Searching for continuous gravitational-waves from Galactic neutron stars

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Overview

- Intro on Continuous waves signals
- Focus on directed searches
- The Galactic Center O2 case
- New sources from Fermi and Integral catalogs for O3

Gravitational waves sources

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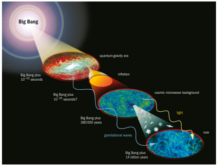
$T \sim$ months or years</td><td></td><td>
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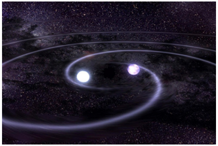
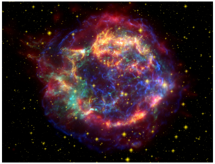
$T \sim$ up to 100 s</td><td></td><td></td></tr>
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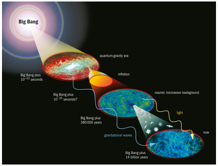
$T \sim$ months or years</td><td></td><td>
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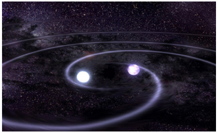
$T \sim$ up to 100 s</td><td>
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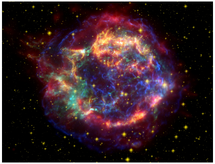
$h_0 \sim 10^{-21}$</td><td></td></tr>
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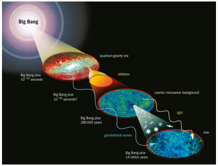
$T \sim$ months or years</td><td></td><td>
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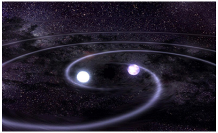
$T \sim$ up to 100 s</td><td>
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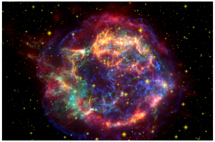
$h_0 \sim 10^{-21}$</td><td>
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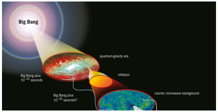
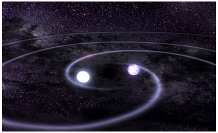
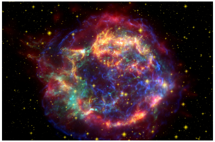
Long-lived $T \sim$ months or years		 Stochastic background $h_0 \sim 10^{-28}$
Transients $T \sim$ up to 100 s	 Compact binary coalescence $h_0 \sim 10^{-21}$	 Burst $h_0 \sim 10^{-21}$

Gravitational waves sources

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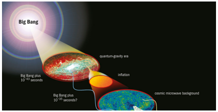
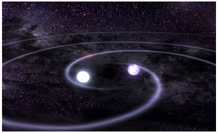
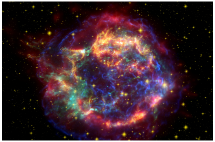
Long-lived $T \sim$ months or years	 Continuous waves $h_0 \sim 10^{-25}$	 Stochastic background $h_0 \sim 10^{-28}$
Transients $T \sim$ up to 100 s	 Compact binary coalescence $h_0 \sim 10^{-21}$	 Burst $h_0 \sim 10^{-21}$

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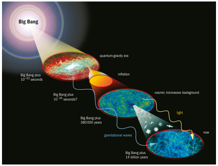
$T \sim$ months or years</td><td></td><td>
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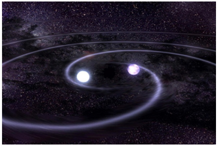
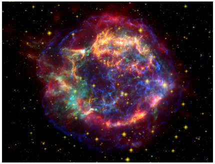
$T \sim$ up to 100 s</td><td></td><td></td></tr>
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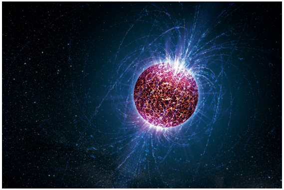
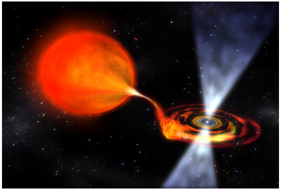
What is a Continuous Wave (CW)?





Credit: C. Reed, Penn State/Mc Gill University

Persistent signal (long-lived)

Produced by a nearly *periodic* mass quadrupole moment variation

Expected sources

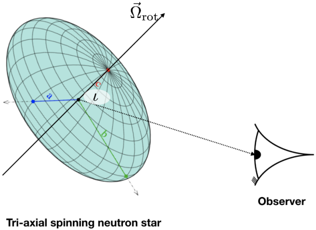
Isolated neutron stars (NS) or NSs in binary systems (Non-axisymmetric)

Expected strain

$$h_0 \cong 10^{-27} \left(\frac{I_{zz}}{10^{38}\mathrm{kg}\cdot\mathrm{m}^2}\right) \left(\frac{10\mathrm{kpc}}{d}\right) \left(\frac{f}{100\mathrm{Hz}}\right)^2 \left(\frac{\epsilon}{10^{-6}}\right) \ll h_{0_{CBC}}$$

[For a CW review: Lasky PASA 32, pp. 34 (2015), Riles Mod Phys Lett A 32, No. 39, 1730035 (2017)]

Isolated neutron stars



Credit: S. Mastrogiovanni

$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz} f^2}{d}\epsilon$$

I_{zz}: moment of inertia

ϵ: ellipticity

- The signal is modulated: Doppler effect, spin-down, sidereal day variation, antenna response, etc.
- The ellipticity can be triggered by different factors: elastic stress, strong internal magnetic fields, thermal gradients, etc. Lasky PASA 32, pp. 34 (2015)
- The maximum ellipticity that a neutron star can sustain is related to the equation of state and to the neutron stare interior model (Johnson-McDaniel+ PRD 88, 044004 (2013))

Estimates on ϵ

Theoretical models (K. Glampedakis & L. Gualtieri 2018 [Astro. and Space Science Lib., vol 457. Springer])

- **Solid strange stars**: $\epsilon \leqslant 6 \times 10^{-4}$
- **Hybrid and meson condensates stars**: $\epsilon \leqslant 3 - 9 \times 10^{-6}$
- **Canonical magnetic deformations**: $\epsilon \leqslant 2 - 6 \times 10^{-7}$
- **Buried magnetic field in MSPs**: $\epsilon_{fid} \sim 10^{-9}$ and a buried magnetic field of 10^{11} G G. Woan+[ApJL,863:L40, 2018]

These are even more stringent than (Johnson-McDaniel+ PRD 88, 044004 (2013))

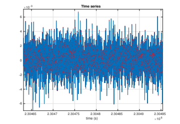
- $\epsilon \leq 10^{-5}$ normal NS
- $\epsilon \leq 10^{-3}$ hybrid stars
- $\epsilon \leq 10^{-1}$ extreme quark stars

Directed searches so far

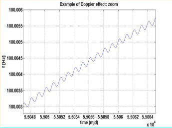
- In directed searches interesting sky regions or astrophysical objects are investigated:
  - O1: 15 SNR + Fomalhaut b (LVC, ApJ 875 122, 2019)
  - O1: LMXB Scorpius X-1 (LVC, ApJ 847 47, 2017)
  - O1: Terzan 5 and the galactic center (Dergachev et al. arXiv:1903.02389)
  - O1: Vela Jr., Cassiopeia A and G347.3 (Ming et al. arXiv:1903.09119)
  - Other (LIGO S6): the Orion Spur, NGC 6544, LMXB XTE J1751-305
- Coherent or incoherent methods can be used

BSD directed search pipeline

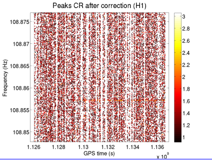
BSD time series
(Piccinni+ CQG 36, 015008, 2019)

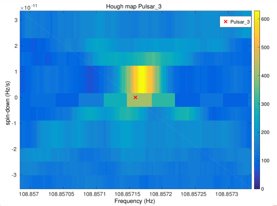


Partial Doppler correction



Time-frequency peaks
(Astone+ CQG 22, S1197, 2005)





Frequency Hough map
(Astone+ PRD 90, 042002, 2014)

The most significant candidates are selected on the final HM. The total computational power needed for this search is ~ 100 CPU hours per target for a "wide" frequency/spin-down range

Motivation for a Galactic center search

- Several independent lines of evidence predict a sizable population of neutron stars in the region ($O(10^8 - 10^9)$ expected in the full Galaxy, only a fraction observed)

- Given the large number of massive stars, the central parsec likely hosts a large neutron star population (mostly MSP (Macquart, J.P. et al. 2015))

- A GC pulsar population could explain the Galactic Center GeV excess measured by Fermi (Bartels et al. 2016, Lee et al. 2016, Fermi-LAT coll. 2017)

- The size of the potentially EM observable population (i.e. those beaming towards us) could include up to 50 canonical pulsars and 10000 millisecond pulsars (Rajwade et al. 2016)

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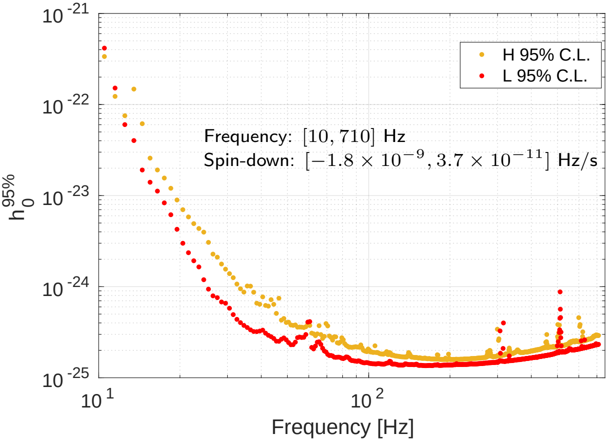
The Galactic center is a good place to look for CWs since it is likely to host several candidates

The Galactic center case: O2

Best results h_0

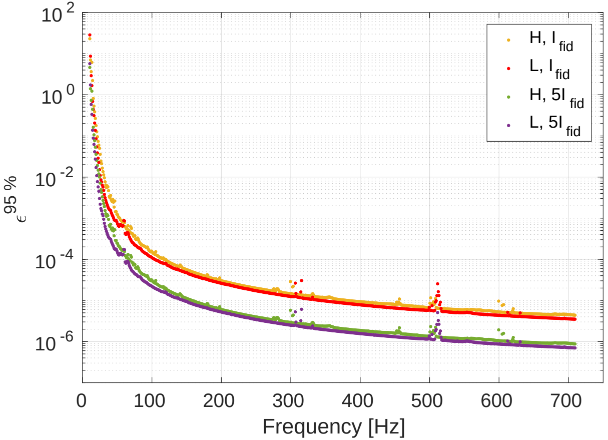
1.4×10^{-25} for L @ 163 Hz, 1.6×10^{-25} for H @ 195 Hz at 95% C.L.



The Galactic center case: O2

Since $h_0 \propto \frac{I_{zz}}{d}\epsilon f^2 \rightarrow \epsilon = \frac{c^4}{4\pi^2 G}\left(\frac{d}{I_{zz}}\right)\frac{h_0}{f^2}$

d=8 kpc and a moment of inertia $I_{zz} = I_{fid} = 10^{38}$ kg m^2 for *standard* NSs or 5 times larger for more *exotic* objects



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(Johnson-McDaniel+ PRD 88, 044004 (2013))

We can exclude the presence of stars with ellipticity bigger than 10^{-6} in the GC region at the highest frequency

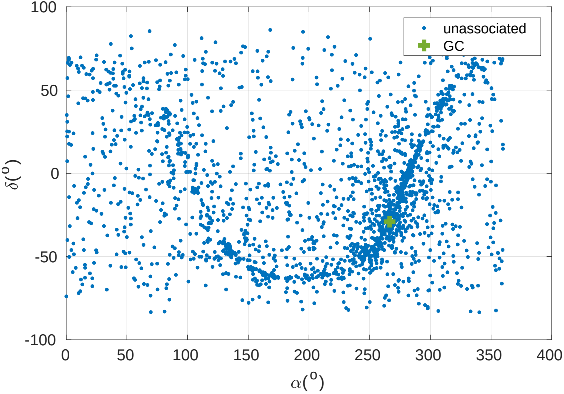
Other potential sources

- Sources which are likely hosting a NS are interesting candidates for our searches.
- Several potential sources are present in the astronomical catalogs like:
  - the pre-release of the 8-years Fermi-LAT point sources catalog[1]: *identified* or *associated* Supernova remnants or Pulsar Wind Nebula or *unassociated* sources ($\sim 39\%$)

[1] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/

Fermi-LAT unassociated

Unassociated: 2132 in Fermi-LAT ($\sim 39\%$) we have only gamma-rays observation, no counterparts at other wavelengths



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  - the IBIS-INTEGRAL soft gamma-ray source catalog (Bird+ 2016): 10 SNR, 19 *pulsar-like* sources and 216 *unidentified* ones (23%)

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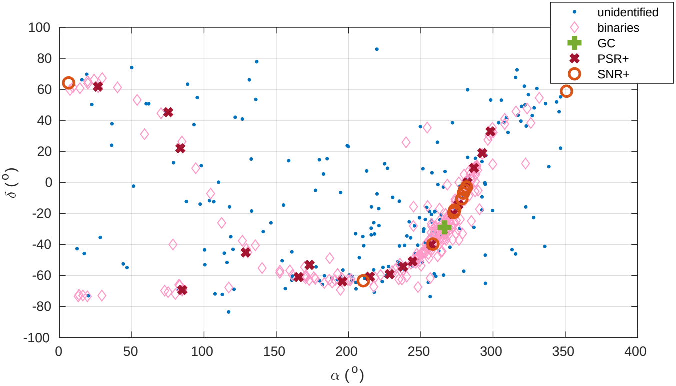
IBIS-INTEGRAL

INTEGRAL catalog presents the following interesting sources: 10 SNR, 19 *pulsar-like* sources and 216 *unidentified* ones (23%) which sky distribution is shown below:



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  - the IBIS-INTEGRAL soft gamma-ray source catalog (Bird+ 2016): 10 SNR, 19 *pulsar-like* sources and 216 *unidentified* ones (23%)
- Most of the sources lie on the Galactic plane

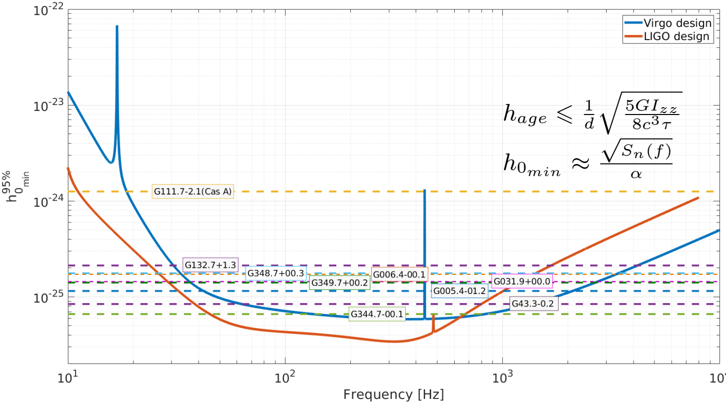
[3] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/

How *good* is a target

- For a given pipeline we can have an estimate of the search sensitivity (Astone+ 2014) as $h_{0_{min}} \approx \frac{\sqrt{S_n(f)}}{\alpha}$ (minimum detectable GW strain amplitude)
- For directed searches we use the *age based upper limit* h_{age} for those sources whose *age* and *distance* is known (Wette 2008)
- A good target will have $h_{age} \geqslant h_{0_{min}}$
- All these quantities can be translated in terms of the star ellipticity ϵ_{age} and ϵ_{min}

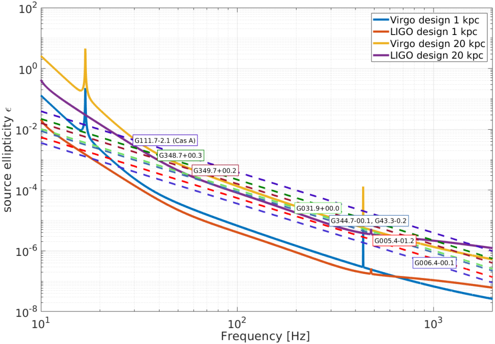
Theoretical indirect upper limits: O3

Potentially detectable sources by our directed search pipeline, with h_{age} bigger than our search sensitivity.



Theoretical indirect upper limits on the ellipticity

Since $h_0 \propto \frac{I_{zz}}{d} \epsilon f^2 \rightarrow \epsilon_{min} = \frac{c^4}{4\pi^2 G} \left(\frac{d}{I_{zz}} \right) \frac{h_{0_{min}}}{f^2}$



ϵ_{min} at 95 % C.L. for Avanced LIGO and Advanced Virgo at design sensitivity for sources at $d = 1$ kpc and 20 kpc The ϵ_{age} theoretical indirect upper limit is

$$\epsilon_{age} \leq \sqrt{\frac{5c^5}{128\pi^4 G I_{zz} \tau f^4}}$$

Conclusion

- CW could be the next surprise in GW astronomy given the enhanced sensitivity of the detectors along with the development of new pipelines
- Astronomical catalogs (Fermi, INTEGRAL,...) provide good targets for our searches, EM observation are crucial
- We plan to analyze O3 data looking for sources from the Galactic center plus other targets
- A CW detection will provide information on the quadrupolar deformation (ellipticity)
- With a joint CW and EM observation we can measure NS radius, mass, magnetic field and ellipticity $\Rightarrow$ EOS


Thank you!