Detecting and setting upper limits on continuous gravitational waves from unknown spinning neutron stars in binary systems

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Outline

- Astrophysical motivation
- Binary orbital parameter space
- TwoSpect search method
- Upper limit validation
- Detectability of signals

Gravitational waves from spinning neutron stars in binary systems

- Non-axisymmetric spinning neutron stars can generate nearly monochromatic gravitational waves
- Sample of mechanisms proposed that could generate asymmetry [1-5]:
  - Accretion of matter builds a "mountain"
  - Accretion buries magnetic field → interior deforms
  - Accretion process drives r-modes
- Observed frequency of the waves has experienced Doppler shifts due to the motion of the source and detector

1. L. Bildsten 1998 ApJ **501**, L89
2. A. Melatos and D. J. B. Payne 2005 ApJ **623**, 1044
3. C. Cuofano et al arXiv:1203.0891v1 [astro-ph.HE]
4. B. J. Owen et al 1998 Phys. Rev. D **58**, 084020
5. G. Ushomirsky 2000 AIP Conf. Proc. **575**, pp. 284-95

Gravitational waves from spinning neutron stars in binary systems

- ATNF catalog (as of May 2012): 251 pulsars spinning faster than 25 Hz
- Of these, 153 are in binary systems (>60%)
- Emission of gravitational waves (>50 Hz) is in the most sensitive region of the LIGO/Virgo frequency band

Torque-balance limit

- Why don't we observe neutron stars spinning near their breakup limit?
- Torque-balance with gravitational waves?
- Estimate gravitational wave amplitude assuming all gained angular momentum is radiated as gravitational waves [6]

$$h_0 \approx 5 \times 10^{-27} \left(\frac{300\,\mathrm{Hz}}{f_{\mathrm{rot}}} \right)^{1/2} \left(\frac{F_{\mathrm{x}}}{10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}}} \right)^{1/2}$$

6. R. V. Wagoner 1984 ApJ **278**, 345-8

All-sky continuous gravitational wave analysis techniques

- All-sky algorithms were developed to search for isolated pulsars
  - Semi-coherent stacking: PowerFlux, StackSlide, Hough [7-10]
  - Long coherence baseline with coincidence: F-statistic (incl. Einstein@Home) [11-13]
  - Search over sky location, frequency, spindown
- Computationally bound
- Adding 5 non-relativistic binary orbital parameters is a significant challenge
- Requires new techniques or extremely massive computing resources

7. B. Abbott et al. LSC 2005 Phys. Rev. D **72**, 102004
8. B. Abbott et al. LSC 2007 Phys. Rev. D **76**, 082001
9. B. Abbott et al. LSC 2008 Phys. Rev. D **77**, 022001
10. B. P. Abbott et al. LSC 2009 PRL **102**, 111102
11. J. Abadie et al. LSC, Virgo 2012 Phys. Rev. D **85**, 022001
12. B. Abbott et al. LSC 2009 Phys. Rev. D **79**, 022001
13. B. P. Abbott et al. LSC 2009 Phys. Rev. D **80**, 042003

Astrophysical parameter space

- Circular orbit, maximum Doppler shift

$$\Delta f_{\max} \simeq 1.82 \left(\frac{f}{1\,\mathrm{kHz}}\right) \left(\frac{M_{\rm NS}}{1.4\,M_\odot}\right)^{1/3} \left(\frac{P}{2\,\mathrm{h}}\right)^{-1/3} \left[\frac{q}{(1+q)^{2/3}}\right] \mathrm{Hz}$$

Source frequency — NS mass — Orbital period — mass ratio $q = M_2/M_{\rm NS}$

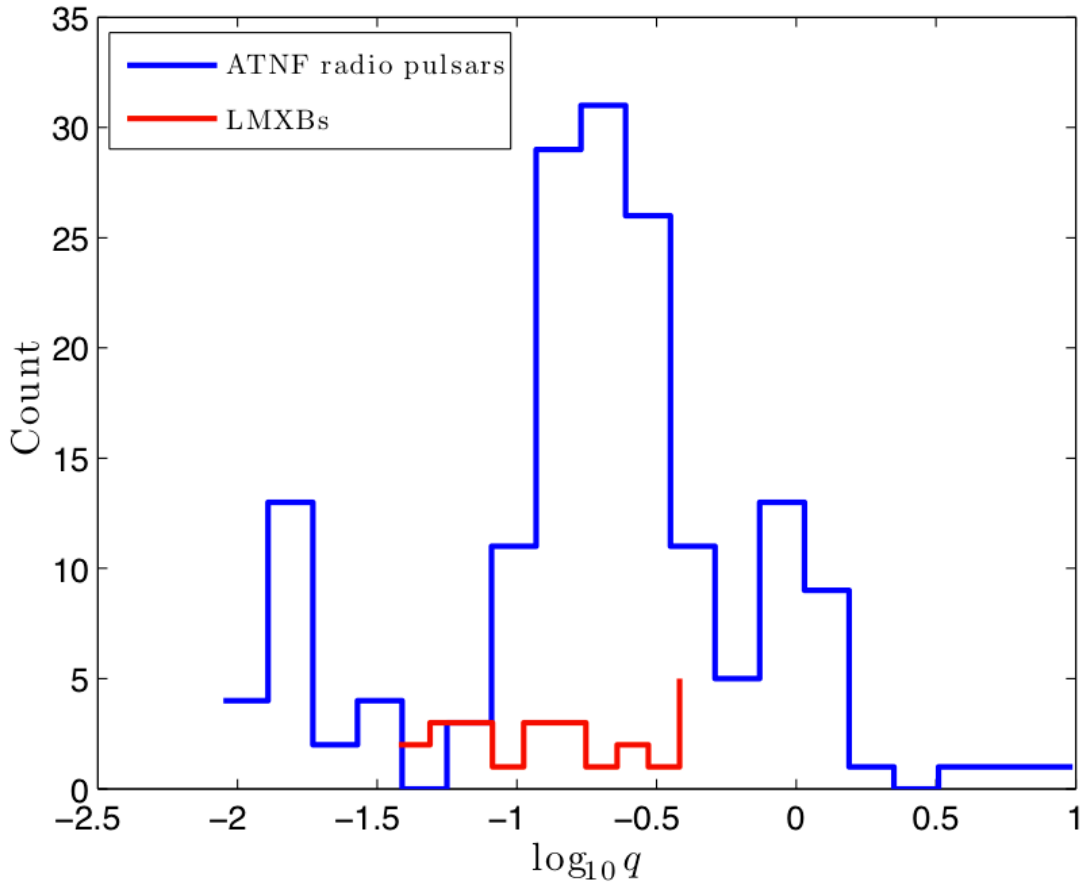
- With $M_{\rm NS} = 1.4 M_\odot \quad q = 1$

$$\Delta f_{\max} \simeq 1.15 \left(\frac{f}{1\,\mathrm{kHz}}\right) \left(\frac{P}{2\,\mathrm{h}}\right)^{-1/3} \mathrm{Hz}$$

- Observable Doppler shift

$$\Delta f_{\rm obs} = \Delta f_{\max} \sin i$$

Observed mass ratios: radio pulsars and LMXBs



Note: ATNF pulsars curve is for the median expected mass ratio

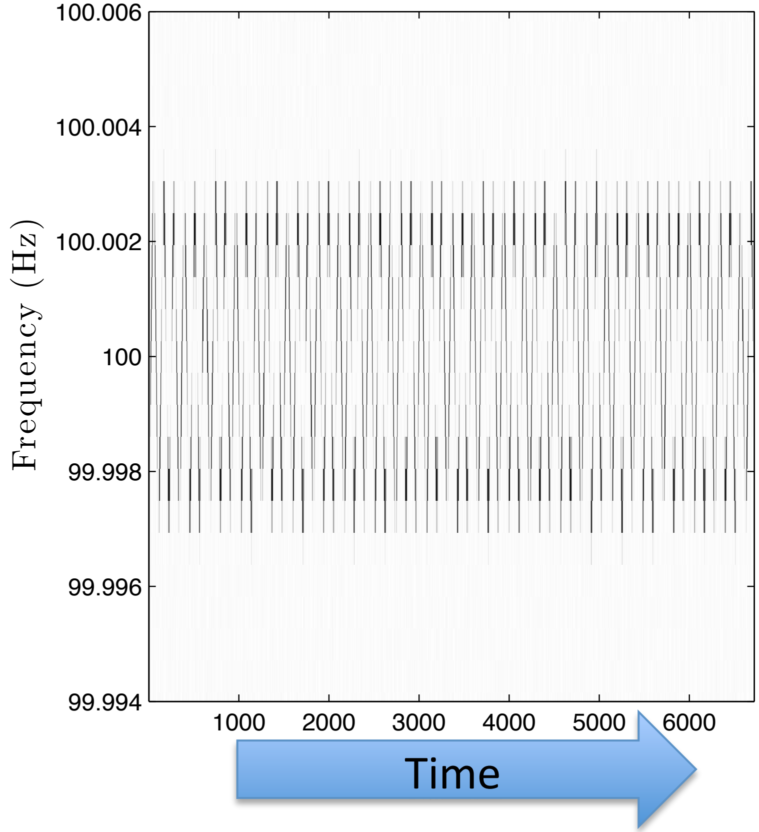
TwoSpect search method

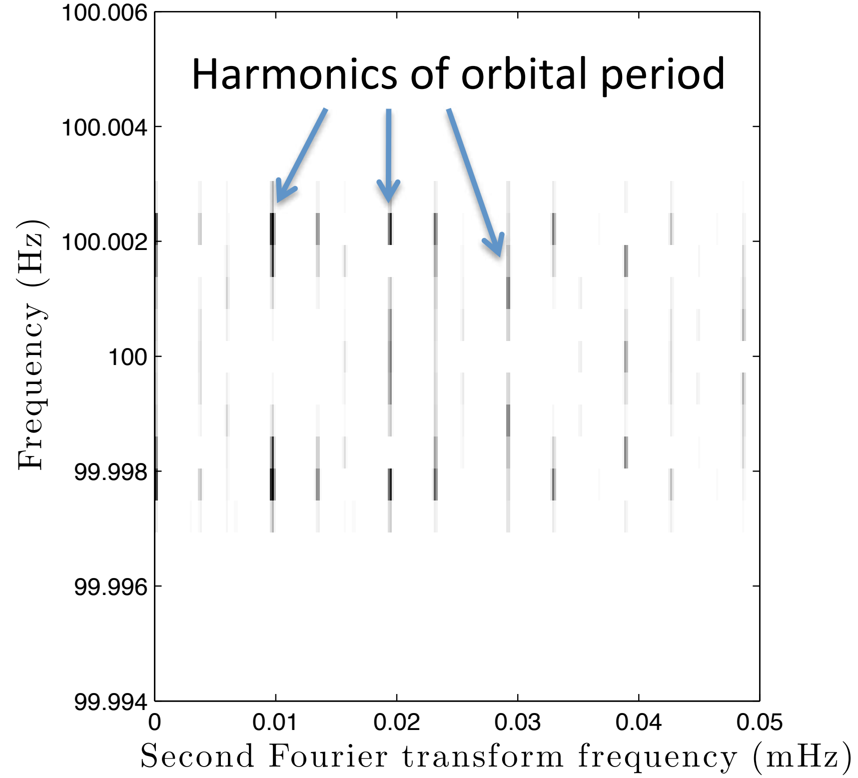
- All-sky search for continuous gravitational waves from unknown spinning neutron stars in binary systems [14]
- Doubly-Fourier transformed data are tested for potential gravitational wave signals
- Upper limits are placed for each 0.25 Hz frequency band

14. E. Goetz and K. Riles 2011 CQG **28**, 215006

TwoSpect analysis method from a simulated signal

After barycentering and weighting according to antenna pattern and noise variations:





Darkest pixels are pixels with power >= 0.5 * maximum power

TwoSpect observable parameter space

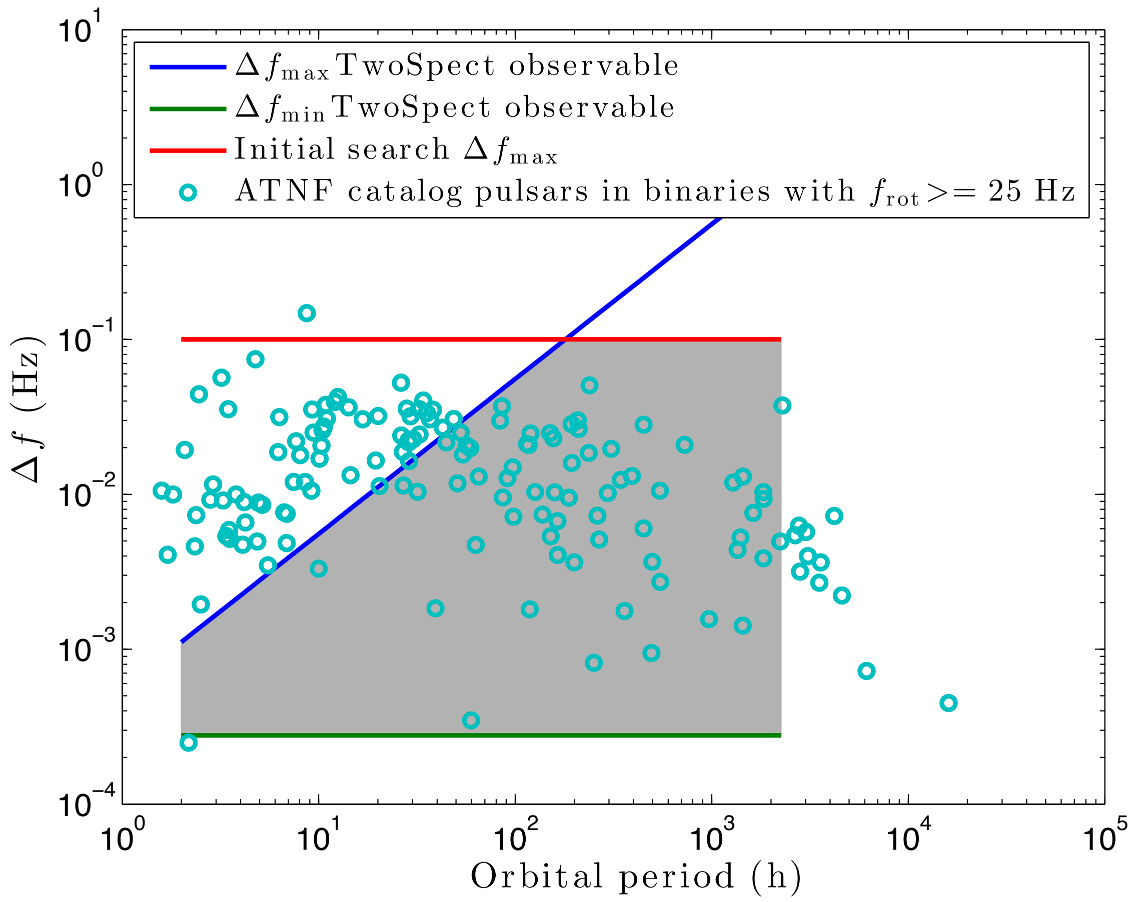
- "Maximum TwoSpect observable" Doppler shift (signal is in single FFT bin per SFT)

$$\Delta f_{\rm max} \leq \frac{P}{2T_{\rm SFT}^2}$$

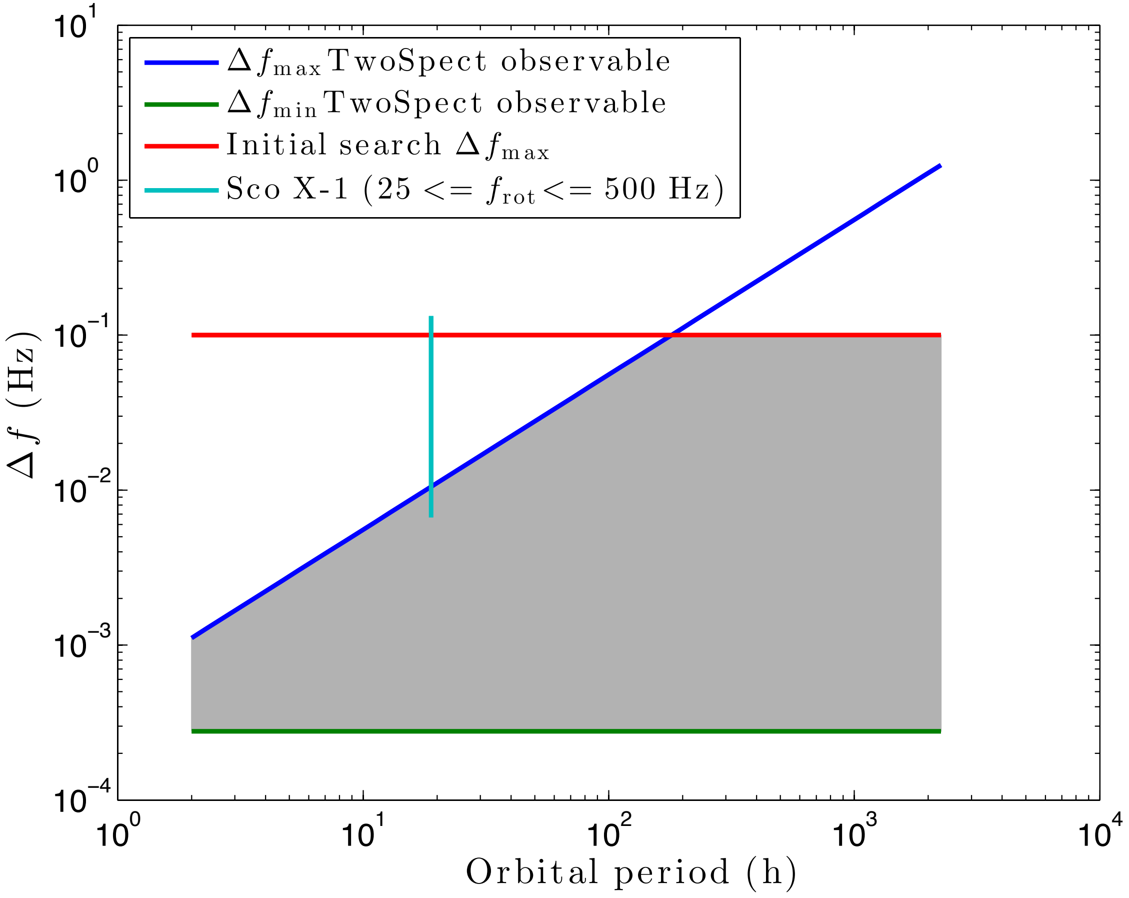
- "Minimum TwoSpect observable" Doppler shift (signal remains in a single frequency bin for all SFTs)

$$\Delta f_{\rm min} \geq \frac{1}{2T_{\rm SFT}}$$

Parameter space searched compared with known pulsar population

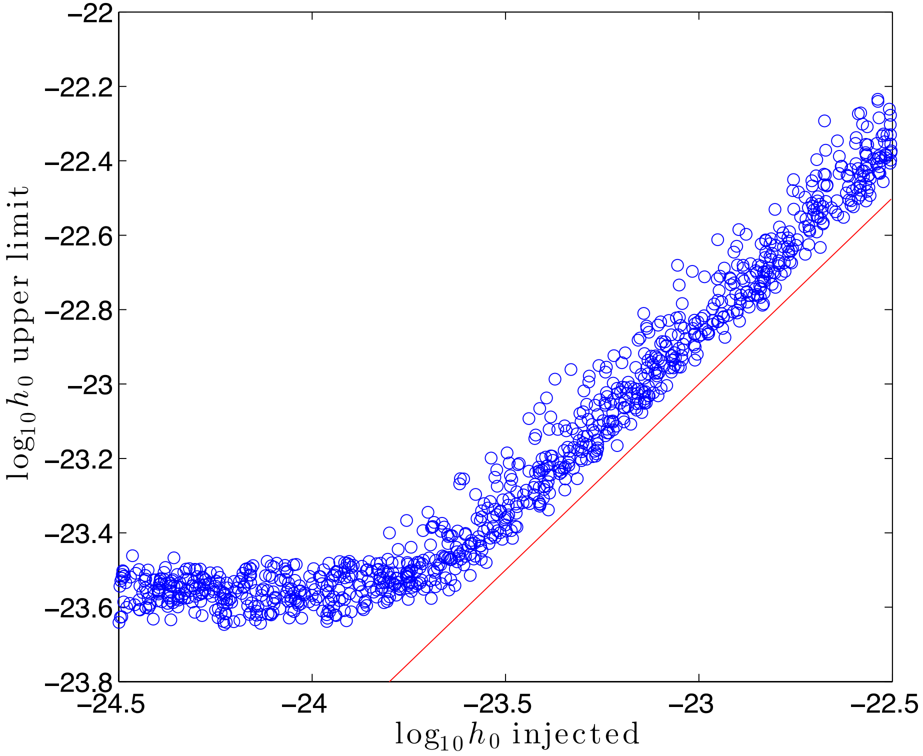


Parameter space searched compared with Scorpius X-1



Upper limit validation

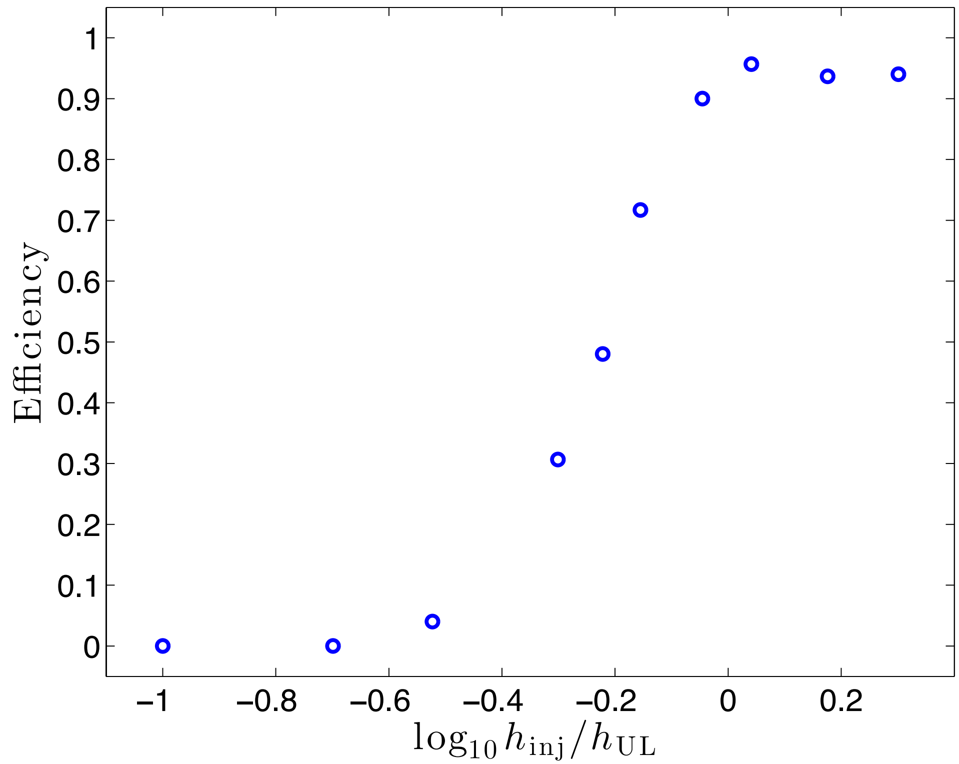
- Simulated data with random signal parameters, circular orbits, and circularly polarized waves
- Upper limit on strain amplitude h_0 is computed and compared against simulated h_0 based on an incoherent harmonic sum (IHS) of summed harmonics in the double-transform plane [15,16]



15. J. H. Taylor and G. R. Huguenin 1969 Nature **221**, 816
16. S. M. Ransom et al. 2002 The Astronomical Jour. **124**, 1788

Detectability of signals

- Simulated data with random signal parameters, circular orbits, and circularly polarized waves
- Signal considered recovered when a candidate signal is near the injected value after template stage



Other searches for continuous gravitational waves from binaries

- Radiometer stochastic known binary search (mature) [17,18]
- Sideband known binary search (nearing maturity) [19]
- Cross-correlation known binary search (active development) [20, J. Whelan's poster]
- Polynomial all-sky, unknown binary search (active development) [21]

17. B. Abbott et al. LSC 2007 Phys. Rev. D **76**, 082003
18. J. Abadie et al. LSC, Virgo 2011 PRL **107**, 271102
19. C. Messenger and G. Woan 2007 CQG **24**, S469
20. C. T. Y. Chung et al. 2011 MNRAS **414**, 2650
21. S. van der Putten et al. 2010 J. Phys.: Conf. Ser. **228**, 012005

Conclusions and future work

- Spinning neutron stars in binary systems are good candidates for gravitational waves
- TwoSpect algorithm can detect and set upper limits on gravitational wave signals from unknown systems
- First search using S6/VSR2 data is underway and will begin to probe interesting regions of parameter space
- Future searches: shorter coherence time, include other wave polarizations, target particular sky locations