CONTINUOUS WAVES FROM ROTATING NEUTRON STARS

Matthew Pitkin - University of Glasgow

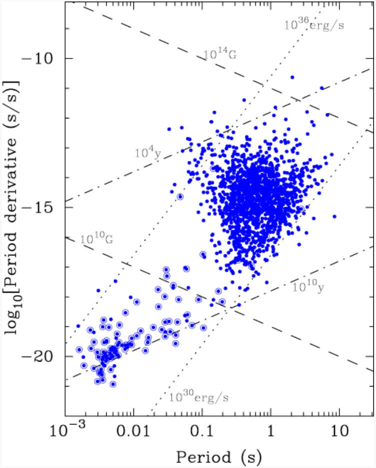
DAWN Workshop

7 May 2015

LIGO G1500603

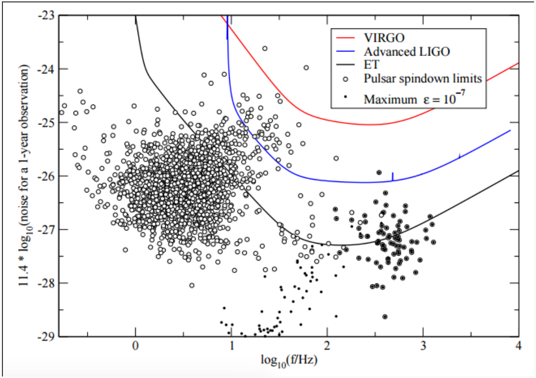
Rotating neutron stars with a non-axisymmetric deformation (a mass, or mass current, quadrupole) *will* emit GWs.

- $\sim 160\,000$ "normal" and $\sim 40\,000$ millisecond active pulsars in the Galaxy[1]
- $\gtrsim 2000$ pulsars have been observed, with $\sim 10\%$ in frequency band of GW detectors



Credit: [1]Lorimer, Living Rev. Relativity, 11 (2008)

Emission strength often characterised by quadrupole ellipticity ε, but this is uncertain within a range from $10^{-12} \lesssim \varepsilon \lesssim 10^{-5}$, maybe extending higher for hybrid/quark stars.



Credit: Andersson *et al*, GReGr, **43** (2011) arXiv:0912.0384

Theoretical maximum sustainable ellipticities provide upper limit, but whether these are realised in nature is unknown/unlikely. Methods of producing/sustaining ellipticities are also highly uncertain:

- mountains *locked-in* to crust following formation
- strong internal magnetic fields

We have no idea how many signal detections to expect in first years of aLIGO/AdV.

Advocate for better modeling of neutron star deformation to enhance science case?

What could we learn from CW gravitational wave emission[1]?

- $f_{\mathrm{GW}} = 2 f_{\mathrm{rot}}$ star is probably a triaxial ellipsoid
- $f_{\mathrm{GW}} \approx 2 f_{\mathrm{rot}}$ shows components producing EM and GW emission are not completely coupled (information on crust and core coupling of star?)
- $f_{\mathrm{GW}} \approx f_{\mathrm{rot}}$ precession play important role in emission
- $f_{\mathrm{GW}} \approx (4/3) f_{\mathrm{rot}}$ emission from r-modes is favoured (information on interior fluid motion of star)

[1] if accompanied by EM observation either from a known pulsar search or through follow-up of unknown sources

What could we learn from CW gravitational wave emission?

- if ellipticities are at the very high range we could potentially narrow down neutron star EOS
- multiple sources could yield information on ellipticity distributions to help constrain models of formation of deformations
    - are there different distributions for "normal" and millisecond pulsars?

But, we actually measure

$$h \propto I_{zz}\varepsilon/d,$$

where I_{zz} is the moment of inertia and d is the distance, so measuring ε requires this additional information.

- **targeted searches**: fully coherent searches for known radio, X-ray and γ-ray pulsars
- **all-sky searches**: semi-coherent searches for unknown sources covering all-sky, wide frequency and frequency derivative ranges
- **directed searches**: (*i.e. searches for targets with unknown rotation rate*) coherent and semi-coherent searches using some knowledge of source (generally sky position) to perform a more sensitive search
    - supernova remnants (e.g. Cas A)
    - galactic center
    - LMXBs (e.g. Sco X–1)

Sensitivity for semi-coherent CW searches scales as

$$h \approx \frac{C}{N^{1/4}} \sqrt{\frac{S_n(f)}{T_{\rm coh}}}$$

where $T_{\rm coh}$ is the coherent time, N is the number of coherent data stretches, $S_n(f)$ is the power spectral density and C is a search dependent pre-factor.

C is proportional to the number of templates used – longer coherent times and larger parameter spaces require more templates to ensure phase coherence. Also, computational cost (for all-sky searches) scales as $\sim T_{\rm coh}^3 - T_{\rm coh}^6$!

Best way to improve search sensitivity is to improve $S_n(f)$

For all-sky and directed searches any candidate detections can be followed up using fully coherent methods to regain $T^{1/2}$ sensitivity increase

- provide better parameter estimation to constrain ellipticity
- for year long (or potentially less) integrations provides source sky position to $\sim$ arcsec precision, which greatly aids EM follow-up

Sensitivity can be improved by narrowing the parameter space (fewer templates), so input from EM observations are vital:

- targeted searches rely on EM information to provide phase evolution templates, so need to make sure we have access to latest radio, X-ray, γ-ray (new surveys, LOFAR, SKA, Fermi, ASTROSAT)
- encourage deeper searches (e.g. Einstein@home) in existing data to find more sources.

Sensitivity can be improved by narrowing the parameter space (fewer templates), so input from EM observations are vital:

- LMXB searches require huge template banks due to many source uncertainties, so narrowing these uncertainties (e.g. finding the rotation period of Sco X–1) would greatly increase sensitivity
- Directed searches could also be improved with more information, e.g. finding rotation periods of isolated X-ray sources, or neutron stars in supernova remnants

Advocate for pulsar surveys and X-ray timing with future radio and high energy observatories

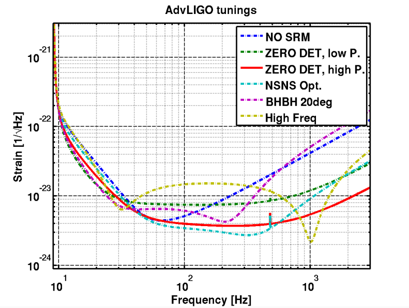
For all-sky searches EM follow-up of detections enables greater physics return

- observations of pulsations gives rotational frequency and immediately narrows down the emission mechanism

But, pulsations may not be observed. We could require deeper imaging to look for faint X-ray source, or supernova remnant/pulsar wind nebula. How much telescope time would be required/could be obtained for these?

Follow-up of LMXBs may be most useful if it is coincident with further GW observations - can observe how GW and EM signals change over the same periods. This would require long term monitoring.

If we start seeing signals, and/or EM observations, and/or theory gives specifics of source parameters then we could narrow-band the detectors. However, with a detectors network *narrow-banding only one detector doesn't help greatly* How would this effect other searches?



Credit: LIGO T0900288

How, feasible are other ways to improve sensitivity?

- Manually suppressing, or filtering, $60\,\mathrm{Hz}$ line from data to help with Crab? Although, the Crab is moving away from $60\,\mathrm{Hz}$ at a reasonable rate (currently at $\sim 59.35\,\mathrm{Hz}$ and slowing down at $\sim 0.02\,\mathrm{Hz\,yr^{-1}}$!)

Unlike other searches *CW searches can make detections with a single detector*. So, if one aLIGO detector was being upgraded the other could still be used (in narrow-band mode?)

Are there things other than rotating neutron stars that we could look for?

- Search for CW emission from axions around a black hole[2] (e.g. Cyg X–1, or SN1987A)
- maybe can adapt current searches for these, but there could be large signal modulation
- potential huge scientific pay-off if discovered
- Adapt searches for newly formed neutron stars following nearby supernovae
- requires searches to handle very high spin-downs and higher frequency derivatives

[2] http://arxiv.org/abs/1004.3558

CONCLUSIONS

- Discovery of CW signal(s) during ADE is highly uncertain
- Improving detector sensitivity is a guaranteed way to help CW searches
- But, more EM input on poorly understood targets (notably Sco X–1 and Cas A) could be as valuable in improving achievable sensitivity and providing more potential sources
- EM follow-up of detections is very important to extract physics