Supernova as Particle-Physics Laboratory

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The neutrino signal of supernova (SN) 1987A has provided numerous particle-physics constraints, primarily by the signal duration that precludes excessive energy losses in new channels. Improving these results with the neutrino signal from the next galactic SN requires a better understanding of the expected standard signal duration and in particular of neutrino opacities. Independently of neutrino observations, one should perform SN simulations including nonstandard flavor changing and lepton-number violating processes to understand their impact on SN dynamics.

1 Introduction

A high-statistics neutrino observation of the next nearby supernova (SN) is one of the major physics motivations for low-energy neutrino astronomy [1, 2, 3]. Above all it would provide detailed information on the core collapse phenomenon and test the delayed explosion scenario [4, 5]. Moreover, the IceCube detector may be able to resolve fast time variations caused by SASI activity and convective overturns [6, 7]. The simultaneous observation with the upcoming round of gravitational wave detectors would provided crucial additional information [8].

On the other hand, SN neutrinos hold crucial particle-physics information [9, 10, 11, 12]. Neutrino flavor oscillations form one central topic, but will be covered mostly by other speakers at this conference. I will here primarily review the traditional SN 1987A constraints and how these would be affected by new theoretical developments and a high-statistics observation of the next nearby SN. Independently of such an observation, I will argue that SN simulations with nonstandard flavor changing and lepton-number violating processes should be performed.

2 Time-of-flight constraints

It was Georgiy Zatsepin who first pointed out that the neutrino burst from SN collapse offers an opportunity to measure the neutrino mass by the energy-dependent time-of-flight delay [13]

$$\Delta t = 5.1\ \mathrm{ms} \left(\frac{D}{10\ \mathrm{kpc}}\right) \left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)^2 \left(\frac{m_\nu}{1\ \mathrm{eV}}\right)^2 .$$

However, when the SN 1987A burst was measured, it provided a mass limit of about 20 eV [14, 15, 16], which even at that time was only marginally interesting and was soon superseded by laboratory limits. The neutrino signal of the next nearby SN could improve this at best to the eV range [17]. It is more interesting to note that the restrictive sub-eV cosmological neutrino mass limits [18] assure that fast time variations at the source will not be washed out by time-of-flight effects and thus are, in principle, detectable at IceCube [6, 7]. In this sense the forthcoming KATRIN direct neutrino mass measurement (or mass limit) [19] will be of interest to the interpretation of a SN neutrino signal.

A putative neutrino electric charge would lead to deflection in the galactic magnetic field and thus to an energy-dependent pulse dispersion in analogy to m_ν, providing the bound $e_\nu \lesssim 3 \times 10^{-17}\, e$ [20, 21].

From a present-day perspective, the most interesting time-of-flight constraint, however, is the one between neutrinos and photons, testing the equality of the relativistic limiting propagation speed between the two species. SN physics dictates that the neutrino burst should arrive a few hours earlier than the optical brightening, in agreement with SN 1987A. Given the distance of about 160.000 light years one finds [22, 23]

$$\left|\frac{c_\nu - c_\gamma}{c_\gamma}\right| \lesssim 2 \times 10^{-9}\,.$$

At the time of this writing, this result plays a crucial role for possible interpretations of the apparent superluminal neutrino speed reported by the OPERA experiment [24], $(c_\nu - c_\gamma)/c_\gamma = (2.48 \pm 0.28_{\rm stat} \pm 0.30_{\rm sys}) \times 10^{-5}$.

Both neutrinos and photons should be delayed by their propagation through the gravitational potential of the galaxy (Shapiro time delay) which is estimated to be a few months toward the Large Magellanic Cloud. The agreement between the arrival times within a few hours confirms a common time delay within about 0.7–4×10^{-3}, i.e. neutrinos and photons respond to gravity in the same way [25, 26]. This is the only experimental proof that neutrinos respond to gravity in the usual way.

It is intriguing that these results could be extended to include the propagation speed of gravitational waves if the next nearby SN is observed both in neutrinos and with gravitational wave detectors. The onset of both bursts would coincide with the SN bounce time to within a few ms and the coincidence could be measured with this precision [27, 28]. In view of the current discussion of superluminal neutrino propagation, such a measurement would provide important additional constraints on possible interpretations.

3 Novel SN energy loss and neutrino signal duration

After core collapse, neutrinos are trapped in the SN core and energy is emitted on a neutrino diffusion time scale of a few seconds [29]. This basic picture was confirmed by the SN 1987A neutrino burst, indicating that the gravitational binding energy was not carried away in the form of some other radiation, more weakly coupled than neutrinos, that would escape directly without diffusion [30, 31, 32]. This "energy-loss argument" has been applied to a large number of cases, notably axions, Majorons, and right-handed neutrinos, often providing the most restrictive limits on the underlying particle-physics model; extensive reviews are Refs. [9, 10, 11, 12]. More recently, the argument was applied to Kaluza-Klein gravitons [33, 34, 35, 36], light neutralinos [37], light dark matter particles [38], and unparticles [39, 40, 41].

While there is no good reason to doubt the validity of this widely used argument, it is based on very sparse data. Measuring a high-statistics neutrino signal from the next nearby SN would put these crucial results on much firmer experimental ground.

Another question is what to use as a theoretical benchmark for comparison with the data. The pioneering work of the Livermore group combined relativistic hydrodynamics with multi-group three-flavor neutrino diffusion in spherical symmetry (1D), simulating the entire evolution self-consistently [4]. These models, however, included significant numerical approximations and omitted neutrino reactions that were later recognized to be important [42]. A crucial ingredient to enhance the early neutrino fluxes was a neutron-finger mixing instability, which today is disfavored [43]. Relativistic calculations of proto neutron star (PNS) cooling were performed with a flux-limited equilibrium [44, 45] or multi-group diffusion treatment [46]. Pons et al. [47] studied PNS cooling for different equations of state and masses, using flux-limited equilibrium transport with diffusion coefficients adapted to the underlying equation of state.

New opportunities to study the neutrino signal consistently from collapse to late-time cooling arise from the class of "electron-capture SNe" or "O-Ne-Mg core SNe." These low-mass stars (8–$10\,M_\odot$) collapse because of rapid electron capture on Ne and Mg and could represent up to 30% of all SNe. They are the only cases where 1D simulations obtain neutrino-powered explosions [48]. It has become possible to carry hydrodynamic simulations with modern neutrino Boltzmann solvers in 1D all the way to PNS cooling. Very recently, the Basel group has circulated first results of the PNS evolution [49] for a representative $8.8\,M_\odot$ progenitor and subsequently the Garching group has simulated explosions with the same progenitor [50]. The multi-flavor neutrino signal is shown in Fig. 1.

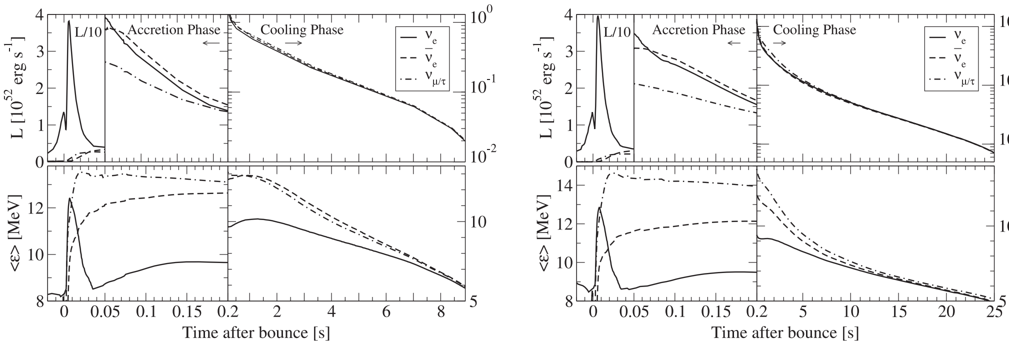

Figure 1: Neutrino emission from a spherically symmetric electron-capture SN according to a Garching simulation [50]. *Left:* Full set of neutrino opacities. *Right:* Reduced set, primarily excluding nucleon-nucleon correlations and nucleon recoils.

The Garching group has performed this simulation with two different sets of neutrino opacities. The full set includes, in particular, nucleon recoil and nucleon-nucleon correlations that can strongly reduce the interaction rate and thus increase the neutrino mean free path. Their reduced set, essentially without these effects, is close to what is used by other groups. The late-time signal duration is quite different between the two cases (left and right panel of Fig. 1). For the "full case" (left panel), the cooling time is so short that it is just barely compatible with the SN 1987A signal duration. In other words, how much energy loss by new particles is allowed by SN 1987A or a future high-statistics signal depends on the treatment of neutrino transport. With long-term cooling calculations, based on a Boltzmann transport scheme, becoming a routine task, improving the microscopic treatment of neutrino interaction in the dense SN medium should be more systematically studied.

4 Flavor and lepton number violation

Conventional SN simulations are based on standard particle-physics assumptions that are not necessarily tested in the laboratory. In particular, lepton-number conservation is crucial in the collapse process because it ensures that the liberated gravitational energy is at first stored primarily in the degeneracy energy of electrons and electron neutrinos, i.e. the SN core after collapse is relatively cold. On the other hand, it is now commonly assumed that lepton number is not conserved in that neutrino masses are widely assumed to be of Majorana type. While neutrino Majorana masses would not suffice for significant lepton-number violating effects in a SN core, other sources of lepton-number violation may well be strong enough, e.g. R-parity violating supersymmetric models that in turn can induce Majorana masses. Therefore, it would be intriguing to study core collapse with "internal" deleptonization, leading to a hot SN core immediately after collapse.

In a SN core, the matter potentials are so large that flavor conversion by oscillation is strongly suppressed even though some of the mixing angles are large. Therefore, the initial ν_e Fermi sea is conserved—in a SN core, flavor lepton number is effectively conserved. On the other hand, certain non-standard interactions (NSI) [51] that are not diagonal in flavor space would allow for flavor lepton number violation in collisions and therefore lead to a quick equipartition among flavors of the trapped lepton number. The required interaction strength is much smaller than what is typically envisioned for NSI effects on long-baseline neutrino oscillation experiments. In other words, a SN core is potentially the most sensitive laboratory for NSI effects. While it has been speculated that such effects would strongly modify the physics of core collapse [52, 53], a numerical simulation including the quick equipartition of flavors has never been performed.

Therefore, one should perform numerical studies of core collapse, allowing for the violation of lepton number and of flavor or both on a dynamical SN time scale. As a first step, a parametric study would be enough—detailed microscopic models are probably not important to understand the possible impact on SN dynamics. Also, such a programme would not depend on measuring neutrinos from the next nearby SN.

5 Conclusions

We have briefly reviewed the role of core-collapse SNe as particle physics laboratories and have discussed time-of-flight and energy-loss arguments. Moreover, we have suggested that simulations should be performed that include lepton and flavor violation. Of course, the field is much broader. For example, we have not touched upon flavor oscillations or the role of sterile neutrinos because these topics are covered by other speakers at this workshop. Measuring a high-statistics neutrino signal from the next nearby SN would greatly help us to put the existing SN 1987A limits on a firm observational footing, but also requires a better theoretical understanding, for example of neutrino transport and particle emission processes.

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