Continuous gravitational wave searches

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Outline

- Astrophysical motivation
- Methods and challenges
- Current results
- Plans for the future
Continuous GW sources vs other types of sources

One-time cataclysmic events, e.g.
last moments of binary systems of
- black holes (GW150914, GW151226, LVT151012),
- neutron stars,

Periodic phenomena, e.g.
- rotating non-axisymmetric neutron stars ("gravitational pulsars"),
- wide binary systems.
Neutron stars = very dense, magnetized stars

The most relativistic **material** objects in the Universe: compactness $M/R \approx 0.5$, observed in all EM spectrum as pulsars, magnetars, in supernovae remnants, in accreting systems, in double neutron star binaries...

About 2500 NS observed to date, $10^8 - 10^9$ in the Galaxy.
Continuous GWs from spinning neutron stars

Characteristics:

★ Long-lived: $T > T_{\text{obs}}$,
★ Nearly periodic: $f_{\text{GW}} \propto f_{\text{rot}}$

Mechanisms that can create time-varying quadrupole moment:

★ ”Mountains” (elastic and/or magnetic stresses, $f_{\text{GW}} = 2f_{\text{rot}}$),
★ Oscillations (r-modes, $f_{\text{GW}} = 4/3f_{\text{rot}}$),
★ Free precession ($f_{\text{GW}} \propto f_{\text{rot}} + f_{\text{prec}}$)
★ Accretion (drives deformations from r-modes, thermal gradients, magnetic fields, $f_{\text{GW}} \simeq f_{\text{rot}}$)

(see PASA 32, 34, 2015 for a review)
GW amplitude and the spindown limit

GW strain \( h_0 = \frac{4\pi^2 G I_3 \epsilon f_{GW}}{c^4 d} \)

with the distance \( d \) and the deformation \( \epsilon = (I_1 - I_2)/I_3 \). Depending on the dense matter model, \( \epsilon_{max} = 10^{-3} - 10^{-6} \).

Rotational energy loss: \( \dot{E}_{rot} \propto f \dot{f} \)

Energy emitted in GWs: \( \dot{E}_{GW} \propto f^6 I_3^2 \epsilon^2 \)

Spindown upper limit: observed spindown fully due to GWs

\[
\dot{E}_{rot} = \dot{E}_{GW}
\]

Assuming \( I_3 \) and \( d \)

\( \rightarrow \) upper limit \( h_0^{sd} = \frac{1}{d} \sqrt{\frac{5G}{2c^3} \frac{\dot{f}}{f}} I_3 \)
Example: a monochromatic signal

In this case a Fourier transform is sufficient to detect the signal (simplest matched filter method):

\[ F = \left| \int_0^{T_0} x(t) \exp(-i\omega t) dt \right|^2 \]

\( T_0 \) - time series duration, \( S_0 \) - spectral density of the data.

Signal-to-noise \( SNR = h_0 \sqrt{\frac{T_0}{S_0}} \)
In reality: signal is modulated
Since the detector is on Earth, planets and Earth’s rotation influences signal’s amplitude and phase.

- Signal is *almost* monochromatic: sources may slow down/spin up,
- it has to be demodulated (detector is moving),
→ precise ephemerides of the Solar System needed.

Detector movement distinguishes a real signal from detector’s spectral artifacts (”lines”).
Example: the $\mathcal{F}$-statistic

$\mathcal{F}$-statistic estimates how well the amplitude and phase modulated model matches the data $x(t)$

$$\mathcal{F} = \frac{2}{S_0 T_0} \left( \frac{|F_a|^2}{\langle a^2 \rangle} + \frac{|F_b|^2}{\langle b^2 \rangle} \right)$$

where $S_0$ is the spectral density, $T_0$ is the observation time, and

$$F_a = \int_0^{T_0} x(t) a(t) \exp(-i\phi(t)) dt, \quad F_b = \ldots$$

$a(t), b(t)$ - amplitude modulation functions that depend on the sources’ sky position $(\alpha, \delta)$,

$\phi(t)$ - phase modulation function that depends on $(f, \dot{f}, \alpha, \delta)$

(PRD 58, 063001, 1998)
Taxonomy of search methods

★ Targeted searches
★ based on matched filtering (data of length $T_0$ correlated with signal templates). Position, $f$ and $\dot{f}$, sometimes source orientation, are known.

$$h_0 \propto \sqrt{S(f)/T_0}$$

★ Directed searches
★ Cases when some parameters are known, e.g. the position:
→ Supernovæ remnants, Sco X-1, the Galactic center, globular clusters etc.

★ All-sky searches
★ Source parameters and position not known → parameter space is large → problem becomes computationally bound
→ Hierarchical approach: analysis of $N$ data segments of length $T_s$ coherently, combining the results incoherently (most sophisticated example: the Einstein@Home project)

$$h_0 \propto \sqrt{S(f)/T_s/N^{1/4}}$$
Example: computational cost for an all-sky search

In order to optimally cover a range of \((f, \dot{f}, \alpha, \delta)\) parameters,

\[
\text{computing power } \propto T_0^2 \times T_0^{[0-3]} \times T_0 \log(T_0) = T_0^{[3-6]} \log(T_0).
\]

(see PRD 90, 122010, 2014). Coherent search of \(T_0 \simeq 1 \text{ yr}\) of data would require zettaFLOPS \((10^{21} \text{ FLOPS})\) scale computers \(\rightarrow\) currently impossible \(\ddagger\).

**Solution:** divide data into shorter length time frames \((T_s \simeq \text{days})\)

\[
B = \frac{1}{2\delta t}
\]

\(\star\) Perform a search in narrow frequency bands: sampling time \(\delta t = 1/2B\), number of data points \(N_p = T_s/\delta t = 2T_sB\)

\(\rightarrow\) feasible on a petaFLOP computer.

**Second stage:** look for coincidences between different \(T_s\) segments.

**Third stage:** Analyze interesting outliers ("targeted search").
O1 targeted search for known pulsars

★ 200 known pulsars analyzed,
★ 11 high-value targets using 3 pipelines: TD Bayesian, TD $\mathcal{F}/\mathcal{G}$-Stat and FD 5-vector method, rest with the TD Bayesian method.
★ ULs improved by a factor 2.5 w.r.t the Initial LIGO/Virgo results,
★ spindown limit beaten for 8 pulsars, including Crab & Vela:
  ★ Crab: less than $2 \times 10^{-3} \dot{E}_{\text{rot}}$ in GW,
  ★ Vela: less than $10^{-2} \dot{E}_{\text{rot}}$.
★ PSR J1918-0642: smallest UL $h_0 = 1.6 \times 10^{-26}$.

All-sky CW search in LIGO O1 [10, 475] Hz

A selection of methods:

- PowerFlux (PRD 94, 042002, 2016)
- FrequencyHough (PRD 90, 042002, 2014)
- SkyHough (CQG 31, 085014, 2014)
- Time domain $F$-statistic (CQG 31, 165014, 2014)
- Einstein@Home followup method of interesting outliers (PRD 94, 122006, 2016)

Example frequency Hough map, with three signals injected into white noise (from CQG 25, 18, 2008).

- At 475 Hz we are sensitive to NSs with equatorial ellipticity $\epsilon \approx 8 \times 10^{-7}$ and as far away as 1 kpc,
- Sensitivity several times better than LIGO S6
Advanced LIGO O1 upper limits
spindown range -1e-8 Hz/s through 1e-9 Hz/s

Preliminary
Search reach (circular polarization)

Frequency (Hz)

Frequency derivative (Hz/s)

$\varepsilon=1\times10^{-5}$

$10\,\text{kpc}$

$1\,\text{kpc}$

$100\,\text{pc}$

$8\times10^{-8}$

$9\times10^{-7}$

$10\,\text{kpc}$

$8\times10^{-9}$

$\varepsilon=1.8\times10^{-7}$

$\text{at } 1975\,\text{Hz}$
Summary and outlook I

Recent results of the LIGO/Virgo CW group with the Initial Detector Era (LIGO S6 and Virgo VSR2, VSR4 runs):

- Mock Data Challenge (PRD 94, 124010, 2016)
- Directed S6 search towards the Orion spur [50-1500] Hz (PRD 93, 042006, 2016)
- FrequencyHough all-sky VSR2 and VSR4 search [20-128] Hz (PRD 93, 042007, 2016)
- All-sky E@H S6 search [50, 505] Hz (PRD 94, 102002, 2016)
- PowerFlux S6 all-sky search [100-1500] Hz (PRD 94, 042002, 2016)
- Directed S6 search for NGC 6544 (100-700) Hz (arXiv:1607.02216)

Why use the ’old’ data? To test algorithmic improvements and develop new methods - these new tools are now being used for O1 (and soon O2) searches.
Summary and outlook II

In the near future with O1 and O2 data:

★ result of searches for signals with more complicated morphology: **transient CWs**,  
  ★ accounting for NSs glitches (sudden changes in spin frequency),  
  ★ hierarchical follow-up of transient CW-like candidates,  
  ★ using machine-learning algorithms.  

★ **Loosely-coherent approach**: methods taking into account  
  ★ NS spin frequency wandering,  
  ★ mismatch between the GW frequency (and spindown) and the parameters inferred from EM observations  

★ Focus on interesting targets like Sco X-1, supernovae remnants (CasA, Vela Jr, G347, Crab)  

★ Search for r-mode frequencies and GWs at multiple frequencies at once,  

★ Search for non-tensorial GWs.