Physics potential of future supernova neutrino observations

Amol Dighe

Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, INDIA

E-mail: `amol@theory.tifr.res.in`

Abstract. We point out possible features of neutrino spectra from a future galactic core collapse supernova that will enhance our understanding of neutrino mixing as well as supernova astrophysics. We describe the neutrino flavor conversions inside the star, emphasizing the role of "collective effects" that has been appreciated and understood only very recently. These collective effects change the traditional predictions of flavor conversion substantially, and enable the identification of neutrino mixing scenarios through signatures like Earth matter effects.

1. Introduction

Time dependent energy spectra of ν_e and $\bar{\nu}_e$ from a future galactic supernova (SN) can be decoded to obtain information on primary neutrino spectra, the neutrino mixing scheme as well as densities encountered by the neutrinos along their path. In particular, these spectra enable us to probe extremely small θ_{13} values and distinguish between normal and inverted mass hierarchies [1]. On the other hand, the neutrino signal provides important astrophysical information that allows us to point at the SN in advance and even track the shock wave while it is still inside the mantle (see [2] for a recent overview).

The only SN observed in neutrinos till now, SN1987A, yielded only $\sim$20 events. Though it confirmed our understanding of the SN cooling mechanism [3], the number of events was too small to say anything concrete about neutrino mixing (see [4] and references therein). On the other hand, if a SN explodes in our galaxy at ~ 10 kpc from the Earth, we expect $\mathcal{O}(10^4)$ events at Super-Kamiokande (SK) through the inverse beta decay process $\bar{\nu}_e + p \to n + e^+$ [5]. This process, dominant at any water Cherenkov or scintillation detector, will be instrumental in determining the $\bar{\nu}_e$ spectrum. The number of events will be higher by an order of magnitude at the planned megaton scale water Cherenkov detectors [6, 7, 8, 9], while large scintillation detectors [10] will determine the neutrino energy with much better precision. Even a gigaton ice Cherenkov detector like IceCube [11, 12], though incapable of detecting SN neutrinos individually, can determine the total $\bar{\nu}_e$ luminosity as a function of time. In order to measure the ν_e spectrum cleanly, one needs a large liquid Ar detector, with the relevant process $\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$, with $\mathcal{O}(10^4)$ events expected at a 100 kt detector [13, 14]. With such a significant statistics, one would be able to reconstruct the ν_e and $\bar{\nu}_e$ spectra, and extract the information encoded therein.

The traditional analysis of neutrino flavor conversions [15] neglected the neutrino-neutrino interactions, which are now known to be significant near the neutrinosphere owing to the large neutrino density. The last couple of years have seen significant progress in our understanding of these neutrino refraction effects, also known as the collective effects. In this talk, we shall concentrate on these recent exciting developments, clarify our current understanding of SN neutrino flavor conversions, and obtain the characteristics of the observed neutrino fluxes. Finally, we shall point out the distinctive features to look for in the neutrino spectra that may be able to settle some of the unresolved problems in neutrino physics and astrophysics. We restrict ourselves to standard three-neutrino mixing.

2. Flavor conversions of supernova neutrinos

2.1. Neutrino production and primary spectra

Before the core collapse, neutrinos of all species are trapped within the star inside their respective "neutrinospheres" around $\rho \sim 10^{10}$g/cc. When the iron core reaches a mass close to its Chandrasekhar limit, it becomes gravitationally unstable and collapses. A hydrodynamic shock is formed when the matter reaches nuclear density and becomes incompressible. When the shock wave passes through the ν_e neutrinosphere, a short ν_e "neutronization" burst is emitted, which lasts for $\sim$10 ms. The object below the shock wave, the "protoneutron star," then cools down with the emission of neutrinos of all species, over a time period of $t \sim 10$ s [3]. The eventual explosion of the star involves the stalling of the original shock wave, its revival by the trapped neutrinos, and a "delayed" explosion where large scale convections play an important role [16, 17].

The SN core acts essentially like a neutrino black-body source with flavor dependent fluxes. Since the fluxes are almost identical for ν_μ and ν_τ ($\bar{\nu}_\mu$ and $\bar{\nu}_\tau$), it is convenient to denote these species collectively by ν_x ($\bar{\nu}_x$). The "primary fluxes" $F^0_{\nu_\alpha}$ are parametrized by the total number fluxes $\Phi_0(\nu_\alpha)$, average energies $\langle E_0(\nu_\alpha)\rangle$, and the "pinching parameters" that characterize their spectral shapes [18]. The values of the parameters are highly model dependent, as can be seen from table 1.

Table 1. Typical neutrino Flux predictions in the Livermore [19] and Garching [20] models. Average energies are given in MeV.

Model	$\langle E_0(\nu_e)\rangle$	$\langle E_0(\bar{\nu}_e)\rangle$	$\langle E_0(\nu_x)\rangle$	$\langle E_0(\bar{\nu}_x)\rangle$	$\frac{\Phi_0(\nu_e)}{\Phi_0(\nu_x)}$	$\frac{\Phi_0(\bar{\nu}_e)}{\Phi_0(\bar{\nu}_x)}$
Livermore	12	15	24	24	2.0	1.6
Garching	12	15	18	18	0.8	0.8

In the light of the large model dependence in the primary neutrino spectra, it is imperative to look for signals at these detectors that are independent of the details of the primary spectra, but depend on distinctive signatures of neutrino mixing schemes. In order to do this, one needs to analyze the neutrino flavor conversions during their propagation outwards from the neutrinospheres.

2.2. Collective effects at large neutrino densities

The neutrino and antineutrino densities near the neutrinosphere are extremely high (10^{30-35} per cm^3), which make the $\nu - \nu$ interactions in this region significant [21, 22]. Such a dense gas of neutrinos and antineutrinos is coupled to itself, making its time evolution nonlinear [23, 24, 25]. The flavor changing terms are sizeable, as a result significant flavor conversions can occur. The distinctive features in the flavor evolution of such a relativistic gas have been identified in [26, 27, 28, 29].

Analytic studies of collective effects reveal a rich phenomenology of flavor conversions, with phenomena that are completely distinct from the traditional vacuum or MSW oscillations. These include "synchronized oscillations" [30], where ν and $\bar{\nu}$ of all energies oscillate with the same frequency, "bipolar oscillations" [31, 32] that correspond to pairwise conversions $\nu_e\bar{\nu}_e \leftrightarrow \nu_y\bar{\nu}_y$ (where ν_y is a specific linear combination of ν_μ and ν_τ), and "spectral split" [34, 35], where $\bar{\nu}_e$ and $\bar{\nu}_x$ spectra interchange completely (barring some possibly non-adiabatic effects at very low energies [33]), whereas ν_e and ν_x spectra interchange only above a certain critical energy E_c.

The dynamics in three generations can be factorized into a superposition of multiple two-flavor phenomena with hierarchical frequencies, and can be visualized in terms of the so-called "$\mathbf{e}_3$–$\mathbf{e}_8$" triangle diagrams [36]. In addition, some new three flavor effects also emerge: for example in early accretion phase, large μ-τ matter potential causes interference between MSW and collective effects, which is sensitive to deviation of θ_{23} from maximality [37].

The dependence of the flavor evolution on the direction of propagation of the neutrino may give rise to direction-dependent evolution [21, 22], or to decoherence effects [28, 38, 39]. Such multi-angle effects, extensively studied numerically in [40, 41], have recently been interpreted in terms of "neutrino flavor spin waves" [42]. However, for a realistic asymmetry between neutrino and antineutrino fluxes, such multi-angle effects are likely to be small [40, 43] and a so-called "single-angle" approximation can be used. Even for non-spherical geometries, one can study the evolution along stream lines of neutrino flux, as long as coherence is maintained [44].

Though the inherent nonlinearity and the presence of multi-angle effects make the analysis rather complicated, the outcome for the flavor conversions turns out to be rather straightforward, at least when the number fluxes of $\nu_e, \bar{\nu}_e$ and ν_x follow an hierarchy $N_{\nu_e} > N_{\bar{\nu}_e} > N_{\nu_x}$. The propagation of the neutrinos can be rather cleanly separated into regions where various collective effects dominate individually [36, 40], and hence the neutrinos experience these effects sequentially. Just outside the neutrinosphere synchronized oscillations occur, which however cause no significant flavor conversions since the mixing angle is highly suppressed owing to large matter density. If the hiearchy is inverted, bipolar oscillations follow, which prepare the neutrinos for the eventual spectral split. Thus when the neutrinos emerge from the region where collective effects dominate, inverted hierarchy simply predicts a complete swap of $\bar{\nu}_e$ and $\bar{\nu}_x$ spectra and a swap of ν_e and ν_x spectra above a critical energy E_c. In the normal hierarchy, collective effects do not cause any intermixing of neutrino spectra [36].

2.3. MSW resonances inside the SN and propagation through vacuum

In iron core supernovae, the collective effects have already become insignificant when neutrinos enter the MSW resonance regions. Therefore, traditional flavor conversion analysis can be applied to the fluxes emerging from the high density region [2]. SN neutrinos must pass through two resonance layers: the H-resonance layer at $\rho_{\rm H} \sim 10^3$ g/cc characterized by $(\Delta m^2_{\rm atm}, \theta_{13})$, and the L-resonance layer at $\rho_{\rm L} \sim 10$ g/cc characterized by $(\Delta m^2_\odot, \theta_{12})$. The outcoming incoherent mixture of vacuum mass eigenstates travels to the Earth without any further conversions, and is observed at a detector as a combination of primary fluxes of the three neutrino flavors:

$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)F^0_{\nu_x} \ , \qquad F_{\bar{\nu}_e} = \bar{p}F^0_{\bar{\nu}_e} + (1-\bar{p})F^0_{\nu_x} \ , \tag{1}$$

where p and $\bar{p}$ are the survival probabilities of ν_e and $\bar{\nu}_e$ respectively.

The neutrino survival probabilities are governed by the adiabaticities of the resonances traversed, which are directly connected to the neutrino mixing scheme. In particular, whereas the L-resonance is always adiabatic and appears only in the neutrino channel, the adiabaticity of the H-resonance depends on the value of θ_{13}, and the resonance shows up in the neutrino (antineutrino) channel for a normal (inverted) mass hierarchy. Table 2 shows the survival probabilities in various mixing scenarios. For intermediate values of θ_{13}, i.e. $10^{-5} \lesssim \sin^2\theta_{13} \lesssim 10^{-3}$, the survival probabilities depend on energy as well as the details of SN density profile [1].

Table 2. Survival probabilities for neutrinos, p, and antineutrinos, $\bar{p}$, in various mixing scenarios, in the cooling phase when $N_{\nu_e} > N_{\bar{\nu}_e} > N_{\nu_x}$. The presence or absence of shock wave effects and Earth effects is denoted by $\surd$ and X respectively. The notation $p_1 \parallel p_2$ indicates that the survival probability is p_1 (p_2) for energies below (above) the critical energy E_c.

	Hierarchy	$\sin^2\theta_{13}$	Survival probability		Shock effects		Earth effects	
			p	$\bar{p}$	ν_e	$\bar{\nu}_e$	ν_e	$\bar{\nu}_e$
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2\theta_\odot$	$\surd$	$\surd$	X	$\surd$
B	Inverted	$\gtrsim 10^{-3}$	$\cos^2\theta_\odot \parallel 0$	$\cos^2\theta_\odot$	X	$\surd$	X	$\surd$
C	Normal	$\lesssim 10^{-5}$	$\sin^2\theta_\odot$	$\cos^2\theta_\odot$	X	X	$\surd$	$\surd$
D	Inverted	$\lesssim 10^{-5}$	$\cos^2\theta_\odot \parallel 0$	0	X	X	X	X

The scenarios A, B, C and D in table 2 are the ones that can in principle be distinguished through the observation of a SN neutrino burst. Note that all these scenarios are characterized by distinct combinations of p and $\bar{p}$, which was not the case when the ν–ν interactions were neglected, making scenarios C and D degenerate [2]. This is a consequence of the sensitivity of collective effects to the mass hierarchy even when θ_{13} is as small as 10^{-10} [45, 46].

2.4. Propagation through the shock wave near MSW resonances

The passage of the shock wave through the H-resonance ($\rho \sim 10^3$ g/cc) a few seconds after the core bounce may break adiabaticity, thereby modifying the flavor evolution of neutrinos that are emitted during this time interval [47, 48, 49, 50, 51, 52]. Such a situation is possible, even in principle, only in the scenarios indicated in table 2. As a result, the identification of shock wave effects provides an important input for distinguishing between neutrino mixing schemes.

The shock wave effects can be diluted by stochastic density fluctuations [53] or turbulence [54]. However, a recent hydrodynamic simulation [55] suggests that some of the shock wave effects survive in spite of these smearing factors.

2.5. Oscillations inside the Earth matter

If the neutrinos travel through the Earth before reaching the detector, they undergo flavor oscillations and the survival probabilities change [56, 57, 58]. This change however occurs only in those scenarios indicated in table 2. The presence or absence of Earth effects in the neutrino or antineutrino channels therefore would help in identifying some of the mixing schemes.

3. Smoking gun signals in neutrino spectra

3.1. Direction of neutrino arrival

Since neutrinos are expected to arrive hours before the optical signal from the SN, the neutrino burst serves as an early warning [59] to the astronomy community. Being able to determine the position of the SN in the sky is also crucial for determining the Earth crossing path for the neutrinos in the absence of the SN observation in the electromagnetic spectrum.

A SN may be located through the directionality of the $\nu e^- \to \nu e^-$ elastic scattering events in a water Cherenkov detector [60, 61]. The large but nearly isotropic $\bar{\nu}_e p \to n e^+$ background can be removed by the addition of a small amount of gadolinium to water so that neutrons from the inverse beta decay are tagged [62, 63].

3.2. Suppression of ν_e in the neutronization burst
Since the primary signal during the neutronization burst is pure ν_e, and the model predictions for the energy and luminosity of the burst are fairly robust [64], the observation of the burst signal gives direct information about the survival probability of ν_e. This probability is $\mathcal{O}(\theta_{13}^2)$ in scenario A and $\sin^2\theta_\odot$ in all the other scenarios [1]. (Note that collective effects do not affect this scenario even for inverted hierarchy, since the absence of $\bar{\nu}_e$ implies that bipolar oscillations do not develop.) Thus, the vanishing of ν_e burst would be a smoking gun signal for scenario A. In order to be able to separate the ν_e burst from the accretion phase signal, time resolution of the detector is crucial [64].

An O-Ne-Mg supernova offers another interesting possibility. For such a light star, the MSW resonances may lie deep inside the collective regions during the neutronization burst, when the neutrino luminosity is even higher. In such a situation, neutrinos of all energies undergo the MSW resonances together, with the same adiabaticity. As long as this adiabaticity is nontrivial, one gets the "MSW-prepared spectral splits", two for normal hierarchy and one for inverted hierarchy [66, 67, 68]. The positions of the critical energies for these splits can be predicted from the primary spectra [68]. The splits imply ν_e suppression that is stepwise in energy. Such a signature may even be used to identify the O-Ne-Mg supernova, in addition to identifying the hierarchy.

3.3. Shock wave effects
Shock wave effects result in sharp changes in characteristics of the observed spectra that occur for a very short time (~ 1 s) while the shock wave is passing the H resonance [47, 48, 49, 50, 51, 52]. Robust observables like the number of events, average energy, or the width of the spectrum may display dips or peaks for short time intervals due to these effects. If a reverse shock is also present, the above features become double-dips or double-peaks [51], which are difficult to be mimicked by uncertainties in the time evolutions of neutrino fluxes. The positions of the dips or peaks in the number of events at different neutrino energies would also allow one to trace the shock propagation while it is in the mantle around densities of $\rho \sim 10^3$ g/cc [51].

For an iron core SN, a positive identification of any of the above shock effects in ν_e spectrum shortlists scenarios A and B, whereas shock effects in $\bar{\nu}_e$ identify scenario A.

If light sterile neutrinos exist, they may leave their imprints in the shock wave [69, 70]. For an O-Ne-Mg supernova, passage of the shock wave through the sharp density profile at the resonance leads to distinctive effects [71].

3.4. Spectral split in ν_e
Table 2 shows that the spectral split in neutrinos is absent (present) in the normal (inverted) hierarchy. Such a feature would in principle be visible in the ν_e spectrum as a sharp jump at the critical energy E_c [45]. This would happen even for values of θ_{13} as low as 10^{-10}, since the split is adiabatic even at such low values [35, 46]. The spectral split, which can in principle be observed at a liquid Ar detector, is therefore a smoking gun signal for inverted hierarchy.

However, the sharp split in p is smeared to some extent by the multi-angle effects [40]. Moreover, for all the reasonable values of model parameters for primary spectra, E_c is less than 10 MeV. At such energies, the low cross section, finite resolution of the detector, and the small difference in the ν_e and ν_x spectra make the observation of the split a challenging task [72].

3.5. Earth matter effects
Earth matter effects can be identified by the comparison of signals at two detectors, only one of which is shadowed by the earth. This could be achieved through the $\bar{\nu}_e$ spectra at two large water Cherenkov detectors [46] or through the time dependent ratio of luminosities at IceCube

and Hyper-Kamiokande [73]. As can be seen from table 2, when θ_{13} is small, Earth effects on antineutrinos are present (absent) for normal (inverted) hierarchy [46].

The Earth effects can be identified even at a single detector as long as it is capable of determining the neutrino energy. The measurement of the Fourier power spectrum of the "inverse energy" spectrum of $\bar{\nu}_e$ [74] gives peaks (multiple ones if the neutrinos traverse the Earth core) whose positions are independent of the primary neutrino spectra, that reveal the presence of earth matter effects [75]. Energy resolution of the detector plays a crucial role in observing this signal, and a smaller scintillation detector may compete with a large water Cherenkov [75] for detecting Earth effects on the $\bar{\nu}_e$ spectrum.

Earth effects on ν_e spectrum may be identified at a liquid Ar detector [72], which would identify scenario C positively, as can be seen from table 2.

4. Concluding remarks

Supernova neutrinos can probe extremely small values of θ_{13} and can determine the neutrino mass hierarchy at θ_{13} as low as 10^{-10}, thanks to collective effects and MSW resonances inside the star. Smoking gun signals of neutrino mixing scenarios can be independently obtained through observations like the suppression of neutronization burst, time variation of the signal during shock wave propagation, and Earth matter effects. SN neutrinos also enable pointing at the SN in advance of the optical signal, and tracking the shock wave while it is still inside the mantle.

A future galactic SN is therefore expected to yield a rich harvest of scientific information for neutrino oscillation physics and SN astrophysics. Though this is a rare phenomenon, occurring only a few times per century in a typical galaxy, we must make the best of it by being ready with suitable detectors.

Acknowledgments

I would like to thank Basudeb Dasgupta, Alessandro Mirizzi and Georg Raffelt for fruitful collaborations, the organisers of Neutrino 2008 for their hospitality, and the Max Planck - India Partnergroup for financial support.

References

[1] Dighe A S and Smirnov A Yu 2000 *Phys. Rev.* D **62** 033007 (*Preprint* hep-ph/9907423)
[2] Dighe A 2008 *AIP Conf. Proc.* **981** 75 (*Preprint* arXiv:0712.4386 [hep-ph])
[3] Raffelt G G 1996 *Stars as Laboratories for Fundamental Physics* (Chicago: The University of Chicago Press)
[4] Lunardini C and Smirnov A Yu 2004 *Astropart. Phys.* **21** 703 (*Preprint* hep-ph/0402128)
[5] Burrows A, Klein D and Gandhi R 1992 *Phys. Rev.* D **45**, 3361
[6] Autiero A *et al* 2007 *J. Cosmol. Astropart. Phys.* JCAP11(2007)011 (*Preprint* arXiv:0705.0116 [hep-ph])
[7] Jung C K 2000 *AIP Conf. Proc.* **533** 29 (*Preprint* hep-ex/0005046)
[8] Nakamura K 2003 *Int. J. Mod. Phys.* A **18**, 4053
[9] Suzuki Y *et al* [TITAND Working Group] 2001 *Preprint* hep-ex/0110005
[10] Wurm M *et al* 2007 *AIP Conf. Proc.* **944** 82
[11] Halzen F, Jacobsen J E and Zas E 1994 *Phys. Rev.* D **49** 1758
[12] Halzen F, Jacobsen J E and Zas E 1996 *Phys. Rev.* D **53** 7359 (*Preprint* astro-ph/9512080).
[13] Gil-Botella I and Rubbia A 2003 *J. Cosmol. Astropart. Phys.* JCAP10(2003)009 (*Preprint* hep-ph/0307244)
[14] Gil-Botella I and Rubbia A 2004 *J. Cosmol. Astropart. Phys.* JCAP08(2004)001 (*Preprint* hep-ph/0404151)
[15] Dighe A 2005 *Nucl. Phys. Proc. Suppl.* **143** 449 (*Preprint* hep-ph/0409268)
[16] Bethe H A and Wilson J R 1985 *Astrophys. J.* **295** 14
[17] Buras R, Janka H T, Rampp M and Kifonidis K 2005 (*Preprint* astro-ph/0512189)
[18] Keil M T, Raffelt G G and Janka H T 2003 *Astrophys. J.* **590** 971 (*Preprint* astro-ph/0208035)
[19] Totani T, Sato K, Dalhed H E and Wilson J R 1998 *Astrophys. J.* **496** 216 (*Preprint* astro-ph/9710203)
[20] Raffelt G G, Keil M T, Buras R, Janka H T and Rampp M 2003 *Preprint* astro-ph/0303226
[21] Duan H, Fuller G M, Carlson J and Qian Y Z 2006 *Phys. Rev.* D **74** 105014 (*Preprint* astro-ph/0606616)
[22] Duan H, Fuller G M, Carlson J and Qian Y Z 2006 *Phys. Rev. Lett.* **97** 241101 (*Preprint* astro-ph/0608050)
[23] Thomson M J and McKellar B H J 1991 *Phys. Lett.* B **259** 113

[24] Sigl G and Raffelt G G 1993 *Nucl. Phys.* B **406** 423
[25] McKellar B H J and Thomson M J 1994 *Phys. Rev.* D **49** 2710
[26] Samuel S 1993 *Phys. Rev.* D **48** 1462
[27] Kostelecký V A and Samuel S 1995 *Phys. Rev.* D **52** 621 (*Preprint* hep-ph/9506262)
[28] Pantaleone J 1998 *Phys. Rev.* D **58** 073002
[29] Samuel S 1996 *Phys. Rev.* D **53** 5382 (*Preprint* hep-ph/9604341)
[30] Pastor S, Raffelt G G and Semikoz D V 2002 *Phys. Rev.* D **65** 053011 (*Preprint* hep-ph/0109035)
[31] Hannestad S, Raffelt G G, Sigl G and Wong Y Y Y 2006 *Phys. Rev.* D **74** 105010 (*Preprint* astro-ph/0608695)
Hannestad S, Raffelt G G, Sigl G and Wong Y Y Y 2007 *Phys. Rev.* D **76** 029901 (*Erratum*)
[32] Duan H, Fuller G M, Carlson J and Qian Y Z 2007 *Phys. Rev.* D **75** 125005 (*Preprint* astro-ph/0703776)
[33] Fogli G L, Lisi E, Marrone A, Mirizzi A and Tamborra I 2008 *Preprint* arXiv:0808.0807 [hep-ph]
[34] Raffelt G G and Smirnov A Yu 2007 *Phys. Rev.* D **76** 081301 (*Preprint* arXiv:0705.1830 [hep-ph])
Raffelt G G and Smirnov A Yu 2008 *Phys. Rev.* D **77** 029903 (*Erratum*)
[35] Raffelt G G and Smirnov A Yu 2007 *Phys. Rev.* D **76** 125008 (*Preprint* arXiv:0709.4641 [hep-ph])
[36] Dasgupta B and Dighe A 2008 *Phys. Rev.* D **77** 113002 (*Preprint* arXiv:0712.3798 [hep-ph])
[37] Esteban-Pretel A *et al* 2008 *Phys. Rev.* D **77** 065024 (*Preprint* arXiv:0712.1137 [astro-ph])
[38] Raffelt G G and Sigl G 2007 *Phys. Rev.* D **75** 083002 (*Preprint* hep-ph/0701182)
[39] Esteban-Pretel A *et al* , 2008 *Preprint* arXiv:0807.0659 [astro-ph]
[40] Fogli G L *et al* 2007 *J. Cosmol. Astropart. Phys.* JCAP12(2007)010 (*Preprint* arxiv:0707.1998 [hep-ph])
[41] Duan H, Fuller G M and Carlson J, *Preprint* arXiv:0803.3650 [astro-ph]
[42] Duan H, Fuller G M and Qian Y Z 2008 *Preprint* arXiv:0808.2046 [astro-ph]
[43] Esteban-Pretel A *et al* 2007 *Phys. Rev.* D **76** 125018 (*Preprint* arXiv:0706.2498 [astro-ph])
[44] Dasgupta B *et al* 2008 *Phys. Rev.* D **78** 033014 (*Preprint* arXiv:0805.3300 [hep-ph])
[45] Duan H *et al* 2007 *Phys. Rev. Lett.* **99** 241802 (*Preprint* arXiv:0707.0290 [astro-ph])
[46] Dasgupta B, Dighe A and Mirizzi A 2008 *Preprint* arXiv:0802.1481 [hep-ph]
[47] Schirato R C and Fuller G M 2002 *Preprint* astro-ph/0205390
[48] Takahashi K *et al* 2003 *Astropart. Phys.* **20** 189 (*Preprint* astro-ph/0212195)
[49] Lunardini C *et al* 2003 *J. Cosmol. Astropart. Phys.* JCAP06(2003)009 (*Preprint* hep-ph/0302033)
[50] Fogli G L *et al* 2003 *Phys. Rev.* D **68** 033005 (*Preprint* hep-ph/0304056)
[51] Tomàs R *et al* 2004 *J. Cosmol. Astropart. Phys.* JCAP09(2004)015 (*Preprint* astro-ph/0407132)
[52] Dasgupta B and Dighe A 2007 *Phys. Rev.* D **75** 093002 (*Preprint* hep-ph/0510219)
[53] Fogli G L *et al* 2006 *J. Cosmol. Astropart. Phys.* JCAP06(2006)012 (*Preprint* hep-ph/0603033)
[54] Friedland A and Gruzinov A 2006 *Preprint* astro-ph/0607244
[55] Kneller J P *et al* 2008 *Phys. Rev.* D **77** 045023 (*Preprint* arXiv:0705.3835 [astro-ph])
[56] Dighe A S 2001 *Preprint* hep-ph/0106325
[57] Lunardini C and Smirnov A Yu 2001 *Nucl. Phys.* B **616** 307 (*Preprint* hep-ph/0106149)
[58] Takahashi K and Sato K 2002 *Phys. Rev.* D **66** 033006 (*Preprint* hep-ph/0110105)
[59] Scholberg K 1999 *Preprint* astro-ph/9911359
[60] Beacom J F and Vogel P 1999 *Phys. Rev.* D **60** 033007 (*Preprint* astro-ph/9811350)
[61] Ando S and Sato K 2002 *Prog. Theor. Phys.* **107** 957 (*Preprint* hep-ph/0110187)
[62] Beacom J F and Vagins M R 2004 *Phys. Rev. Lett.* **93** 171101 (*Preprint* hep-ph/0309300)
[63] Tomàs R *et al* 2003 *Phys. Rev.* D **68** 093013 (*Preprint* hep-ph/0307050)
[64] Kachelrieß M *et al* 2005 *Phys. Rev.* D **71** 063003 (*Preprint* astro-ph/0412082)
[65] Wong Y Y Y 2003 *AIP Conf. Proc.* **655** 240 (*Preprint* arXiv:hep-ph/0211045)
[66] Duan H *et al* 2008 *Phys. Rev. Lett.* **100** 021101 (*Preprint* arXiv:0710.1271 [astro-ph])
[67] Duan H, Fuller G M and Qian Y Z 2008 *Phys. Rev.* D **77** 085016 (*Preprint* arXiv:0801.1363 [hep-ph])
[68] Dasgupta B *et al* 2008 *Phys. Rev.* D **77** 113007 (*Preprint* arXiv:0801.1660 [hep-ph])
[69] Choubey S, Harries N P and Ross G G 2006 *Phys. Rev.* D **74** 053010 (*Preprint* hep-ph/0605255)
[70] Choubey S, Harries N P and Ross G G 2007 *Phys. Rev.* D **76** 073013 (*Preprint* hep-ph/0703092)
[71] Lunardini C, Muller B and Janka H T 2008 *Phys. Rev.* D **78** 023016 (*Preprint* arXiv:0712.3000 [astro-ph])
[72] Choubey S, Dasgupta B, Dighe A and Mirizzi A 2008 *In preparation*
[73] Dighe A S *et al* 2003 *J. Cosmol. Astropart. Phys.* JCAP06(2003)005 (*Preprint* hep-ph/0303210)
[74] Dighe A S *et al* 2003 *J. Cosmol. Astropart. Phys.* JCAP06(2003)006 (*Preprint* hep-ph/0304150)
[75] Dighe A S *et al* 2004 *J. Cosmol. Astropart. Phys.* JCAP01(2004)004 (*Preprint* hep-ph/0311172)