Observing Gravitational Waves from Failed Core-Collapse Supernovae

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Failed core-collapse supernova (CCSN) explosions have no electromagnetic (EM) counterpart, but posses neutrinos and gravitational waves. We aim to put quantitative constraints on the fraction of CCSNe from observations of gravitational waves (GWs) and neutrinos. The usage of neutrino observations for these detectability prospects resulting from failed CCSNe will be considered for both GW and neutrino detectors such as Advanced LIGO and Advanced Virgo, the Einstein Telescope, Super-Kamiokande, and Hyper-Kamiokande, in place of the current megaton-scale detectors. In the next few years the improved sensitivity of Advanced LIGO and Advanced Virgo combined with more sophisticated algorithms for identification and parameter estimation of supernova signals will greatly enhance LIGO′s contributions to supernova astrophysics.

I. INTRODUCTION

Formation, whether via direct collapse or fall-back accretion, can tell us much about the physical processes driving the explosion itself. Gravitational wave (GW) observations of formation in such systems provide an unparalleled opportunity to probe failed supernova explosions that provide no electromagnetic (EM) counterpart. There are three identified signatures for a failed supernova: (1) the star collapses into a black hole; (2) the unbound outer atmosphere of the star may expand, gain luminosity as it expands, and cool; (3) production of a shock breakout flash from the creation of the neutrino sphere that propagates through the atmosphere [1]. The large range of the predicted percentage of failed CCSNe in solar metallicity stars is due to the uncertainty in massive star evolution, in particular the mass loss rates of very massive stars. The predicted mass range that originates from stars is in order to produce a failed CCSN, at minimum, 25 - 40 $M_{\odot}$, with evidence that roughly 20% of events fail to produce a luminous CCSN, and that specifically luminous supergiants may be more prone to become failed CCSN [2]. The absence of red supergiant progenitors above M $\geq 17\ M_{\odot}$, which are quantified as high mass CCSNe progenitors, may be explained by the $20-30\%$ of failed CCSNe that form without an external explosion [1]. Pre-explosion observations of CCSNe progenitors suggest that standard Type II-P CCSNe typically have a rough progenitor mass range from 17 $M_{\odot}$ to 20 $M_{\odot}$ [1]. Assuming that most others fail after a successful but undetectable explosion, this would correspond to a black hole fraction upper limit of roughly $30-35\%$ of massive stars above 8 $M_{\odot}$. Although there an absence of EM counterparts, there are still neutrino and GW emission from failed CCSNe, and therefore quantitative estimates on constraints on the fraction of CCSNe explosions that fail will be made.

For galactic CCSNe, at a fiducial distance of 10 kpc, ~ 8000 neutrinos will be detected by Super-Kamiokande (SuperK), a water-Cherenkov neutrino detector [3]. The overall neutrino luminosity may allow the precise determination of the time of bounce for different detectors. The IceCube detector is able to determine the time of bounce to within 3.5 ms [3], Super-K may estimate the time of bounce to an accuracy of 2 ms at 1 kpc, while Hyper-Kamiokande (HyperK) [4], the proposed megaton successor to SuperK, may estimate it to an accuracy of 3 ms at 7 kpc [5]. Within the detection window for neutrinos, one expects a sharp drop in the neutrino signal. This may happen in a failed CCSN before the shock is reenergized, or after the shock is launched via fallback or due to a late-time phase transition [3]. Prospects for combined GW/neutrino observations resulting from failed CCSNe will be considered [6].

II. OBJECTIVES

It is predicted that 10-20% of CCSNe result in no explosion [7]. If the supernova explosion fails, there will be no EM counterpart, but GW and neutrino emission may be detectable. We will also determine the distance out to which GWs from failed CCSNe can be detected with Advanced LIGO (aLIGO)[8], Advanced Virgo (AdVirgo)[9], and correspondingly the maximum detection distance for neutrinos with SuperK. We will also consider the sensitivity of prospective GW and neutrino detector networks, including Einstein Telescope (ET), and Hyper-Kamiokande (Hyper-K)[4].

III. APPROACH

Leading studies of CCSN rates over the past two decades have tried to constrain and understand progenitor systems by monitoring nearby galaxies [10–12]. Currently, the major observational biases against CCSNe discoveries are progenitor misclassification, the assumed mix of faint and bright supernova types, and obscuration resulting from factors such as absorption due to sources of dust and stellar remnants, light pollution from galaxy nuclei and the limited sky coverage of ground-based telescopes. Using the Gravitational Wave Galaxy Catalog [13], a collection of galaxies containing electromagnetic counterparts within 20 Mpc were identified.

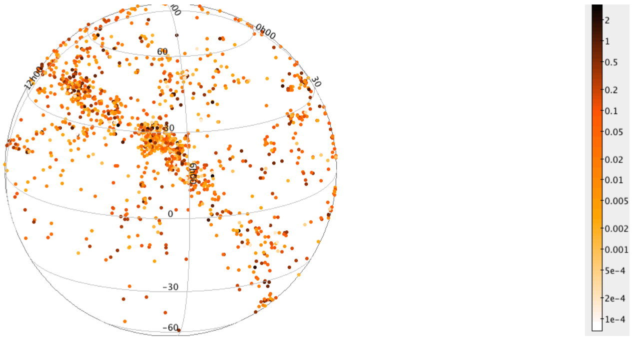

FIG. 1:
Distribution of CCSNe host galaxies and their respective rates projected onto Earth.

By using blue light and far-infrared luminosity as tracers of star formation, the rate of CCSNe was estimated within a volume of 20 Mpc. The improved estimation of the CCSNe rate is 4.32 ± 2.07 CCSNe $\mathrm{yr}^{-1}\mathrm{Mpc}^{-1}$ [14]. The distributional movie illustrating where the highest likelihood of identifying CCSNe, displayed as figures 1 and 2, may be found on my personal webpage [15].

Using megaton-scale detectors, these bursts might be identified as far as 4 - 5 Mpc away with a time window of roughly one second [7, 16]. We assume an approximate upper limit for the cumulative CCSN rate of 0.232 CCSNe yr^{-1} within 5 Mpc, and primarily target Type II-P CCSNe due to the easily identifiable plateau phase in their light curves [1]. This brings us to about 0.058 Type II-P SNe exploding per year. Furthermore, if 35% of Type II-P SNe result in failed CCSNe explosions, that results in 0.0203 failed Type II-P SNe per year. Now, incorporating astronomical surveys, if observing at a max distance of 5 Mpc due to the limitations of neutrino observatories and assuming that in the present survey occurring over a period of T = 4 years there are no vanished supergiants to be found, then if the failed CCSN rate is some fraction, f_{fs}, of the CCSN rate, R, the expected number of failed CCSN is $N_{fs} = f_{fs} * R * T$. Even if no viable candidates are found, there can be an assumption of a 90% confidence limit, $\mathrm{P}(0) = e^{-(f_{fs} * R * T)} = 0.1$, of $f_{fs} < 0.6$. If this survey continues 10 years, and the actual rate is $f_{fs} = 0.1$ failed type IIP SNe/yr, then there is a 63% probability of successfully identifying a failed CCSN [17]. We will focus on GW signal emission from failed CCSNe and if the incorporation of neutrino signals improves the overall detectability of failed CCSNe. This process might also indicate a method to detect the first evidence of direct BH formation [7].

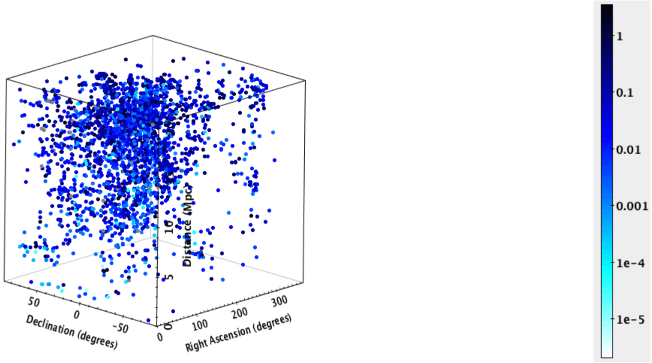

FIG. 2:
Distribution of CCSNe host galaxies and their respective rates as a function of distance.

We will also quantify the likelihood that the subprime neutrino triggers detectors are connected to the supernova as a function of the distance of the SN, for both the existing detectors such as Borexino, IceCube, and Super-K, as megaton-scale detectors will be outdated within a time scale of 20 years [18]. It would aid in exploring if the development in the neutrino detection rate would lend an improvement in the GW search trigger estimation method.

IV. PROJECT TIMELINE

- June 14th, 2016 - July 1st, 2016
    - Literature Review on the GW and neutrino detectors considered; aLIGO, AdVirgo, ET, SuperK, and HyperK.
    - Understand different distance constraints for these present and future detectors for neutrino and GW detection from failed CCSNe.
- July 4th, 2016 - July 22nd, 2016
    - Study different theoretical noise curves for both GW and neutrino detectors
    - Identify timescale needed to put a constraint on GW and neutrino emission from failed CCSNe.
- July 25th, 2016 - Aug 12th, 2016
    - Understand probability of black hole (BH) formation resulting from failed CCSNe from direct collapse and/or fallback accretion at different distances with range of progenitor masses
    - Constraint on BH associated horizon distance for both the GW and neutrino approach.
- Aug 15th, 2016 - Aug 19th, 2016
    - Prep technical paper and oral presentation for the SURF Seminar Day

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