Prospects for a Joint Supernova Search Between KamLAND and LIGO

Emmett Krupczak
Advisor: Lindley Winslow
Massachusetts Institute of Technology

Introduction

Core-collapse supernovae are extremely hard to detect. SNEWS has not detected any supernovae since 2005. Except for the famous SN1987A supernovae, Super Kamiokande has not detected any evidence of supernova explosions [7]. A search of KamLAND's data for ≥ 7.5 MeV neutrinos uncovers no neutrino bursts. Our best chance for detecting core-collapse supernovae comes from detecting the neutrinos or gravitational waves emitted by the explosion. Neutrino-only searches have largely come up empty. Searches by LIGO, Virgo and GEO600 collaborations using gravitational-wave data alone have not uncovered any gravitational wave (GW) signatures of supernovae [6][5]. Our best chance of detection comes from a joint search, combining both weak signals to increase our noise-tolerance and lower the false alarm rate.

Supernovae Search with KamLAND

- Chose a neutrino energy threshold of 7.5 MeV
- Found 65 events between 11 Nov 2002 and 4 June 2013.
- Looked for events occurring within a 10-second window.
- No such bursts were found. Shortest delay between subsequent neutrino events was 74686 seconds ($\sim$ 20.7 hours).

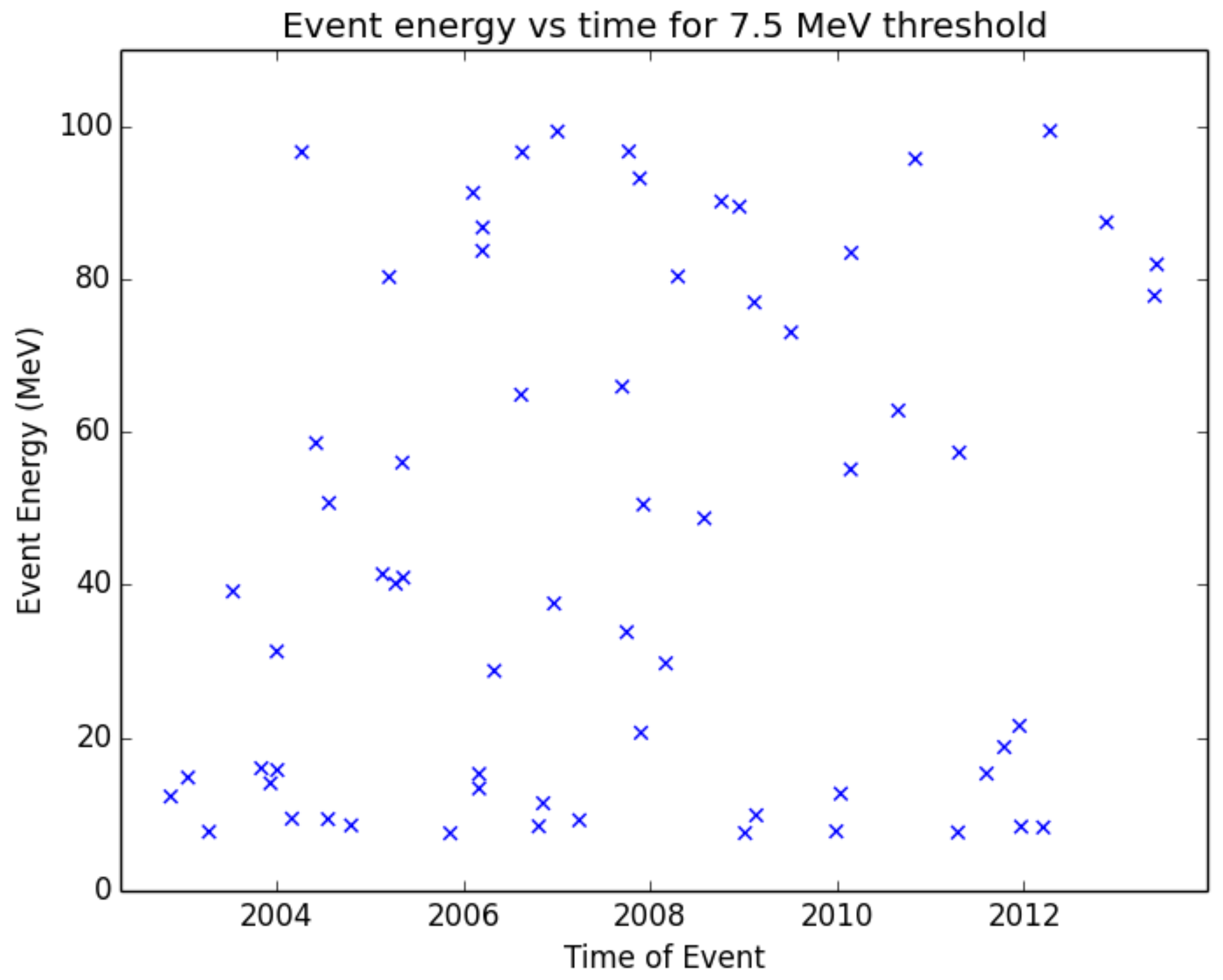

Figure 1: Candidate neutrino events, plotted by energy and time [9].

Choice of Candidate Neutrino Events

When choosing candidate neutrinos for a joint study, we must choose a threshold which includes the majority of supernovae neutrinos, but excludes other neutrino sources like geoneutrinos and reactor neutrinos.

The expected distribution of neutrino energies from a core collapse supernovae is shown below. For this study, we chose a threshold of 7.5 MeV.

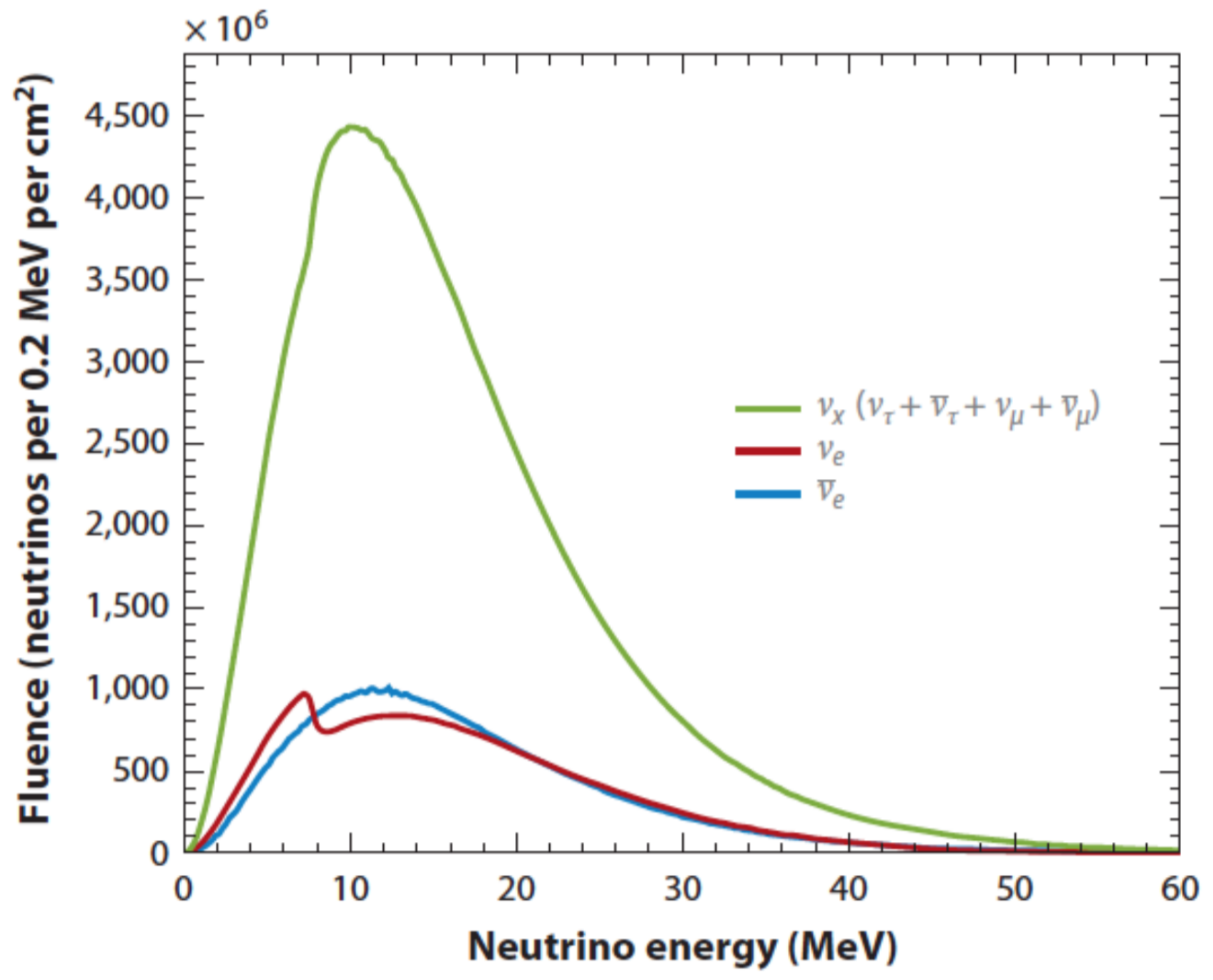

Figure 2: Expected supernovae neutrino spectrum, separated by flavor. Spectrum is integrated over 10 seconds [9].

Benefits of a Joint Search

1. Lower false alarm rate
2. Can consider single-neutrino events
3. Better characterization of supernovae because neutrinos and GW carry different kinds of information

LIGO's Data

In order to perform a multimessenger search for core-collapse supernovae, a triggered search would be performed on LIGO's data using neutrino events as the triggers. Such a search looks for GW events over a period of time spanning the approximate expected discrepancy in arrival time between neutrinos and gravitational waves, which is usually between 0 and 20 seconds.

A triggered GW event contains the following information:

- Time stamp of event in three detectors (can use to triangulate event location).
- Signal-to-noise ratio, ρ.
- Root-mean-squared strain amplitude, h_{rss}, in each detector.
- Frequency of potential gravitational wave
- Spherical coordinates (θ, ϕ) and R.A./Dec denoting locations in sky.
- Probability of event originating from each designated location of sky.

The sensitivity of LIGO depends on the desired threshold for signal to noise ratio, ρ. To account for the non-Gaussian nature of the noise, time-shift analysis is used to generate a sample background for use in computing ρ [8].

Time-Shift Analysis of Background

- GW background is non-Gaussian and non-stationary [10].
- Cannot shield detector from GW.
- Combine time-shifted data from multiple detectors to scramble GW signals and produce estimated background [2].

Time-shift step size is greater than the time of flight between detectors (~ 30 ms) and the coherence time scale of the detector noise (a few seconds) [2].

Determining Location of Source

A LIGO triggered event includes spherical coordinates (θ, ϕ) and R.A./Dec denoting locations in sky, and the probability that the event originated from each marked location.

The scatter plot below shows the likely location of a sample event.

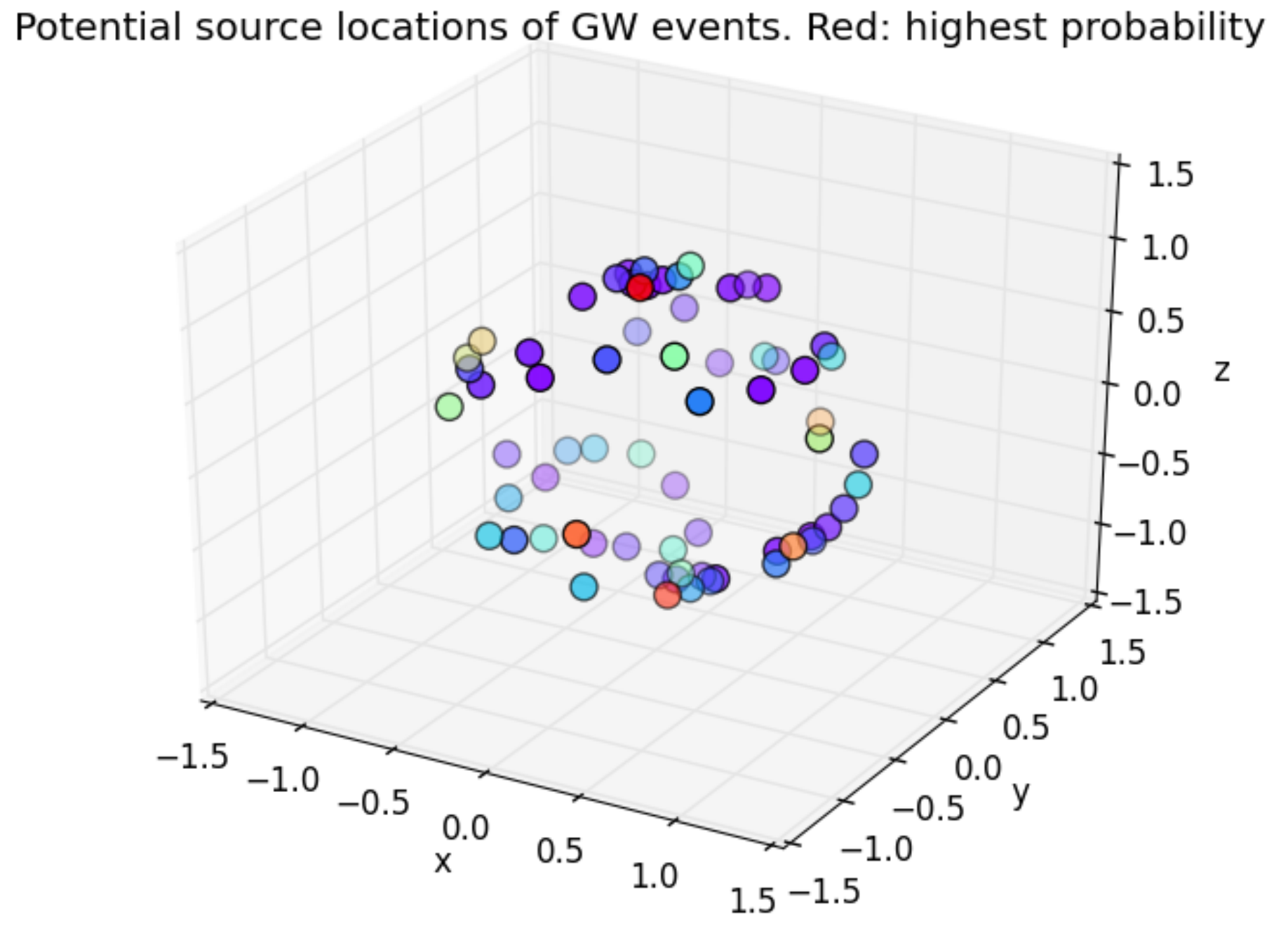

Figure 3: Possible trigger event locations, with the higher probability locations denoted by redder colors and the lowest probability locations denoted by the purple colors. The highest probability pixel, denoted by the red point, has a probability of 6.69×10^{-2}. The lowest probability pixel, denoted by purple, has a probability of 6.91×10^{-4}. The probabilities of each location sum to one.

The probable location of event should align with the galactic disk. If available, directional information about the neutrino source event could also be considered.

Outline of a Joint Search

1. Choose candidate neutrino events from KamLAND's data.
2. Determine the threshold for identifying a GW event in LIGO's data.
3. Perform a triggered search on LIGO data using KamLAND neutrino events as triggers.
4. Determine if any of the gravitational wave events produced by the triggered search meet the criteria to be considered a likely real event.

Joint False Alarm Rate

The joint false alarm rate, R_j, is given by:

$$R_j = R_{GW} \times R_\nu \times w$$

where R_{GW} is the gravitational wave background rate, R_ν is the neutrino background rate, and w is the coincidence window.

The KamLAND neutrino data spans 3.33×10^8 seconds. There are 65 events over the chosen 7.5 MeV threshold. This gives a background rate of:

$$R_\nu = \frac{65 \text{ events}}{3.33 \times 10^8 \text{ sec}} = 1.95 \times 10^{-7} \text{ Hz}$$

A reasonable choice for all-sky gravitational wave search false-alarm rate is [1]:

$$R_{GW} \sim 3.5 \times 10^{-9} \text{ Hz}$$

and we choose coincidence windows of $w = 2$ sec and $w = 20$ sec, we find:

$$R_j(2 \text{ s}) = 3.5 \times 10^{-9} \cdot 1.95 \times 10^{-7} \cdot 2 = 1.37 \times 10^{-15} \text{ Hz}$$

$$R_j(20 \text{ s}) = 3.5 \times 10^{-9} \cdot 1.95 \times 10^{-7} \cdot 2 = 1.37 \times 10^{-14} \text{ Hz}$$

The 20 second coincidence window corresponds to a false alarm rate of 1 event per 2.32×10^6 years.

References

[1] Neutrinos meet gravitational waves: Preparing for the next nearby core-collapse supernova, March 2013.

[2] Éric Chassande-Mottin, the LIGO Scientific Collaboration, and the Virgo Collaboration. Data analysis challenges in transient gravitational-wave astronomy. *AIP Conference Proceedings*, 1535(1):252–259, 2013.

[3] The ANTARES collaboration, the LIGO Scientific Collaboration, and the Virgo Collaboration. A first search for coincident gravitational waves and high energy neutrinos using LIGO, Virgo and ANTARES data from 2007. *Journal of Cosmology and Astroparticle Physics*, 2013(06):008, 2013.

[4] The IceCube Collaboration, the LIGO Scientific Collaboration, and the Virgo Collaboration. Multimessenger Search for Sources of Gravitational Waves and High-Energy Neutrinos: Results for Initial LIGO-Virgo and IceCube. *Phys. Rev. D*, 90:102002, Nov 2014.

[5] The LIGO Scientific Collaboration and The Virgo Collaboration. All-sky search for gravitational-wave bursts in the second joint LIGO-Virgo run. *Phys. Rev. D*, 85:122007, Jun 2012.

[6] The LIGO Scientific Collaboration and the Virgo Collaboration. All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run. *Phys. Rev. D*, 81:102001, May 2010.

[7] The Super-Kamiokande Collaboration. Search for Supernova Neutrino Bursts at Super-Kamiokande. *The Astrophysical Journal*, 669(1):519–524, June 2007.

[8] S. Klimenko and C. Pankow. Detection statistic for multiple algorithms, networks, and data sets. Technical report, Apr 2012. LIGO-T-1200169.

[9] Kate Scholberg. Supernova Neutrino Detection. *Ann. Rev. Nucl. Part. Sci.*, 62:81–103, 2012.

[10] Patrick Sutton. The Signal-to-Noise Ratio as a Predictor of Detectability in the S1 Burst Search. Technical report, Jan 2004. LIGO-T040002-00-Z.