Supernova Neutrino Estimation for Present and Future Telescopic Surveys

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Stars with a mass over $8M_{\odot}$ will end their life with a violent explosion known as a core collapse supernova. The majority of a core collapse supernova's energy comes from neutrinos. Neutrinos give substantial information about the physics of a supernova. Furthermore, these supernovae explosions can teach us a lot about neutrinos, since these explosions occur under conditions that are not feasible on Earth. At present, there have only been approximately 20 neutrinos detected from supernovae, which all originated from SN1987A. To further probe the physics of a supernova and neutrinos, more neutrinos must be detected. However, the next supernova explosion from the Milky Way galaxy may be decades away. Currently, there are programs that are continually looking for supernovae, such as the All Sky Automated Survey for SuperNovae (ASAS-SN), and the Zwicky Transient Facility (ZTF). Data from these on-going surveys was visualized to gauge the importance of several factors. This information was used to estimate the total number of neutrino events that could be detected at the Hyper-Kamiokande (HK) detector from an energy range of 16-30 MeV. New telescopes are being constructed, such as the Legacy Survey of Space and Time (LSST), that will detect thousands of new supernovae from further distances, which will increase the number of neutrino events seen. Observation time since the explosion and distance of the supernovae are important factors when determining how many neutrino events can be observed. We have predicted the number of supernovae LSST will detect over a range of distances with the hopes of determining the best range of time and distance to find neutrinos.

I. INTRODUCTION

Most massive stars will end their lives with an extravagant explosion called a supernova. Supernovae come in many types such as Ia, Ib, Ic, and II. Types Ib, Ic, and II are known as core collapse supernovae, which are a special kind of supernovae that emit a burst of neutrinos during the explosion. These neutrinos account for approximately 99% of a core collapse supernova's energy [10].

A core collapse supernova happens when a star's core begins to fuse into iron. The iron core will become extremely dense, and the star will begin to collapse in on itself [9]. At the very beginning of the collapse, an immense amount of neutrinos are produced through electron capture.

$$p + e^{-} \rightarrow n + \nu_e \tag{1}$$

Neutrinos are then trapped and the core will form into a massive nucleus. This massive nucleus creates a shock wave that expands the iron core and releases neutrinos. Soon after the expansion, the shock wave will become stagnant, then turn into an accretion shock. During this phase, neutrinos react with protons and neutrons creating a massive amount of energy. This energy causes a shock revival, where the shock wave begins to expand outwards again. This shock wave results into a supernova [6]. During the explosion, neutrinos will escape the core collapse before any photons. Therefore, a detection of a neutrino signal can be used as an early warning for astronomers that a supernova is coming [12]. Moreover, neutrinos can reveal many properties of a supernova such as the time and location of the explosion [1]. Although these supernovae produce enormous amounts of neutrinos during their explosions, only 20 neutrinos have ever been detected to date from a single supernova, SN1987A [12].

In the near future, larger telescopic surveys and more sensitive detectors will begin running that will observe supernovae from much greater distances and have the capability of detecting more neutrinos. Presently, there are numerous surveys that find new supernovae every day. This paper will focus on the All Sky Auto-mated Survey for SuperNovae, Zwicky Transient Facility, and the upcoming Legacy Survey of Space and Time. The goal of this paper is to determine how many neutrinos can be detected from each survey and determine the best range of time and distance to find neutrinos.

II. SURVEYS

A. ASAS-SN

The All Sky Auto-mated Survey for SuperNovae (ASAS-SN) is an on-going survey that has been running since late 2013. ASAS-SN began as a small project with only four telescopes, but now has numerous telescopes spread throughout the world that can survey both hemispheres every night [13]. Presently, ASAS-SN has observed over 220 confirmed core collapsing supernovae up to a distance of 350 Mpc [2]. Figures 1, 2, 3 are visualizations of ASAS-SN data.

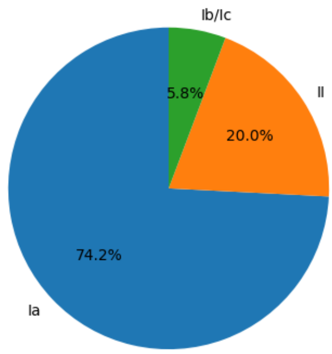

FIG. 1: Pie chart illustrating the various types of supernovae ASAS-SN observed.

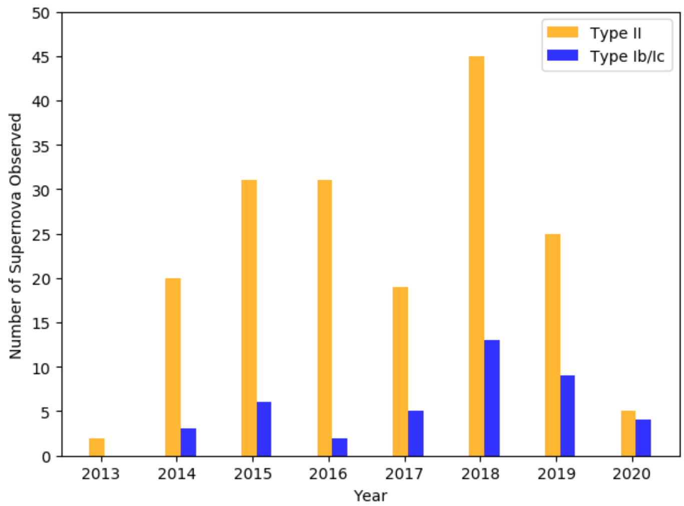

FIG. 2: Bar chart showing how many supernovae of each type ASAS-SN has observed every year during its run time.

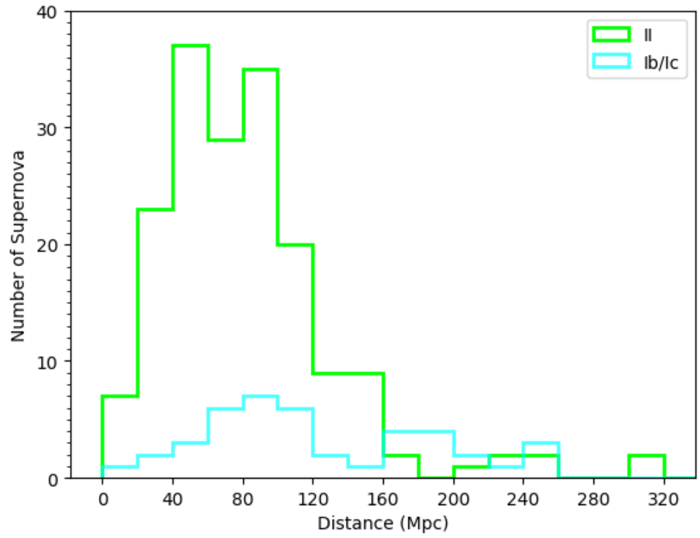

FIG. 3: Histogram of distances of core collapsing supernova observed by ASAS-SN with a bin width of 20 Mpc.

B. ZTF

The Zwicky Transient Facility (ZTF) is a larger, more recent survey, that has been running since 2017. ZTF surveys the entire northern sky, and scans more than more than 3750 square degrees an hour. ZTF has currently surveyed over 530 core collapse supernovae out to 440 Mpc. Visualizations of ZTF data are shown in figures 4, 5, 6.

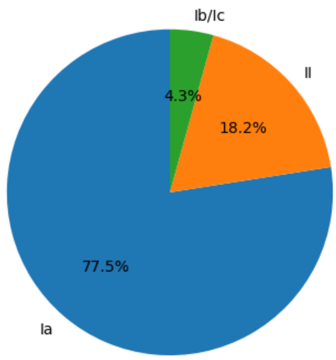

FIG. 4: Pie chart illustrating the various types of supernovae ZTF observed.

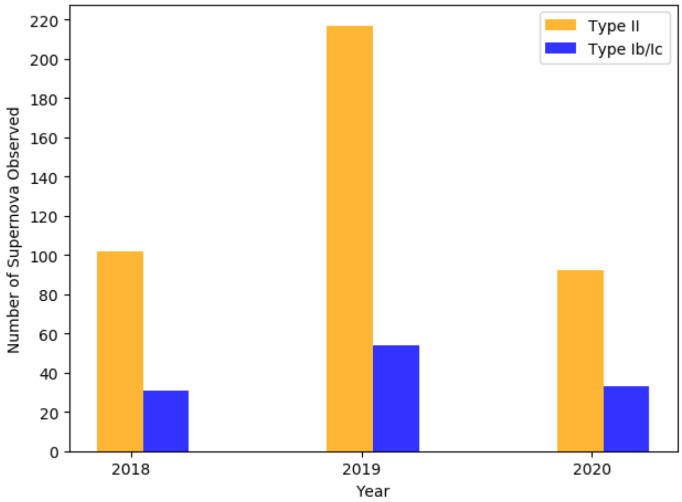

FIG. 5: Bar chart showing how many supernovae of each type ZTF has observed every year during its run time.

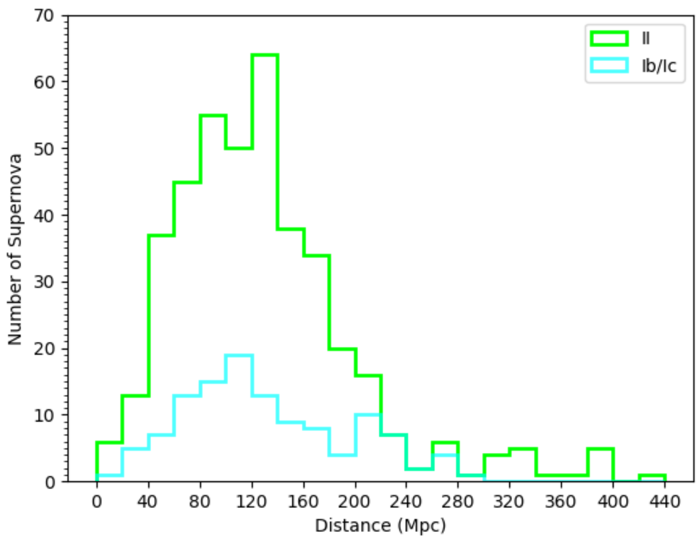

FIG. 6: Histogram of distances of core collapsing supernova observed by ZTF with a bin width of 20 Mpc.

C. LSST

The Legacy Survey of Space and Time (LSST) is an upcoming survey that will run for 10 years at the Vera C. Rubin Observatory in Chile. The survey will consist of an 8.4-meter, three-mirror telescope, that will survey the entire sky every three nights. Furthermore, LSST will have the world's largest CCD camera, and will have the ability to take over 800 images every night. Construction of the Rubin Observatory began in 2014 and is predicted to be in full operations by 2022.

Due to the large scale of this survey, LSST will observe tens of thousands of supernovae during its run time. In order to determine how many supernovae LSST will discover, we adopt a method described by Lien and Fields [8]. This method calculates the total number of supernovae LSST will detect in x-band at a specific limiting magnitude m_{lim}^{sn} and redshift bin.

$$\Delta N_{SN,obs,x} = \Delta\Omega_{scan}\Delta t_{obs}\Delta z\Gamma_{SN,obs,x}(z) \tag{2}$$

Where $\Delta\Omega_{scan}$ is the scan area, which is 20,000 deg^2 for LSST. Δt_{obs} is the monitoring time, Δz is the redshift bin width, and $\Gamma_{SN,obs,x}(z)$ is the observed supernova rate. $\Gamma_{SN,obs,x}(z)$ can be defined as,

$$\Gamma_{SN,obs,x}(z) = R_{SN}(z) f_{detect,x}(z; m_{lim}^{SN}) \frac{r(z)^2}{1+z} \frac{dr}{dz} \tag{3}$$

Where $R_{SN}(z)$ is the supernova rate, f_{detect} is net supernova detection probability, and $r(z)$ is the comoving distance. $R_{SN}(z)$ depends on three terms: the mass fraction of new stars that will go into supernova X_{SN}, the mean supernova progenitor mass $\langle m \rangle_{SN}$, and the cosmic star formation rate $\dot{p}_*$.

$$R_{SN} = \frac{X_{SN}}{\langle m \rangle_{SN}} \dot{p}_* \tag{4}$$

$\frac{X_{SN}}{\langle m \rangle_{SN}}$ is a constant value of $0.00914 M_\odot$, while $\dot{p}_*$ has a redshift dependence.

$$\dot{p}_* = \frac{0.017 + 0.13z}{1 + (z/3.3)^{5.3}} h M_\odot yr^{-1} Mpc^{-3} \tag{5}$$

f_{detect} is a product of the fraction of all unobscured supernovae $f_{maglim}(z; m_{lim}^{sn})$ and the fraction of supernovae that can be detected after dust extinction $f_{dust}(z)$.

$$f_{detect}(z; m_{lim}^{sn}) = f_{maglim}(z; m_{lim}^{sn}) f_{dust}(z) \tag{6}$$

$f_{dust}(z)$ is defined as,

$$f_{dust}(z) = \begin{cases} 0.95 - 0.28z, & z < 3.3 \\ 0.02, & z \geq 3.3 \end{cases} \tag{7}$$

f_{maglim} is calculated with the following equation,

$$f_{maglim} = \sum_{\text{types}} \frac{\int^{m_{lim}^{sn}} \phi_{snlf,x}[m_x - \mu(z) - K_x(z) - \eta_{xB}] dm}{\int \phi_{snlf,x}(m_x) dm} \tag{8}$$

Where $\mu(x)$ is the distance modulus, and $K_x(z)$ is the k-correction, which was found by digitizing figure 11 from [8]. η_{xB} is a color index which translates between the x and B magnitudes in the rest frame. We varied this value among each supernova type until we found the best fit for $\Gamma_{SN,obs,x}(z)$. We found that the best fits were 1.9, 2.0, and 1.4 for Type IbIc, Type IIL, and Type IIP respectively. $\phi_{snlf,x}$ is the supernova luminosity function which is defined as a Gaussian function. Mean and standard deviation values are obtained from [11]. A histogram of this calculation is found in figure 7.

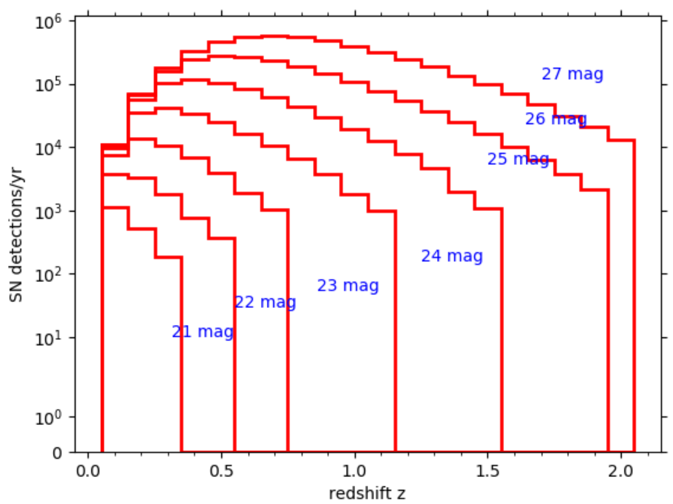

FIG. 7: Histogram of the number of supernovae LSST will detect in one year over various limiting magnitudes. A bin width of 0.01 redshift was used. For the neutrino calculation, the bin width was adjusted to 0.001 to give more precise results.

III. DETECTORS

There are numerous ways that neutrinos can be detected such as water Cherenkov detectors. These detectors are giant tanks of water buried deep underground with walls aligned with photomultiplier tubes (PMTs) [12]. The neutrinos are detected through inverse-beta decay (IBD).

$$\bar{\nu_e} + p \rightarrow e^+ + n \tag{9}$$

The positron from IBD creates Cherenkov rings that are detected by the PMTs [5]. However, this positron can be difficult to distinguish from various backgrounds like atmospheric neutrinos. Some detectors, such as the Super-Kamiokande (SK) detector, are able to separate supernova neutrinos from backgrounds with a process known as neutron tagging. During this process, the neutrons from IBD will interact with free protons with the following interaction,

$$n + p \rightarrow d + \gamma \tag{10}$$

This interaction will have a delay of approximately 200 μs after the IBD [5, 14]. In the future, SK is planned to be doped with Gadolinium, which will enhance neutron tagging and be able to distinguish neutrinos from backgrounds even more [14].

IceCube and SK are two Cherenkov detectors that are running today [12]. IceCube is located under Antarctic ice and can detect supernovae inside the Milky Way [12]. SK is located in the Kamiokande mine in Japan and has a fiducial volume of 22.5 ktons [3]. Currently, larger detectors such as Hyper-Kamiokande (HK), the successor of SK, are being constructed. HK is planned to have two tanks that will have a total fiducial volume of 374 kton [5]. HK will be an order of magnitude larger than SK, and will be able to detect more neutrino events. Moreover, there are proposals for detectors as large as 5 Mton that would be able to detect at least one event per year [7].

IV. METHOD

To calculate the number of neutrinos these surveys could detect, we used the following equation,

$$N_\nu = \frac{N_t}{4\pi D^2} \int_{16}^{30} \sigma(E_\nu)\, F(E_\nu)\, dE_\nu \tag{11}$$

Where N_t is the number of free target protons, E_ν is the neutrino energy, σ is the cross section, and F is the Fermi-Dirac energy spectrum. The bounds on the integral correspond to the range of positron energies HK will be able to detect. We relate positron energy to neutrino energy below.

$$E_{e^+} = E_\nu - \Delta = E_\nu - 1.3MeV \tag{12}$$

For the neutrino calculation, we used an alpha fit where,

$$F(E_\nu) = \frac{L}{\langle E_\nu \rangle^2} \frac{(\alpha+1)^{(\alpha+1)}}{\Gamma(\alpha+1)} \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu \rangle}\right] \tag{13}$$

Where L is the total luminosity of neutrinos, $\langle E_\nu \rangle$ is the average energy, Γ is the Euler Gamma function, and α is a dimensionless pinching parameter. Here, we assume L to be $5 * 10^{52}$ ergs, $\langle E_\nu \rangle$ to be 15 MeV, and α to be 2.3. All of our neutrino calculations are for the HK detector.

In order to determine the best range of time and distance to find neutrinos, background noises in the detectors must also be considered. Neutrino detectors pick up on various background noises such as atmospheric and solar neutrinos, and radioactive events inside the detector [3]. Furthermore, there is also a hypothetical background called the Diffuse Supernova Neutrino Background (DSNB), which is theorized to be the population of neutrinos from all core collapsing supernovae in the universe. However, this has yet to be discovered. We calculated background events for the supernova that contributed the most to the neutrino rate by using data from the DSNB search [3]. We used data points from SK-I, SK-II, and SK-III runs with an energy range of 16-30 MeV and Cherenkov angles of 38-40 degrees. We summed all of the data points together and divided by the number of days SK ran and by the fiducial volume of SK. We then multiplied by the cadence of the supernova. We also wanted to scale this background to the size of HK. Therefore, we multiplied the background rate by the fiducial volume of HK. This process was repeated for each period of SK. Backgrounds can be found in Table I.

V. RESULTS

Data from ASAS-SN and ZTF was used to determine how many neutrinos could be detected from each supernova. Most supernovae had under 0.01 events. Figures 8 and 9 are histograms that illustrate the distribution of neutrinos detected.

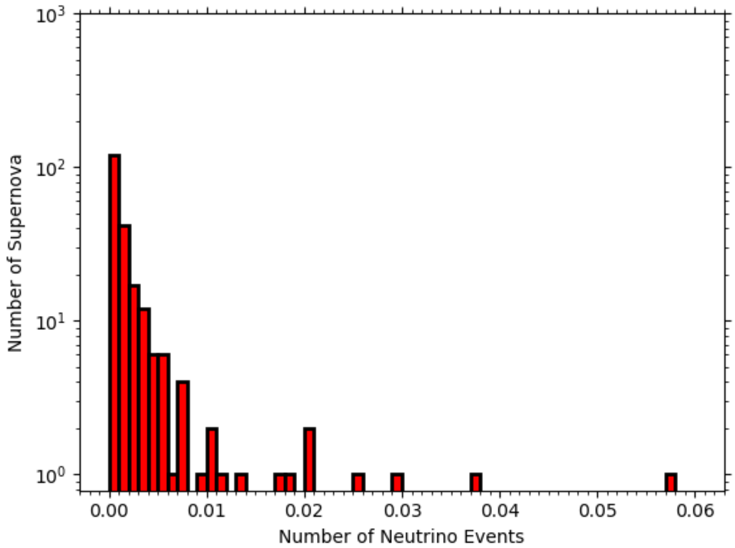

FIG. 8: Histogram of neutrino events for ASAS-SN with a bin width of .001.

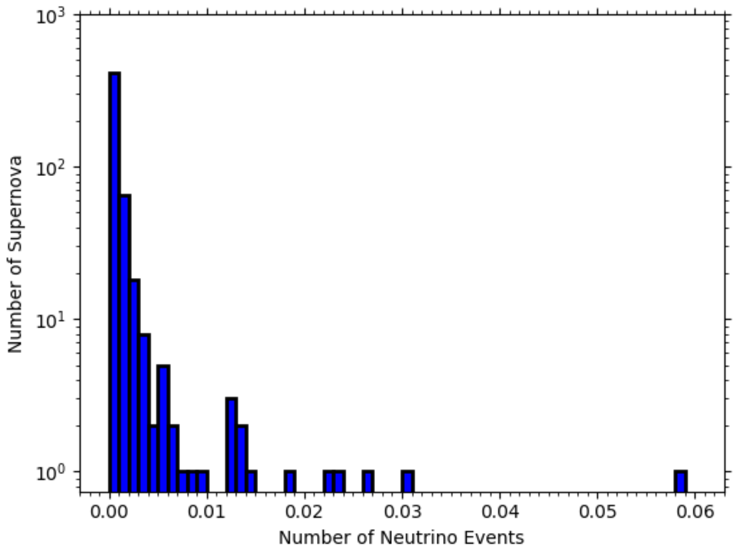

FIG. 9: Histogram of neutrino events for ZTF with a bin width of .001.

For LSST, we used the number of supernovae detected at limiting magnitude of 24. The number of supernovae can be seen in figure 7. We chose a limiting magnitude of 24 because we believed this was the most accurate result compared to [8]. The calculation for the number of supernovae LSST would detect also uses a bin width of 0.001. The number of neutrino events that could be detected from LSST is shown in figure 10.

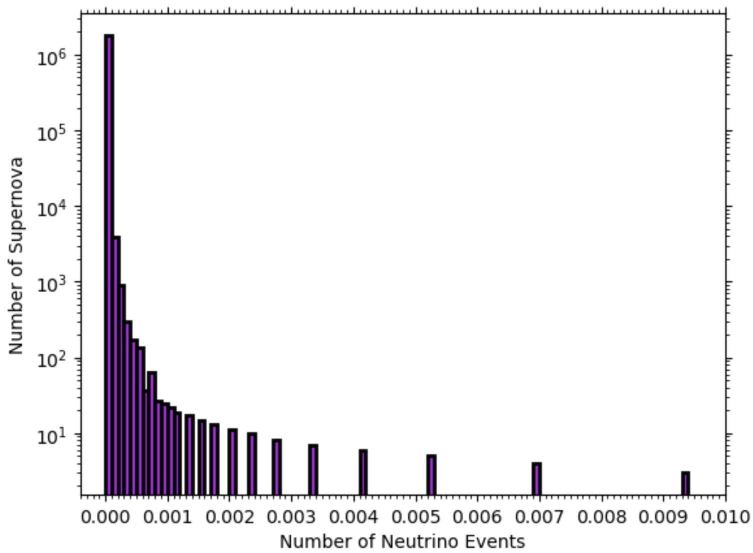

FIG. 10: Histogram illustrating neutrino event distribution for LSST with a bin width of 0.0001 neutrino events.

The number of neutrinos from each supernova was summed to determine the total number of neutrinos from each survey. ASAS-SN had a total of neutrinos 0.635, ZTF had a total of 0.649 neutrinos, and LSST had a total of 12.2 neutrinos. Tables I and II show the supernovae from ASAS-SN and ZTF that contributed the most to the neutrino rate respectively.

ASAS-SN ID	Distance (Mpc)	N_ν	Cadence (days)	HK Bkg (SK-I)	HK Bkg (SK-II)	HK Bkg (SK-III)
ASASSN-16fq	9.846	0.0574	4	2.06	2.12	2.62
ASAS-SN-17qp	12.178	0.0375	–	–	–	–
ASASSN-19ml	13.810	0.0292	3	1.54	1.58	1.97
ASASSN-16fp	14.799	0.0254	6	3.09	3.16	3.93
ASASSN-16cc	16.299	0.0209	2	1.03	1.05	1.31
ASASSN-18vc	16.583	0.0202	4	2.06	2.12	2.62

TABLE I: Supernovae contributing most to ASAS-SN's neutrino events and their respective cadence and background estimations for the first three periods of SK.

SN ID	Distance (Mpc)	N_ν
SN2018hna	9.744	0.0586
SN2018aoq	13.436	0.0308
SN2018imf	14.612	0.0260
SN2018ivc	15.383	0.0235
SN2020cxd	15.748	0.0224

TABLE II: Supernovae contributing most to ZTF's neutrino events.

We also investigated the explosion time estimate for ASAS-SN supernovae that contributed the most neutrinos. We found the days between the first confirmed detection and last non-detection of each supernovae to estimate the explosion time. To obtain an accurate measurement for the explosion time, it is important to have low cadence values [4]. These cadence values were used to calculate the background rates at HK shown in I. Lower cadence values result in lower background rates.

VI. CONCLUSION

Our neutrino estimations for ASAS-SN and ZTF show promising outcomes because they are much higher than we anticipated. In the future, we hope to refine our estimation for the number of supernovae LSST will detect each year, which will lead to better neutrino estimations. Furthermore, we want to examine the neutrino background rate LSST would experience at HK. This would lead to determining the best strategy to detect supernovae neutrinos.

VII. ACKNOWLEDGEMENTS

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