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Supernova Neutrinos: New Challenges and Future Directions

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Abstract. Neutrinos are key particles in core-collapse supernovae. Traveling unimpeded through the stellar core, neutrinos can be direct probes of the still uncertain and fascinating supernova mechanism. Intriguing recent developments on the role of neutrinos during the stellar collapse are reviewed, as well as our current understanding of the flavor conversions in the stellar envelope. The detection perspectives of the next burst will be also outlined.

1. Introduction

Since the last core-collapse supernova (SN), the only one detected in neutrinos, substantial progress has been made as for our understanding of the physics leading to the stellar explosion [1, 2], the role of neutrinos in the star, and the flavor oscillations in neutrino-dense media [3, 4]. Several large scale detectors are in place (or will be soon) to detect the next galactic burst [3, 5, 6]. Nevertheless, we are still far from fully grasping the core collapse physics and the role of neutrinos in it. In this sense, the detection of the next galactic burst will provide us with a precious test of our understanding of the stellar dynamics.

Besides the single SN burst, the detection of the diffuse SN neutrino background (DSNB, the neutrino flux emitted from all SNe exploding somewhere in the Universe) is approaching. The DSNB will allow us to learn about the stellar population, other than provide with an independent test of the SN rate [3, 7, 8]. In what follows, we will outline some of the open issues in SN and neutrino astrophysics, as well as future directions.

2. Supernova simulations: The 3D frontier and recent developments

A core-collapse SN explosion originates from the death of stars with $M > 8M_{\odot}$ [1]. The SN iron core is surrounded by shells of lighter elements; once the Chandrasekhar limit is reached, the core collapses and the explosion is triggered. The 99% of the explosion energy is released in neutrinos with average energies of $\mathcal{O}(10)$ MeV. The neutrino signal should last for about 10 s.

The SN neutrino signal can be divided in three windows, see Fig. 1: The *neutronization burst* marked by a large peak in the ν_e luminosity (generated because of the rapid electron capture by nuclei and free protons, as the shock wave crosses the iron core dissociating its nuclei); the *accretion phase* where the differences among the fluxes of different flavors are still large especially between the electron and non-electron flavors; the *cooling phase* where the neutrino emission properties of the different flavors become very similar and the luminosity progressively decreases.

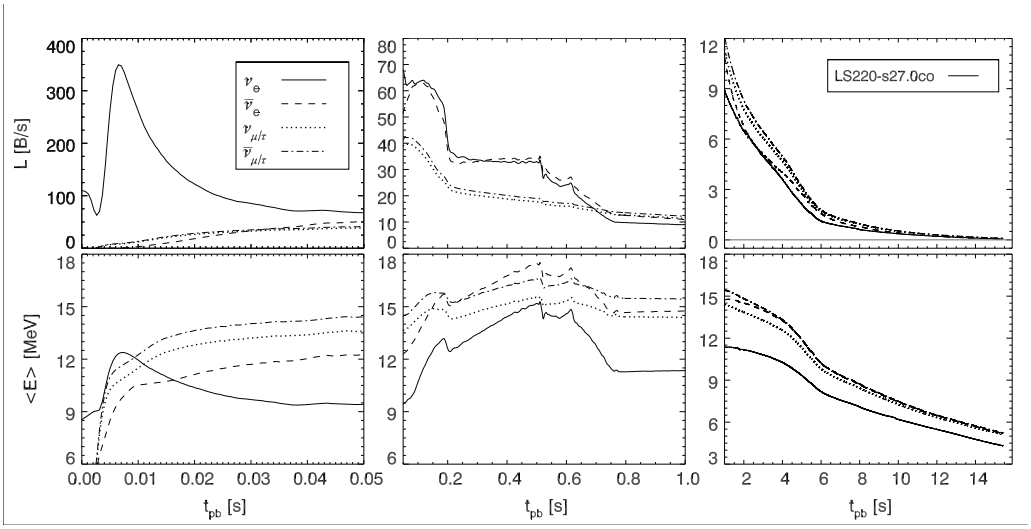

Figure 1. Neutrino luminosities (on the top) and mean energies (on the bottom) for the three flavors [continue line stands for ν_e's, dashed line for $\bar{\nu}_e$'s, dotted (dashed-dotted) line for $\nu_{\mu,\tau}$ ($\bar{\nu}_{\mu,\tau}$)] as a function of the post-bounce time for a 27 $M_\odot$ SN progenitor. The panels on the left refer to the neutronization phase, the middle panels to the accretion phase, and the panels on the right to the cooling phase. Figure adapted from from Ref. [3].

Core-collapse hydrodynamic simulations have recently reached the 3D front, unveiling new and unexpected features [2]. The first successful explosions have been obtained in 3D by several groups [9, 10, 11, 12] with different degrees of sophistication. Although the SN modelling still needs to be refined and long-term 3D simulations of the core-collapse are not yet available, the available hydro simulations are a precious benchmark to test the neutrino mechanism.

The SN explosion is expected to occur according to the delayed neutrino explosion mechanism [13]: Neutrinos provide new energy to revive the stalled shock wave and trigger the explosion. During the shock revival phase, hydrodynamical instabilities occur, such as convective overturns and the standing accretion shock instability (SASI) contribute to enhance the efficiency of the energy transfer between the neutrinos and the shock wave. Recent 3D SN simulations suggest that the neutrino signal carries imprints of such instabilities [14, 15]. SASI episodes will be clearly detectable with neutrino telescopes such as IceCube and Hyper-Kamiokande as shown in the left panel of Fig. 2. Another instability has been recently discovered: The lepton emission self-sustained asymmetry (LESA) [2, 16]; LESA is the first instability driven by neutrinos and it consists of an asymmetric emission of the ν_e number flux with respect to the $\bar{\nu}_e$ one, see the right panel of Fig. 2. LESA is characterized by a large scale dipolar character and is responsible for a strong directional dependence of the neutrino fluxes that could affect the SN nucleosynthesis, oscillations and neutron star kicks.

Besides ordinary core-collapse progenitors, a black-hole forming SN may occur when a SN collapses in a black hole and the neutrino signal abruptly ends after a few hundreds of ms. In the past we thought that only progenitors with mass larger than $40M_\odot$ could evolve in black-hole forming SNe, however recent work shows that low mass progenitors may fail and the abundance of black-hole forming SN progenitors can reach up to the $30-40\%$ of the total SN population [17, 18]. Black hole forming SNe may considerably enhance the expected DSNB signal [3].

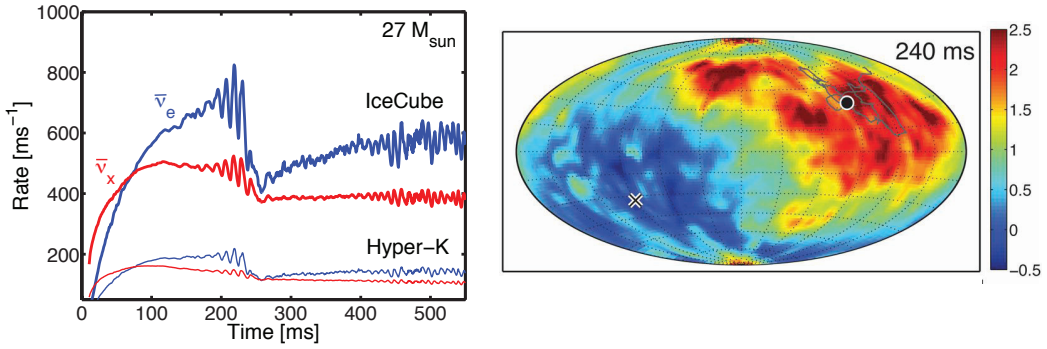

Figure 2. Left: Detection rate in IceCube and Hyper-Kamiokande as a function of the post-bounce time for a 27 $M_\odot$ SN progenitor for an observer at 10 kpc located along a direction where the neutrino signal shows strong SASI modulations. Right: Neutrino lepton number flux ($\nu_e - \bar{\nu}_e$) normalized by its average value for a 11.2 $M_\odot$ progenitor at $t_{\rm p.b.} = 240$ ms. Figure adapted from from Refs. [14, 16].

3. Flavor evolution in supernovae

The flavor evolution of neutrinos is described by matrices of densities by the following equations of motion

$$\partial_t + \vec{v} \cdot \vec{\nabla}_p \rho(t, \vec{x}, \vec{p}) = -i[H(t, \vec{x}, \vec{p}), \rho(t, \vec{x}, \vec{p})] + \mathcal{C}[\rho(t, \vec{x}, \vec{p})] \ , \tag{1}$$

where the Hamiltonian contains vacuum, matter, and neutrino–neutrino terms; in particular, the latter is due to the fact that SNe are neutrino-rich environments and therefore ν–ν interactions cannot be neglected [3, 4, 19]. This term makes the equations non-linear and it depends on the angle between the momenta of the colliding neutrinos. Solving these equations means to deal with a 7D problem involving quantities changing on different time scales. Simplifications are therefore required.

The modelling of neutrino–neutrino interactions has been first developed by assuming a stationary and spherically symmetric SN within the so-called *neutrino bulb model* [20]: Neutrinos of all flavors are emitted from each point of the neutrino-sphere in the forward solid angle uniformly and isotropically. Under this approximation, general features were found such as the *spectral split*: A complete swap of the neutrino energy spectra for certain energy ranges and according to the neutrino mass hierarchy, as shown in Fig. 2. Within this model, it was proved that the high matter density profile, typical of early post-bounce times (i.e., during the SN accretion phase), locks the neutrino modes inhibiting multi-angle flavor conversion effects ($N_e \geq N_\nu$) [22]. On the other hand, during the cooling phase, where the fluxes of the neutrinos of different flavors are more similar to each other, multiple spectral splits were expected to occur [23].

The above conclusions have been drowned by relying on the assumption that we have a stationary, spherically symmetric SN, where the neutrino fluxes evolve with radius. However, more recently, it has been pointed out as new instabilities in the flavor space may arise by releasing such approximations. For example, within a simplified setup, it has been shown as breaking the axial symmetry [24], the spatial and directional symmetry [25], or by introducing temporal instabilities [26], flavor conversions could be induced (i.e., flavor instabilities can be determined because of the non-homogeneous or non-stationary conditions occurring within the stellar envelope). The same should be expected by considering a neutrino angular distribution not limited to the outward direction, as well as in the presence of large 3D effects that make the system inhomogeneous, non-stationary and anisotropic [15, 16]. Some of the most recent work

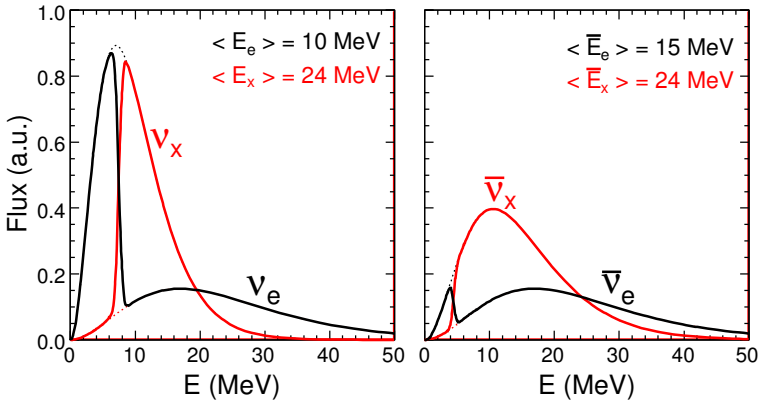

Figure 3. Neutrino (on the left) and antineutrino fluxes (on the right) as a function of the energy after ν–ν interactions assuming inverted mass ordering. The fluxes at the neutrino sphere are shown as dotted lines. Figure taken from Ref. [21].

in this direction seems to suggest flavor equipartition might occur already very close to the SN core. Existing investigations in this contest are still simplified cases of study and further work is necessary.

4. What could we learn from the next supernova burst?

A network of neutrino detectors around the world (SNEWS) will alert astronomers in the event of a SN burst [27], neutrinos arriving earlier than photons on Earth. Moreover, we could determine the angular location of a SN with its neutrinos [28, 29] with an error of about 5^o in e.g. Super-Kamiokande. Triangulation would be also possible [30]. Such measurements will be crucial for dim or optically weak SNe where neutrinos could be the only detected particles. These measurements will be also important for multi-messenger searches.

The neutronization burst signal is independent of the progenitor mass and the nuclear equation of state. It can be adopted as a standard candle to define the distance of the SN event [31]. Since the slope of the $\bar{\nu}_e$ and $\bar{\nu}_x$ light-curves is different, the observed neutrino event rate will be sensitive to the neutrino mass ordering in, e.g., Cherenkov telescopes. The same holds for the neutrino channel; if we consider the ν_e event rate as seen in e.g., a liquid argon detector, the absence (presence) of the peak of the neutronization burst will hint towards a normal (inverted) mass ordering [32].

During the accretion phase, the neutrino signal carries characteristic signatures of the SASI motions and convective overturns, clearly detectable in, e.g., Cherenkov telescopes [15, 14] providing insights on the core-collapse physics complementary to the ones coming from gravitational waves. By looking at the first detected neutrino event, we could probe the core bounce time [33].

The cooling phase signal is strongly sensitive to the nuclear equation of state as well as to the SN progenitor mass. The exact composition in neutrinos of different flavors is responsible for determining the nucleosynthesis outcome in the neutrino driven wind [34, 35]. Recent first attempts of coupling the oscillation codes to the nucleosynthesis networks suggest that, even by taking into account the existence of an extra light sterile family, it is difficult to create a n-rich environment in the SN neutrino driven wind (i.e., $Y_e < 0.5$) and to activate the r-process [35], see e.g. Fig. 4. However, the role of oscillations in the production of heavy elements remains to be clarified.

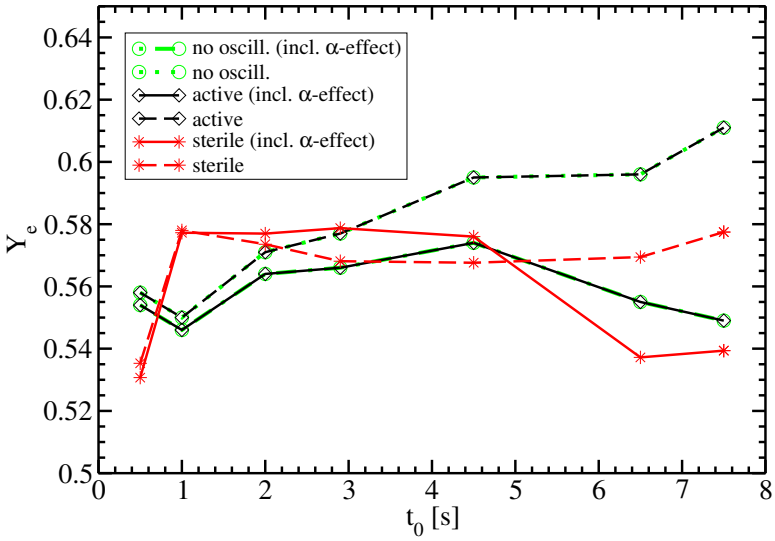

Figure 4. Asymptotic electron fraction (Y_e) as a function of the post-bounce time (t_0) in the presence of only active states, 2active+1sterile families and with and without oscillations. The electron abundance Y_e should be lower than 0.5 in order to create favourable conditions for the r-process. Figure adapted from Ref. [35].

In synthesis, each of the three phases of the SN neutrino signal offers different opportunities to learn about the stellar collapse or neutrino properties.

5. Diffuse Supernova Neutrino Background

On average a SN explodes every second in the Universe and we could detect the cumulative neutrino flux, the DSNB [3, 7, 8]. The DSNB should be clearly detectable in the region around 20–30 MeV, where it is expected to be above the reactor and atmospheric backgrounds.

The detection of the DSNB will be instrumental to constrain the stellar population, it will provide us with an independent test of the SN rate, and will help us to constrain the fraction of black-hole forming versus core-collapse SNe. At the same time, the DSNB detection could help us to constrain the neutrino emission properties as well as exotic physics scenarios. The possibility of detecting the DSNB will be improved in the next future with the planned JUNO scintillator detector as well as with the approval of the Gd project for the Super-K detector [3].

6. Summary

Neutrinos play a fundamental role in the physics of a core-collapse supernova. The first successful supernova hydrodynamic simulations in 3D revealed unexpected and fascinating phenomena and proved as the detection of the supernova neutrino signal will be instrumental to test the explosion mechanism.

Core-collapse supernovae are neutrino-dense environments and ν–ν interactions cannot be neglected. A careful modelling of the SN environment for studying the oscillation phenomenology is compulsory and it still incomplete at the moment, despite the intense theoretical activity in this direction. Neutrino self-interactions are non-linear effects and it has been shown as, by releasing some of the traditionally adopted symmetry assumptions, instabilities in the flavor space could be induced.

Each phase of the core collapse neutrino signal could offer different opportunities to learn about the supernova physics and the synthesis of the new elements. The detection of the DSNB is expected to happen within the next decade and will offer us with a chance to constrain the

stellar population as well as to independently test the supernova rate.

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