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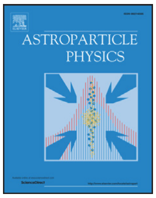

Diffuse supernova neutrinos at underground laboratories

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ABSTRACT

I review the physics of the Diffuse Supernova Neutrino flux (or Background, DSNB), in the context of future searches at the next generation of neutrino observatories. The theory of the DSNB is discussed in its fundamental elements, namely the cosmological rate of supernovae, neutrino production inside a core collapse supernova, redshift, and flavor oscillation effects. The current upper limits are also reviewed, and results are shown for the rates and energy distributions of the events expected at future liquid argon and liquid scintillator detectors of $\mathcal{O}(10)$ kt mass, and water Cherenkov detectors up to a 0.5 Mt mass. Perspectives are given on the significance of future observations of the DSNB, both at the discovery and precision phases, for the investigation of the physics of supernovae and of the properties of the neutrino.

1. Introduction

After a first phase of exploration, focused on solar and atmospheric neutrinos studies, neutrino physics has now entered a second phase of greater precision studies. A new generation of neutrino beam experiments is being developed to achieve a full reconstruction of the neutrino mass spectrum and mixing matrix. These experiments, primarily designed for oscillation physics, will also serve as powerful neutrino observatories: thanks to their larger detector masses and improved technologies, they will surpass their predecessors in the ability to detect and study neutrino sources of increasing distance from Earth, increasing energy, and increasing physical complexity.

The still mysterious core collapse supernovae are among these sources. After the handful of neutrino data from SN1987A, the scientific community is still waiting for the next detection of supernova neutrinos, to have the opportunity to learn about the physics of core collapse, to test neutrino properties, and to answer a large number of questions regarding new particles and new forces of nature. Considering that supernovae in our galaxy and its satellites are rare (1–3 per century, see e.g. [1,2]), it is likely that the opportunity will first be offered by the *diffuse* supernova neutrino flux (commonly called “diffuse supernova neutrino background”, DSNB). This flux receives contributions from all the supernovae in the universe and therefore is practically constant in time,[1] requiring only the right experimental sensitivity to be seen. Once observed, it will turn the field of supernova neutrinos from the realm of rare events to the territory of a moderately paced and steady progress.

In addition to testing the variety of physics already probed by SN1987A—like neutrino masses and mixings, neutrino spectra formation in the star, and a number of exotica—the diffuse flux will offer other, complementary, information. Most importantly, the diffuse flux images the whole supernova population of the universe, comprised of progenitor stars of different mass and distance. Thanks to the fast rising of the supernova rate with the redshift, a substantial fraction of the DSNB at Earth originates at cosmological distances. This opens the exciting possibility to do cosmology with neutrinos, and test not only the supernova rate, but also the rate of star formation, of which supernovae are tracers.

Since the original idea that diffuse supernova neutrinos might be detectable [3,4], the physics of the DSNB has matured considerably. After early upper limits that exceeded the predictions by orders of magnitude [5,6], a turning point happened in 2003 when SuperKamiokande [7] placed a bound that touched the interval of existing theoretical predictions, $\Phi \sim 0.1–1\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ above 19.3 of neutrino energy (see e.g.: [8–13]), thus raising the hopes that the DSNB might be detected soon. That first SuperKamiokande result, and its later updates [14,15], have motivated more detailed theoretical predictions of the DSNB, which now include several neutrino oscillation effects [16–24], supernova rate functions motivated by different data sets [18,20,25–30], neutrino spectra from several numerical calculations [18,24,31,32] and inspired by SN1987A as well [20,31,33–35], and even possible new non-standard physics [36–40] and new supernova types [29,30,41–43]. Studies show that the

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[1] Fluctuations in time could be seen due to individual supernovae at several megaparsecs of distance [2].

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current bound implies conditional constraints on the supernova rate [42,44] and on the neutrino flux parameters [14,43,45], and discuss what will be learned from a future detection on the neutrino spectra [46].

While developing the phenomenology of the DSNB, the neutrino community looks ahead to the next generation of large scale detectors [47–53], of which some will expand existing projects, while others will be in completely new multi-disciplinary facilities, like the US-based Deep Underground Neutrino Experiment (DUNE) [50,51,54,55].

For the new neutrino experiments, observing the DSNB is an important item of the agenda, to the point that technical upgrades are sometimes driven by this specific goal [56]. For all detection technologies backgrounds are the main limiting factors, as they often restrict the sensitive energy window considerably (to the ∼20–40 MeV interval, in the case of a water Cherenkov detector). Even within the energy window, backgrounds limit the benefits of the larger detector mass.

Interestingly, searches for the DSNB show how, in the new chapter of neutrino astrophysics, what were once sought after signals—such as solar and atmospheric neutrinos—will become well known backgrounds that will have to be reduced or subtracted. This shift in the focus might have interesting implications on what characteristics might define an ideal detector several decades from now.

In this time of intense activity on the diffuse supernova neutrino flux, this review may offer a timely summary as well as a useful perspective on this new direction of research, within the activity of scoping of the next generation of neutrino observatories. The paper opens with a section of essential facts (Section 2), which are then developed in Section 3 for the theory and in Section 4 for detection aspects. A section of discussion of the physics potential of the DSNB follows in closing (Section 5).

Note: Many of the numerical results (figures and tables) that appear here were prepared specifically for this review—and not taken from previous literature—for the sake of consistency in the graphics styles and in the sets of input parameters. The original works where analogous results appear will be referenced as accurately as possible, with apologies in advance for involuntary omissions.

2. Diffuse supernova neutrinos: The essentials

This section gives a minimal introduction to the subject of diffuse supernova neutrinos. It might be useful to the reader who needs only the essential information, and to others as a summary of the reminder of the review.

Stars with masses larger than $\sim 8 M_\odot$ (with $M_\odot = 1.99 \times 10^{30}$ kg the mass of the Sun) end their lives with the gravitational collapse of their core, followed first by neutrino emission over a time scale of about 10 s, and then by a shock-driven, very luminous, explosion called a supernova (SN). These core collapse supernovae[2] are relatively rare phenomena: their rate in the universe today (redshift $z = 0$) is $R_{SN}(0) \sim 10^{-4}$ year^{-1} Mpc^{-3}. Interestingly, the supernova rate is a growing function of the redshift, z, signifying that supernovae were more frequent in the past (Section 3.1).

The matter inside a supernova is dense enough (reaching nuclear density in the core, $\rho \simeq 3 \times 10^{14}$ g cm^{-3}) to host a thermal population of neutrinos of all species ($\nu_e, \bar\nu_e, \nu_\mu, \nu_\tau, \bar\nu_\mu, \bar\nu_\tau$) which then diffuse out and reach the Earth, carrying information on the stellar temperature in their nearly thermal energy spectrum, which peaks at ∼10–20 MeV. It is expected that ν_e and $\bar\nu_e$ have colder spectra than the other species, as they are more strongly coupled to matter (Section 3.2). Neutrinos dominate the energetics of a supernova: they carry away about 99% of the gravitational binding energy released in the collapse, $E_b \simeq 3 \cdot 10^{53}$ ergs ($= 3 \times 10^{46}$ J), which is roughly equipartitioned between the six neutrino species.

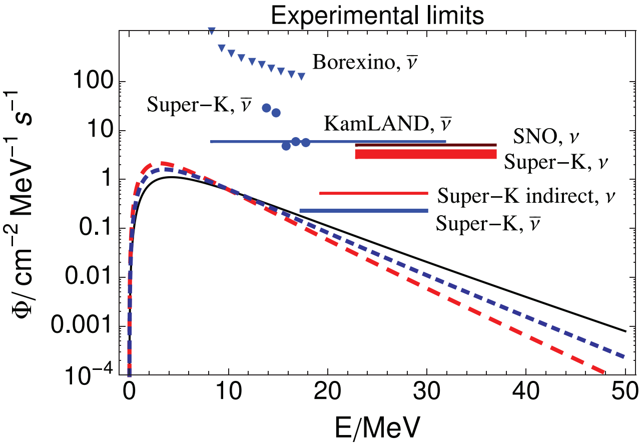

Fig. 1. Experimental limits for the ν_e and $\bar\nu_e$ components of the DSNB, (Table 8) compared with theoretical predictions for three different examples of neutrino spectra. The upper to lower curves at 20 MeV refer to the H, W and C spectrum (Table 1), and complete flavor permutation ($p = \bar p = 0$), for which fluxes are maximal for the energies of interest. To make the comparison meaningful, limits on the energy-integrated fluxes have been divided by the size of the energy window of sensitivity of the experiment (see Section 4.1). For the SK limits, the widths of the lines represent how each bound varies with the variation of the neutrino energy spectrum. See Section 4.3 for details.

On the way between their production point and a detector on Earth, the neutrinos undergo redshift of energy and flavor conversion (oscillations), so that the flux of neutrinos (antineutrinos) of a given flavor in a detector is a linear combination of the fluxes of neutrinos (antineutrinos) originally produced in different flavors (Section 3.3). If all supernovae are outside our immediate galactic neighborhood (farther than few megaparsecs), the flux we receive from each of them is practically infinitesimal, but the total, diffuse, flux from all supernovae combined is in principle observable. In terms of the (comoving) supernova rate, $R_{SN}(z)$, the diffuse flux of $\bar\nu_e$ in a detector at Earth, differential in energy, surface and time, is given by:

$$\Phi_{\bar e}(E) = \frac{c}{H_0} \int_0^{z_{\max}} R_{SN}(z) F_{\bar e}(E') \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \qquad (1)$$

(see e.g. [18]), where $F_{\bar e}(E')$ is the contribution of an individual supernova, inclusive of neutrino oscillations and of the redshift of energy, $E' = E(1+z)$, and differential in E'. Ω_m and Ω_Λ are the fractions of the cosmic energy density in matter and dark energy respectively; c is the speed of light and H_0 is the Hubble constant. $z_{\max}$ is the maximum redshift for which there is substantial star formation, $z_{\max} \sim 5$ (Section 3.1).

Estimates (Fig. 1) show that for realistic neutrino spectra and flux normalizations, the DSNB peaks around 5–7 MeV of energy, where it can be as large as $\Phi \sim 5$ cm^{-2}s^{-1}MeV^{-1} for each neutrino species. It decays exponentially with energy above the peak. The flux in each neutrino type is typically in the range 12–20 cm^{-2}s^{-1} if integrated over all energies, and ∼0.1–0.8 cm^{-2}s^{-1} in the energy window of current experimental interest: $E \sim 18$–35 MeV. This window is determined by backgrounds such as spallation and solar neutrinos at low energy, and atmospheric neutrinos at high energy (Section 4.1).

Experimentally, many upper bounds on the DSNB exist (Fig. 1; Section 4.3). The strongest is on the $\bar\nu_e$ component, from the

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[2] Core collapse supernovae are astronomically classified as type II, Ib and Ic. Type Ia supernovae are of entirely different nature and do not involve a collapse of the stellar core.