LSST Target of Opportunity proposal for locating a core collapse supernova in our galaxy triggered by a neutrino supernova alert

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Abstract

A few times a century, a core collapse supernova (CCSN) occurs in our galaxy. When such galactic CCSNe happen, over 99% of its gravitational binding energy is released in the form of neutrinos. Over a period of tens of seconds, a powerful neutrino flux is emitted from the collapsing star. When the exploding shock wave finally reaches the surface of the star, optical photons escaping the expanding stellar envelope leave the star and eventually arrive at Earth as a visible brightening.

By combining the multi-messenger signal from optical, neutrino, and gravitational waves, we afford an unprecedented opportunity to learn about the astrophysics of these rare objects. Carefully measuring the optical light curve of the explosion will give critical information about the size and composition of the progenitor star and help understand the dynamics of the explosion.

Crucially, although the neutrino signal is prompt, the time to the shock wave breakout can be minutes to many hours later. This means that the neutrino signal will serve as an alert, warning the optical astronomy community the light from the explosion is coming. Quickly identifying the location of the supernova on the sky and disseminating it to the all available ground and spaced-based instruments will be critical to learn as much as possible about the event.

Some neutrino experiments can report pointing information for these galactic CCSNe. In particular, the Super-Kamiokande experiment can point to a few degrees for CCSNe near the center of our galaxy. A CCSN located 10 kpc from Earth is expected to result in a pointing resolution of the order of 3°. LSST's field of view (FOV) is well matched to this initial search box. LSSTs depth is also uniquely suited for identifying CCSNe even if they fail or are obscured by the dust of the galactic plane.

This is a proposal to, upon receipt of such an alert, prioritize the use of LSST for a full day of observing to continuously monitor a pre-identified region of sky and, by using difference imaging, identify and announce the location of the supernova. In this proposal, we propose to use one night (approximately 0.03% of the survey period) if a galactic supernova occurs. Based on estimates of the rate of such CCSNe there is approximately a 20% chance that a CCSN will occur during the survey period.

1 White Paper Information

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Categorization:

1. **Science Category:** Exploring the transient optical sky
2. **Survey Type Category:** Target of Opportunity observation
3. **Observing Strategy Category:** A single night, continuous observation strategy focused on one few degree field pointing as given by a neutrino supernova alert trigger.

2 Scientific Motivation

No visible galactic CCSNe have been seen and measured in the modern scientific era. They are only thought to occur two or three times a century [1, 2]. The closest modern CCSN we have observed was SN 1987A in the LMC. Using an alarm from neutrino detectors as a trigger, LSST can quickly identify and characterize a galactic CCSN and then notify the rest of the astronomical community which can then track it in multiple wavelengths from the ground and space. The early identification of the supernova optical counterpart will be key in an extensive program of multi-messenger astronomy.

How a neutrino-based supernova alarm can be used to prepare for the arrival of an optical signal in LSST can be understood from the basic sequence of CCSN formation. As massive ($> 8M_\odot$) stars approach the end of their lives, they begin to run out of the hydrogen which has been fueling their fusion burning. The resulting loss of pressure results in a contraction of the star, raising its temperature until the burning of the helium produced in the previous hydrogen fusion can begin. This cycle repeats, next burning carbon, neon, oxygen, and silicon until finally a core of iron remains. Upon reaching the Chandrasekhar mass, this iron core collapses. Not until nuclear densities does the collapse halt, the supernova shock form, and the neutrinos begin to stream towards Earth. At this point the ultimate fate of the star is determined by a battle between the accreting matter and the intense outward pressures from heat, neutrinos, and turbulence. If the former wins, a black hole is formed, if the latter wins, the supernova shock drives out into the star starting an explosion. Depending on the size of the star, only minutes to many hours later will the shock wave actually break out of the stellar envelope and become visible as a supernova explosion to optical telescopes.

Studying a galactic supernova in detail is an amazing opportunity to do multi-messenger astronomy [3]. Neutrino, gravitational wave, and optical signals all tell us something unique about the system. The supernova converts the binding energy of the star into energy and over 99% of it is released in the form of neutrinos. Crucially, all of these neutrinos escape the star in the first several tens of seconds of the explosion. Much can be learned about the dynamics of the explosion by studying the neutrino signal. Even the formation of a black hole, where the neutrino signal will be abruptly terminated, should be visible [4, 5].

Additionally, studying the optical explosion signal in detail from the beginning of the explosion will probe how the explosion proceeds and will give crucial insights into the character, composition and size of the progenitor star. This will allow us to better understand the final stages of stellar evolution and the environment that exists as the collapse begins. Examples of strategies to constrain the progenitor characteristics and explosion dynamics from light curves include [6, 7, 8]. Some models of black hole formation even include a much reduced, but possibly visible, electromagnetic signal [9]. With the progenitor information gained from the light curve we can connect what is happening on the outside of the star to what is happening on the inside as measured by the neutrino and gravitational wave signal.

A world-wide network of neutrino detectors including Super-Kamiokande (Super-K) [10] have prompt alarms to alert the world if a supernova neutrino burst has been seen. All of these experiments are also networked together into a system known as SNEWS (The

Supernova Early Warning System; website and more information at `https://snews.bnl.gov`) [11]. SNEWS does a blinded coincidence between experimental alerts sending out an automated announcement to the GCN if more than one neutrino experiment has seen a burst of neutrinos, and is also capable of sending a individual confirmed alerts from a single experiment. Currently, Super-K is the only running experiment with pointing ability, and we concentrate on its performance for this proposal. The neutrino interactions inside of Super-K from a CCSN consist of inverse beta decay (IBD) interactions on nuclei with only weak directional memory and also scattering on atomic electrons which point to their source quite well.

For a more detailed description of the expected fluxes from each neutrino type and neutrino interactions expected in detector refer to the review [12] and section 3.2 below. Figure 1 taken from [13] shows a simulated example of interactions from a supernova near the galactic center with its direction reconstructed. In the figure, the electron scattering interactions are in red, the IBD interactions in blue. The fluxes (and resulting pointings) are model dependent, but studies have shown that for a CCSN located 10 kpc away it is possible to determine the direction of the star to within about 3-5 degrees [13]. Closer or more luminous CCSNe will have better pointing. The expected time delay ranges from minutes to more than a day depending on the mass of the progenitor star. Figure 2 taken from [14] shows the range of expected times. The SN 1987A progenitor was thought to be a blue giant with a time delay of around 3 hours.

LSST is particularly well suited to do the initial CCSN identification. LSST's large 3.6 degree FOV is well matched to the initial search region that would come from Super-K. LSST can continually collect exposures in the region until the explosion is seen. Next is LSST's depth. There are other wide-field surveys that might easily see the supernova if it is bright. But, even with a large neutrino signal, the optical signal from the CCSN could be quite dim. This is a place where LSST will make a particularly vital contribution. Recent work has estimated that a supernova located in the disk obscured by dust could be as dim as magnitude 25 [3]. The explosion could also fail or form a black hole [4, 5]. The expected range of brightnesses are explored in [3], figure 3 taken from that paper shows the reach of LSST for the dimmest supernova compared to other facilities.

Finally, to quickly identify the CCSN, deep image templates of the area will be necessary for image subtraction and candidate identification. Likely the depth of these templates will be the main limiting factor for identifying faint candidates. LSST should have templates across the sky after Y1. The depth × area on average across the sky will be deeper for LSST than any other survey.

Identifying and studying a galactic supernova would be a scientific gold-mine for astronomy and particle physics. The merit of enabling these studies is very high. The impact on running is minimal. Using the rate of three per century there is a 20% chance that we would receive a neutrino alarm. In that case we advocate for a strategy of a full day of observing with follow-up over next few days to ensure the candidate. Depending on how bright it is, we would quickly hand off to other ground and space-based telescopes. It would take approximately 0.03% of the survey's time to contribute to a major discovery.

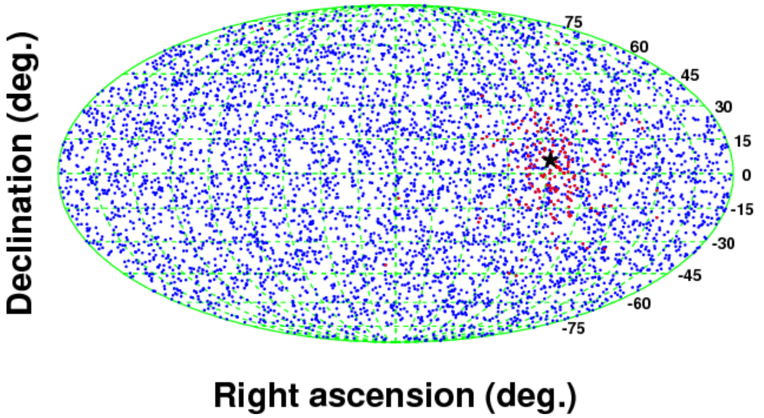

Figure 1: Figure 7 from [13] shows how the CCSN location is determined. A simulated set of neutrino interactions from a supernova 10 kpc from Earth are displayed. The blue points are the IBD events, the red the electron scattering events. The reconstructed direction after fitting the peak is shown with a star. See reference [13] for more detailed information.

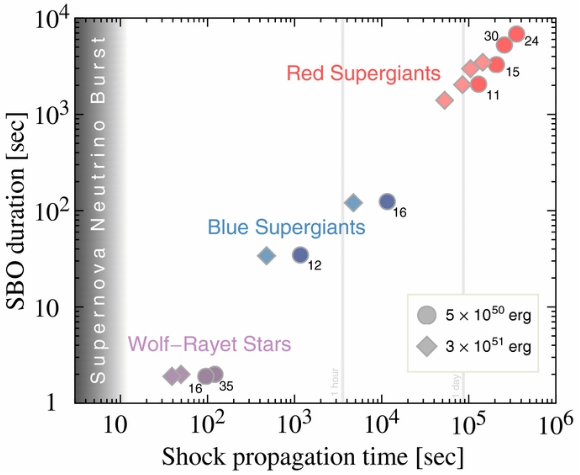

Figure 2: Figure 2 from [14] shows calculated shock propagation times for different classes of stellar progenitors. The propagation time sets the delay between the prompt neutrino signal and the optical signal which appears when the shock breaks out of the stellar envelope. See reference [14] for more details.

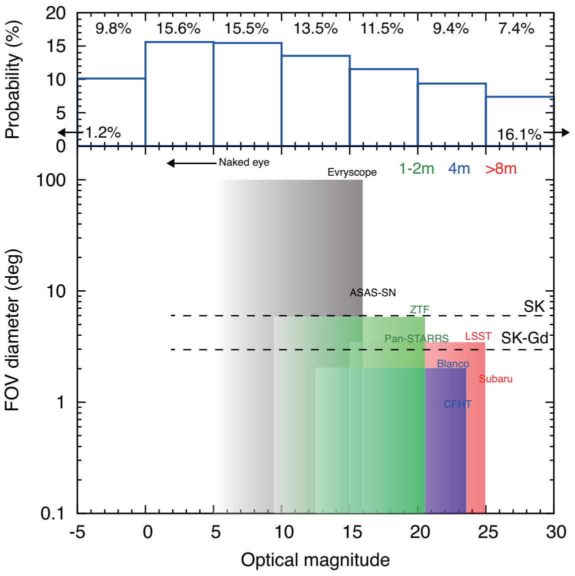

Figure 3: The top panel of figure 9 from [3] shows the predicted dust-attenuated peak magnitudes and corresponding percentage fraction of all CCSNe. The bottom panel shows typical magnitudes and FOV for various optical telescopes including LSST. The SK expected resolution is also indicated. See reference [3] for more details.

3 Technical Description

In order to describe the survey strategy for footprint, tiling method, depth, and observation frequency it is important to understand the expected time delay and pointing signal along with the form of the alarm signal. Those are first summarized here.

3.1 Expected Time Delay

The time delay between the neutrino alarm and the light signal reaching LSST can range from minutes in the case of Wolf-Rayet stars, to hours for blue supergiants, all the way up to a day or two for the largest red supergiants. The time is set by the radius of the star when the collapse happens, as that sets the distance that the shock wave must travel. Figure 2 taken from [14] shows how the breakout time of the shockwave varies for different classes of stellar objects. Table 2 in [15] calculates the delay times for various modeled red supergiants. Fractions of CCSN classification taken from [16] suggest that Wolf-Rayet stars will have a delay of 1 to 10 minutes and are approximately 30% of CCSN, blue supergiants a few hours and 15%, and red supergiants one to two days and 55%.

3.2 Neutrino Interactions

The expected pointing resolution in a water Cherenkov detector will scale with the number of interactions detected. As explained in section 2 a set of electron scattering interactions which point back to the supernova will be sitting on top of a background of poorly-pointing interactions from the IBD neutrino captures. For a supernova located 10 kpc from the Earth (the galactic center is approximately 8 kpc away) the order of 10,000 neutrino interactions are expected in Super-K. Supernova that are closer or further away will have their fluxes scaled simply by scaling to their distance with a factor of $1/r^2$. Although something like 10,000 interactions are typical, expected fluxes are found to have a range of values by different simulation groups.

Some detectors can only report the time and size of a neutrino burst, and do not have the ability to supply directional information. In the near future, there will be new detectors with pointing ability and the SNEWS system will also add pointing information utilizing intra-detector timing by using the fact that travel times across the Earth from multiple detectors (such as Super-K and IceCube) can triangulate the CCSN position [17] and [N. Linzer and K. Scholberg in preparation]. However, currently, Super-K is the only running experiment with pointing ability, and we use its performance for this proposal.

Most of the neutrino interactions in the water of the Super-K experiment are inverse beta decay (IBD)

$$\overline{\nu}_e + p \rightarrow e^+ + n,$$

where a neutrino is captured by a proton resulting in a positron (which is detected through its Cherenkov radiation) and a neutron. The positron in this reaction carries only very weak directional memory of the incoming neutrino. However, a few percent of the neutrino interactions proceed through atomic electron scattering:

$$\nu + e^- \rightarrow \nu + e^-.$$

Unlike the IBD reactions, these atomic electron scattering interactions **do** point back to the supernova well. In order to find the direction of the CCSN a fit is done to the two components of the signal resulting in an inferred position and error region on the sky for the supernova position.

3.3 Expected pointing resolution

Given a number of interactions, pointing to the supernova using the electron scattering signal only given is by the kinematics of the interaction and is found to give a resolution of roughly

$$\Delta\theta = \frac{30^\circ}{\sqrt{N}.},$$

where N is the number of electron-neutrino scattering interactions and the angular resolution is a half-opening angle [12]. With a few percent of 10,000 interactions from a 10 kpc supernova being electron scattering events, this tells us that we should expect a rough pointing resolution of close to 1.5°. However, this resolution will be degraded due to the fact that the scattering signal is on top of the IBD background. Closer supernovae will have higher numbers of interactions with better pointing, and those further away will have their resolution decreased.

A careful study by the Super-K collaboration in [13] plots a 68% opening angle coverage as a function of distance for a few flux models with a realistic fitting procedure to accommodate the IBD background. Figure 4 shows how the pointing is expected to scale as a function of distance with neutrino oscillations taken into account for one of the models. At 10 kpc the pointing is near 3°.

By the time the LSST survey begins we expect Super-K to be doped with 0.02% $\mathrm{G}d_2(SO_4)_3$ [18]. The addition of gadolinium (which has a high neutron cross-section) to the water will allow the neutron to be tagged in IBD events thus removing a portion of the non-pointing background and improving the pointing resolution to be closer to the formula above.

3.4 Alert input

In order to point LSST, the observatory control system (OCS) must first receive information from the neutrino experiments that a light from a galactic supernova is about to arrive. Time is of the essence since depending on the size and type of the star the breakout time could range from minutes to many hours [14]. There is currently more than one way to receive an alert. If this proposal is selected LSST must work with the neutrino community to ensure that the information that LSST needs is being promptly transferred.

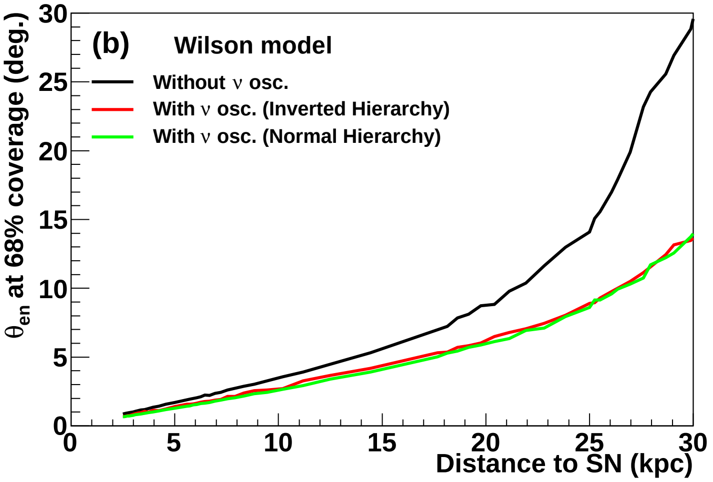

Figure 4: Figure 9b from [13] shows the 68% $\Delta\theta$ reconstructed by the Super-K algorithm as a function of distance to the CCSN from the Earth in kpc using simulated data in Super-K from a particular (the Wilson) model. With neutrino oscillations properly accounted for, a supernova from near the Galactic center results in an opening angle resolution of about 3°.

There are two broad classes of alerts to consider. Each experiment has the option to send its own alert to the astronomical community. For example, if Super-K determines a CCSN in our galaxy has occurred it might send the following template-like text example to the Astronomers Telegram:

```
Super-Kamiokande, a 50000 ton water Cherenkov imaging detector
situated 1000 meters underground in the Kamioka mine, Gifu, Japan, has
observed a neutrino burst from a nearby supernova.  Within a fiducial
volume of 22500 tons, preliminary results indicate 5227
neutrino-produced events have been detected with energies greater than
7.0 MeV. An SN1987A-like explosion would be expected to produce such a
signal in Super-Kamiokande if the progenitor star was located at a
distance between 7.55 and 10.36~kpc from Earth. These events were
observed over an interval of 17.9 seconds, with the first event
arriving at 2017 Nov 2.318437 UT. The estimated supernova direction is
R.A. = 110 (degrees) and Dec.= 6 (degrees), within 3.29, 4.72 and 5.62
degrees for, respectively, 68, 90 and 95% C.L. error circles.
The probability to have the SN located within 2, 5, and 10 degrees
of the central position is 0.36, 0.92 and 1.00, respectively.
```

C.W. Walter is a member of both Super-K and the LSST project and Super-K has expressed interest (in personal communications) to CWW to supplying direct information to the LSST OCS in whatever form is most appropriate if necessary.

For many years the neutrino community as a whole has being preparing for a galactic supernova through the creation of the Supernova Early Warning System (SNEWS). SNEWS acts as a broker and a blinded system to look for coincidences in time between supernova alarms coming from different neutrino experiments. If one is seen, then they alert the entire astronomical community through several channels. This reduces the false coincidence rate to less than one alert per century. SNEWS can also act as a broker passing alarms from individual experiments to their alert system

SNEWS has several ways of making announcements to the community. They also give a direct connection to the IceCube experiment which benefits from an external trigger. A direct connection to LSST could also be requested. Current alerts include announcements to the GCN (a template is seen below):

```
TITLE:         GCN/SNEWS EVENT NOTICE
NOTICE_DATE:   Tue 26 Jun 18 16:00:08 UT
NOTICE_TYPE:   TEST COINCIDENCE
TRIGGER_NUM:   1000182
EVENT_RA:      Undefined (J2000),
              Undefined (current),
              Undefined (1950)
EVENT_DEC:     Undefined (J2000),
              Undefined (current),
              Undefined (1950)
EVENT_ERROR:   360.0 [deg radius, statistical plus systematic], 68.00% containment
EVENT_FLUENCE: 0 [neutrinos]
EVENT_TIME:    57601.00 SOD {16:00:01.00} UT
EVENT_DATE:    18295 TJD;   177 DOY;   18/06/26
EVENT_DUR:     0.00 [sec]
EXPT:          Detector_A Good, Detector_B Good, Detector_D Possible, Detector_E Good, D
SUN_POSTN:      95.45d {+06h 21m 49s}  +23.34d {+23d 20’ 30"}
SUN_DIST:      Undefined [deg]
MOON_POSTN:    257.26d {+17h 09m 02s}  -19.06d {-19d 03’ 38"}
MOON_DIST:     Undefined [deg]
MOON_ILLUM:    98 [%]
GAL_COORDS:    Undefined,Undefined [deg] galactic lon,lat of the event
ECL_COORDS:    Undefined,Undefined [deg] ecliptic lon,lat of the event
COMMENTS:      SNEWS Event without RA,Dec coordinates.
COMMENTS:      This is a Test COINCIDENCE notice.  It is NOT a Real event.
COMMENTS:      This is a Test COINCIDENCE notice.  The EXPT labels have been anonymized.
COMMENTS:
COMMENTS:      RA,Dec fields undefined.
COMMENTS:      For more information see:
COMMENTS:
```

and email alerts such as the template below.

```
-----BEGIN PGP SIGNED MESSAGE-----
Hash: SHA1

- ---------------------------------------------
*** SNEWS ALERT ***
Coincidence rating: GOLD
Alarms in the coincidence:
Experiment: 5 LVD
Level: GOOD
Time: Jan 02 2006 22:34:37.000000000
Duration:   10.00
No. of signal events:    0.00
Right Ascension:    0.00
Declination:    0.00
Error:  360.10
- ---------------------------------------------
Experiment: 3 SNO
Level: GOOD
Time: Jan 02 2006 22:34:37.000000000
Duration:   10.00
No. of signal events:    0.00
Right Ascension:    0.00
Declination:    0.00
Error:  360.10
- ---------------------------------------------
Experiment: 1 Super-K
Level: POSSIBLE
Time: Jan 02 2006 22:34:37.000000000
Duration:   10.00
No. of signal events:    0.00
Right Ascension:    13.00
Declination:    -3.00
Error:  4.0
- ---------------------------------------------

For information, see web page http://snews.bnl.gov/
-----BEGIN PGP SIGNATURE-----
Version: GnuPG v1.4.9 (GNU/Linux)

iD8DBQFMhguY4A2qNGjfk/cRAp+DAKD2cFdN4aHZomU87XhhA2r7GalWcACgt/oM
ffObwWjd44FA6kx5gx/RLDQ=
```

```
=DtVE
-----END PGP SIGNATURE-----
```

Currently, a fast alarm goes directly from Super-K to the SNEWS system with no human intervention. However, that alarm does not contain pointing information. Now, that information is released only after a virtual meeting of Super-K collaborators to confirm the alarm. However, it is recognized that this step slows down dissemination, so discussion is starting on the best way to pass this information either directly to projects like LSST or through systems like SNEWS.

LSST could decide to require multiple or single experimental alerts, while taking the pointing system from Super-K. In the future, SNEWS is also expected to supply pointing based on triangulation using timing and this information could be combined with the electron scattering signal [17] and [N. Linzer and K. Scholberg in preparation].

3.5 High-level description

We propose a new LSST "Supernova watch mode" that would be triggered by a neutrino supernova alert and would stay engaged for the rest of the observing day. Schematically the sequence of events would be as follows:

- Receive neutrino alert
- Alert is immediately passed to relevant personnel on duty
- If the telescope is not observing (because it is day time or bad weather), if the field is not currently visible, or if the candidate position is too near the Sun at all times, the relevant personnel can override the default strategy
- If the field is visible, or when it becomes visible, preempt all the other observing plans
- Note that if field rises hours after the first alert it might be possible that:
  - The object has already been identified with high certainty in which case the operator on duty may decide for forfeit the opportunity
  - The SN has already brightened, in which case it will be discovered in the first image, assuming good templates exist.
- Verify up-to-date deep templates have been built and are accessible for that sky area in all filters. If there are no recent deep templates available, the continuous exposures taken during the period wanting for the optical signal should be used to build one. In this case, the sensitivity will increase the longer the time between the neutrino and optical signal.
- Choose exposure, filter and dither plan:

  - Filter and exposure plans should be pre-determined in conjunction with relevant experts. We do not currently possess a detailed recommendation. General guidelines are given below.
  - If the search region exceed the LSST pointing size, a dithering strategy covering 99% of the area should be used.

- Observe repeatedly in the region while continuously performing DIA analysis with the template for each short group of exposures and for the stacked nightly visit total at that time

- If CCSN candidates are identified, pass this information to community and event brokers

- Follow the light curve for the rest of the night of observation. This serves several purposes:
  - It will help identify further candidates in case the first candidate was a misidentification
  - It puts the full light-curve on the same calibration basis, facilitating cross-calibration with other instruments which will presumably be following up.

- If no candidate is seen on the first night of observation at the LSST site, the CCSN may have failed, been obscured, or the progenitor star may be so large that the shock wave has not yet broken out of the stellar envelope. A completely automatic response the first night is necessary, but we advise a protocol including consultation with experts and the rest of the community for the next night's observing plan.

3.6 Footprint – pointings, regions and/or constraints

LSST can expect to receive an indicated region of the sky with a target RA and Dec and (for example) and a half angle opening region with a 68% coverage. We advocate covering 99% of the localization area with a strategy of dithered sampling that emphasizes regions with higher probability based on the neutrino data prior. The distance and neutrino luminosity of the CCSN could result in pointing resolution ranging from 1 to several degrees on the sky with a typical 10 kpc supernova being localized to about a 6 degree FOV (twice the opening angle resolution).

3.7 Image quality

The image quality is not relevant. Exposures should be taken if at all possible.

3.8 Individual image depth and/or sky brightness

Single visits have a depth of 23.14, 24.54, 24.20, 23.65, 22.77, 21.92 in ugrizy. Whether single exposures and differences are effective in seeing the transient will depend on the optical brightness. Trade offs in allocation of filter time are likely galactic coordinate dependent as they depend on dust, and an optimal strategy will require further study.

3.9 Co-added image depth and/or total number of visits

As this proposal covers a single night, final multi-year co-added depths are not relevant.

3.10 Number of visits within a night

This mode would be envisioned to completely take over the facility for one dark period after the alarm arrives.

3.11 Distribution of visits over time

This proposal recommends and is relevant to a continuous exposure strategy from as soon as the neutrino alert is received, through identification and announcement and for the rest of the observing night. Possible later followup visits would depend on the nature of the observed CCSN and the perceived need for LSST followup.

3.12 Filter choice

As the CCSN may be located in a high dust region, we prefer that the filter wheel contain the griz and y filters, as the y filter may be particularly useful in that case.

3.13 Exposure constraints

In Figure 7 of [3] Nakumura and all show that the extincted optical signal in the visible for a galactic center CCSN could range from magnitude 5 to 26. The apparent magnitude of the light curve is a strong function of galactic position (shown in Figure 8 of the same paper). A dynamic exposure scheme where the exposure time is shortened for positions of little extinction, or identification of a very bright object could be considered.

3.14 Other constraints

No other relevant constraints. Clearly the target CCSN would need to be visible to LSST to enter a supernova watch mode. Depending on the time of day, and time delay we might enter watch mode as soon as it become dark.

3.15 Estimated time requirement

We expect no more than one night in the 10 year survey would be affected by this program. With an expected rate of 3 per century there is a 22% chance one CCSN would be seen and a 3% chance there could be two.

3.16 Technical trades

Not relevant for this proposal.

4 Performance Evaluation

Not relevant for this proposal. Performance would be measured in successfully identifying and quickly notifying the community of the location of the of the supernova.

5 Special Data Processing

A version of the DIA pipeline would need to be utilized to make the initial identification. As one of the advantages of leveraging LSST for this work is its ability to see CCSNe which have been obscured by dust in the galactic plane, we also advocate building a set of templates in the galactic plane to use if the neutrino signal points us to that region of the sky.

6 Acknowledgments

The authors would like to thank Kate Scholberg of Duke University for information on the SNEWS system and general information on supernova neutrino detection, Evan O'Connor of Stockholm University for very useful information and references related to the modeling of CCSNe and the properties of the progenitor stars and light curves, and the Super-Kamiokande Spokesperson Masayuki Nakahata for information on Super-K performance and plans.

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