Snowmass2021 - Letter of Interest

SNEWS 2.0: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy

NF Topical Groups: (check all that apply □/■)

□ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
□ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (Other) *[CF1, Dark Matter Direct Detection]*

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Abstract: The next core-collapse supernova in the Milky Way or its satellites will represent a once-in-a-generation opportunity to obtain detailed information about the explosion of a star. A core-collapse supernova provides an opportunity for significant scientific insight in a variety of fields because of the extreme conditions in the explosion. Supernovae in our galaxy are not only rare on human timescales but also happen at unscheduled times, so it is crucial that we be alerted early and be ready to use all available instruments to capture the maximum information from the event in all possible channels. The first indication that a star is exploding will be the arrival at Earth of a bright burst of neutrinos. Its observation by multiple neutrino detectors worldwide can provide an unambiguous early warning for the subsequent electromagnetic fireworks, and a trigger to other detectors with significant backgrounds that they should store their recent data. The Supernova Early Warning System (SNEWS) has been operating in automated mode since 2005 as a simple coincidence between neutrino experiments. In the current era of multi-messenger astronomy there are new opportunities for SNEWS to optimize sensitivity to science from the next Galactic supernova beyond such a simple early alert. SNEWS 2.0 will be an upgraded SNEWS with enhanced capabilities exploiting the unique advantages of prompt neutrino detection to maximize the science gained from such a valuable event.

The explosion of a star within the Milky Way Galaxy will provide us with a front row seat of physics under conditions that could never be produced in a terrestrial experiment. While the remnants of the explosion will be observable for many thousands of years, the information about what occurred in the core of the star to cause the explosion will be most easily found in the first minutes and hours. It is imperative that we be able to detect the supernova as soon as it begins.

Expected features in the neutrino signal will permit us to probe key aspects of the supernova explosion mechanism such as the nuclear equation of state, the stellar radius and interior structure, explosive nucleosynthesis, the nature of the remnant core (neutron star vs. black hole), as well as answer questions about the fundamental properties of neutrinos, and even test Beyond-Standard-Model physics. The emission of gravitational waves is strongly dependent on the asymmetry of the collapsing core and the nuclear equation of state. Key aspects of the collapse, from the spin of the collapsed core to the supernova explosion mechanism and black hole formation, can also be probed. The EM radiation from the star begins to change when the supernova shock breaks out of the progenitor surface suddenly releasing a flash of UV and X-rays. The shock breakout can tell us about the radius, mass, and structure of the progenitor star, and the kinematic energy associated with the rapidly expanding ejecta. While each cosmic messenger is valuable by itself, when analyzed together, they provide a comprehensive understanding that is impossible to achieve from any single one of them alone.

Neutrinos escape a supernova explosion well before the EM emission changes and currently have a larger detection range than gravitational waves. Thus they provide the earliest opportunity to anticipate the imminent appearance of a Galactic supernova in time to alert observatories and indicate to gravitational wave detectors to store their recent data. The current Supernova Early Warning System (SNEWS) is an open, public alert system that provides an early warning by combining the detection capabilities of a variety of neutrino detectors worldwide[1]. If several detectors report a neutrino burst within a small time window, SNEWS will issue an alert to its subscribers which include astronomical observatories, neutrino detectors, as well as amateur astronomers and citizen scientists. SNEWS (`https://snews.bnl.gov`) currently involves an international collaboration of neutrino detectors: Super-Kamiokande, LVD, IceCube, Borexino, KamLAND, HALO, and Daya Bay (the NOvA, KM3NeT, and Baksan are testing their connections and will join soon). SNEWS has been operational since 1998 and funded by NSF since 2003. It has been running in a fully-automated mode since 2005 with near-100% up-time. This automated mode allows alarms from individual detectors to go out promptly without needing a human check. The original SNEWS system was designed to give a supernova neutrino alert that was

- **Prompt**, providing an alert within minutes and follow-up within hours;
- **Positive**, with less than one false alarm per century; and
- **Pointing**, providing a sky location by passing along experiments' estimates.

The design was primarily driven by the Positive requirement. Only extremely high quality coincidences could automatically trigger an alert. All other coincidences would require human intervention before an alert could be triggered. While adequate at the time, this requirement no longer needs to dictate the scientific reach of the network.

Since the SNEWS network was first established, the particle astrophysics landscape has evolved considerably. The detection of gravitational waves by LIGO/VIRGO along with electromagnetic observations of a neutron star merger[2], and the subsequent observation of neutrinos from a blazar by IceCube[3], have ushered in a new era of multi-messenger astrophysics. At the same time, neutrino detector technologies and data analysis techniques have progressed in recent years such that the ability of detectors to detect and analyze neutrinos from Galactic supernovae in real time has improved substantially.

SNEWS 2.0 will be an upgrade of the SNEWS system for the age of multi-messenger astronomy. In this environment, false alarms are acceptable, and low probability events should be reported, as SNEWS will be one of many multi-messenger alert systems. Nevertheless, SNEWS remains unique as it is the only alert system which combines data from different neutrino observatories. The functionality of the SNEWS network can be extended in a number of ways with the overarching aim to enhance the overall science obtained from the next galactic core-collapse supernova. Specifically, the goals of SNEWS 2.0 are to:

- reduce the threshold for generating alerts and thus increase the reach in distance and flux sensitivity;
- reduce alert latency;
- enhance the pointing ability by combining information from individual experiments with triangulation via timing differences between detectors;
- implement a pre-supernova alert based on the rising neutrino flux which precedes core-collapse;
- develop a follow-up observing strategy to prepare the astronomical community; and
- engage amateur astronomer and citizen science communities through alert dissemination and outreach.

The general benefit of combining detectors' data real-time would be the lowering of the effective threshold for observing a signal. An astrophysical neutrino signal would be observable in many detectors at once, but might be not strong enough to be significant in any one alone. Since most detectors are already large enough to be sensitive to a core-collapse supernova somewhere in our galaxy, the benefit of lowered thresholds is an enhanced ability to detect supernovae in the Magellanic clouds where the distance is substantial and the flux is borderline for most detectors, and the ability to detect Type Ia and pair-instability supernovae which have smaller and less energetic neutrino fluxes. Combining detector data would also allow better pointing to the source of the neutrinos, either from anisotropy of the interactions in experiments (primarily neutrino-electron scattering)[4;5] or by timing "triangulation" between different experiments[6;7]: the angular resolutions obtained by these methods are sufficient for current EM followups.

SNEWS 2.0 also intends to develop and provide a pre-supernova alert based on the predicted uptick in neutrino production that accompanies the final burning stages of a doomed star[8–10]. This alert has been implemented in KamLAND[11], and provides a $3\,\sigma$ detection 48 hours prior to the explosion of a $25\,\mathrm{M}_\odot$ star at $690\,\mathrm{pc}$. Extending this capability to the entire SNEWS network should expand the sensitivity to a larger fraction of the galaxy. Finally, alerts under SNEWS 2.0 will be accompanied by suggestions for optimized observing strategies and alerts to suitable facilities. Pre-planned strategies for coordinated response of facilities are necessary and detection, location, and information regarding explosion type (e.g., formation of neutron star vs. black hole) will inform the strategies to maximize scientific return. Having observing strategies that leverage an observing alliance of professional and amateur observers that join the SNEWS 2.0 response network will maximize use of available technological resources while reducing redundancy and missed observing opportunities.

The SuperNova Early Warning System is one of the oldest multi-messenger astronomy networks, set up to provide advance warning of the next galactic core collapse supernova by looking for coincident bursts in multiple neutrino detectors around the world. Since its construction, the ability of astronomers to follow-up astrophysical transients has changed dramatically and modern multi-messenger astronomy is a burgeoning field across many messengers. The experience gained from successes in simultaneous detection of gamma ray bursts[12], gravitational waves[13], and ultra-high energy neutrinos[14] can be applied to creating a new "SNEWS 2.0" network capable of delivering more and better neutrino-based information reliably and promptly thus enabling the extraction of the best science possible from the next nearby supernova.

References

[1] P. Antonioli *et al.*, New J. Phys. **6**, 114 (2004), arXiv:astro-ph/0406214 [astro-ph] .

[2] B. P. Abbott *et al.* (GROND, SALT Group, OzGrav, DFN, DES, INTEGRAL, Virgo, Insight-Hxmt, MAXI Team, Fermi-LAT, J-GEM, RATIR, IceCube, CAASTRO, LWA, ePESSTO, GRAWITA, RIMAS, SKA South Africa/MeerKAT, H.E.S.S., 1M2H Team, IKI-GW Follow-up, Fermi GBM, Pi of Sky, DWF (Deeper Wider Faster Program), MASTER, AstroSat Cadmium Zinc Telluride Imager Team, Swift, Pierre Auger, ASKAP, VINROUGE, JAGWAR, Chandra Team at McGill University, TTU-NRAO, GROWTH, AGILE Team, MWA, ATCA, AST3, TOROS, Pan-STARRS, NuSTAR, ATLAS Telescopes, BOOTES, CaltechNRAO, LIGO Scientific, High Time Resolution Universe Survey, Nordic Optical Telescope, Las Cumbres Observatory Group, TZAC Consortium, LOFAR, IPN, DLT40, Texas Tech University, HAWC, ANTARES, KU, Dark Energy Camera GW-EM, CALET, Euro VLBI Team, ALMA), Astrophys. J. **848**, L12 (2017), arXiv:1710.05833 [astro-ph.HE] .

[3] M. G. Aartsen *et al.* (Liverpool Telescope, MAGIC, H.E.S.S., AGILE, Kiso, VLA/17B-403, INTEGRAL, Kapteyn, Subaru, HAWC, Fermi-LAT, ASAS-SN, VERITAS, Kanata, IceCube, Swift NuSTAR), Science **361**, eaat1378 (2018), arXiv:1807.08816 [astro-ph.HE] .

[4] J. F. Beacom and P. Vogel, Phys. Rev. **D60**, 033007 (1999), arXiv:astro-ph/9811350 [astro-ph] .

[5] R. Tomas, D. Semikoz, G. Raffelt, M. Kachelriess, and A. Dighe, Phys. Rev. D **68**, 093013 (2003), arXiv:hep-ph/0307050 .

[6] V. Brdar, M. Lindner, and X.-J. Xu, JCAP **1804**, 025 (2018), arXiv:1802.02577 [hep-ph] .

[7] N. Linzer and K. Scholberg, Phys. Rev. D **100**, 103005 (2019), arXiv:1909.03151 [astro-ph.IM] .

[8] A. Odrzywolek, M. Misiaszek, and M. Kutschera, Astropart. Phys. **21**, 303 (2004), arXiv:astro-ph/0311012 [astro-ph] .

[9] C. Kato, H. Nagakura, S. Furusawa, K. Takahashi, H. Umeda, T. Yoshida, K. Ishidoshiro, and S. Yamada, Astrophys. J. **848**, 48 (2017), arXiv:1704.05480 [astro-ph.HE] .

[10] K. M. Patton, C. Lunardini, and R. J. Farmer, Astrophys. J. **840**, 2 (2017), arXiv:1511.02820 [astro-ph.SR] .

[11] K. Asakura *et al.* (KamLAND), Astrophys. J. **818**, 91 (2016), arXiv:1506.01175 [astro-ph.HE] .

[12] S. D. Barthelmy, P. Butterworth, T. L. Cline, N. Gehrels, G. J. Fishman, C. Kouveliotou, and C. A. Meegan, Astrophysics and Space Science **231**, 235 (1995).

[13] B. Abbott *et al.* (KAGRA, LIGO Scientific, VIRGO), Living Rev. Rel. **21**, 3 (2018), arXiv:1304.0670 [gr-qc] .

[14] M. Aartsen *et al.* (IceCube), Astropart. Phys. **92**, 30 (2017), arXiv:1612.06028 [astro-ph.HE] .

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