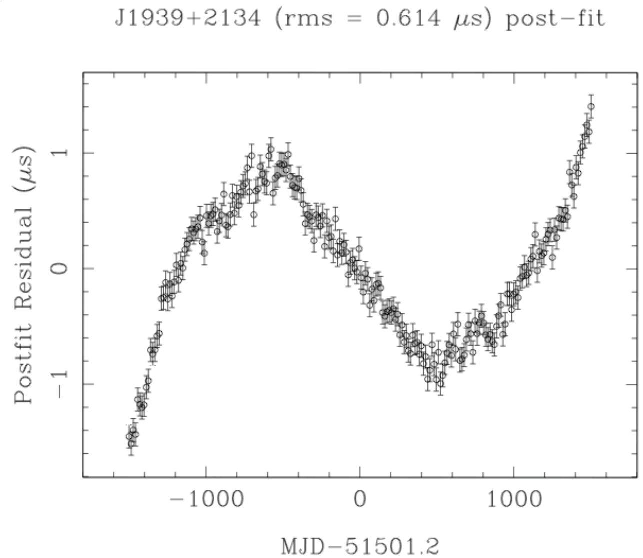
Power spectrum of ToA perturbations induced by GWB

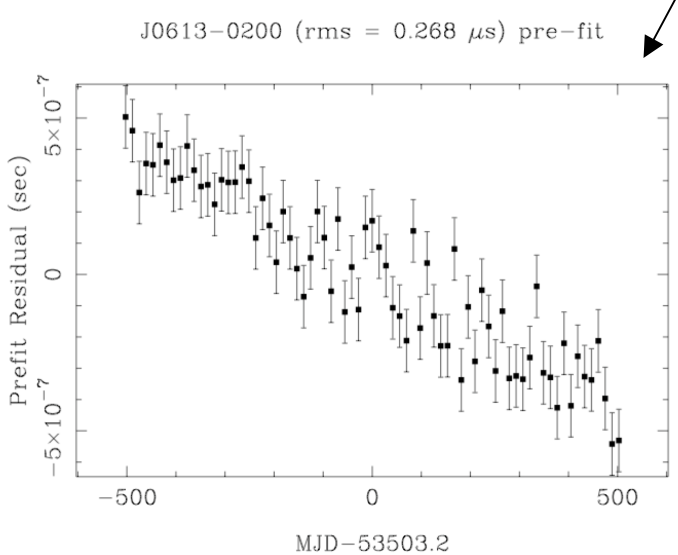
$$h_c(f) = A\left(f / f_{1yr}\right)^{-2/3} \longrightarrow P_g(f) = \frac{A^2}{12\pi^2}\left(f / f_{1yr}\right)^{-4.33}$$

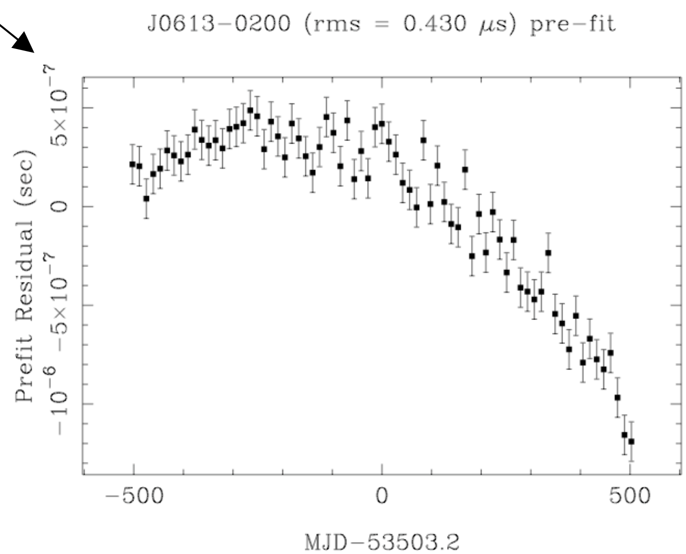
GWB Signal Removed by Pulsar Parameter Estimation

• The GWB induces perturbations in the ToAs with a steep red power spectrum.

• Some of the GWB signal is removed when estimating the period and period derivative of the pulsar.



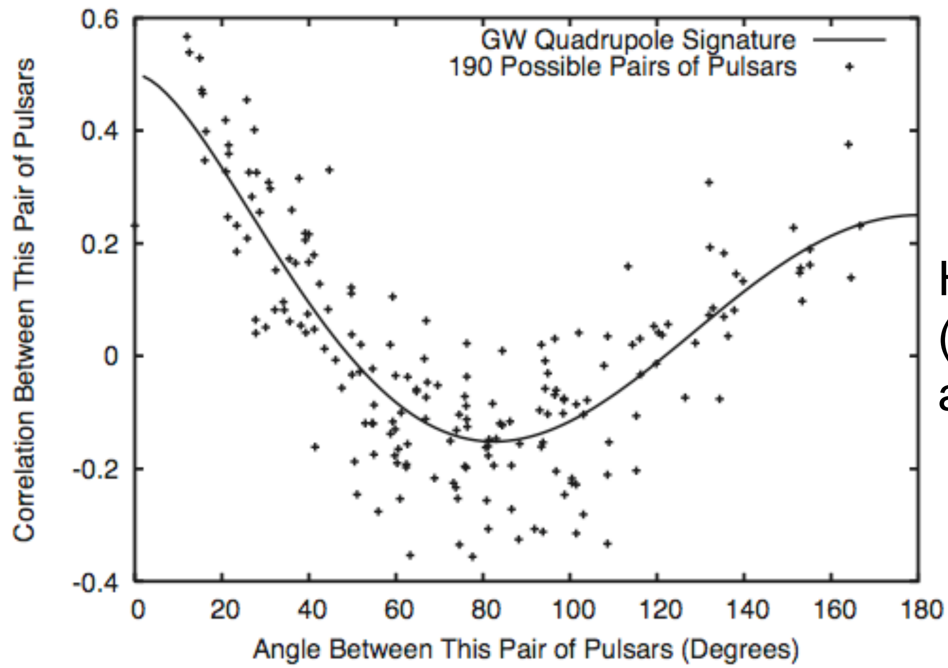




Detecting the GWB signal

- The GWB signal induces correlated residuals between pulsars.
- For an array of 20 pulsars, there are 190 different pulsar pairs.

!!!Simulated GWB Signal!!!



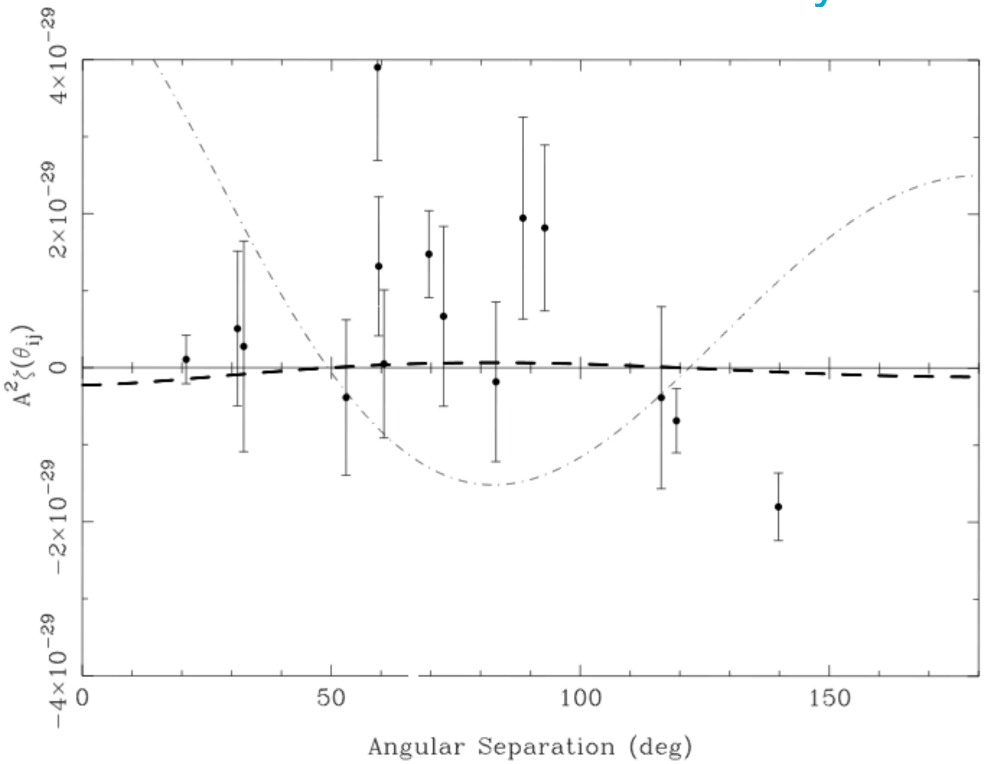
Hellings & Downs (1983), Jenet et al. (2005)

- Hence we can detect the GWB if we can detect this variation of the correlation between the residuals of each pulsar pair.

Technique for detecting the GWB signal in a pulsar timing array

- For a subset of the Parkes Pulsar Timing Array observations, the 15 covariance estimates with the smallest uncertainty are below:

NB! The y-axis is "correlation" times "amplitude squared".



Yardley et al. (2011)

- We have not made a detection of the GWB signal.

Result of making (or not making) a detection

- If we detect a GWB caused by supermassive black-hole binaries, then we can measure unknown parameters that describe the formation and evolution of supermassive black holes.

  These include the binary coalescence efficiency, the black-hole mass function, the supermassive black-hole merger rate, …

- The attempts at detection of a GWB signal in Yardley et al. (2011) and van Haasteren et al. (2011) did not succeed.

- However, an upper bound on the amplitude of the GWB signal constrains the SMBHB merger rate (Wen et al., 2011), cosmic string theories (Jenet et al., 2006, van Haasteren et al., 2011), quantum phase transitions in the early universe (Caprini et al.,2010), …

Next steps toward GW detection

- improve detection algorithms (Coles et al., 2011), reduce computation time for van Haasteren et al. (2011) algorithm.
- combine timing of pulsars from different projects into an International Pulsar Timing Array (e.g., Hobbs et al., 2010)
- more precise timing of known pulsars, using improved processing [e.g. removing correlated noise from residuals (Hobbs et al., 2010, Champion et al., 2010), removing phase offsets between observing hardware (Manchester, 2011)], or observing pulsars with FAST / SKA.
- find new pulsars that can be timed accurately [see Mike Keith's talk after lunch!!]

Aspects I have not discussed

- Sources producing non-sinusoidal GW waveforms, “burst” sources of individual GWs that are not periodic (e.g., Finn and Lommen, 2010).

- A multitude of techiques for detection of single sources of GWs (van Haasteren et al., 2010, Burt et al., 2011, Lee et al., 2011, …).

- A possible detection of a GWB with a very strong amplitude that is well above current limits (Rodin 2011).

- The fact that we can simulate many types of GWs with TEMPO2 (George Hobbs’s talk).

Emails: daniel.yardley@csiro.au;

dyardley@physics.usyd.edu.au;

daniel.yardley@gmail.com;

www.csiro.au

Thank you (xie xie nin)

Contact Us
Phone: 1300 363 400 or +61 3 9545 2176
Email: enquiries@csiro.au Web: www.csiro.au

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