The Progenitor Dependence of the Preexplosion Neutrino Emission in Core-Collapse Supernovae

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ABSTRACT

We perform spherically-symmetric, general-relativistic, neutrino-radiation transport simulations of core collapse and the postbounce preexplosion phase in 32 presupernova stellar models of solar metallicity with zero-age-main-sequence masses of 12 to 120 solar masses. We show that the emitted neutrino luminosities and spectra follow very systematic trends that are correlated with the compactness of the progenitor star's inner regions via the accretion rate in the preexplosion phase. We investigate the simulated response of water Cherenkov detectors to the electron antineutrino fluxes from our models and find that the large statistics of a galactic core collapse event may allow robust conclusions on the inner structure of the progenitor star.

INTRODUCTION

Neutrinos play a pivotal and dominant role in stellar collapse and core-collapse supernovae. Neutrinos and antineutrinos of all flavors carry away the ~300 B (= 3×10^{53} ergs) of gravitational binding energy of the remnant neutron star over tens of seconds after core bounce.

For a galactic or near-extragalactic core-collapse supernova, neutrinos offer the unique possibility of directly observing the dynamics and thermodynamic conditions prevalent in the supernova core.

In this poster, we present the work of O'Connor and Ott (2012). We perform 1D general relativistic radiation-hydrodynamics core collapse simulations of 32 progenitor models from the single-star solar-metallicity presupernova model suite of Woosley & Heger (2007) and follow the postbounce preexplosion evolution for 450 ms. We look at the progenitor dependence of the neutrino signature.

MODELS AND METHODS

We make use of the open-source 1D general relativistic hydrodynamics code GR1D (O'Connor & Ott 2010; available at `http://www.stellarcollapse.org`) outfitted with an energy-dependent multi-species M1 neutrino transport scheme in which the zeroth and first moments of the neutrino distribution function are evolved.

Our M1 scheme closely follows Shibata et al. (2011), who formulate the M1 evolution equations in a closed covariant form. The evolution equation for the energy-dependent neutrino distribution moments are

$$\boxed{\partial_t E_{(\nu)} + \frac{1}{r^2}\partial_r\left(\frac{\alpha r^2}{X^2} F_{r,(\nu)}\right) = \alpha^2 \mathcal{S}^t_{(\nu)},} \quad (1)$$

$$\boxed{\partial_t F_{r,(\nu)} + \frac{1}{r^2}\partial_r\left(\frac{\alpha r^2}{X^2} P_{rr,(\nu)}\right) = \alpha X^2 \mathcal{S}^r_{(\nu)} + \alpha\frac{E_{(\nu)}(1-p_{(\nu)})}{r}} \quad (2)$$

we use a closure relation for estimating the Eddington tensor and we use NuLib (`http://www.nulib.org`) to calculate the neutrino source terms S^t and S^r. For full details, see O'Connor and Ott (2012).

CONCLUSIONS:

The next nearby core-collapse supernova will be extremely well observed in neutrinos. Super-Kamiokande alone will observe ~7000 electron antineutrinos from a typical core-collapse supernova at a fiducial galactic distance of 10kpc. Future detectors of the scale of the proposed Hyper-Kamiokande may see in excess of 10^5 interactions. Such high-statistics observations will provide rich information on the neutrino signal.

In this study, our focus has been on the imprint of the progenitor star's structure on the neutrino signal in the postbounce preexplosion phase of core-collapse supernovae. Our results show that preexplosion neutrino signal has an essentially monotonic dependence on progenitor structure described by a single parameter, the compactness. The monotonic dependence of the preexplosion neutrino emission on progenitor compactness translates directly to the neutrino signal observed by detectors. Neutrino observations of the next nearby core collapse event thus may, in principle, allow quantitative constraints on the inner structure of the progenitor star.

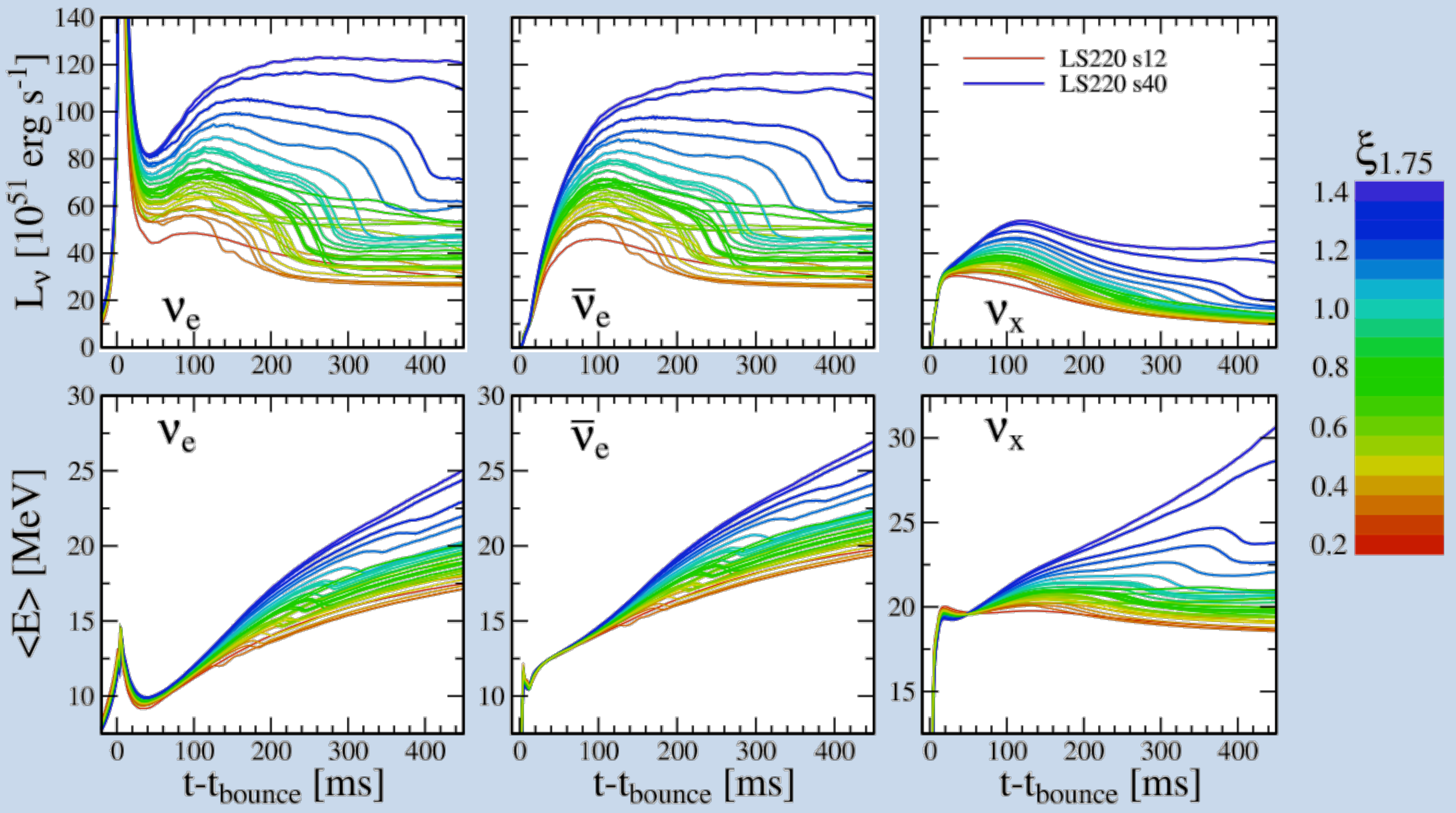

Figure 1: Neutrino luminosities (top panels) and average energies (bottom panels) plotted as a function of postbounce time for all 32models. The left, center, and right panels show results for ν_e, anti-ν_e, and ν_x, respectively. The curves are color- and line-weight-coded with increasing compactness ($\xi_{1.75}$), the mapping from color to compactness parameter is shown on the right. There is a clear trend in all luminosities and average energies with compactness parameter. The steep drop in luminosity observed for some models models here is due to the sudden decrease of the accretion rate when the silicon--oxygen interface reaches the stalled shock.

RESULTS

We find that the neutrino luminosities and average energies during the preexplosion phase of core-collapse supernovae are closely related to the compactness of the progenitor star. We define compactness in Equation (3), chose M=1.75 as a typical protoneutron star mass, and measure $\xi_{1.75}$ at bounce. Progenitors with *high compactness* have *higher postbounce accretion rates* and consequently *higher accretion luminosities* as seen in Figure 1. We make the important note that the compactness is not a monotonic function of ZAMS mass, rather, it sensitively depends on the advanced burning stages of stellar evolution.

$$\boxed{\xi_M = \left.\frac{M/M_{sun}}{R(M_{bary}=M)/1000km}\right|_{t=t_{bounce}}} \quad (3)$$

The close relation between the progenitor star's structure at the onset of collapse and the preexplosion phase neutrino luminosities allows us to connect the observed neutrino signal from a galactic or near-galactic core-collapse supernova to properties of the progenitor star. To predict the observed signal on Earth from each of our models, we use the publicly available software SNOwGLObES (`http://www.phy.duke.edu/~schol/snowglobes/`). Using SNOwGLObES, we calculate the expected number of inverse b-decay interactions in a Super-Kamiokande-like water Cherenkov detector assuming a fiducial galactic distance of 10kpc. As can be seen in Figure 2, the number of events observed in the first few 100s of ms is a direct measure of the compactness of the progenitor core. For example, a core-collapse supernova at 10kpc in a Super-Kamiokande-like water Cherenkov detector with a progenitor similar to s40WH07 predicts ~2500 IBD events in the first 200ms, while the s12WH07 progenitor predicts only ~1000.

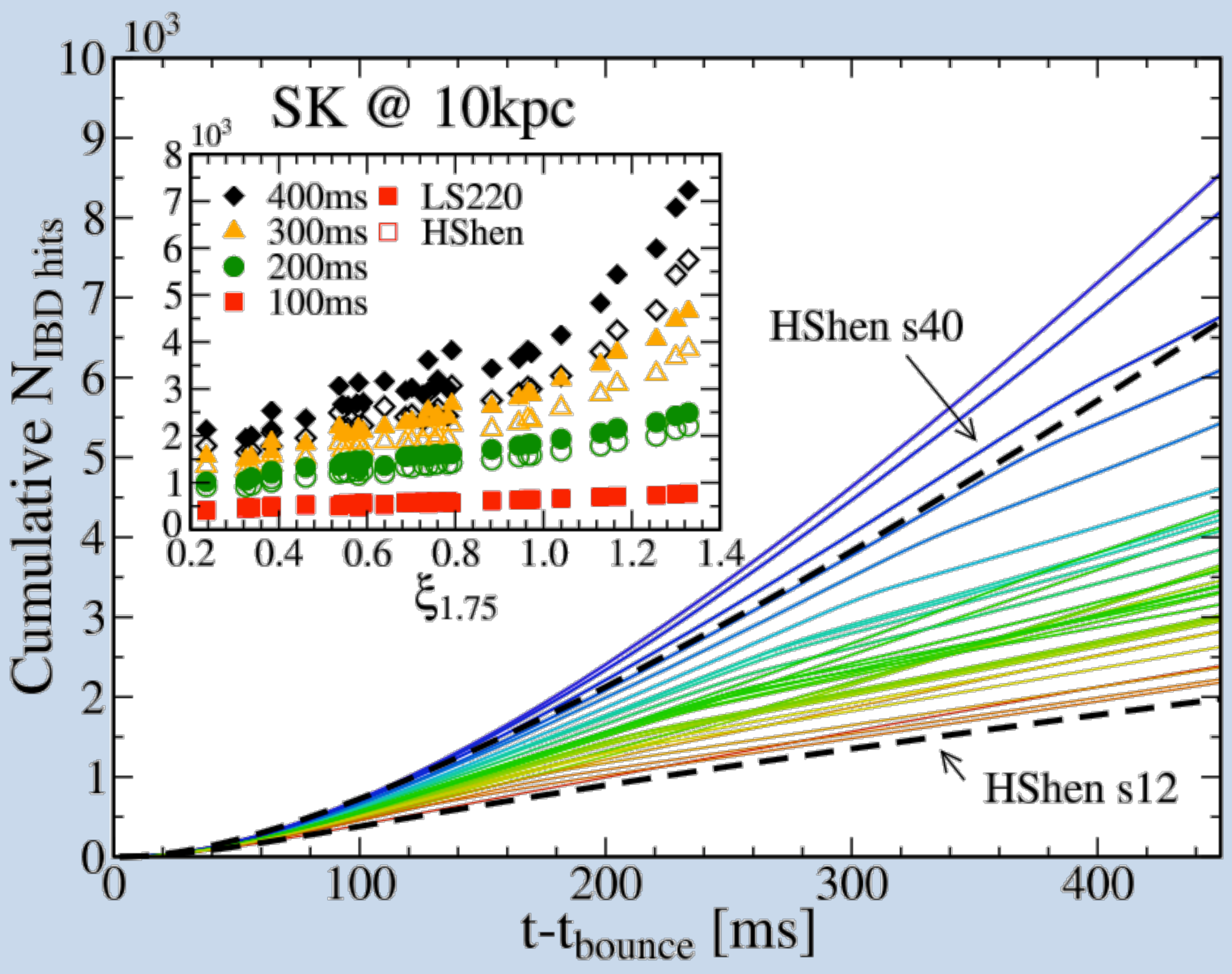

Figure 2: Cumulative inverse β-decay (IBD) interactions in a Super-Kamiokande-like water Cherenkov detector at a fiducial galactic distance of 10kpc versus postbounce time. We use the SNOwGLoBES package to determine the integrated IBD interaction rate in a 32kT water Cherenkov detector at 10kpc. The color coding corresponds to the value of $x_{1.75}$ and is provided in Figure 1. The dashed lines are results for models s12WH07 and s40WH07 run with the HShen EOS. In the inset we show the cumulative IBD interactions as a function of $x_{1.75}$ for each model and EOS at four postbounce times: 100, 200, 300, and 400ms.

There are many degeneracies that may prevent conclusive statements being made regarding the progenitor structure from the observed neutrino signal. Briefly, these include nuclear EOS, rotation, viewing angle, distance, and neutrino oscillations (including collective oscillations). For an in-depth discussion of these degeneracies, see O'Connor and Ott (2012).

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