Data Analysis of Continuous Gravitational Waves in the Advanced Detector Era

Erin Macdonald

Cardiff University

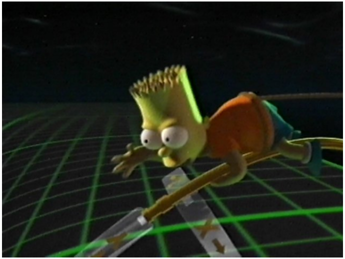
erin.macdonald@astro.cf.ac.uk

11 October, 2012

Outline

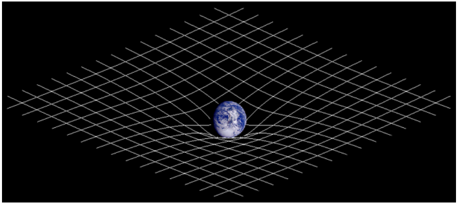
General Relativity

- Developed by Albert Einstein
- Space tells matter how to move, matter tells space how to behave
- Has been confirmed in all observations and experiments to date



Gravitational Waves

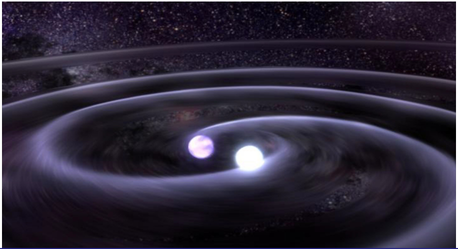
- "Ripples in spacetime"
- Travel at the speed of light
- Carry information about changing gravitational fields
- Derived from Einstein Field Equations:
  $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$



Sources of Gravitational Waves

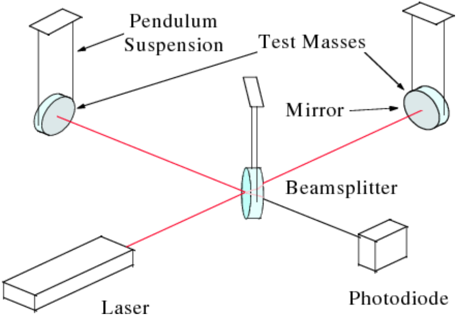
There are four primary classes of gravitational wave sources

- Single/Transient events
  - Stellar Collapse/Supernova
  - Binary Coalescence (BH/BH, NS/BH, NS/NS)
- Continuous Emission
  - Asymmetric neutron stars/pulsars
  - Stochastic background (Big bang remnant, cosmic strings)



Gravitational Wave Detectors

- Initially used “Weber bars” to search for specific frequencies
- Ground-based laser interferometers are currently used for greater frequency bands



Advanced LIGO/Virgo

- Initial detectors completed science runs at and beyond design sensitivity
- Fully operational by 2015/16
- Currently upgrading detectors to a sensitivity which would result in regular detections

1 Background
- Gravitational Waves

2 Detection Criteria
- Current detection criteria
- Detection confidence over various scenarios
- Possible changes/additions for advanced era

3 Population Studies
- Motion in the sky

4 Software injections and Mock Data Challenge
- Software injection challenge
- Distribution of pulsars
- First tests of software injections

5 Next steps?
- Future Work

Continuous wave searches

There are three main types of searches for continuous waves:

- All-sky search
- Directed search
- Targeted search

Current detection criteria

The Continuous Wave (CW) working group has developed criteria for detection confidence

- Be able to exclude environmental/instrumental artifacts
  - No known instrumental artifact can contribute significantly to measured SNR ($> 20\%$)
- Must be seen by two independent pipelines (SFTs and time-domain)
- Must be *self*-consistent
  - Combined SNR generally higher than for a single interferometer
  - The 95% confidence band for f, $\dot{f}$, RA and DEC must overlap for interferometers with high SNR
  - Consistent time dependencies
  - Astrophysically self-consistent w.r.t. amplitude, frequency, spin-down and distance

Detection confidence over various scenarios

Isolated, non-glitching pulsar in all-sky search

- All-sky search will yield outliers for multi-months worth of data
- Utilise hierarchical algorithm to "zoom in" on signal, increase SNR to O(100)
- Can explore past data with known parameters to verify (handy aspect of CWs!)

Isolated, non-glitching pulsar in directed search

- Directed search: location known, frequency unknown...
- Vary assumed source location to verify maximum SNR
- For long coherence times, location may shift and max SNR may grow faster

Isolated, non-glitching pulsar in targeted search

- Most difficult as little to no additional SNR gained through follow-up
- Alternative pipeline is straightforward to use and measure
- Examine signal with both Bayesian and frequentist searches
- Run same pipeline on other points in sky to assess bugs and uncertainties

Binary pulsar signal

- Similar to criteria established for isolated pulsar in all-sky and directed searches
- More parameters for binaries, need to search unknown
- If binary signal is seen in an isolated search, SNR significantly lower than possible

Transient continuous wave signals, signals of lifetimes O(days-weeks)

- Would not increase SNR by increasing observation time
- Could still verify easily if strong to begin with
- If the transient signal repeats with same signal parameters
- Check coincidence with pulsar glitches, spindown
- Coincidence with non-targeted searches at an astrophysical source

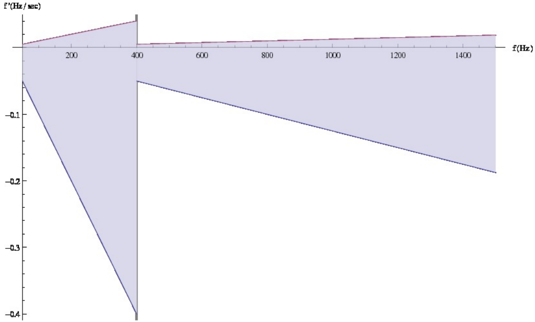
Detections likely in advanced detectors, so need to test these criteria against realistic scenarios

- Study possible astrophysical issues for pipelines
- Conduct a mock-data challenge with O(1000) signals
- Test performance of algorithms, both alone and as hierarchical system

Close is good, but not too close!

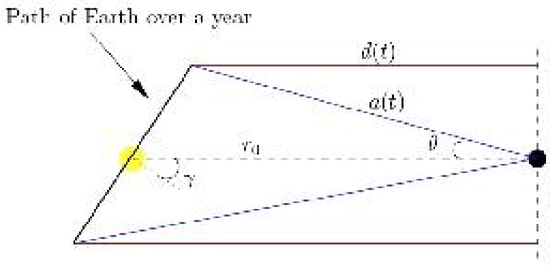
For advanced detectors, a detailed understanding of neutron star populations is necessary.

Einstein@Home (all-sky) searches parameter space of f and $\dot{f}$:

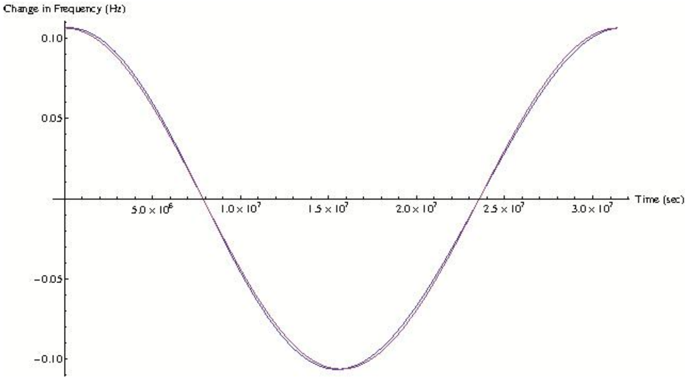


Parallax

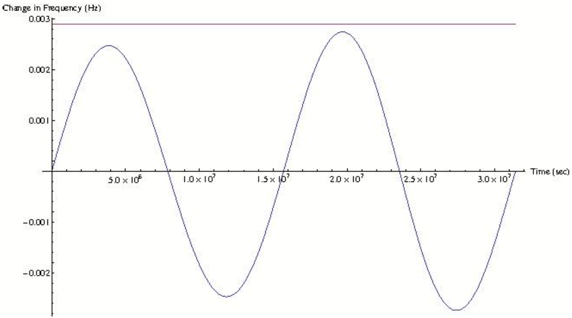
Apparent motion of objects due to Earth's motion, results in Doppler shift of frequency



Apparent change of frequency over a six month period for $d(t)$ and $a(t)$ at an extremely close initial r_0



The difference between the frequencies for $d(t)$ and $a(t)$ with the Einstein@Home limit shown

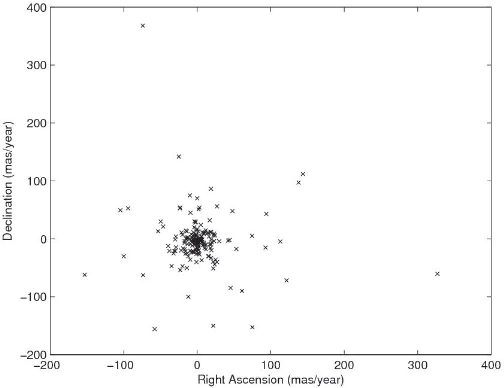


The distance at which parallax becomes a problem is...

Motion in the sky

Proper Motion

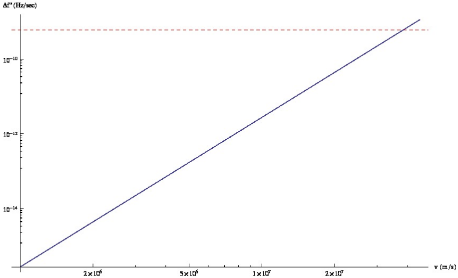
Stars' motion tangential to the line of sight as seen from the SSB



- $\Delta \dot{f}$ is highly dependent on velocity:

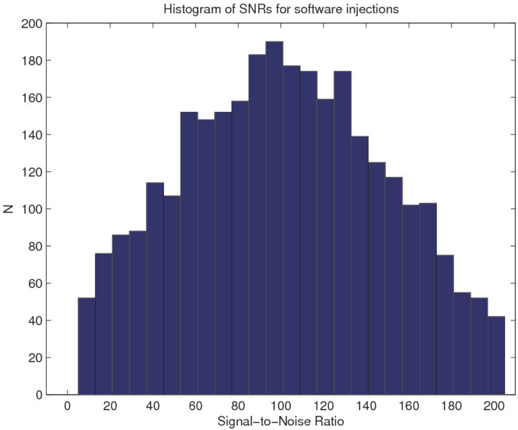
$$\Delta \dot{f} = \frac{f_0 v^2}{c} \left[\frac{1}{r_0} + \frac{t^2 v^4}{(r_0^2 + t^2 v^2)^{3/2}} - \frac{1}{\sqrt{r_0^2 + t^2 v^2}} \right]$$

- The velocity becomes an issue for Einstein@Home at 3.83×10^7 m s^{-1}, which would be an angular velocity of 10.3 arcsec yr^{-1} at 100 pc.

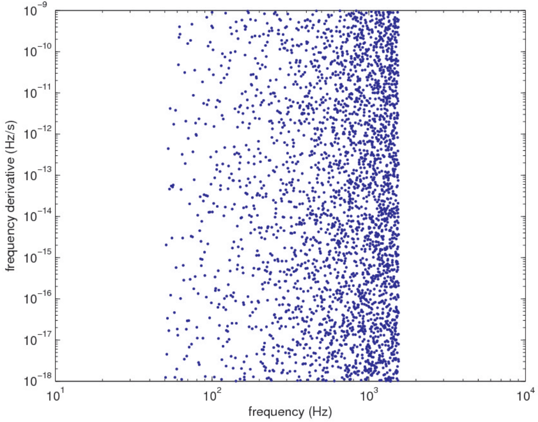


- 3000 isolated pulsar signals
- Inject into recent science run data (S6)
- Parameters:
  - Generated with $\mu_{\mathrm{SNR}} = 100$ for targeted searches
  - One year integration on Hanford detector with S5 Sensitivity
  - Randomly distributed on the sky
  - Random distribution of $\dot{f}$ with $< 5\%$ spin-up

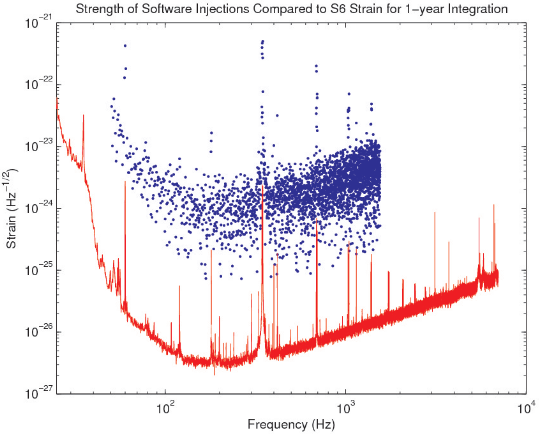
SNR distribution



Frequency and frequency derivatives



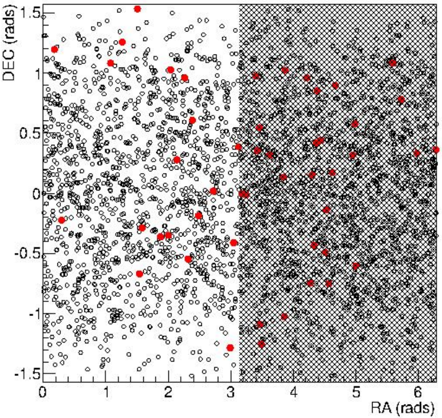
Specific targets and sensitivity



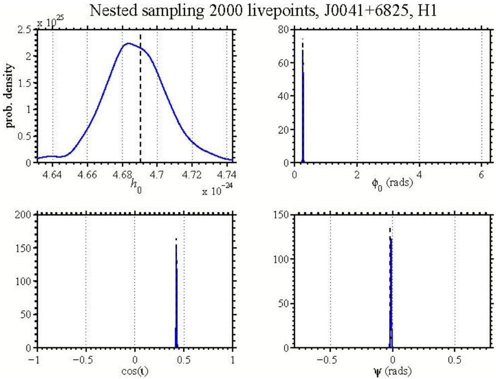
First tests of software injections

- Colin Gill at Glasgow ran targeted search
- Vladimir Dergachev ran PowerFlux (all-sky search)
- Positive results showing that signals can be found

Challenge 1

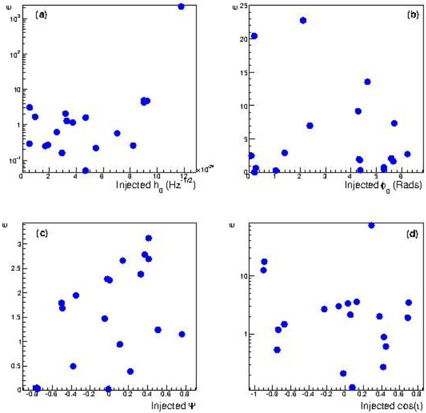


Glasgow targeted results

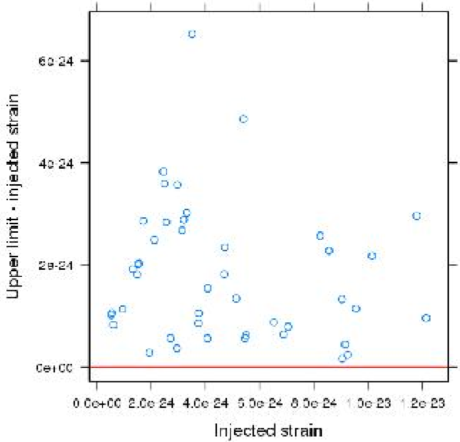


Glasgow targeted results

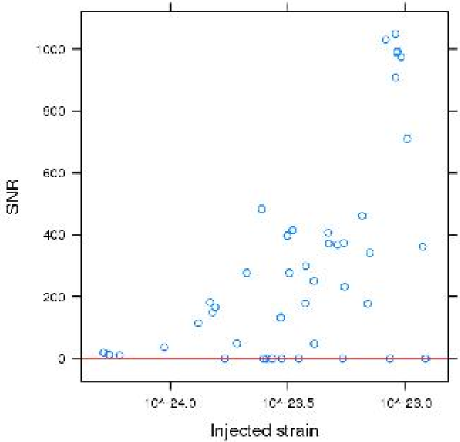
$$\epsilon = \frac{|\mathcal{A}_{\text{inj}} - \hat{\mathcal{A}}|}{\sigma}$$



PowerFlux all-sky results



PowerFlux all-sky results



Mock Data Challenge

- Challenge One and all the frames have been passed to group
- Individual processing has begun, some difficulties!
- Chairs have requested results by January 2013 from all pipelines on 49 sources

Expanding the data challenge

- Expand in steps to include all 3000 signals across frequency band
- Write a separate injection frame set with 1000 binary pulsars

Detection Criteria

- Use results from SW Challenge to assess criteria
- Prepare more thorough quantitative justification for criteria
- Propose changes with Advanced LIGO/Virgo in mind

The End