Physics with Supernovae

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Core-collapse supernovae (SNe) are powerful neutrino sources and as such important targets for the growing array of neutrino observatories. We review the current status of SN theory and the expected characteristics of the neutrino signal. After recalling what we have learned from SN 1987A and general SN properties we review the physics potential of a future galactic SN observation.

1. SUPERNOVA TYPES AND RATES

Supernovae are exploding stars [1–5]. However, there are two entirely different classes, both of which are of current interest for astro-particle physics and cosmology. One physical class are the type Ia supernova (SN) explosions. A SN Ia is thought to occur when a carbon-oxygen white dwarf accretes matter from a companion star until it reaches its Chandrasekhar limit and begins to collapse, thereby triggering a nuclear explosion, powered by the fusion of carbon and oxygen to heavier nuclei. SNe Ia are spectroscopically characterized by the absence of hydrogen and the presence of silicon lines. The explosion disrupts the progenitor white dwarf entirely; what remains is an expanding nebula without a central compact object. While the exact SN Ia lightcurves depend on some parameters, they are surprisingly reproducible and thus lend themselves as cosmological standard candles. The main astro-particle interest in SNe Ia is their potential to explore the space-time geometry of the universe; the observed SN Ia Hubble diagram suggests the presence of “dark energy” or a cosmological constant [6,7].

The present lecture is exclusively about the other class of explosions which mark the evolutionary end of massive stars ($M \gtrsim 8 M_\odot$). Such stars have the usual onion structure with several burning shells, an expanded envelope, and a degenerate iron core that is essentially an iron white dwarf. The core mass grows by the nuclear burning at its edge until it reaches the Chandrasekhar limit. The collapse can not ignite nuclear fusion because iron is the most tightly bound nucleus. Therefore, the collapse continues until the equation of state stiffens by nucleon degeneracy pressure at about nuclear density $(3 \times 10^{14} \text{ g cm}^{-3})$. At this “bounce” a shock wave forms, moving outward and expelling the stellar mantle and envelope. The explosion is a reversed implosion, the energy derives from gravity, not from nuclear energy. Within the expanding nebula, a compact object remains in the form of a neutron star or perhaps sometimes a black hole. The kinetic energy of the explosion carries about 1% of the liberated gravitational binding energy of about $3 \times 10^{53} \text{ erg}$, 99% going into neutrinos. This powerful and detectable neutrino burst is the main astro-particle interest of core-collapse SNe; the Ia explosions do not produce significant neutrino emission. In core-collapse SNe only $10^{-4}$ of the total energy shows up as light, i.e. about 1% of the kinetic explosion energy. Core-collapse SNe are dimmer than SNe Ia, and their lightcurves are different from case to case, the details depending on the structure of the progenitor star. Core-collapse SNe are not useful as standard candles.

If the progenitor star has retained a hydrogen envelope, hydrogen lines will appear in the lightcurve, qualifying the SN spectroscopically as type II, while type I are the ones without hydrogen lines. If the star has lost its hydrogen envelope (all stars suffer significant mass loss during their giant phase), but has retained helium, the helium lines in the SN lightcurve make it a type Ib. Without hydrogen and helium lines it is of type Ic, unless it shows silicon lines, which
characterize a type Ia. Confusingly the spectroscopic types Ib, Ic and II form the physical class of core-collapse SNe.

Table 1 gives the observed SN rates for different galaxy types according to Refs. [5,8], some of them significantly smaller than the rates in an earlier review [10]. The SN rate is expressed in the “Supernova unit,” defined as 1 SNu = 1 SN per $10^{10} L_{\odot,B}$ per 100 yrs where $L_{\odot,B}$ is the solar luminosity in the blue spectral band. Therefore, 1 SNu corresponds roughly to 1 SN per galaxy per century. Moreover, $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$. Early-type galaxies, where little star formation takes place, do not host core-collapse SNe as this type depends on the formation of massive stars which are short-lived on cosmological scales. About 2/3 of all SNe are core collapse, and of those the vast majority is type II (hydrogen lines). On the other hand, because SNe Ia are intrinsically brighter, the majority of observed SNe are of that type. About 2000 SNe have been observed, but many have not been classified—for an up-to-date catalogue see [9].

One approach to estimate the galactic SN rate is to apply the relevant average rate of Table 1 to the Milky Way. Assumming a morphological type Sb–Sbc, a blue luminosity of $2.3 \times 10^{10} L_{\odot,B}$, and a Hubble constant $h = 0.75$ one finds $2 \pm 1$ core-collapse SNe per century [5], about a factor of 2 smaller than the corresponding estimate in [10] or [11]. Note that the morphological type of our galaxy is not well determined.

Another approach relies on the historical SN record, extrapolated to the entire galaxy. (Because of obscuration by dust, only SNe out to a few kpc have been observed.) The rate of core-collapse SNe is then estimated to be 3–4 per century [11,12], with a large Poisson uncertainty from the small number of observed cases (5 SNe during the second millennium).

Given the vagaries of small-number statistics, these estimates agree with each other, and with circumstantial evidence such as the estimated population of progenitor stars or the neutron-star formation rate. Except for SN 1987A in the Large Magellanic Cloud, no neutrino burst has been observed, even though large neutrino detectors have been in operation continuously since the Baksan Scintillator Telescope began operations in June 1980 [13]. This non-observation is in agreement with the estimated SN rate and suggests that stellar collapse events without SN explosions are not frequent relative to normal SNe.

## 2. CORE-COLLAPSE SUPERNOVA EXPLOSION MECHANISM

The bounce-and-shock explosion scenario of core-collapse SNe [1–4] is essentially a hydrodynamic phenomenon—see, for example, Ref. [14] which includes very intuitive animations. However, realistic numerical simulations have difficulties exploding for a physical reason. The shock wave at core bounce forms within the iron core. As it moves outward energy is dissipated by the dissociation of iron. The nuclear binding energy

<table>
<thead>
<tr>
<th>Galaxy type</th>
<th>Supernova type</th>
<th>Ia</th>
<th>Ib/c</th>
<th>II</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>E–S0</td>
<td></td>
<td>0.32 $\pm$ 0.11</td>
<td>&lt; 0.02</td>
<td>&lt; 0.04</td>
<td>0.32 $\pm$ 0.11</td>
</tr>
<tr>
<td>S0a–Sb</td>
<td></td>
<td>0.32 $\pm$ 0.12</td>
<td>0.20 $\pm$ 0.11</td>
<td>0.75 $\pm$ 0.34</td>
<td>1.28 $\pm$ 0.37</td>
</tr>
<tr>
<td>Sbc–Sd</td>
<td></td>
<td>0.37 $\pm$ 0.14</td>
<td>0.25 $\pm$ 0.12</td>
<td>1.53 $\pm$ 0.62</td>
<td>2.15 $\pm$ 0.66</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td>0.36 $\pm$ 0.11</td>
<td>0.14 $\pm$ 0.07</td>
<td>0.71 $\pm$ 0.34</td>
<td>1.21 $\pm$ 0.36</td>
</tr>
</tbody>
</table>
of 0.1 $M_{\odot}$ iron is about $1.7 \times 10^{51}$ erg and thus of the same order as the SN explosion energy. Therefore, the shock wave stalls without driving off the stellar mantle and envelope. This behavior is illustrated in Fig. 1 which represents a state-of-the-art spherically symmetric collapse calculation [15]. The figure shows the trajectories (radial position vs. time) of selected mass shells, and also shows the boundaries of the iron core and silicon shell as well as the shock trajectory. The shock wave stagnates at about 200 km while mass accretion continues—mass shells continue to cross the shock position. The shock wave never “takes off” to explode the star. Similar state-of-the-art results are reported by the Oakridge group [16].

The standard scenario of SN explosions holds that the stagnating shock will be “re-juvenated” by energy deposition so that enough pressure builds up behind the shock to set it back into motion. This “delayed explosion scenario” was first proposed in the early 1980s by Bethe and Wilson [18]. One source of energy deposition behind the shock wave is energy absorption from the nearly freely streaming neutrinos which originate from the neutrino sphere near the neutron-star surface. The required conditions for a successful shock revival have been studied numerically and analytically—see Ref. [19] for details and references. Continued mass accretion and convection below the shock wave also deposit energy and thus contribute to the shock revival.

The main recent progress in numerical SN calculation has been the implementation of efficient Boltzmann solvers so that an exact neutrino transport scheme can be self-consistently coupled with the hydrodynamic evolution [15–17]. Such state-of-the-art spherically symmetric calculations do not lead to successful explosions. However, these calculations are not self-consistent in that the regions below the shock wave are convectively unstable. Likewise, convection may arise in the neutron star below the neutrino sphere. Forthcoming calculations will reveal if convection, perhaps coupled with more accurate neutrino interaction rates, will lead to successful explosions.

The Livermore group does obtain robust explosions [20]. In their spherically symmetric calculations they include a mixing-length treatment of “neutron finger convection,” thereby enhancing the early neutrino luminosity and thus the energy deposition behind the shock [21]. Their results agree with the findings of other groups that diffusive neutrino transport alone is not enough to trigger the explosion.

The delayed explosion scenario may involve new particles or new interactions. Of course, too much energy deposition in the SN mantle would make the explosions too energetic, providing limits on radiative neutrino decays [22]. On the other hand, new particles could transfer additional energy from the inner core to the shock wave and thus trigger the explosion [23,24]. An intriguing scenario involving resonant neutrino flavor...
oscillations would have required mass differences much larger than indicated by current oscillation experiments and thus is no longer viable [25].

It is not known at present if the standard delayed explosion scenario is the correct picture, or if new physical ingredients beyond the self-consistent inclusion of neutrino transport and convection are needed. Even if robust explosions are obtained in future 2- and 3-dimensional calculations, the long-standing problem of the large neutron-star velocities remains unresolved—for a recent review see [26].

The high-statistics neutrino light curve from a future galactic SN in a large neutrino detector would allow one to observe directly the collapse dynamics. For example, the early accretion-powered neutrino emission could be clearly distinguished from the subsequent neutron-star cooling phase [20]. One of the most energetic astrophysical phenomena would be caught in the act, allowing one to unravel the underlying physics.

3. EXPECTED NEUTRINO SIGNAL

The expected neutrino fluxes and spectra are illustrated by the numerical results shown in Fig. 2. The $\nu_e$ lightcurve shows a conspicuous spike early on, representing the prompt neutrino burst which occurs when the shock wave reaches the region of neutrino trapping in the iron core. The dissociation of iron allows for the quick neutronization of a layer of the proto neutron star. Of course, most of the lepton number remains trapped and slowly escapes by neutrino diffusion.

The subsequent broad shoulder up to about 500 ms, best visible in the lower panel with linear scales, represents the accretion phase where material keeps falling in and powers the neutrino emission. After this phase the shock wave has driven off the stellar mantle. The subsequent long and flat tail represents the neutron star cooling by neutrino emission.

The duration of the accretion phase depends on how long it takes to revive the shock wave. In the Livermore simulation, an explosion is obtained by a phenomenological treatment of neutron-finger convection which boosts the early neutrino luminosity [21]. In the absence of a confirmed robust

Figure 2. Neutrino luminosities and average energies in a SN collapse and explosion simulation with the Livermore code. The $\nu_e$ line represents each of $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$ and $\bar{\nu}_\tau$. Upper panel: Logarithmic luminosity and time scales. Upper panel: Linear scales. (Figures from Ref. [20] with permission.)
Despite the exact duration of the accretion phase is not known—other simulations do not obtain explosions and thus do not get beyond the accretion phase.

After about 100 ms, the neutrino luminosities are virtually equal in each flavor. The equipartition of the emitted energy is almost perfect in this simulation. In the recent Oakridge simulation [16], which includes a state-of-the-art Boltzmann solver, the equipartition is also nearly perfect between $\nu_e$ and $\bar{\nu}_e$, but the $\nu_x$ luminosity is less than 1/2 after 50 ms out to 600 ms when this simulation terminates. Therefore, “equipartition” probably should be taken to mean “equal to within about a factor of two.”

The neutrino average energies obey the well-known hierarchy $\langle E_{\nu_x} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_e} \rangle$ which is explained by the different trapping processes, $\beta$ processes for the electron flavor and elastic scattering on nucleons for the rest. Therefore, the different flavors originate in layers with different temperatures. A physical understanding of the neutrino spectra can be developed without large-scale numerical simulations [27]. While the flavor hierarchy of average energies appears to be generic, the differences are likely smaller than previously thought after all relevant processes have been included, notably nucleon bremsstrahlung and energy transfer by recoils [27,28]. However, no state-of-the-art numerical simulation yet exists that includes all of the relevant microphysics.

In all numerical simulations the $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$, and $\bar{\nu}_\tau$ are treated equally. However, the transport of neutrinos and antineutrinos is different even for the heavy flavors because the cross section for $\nu N \rightarrow N \nu$ is different from $\bar{\nu} N \rightarrow N \bar{\nu}$ because of weak magnetism [29]. Moreover, the presence of muons is not entirely negligible, at least in the deep interior of the SN core so that muonic beta reactions are also possible. While this may not affect the spectra formation near the neutron star atmosphere, it is not assured that the $\mu$- and $\tau$-flavored neutrino spectra are the same. In principle, then, neutrino transport in a SN core involves six different neutrino degrees of freedom. However, muons are not included in the available equations of state, and treating all flavors differently enhances the numerical CPU requirements.

The average neutrino energies increase for the first few seconds. This is a generic effect because the neutrino-emitting regions heat up by accretion and by the contraction of the neutron star. Of course, eventually the average energies must decrease when the neutron star cools.

Numerical neutrino light curves can be compared with the SN 1987A data where the measured energies are found to be “too low.” For example, the numerical simulation of Fig. 2 yields time-integrated values $\langle E_{\nu_e} \rangle \approx 13$ MeV, $\langle E_{\nu_x} \rangle \approx 16$ MeV, and $\langle E_{\nu_\mu} \rangle \approx 23$ MeV. On the other hand, the data imply $\langle E_{\nu_e} \rangle = 7.5$ MeV at Kamiokande and 11.1 MeV at IMB [30]. Even the 95% confidence range for Kamiokande implies $\langle E_{\nu_e} \rangle < 12$ MeV. Flavor oscillations would increase the expected energies and thus enhance the discrepancy [30]. It has remained unclear if these and other anomalies of the SN 1987A neutrino signal should be blamed on small-number statistics, or point to a serious problem with the SN models or the detectors.

4. OBSERVING A FUTURE GALACTIC SUPERNOVA

Detectors for measuring the neutrino signal from a galactic SN have almost continuously operated since 1980 when the Baksan Scintillator Telescope (BST) took up operation. For a galactic SN at a distance of 10 kpc with neutrino fluxes and spectra roughly like those of Fig. 2, BST would register about 70 events. The neutrinos from SN 1987A in the Large Magellanic Cloud at a distance of 50 kpc were actually measured in Kamiokande [31], IMB [32], and BST [33] with a few events each. Today, much larger detectors are available, although BST keeps running. Super-Kamiokande would measure about 8000 events for a SN at 10 kpc. A simulated light curve based on the SN model of Fig. 2 is shown in Fig. 3.

Super-Kamiokande is not operational at the time of this writing because of the destructive accident during re-filling on 12 November 2001. The exact capabilities for SN neutrino detection after repair are not known at present, but hopefully will not be dramatically worse. In the following, all statements concerning the Super-Kamiokande
Figure 3. Simulated Super-Kamiokande neutrino light curve for a galactic SN at 10 kpc. (Figures from Ref. [20] with permission.)

capabilities rely on the pre-accident literature.

Fortunately, there are other large detectors available. The Sudbury Neutrino Observatory (SNO) would register about 800 events from our fiducial SN [34], where for now we ignore flavor oscillations. The Large Volume Detector (LVD) in the Gran Sasso Laboratory is a scintillation detector that would register about 400 events [35]. A similar number of events would be expected in the KamLAND scintillation reactor neutrino experiment which recently began taking data [36]. The Borexino solar neutrino experiment, that will soon be ready, is smaller and would register about 100 events [37]. The AMANDA South Pole neutrino telescope also works as a SN neutrino detector in that the correlated noise of all photomultipliers caused by the Cherenkov light of the SN neutrinos produces a significant signal, especially when AMANDA is enlarged to the cubic-kilometer IceCube [38].

The dominant signal is usually the charged-current reaction $\bar{\nu}_e p \rightarrow ne^+$. SNO has a unique $\nu_e$ detection capability from the charged-current deuterium dissociation $\nu_e d \rightarrow pp^-$. Neutral-current reactions which are sensitive to all flavors include elastic scattering on electrons, the deuterium dissociation $\nu d \rightarrow np\nu$ in SNO, the excitation of $^{16}$O in water Cherenkov detectors, and the corresponding excitation of $^{12}$C in scintillation detectors, notably in LVD and KamLAND, where the $\gamma$-rays from the subsequent de-excitation can be measured. Another recent suggestion is the elastic scattering on protons which can cause a measurable signal in low-threshold scintillation detectors [39,40].

Specific neutral-current detectors for SN neutrinos have been proposed on the basis of the reaction $\nu + (A, Z) \rightarrow (A-1, Z) + n + \nu$ where the neutron will be measured. For example, lead or iron could be used as targets in the proposed OMNIS detector [41,42]. This sort of detector would be complementary to Super-Kamiokande and SNO in that it is primarily sensitive to the heavy-flavor neutrinos.

At present one debates the possibility of building even larger detectors for the purpose of precision neutrino long-baseline oscillation experiments, for proton decay, and high-statistics solar, atmospheric and SN neutrino detection. A typical size could be a megatonne of water or scintillator. This option is discussed under the name of Hyper-Kamiokande in Japan [43], under UNO in the US [44], and is also debated in Europe [45]. Such a detector could produce as many as $10^5$ events from our fiducial SN at 10 kpc.

The operation of large neutrino detectors is motivated by many physics goals so that it is not unrealistic to expect that another few decades will be covered by neutrino observatories sensitive to a galactic SN. Therefore, even though the galactic SN rate is low, the chance of observing one within a few decades is not small so that it is worthwhile to discuss the possible benefits from such an observation.

Arguably the most important gain would be the direct observation of stellar collapse where a high-statistics neutrino observation would map out the dynamics of a cataclysmic astrophysical event that could never be observed directly in any other way. Whether or not numerical SN simula-
tions will soon converge on a theoretical standard model for the collapse and explosion mechanism, the importance of its independent verification or falsification by a detailed neutrino light curve can not be overstated.

Another benefit is the possibility of an early warning for the occurrence of a SN because the neutrino signal precedes the optical explosion by several hours. This project has been taken up by the Supernova Early Warning System (SNEWS), a network of detectors with SN neutrino capabilities [46]. Unfortunately, the triangulation of the SN by the arrival time at various detectors is relatively poor. However, the electron recoil signal in Super-Kamiokande can locate the SN within a circle of radius $7^\circ$–$8^\circ$ in the sky [47,48]. A future megatonne detector probably could do much better.

5. FLAVOR OSCILLATIONS

Neutrino oscillations are now firmly established so that the SN neutrino fluxes and spectra expected in a detector can be very different from those emitted at the source. This is especially true if the solar neutrino problem is solved by the large-mixing angle (LMA) case, which is presently favored, and which can be confirmed or refuted by the KamLAND experiment in the immediate future [36]. The relevant mass difference of $\Delta m^2_{12} = 1\text{--}10 \times 10^{-5}$ eV$^2$ implies that matter effects are important in the SN and also in the Earth if the neutrinos happen to enter the detector “from below.” The large “solar” mixing angle $\theta_{12}$ implies that oscillations will be important in both the $\nu_e$ and the $\bar{\nu}_e$ channel.

If the LMA case obtains, it is unavoidable that oscillation effects influence the SN 1987A signal interpretation, and that the detectors saw different spectra due to different Earth-crossing segments of the neutrino paths [30,49–51]. While this effect can make the measurements slightly more consistent with each other, the unexpectedly soft neutrino energies become even more worrisome.

Assuming that the SN 1987A neutrino anomalies are caused by statistical flukes, we may gauge our expectations for a future SN by theoretical predictions based on numerical simulations. In any case, the signal of a future SN itself will determine if SN theory is correct with regard to the neutrino fluxes and spectra. Taking the numerical model of Fig. 2 for the source, the time-integrated spectra at Super-Kamiokande, SNO and LVD are shown in Fig. 4 as a function of the nadir angle which determines the Earth-segment of the neutrino path. The oscillation parameters were chosen for the LMA case with $\Delta m^2_{12} = 2 \times 10^{-5}$ eV$^2$, $\Delta m^2_{13} = 3.2 \times 10^{-3}$ eV$^2$, $\sin^2 \theta_{12} = 0.87$, and $\sin^2 \theta_{23} = 1.0$. The unknown third mixing angle was chosen small as $\sin^2 \theta_{13} = 1.0 \times 10^{-6}$. Figure 4 illustrates that rather dramatic modifications of the spectra can be expected for certain cases.

It is difficult to anticipate everything about future data. If a galactic SN is observed, what we can learn about neutrino oscillations depends on the detectors operating at that time and their geographical location. It will also depend on the true source properties regarding flavor-dependent spectra and fluxes, and what is already known about the neutrino oscillation parameters as input information at that time. Many authors have studied these questions [52–61]. It appears that one may well distinguish between large and small values of the elusive $\theta_{13}$ and to distinguish between normal or inverted mass hierarchies, or even accurately pin down $\Delta m^2_{12}$. Therefore, a SN neutrino observation would complement the upcoming efforts of precision determination of neutrino oscillation parameters in long-baseline experiments [62–64].

While neutrino oscillations are crucial for SN neutrino observations, the smallness of the measured mass differences implies that oscillations are not important in the SN core, and also not in the SN atmosphere within the stalled shock wave because the matter-induced weak potential dominates over the mass differences for the flavor-dependent neutrino refractive index. In these regions and on the relevant time-scales the separate flavor lepton numbers are effectively conserved, in spite of maximal neutrino mixing [65–67].
6. STERILE NEUTRINOS

The existence of sterile neutrino degrees of freedom is a logical possibility that has received much attention. One possible role for such particles is to constitute the cosmic dark matter. Depending on their masses and their mixings with active neutrinos, they can be hot, warm, or cold dark matter [68]. These particles would be emitted from SN cores so that the SN 1987A energy-loss argument (Sec. 8) provides some of the most important constraints on this conjecture.

If sterile neutrinos have masses in the eV range and mix with active flavors, they can modify the nucleosynthesis processes that take place in the neutrino-driven wind of a SN core after the explosion. The r-process nucleosynthesis of heavy elements requires a neutron-rich environment. The n/p ratio is governed by the β processes involving the ν_e and ¯ν_e flux. In standard SN calculations the required conditions for r-process nucleosynthesis are not achieved. However, if ν_e → ν_sterile oscillations are efficient enough, the ν_e + n → p + e^- reactions are quenched, reducing the proton fraction, and thus allowing enough neutrons to escape being trapped in α particles [69,70]. Therefore, low-mass sterile neutrinos can play a crucial role in this environment.

7. NEUTRINO MASS SENSITIVITY

The ever accumulating evidence for neutrino oscillations and for neutrino mass differences in the 50 meV range and below has reduced the neutrino mass question to one unknown overall mass scale m_ν that could be much larger than the mass differences. Tritium end point experiments reveal m_ν < 2.8 eV [71,72], the future sensitivity at KATRIN may reach the 0.3 eV level [73]. The observed power spectrum of the galaxy distribution function and of the cosmic microwave background radiation reveals similar constraints and future sensitivities [74].

The SN 1987A signal duration gave a time-of-flight limit of m_ν < 20 eV [75], a refined recent analysis even claims m_ν < 6 eV at 95% CL [76]. The neutrino signal of a galactic SN observed in Super-Kamiokande would be sensitive to about

Figure 4. Earth effect on SN spectra in different detectors as a function of the nadir angle. For SNO only CC events are taken into account. The oscillation parameters correspond to the solar LMA case and a small θ_{13} as described in the text. (Figures from Ref. [52] with permission.)
3 eV [77]. If a black hole forms a few seconds after the original collapse, the quick termination of the neutrino burst imprints a structure on the neutrino light curve, corresponding to an $m_\nu$ dispersion sensitivity of about 2 eV [78]. A further improvement is possible if the SN collapse emits a measurable gravitational wave signal that can serve as a zero-point for the neutrino time-of-flight delay. Independently of black-hole formation, a Super-Kamiokande mass sensitivity of around 1 eV has been claimed [79]. Further improvements with a megatonne detector may be possible, but have not been investigated in detail.

Therefore, while the SN time-of-flight method would provide new and independent direct limits on the neutrino mass, this method does not seem competitive with future tritium endpoint and cosmological sensitivities. None of these methods seems able to reach the crucial 50 meV range characteristic of the neutrino mass differences.

8. LIMITS ON NEW PARTICLES

The neutrino signal of SN 1987A has been used to derive numerous limits on new particles or novel neutrino properties. One standard argument holds that the signal duration of about 10 s precludes that too much energy was carried away by axions, right-handed (sterile) neutrinos or other exotic channels. This classic “energy-loss argument” has been applied to constrain axion or Majoron interactions, neutrino dipole moments, active-sterile mixings, or right-handed currents [80,81]. Most recently, it has been used to constrain the compactification scale of large extra dimensions by constraining the emission of Kaluza-Klein gravitons [82,83].

The SN 1987A energy-loss argument is problematic because far-reaching conclusions depend on a few late events in the Kamiokande II and IMB detectors. Evidently a high-statistics neutrino light curve from a future galactic SN would place such limits on firm experimental grounds.

Of course, not all SN particle-physics limits depend on the sparse SN 1987A data. For SN graviton emission in theories with large extra dimensions, the $\gamma$-rays from the subsequent decay of the Kaluza-Klein gravitons can leave observable signatures in the cosmic $\gamma$-ray background [84] or from young SN remnants and neutron stars [85].

9. NEW PHASES OF NUCLEAR MATTER

Standard numerical SN simulations generally rely on a nuclear equation of state and neutrino opacities which are based on the assumption that nuclear matter at all relevant densities and temperatures is well described in terms of nucleons. However, the QCD phase diagram in the temperature-density plane may be far more complicated. One long-standing speculation holds that the true ground state of dense matter consists of quarks rather than nucleons, leading to various modifications of standard SN and neutron-star physics [86,87]. More recently, the existence of an intriguing color-superconducting phase has been debated [88].

When the equation of state and/or the neutrino opacities suddenly change during the first few seconds after SN collapse due to a nuclear phase transition, an observable signature in the neutrino light curve could obtain. For example, instead of tapering off, the neutrino luminosity could show a second burst [89,90] or could suddenly terminate by a secondary collapse to a black hole [91]. Evidently, a high-statistics neutrino light curve from a galactic SN would shed new light on the existence or non-existence of new phases of nuclear matter.

10. COSMIC RELIC NEUTRINOS FROM PAST SUPERNOVAE

All supernovae which occurred since the birth of the universe contribute to a cosmic background of neutrinos in the energy range up to about 50 MeV. A simple estimate shows that the average neutrino luminosity of a galaxy from stellar collapse is roughly comparable to its optical photon luminosity. If the past SN rate is assumed to be constant at the present-day levels of Table 1, the SN relic neutrinos amount to an approximate flux of 1 cm$^{-2}$ s$^{-1}$. However, when galaxies first formed they must have been much more active at star formation, leading to flux es-
timates of 5–50 cm$^{-2}$ s$^{-1}$ [92–94] where the high number is thought to be a plausible upper limit. A positive detection of this flux would provide a new window to the universe at redshifts of a few.

Such flux levels are, in principle, detectable because they stick above solar and atmospheric neutrinos for $20 \lesssim E_\nu \lesssim 50$ MeV. The limit from the Kamiokande II detector is 226 cm$^{-2}$ s$^{-1}$ (90% CL) for energies 19–35 MeV [95]. A preliminary Super-Kamiokande limit is 39 cm$^{-2}$ s$^{-1}$ [96], assuming the energy spectrum of [94], i.e. Super-Kamiokande has touched the upper range of theoretical estimates.

A further improvement of the sensitivity requires a new detector concept because Super-Kamiokande is limited by an irreducible background of “invisible muons,” i.e. sub-Cherenkov muons produced by atmospheric neutrinos. Their subsequent decays produce electrons or positrons in the energy window of the SN relic neutrinos.

11. CONCLUSIONS

Core-collapse supernovae are powerful neutrino sources. The observation of the SN 1987A neutrino burst has provided a crude confirmation of the idea that stellar collapse leads to a neutrino burst which carries away the gravitational binding energy of the collapsed object, but leaves many questions open.

The high-statistics neutrino observation of a galactic SN would allow one to watch directly the stellar collapse, to confirm or refute the delayed explosion mechanism, and to search for signatures of new nuclear phases in the late-time behavior of the neutrino light curve. The neutrino burst precedes the optical explosion by a few hours, hence an early warning can be given to direct telescopes in the SN direction in the sky.

Many of the classic SN 1987A particle-physics limits are problematic because of the sparse data. A high-statistics observation would provide these important results with a firm experimental basis.

One would obtain new time-of-flight neutrino mass limits, but neutrino masses in the sub-eV range will likely remain elusive.

The detailed characteristics of the neutrino signal can discriminate between different neutrino mass and mixing scenarios. If the SN neutrinos propagate through the Earth before reaching the detector, spectacular regeneration effects can obtain in some cases. The SN 1987A signal interpretation already requires including the Earth effect if the “solar-neutrino mixing angle” is large.

In summary, the high-statistics neutrino observation of a future galactic SN guarantees a rich astrophysical, particle-physics, and nuclear-physics harvest. Of course, the SN rate is low, but still, the neutrinos from about a thousand galactic SNe are on their way. Hopefully one of these bursts will be intercepted at Earth by one or more large neutrino observatories.

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