Prospects of continuous gravitational waves searches from Fermi-LAT sources
Outline

Aim of the talk: I would like to give you a general idea on how searches for continuous gravitational waves work.

- Gravitational waves (GW) from neutron stars
- Principles of gravitational waves detection
- Continuous GW searches
- Gamma-ray sources and Fermi-LAT
- GW searches from:
  - Known Pulsars
  - Supernova remnants and pulsar wind nebulae
  - Unassociated
- Perspectives
- What we can infer?
- Summary and conclusion
Gravitational waves from neutron stars

Asymmetric neutron stars (NS) are one of the expected sources of gravitational waves.

In the standard NS configuration we expect a GW at two times the NS rotational frequency.

\[ h_+ = h_0 \frac{1 + \cos^2 \iota}{2} \cos(4\pi \nu_{NS} t) \]
\[ h_\times = h_0 \cos \iota \sin(4\pi \nu_{NS} t) \]
\[ h_0 = \frac{1}{r} \frac{16\pi^2 G}{c^4} I_{zz} \nu_{NS}^2 \epsilon \]

Neutron stars are pretty peculiar astrophysical objects:

- High stability in rotation period (Spin-down \(\sim 10^{-12}\) Hz/s)
- For the pulsars sub-class it is possible in principle to infer the rotational parameters from electromagnetic observations.
- Long-lived coherent signal (>months), depends on glitches.
- Are supposed to be very dense (\(\sim 10^{14} \text{ g/cm}^3\)).
- Spin-down limit (absolute theoretical upper-limit):

\[ h_0 \leq 8.06 \cdot 10^{-19} \left( \frac{I_{zz}}{kg \text{ m}^2} \right) \sqrt{\left( \frac{\dot{\nu}}{Hz/s} \right) \left( \frac{Hz}{\nu} \right)} \]

This type of GW signal are called **continuous gravitational waves**.
A crossing GW changes the distance between two test masses. LIGO and Virgo are experiments based on Michelson interferometry suitable to detect GWs.

Principle of GW detection

\[ I(t) \propto h(t) \]

Seems simple... but it’s not
Principle of GW detection

The typical length of Virgo and LIGO science Run is of order of several months, sampled at 4096 Hz.

Hardware injection in VSR4, Amplitude = $8.4 \times 10^{-24}$ (we can see it)

We expect a signal deeply buried into noise
**Continuous GW searches**

**Doppler due to the Earth motion:** It is needed to know with very high precision the location of the neutron star

\[ f_d = f(t) \left( 1 + \frac{\vec{v} \cdot \vec{n}}{c} \right) \]

Fix R.A. and declination

**Neutron star frequency:** It is needed to know with high precision the frequency and its derivatives of the neutron star

\[ f(t) = \sum_{n=0}^{\infty} f^{(n)} \frac{(t - t_0)^n}{n!} \]

Fix frequency and spin-down

**Antenna response:** It is needed to know the source position and the interferometer position

\[ F_+ (\theta, \phi) = \frac{1}{2} (1 + \cos^2 \theta) \cos 2\phi \]
\[ F_\times (\theta, \phi) = \cos \theta \sin 2\phi \]

Fix the interferometer position with respect to the source

**Signal buried in noise:** Compute the analysis to extract the signal from the noise

[Maggiore, 2008]
Continuous GW searches

The simplest way to look for cGWs is to search for a monochromatic signal after that all the corrections have been applied.

From the basic theory of signal processing we know that the longer is the coherence time, the better I can see the signal in the spectrum.

This procedure is not always suitable for several reasons but the more important is the computational costs of the analysis.

Analyzing 4 months of data means that our frequency and spin-down bins are:

\[ \delta f \approx 10^{-7} \text{Hz} \quad \delta f \approx 10^{-14} \text{Hz/s} \]
The simplest way to look for cGWs is to search for a monochromatic signal after that all corrections have been applied.

Continuous GW searches

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\[ \delta f \approx 10^{-7} \]

![Cartoon of two scientists searching through a haystack with one exclaiming "Found it!" and the other saying "Congratulations, it only took you 65298 seconds." ](image)
Continuous GW searches

In order to look for GW we have to explore a $4+N$ dimensional space (R.A, decl, frequency, spin-down+Spin-down's derivatives)

**Targeted searches**: Based on the application of a matched filter, the knowledge of all the source parameters is mandatory.

$$h_{min} \approx 10 \sqrt[5]{\frac{S_n(f)}{T_{obs}}}$$

[Astone et al., 2010]

**Directed searches**: Apply the matched filter on many shorter data chunks and then combine the detection statistic incoherently.

$$h_{min} \approx 30 \sqrt{\frac{S(f)}{T_{coh}}}$$

[Aasi et al., 2016]

**All-sky searches**: Based on the incoherent combination of several data chunks.

$$h_{min} \approx \frac{A}{N^{1/4}} \sqrt[5]{\frac{S_n(f)}{T_{coh}}}$$

[Krishnan et al., 2004]

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5-vectors pipeline

*F-Statistic* pipeline

Bayesian Heterodyne pipeline

Directed *F-statistic*

Sky Hough

Frequency Hough

PowerFlux

All-sky *F-stat*
Fermi-LAT collaboration produced 3 source catalogs so far.


The LAT team distinguish between Associated and Identified sources

Detects gamma-ray in a range of 20 MeV to 300 GeV measuring times, energy and directions.
### Identified sources:

<table>
<thead>
<tr>
<th>Source</th>
<th>Number</th>
<th>Frequency</th>
<th>Position</th>
<th>Search</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar (flag: PSR)</td>
<td>143</td>
<td>Well known</td>
<td>Well known</td>
<td>Targeted</td>
</tr>
<tr>
<td>Pulsar Wind Nebula (flag: PWN)</td>
<td>9</td>
<td>Not-known</td>
<td>Known</td>
<td>Directed</td>
</tr>
<tr>
<td>Supernova remnant (flag: SNR)</td>
<td>12</td>
<td>Not-known</td>
<td>Known</td>
<td>Directed</td>
</tr>
</tbody>
</table>

### Associated sources:

<table>
<thead>
<tr>
<th>Source</th>
<th>Number</th>
<th>Frequency</th>
<th>Position</th>
<th>Search</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar (flag: psr)</td>
<td>24</td>
<td>Not well known</td>
<td>Known</td>
<td>Narrow-band</td>
</tr>
<tr>
<td>Pulsar Wind Nebula (flag: pwn)</td>
<td>2</td>
<td>Not known</td>
<td>Not well known</td>
<td>All-sky</td>
</tr>
<tr>
<td>Supernova Remnant (flag: snr)</td>
<td>11</td>
<td>Not known</td>
<td>Not well known</td>
<td>All-sky</td>
</tr>
<tr>
<td>Potential pwn or snr (flag: spp)</td>
<td>49</td>
<td>Not known</td>
<td>Not well known</td>
<td>All-sky</td>
</tr>
</tbody>
</table>

### Unassociated sources:

Sources for which we have only gamma-rays observation: 1010
Mainly on the galactic plane

Depending on the knowledge of source parameters different searches can done
GW searches from: Known pulsars

Target searches applied to pulsars for which we have updated ephemeris and the knowledge of the rotational parameters

See C. Palomba’s talk.
If we have some uncertainties on the rotational parameters or the ephemeris are not updated, narrow-band searches can be applied.

We have applied this type of searches for 11 known pulsars using O1 data (results under internal review, paper in preparation)
GW searches from: Known pulsars

If we have some uncertainties on the rotational parameters or the ephemeris are not updated, narrow-band searches can be applied.

We have applied this type of searches for 11 known pulsars using O1 data (results under internal review, paper in preparation)

First discovered in Fermi-LAT data
Moreover with the future runs of the advanced detectors we will be able to beat the spin-down limit for several pulsars in the second *Fermi-LAT pulsars catalog*. 

Spin-down limit predicted for the low frequency pulsars present in the catalog.
Moreover with the future runs of the advanced detectors we will be able to beat the spin-down limit for several pulsars in the second Fermi-LAT pulsars catalog.

Spin-down limit predicted for the low frequency pulsars present in the catalog.
Pulsars are not the only interesting candidates for GW in Fermi-LAT catalogs. There are a lot of sources that are difficult to analyze with the current pipelines but are very promising under a GW point of view.

**Supernova Remnant & PWN:** For this type of sources the position is accurately known (in most of the cases) but the rotational parameters are completely unknown.

We need to explore 1 sky bin and many frequency bins.

**Unassociated sources:** Besides the fact that they are the 33% of the 3FGL, the unassociated sources are expected to be a large population of NS. This sources have a narrow-localization in the sky and their rotational parameters are unknown.

We need to explore several sky bins and many frequency bins.
GW searches from: SNR and PWN (past)

- Analysis performed for 9 SNR observed in many wavelengths using S6 data
- Semi-coherent analysis on chunks long 1800s
- 140 000 CPU hours
- Upper-limit set ever 5 Hz

We can estimate the spin-down limit using the age of the remnant

\[ h_0 \leq 1.24 \cdot 10^{-24} \left( \frac{3.8 \text{kpc}}{d} \right) \sqrt{\left( \frac{I_{zz}}{10^{38} \text{kg}} \right) \left( \frac{300 \text{yr}}{\tau} \right)} \]

Simone Mastrogiavanni
SciNeGHE Workshop 20/10/2106

[Aasi et al, 2016]
GW searches from: unassociated

Fermi -LAT unassociated sources are really interesting.

These sources lie on the galactic plane covering many sky-bins and many of them are present also in the previous catalogs.

47% are expected to be unseen neutron stars.
GW searches from: unassociated

A typical *unassociated* source is the one shown below.

Coherence time:
86400 s

Max Search frequency:
100 Hz

For this type of sources we would explore about 500 Hz on the frequency band and several sky-bins.

**For just one source**

This type of analysis would be very heavy for a computational point of view with current methods.
GW searches from: unassociated

- A GW search from the galactic center was performed
- Semi-coherent analysis on chunks long 1800s
- 1 million CPU hours
- Upper limit every 1 Hz band 20 Hz to 498 Hz

We are currently performing all-sky analysis. No search of GW from the unassociated sources of LAT is ongoing
Perspectives

We are working to develop new method to analyze Fermi-LAT sources.

The new starting point will be the **Band Sampled Data collection (BSD)** *(see Piccini O.J. poster)*

Allows to increase the coherence time in a computational cheap way.

**Unassociated:**
- GW flag in your catalog?
- Longer FFTs to improve the sensitivity
- Incoherent methods in the neighborhood of the source position (e.g. Hough transform)
- Fast follow-up methods
- New type of algorithms?

**SNR and PWN:**
- Improvements of semi-coherent methods
- Fast follow-up methods
- New type of algorithms?
What can we infer?

- According to standard stellar evolution, we expect $O(10^8)$ NS be hosted in the Galaxy, but only ~2500 have been observed.

- Many of them can be hidden in their supernova remnant (Ex: Cas A, 1987a)
  Or totally unseen

- NS demography

- Infer information on the internal magnetic field through the deformation
  [Owen et al., 2006]

- Moreover GW can probe the NS internal structure, I.e the equation of state (EOS).

  [Read et al., 2009]
What can we infer?

**Only detection:**
- The rotational parameters, i.e. frequency and spin-down
- The position of the source in the sky, hence if a compact object is present in a remnant or in a unassociated source

**Studying the signal:**
- The amplitude of the GW
- The polarization angle
- The line of sight angle
- Upper-limit on ellipticity

**Studying the signal jointly with EM observation:**
- Age of the neutron star
- Braking Index study
- Possible mismatches in EM and GW frequencies
- Distance

GW can carry out a lot of information...so let's keep going!
Continuous gravitational waves are good probes to spot and study NS.

Fermi-LAT pulsars and supernova remnants are good targets for GW searches.

Current pipelines are limited by the computational load. Only 9 supernova remnants were studied so far.

Unassociated sources are also interesting possible GW sources.

Hopefully we will see the first detection of a continuous gravitational waves from NS in the next runs of the advanced detectors.

However, more work is needed to develop pipeline and methods suitable to the analysis of sources with some uncertainties like the ones in Fermi Catalog.

So…..
Brace yourself multi-messenger astronomy is coming

Thanks for the attention

Questions?
References

- P. Astone et al., *A method for detection of known sources of continuous gravitational wave signals in non-stationary data*, Class. Quantum Grav. 27 194016(2010)
- B. Owen, “*Detectability of periodic gravitational waves by initial Interferometers*”, Class. Quantum Grav. 23 S1
Backup slides
Spin-down limit

Assume that all the rotational energy is lost due to GW

\[ L_{GW} = \frac{32G}{5c^5} \Omega^6 I_{zz}^2 \epsilon^2 \]

\[ (2\pi)^2 \nu \nu = L_{GW} \]

\[ \dot{\nu} = \frac{32G}{5c^4} (2\pi)^4 \nu^5 I_{zz} \epsilon^2 \]
## Some rotational parameters

<table>
<thead>
<tr>
<th>Source</th>
<th>Freq [Hz]</th>
<th>spin-down [Hz/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>59.32365204</td>
<td>-7.3883e-10</td>
</tr>
<tr>
<td>J0205+6449</td>
<td>30.40958196</td>
<td>-8.9586e-11</td>
</tr>
<tr>
<td>J1813-1246</td>
<td>41.60103328</td>
<td>-1.2866e-11</td>
</tr>
<tr>
<td>J1813-1749</td>
<td>44.71284639</td>
<td>-1.5000e-10</td>
</tr>
<tr>
<td>J1833-1034</td>
<td>32.29409580</td>
<td>-1.0543e-10</td>
</tr>
<tr>
<td>J1952+3252</td>
<td>50.58823360</td>
<td>-7.4797e-12</td>
</tr>
<tr>
<td>J2043+2740</td>
<td>20.80486277</td>
<td>-2.7415e-13</td>
</tr>
<tr>
<td>J2229+6114</td>
<td>38.71531561</td>
<td>-5.8681e-11</td>
</tr>
<tr>
<td>Vela</td>
<td>22.37409813</td>
<td>-3.1191e-11</td>
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<tr>
<td>J1400-6326</td>
<td>64.12537215</td>
<td>-8.0017e-11</td>
</tr>
<tr>
<td>J2022+3842</td>
<td>41.16008453</td>
<td>-7.2969e-11</td>
</tr>
</tbody>
</table>
Computational efficiency

Frequency bin \(= \frac{1}{T_{coh}}\)
Spin-down bin \(= \frac{1}{T_{coh}^2}\)
Sky bin \(\propto \frac{1}{T_{coh}^2}\)

Supernova remnant search:
1-day coherent time
Frequency 100 Hz

Pulsar search:
1-day coherent time
Frequency 100 Hz
Computational efficiency - Coherence time

E@Home:
60 hours

Time-domain $F$:
48 hours

Sky-Hough:
1800 s

Power flux:
900 s

Frequency Hough:
1024 s

[Walsh, 2016]
Continuous GW searches

**Targeted and directed searches**: This type of searches assume known the position and search for GW for different frequency and spin-down values.

Directed searches divide the observation time in shorter data-chunks in order to explore more frequency bins.

[Astone et al., 2014]
Continuous GW searches

All-sky searches: Don’t use the matched filter technique and explore a wide range in the parameter space.

No matched filter, other techniques:
- Hough transform
- Correlation
- Incoherent summation

Select candidates to follow up

Acquire data

Break up data into smaller segments

Analyze each segment coherently

Combine segments incoherently

Acquire more data

Select candidates in parameter space

Analyze candidates fully coherently

Announce detection or set upper-limits

[Krishnan et al., 2004]