Directed searches for periodic gravitational waves

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Abstract

We summarize plans for searches for periodic gravitational waves of well-known sky location but unknown frequency and frequency derivatives. These include point searches (such as the central compact object in supernova remnant Cas A) and small-area searches (such as the galactic center). We discuss data analysis constraints and astrophysical issues informing the construction of target lists for initial and advanced LIGO directed searches.

A new type of search

The LIGO Science Collaboration has published several types of searches for periodic signals [see Greg Mendell's talk]. There is another type: directed searches for isolated neutron stars with no observed pulsations. This type of search encompasses point sources of non-pulsed x-rays or γ-rays as well as small sky regions likely to contain previously unseen neutron stars. A search for Cas A is underway [see Karl Wette's talk]. For this and several other targets LIGO can beat the indirect upper limits from photon astronomy even with its current sensitivity!

The indirect limit assumes that the object (1) is emitting in the LIGO frequency band, (2) is spinning down mainly due to gravitational radiation, and (3) has spun down substantially from its birth frequency. Then the quadrupole formula can be manipulated to give (*e.g.*, [1])

$$\boxed{h_{\rm IL} = 2.3 \times 10^{-24} D_{\rm kpc}^{-1} I_{45}^{1/2} a_{\rm kyr}^{-1/2},}$$

where D is the distance to the object, I_{45} is its moment of inertia in units of $10^{45}\,{\rm g\,cm}^2$, and a is the age of the object.

Without pulsations to guide us, we search over the gravitational wave frequency f and its first and second time derivative. This is feasible with a computer cluster only if we have the sky location narrowed down to one or a few "pixels" in LIGO's sky map. The computational cost scales as f^3T^7, where T is the time spanned by the data segments. Searching up to 300 Hz we can afford T up to about two weeks for a single coherent integration. The 95% confidence threshold for detection is

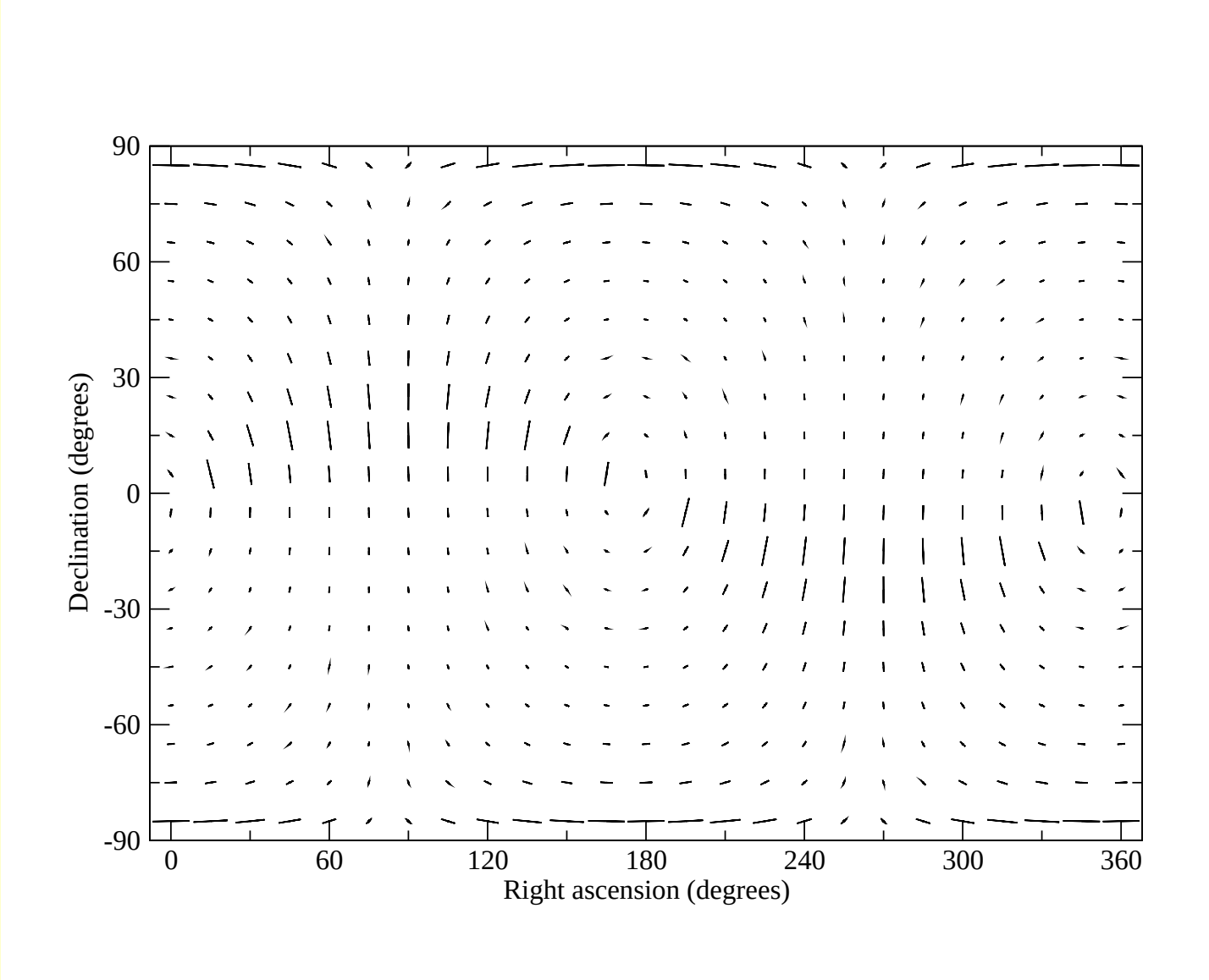
$$\boxed{h_{95\%} \approx 30\sqrt{S_h(f)/T_{\rm dat}},}$$

where S_h is the strain power spectral density and $T_{\rm dat}$ is the live time of the data within T. The statistical factor in front varies from search to search but is usually about 30 for a wide parameter search [1]. Thus a two-week search can achieve $h_{95\%} < 10^{-24}$ over about a 100 Hz band.

In the future we can search longer data sets by incoherently combining short coherent integrations with "hierarchical" techniques (*e.g.*, [2]). This greatly reduces the computational cost, but the sensitivity improves only as $T_{\rm dat}^{1/4}$ beyond the coherent integration time. Thus we could further reduce $h_{95\%}$ by a factor two or more using the whole S5 data set.

LIGO pixel size

The LIGO "pixel size" or directional sensitivity is determined by how much the Doppler shift due to the instrument's motion changes with sky position. We define a pixel as the region where we lose less than 20% power due to correcting for the wrong Doppler shift. Pixels are roughly elliptical, with axis size scaling as $1/(fT)$ in each direction [3].



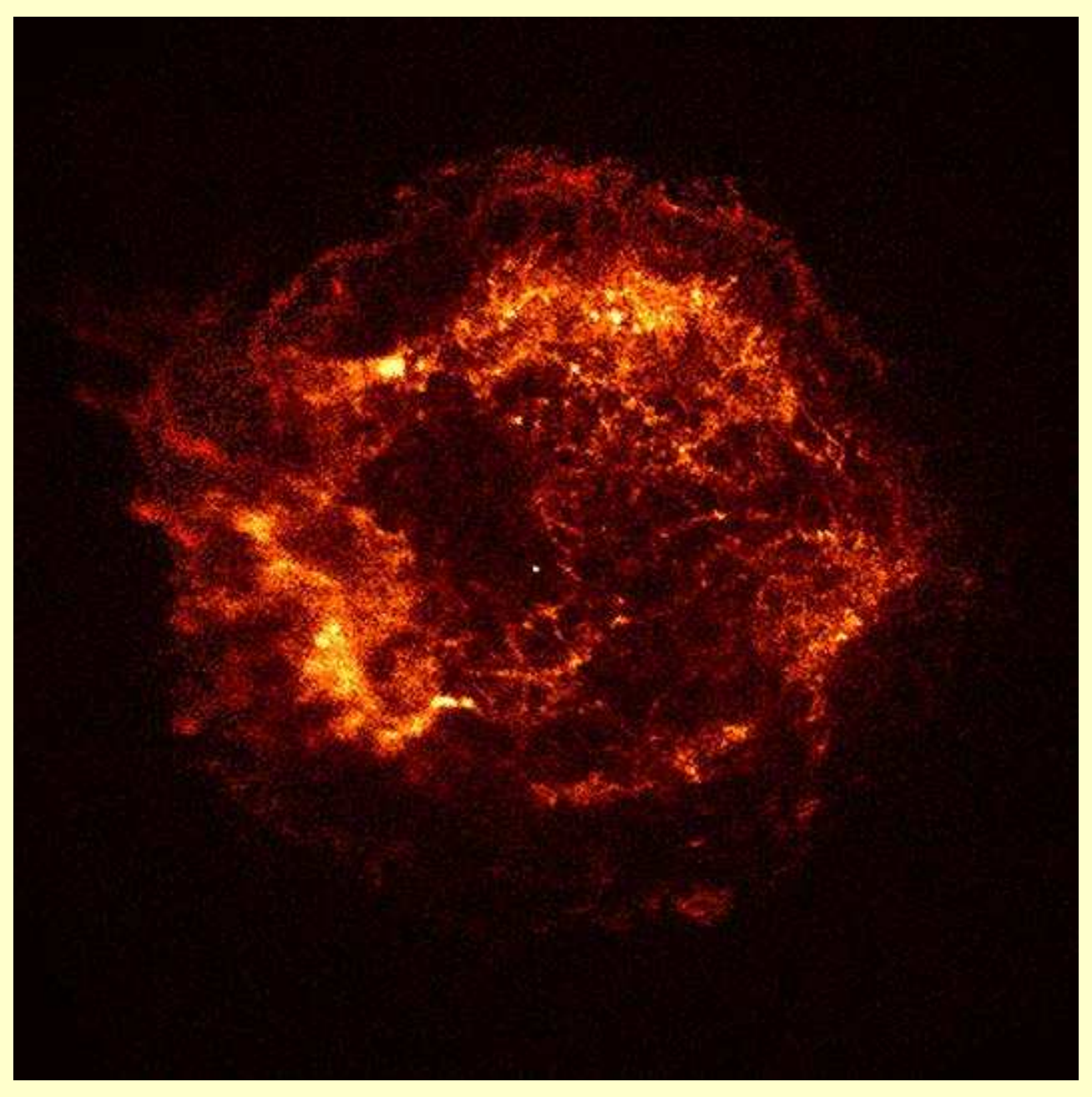
For most sky locations the semiminor axis is about 0.8–2.2 arc minutes and the semimajor axis is 0.5–2 degrees. Thus many pulsar wind nebulae and globular cluster cores can be covered by one pixel or a few pixels for two-week observations. Year-long observations require sub-arcsecond resolution, available only for x-ray point sources localized with Chandra.

Point searches

Several objects are localized to arc second accuracy and thus feasible even with long hierarchical searches. Here are some highlights:

Cas A (the youngest in our galaxy)

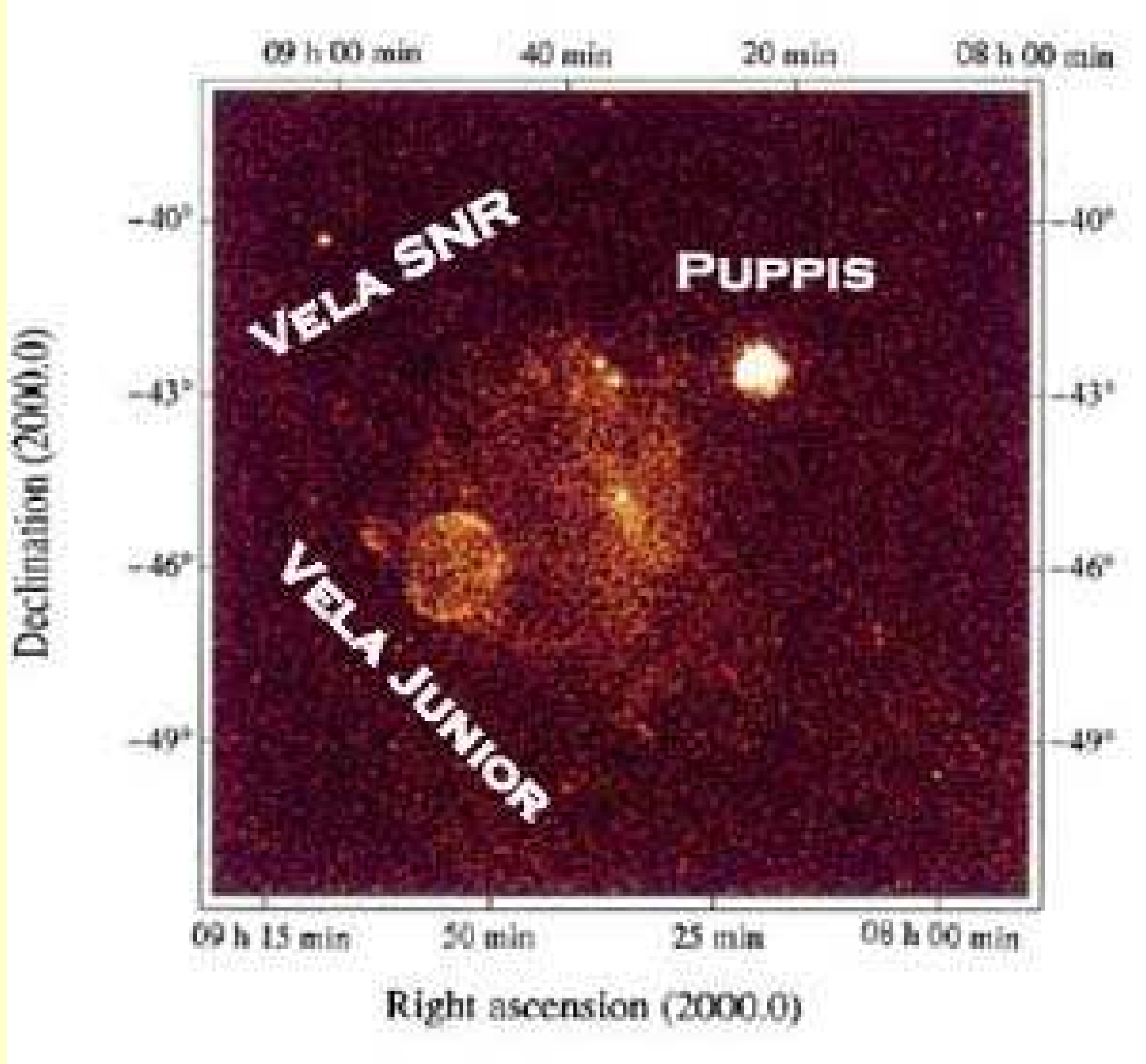
The point source at the center of the remnant was discovered with the Chandra X-ray Observatory's first observation.



Spectral studies of the remnant indicate a distance of 3.4 kpc and age of about 325 years [4]. Thus $h_{\rm IL} = 1.2 \times 10^{-24}$, comparable to the Crab. As the youngest such object, Cas A might be expected to be the most mountainous and thus the best source.

Vela Junior (the closest)

Behind the Vela remnant lie the smaller Vela Junior and Puppis A remnants, both of which contain central non-pulsing x-ray point sources.



The object in Vela Junior could be 480 pc away and 680 yr old [5] for an indirect limit $h_{\rm IL} = 5.7 \times 10^{-24}$. This is larger than $h_{\rm IL}$ for Cas A, but much more uncertain.

SN 1987a (the youngest?)

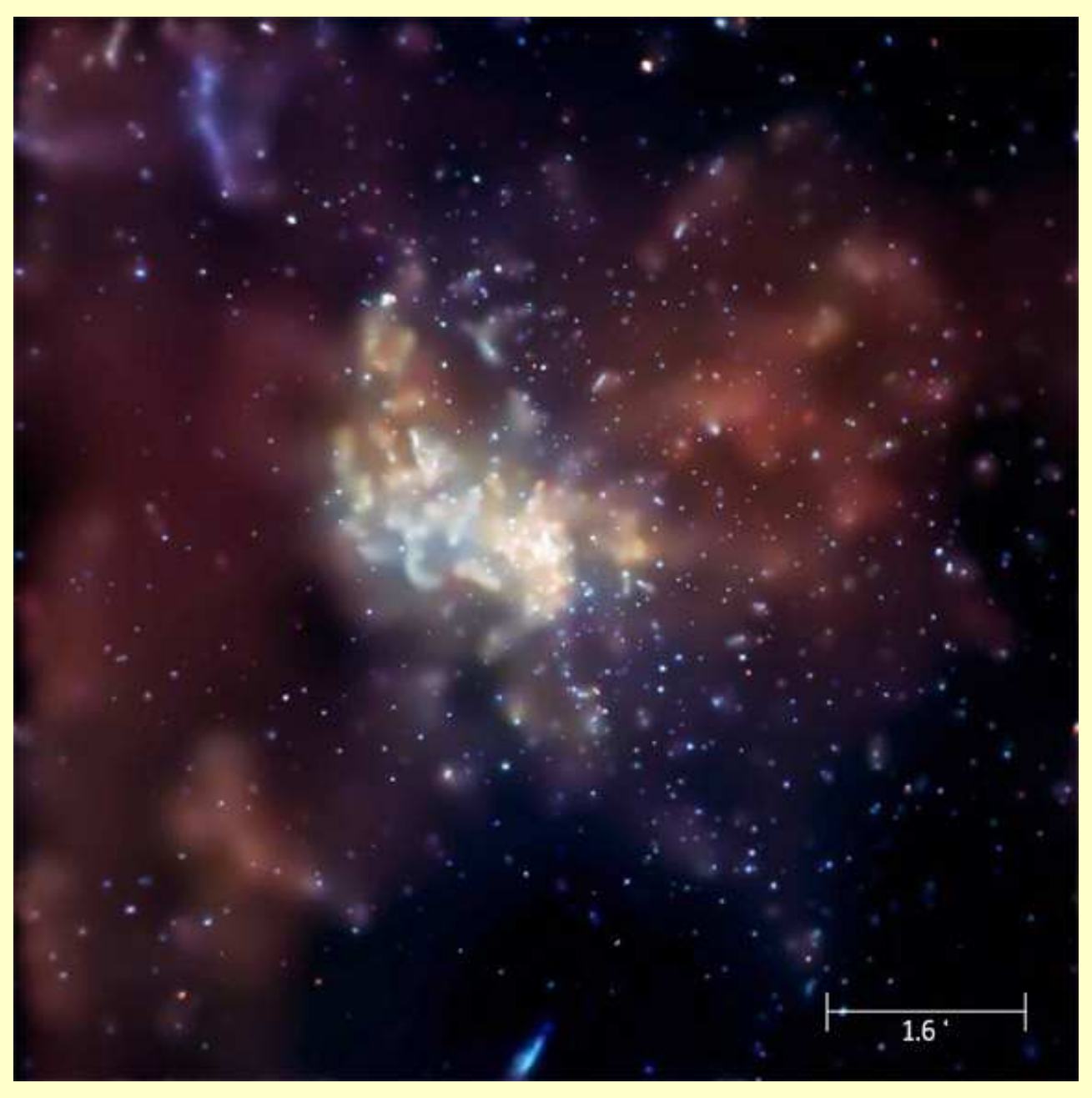
A neutron star may be hidden behind the ejecta of the most recent local supernova (in the Large Magellanic Cloud). At 20 years old, it could still be highly deformed and radiating strongly.

The distance of 50 kpc means $h_{\rm IL} = 3.2 \times 10^{-25}$, unattainable by initial LIGO. It is a tempting target for advanced LIGO if the problem of searching an enormous parameter space can be resolved.

Small-area searches

Galactic center

There are a lot of hot blue stars near the central black hole [6] 8 kpc away which must be making young neutron stars.



Initial LIGO has a shot at any that formed within 100 yr or so.

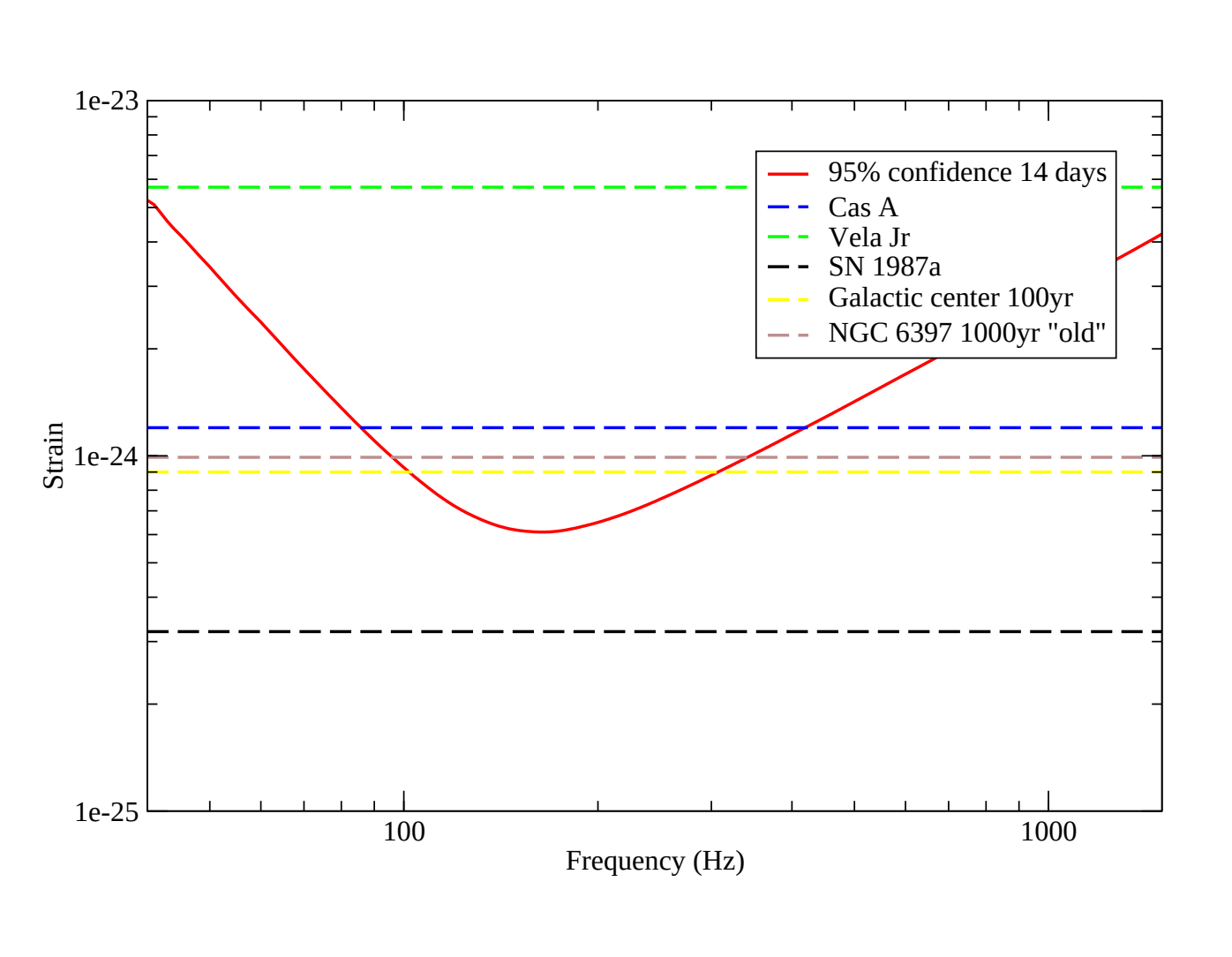
Globular clusters

These are full of old neutron stars interacting with other objects in crowded conditions. Some have planets and may occasionally accrete them, thus "rejuvenating" for our purposes.

M4 and NGC 6397 are 2 kpc away, so LIGO could see the aftermath of impacts up to about 1000 yr ago.

Conclusions

Initial LIGO can beat the indirect limits with several directed searches.



Emission at these limits would require a quadrupole more than 10^{-5} times the moment of inertia [1]. This is possible in the most speculative theories of dense matter [7], and thus LIGO can soon start confronting these theories with observations.

References

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