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Neutrino Probe Comparisons of Supernovae as a Function of Redshift

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Abstract.
We compare aspects of supernova explosions produced in the current epoch against those produced in the first round of star formation. Although the total final mass of stars can change dramatically between these two epochs due to different mass-loss rates from winds, their cores remain very similar. The core structure is more sensitive to the stellar evolution code than it is to the amount of metals. As such, current stellar models produce supernovae from first stars that look very similar to that of stars produced in the current epoch. The neutrino signal, a powerful probe of the inner core, is identical to the few percent level for both star formation epochs. A change in the neutrino signal in the supernova population between these two star formation epochs will only arise if the initial mass function is altered.

1. Neutrinos in Core collapse

Core-Collapse supernovae are important to many fields of astronomy and physics. They mark the endpoints of the lives of massive stars and can be used to understand the evolution of these stars. They inject most of the heavy elements into the universe and seed future star formation. They produce many of the neutron stars and stellar-massed black holes in the universe: magnetars, pulsars and the initial conditions for X-ray binaries. Their remnants (both compact and otherwise) are prime sources of cosmic rays. And they are ideal nuclear and particle physics laboratories for the study of matter at nuclear densities and the evolution of neutrinos.

Colgate & White (1966) argued that neutrinos leaking from the collapsed core of a massive star would power the explosion of massive star. Over four decades later, this neutrino-heating mechanism remains the favored engine, but the picture is far from the simple picture outlined by Colgate & White (1966). First and foremost, it has been realized that convection above the proto-neutron star is important to convert the thermal energy of neutrinos into the kinetic energy in the explosion [Herant et al. (1994); Fryer (1999); Fryer & Warren (2002); Burrows et al. (2006); Marek & Janka (2009)]. Scientists have also made considerable progress in both our understanding of the emission and interaction of neutrinos as well as the behavior of matter at nuclear densities.

In this paper, we study how this neutrino engine varies with redshift. Two redshift-dependent effects alter the progenitor, and hence possibly the collapse: changes in the mass-loss from stellar winds (section 2), and changes in the initial mass function (section 3). The latter section has been modified to fit some of the excellent discussions at this SnowPAC meeting about dark matter annihilation in the first stars. Before we discuss the effect of redshift on the distribution of supernova explosions, let's first review the currently favored engine behind core-collapse supernovae.

The Collapse: As the iron core in a massive star builds up, it becomes too large for the thermal and electron-degeneracy pressure to support. The iron core compresses, leading to endothermic disassociation of the iron into alpha particles and the capture of electrons. Both these reactions reduce the pressure in the core, causing it to compress even further and leading to more rapid disassociation of the iron and electron capture. Very quickly, the pressure in the core is removed and the collapse proceeds nearly at free-fall.

Bounce: The collapse proceeds until the inner core (roughly inner $\sim 0.6 \pm 0.2\,M_{\odot}$) reaches nuclear densities, halting the collapse and creating a bounce that sends a shock out through the star. This bounce shock moves outward until neutrino leakage saps its internal energy and the shock stalls. This occurs at an enclosed mass coordinate of $\sim 1.0 \pm 0.2\,M_{\odot}$.

Shock Revival: It is believed that the shock will be revived by neutrinos from the hot proto-neutron star. As the rest of the star falls onto the stalled shock, a convection carries heated material from the proto-neutron star surface to the edge of the stalled shock. It also carries infalling stellar material to the proto-neutron star surface. Some of this material accretes onto the proto-neutron star, releasing further energy to drive an explosion. At any given time, the convective region contains $\sim 0.1 - 0.3\,M_{\odot}$.

Depending on the structure of the progenitor core, this convection proceeds until either an explosion is launched or the proto-neutron star exceeds the maximum neutron star mass ($\sim 2\,M_{\odot}$) and collapses to form a black hole. It is this inner $\sim 2\,M_{\odot}$ of the stellar core that determines the fate of the collapsing star. Only those redshift effects that alter the structure of this core will change the fate of the collapse.

2. Wind Effects

The primary effect cited in the literature describing the difference between the first stars and the current epoch of star formation lies in the strong metallicity dependence of stellar winds. At solar metallicity, these winds can drastically alter the final mass of the progenitor star. In some models, a $50\,M_{\odot}$ solar metallicity star can lose over 80% of its mass. At zero metallicity, it loses less than $1\,M_{\odot}$.

Figures 1 shows the average atomic weight of the inner $10\,M_{\odot}$ of three models of a $25\,M_{\odot}$ initial-mass star: a zero metallicity model from Limongi & Chieffi (2006), a zero metallicity star from Woosley et al. (2002), and a solar metallicity model from Woosley et al. (2002). The Woosley et al. (2002) models vary with metallicity more than those of other groups (e.g. Limongi & Chieffi), so we will focus on the metallicity variations of these models to study the extreme effect of winds on the collapse. If we study the mean atomic weight of the core, we see that the zero metallicity star is very similar to the solar metallicity case. The edge of the silicon layer is roughly 5% further out, as is the edge of the C/O layer. The Limongi & Chieffi (2006) appear, on the surface, to be very

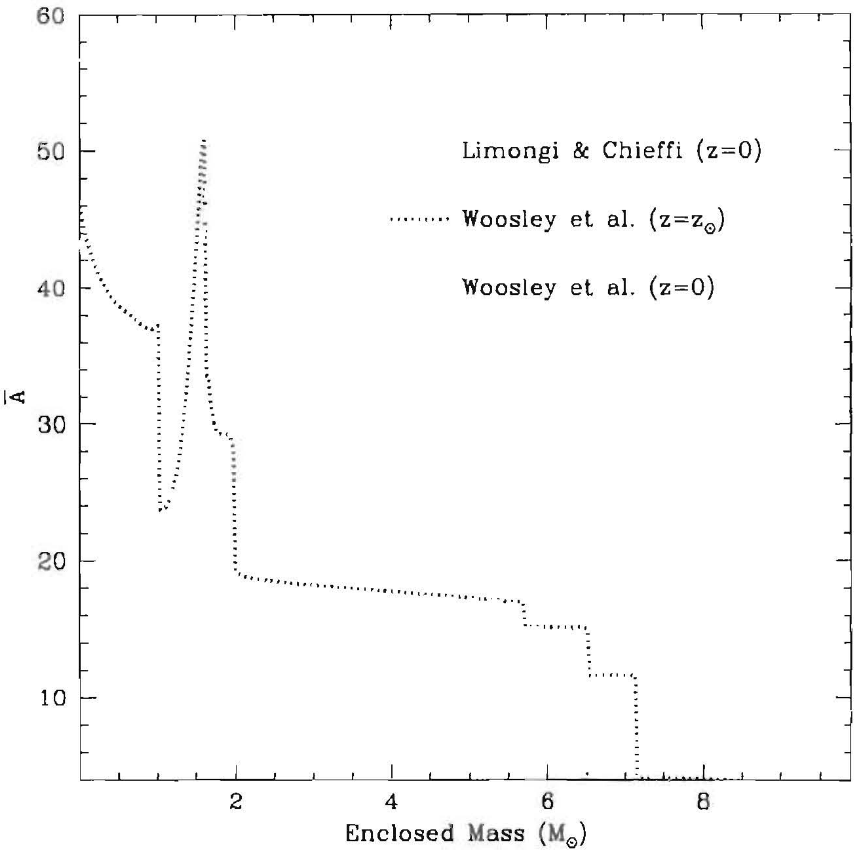

Figure 1. Average atomic weight versus enclosed mass for three 25 $M_\odot$ models: solar (dotted) and zero (dashed) metallicity simulations from Woosley et al. (2002), and a zero metallicity simulation from Limongi & Chieffi (2006). The inner atomic weight is very sensitive to the time prior to collapse. At later times, iron dissociation will have set in, lowering the average atomic mass. At high metallicities, winds remove mass from the star as it evolves. If strong enough, it can alter the mass of the various cores. We can see this by studying the mass-coordinate boundaries of the various abundance layers (e.g. the edge of the C/O abundance layer is further in for the solar metallicity simulation).

different. But realize that the inner abundance is strongly dependent on the exact timing of the end-state model. In this case, the Woosley et al. (2002) models followed the collapse a bit further, allowing the core to dissociate a bit, lowering the average atomic weight. If we just compare the edge of various layers there is a bit more agreement. However, even if we limit our comparison to mass coordinates of the boundary layers, the Limongi & Chieffi (2006) zero metallicity model agrees more with the solar metallicity Woosley et al. (2002) model. The Woosley et al. (2002) models varying from zero to solar metallicity agree more

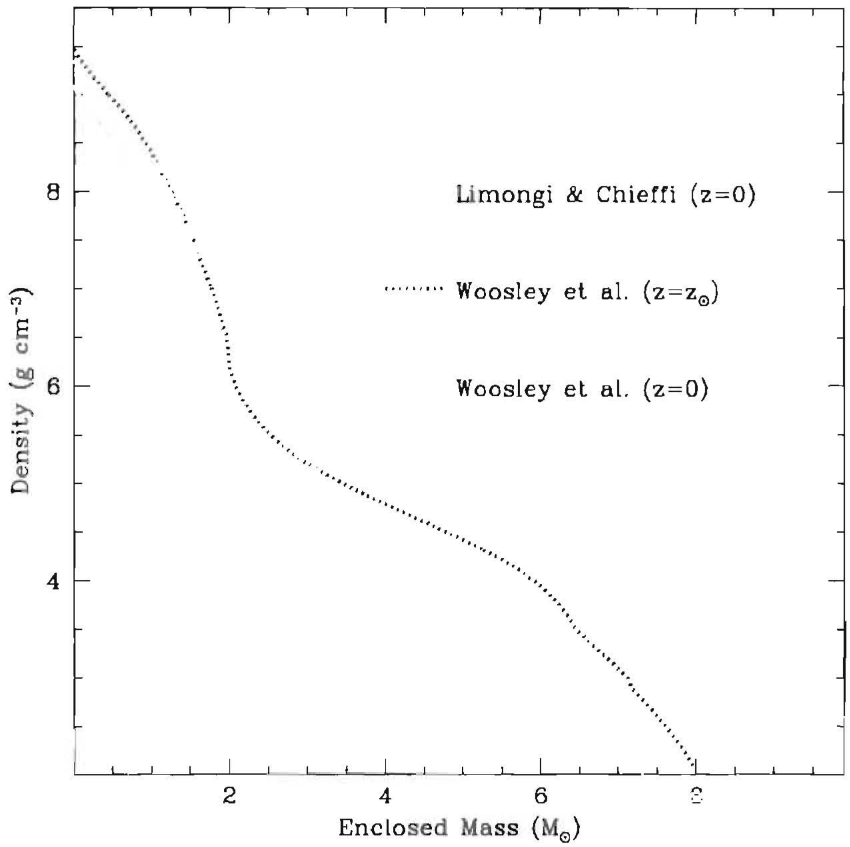

Figure 2. Density profiles for these same 3 models as figure 1. Again, the exact density in the inner core is determined by "time-at-collapse", but we can compare model differences by comparing densities beyond $2\,M_\odot$. In both images, it is clear that code differences are larger than the effect of metallicity.

closely with themselves than they do with the Limongi & Chieffi (2006). That is to say, in the inner $10\,M_\odot$ of a initial-mass $25\,M_\odot$, the choice of stellar evolution code makes a bigger difference than mass loss.

Now we can turn to the density distribution (Fig. 2). As we discussed, the Woosley et al. (2002) models are further evolved, so the central density is a bit higher than the Limongi & Chieffi (2006) models. The zero and solar metallicity models agree quite well and again the differences between solar and zero metallicity is much less than the model differences.

The entropy profile is perhaps the most clean comparison quantity. Although the "time-at-collapse" is not consistent between models, entropy is reasonably conserved at the beginning of the collapse. As we can see, although the exact shape of the entropy profiles are slightly different, they agree at the 20-30% level. The variations in mass coordinate of the entropy jumps between

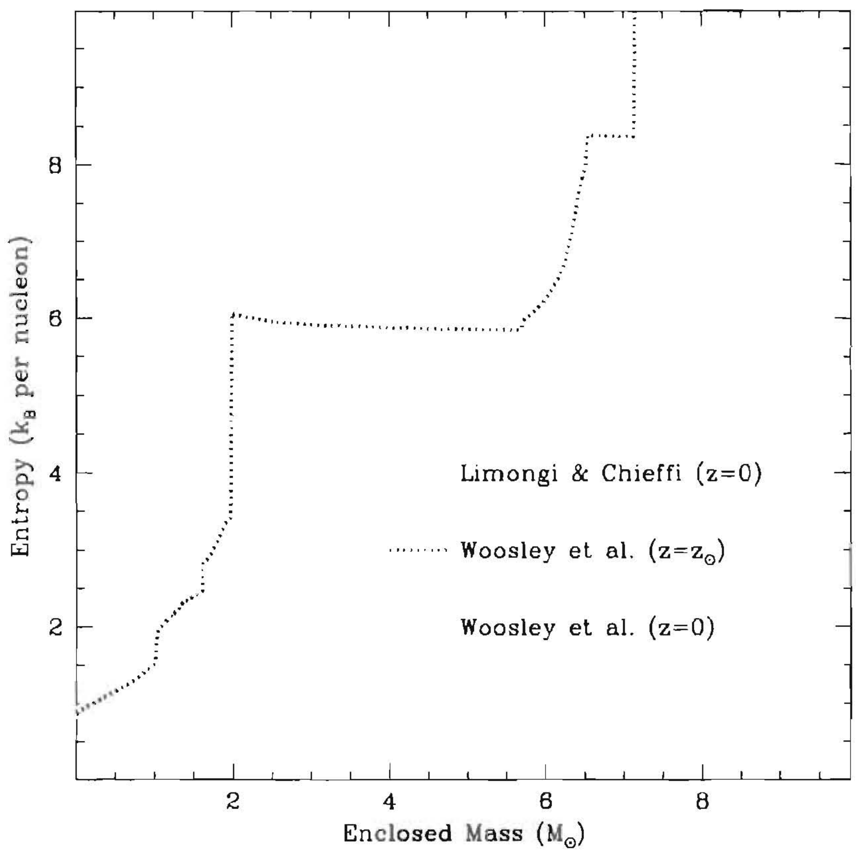

Figure 3. Entropy vs. enclosed mass in the inner core for the 3 models shown in figure 1. The entropy is less susceptible to differences caused by the choice for "collapse time". As with the density and average atomic weight, the entropy profile is shifted slightly for between zero and solar metallicity models. The largest differences, however, are caused by differences in the stellar evolution codes.

the Woosley et al. (2002) solar and zero metallicity models corresponds to the varying sizes in the boundary layers caused by mass-loss in winds. In the core, this shift is roughly 10%. Unfortunaely, once again, the differences between codes is greater than the difference between metallicity.

From these comparisons, we find that metallicity has very little effect on the inner $2\,M_\odot$ of a $25\,M_\odot$ star, and the effect out to 6-8 $M_\odot$ is at the 5-10% level. By far, the greater differences arise from the different codes currently used to model stellar evolution. For lower-mass progenitors, this metallicity dependency will be even lower. For most standard initial mass function for stars, more than 90% of core-collapse supernova progenitors will have a mass below $25\,M_\odot$. Although the effect increases with mass, for metallicity to make a big difference, the initial stellar mass must be above 40-50 $M_\odot$ (assuming the Woosley et al. (2002) progenitors). The inner cores of the entire mass range of Limongi & Chieffi (2006) progenitors do not vary from zero to solar metallicity.

2.1. Neutrinos and the Supernova Engine at High Redshift

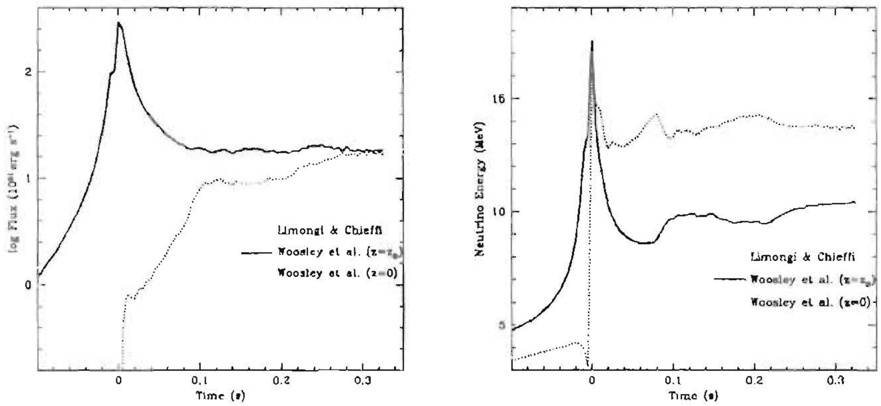

Figure 4. **Left:** Electron neutrino luminosity (solid) and electron anti-neutron luminosity (dotted) as a function of time for the 3 models in figure 1. The flux rises above $3 \times 10^{53}\, erg\, s^{-1}$ as the bounce shock becomes optically thin to neutrinos and then stabilizes at roughly $10^{52}\, erg\, s^{-1}$. Without some recipe to mimic convection, 1-dimensional models tend not to explode and these models are no different, cooling with time. As expected, all three models are very similar. **Right:** Average neutrino and anti-neutrino energy for the same three models as a function of time. Even the neutrino average energies are nearly identical. If these models explode in multi-dimensional explosions, it is very likely that the energy for all 3 models will be the same.

The fact that the structure in the inner 2 $M_\odot$ does not change significantly with metallicity for a 25 $M_\odot$ star means that the collapse, bounce and explosion for initial mass star will not vary considerably with mass. We expect, then, that the neutrino signal also not change with mass. To test this expectation, we have modeled the collapse and bounce of our three progenitors with a 1-dimensional core-collapse code described in Herant et al. (1994); Fryer et al. (1999). This code follows the evolution of the supernova engine from the onset of collapse and through bounce. Because it is 1-dimensional, it does not model the convective engine and it does not have any recipe to mimic convection. Without the effects of convection, our models do not produce explosions. Instead, we will focus on the collapse, bounce, and subsequent heating phase. Neutrinos are a sensitive probe to the core evolution and we will use them to gauge the differences between our progenitors.

Not suprisingly, the time evolution of the neutrinos for our 3 models are nearly identical (Fig. 4). Figure 4 shows the results for both electron neutrinos and anti-neutrinos. Both the neutrino energies and neutrino luminosities are within a few percent for most of the duration. These different progenitors have nearly identical collapse evolution.

If the initial mass function describing the distribution of stellar masses did not evolve with redshift, the neutrino signature from supernovae would be the same today as it was at the beginning of the universe. The near identical collapses also mean that the rate of neutron star and black hole formation as a function of redshift. Again, if the initial mass function remained constant, the formation rate of neutron stars and black holes would not vary with redshift. The neutron star mass distribution would also not vary too strongly, arguing that the neutron star mass distribution given by Fryer & Kalogera (2001) would also hold at high redshift. Because metallicity does change the total mass of the star, the black hole mass distribution would change, especially those black holes formed by direct collapse. But, as we shall see in the next section, the initial mass function does vary with redshift.

3. Changes in the Initial Mass Function

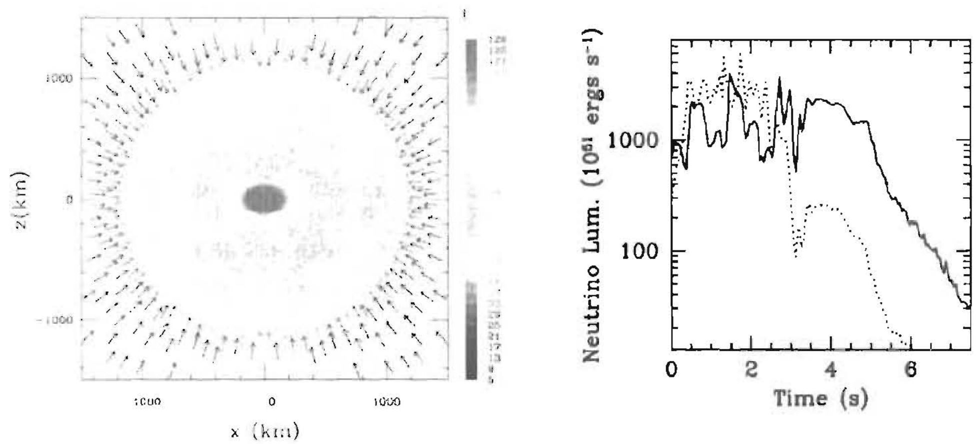

Figure 5. **Left:** Collapsed core of a $300\,M_{\odot}$ star 0.5 s before black hole formation (Fryer et al. 2001). Roughly $90\,M_{\odot}$ lies within the stalled shock front (~ 1000 km) and $20\,M_{\odot}$ lies within 100 km. This collapsed core material releases nearly 100 times the potential energy of a core in a normal supernova. **Right:** Neutrino luminosity as a function of time for the collapse of this star. In the proto-black hole state, the neutrino luminosity remains above $10^{54}\,\mathrm{erg\,s^{-1}}$, but this luminosity drops after black hole formation when the only neutrino emission is powered by accretion.

Many suggest that the initial mass function will vary with redshift. For the first stars, there are no metals to cool the collapsing proto-stellar clouds. Cloud compression is slower and, hence, have more time to accrete material on the core. This idea argued for more massive stellar progenitors and an initial mass function more skewed to massive stars. If such conditions could allow the formation $300\,M_{\odot}$ stars, we can strongly alter neutrino signal from the stellar population. As cosmology calculations become more accurate, the "skewed" initial mass function has become more normal. The strongest chance to produce these massive stars now is the possibility that dark matter annihilation in the core could prevent the core from collapsing, effectively preventing an early collapse and allowing it to accrete longer, forming a more-massive star (see Paolo Gondolo's presentation here).

Fryer et al. (2001) modeled the collapse and ultimate black hole formation of a $300\,M_\odot$ star. They found that the star collapsed into a proto-black hole: not compact enough to form an event horizon immediately (it is held up by a combination of thermal and rotational pressure), but nearly $90\,M_\odot$ of the core condensed into a $\sim$1000 km radius. The neutrinos are trapped only in the inner core and the rest of the core emits copious neutrinos. Ultimately, this neutrino transport saps the thermal support and the core collapses to a black hole. The left panel of figure 5 shows the this core 0.5 s prior to black hole formation where both the dense inner and accretion shock front are visible.

Much of the potential energy released in the collapse of the massive star is emitted in neutrinos prior to the formation of the black hole. Whereas most core collapse supernovae peak at neutrino luminosities of $10^{54}\,\mathrm{erg\,s^{-1}}$ for 10s of milliseconds at most, these stars emit at this high luminosity for roughly 5 s (Fig. 5), emitting 20 times that energies from neutrinos of a normal supernovae in a very brief time. If these stars are common at high redshift, the supernova outbursts and neutrino signals from the population of high-redshift stars will be very different than current-epoch stars. But if a small amount of metals reverts the initial mass function to something closer to the current epoch initial mass function, this effect will only be visible at high redshift.

We have found that the nature of core-collapse supernovae does not depend that sensitively on redshift. For these supernovae, the primary differences in the evolution are metallicity effects: effects in the initial mass function describing the distribution of stars and in the mass loss from stellar winds. For some stellar evolution codes, the supernovae from the most massive stars (above 40-60 $M_\odot$) will vary from zero metallicity. But for most stars (for all stars using some codes), the supernova explosions will not vary with redshift. The first stars may have a different distribution of stellar masses, but their contribution to the supernova rate will only be dominant above redshifts of 8-10. The fact that most stars will have redshift independent supernovae has implications not only for the neutrino signal, but for the neutron star mass formation rates and mass distributions.

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