Prospects for the Detection of the Standing Accretion Shock Instability in IceCube-Gen2

Jakob Beise[a,*] **on behalf of the IceCube-Gen2 Collaboration**

[a]*Department of Physics and Astronomy, Uppsala University, Box 516, S-75120 Uppsala, Sweden*

E-mail: jakob.beise@icecube.wisc.edu

Core-collapse supernovae (CCSNe) are among the most energetic processes in our Universe and are crucial for the understanding of the formation and chemical composition of the Universe. The precise measurement of the neutrino light curve from CCSNe is crucial to understanding the hydrodynamics and fundamental processes that drive CCSNe. The IceCube Neutrino Observatory has mass-independent sensitivity within the Milky Way and some sensitivity to the higher mass CCSNe in the Large and Small Magellanic clouds. The envisaged large-scale extension of the IceCube detector, IceCube-Gen2, opens the possibility for new sensor design and trigger concepts that could increase the number of neutrinos detected from a CCSNe burst compared to IceCube. In this contribution, we study how wavelength-shifting technology can be used in IceCube-Gen2 to measure the fast modulations of the neutrino signal due to standing accretion shock instabilities (SASI).

*Speaker

1. Introduction

The IceCube Neutrino Observatory [1] is a Cherenkov detector instrumenting 1 km of glacial ice at the geographical South Pole. Consisting of 5160 optical sensors on 86 vertical cables, called "strings", buried 1450 m to 2450 m underneath the ice, IceCube has detected neutrinos ranging in energy from GeV to PeV. Though IceCube's primary strength is the study of high-energy astrophysical neutrinos and their sources, IceCube has sensitivity to MeV supernova (SN) neutrinos on a statistical basis.

IceCube is primarily sensitive to the $\overline{\nu}_e$ flux which produces positrons via inverse-beta decay. Due to the sparse detector instrumentation, Cherenkov photons generated by individual secondary positrons will be picked up by at most one Digital Optical Module (DOM) in the vast majority of cases with a sensor dark noise rate of about 540 Hz per DOM. Instead, a galactic CCSNe can be observed as an excess of the collective detector rate over the background for a few 10 s during the accretion and cooling phase of a CCSNe [2]. Ultimately, for SN detection in IceCube, the signal-to-noise ratio is paramount. IceCube can neither identify the neutrino flavour nor reconstruct the direction in the low-energy regime. On the other hand, due to the high statistics of the detected signal, IceCube has excellent resolution for detecting fast-time features in the supernova light curve [2]. IceCube has sensitivity above 10σ independent of the progenitor mass within the entire Milky Way and limited sensitivity in the Large and Small Magellanic Clouds (LMC and SMC) [2].

IceCube-Gen2 [3] is an envisioned large-scale extension adding a total of 9,600 new optical sensors on 120 new vertical "strings" with 80 modules each, spanning depths between 1369 m and 2689 m (see Fig. 1a). With a vertical spacing of 17 m and horizontal spacing of 240 m the detector is too sparse to observe a single inverse-beta decay in more than one module. IceCube-Gen2 will utilize segmented sensors housing multiple, small-diameter Photomultiplier Tubes (PMT) which, given the increased photocathode area, will enhance photon collection as well as sensor noise suppression. This will extend the sensitivity to low mass CCSNe out to the LMC and SMC [3, 4].

Wavelength shifters (WLS) shift the UV contribution of the Cherenkov spectrum into the visible regime, thereby augmenting the photon collection of a module. Because of the relatively small read-out PMTs little sensor noise is added, which further improves the signal-to-noise ratio in SN detection. A Wavelength-Shifting Optical Module (WOM) [5, 6] is currently developed and a total of 12 modules will be deployed in the IceCube Upgrade [7], a planned dense infill of roughly 700 new sensors in the DeepCore region targeted to improve detector calibration and obtaining world leading measurements on neutrino oscillations. For IceCube-Gen2, WLS tubes as an add-on to the already planned segmented sensors (see Fig. 1b) have been discussed as a cost-efficient photon collector. Such a passive component would operate without electronics or PMT readout and instead be viewed by PMTs on another module. Because of the absence of a pressure housing, these tubes would be more efficient and larger geometries could be achievable. In addition, the only noise contribution of the WLS tubes would come from radioactive decays in the tube material.

In Ref. [8] it was noted, that WLS can improve the sensitivity towards detecting CCSNe. In this contribution, we study the capability to distinguish a SN light curve featuring the fast, time-varying standing accretion shock instability (SASI), arising from hydrodynamical instabilities during the CCSN accretion phase, from a "flat" light curve exhibiting no modulations. Section 2 describes the analysis method, Sec. 3 presents the results and in Sec. 4 we summarise our findings.
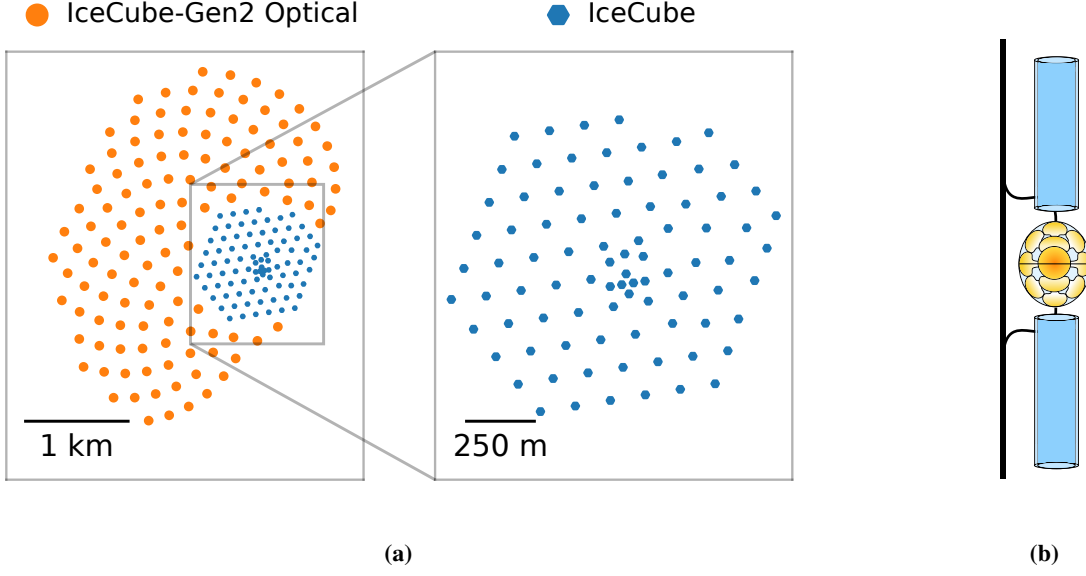
(a)   **(b)**

Figure 1: (a) Top view of the planned, sunflower-shaped IceCube-Gen2 optical array (left) and the current IceCube detector layout (right). Figure adapted from [3]. (b) Sketch of two WLS tubes mounted above and below a mDOM module. The figure is not to scale.

2. Analysis

For this study we use `SNEWPY` [9] to simulate the initial neutrino flux of the Tamborra 2014 $20\,M_\odot$ model [10] during the entire simulation window from 6 ms to 338 ms post-bounce. The default case in this study assumes the optimistic case of no flavour mixing. We use `ASTERIA` [11] to simulate the detector response for three detector geometries which we will refer to as IceCube (incl. DeepCore), Gen2 (IceCube-Gen2 excluding WLS) and Gen2+WLS (IceCube-Gen2 including WLS) in the following. The baseline design for IceCube-Gen2 uses Long Optical Modules (LOMs) [3, 12], multi-PMT modules that are optimised for low-power consumption and that fit narrower bore holes. However, since the properties of the LOM are still being characterised we use the multi-PMT Digital Optical Module (mDOM) [3, 13] in this study. The WLS component of this study considers a 2 m long tube with an outer diameter of 256 mm, a tube thickness of 10 mm and the same material properties as the inner tube of the WOM [5].

The time-dependent number of detected photons from a CCSN in all detector components can be expressed as the double sum over all neutrino and antineutrinos of all flavours $l = e, \mu, \tau$ and detector components i of the product of the time-dependent neutrino density $n_{\nu_l}(t)$, the number of modules m_i, the energy-dependent number of radiated Cherenkov photons $N_{\gamma,l}(E_l)$ by a lepton of energy E_l and the depths-averaged, single photon effective volume $\overline{V_{\gamma,i}^{\text{eff}}}$ [2]:

$$N_{\text{SN}}(t) = \sum_l \sum_i n_{\nu_l} \cdot m_i \cdot \epsilon_{\tau,i} \cdot N_{\gamma,l} \cdot \overline{V_{\gamma,i}^{\text{eff}}}, \tag{1}$$

where $\epsilon_{\tau,i}(R_{\text{SN}}) = \epsilon_{\tau,i}^{\max}/(1 + R_{\text{SN}}\tau)$ is the rate-dependent dead-time efficiency for a non-paralysing dead time τ. The number of background hits during a time window Δt is the sum over all noise rates $R_{\tau,i}$:

$$N_{\text{bkg}} = \sum_i m_i \cdot \Delta t \cdot R_{\tau,i} \,. \tag{2}$$

Table 1: Characteristics of the modules considered in this study. For Gen2 and Gen2+WLS we consider the IceCube geometry together with the indicated number of additional sensors. $\epsilon_\tau^{\max}$ is simulated for a 250 µs dead time.

geometry	module	m	$\overline{V_\gamma^{\text{eff}}}$ [m³]	R_τ [Hz]	$\epsilon_\tau^{\max}$ [%]
IceCube	DOM	4800	0.17	285	88.3
	HQE DOM	360	0.23	359	84.6
Gen2	+ mDOM	9760	0.33	2300	95.8
Gen2+WLS	+ mDOM + 2 WLS	9760	0.60	2700	95.8

Table 1 lists all relevant data for the modules considered in this study. For IceCube, we simulate a combination of DOMs and high quantum efficiency (HQE) DOMs. For Gen2, we add about 10,000 additional mDOMs, while in the case of Gen2+WLS those mDOMs are complemented by two WLS tubes: one above and one below the mDOM (see Fig. 1b). The WLS component nearly doubles the effective volume, while the noise rate only increases by 400 Hz, or 17%. For the time resolution we chose $\Delta t = 1$ ms.

We denote H_0, the null hypothesis, as the case in which a CCSNe is detected but whose light curve *does not* feature SASI modulations, and H_1, the signal hypothesis, as the case in which a CCSNe is detected and whose light curve *does* feature SASI modulations. Fig. 2 (left) shows the number of detected photons in IceCube for the Tamborra 2014 20 M$_\odot$ model [10] at 10 kpc corrected by the average background rate. We take the discrete Fourier transform of the 1 ms-binned light curves of H_0 and H_1 and compute the power spectrum (see Fig. 2 right). To construct the test statistic (TS) distribution we select the maximum in the power spectrum for frequencies larger than 75 Hz for 10,000 random noise realisations. This cutoff frequency is motivated by the 80 Hz SASI frequency predicted in Ref. [10].
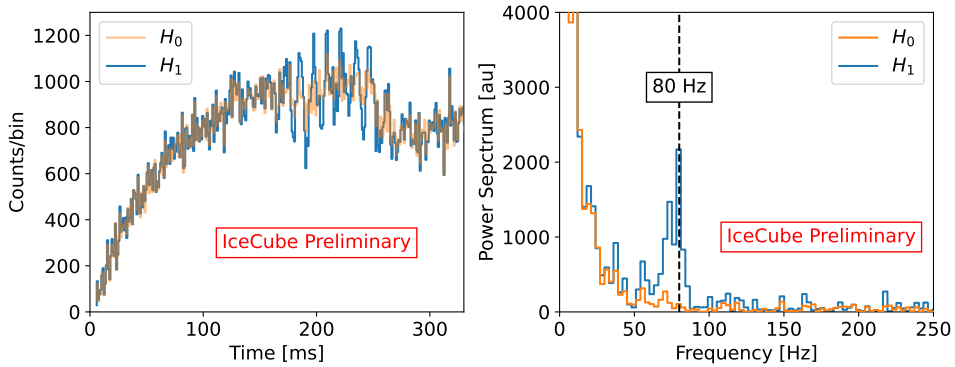

Figure 2: (Left): Number of hits in IceCube for the Tamborra 2014 20 M$_\odot$ model [10] at 10 kpc. (Right): Power density spectrum for the same model. The null hypothesis H_0 is shown in blue and the signal hypothesis H_1 in orange.

3. Results

When we repeat the procedure over a range of source distances for H_0 and H_1 we obtain Fig. 3 (left), which displays the median (line) and 16% to 84% quantiles (size of error bars) of the TS distribution as a function of distance. We note that the error bars for the signal hypothesis are not displayed to improve visibility. We can directly infer the p-value and two-sided significance of the deviation which is plotted in Fig. 3 (right), where the coloured bands indicate the 16% and 84% quantiles. We also show the cumulative galactic CCSNe distribution from Ref. [14] to translate the increase in reach into coverage. As can be seen, IceCube-Gen2 with WLS will cover more than 98.5% of the Milky Way at 5σ compared to 82.8% in IceCube alone.
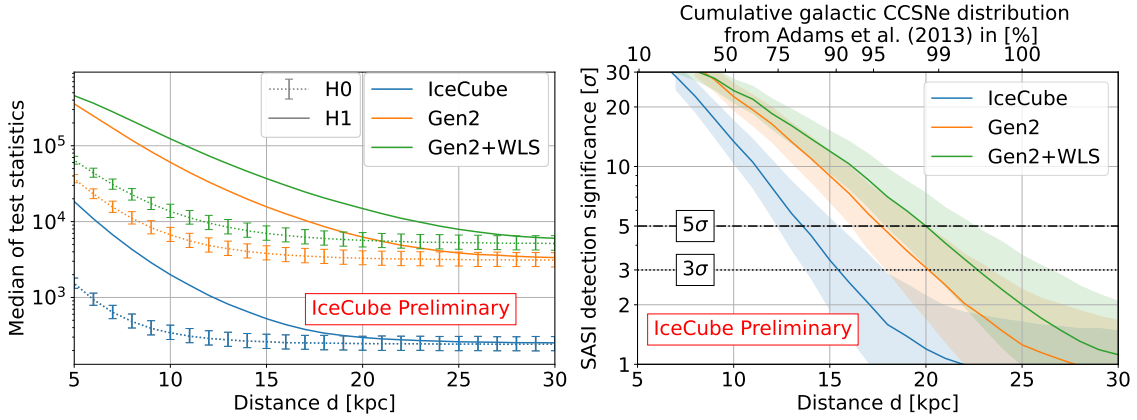

Figure 3: (Left) Median and 16%-84% quantiles of the H_0/H_1 TS distribution as a function of progenitor distance. (Right) SASI detection significance over distance shown for IceCube, Gen2 and Gen2+WLS.

We note that the results obtained are sensitive to the analysis method and analysis cuts set, the assumed neutrino flavour mixing and the CCSNe model. Regarding the analysis cuts, we ran the same analysis with tighter frequency cuts (75 Hz $< f <$ 85 Hz), time windows centred around the SASI period (150 ms $< f <$ 300 ms) and a combination of both. For the flavour mixing, we considered the most pessimistic case of complete flavour exchange as well as the MSW effect for normal and inverted hierarchy. Finally, we also considered the Tamborra 2014 27 $M_\odot$ model [10] for three different observer directions d_1, d_2, d_3 relative to the SASI plane.

Figure 4 shows the 5σ significance horizon as well as the galactic CCSNe coverage for all considered simulation setups. The results of Fig. 3 are shown as "Default", while the adaptation from that setting is indicated on the x-axis. We find that the stronger the analysis cut, the larger the reach but the lesser the capability to generalise the study to different models. We also find that a more realistic treatment of flavour conversion results in decreased coverage. Finally, the 27 $M_\odot$ model yields a much-reduced significance horizon.

4. Conclusion

IceCube has a unique capability to observe small-scale modulations of the CCSN light curve with high precision giving valuable insights into the hydrodynamics of exploding stars. In this
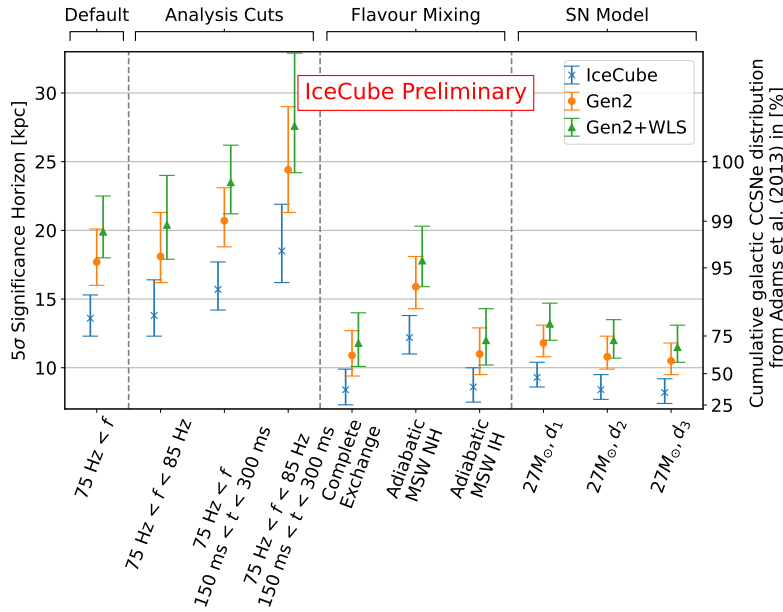
Figure 4: Compilation of all systematic modification to the default setting.

contribution, we demonstrated the potential of IceCube-Gen2 and the use of wavelength shifters to detect the effect of SASI on the SN light curve. While the improvement of adding WLS is marginal for the detection of SASI, which is already a significantly strong signal in IceCube-Gen2, there are potential opportunities to enhance fainter signals of fast-time variations (i.e. from rotational CCSNe). The procedure outlined here can also be further used for studies of generic models of SASI modulation such as a neutrino light curve with a custom frequency and amplitude.

References

[1] IceCube collaboration, *The IceCube Neutrino Observatory: Instrumentation and Online Systems*, *JINST* **12** (2017) P03012 [1612.05093].

[2] IceCube collaboration, *IceCube Sensitivity for Low-Energy Neutrinos from Nearby Supernovae*, *A&A* **535** (2011) A109 [1108.0171].

[3] IceCube-Gen2 collaboration, A. Abbasi et al., *IceCube-Gen2 Technical Design*, 2023.

[4] L. Mariscal et al., *Sensitivity of multi-PMT optical modules in Antarctic ice to supernova neutrinos of MeV energy*, *EPJ C* **81** (2021) 1058 [2106.14199].

[5] B. Bastian-Querner et al., *The Wavelength-Shifting Optical Module*, *Sensors* **22** (2022) .

[6] J. Rack-Helleis et al., *The Wavelength-shifting Optical Module for the IceCube Upgrade*, *PoS* **395** (2022) 1038.

[7] A. Ishihara, *The IceCube Upgrade-Design and Science Goals*, *PoS* **358** (2019) 1031.

[8] Y. Popovych et al., *The Wavelength-Shifting Optical Module in Application to the IceCube Neutrino Observatory*, *PoS* **444** (2023) 992.

[9] SNEWS collaboration, *SNEWPY: A Data Pipeline from Supernova Simulations to Neutrino Signals*, *ApJ* **925** (2022) 107 [2109.08188].

[10] I. Tamborra et al., *Neutrino emission characteristics and detection opportunities based on three-dimensional supernova simulations*, *Phys. Rev. D* **90** (2014) 045032.

[11] S. Griswold et al., *ASTERIA: A Supernova TEst Routine for IceCube Analysis*, July, 2020. 10.5281/zenodo.3926835.

[12] V. Basu et al., *A next-generation optical sensor for IceCube-Gen2*, *PoS* **395** (2021) 1062.

[13] M. Kossatz et al., *The mDOM - A multi-PMT Digital Optical Module for the IceCube-Gen2 neutrino telescope*, *PoS* **301** (2017) 1047.

[14] S.M. Adams et al., *Observing the Next Galactic Supernova*, *ApJ* **778** (2013) 164.