Snowmass2021 - Letter of Interest

Monitoring Galactic core-collapse supernova neutrinos with IceCube and IceCube-Gen2

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) (CF7) Cosmic Probes of Fundamental Physics

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Abstract:

The next Galactic core-collapse supernova will be an unprecedented opportunity for multi-messenger observations of the death of a massive star. It will not only provide the first real-time measurements of the phase change of a stellar core into a neutron star or a black hole, but also yield evidence (or an absence of evidence) for a number of well-motivated extensions of the Standard Model. For multi-wavelength follow-up of the collapse, measurements of supernova neutrinos provide a crucial early warning to prepare for observations of the shock breakout and early post-explosion phase. During the past decade, the IceCube Neutrino Observatory has provided a high-statistics, $> 99\%$-uptime monitor for supernova neutrinos. With the proposed extension of IceCube in the coming decade, IceCube-Gen2, the observatory will enhance its supernova monitoring by doubling its photocathode area, improving its resolution of the supernova neutrino energy spectrum, and significantly reducing detector backgrounds. IceCube and IceCube-Gen2 will play a leading role in the search for these very rare and scientifically priceless astrophysical events.

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Supernova Detection with IceCube and IceCube-Gen2

Core-collapse supernovae (CCSNe) are triggered by the collapse of the iron cores of massive stars at the end of their supergiant phase. A CCSN in the Milky Way will provide a unique multi-messenger probe of the death of a star, and will be a rich laboratory for fundamental physics. Neutrinos play a major role driving the explosion and cooling the stellar remnant after core collapse[1–5], with 99% of the gravitational binding energy of the stellar remnant converted into neutrinos of average energy 10-20 MeV[1]. The neutrino burst occurs in three stages: (1) an intense flash of ν_e due to electron capture, lasting ~ 10 ms; (2) production of ν_e and $\bar{\nu}_e$ over ~ 1 s as matter accreting on the remnant cools via neutrino emission; and (3) a cooling tail detectable for ~ 10 s to 100 s as the core, now a protoneutron star, emits neutrinos of all flavors.

The IceCube Neutrino Observatory is a cubic-kilometer scale neutrino detector embedded 1.4 km below the surface of the clear glacial ice at the South Pole[6;7]. The detector is optimized to reconstruct neutrinos above 10 GeV, but due to its large volume and the cold environment, it is sensitive to the inverse beta decay of $\bar{\nu}_e$ events from the accretion and cooling phases of a core collapse[8;9]. Although the Cherenkov light produced by individual $\bar{\nu}_e$ interactions is insufficient to reconstruct individual supernova neutrinos in IceCube, the supernova $\bar{\nu}_e$ burst will produce a significant correlated rise above background in hit rates in the detector. The hits above background provide a detailed neutrino light curve from a core-collapse supernova in the Milky Way.

High-Statistics Measurements of Accretion and Cooling

The predicted neutrino flux from a supernova can easily vary by an order of magnitude or more[10–12], with predictions affected by astrophysical uncertainties such as the mass and equation of state of the stellar progenitor[13–15], the distance to the progenitor[9;16], and the details of supernova simulation codes. Thus, high statistics are crucial. Due to its volume, IceCube will record Galactic supernova neutrinos with excellent sensitivity regardless of the details of the explosion or its location in the Milky Way[16].

High-Uptime Monitoring for Local CCSNe

The rate of Galactic CCSNe is thought to be 1-2 per century, but the last optically-observed core collapse supernova in the Milky Way occurred over 400 years ago. The next such event will be a once-in-a-lifetime opportunity, making continuous monitoring essential. The IceCube detector has an uptime in excess of 99.7% for supernova monitoring[16;17], and it provides crucial early-warning capability for optical follow-up. IceCube is a key component of the SuperNova Early Warning System (SNEWS)[18;19], a network of neutrino detectors monitoring the neutrino sky for nearby CCSNe.

IceCube and IceCube-Gen2: Current and Future Capabilities

During the next decade, improvements to supernova searches in IceCube[20] and the commissioning of the proposed IceCube-Gen2 detector[21] will greatly enhance the value of a supernova neutrino detection.

- IceCube has improved the model independence of its online supernova trigger using an adaptive/self-learning algorithm[22], and has achieved sub-ms precision in its light curve with a triggered offline supernova analysis[20].
- With the multi-anode design of the photosensors in IceCube-Gen2, the observatory will provide strong constraints on the mean energy and shape of the supernova neutrino spectrum. The resolution of the mean energy will improve from $> 25\%$ in IceCube to 5% in IceCube-Gen2[23].
- The enhanced background reduction made possible with multi-anode sensors will grow the CCSN detection horizon from ~ 80 kpc in IceCube to ~ 300 kpc in IceCube-Gen2[23]. This not only provides much higher sensitivity to CCSN neutrinos from the Milky Way and the Magellanic Clouds, but also increases the time IceCube can observe the neutrinos in the cooling tail, when the stellar core transitions to a neutron star or a black hole[5].

Sensitivity to Fundamental Neutrino Properties

Neutrino oscillation and mixing effects are imprinted on the supernova neutrino light curve, allowing us to probe the properties of neutrinos with IceCube, IceCube-Gen2, and other large neutrino detectors.

- Mass hierarchy. Standard MSW mixing in the dense material of a supernova efficiently converts neutrinos into definite mass eigenstates. The final states will depend on the mass hierarchy[24;25], so a CCSN signal in IceCube has excellent sensitivity to discriminate between normal and inverted mass ordering[9].
- Unique oscillation effects. Supernova neutrinos probe effects that occur only at extreme densities and energies not accessible in the laboratory, such as collective oscillations from neutrino self-coupling[26;27].

Multimessenger Physics

- Black hole formation. In the most massive stars, a core collapse is expected to create a black hole, visible in neutrinos as a sudden cutoff in the neutrino emission. Such a "failed supernova" may only be observable in neutrinos, though there is the exciting possibility it would be a multi-messenger neutrino and gravitational wave (GW) event[28–32].
- CCSN Localization. A sharp cutoff in neutrino emission due to black hole formation would enable excellent localization of the event using IceCube in combination with other detectors[33–35].
- Measurement of GW properties. The sharp time structure in the neutrino flux caused by black hole formation would yield a sensitive measurement of the propagation speed of gravitational waves[36].
- Phase transitions in the protoneutron star. IceCube is particularly sensitive to temporal structures in the accretion-phase and late-time neutrino signal of a CCSN[37]. A phase transition in the protoneutron star from hadronic matter to quark matter[2;38–42] would produce a second collapse and neutrino burst easily visible in IceCube[9] and potentially GW detectors.
- Protoneutron star rotational modes. In CCSNe with significant rotation in the protoneutron star, neutrinos detected in IceCube, alone or with GWs, could be used to probe the rotational modes of the system[43;44].
- Signatures of hydrodynamical effects. Standing accretion shock instability (SASI) oscillations[44–48] would be observed easily in IceCube and IceCube-Gen2[20]. Not all simulated explosions produce SASI oscillations[49;50], so a non-observation would be an invaluable constraint on CCSN models.

Exotic Nuclear Physics and Searches Beyond the Standard Model

- Protoneutron star equation of state. Neutrinos act as cosmic probes and provide insight into the physics of the supernova and properties of the resulting protoneutron star[14;15]. IceCube measurements of the accretion phase and cooling tail will be sensitive probes of these properties.
- Probing matter in extreme states. "Pasta-like" structures of nucleons may significantly increase neutrino scattering in the interior of the protoneutron star[47;51–53]. The increased opacity would produce a corresponding increase in the timescale of neutrino cooling and lengthen the cooling tail well beyond 10 s. The improved backgroud rejection capability of IceCube-Gen2 will be key to exploring this scenario.
- Searches for axions and axion-like particles (ALPS). Axions would compete with neutrinos to cool the explosion, reducing neutrino emission in the cooling tail[47;54–61]. IceCube and IceCube-Gen2 can conduct "neutrino disappearance" searches that are sensitive to axion production[22] and are complementary to "photon appearance" searches with gamma-ray detectors[62–65].
- Searches for sterile neutrinos. Even for very small active-sterile mixing angles, MSW resonances could produce significant quantities of sterile neutrinos in a supernova[66;67]. IceCube is sensitive via $\bar{\nu}_e$ disappearance or, conversely, could contribute to a multi-messenger detection of excess gamma rays and daughter $\bar{\nu}_e$ events in the neutrino flux[68;69].

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