# Neutrino signatures of dying massive stars: From main sequence to the neutron star.*


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We present an overview of the life of massive stars from the point of view of neutrino emission. Stars are persistent sources of neutrinos, starting at hydrogen ignition, continuing through the advanced burning stages and culminating during supernova explosion. Finally the neutrino flux goes to zero as neutron star cools down or drops rapidly if a black hole is formed. In fact, after helium burning the star's neutrino luminosity outshines is visible photon flux by many orders of magnitude, and the visible supernova is only a pale reflection ($< 1/10,000$) of the neutrino signal. Emerging new generations of giant advanced neutrino detectors, from the LAGUNA initiative and other projects, will be able to detect not only the supernova neutrinos, but possibly also pre-supernova neutrinos and the cooling signal of proto-neutron stars.



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## 1. Introduction

### *1.1. Modern supernova classification*

Observationally, a zoo of supernovae types has been classified. On the other hand, from a theorist's point of view, only few physical mechanisms

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Table 1. Modern astrophysical classification of the supernovae.

| Class | Thermonuclear | Core-Collapse |
|---|---|---|
| Type | Ia, PISN | II, Ib/c, L-GRB |
| Energy source | thermonuclear | gravitational |
| Explosion energy | $10^{51}$ erg | $10^{53}$ erg |
| Neutrinos | $10^{49}$ ergs (1%) | $10^{53}$ ergs (99%) |
| Progenitor | CO white dwarf in binary, supermassive star | massive star $M > 7 - 10\,\mathrm{M}_{\odot}$ |
| Examples | SN1994D | SN1987A |
| Remnant | spherical nebula | asymmetrical nebula + NS or BH |

could provide the observed explosion energy to power these enormous explosions.

For a single star to explode, the required amount of energy, which is of the order of $10^{51}$ ergs (1 Bethe, 1 B) or more can only be provided by a thermonuclear explosion [1] or a gravitational collapse [2]. A simple classification scheme (Table 1) based on this assumption is now commonly used[1]. The observed variety of the explosion can be understood in terms of the physical properties (mass, density, composition) of the outer layers of the evolved star surrounding the central "engine". For example, core-collapse supernovae form a continuous family of types: II-P (very large mass of the outermost hydrogen shell), II-L (small amount of H), IIb (tiny layer of hydrogen), Ib (no H at all, He layer still present) and Ic (no H and He). Most of supernovae fit well into this simple scheme, but many known extreme cases, however, require additional parameters, e.g., the amount of rotation in the core (long-duration gamma ray bursts (GRBs), some hypernovae (HN) like SN1998bw [3]) or interaction with interstellar medium (Type IIn "hypernovae").

There appears to be increasing observational evidence for another kind

[1] This classification probably will survive until new sources of the energy (if they exist) will be discovered. For example, let astrophysicists and astronomers do a major mistake of mis-identification, placing a new class of the thermonuclear events in the core-collapse column of Table 1. Simply by moving these events into correct position error if fixed and classification scheme ("thermonuclear"–"core-collapse") preserved.

of powerful thermonuclear explosion, the pair-instability supernovae (PISN) [4, 5]. Their progenitors are very massive stars with masses above 140 $M_\odot$ and 260 $M_\odot$ [6]. Although they are potentially interesting for the neutrino community [7], little is known on the details of their $\nu$ emission. Other kinds of supernova associated with very massive stars are:

(1) pulsational pair-instability supernovae (PPSN) that may have a series of nuclear-powered outbursts followed by core collapse to neutron star or (more likely) black hole ($100\,M_\odot < M < 140\,M_\odot$) and

(2) Type III collapsars ($M > 260\,M_\odot$), stars that also collapse after central carbon burning due to pair instability, but photo-disintegration in the center of the star leads to direct collapse to a black hole instead of thermonuclear explosion [8].

### *1.2. Massive stars: important facts*

Here we only consider stars that are "massive" enough to ignite all thermonuclear burning stages in a non-explosive way and form an iron core that collapses under its own weight (due to electron captures and photo-disintegration) - stars that explode as a "garden variety" core collapse supernova. The lower mass limit does depend on the star's initial metallicity and rotation rate. For non-rotating stars of solar initial composition the lower mass limit should be somewhere in the range from $7\,M_\odot$ to $11\,M_\odot$, depending on the stellar evolution code used and the implementation of mixing physics (convection, convective overshooting, semi-convection, etc.). To ease our discussion, in this review we only consider the stellar models of $15\,M_\odot$ and $25\,M_\odot$ of Woosley *et al.* [9].

Massive stars can loose significant amounts of mass due to stellar wind. Therefore, by "mass" of the star we actually refer to the initial mass of the star when it first came into hydrodynamic and thermal equilibrium and started hydrogen burning in its center, so-called ZAMS (**Z**ero **A**ge **M**ain **S**equence ) mass. For example, by the time our "$15\,M_\odot$ star" of solar metallicity star explodes, it has shrunk to total mass of mere $12\,M_\odot$. More massive stars have stronger winds and lose even more mass during their life, cf. Fig. 2. Stars can also experience additional mass loss (or mass gain) if they interact with a close binary star companion.

Compared to the sun, the lifetime of the pre-supernova stage of a massive star is relatively short, only a few millions of years. Out of this, about 90 % is spent during central hydrogen burning. This evolution stage is called the *main sequence* as most stars we observe are in this burning stage and obey a well-defined relation between luminosity and surface temperature. In massive stars hydrogen burning is almost exclusively by the CNO cycle;

other cycles contribute only negligibly. As burning hydrogen to helium requires the conversion of two protons into neutrons for each helium nucleus formed, two weak decays per helium nucleus have to occur. These carry away about 7 % of the total energy release. The over-all resulting neutrino spectrum is usually assumed to be similar to the (rescaled) solar CNO, see [10], Sect. 6.5 *Fluxes from other stars*, p. 165.

One of the key ingredients for neutrino detection from supernovae is the rate of suitable supernova explosions within the volume of space accessible to our detector. This can be estimated from the total rate at which mass is converted into stars ("star formation rate", about $1\,\mathrm{M}_{\odot}/\mathrm{yr}$ for our galaxy) and the spectrum of initial stellar masses, the initial mass function (IMF). Observationally, in the present-day universe, the IMF seems to be a global law, almost independent of location. For massive stars, the IMF given by Salpeter [11] seems to be a good approximation:

$$\frac{dN}{dM} \propto M^{-\alpha}, \qquad \alpha = 2.35 \quad . \tag{1}$$

The typical mass of star forming today is about the mass of the sun.

Stars with masses above $100\,\mathrm{M}_{\odot}$ are rare in the Galaxy today (e.g., Eta Carina), but current theory and simulations indicate [12], that they may have dominated the IMF among the first generation of stars that formed only from pristine material synthesized during the big bang. These are the so-called Population III stars. These simulations are based on the standard cold dark matter (SCDM) model for structure formation in the universe.

In non-standard models for structure formation [13] the initial mass function of those "first stars" may be different, possibly more similar to the present-day IMF. In that case the expected diffuse supernova neutrino background (DSNB) $\bar{\nu}_e$ flux could be significantly reduced.

### *1.3. Burning cycles*

The evolution stages of a massive pre-supernova star roughly follow the basic scheme:

**Start:**
contraction → release of the gravitational energy → compressional heating → ignition of fuel → nuclear burning phase → fuel shortage →
`GOTO` **Start**

For low mass star (e.g., the Sun) this cycle terminates on He burning; even helium burning does not ignite in the center of the star due to degeneracy. Burning in "massive enough" stars proceed until the most strongly bounded nuclei of the iron group are formed:

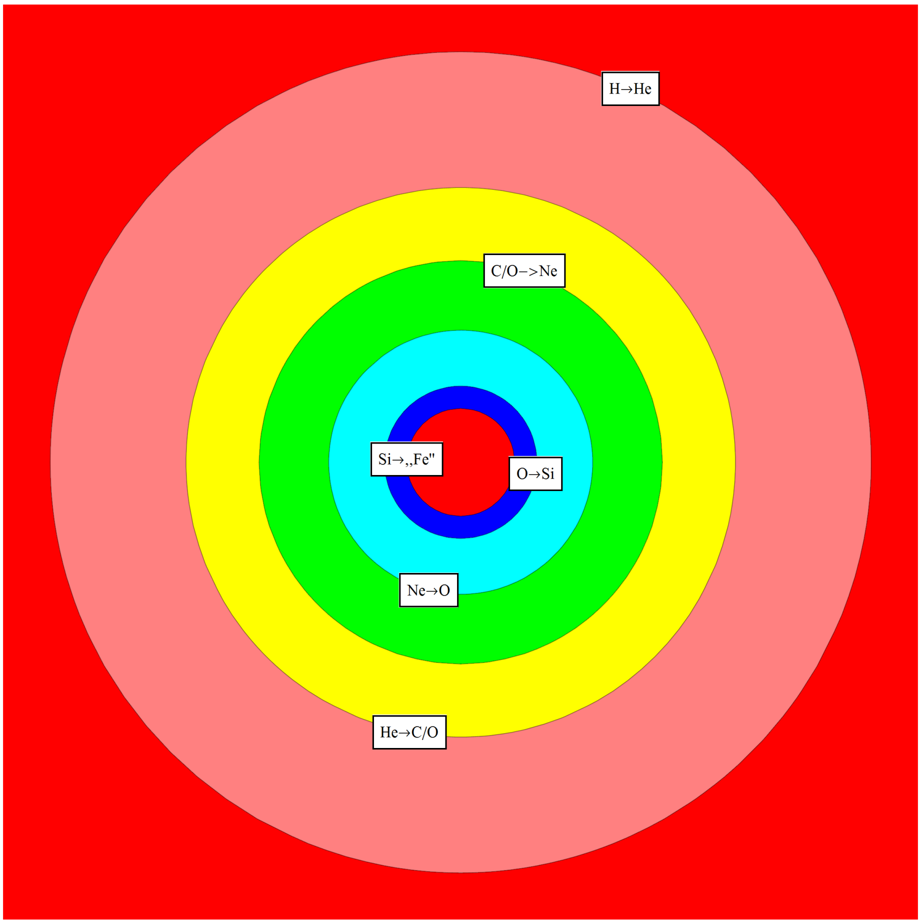


Fig. 1. Schematic picture of the onion-like structure of a massive star at the time of core collapse (not to scale).

1. H $\longrightarrow$ $^{4}$He (main sequence, millions of years)
2. $^{4}$He $\longrightarrow$ $^{12}$C, $^{16}$O (helium burning, red giant , $\sim 10^{5}$ years)
3. $^{12}$C $\longrightarrow$ $^{16}$O, $^{20}$Ne, $^{24}$Mg (carbon burning, hundreds of years)
4. $^{20}$Ne $\longrightarrow$ $^{16}$O, $^{24}$Mg (neon burning, years/months)
5. $^{16}$O $\longrightarrow$ $^{28}$Si, $^{32}$S (oxygen burning, years/months)
6. $^{28}$Si $\longrightarrow$ ,,Fe" ("silicon" burning, few weeks/days)

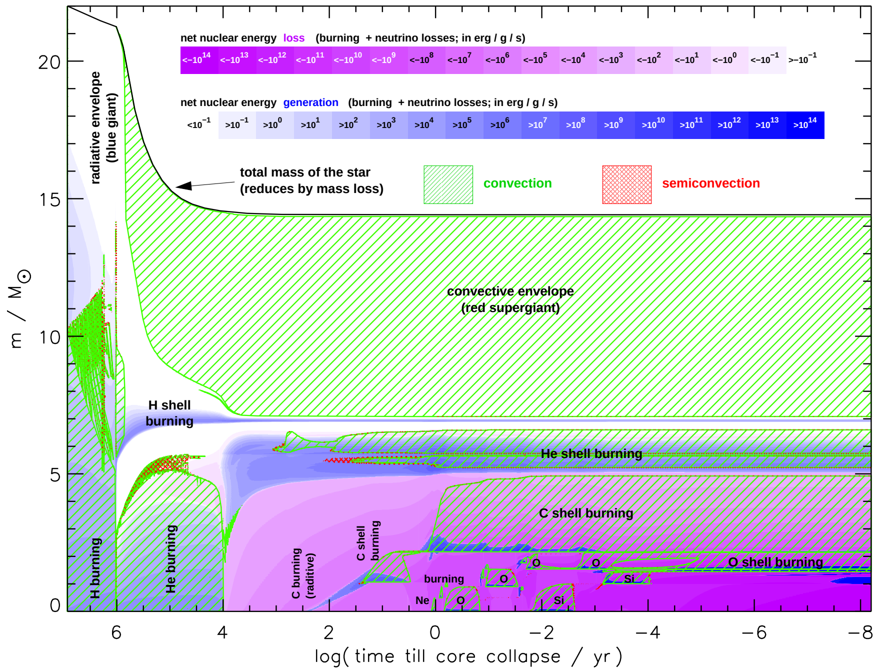


Fig. 2. Structure of a 22 $M_\odot$ star (mass coordinate) as a function of time till core collapse (logarithmic). Green hatching indicates convective regions, red cross hatching indicates semiconvective regions, blue shading indicates net nuclear energy generation (energy release due to burning minus neutrino losses) and purple shading indicates net energy loss (neutrino losses dominate over nuclear burning). Different burning phases are indicated.

7. Fe (”iron”) is no longer source of fuel - cycles terminate leading after short (∼hours) delay to the *gravitational collapse*

After burning in the center, every phase can re-occur in layers further out, in burning shells (Fig. 1), though not all shells may burn at the same time. As with central burning, and often alternating with central burning, we find shell burning can delay contraction phases in the late core; some of the outermost burning phases may be less affected.

Subsequent burning cycles are usually progressively faster. For helium burning, the difference in time scale is due to the lower amount of energy release per nucleon in the burning. For the burning phases after helium burning, the star the mostly loses energy due to neutrinos immediately es-

Table 2. Schematic view of the neutrino emission from the massive star.

| Stage | $\langle L_\nu \rangle$ [erg/s] | $E_\nu^{tot}$ [erg] | Time | $\langle \mathcal{E}_\nu \rangle$ [MeV] | Process | Flavor |
|---|---|---|---|---|---|---|
| 1. | $10^{36}$ | $10^{52}$ | $10^7$ yrs | 0.5-1.7 | CNO | $\nu_e$ |
| 2. | $10^{31}$ | $10^{49}$ | $10^6$ yrs | 0.02 | plasma | all |
| 3. | $10^{38}$-$10^{46}$ | $10^{51}$ | $10^4$ yrs | 0.5-1.5 | pair | all |
| 4. | $10^{54}$ | $10^{51}$ | $10^{-2}$ sec | 10 | $\epsilon^-$ | $\nu_e$ |
| 5. | $10^{52}$-$10^{48}$ | $10^{53}$ | $\sim 100$ sec | 10-40 | $\nu$ transport | all |
| 6. | $< 10^{48}$ | $< 10^{51}$ | $10^4$ yrs | 1 | URCA | $\nu_e, \bar{\nu}_e$ |

caping stellar core (see the next section) rather than photons traveling to the surface of the star on thermal time scale - the star becomes a "neutrino star". In helium burning itself, neutrino losses are unimportant. The shell burning phases are usually hotter than central burning, emitting neutrinos faster than during core burning, and hence their burning time scale is accordingly shorter.

## 2. Neutrino emission from massive stars

Stellar evolution for "neutrino astronomers" is outlined in Table 2. For a more complete description of the calculations of the neutrino processes reader if redirected to our papers [14, 15, 16] and references therein. For an overview and general ideas see refs. [17, 18, 19, 20] as well as conference talks [21, 22] and WWW [23]. Review of massive star modeling can be found in Ref. [9].

### *2.1. Stage 1: hydrogen burning*

Except of the sun, hydrogen burning neutrinos are not subject of detailed theoretical calculations. Usually, solar neutrino spectrum (pp and CNO) is renormalized to obtain $\nu_e$ spectrum for other stars [10], though hydrogen burning for massive stars is entirely dominated by the CNO cycle whereas the pp chains contribute only negligibly to the energy generation. According to [10] these neutrinos are not detectable even if integrated over entire Galaxy. Noteworthy, the only flavor produced[2] is $\nu_e$, and matter is heavily neutronized during the main sequence. Initial composition of the star is roughly that of Big Bang nucleosynthesis with number of electrons per baryon $Y_\mathrm{e} \simeq 0.87$. After H burning, the star is almost pure $^4$He and $Y_e$ drops to $Y_\mathrm{e} \simeq 0.5$. An enormous number of $\nu_e$ is therefore produced, carrying energy of the order of about 7 % of the star's luminosity, i.e., a total of about $10^{52}$ ergs (Stage 1 in Table 2), slightly short of the energy released in neutrinos during the core-collapse supernova neutrinos (a few $10^{53}$ ergs). These neutrinos, however, are emitted at a very slow pace (millions of years), compared to tens of seconds for core-collapse supernova, see Table 2.

### *2.2. Stage 2: helium burning*

Helium burning is also not well analyzed from the neutrino astronomy point of view. Usually, it is assumed that the most dominant neutrino emission process is the plasmon decay [26], producing all flavors (Stage 2 in Table 2). Longitudinal and transverse plasmons produce distinct spectra [15], but in both cases average neutrino energy is of the order of tens of keV at best. Due to the low temperature (compared to later burning phases), however, the rate of neutrino emission is also very slow. In contrast to hydrogen burning, where the neutrinos come from weak reactions, converting protons into neutrons, helium burning is dominated by *strong* reactions that do not require weak decays, so the main burning does not produce neutrinos in this case; only the "thermal" neutrinos mentioned above contribute. Therefore, these neutrinos must be considered undetectable. A minor contribution to "weak" neutrinos may come from burning of $^{14}$N at the beginning of helium burning due to the radioactive decay of the $^{18}$F produced [27]. During the end of central helium burning the *s*-process starts to operate and the neutron-rich nuclei may decay by $\beta^-$ producing $\bar{\nu_e}$. The resulting neutrino spectrum, however, has not been studied in detail and is probably not very strong. The neutrino emission during helium core burning overall is therefore dominated by the $\nu_e$ emission from the hydrogen burning in the shell, not the He burning core.

### *2.3. Stage 3: neutrino-cooled stage*

The contraction phase after end of central helium burning toward central carbon ignition marks an essential change in the stellar life. Large temperatures required for C burning (kT>0.05 MeV) also cause small production of the $e^+e^-$ pairs from the high energy tail of the thermal distribution.

[2] Emitted flavor composition includes also other neutrinos, because of the neutrino oscillations inside the star, caused by the MSW effect [24, 25]

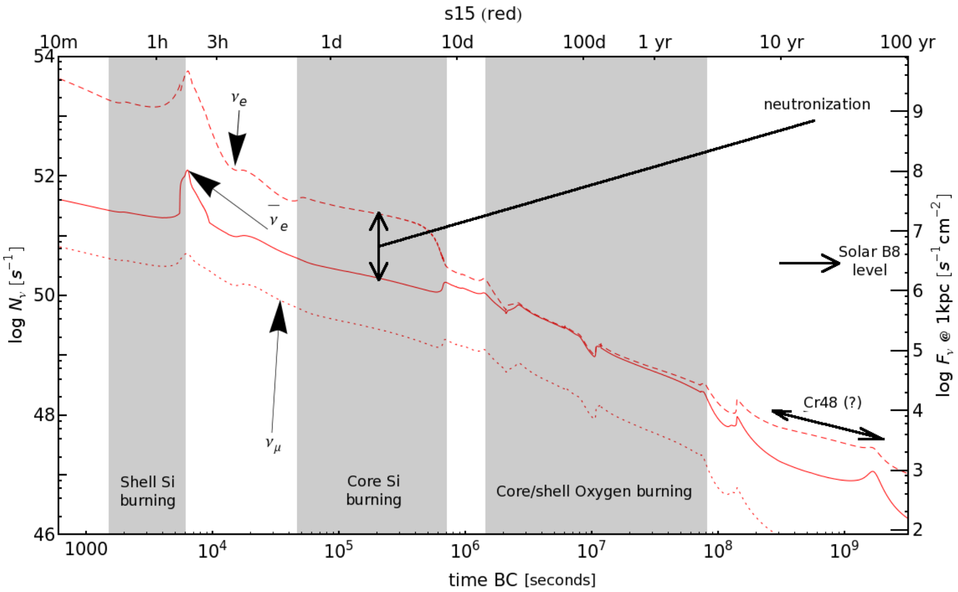


Fig. 3. Neutrino flux 100 years before supernova. Time "BC" means Before Collapse.

Electron-positron pairs do annihilate sometimes into $\nu$-$\bar{\nu}$ pairs. This process leads to strong neutrino emission, with number of neutrinos emitted proportional to $T^8$. Actually, the overwhelmingly dominating fraction of energy produced by nuclear burning or contraction is emitted as neutrinos from this point on. The pre-supernova star becomes a $\nu$-star or $\nu$-cooled star [28]. Basic processes and neutrino emission from realistic stellar models has been presented in the series of papers [14-20] beginning with [19].

Detailed neutrino light curves and energies of the neutrinos for the s15 model, an initially 15 $M_\odot$ star of solar composition, are presented in Figs. 3 and 4.

Core and shell oxygen burning are the classical neutrino-cooled stages. Both $\nu_e$ and $\bar{\nu}_e$ fluxes are exactly the same (solid and dashed lines in Fig. 3) and changes of the $\nu_\mu$ flux[3] follow other flavors. Dominant process leading to production of the neutrino-antineutrino pairs is the pair-annihilation. Energies of the neutrinos are very similar, and on average [16]:

$$\langle \mathcal{E}_\nu \rangle \simeq 4.11\ kT \qquad (2)$$

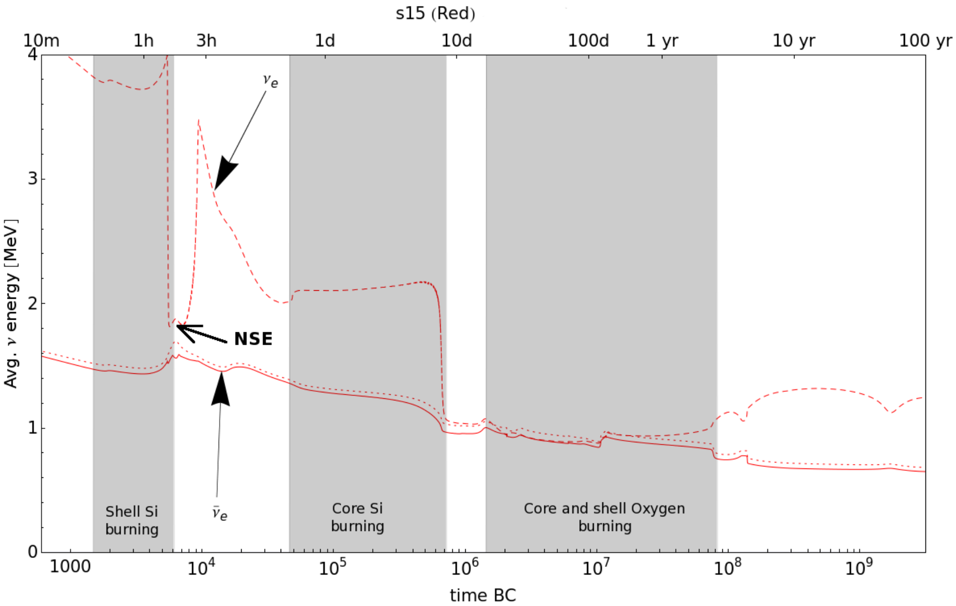


Fig. 4. Mean neutrino energy $\langle \mathcal{E}_\nu \rangle$ 100 years before core-collapse.

### 2.4. *Stage 4: neutronization*

To understand large deviation of the $\nu_e$ flux from purely thermal neutrino emission during and after Si burning, we must refer to Fig 5. Figure shows the evolution of the electron fraction $Y_{\rm e}$ inside pre-supernova stars. Before Si ignition, matter is composed mainly of nuclei with equal number of neutrons and protons: $^4$He, $^{12}$C, $^{16}$O, . . . i.e., $Y_{\rm e} = 0.5$. Strong and electromagnetic interactions do not change proton/neutron ratio, while weak interactions are too slow compared to C, Ne, and O burning timescales. The situation changes when Si ignites because of the high density (partial degeneracy) and high temperature. The mean energy of the electrons becomes larger than the "$Q$-value"[4] of many nuclei, causing massive $e^-$ captures:

$$\begin{array}{ccc} e^- + (A,Z) & \longrightarrow & (A,Z-1) + \nu_e \\ \uparrow & & \downarrow \\ \bar{\nu}_e + e^- + (A,Z) & \longleftarrow & (A,Z-1) \end{array} \tag{3a}$$

[3] Curve denoted $\nu_\mu$ is actually averaged flux of $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$ and $\bar{\nu}_\tau$.
[4] Difference in Binding Energy (BE) of (A,Z) and (A,Z-1) minus m$_e$c$^2$.

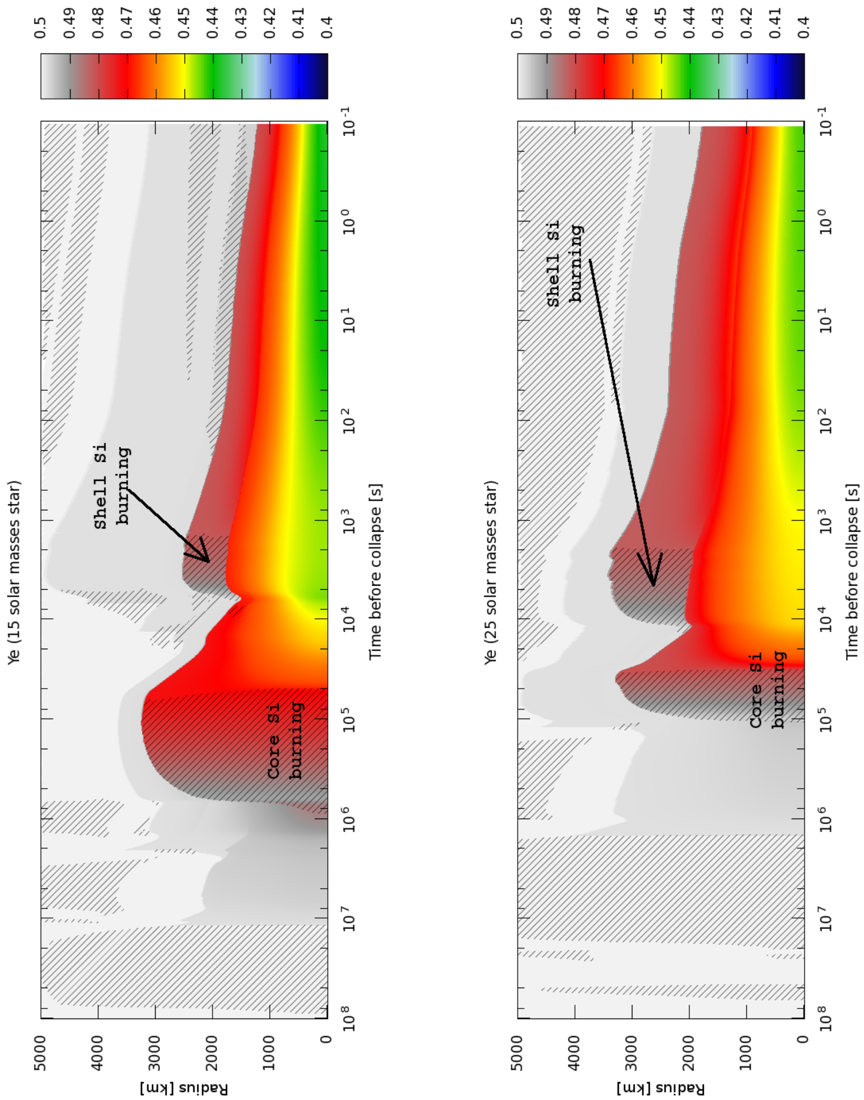


Fig. 5. 15 $M_\odot$ *versus* 25 $M_\odot$: neutronization.

$$\begin{array}{ccc} e^+ + (A, Z-1) & \longrightarrow & (A,Z) + \bar{\nu}_e \\ \uparrow & & \downarrow \\ \nu_e + e^+ + (A, Z-1) & \longleftarrow & (A,Z) \end{array} \tag{3b}$$

Because both forward and inverse processes do operate involving many nuclei, the situation is difficult to describe in simple words. Overall effect is significant decrease of the $Y_{\rm e}$ (Fig. 5), accompanied by a strong $\nu_e$ flux (Fig. 3). Whereas the calculated $\nu_e$ flux does not depend on the computational method, the energy $\langle\mathcal{E}_{\nu_e}\rangle$ calculated using an $\alpha$-network is $\langle\mathcal{E}_{\nu_e}\rangle \simeq 4$ MeV compared to using the NSE (**N**uclear **S**tatistical **E**quilibrium, [14, 29, 30]) approximation we obtain $\langle\mathcal{E}_{\nu_e}\rangle \simeq 2.5$ MeV, see Fig. 4 (onset of the shell Si burning). To resolve this discrepancy, which would be essential to making predictions on pre-SN neutrino detectability, will require new stellar models with large and accurate nuclear reaction network in the core.

Despite the drop of $Y_{\rm e}$ from 0.5 to 0.45-0.43 does not look dramatic, this small change of $Y_{\rm e}$ leads to a significant changes of the nuclear composition in the matter in the core as approximated by NSE[5]. This neutronization continues after the end of all nuclear burning processes, and on into the onset of the collapse.

### *2.5. Stage 5: collapse neutrinos*

The neutronization of the pre-supernova stage continues on into the onset of core collapse. Results of calculations for the same stellar model s15 by [31] are shown in Figs. 6,7 and 8. Note that our neutrino signals for the pre-supernova star are in perfect agreement with results of [31], with exception of a small jump in the $\bar{\nu}_e$ flux (Fig. 8).

The results presented in Fig. 6 are not current state of the art, and the neutrino signals were analyzed in numerous papers [32-63]. Here we provide some description for completeness, and to show the entire neutrino emission history of a massive star.

### *2.6. Stage 6: early and late cooling of the protoneutron star*

After core collapse and shock breakout the star enters stage which is essence of the modern neutrino astrophysics, because of the detection of the $\nu$ from SN 1987A[6]

Roughly speaking, a newly born PNS (**P**roto **N**eutron **S**tar) eventually becomes NS by neutrino by cooling slowly on a time scale of $\sim 100$ seconds while contracting from an initial radius of $\sim 60$ km to $\sim$10 km. An enormous gravitational binding energy of the order of a few $10^{53}$ ergs (cf. Table 2) is released in the form of neutrinos of all flavors.

This, however, is not the end. The neutron star continues to cool by neutrinos emission for thousands, or even millions of years. We observe

[5] See http://ribes.if.uj.edu.pl/psns/Artwork/NSE/NSE.html .

[6] See http://sn1987a-20th.physics.uci.edu/ for historical perspective review and excellent talks on a new developments.

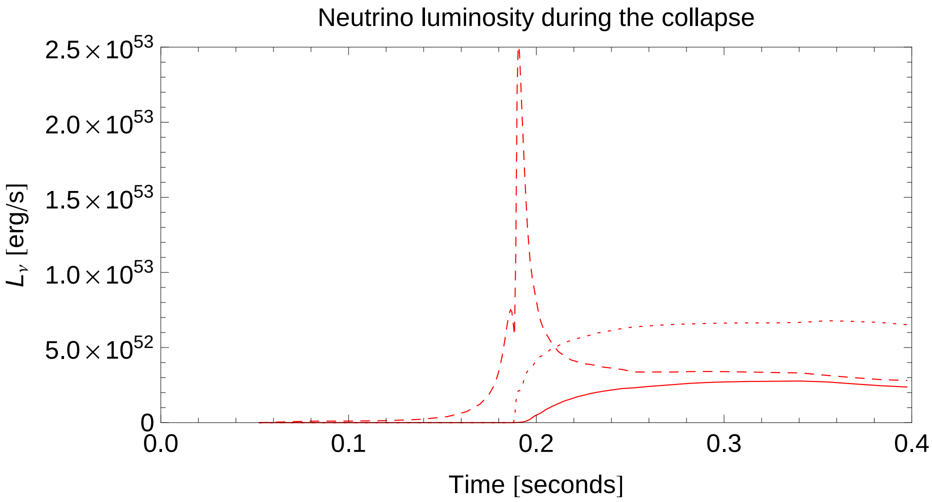


Fig. 6. Neutrino emission from the collapse. Data source: http://www.astro.princeton.edu/˜burrows/tbp/tbp.html

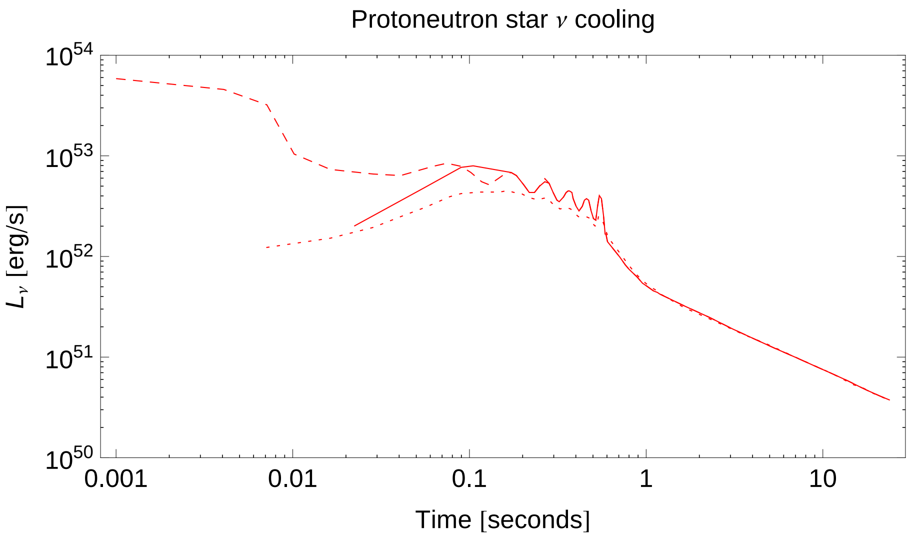


Fig. 7. Proto-neutron star evolution. Data from A. Burrows homepage http://www.astro.princeton.edu/˜burrows.

this indirectly due to a drop of surface temperature that corresponds to an energy loss much faster than the thermal emission from the surface of the neutron star [7] .

[7] See http://www.astro.umd.edu/ miller/nstar.html and [64] for a review.

For some EOS (**E**quation **O**f **S**tate), e.g., kaon condensate [65], some PNS (depending on mass) might collapse to a black hole after $\sim 100$ seconds delay, and in this case the neutrino flux would abruptly go to zero [66, 67]. This could be one possible explanation why the search for the neutron star in the remnant of SN 1987A may not have been successful to date. In general, delayed black hole formation after a supernova could explain missing neutron star remnants.

In Fig. 8, the stage of most intense neutrino emission during the life of a star are: $\nu$-cooled (Si burning), neutronization (shell Si burning, direct pre-collapse stage and beginning of the collapse, supernova neutrinos (shock breakout peak and PNS cooling) and late cooling of NS, with conditional delayed black hole formation.

## 3. Neutrino signatures of the incoming core-collapse

Taking 15 $M_{\odot}$ star (Model s15) as an example, we can distinguish several potential neutrino signatures:

1. Core/shell O burning, months before supernova, with detection limited to the Betelgeuse ($d = 100 \ldots 200$ pc).
2. Core Si burning , 8 - 0.5 days before collapse, detectable using future detectors for stars at 1-2 kpc. This covers ∼0.5% of the Galaxy.
3. Shell Si ignition, 2-0.5 hours before start of the collapse, potentially detectable up to 10 kpc with megaton class detectors.
4. Direct pre-collapse stage $\nu_e$ (30 - 0 minutes), with continuous transition into shock breakout $\nu_e$ peak, easily detectable from the Galaxy, given accurate timing of the subsequent supernova events

## 4. Summary

Neutrino emission from massive stars already starts at H ignition, significantly increases during the advanced stellar burning stages (carbon burning and beyond), and finally peaks during core bounce (neutronization) and protoneutron star cooling, just after core-collapse. Then neutrino emission declines again. So far we experienced on some “taste” of detection of neutrinos from the deaths of massive stars thanks to SN1987A. Core Si burning pair-annihilation $\nu_e$ and $\bar{\nu}_e$, shell Si burning $\bar{\nu}_e$, neutronization $\nu_e$ after core Si ignition, shock-breakout $\nu_e$ peak, and late-cooling protoneutron star neutrinos are a new challenges. They are goals for the current (Borexino [68], Super-Kamiokande [69]) and the next generations of neutrino detectors

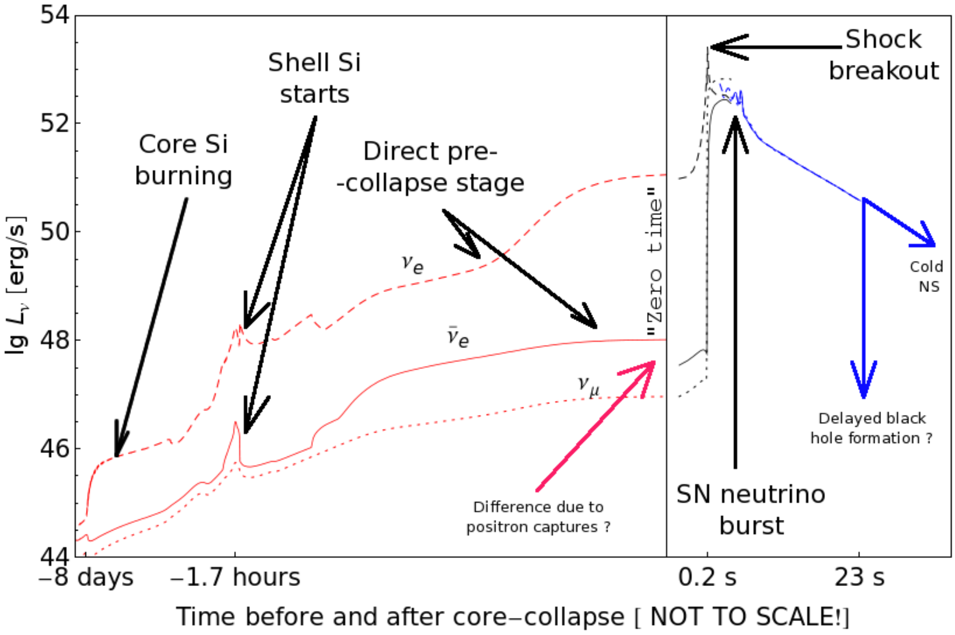


Fig. 8. Neutrinos BEFORE and AFTER collapse.

(LENA [70, 71, 72], Hanohano [73], Memphys [70, 74], Titan-D [75, 76, 77], etc.), which are part of the LAGUNA, DUSEL, LBNE [78] and other recent initiatives [79].

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