Search For Scalar Polarized Gravitational Waves

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Abstract.

According to Einstein's Theory of General Relativity, gravitational waves have two polarizations, plus and cross. In other contrasting theories, such as Brans-Dicke, gravitational waves can have up to six different types of polarization. One of the most common extra modes is the scalar or "breathing" mode, which is a transverse mode that stretches space equally in all directions transverse to the direction of propagation. Unlike the plus/cross modes, it could be emitted by spherically symmetric systems like core-collapse supernvoae. The focus of this paper will outline a search for the theorized breathing (scalar) polarization mode of gravitational waves from supernovae. Similar searches for scalar modes were conducted simaltaneous to our supernovae search and provided evidence that an independent search may be necessary for supernovae, gamma-ray bursts (GRB), and other position specific astrophysical phenomena. The algorithm used to conduct this search is X-Pipeline, which is a software package for the coherent analysis of data from networks of interferometers for detecting bursts associated with supernovae and other astrophysical triggers. A modified version of X-pipeline searches for scalar mode waveforms that could be coming from supernovae. The supernovae chosen for this search were SN2006iw and SN2007gr. Similar searches for scalar modes were being conducted simulataneously and provided evidence that an independent scalar search may be necessary for supernovae, gamma-ray bursts, and other position specific astrophysical phenomena. The results of the supernovae search and future plans for indepedent scalar mode search are highlighted at the end of this paper.

1. Introduction

The general theory of relativity predicts that all accelerating objects with non-symmetric mass distributions produce gravitational waves (GWs). LIGO (the Laser Interferometer Gravitational-Wave Observatory) [1] and Virgo [2] experiments seek to directly detect GWs and use them to study astrophysical sources. Beginning in 2011, the detectors expect to undergo upgrades, known as Advanced Virgo (AdV) and Advanced Ligo (aLigo), to improve their distance sensitivity by one order of magnitude [3].

Gravitational-wave bursts (GWBs) are a class of signals being sought by the new generation of GW detectors. Possible sources for these bursts include core-collapse supernovae [4], gamma-ray bursts [5], and other relativistic systems. These systems typically have very strong gravitational fields, making GWBs potential sources of information on relativistic astrophysics.

Unfortunately, the analysis of GW data tends to be a slow process. The rapid analysis of GW data is not trivial, particularly given the non-stationary nature of the background noise in GW detectors and the lack of accurate and comprehensive waveform models for GWB signals. Specifically, we need methods capable of detecting weak signals with a priori unknown waveforms, yet which are simultaneously insensitive to the background noise "glitches" that are common in data from GW detectors. These glitches can include anything as trivial as a car passing by the detector or as nontrivial as an earthquake in the area. Glitch rejection is particularly important since it is the limiting factor in the sensitivity of current burst searches, and a confident detection of a GWB will depend critically on robust background estimation. X-pipeline software package is a solution to all of these data analysis issues as it accounts for glitches, it self-tunes, and it finishes fairly rapidly.

The standard version of X-Pipeline focuses on detecting the be used to detect cross and plus polarization of GWs predicted. With a few modifications, however, the code can be used to search for other non-GR waveforms such as breathing (scalar) polarizations. The goal of this project was to search the supernovae for this polarization mode. We inject into the data simulated scalar waveforms and then see if the code can detect the scalar polarized GW. Some important factors go into this, such as time of day, sky position, and coverage of the detectors. This is because at certain angles, the scalar mode would be very weakly detected by the detectors. This measurement is, in fact, 0 at an angle of 45 degrees between the detectors arms. Ideally, the GW would be coming straight on at one of the detector arms for the best measurement.

Another important facet of this project is the comparison of the efficiency of the scalar mode search on the supernovae to the GR search on the supernovae. More specifically, we determine whether the scalar mode search detects the scalar injection waveforms more efficiently than the regular GR search does. Research has been done on this by the LIGO-Virgo All-Sky Search team and has produced some interesting results that relate to the importance of this project. This is important in determining the necessity of a dedicated scalar search on the LIGO/VIRGO data or whether current searches are efficient enough to detect the scalar polarization.

Section 2 discusses in brief the tool used when analyzing data, i.e. X-pipeline and basic principles of data analysis for GW bursts. Section 3 describes test all-sky scalar mode searches by the all-sky team, which motivates our work, while section 4 summarizes the analysis done on the supernovae. Section 5 presents our conclusions.

2. X-pipeline

This section details the important facets of the X-Pipeline algorithm used in the scalar supernovae search.

2.1. Method for GWB detection

X-pipeline looks for any bursts of excess power that might be caused by a GW. Also, X-Pipeline eliminates much of the background noise and the glitches. It is important to note that currently the cuts made on the background noise are not ideal as of yet. The false alarm rate of the analysis that is generally used is either -p 99-99 or -p 98-98. This means that our stated efficiencies are for a false alarm probability of 1 or 2 perccent. This means that there is a 1 or 2 percent chance that a background event would survive the cuts used to make the efficiency curves. To claim evidence for a GW in a publication, we would want to see an even better with a false probability of less than 0.3 (3-sigma), so the efficiency at this higher threshold would be a little worse than the results we currently have but not dramatically. Continued work on this project will look to increase the percentage threshold used in the background cuts.

The X-Pipeline package is an impressive and comprehensive analysis tool. X-Pipeline targets GWBs associated with external astrophysical 'triggers' such as gamma-ray bursts (GRBs) and has been used to search for GWBs associated with more than 100 GRBs that were observed during S5-VSR1 [6]. It performs a fully coherent analysis of data from arbitrary networks of GW detectors, while being robust against noise-induced glitches. We emphasize the novel features of X-Pipeline, particularly a procedure for automated tuning of the background rejection tests. This allows the analysis of each external trigger to be optimized independently, based on background noise characteristics and detector performance at the time of the trigger, maximizing the search sensitivity and the chances of making a detection. This tuning uses independent data samples for tuning and estimating the significance of candidate events, for unbiased selection of GWB candidates. X-Pipeline can also account automatically for effects like uncertainty in the sky position of astrophysical trigger and detector calibration uncertainties [7].

Most algorithms currently used in GWB detection can be grouped into two broad classes. In incoherent methods [8, 9], candidate events typically are constructed from each detector data stream independently, and one looks for events with similar duration and frequency content that occur in all detectors simultaneously. By contrast, coherent methods [10, 8] combine data from multiple detectors before processing and create a single list of candidate events for the whole network. Coherent methods have some advantages over incoherent methods, such as demonstrated usefulness in rejecting background noise 'glitches' [10, 11, 12] and for reconstructing GWB waveforms [13, 14]. A less-recognized advantage of coherent methods is that they are relatively easy to tune. For example, time-frequency coincidence windows for comparing candidate GWBs in different detectors are not necessary. Detectors are naturally weighted by their relative sensitivity, so there is no need to tune the relative thresholds for generating candidate events in each detector. This ease of tuning makes coherent methods particularly useful for rapid searches [7]. The scalar search falls under the category of the coherent search method.

Provided below in Figure 1 is a graph which highlights an example of how X-Pipeline makes its cut of background noise. This also highlights an example of incoherent method and coherent method. The incoherent being marked by an "I" on the y-axis of the graph. As you can see the cut is very good and keeps most of the injected GWB signals while only retaining about 2 percent of the background noise.

3. All-Sky Search

In this section, I give a brief overview of the All-Sky Search and the research and conclusions that pertain to the scalar analysis of supernovae that I conducted this summer. The work dscribed in this section was conducted by Scott Sullivan and Peter Shawhan (University of Maryland) and Gabriele Vedovato (INFN).

3.1. Brief Overview

The All-Sky team searches the whole sky looking for loud signals that could be potential GWBs. The basic principles of maximum likelihood analysis are very similar to that of X-Pipeline. This is why the scalar versus GR analysis done by the group was very helpful in understanding the importance of the same search we were conducting on the Supernovae and GRBs.

3.2. Scalar Versus Tensor Analysis

A modified version of Coherent Wave Burst (CWB) was produced by Gabriele Vedovato to look for scalar injections. Both the original and modified versions of CWB were run

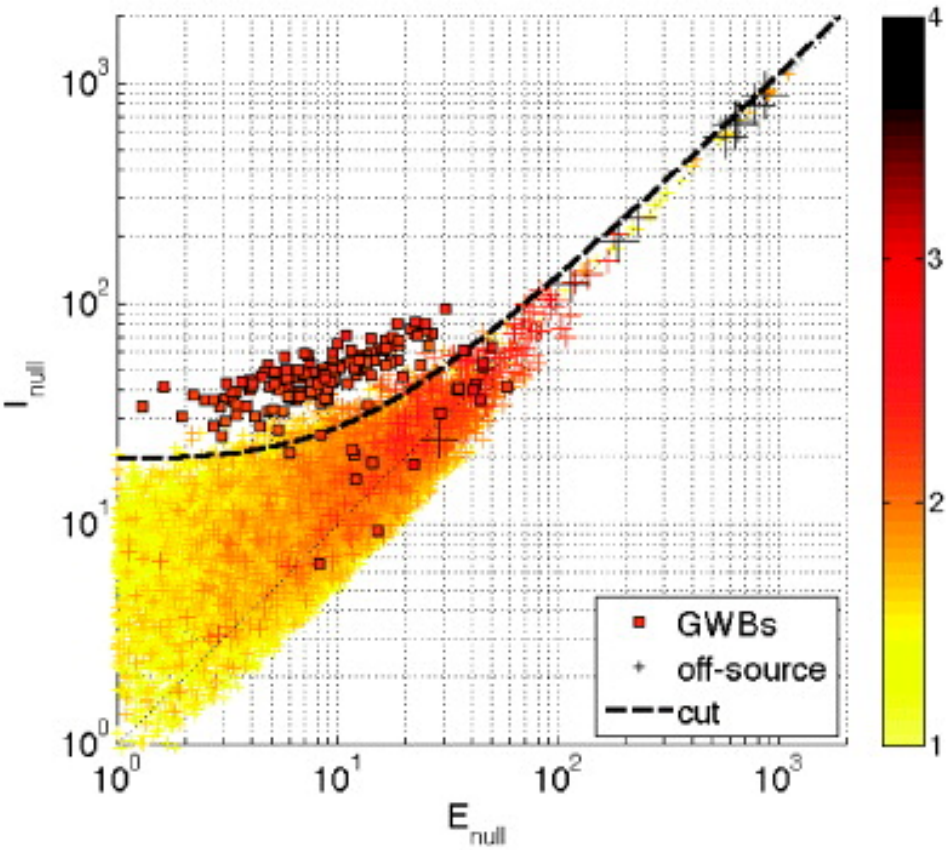

Figure 1. Inull versus Enull for clusters produced by background noise (+) and by simulated gravitational-wave signals (square). The colour axis is the base-10 logarithm of the cluster significance S . Loud glitches are vetoed by discarding all clusters that fall below the dashed line [7].

with scalar injections. This meant that both a scalar and GR search were done on the scalar injected waveforms. The detection efficiencies and "sky localization" reports are compared below [15].

The tensor and scalar versions of CWB had similar detection rates of the scalar injections. Shown below in Figure 2 are detection efficiencies for waveforms which are Gaussian (GA), Sine Gaussian Q9 (SGQ9), and White Noise Burst (WNB). It is important to note that the efficiencies curves do not account for how accurately the code can locate where the waveform is coming from in the sky.

Shown below in figure 3 are probability skymaps for two individual simulated scalar signals. These are the maps of the estimated probabilty that the signal came from any given direction on the sky, as estimated by CWB. The white star is the source direction, and the black star is the reconstructed direction. The scalar CWB is significantly better at finding the source locations than the tensor CWB. Not only does the scalar version pinpoint the correct location more often, but the probability is concentrated into smaller regions. The white star is the source direction, and the black star is the reconstructed

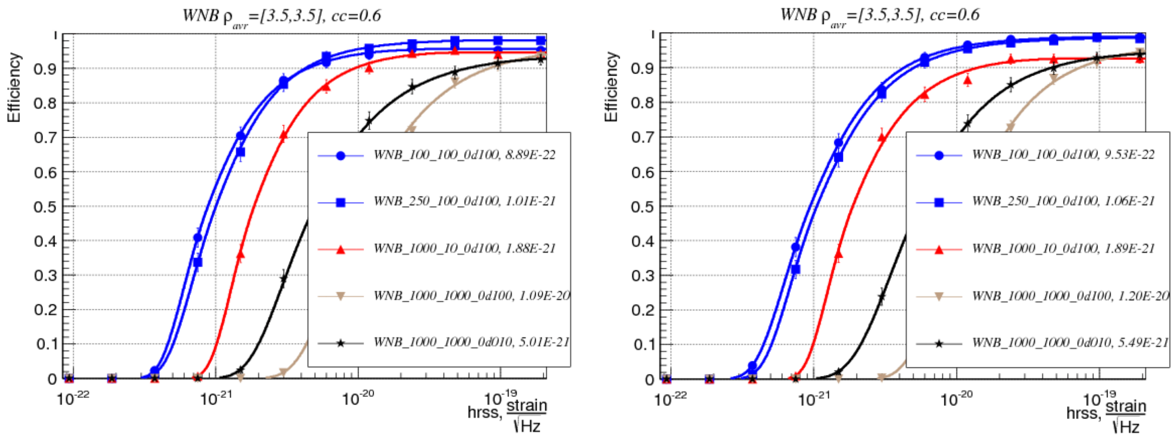

Figure 2. Left: The efficiency of the tensor (GR) search at detecting the scalar polarization of the scalar injections. Right: The efficiency of the scalar search at detecting the scalar polarization of the scalar injections [15].

direction. This difference in location occurs because during the GR search there is a location (not necessarily anywhere close to the actual location) in the sky where the plus and cross polarizations look just like the breathing polarization.

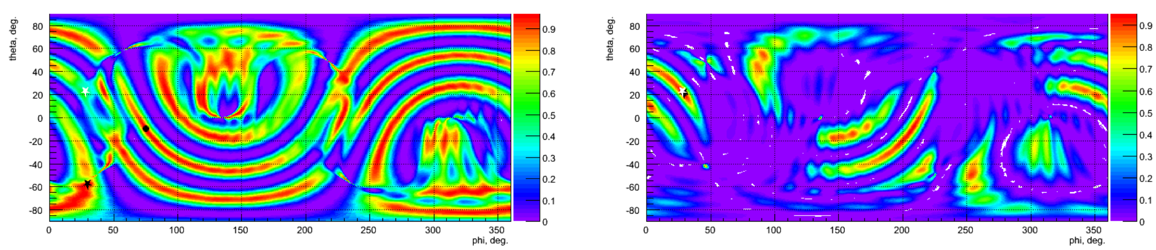

Figure 3. Left: The probable source location of the scalar GW accoridng to the Tensor (GR) search. Right: The probable source location of the scalar GW according to the scalar search [15].

In conclusion, the search had two clear statements to make concerning a dedicated scalar search versus the GR search. As far as the All-Sky search team is concerned, a dedicated scalar search appears unnecessary as the GR search could pick up the scalar polarization nearly as efficiently as the scalar search. However, when determining the location of the scalar signal in the sky the GR search was at times very off in locating the source of the signal. On the contrary, the scalar search was very accurate when determining where the signal most likely was detected, i.e. at the source itself. The latter of the two discoveries was unimportant to the All-Sky Search as position was not crucial since the entire sky is searched. However, if you were searching an event of which the position is very specific in the sky such as a supernovae or gamma-ray burst then the GR search may not be helpful or not nearly as efficient. This is the goal of the scalar search of supernovae to determine whether the GR search can detect scalar polarizations as efficiently as a dedicated scalar search when dealing with position specific astrophysical phenomena. The next section provides the results of this search.

4. Scalar Search of Supernovae

Here, I present the modifications to the X-Pipeline algorithm and the subsequent scalar and GR analysis of the supernovae SN2006iw and SN2007gr.

4.1. Choice of Scalar Waveforms

The picture below demonstrates the various theorized polarizations. As you can see the scalar polarization is the simplest type. It simply scales the wave by some factor.

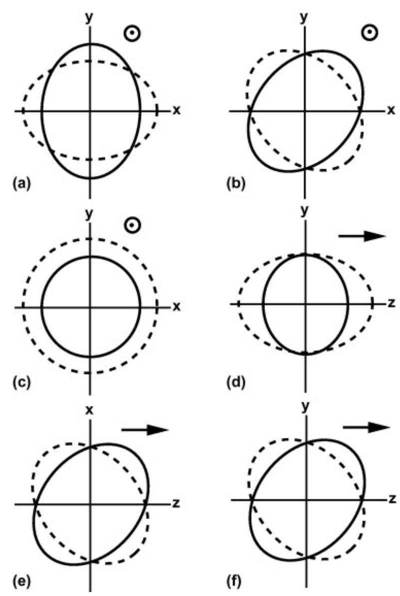

Figure 4. a.) Plus polarization b.) Cross Polarization c.) Scalar Polarization d.) Longitudinal Polarization e.) x-vector f.) y-vector [16].

As to what a potential scalar polarized waveform could look like, we decided to inject two types of scalar waveforms. One waveform that was theorized by A. Nishizawa, A. Taruya, K. Hayama, S. Kawamura, and M. A. Sakagami [16].

4.2. Choice of Supernovae

There are three main criteria for choosing these supernovae. The first is a relatively small on-source window and good detector coverage. To find the small on-source window requires a bit of good luck because it requires a telescope to be pointed at the same location in the sky within about 3-5 days of the original picture of the sky. Not only

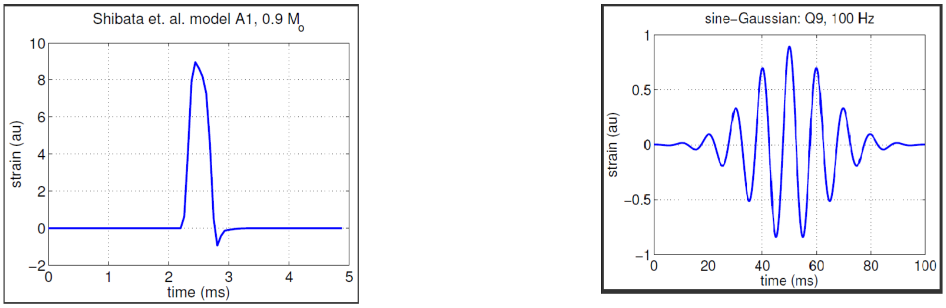

Figure 5. Left: Theoretical SNN scalar waveform caused by dust collapsing into a black hole and then being shot back out. Right: A standard scalar chirplet waveform [15].

that but it requires in the second shot there is, in fact, a supernovae and in the picture 3-5 days prior there is nothing. Good detector coverage is also a bit tricky. The 2006iw and 2007gr were going on during the S5 LIGO science run. LIGO science runs are periods of time where they keep all detectors on as much as possible while occasionally shutting them down to make updates and other repairs as necessary. Below is a picture of the "on-times" of the various GW detectors. As you can see from the graph, these two supernovae had good coverage time.

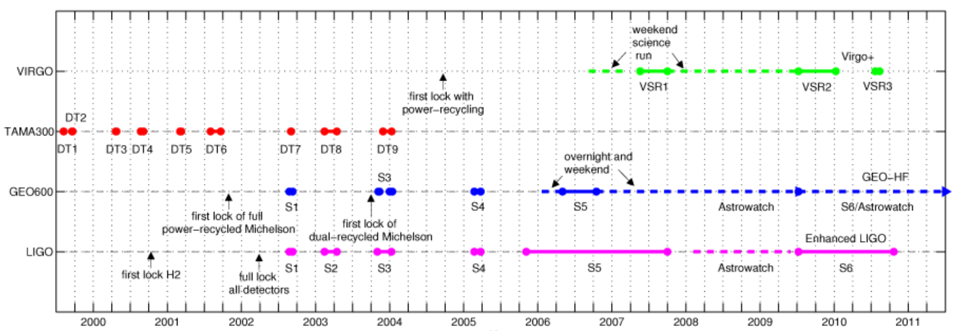

Figure 6. The detector coverage times versus peak GR responses times. Red line is time detector was on and 1 represents excellent GR response from the detectors [17].

The second criteria is that it be a type II or type Ib/c supernova. These are the types of supernovae believed to most likely contain GWBs. Along with the right type a supernovae that is close is also preferable. The third criteria for our search is good scalar polarization coverage time. The picture below demonstrates the difference in peak scalar response times and peak GR response times.

The GR coverage times all appear to be just fine for these four supernovae. When looking at the scalar response times, however, a few of the supernovae must be thrown out.

The detectors display such varying times of peak response for GR and scalar because

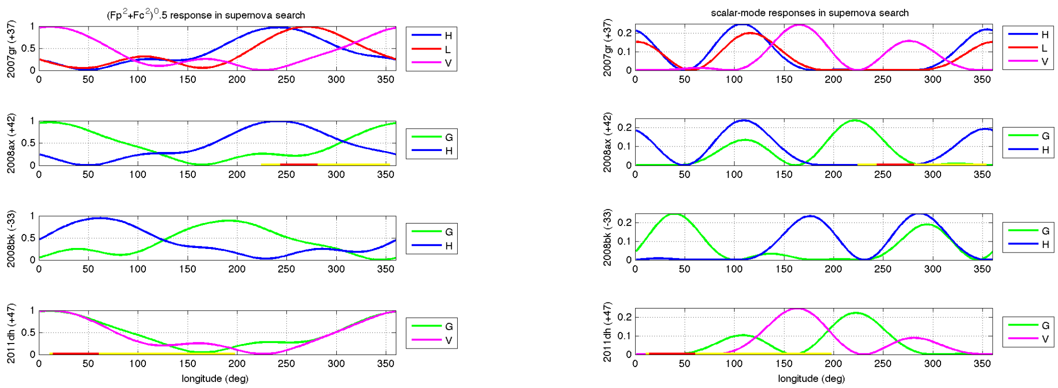

Figure 7. Left: The detector coverage times versus peak GR responses times. Red line is time detector was on and 1 represents excellent scalar response from the detectors.In SN2008ax and SN2011dh, there is limited coverage during peak scalar response times which would lead us to expect to not detect any scalar polarizations even if they occured during that time. [17].

certain angles at which the GWs comes in at the detector cause maximum and minimum response. A 45 degree angle of entry will result in a repsonse of zero from the detectors but a entry angle straight down one of the tubes of the detectors will result in a peak response from the detectors. The antenna response equations for the detectors are given in the pciture below. As you can see an angle of 45 degrees for scalar (and the cross and plus) will result in a response of zero and thus no detection.

$$F_+(\theta,\phi,\psi) = \frac{1}{2}(1+\cos^2\theta)\cos 2\phi\cos 2\psi - \cos\theta\sin 2\phi\sin 2\psi \ , \tag{3}$$

$$F_\times(\theta,\phi,\psi) = -\frac{1}{2}(1+\cos^2\theta)\cos 2\phi\sin 2\psi - \cos\theta\sin 2\phi\cos 2\psi \ , \tag{4}$$

$$F_x(\theta,\phi,\psi) = \sin\theta\left(\cos\theta\cos 2\phi\cos\psi - \sin 2\phi\sin\psi\right) \ , \tag{5}$$

$$F_y(\theta,\phi,\psi) = -\sin\theta\left(\cos\theta\cos 2\phi\sin\psi + \sin 2\phi\cos\psi\right) \ , \tag{6}$$

$$F_b(\theta,\phi) = -\frac{1}{2}\sin^2\theta\cos 2\phi \ , \tag{7}$$

$$F_\ell(\theta,\phi) = \frac{1}{\sqrt{2}}\sin^2\theta\cos 2\phi \ . \tag{8}$$

Figure 8. The equations for the detector response to the varying theorized polarizations. As you can see scalar is zero with an angle of [10].

The following graphs below give an idea of what angles create the best response for both the GR and scalar modes. We are aiming for angles of entry with respect to the arms of the detectors that correspond to the red area on the graphs.

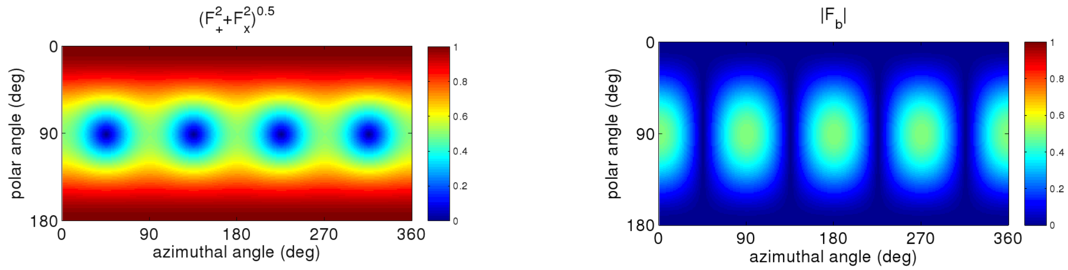

Figure 9. Left: The GR response of the detectors based on the angle of the gravitational wave with respect to the detectors. Left: The scalar response of the detectors based on the angle of the gravitational wave with respect to the detectors.

4.3. Supernovae Search Results

The supernovae search produced results as we had anticipated. It efficiently detected the two scalar mode injections and made nice cuts. In the pictures below, you can see the cut and efficiency of the scalar chirplet injections SNN94 and the scalar chirplet as analyzed by the dedicated scalar search.

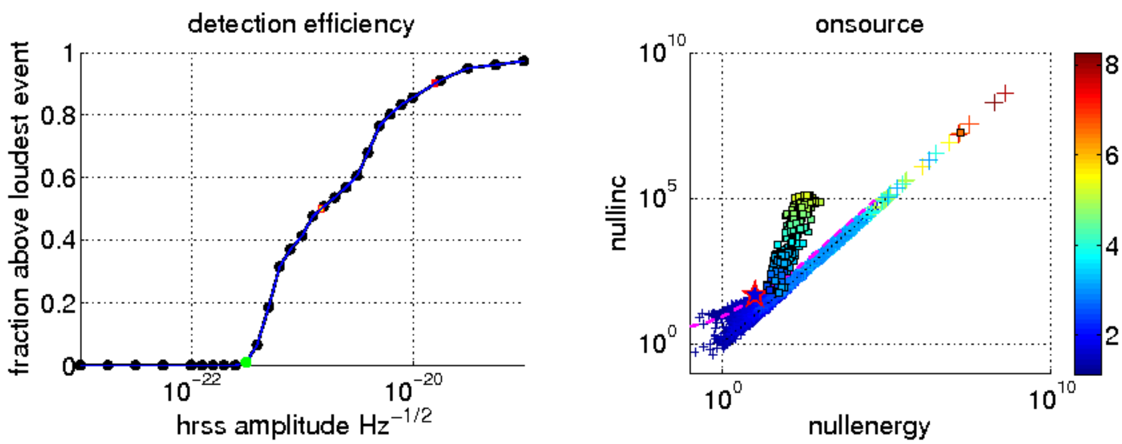

Figure 10. Left: The effeciency of the scalar search at detecting the scalar chirplet injected waveform. Right: The cuts made by the dedicated scalar mode search. There is a 99 percent cut rate. That means that about 1 percent of background noise is still present after the cuts are made.

On the other hand, doing the GR search on the same injections produced the following results.

It appears as if the conclusions of the All-Sky Search team were correct. The GR search is not a efficient enough search for scalar modes when searching source position specific astrophyscial phenomena such as supernovae and GRB. The dedicated scalar mode search is considerably more efficient than the GR search.

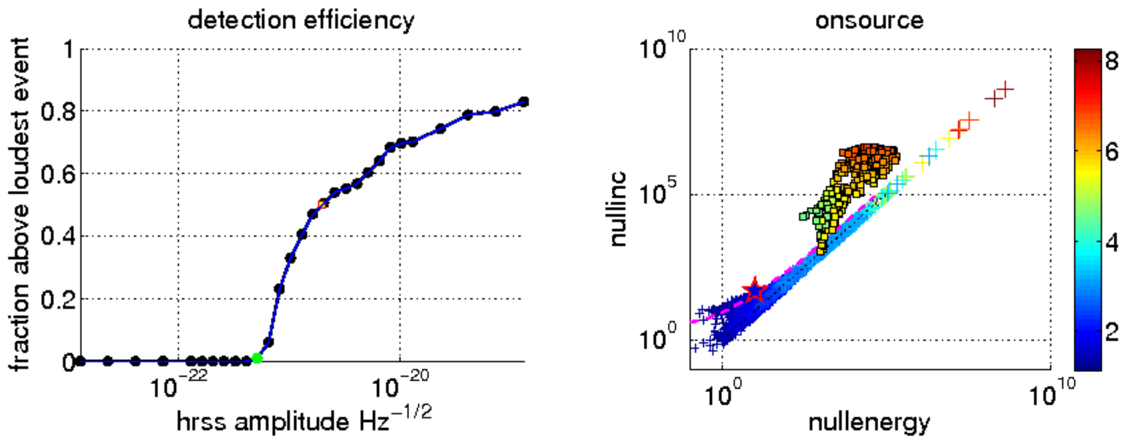

Figure 11. Left: The efficiency of the GR search at detecting the scalar chirplet injected waveform. Right: The cuts made by the dedicated scalar mode search. There is a 99 percent cut rate. That means that about 1 percent of background noise is still present after the cuts are made.

5. Conclusion

In conclusion, the search was a success. At the outset of the project we believed that doing a dedicated scalar search would prove to be a fruitful endeavor instead of just doing a GR analysis. The All-Sky search team's results from there GR versus Scalar analysis on scalar injected waveforms provided us with extra evidence to support our belief. Although in the All-Sky search the efficiencies were very similar, the location error in the GR code leads us to believe that when searching position specific phenomena that the GR search would not be nearly efficient enough at detecting the scalar injections. After modifying the code to look for the scalar polarization and running the search on the two Supernovae, these hypothesize were proved correct. It does appear that although the GR can still detect the scalar mode, it is not nearly efficient enough. Continued work does need to be done on this search. As mentioned earlier, the threshold is too low for the background noise cuts in terms of what is acceptable for claiming a real discovery. Therefore, I will increase the threshold to reach levels which are closer to the ideal threshold cuts in order to make a claim of discovery.

I believe that given the quickness with which a scalar search can be done, a dedicated scalar search on Supernovae and GRBs is recommended. This is an important discovery because it means that future work should be done to figure out the efficiency on the GR analysis on the other theorized polarization modes. It is important to look outside the conventional belief of the validity of GR and explore other theories. This analysis shows that to do that search properly on Supernovae and GRBs that a dedicated search of that polarization is necessary and we cannot just rely on the GR search. I look forward to seeing what future work is done regarding non-GR theories in the LIGO and VIRGO collaboration and elsewhere in scientific research.

Acknowledgments

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