Continuous wave searches with ET

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Outline

The waveform

Search techniques and current results

Preliminary expectations from ET

The waveform

In the rest frame of the neutron star, the signal is a sinusoid with a quadrupole pattern for the amplitude:

$$
\begin{aligned}
h_+(\tau) &= A_+ \cos\Phi(\tau) \qquad h_\times(\tau) = A_\times \sin\Phi(\tau) \\
A_+ &= h_0 \frac{1+\cos^2\iota}{2} \qquad A_\times = h_0 \cos\iota \\
h_0 &= \frac{16\pi^2 G}{c^4} \frac{I_{zz}\epsilon f_r^2}{d} \rightarrow \text{Model Dependent}
\end{aligned}
$$

- ι: pulsar orientation w.r.t line of sight
- $\epsilon = (I_{xx} - I_{yy})/I_{zz}$: equatorial ellipticity
- f_r: rotation frequency
- d: distance to star

The waveform phase

The phase model is taken to be a polynomial corresponding to a reference time τ_0:

$$\Phi(\tau) = \Phi_0 + 2\pi\left[f(\tau - \tau_0) + \frac{1}{2}\dot{f}(\tau - \tau_0)^2 + \ldots\right]$$

Need to correct for the arrival times

- For an isolated pulsar:

$$\tau = t + \frac{\mathbf{r}_D \cdot \mathbf{n}}{c} + \text{relativistic corrections}$$

- For a pulsar in a binary system:

$$\tau = t + \frac{\mathbf{r}_D \cdot \mathbf{n}}{c} + \frac{\mathbf{r}_P \cdot \mathbf{n}}{c} + \text{relativistic corrections}$$

- $\mathbf{n}$: sky-position, $\mathbf{r}_D$: Detector in SSB frame, $\mathbf{r}_P$: Pulsar in binary frame
- This simple model might be complicated by glitches and accretion
- We assume the signal to last months or years

Search techniques

Fully coherent matched filter searches

- Feasible only for precisely known sources

Semi-coherent searches

- Break up data T_{obs} into N smaller segments T_{coh} and combine the segments semi-coherently
- This is forced upon us for targeted or blind searches by computational cost constraints – situation probably similar in the ET era
- Different flavors depending on what one does in the coherent and incoherent steps
- In the most general sense, this includes
  - SFT based searches (Powerflux, Hough, Stackslide)
  - Segments are demodulated coherently (“Hierarchical search”)
  - Cross-correlation (similar in some ways to a Hierarchical search but simpler to implement)

Search techniques

- The basic software infrastructure is now well developed – at least for isolated neutron stars
- The codes have been implemented on both standard LSC clusters and `Einstein@Home`
- We can expect large gains from implementations on GPU units
- However, we still do not have a clear demonstration of a pipeline which can follow-up candidates in a multi-stage scheme
- This should happen in the next few years, certainly before AdvLIGO comes online

Search techniques

To simplify life for this talk, we write the sensitivity of the searches in two cases

- Single template search

$$h_0 \approx 11 \sqrt{\frac{S_n(f)}{DT_{obs}}}$$

- Wide parameter space semi-coherent search

$$h_0 \approx \frac{25}{N^{1/4}} \sqrt{\frac{S_n(f)}{DT_{coh}}}$$

- The factor of 25 is meant to include both hits due to computational cost and multiple statistical trials
- This is just a useful fudge at the moment, and we will eventually need a more careful analysis for a given source and search technique
- Do not expect to be accurate to better than 50% with these estimates!

Summary of key LIGO results

- LIGO data has been used to do better than other indirect limits on h_0 coming mostly from EM observations
- The Crab spindown limit has been beaten: less than $\sim 6\%$ of its spindown energy is going into gravitational waves
- The spindown limit will be challenged for J0537-69 using S5 data, and Vela should be beaten by Virgo
- Indirect limits on objects like Cas A have been beaten – but this is a weaker statement than the Crab result
- The Bladford limit on h_0 based on a population of GW pulsars has been beaten by the wide parameter space semi-coherent search – though the more stringent limits by Knispen-Allen are still out of reach

Targeted searches

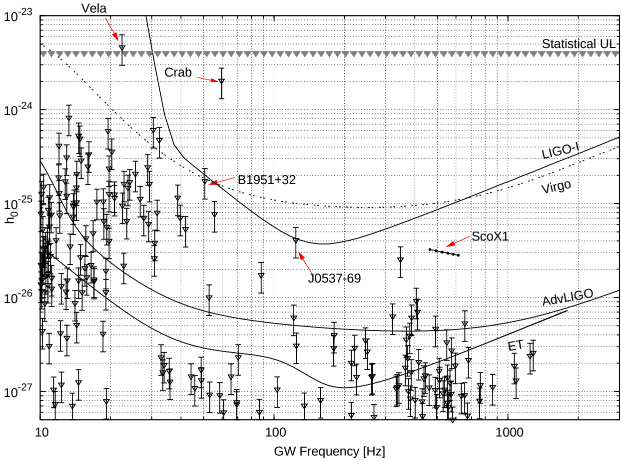
- We will (hopefully!) move onto detection with AdvLIGO or ET

Very interesting astrophysics possible

- The emission frequency will tell us a lot about the emission mechanism
- The GW amplitude will set constraints on nuclear EOS and NS crusts
- Is the GW signal correlated with glitches and other EM observations?
- Does nature choose to use the Bildsten spin-balance mechanism for accreting netron stars?
- ...

Targeted searches

(Adapted from R.Prix, 2006)



- 1 year integration
- 3 detectors for Adv LIGO, single detector for ET and Virgo
- Error bars correspond to 10% uncertainty in distance and $I_{zz} = [1 - 3] \times 10^{38}$ kg-m^2

Expected sensitivity for the Crab

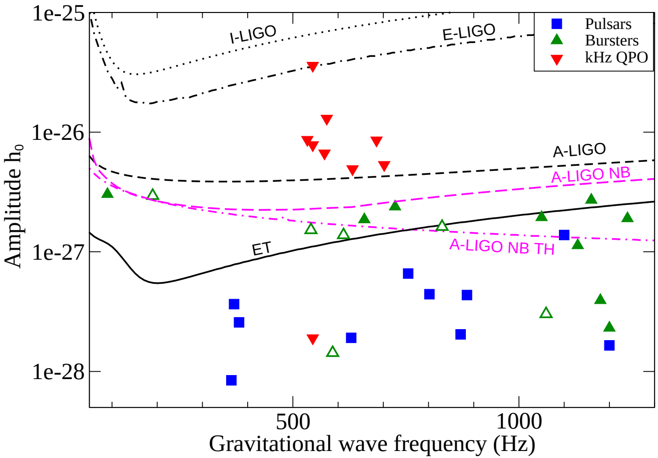
Expected improvements for the Crab upper limit:

	h_0^{sens}/h_0^{sd}	$(h_0^{sens}/h_0^{sd})^2$	ϵ
Initial LIGO	0.07	0.5%	1.8×10^{-4}
enhanced LIGO	0.03	0.1%	7.7×10^{-5}
Advanced LIGO	0.004	1.6×10^{-3}%	1.0×10^{-6}
ET	0.0014	2×10^{-4}%	3.6×10^{-7}

But it would be disappointing if we were still doing upper limits!

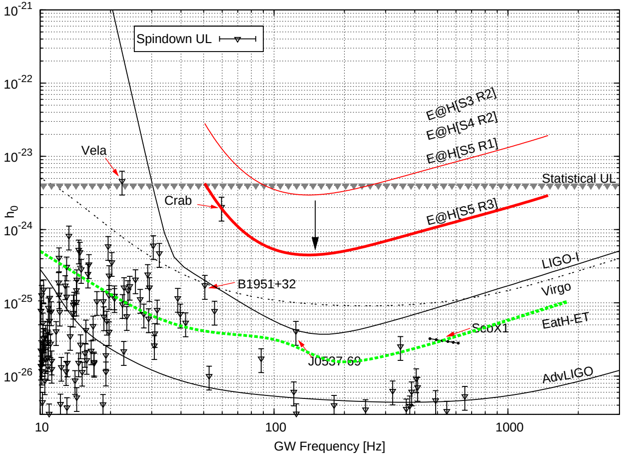
Accreting neutron stars

(From Watts et al., 2008)



- 2 year integration, single template
- Assume frequency is known for kHz QPO sources
- Very important to have X-ray timing missions in ET era!

Wide parameter space searches



- Scale up current `Einstein@Home` search to ET sensitivity with single instrument
- Can reasonably expect to beat the spindown limit of unknown neutron stars to a few kpc

Future work

- Need more reliable sensitivity estimates for wide parameter space searches
- Improvements in computational algorithms and infrastructure will be crucial
- Electromagnetic timing, especially X-ray timing of accreting neutron stars will be almost as important
- More exploration of astrophysical implications of this gain in sensitivity is needed
- More generally, the increased sensitivity of ET (and Adv LIGO) is really important for detecting CW signals