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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 a neutron star cools down or drops rapidly if a black hole is formed. In fact, after helium burning the star's neutrino luminosity outshines its 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 could provide the observed explosion energy to power these enormous explosions.

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[**] Presentation available at `http://epiphany.ifj.edu.pl/current/pres/odrzywolek.pdf`

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 I) based on this assumption is now commonly used[1]. The observed variety of the explosions 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").

TABLE I

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 $M > 7$–$10\,M_{\odot}$
Examples	SN1994D	SN1987A
Remnant	spherical nebula	asymmetrical nebula + NS or BH

There appears to be increasing observational evidence for another kind 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 ν emission.

Other kinds of supernovae associated with very massive stars in the early Universe are:

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[1] This classification probably will survive until new sources of the energy (if they exist) are discovered. For example, suppose that 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 I. Simply, by moving these events into correct position the error if fixed and classification scheme (thermonuclear–core-collapse) preserved.

(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 ($100\,M_\odot < M < 140\,M_\odot$);

(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 (Zero Age Main Sequence) mass. For example, by the time our "$15\,M_\odot$ star" of solar metallicity 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. 1. 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.

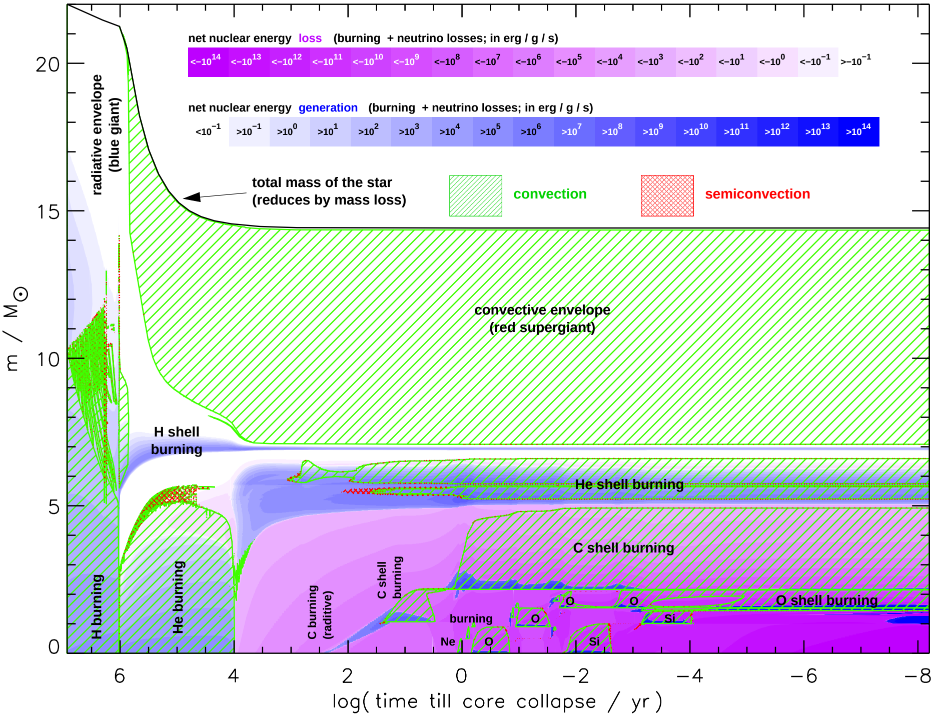

Fig. 1. Structure of a $22\,M_\odot$ star (mass coordinate) as a function of time till core collapse (logarithmic). Hatching indicates convective/semiconvective regions. Different burning phases are indicated.

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 $1\,M_\odot$/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:

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

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

Stars with masses above $100\,M_\odot$ 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:

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

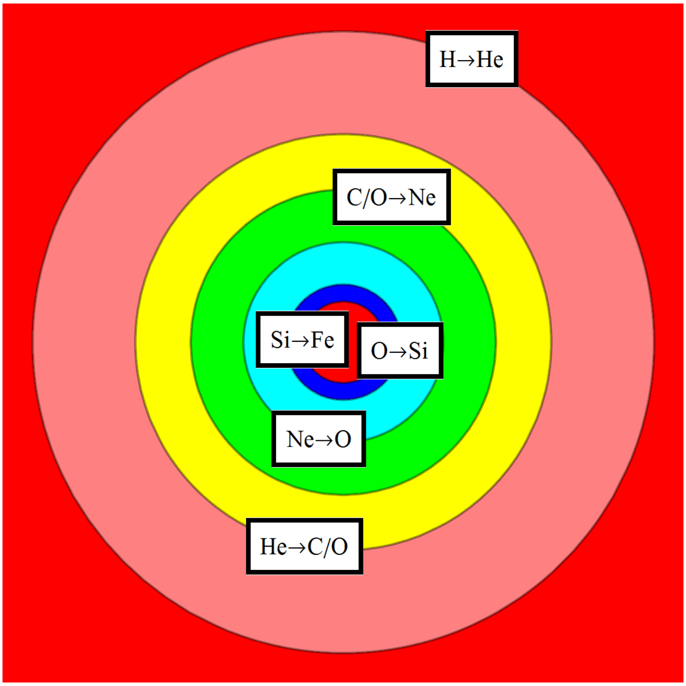

Fig. 2. Schematic picture of the onion-like structure of a massive star at the time of core collapse (not to scale).

burning, the star loses energy mostly due to neutrinos immediately escaping stellar core (see the next section) rather than to 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 II. For a more complete description of the calculations of the neutrino processes reader if redirected to our papers [14–16] and references therein. For an overview and general ideas see Refs. [17–20] as well as conference talks [21,22] and `www` [23]. Review of massive star modeling can be found in Ref. [9].

TABLE II

Schematic view of the neutrino emission from the massive star.

Stage	$\langle L_\nu \rangle$ [erg/s]	$E_\nu^{\rm tot}$ [erg]	Time	$\langle \mathcal{E}_\nu \rangle$ [MeV]	Process	Flavor
1.	10^{36}	10^{52}	10^7 yrs	0.5-1.7	CNO	ν_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	ϵ^-	ν_e
5.	10^{52}–10^{48}	10^{53}	~ 100 sec	10–40	ν transport	all
6.	$< 10^{48}$	$< 10^{51}$	10^4 yrs	1	URCA	$\nu_e, \bar{\nu}_e$

2.1. Stage 1: hydrogen burning

Except for the Sun, hydrogen burning neutrinos are not subject of detailed theoretical calculations. Usually, the solar neutrino spectrum (*pp* and CNO) is renormalized to obtain the ν_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 the entire Galaxy. Noteworthy, the only flavor produced[2] is ν_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 $Y_e \simeq 0.87$. After H burning, the star is almost pure ^{4}He and Y_e drops to $Y_e \simeq 0.5$. An enormous number of ν_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 II), slightly short of the energy released in neutrinos during the core-collapse (a few times 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 II.

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 dominant neutrino emission process is the plasmon decay [26], producing all flavors (Stage 2 in Table II). Longitudinal and transverse plasmons produce distinct spectra [15], but in both cases the 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

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

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 slow neutron capture process starts to operate and the neutron-rich nuclei may decay by β^- 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 ν_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. Electron–positron pairs do annihilate sometimes into ν–$\bar{\nu}$ 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 ν-star or ν-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 ν_e and $\bar{\nu}_e$ fluxes are exactly the same (solid and dashed lines in Fig. 3) and changes of the ν_μ 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]

$$\langle \mathcal{E}_\nu \rangle \simeq 4.11 \text{ kT} . \tag{2}$$

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[3] Curve denoted ν_μ is actually averaged flux of ν_μ, $\bar{\nu}_\mu$, ν_τ and $\bar{\nu}_\tau$.

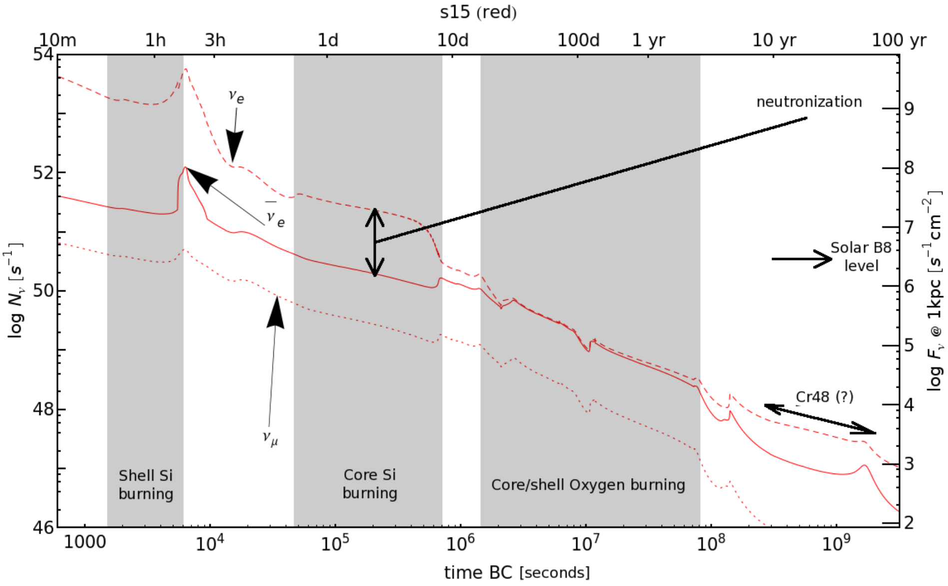

Fig. 3. Neutrino flux 100 years before supernova. Time "BC" means Before Collapse.

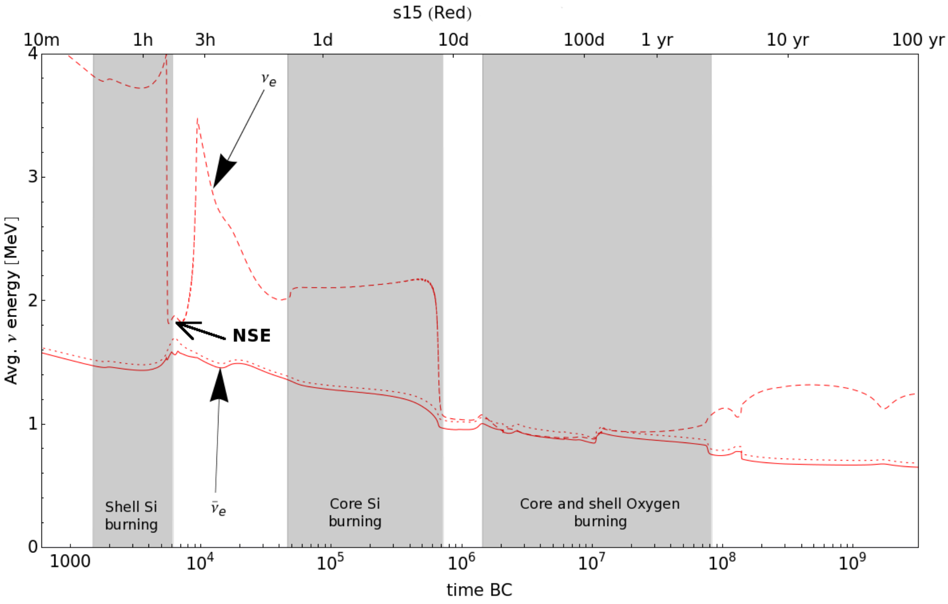

Fig. 4. Mean neutrino energy $\langle \mathcal{E}_\nu \rangle$ 100 years before core-collapse.

2.4. *Stage 4: neutronization*

To understand large deviation of the ν_e flux from purely thermal neutrino emission during and after Si burning, we must refer to Fig 5. The figure shows the evolution of the electron fraction Y_e inside pre-supernova stars. Before Si ignition, matter is composed mainly of nuclei with equal

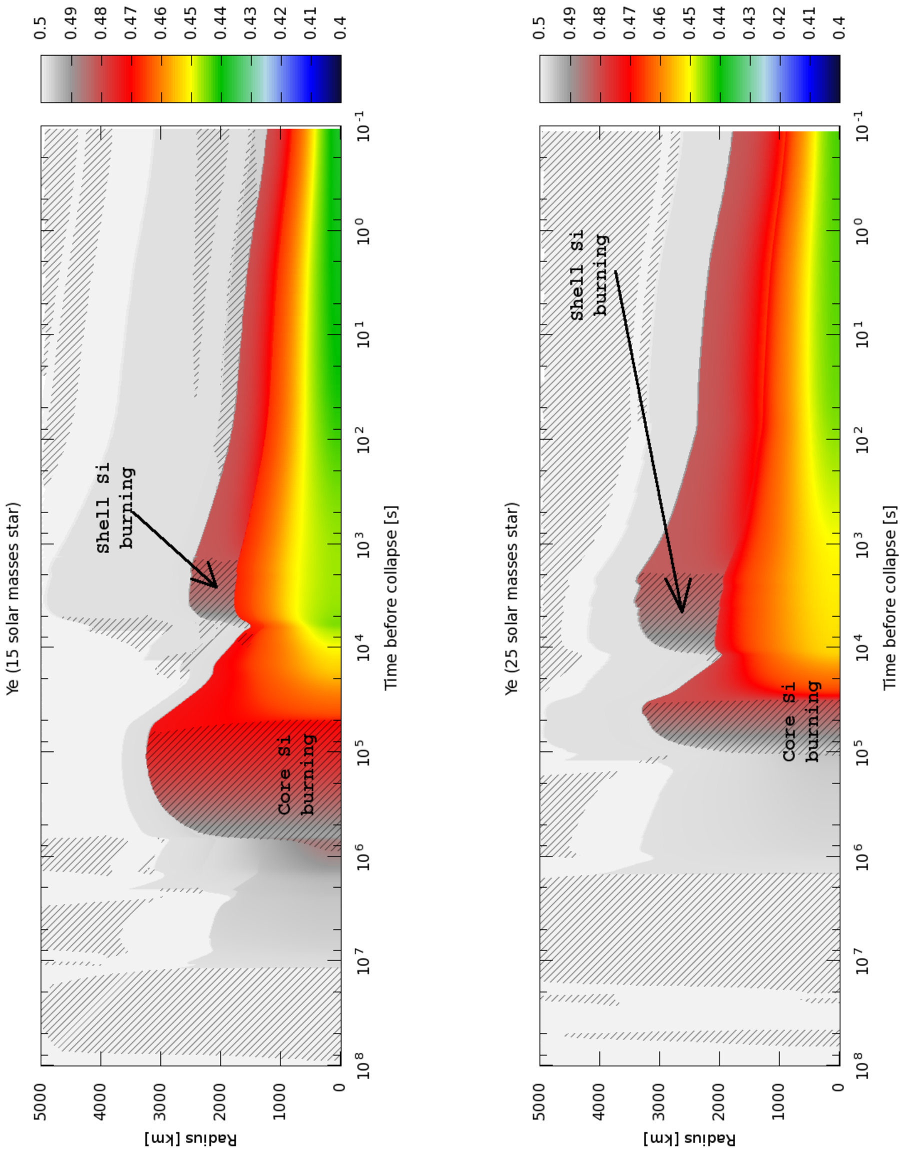

Fig. 5. 15 $M_\odot$ *versus* 25 $M_\odot$: neutronization.

number of neutrons and protons: ^{4}He, ^{12}C, ^{16}O, ... *i.e.*, $Y_e = 0.5$. 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:

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

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

Because both forward and inverse processes do operate involving many nuclei, the situation is difficult to describe in simple words. The overall effect is a significant decrease of the Y_e (Fig. 5), accompanied by a strong ν_e flux (Fig. 3). Whereas the calculated ν_e flux does not depend on the computational method, the energy $\langle \mathcal{E}_{\nu_e} \rangle$ calculated using an α-network is $\langle \mathcal{E}_{\nu_e} \rangle \simeq 4$ MeV while using the NSE (Nuclear Statistical Equilibrium, [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.

Although the drop of Y_e from 0.5 to 0.45–0.43 does not look dramatic, this small change of Y_e leads to significant changes of the nuclear composition in the core matter 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).

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[4] Difference in Binding Energy (BE) of (A, Z) and $(A, Z-1)$ minus $m_e c^2$.

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

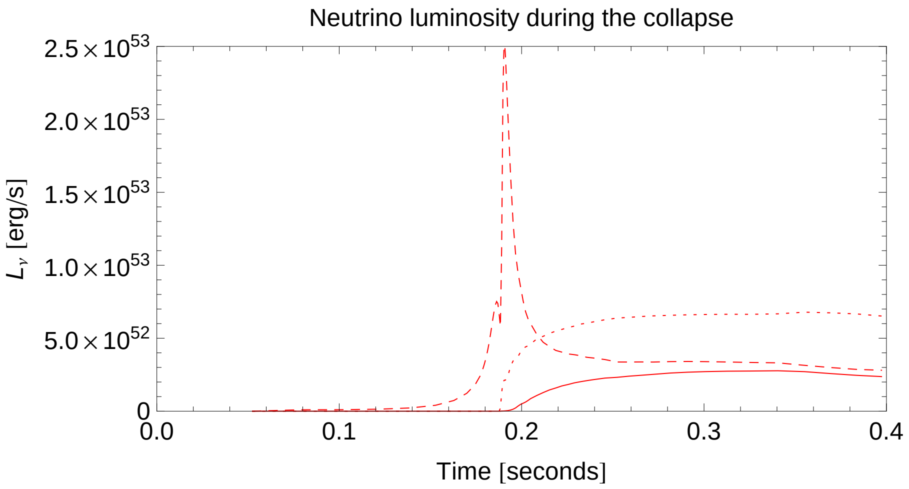

Fig. 6. Neutrino emission from the collapse. The dashed, dotted and solid lines correspond to the ν_e, ν_μ and $\overline{\nu}_e$ fluxes, respectively. Data source: `http://www.astro.princeton.edu/~burrows/tbp/tbp.html`

The results presented in Fig. 6 are an example of the neutrino flux calculations. The neutrino signals were further analysed in numerous papers [32–63].

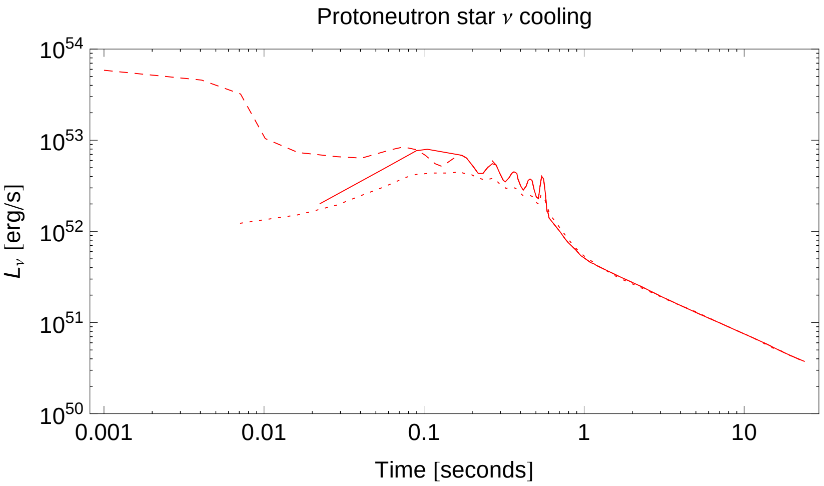

Fig. 7. Proto-neutron star evolution. The dashed, dotted and solid lines correspond to the ν_e, ν_μ and $\overline{\nu}_e$ fluxes, respectively. Data from A. Burrows homepage `http://www.astro.princeton.edu/~burrows`

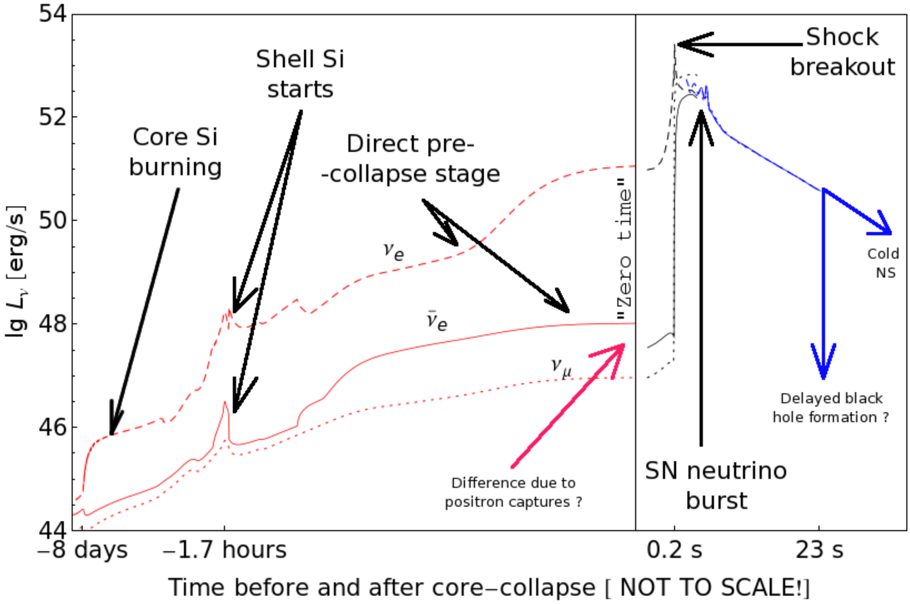

Fig. 8. Neutrinos BEFORE and AFTER collapse.

2.6. Stage 6: early and late cooling of the proto-neutron star

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

Roughly speaking, a newly born PNS (Proto Neutron Star) eventually becomes NS by neutrino 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 times 10^{53} ergs (*cf.* Table II) 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 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].

For some EOS (Equation Of State), *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

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

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

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 stages of most intense neutrino emission during the life of a star are shown. They are: ν-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 a $15\,M_\odot$ 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 ($d = 100\ldots200$ pc).

2. Core Si burning, 8–0.5 days before collapse, detectable using future detectors for stars at 1–2 kpc, *i.e.* within $\sim 0.5\%$ 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 ν_e (30–0 minutes), with continuous transition into shock breakout ν_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 proto-neutron 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 ν_e and $\bar{\nu}_e$, shell Si burning $\bar{\nu}_e$, neutronization ν_e after core Si ignition, shock-breakout ν_e peak, and late-cooling proto-neutron star neutrinos are new challenges. They are goals for the current (Borexino [68], Super-Kamiokande [69]) and the next generations of neutrino detectors (LENA [70–72], Hanohano [73], Memphys [70, 74], Titan-D [75–77], *etc.*), which are part of the LAGUNA, DUSEL, LBNE [78] and other recent initiatives [79].

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