Abstract. Twenty years after SN 1987A, the vast international programme of experimental neutrino physics and neutrino astronomy suggests that large detectors will operate for a long time. It is realistic that a high-statistics neutrino signal from a galactic SN will be observed. I review some of the generic lessons from such an observation where neutrinos largely play the role of astrophysical messengers. In principle, the signal also holds valuable information about neutrino mixing parameters. I explain some recent developments about the crucial importance of collective neutrino oscillations in the SN environment.

1. Introduction
Twenty years ago, the neutrino burst from supernova (SN) 1987A in the Large Magellanic Cloud was observed. On 23 February 1987 at 7:35 h universal time, the Kamiokande II [1] and IMB [3] water-Cherenkov detectors each registered a burst clearly attributed to SN 1987A. A contemporaneous signal in the Baksan scintillator detector [5] may have been caused by the neutrino burst as well. A significant event cluster in the LSD experiment [7] was observed several hours earlier and had no counterpart in the other detectors and vice versa. It can be associated with SN 1987A only if one invokes very non-standard double-bang scenarios of stellar collapse [9]. A lively account of the exciting and somewhat confusing history of the SN 1987A neutrino detection was given by M. Koshiba [10] and A. Mann [11].

This unique observation of stellar-collapse neutrinos helped to pave the way for a new era of neutrino physics. Today, the discovery of neutrino masses, lepton mixing, and flavor oscillations are quickly fading to become yesterday’s sensation while the experimental efforts are turning to yet more challenging issues, notably the question of leptonic CP violation, the absolute neutrino masses, and their Majorana nature. A broad programme of experimental neutrino physics, dedicated SN neutrino observatories, and the construction of IceCube as a high-energy neutrino observatory almost guarantee the operation of large detectors for a long time so that the eventual observation of a high-statistics SN neutrino burst is a realistic possibility. A review of the ongoing, planned or proposed neutrino experiments with SN detection capabilities was given by K. Scholberg at this conference [12].

In our galaxy, the SN rate is perhaps 1–3 per century, so that the observation of a SN neutrino burst is a once-in-a-lifetime opportunity. What can we learn? There is no simple answer to this question because what we will learn depends on the detectors operating at that time, what they will observe, what else we then know about neutrinos, and which non-neutrino observations will
be available. Galactic SNe are typically obscured, but even then probably would be seen, for example, in x- or γ-rays. Moreover, a gravitational wave signal could be observed.

Forecasting all possible scenarios would be both impossible and moot. Rather, I will focus on a number of generic issues. First, in Sec. 2 I review current estimates of the galactic SN rate and about their distance distribution. In Sec. 3 I will review some of the obvious lessons from a SN neutrino observation. Here, neutrinos largely play the role of astrophysical messengers. In Sec. 4 I turn to flavor oscillations where the observations could reveal crucial information about neutrino mixing parameters. Until recently, the impact of collective neutrino oscillations in the SN context had been underestimated. Therefore, the overall picture of SN neutrino oscillations is in a state of flux. Sec. 5 is given over to a summary and conclusions.

2. Next supernova: Where and When?
Existing and near-future neutrino detectors [12] do not reach beyond the galaxy and its satellites. Super-Kamiokande would observe about $10^4$ events from a SN at a typical galactic distance of 10 kpc. The next significant target would be the Andromeda region at a distance of 760 kpc, reducing the rate by $(10/760)^2 = 1.7 \times 10^{-4}$, i.e., Super-K would register 1–2 events. If a megatonne detector is built with perhaps 30 times the Super-K fiducial volume, it would provide several tens of events. Even such a low-statistics observation would be very useful as we shall see below. From the nearest galaxies beyond Andromeda, even a megatonne detector would register only 1–2 events. It was noted, however, that correlating them with astronomical SN observations may allow one to reduce background enough to build up SN neutrinos at a rate of perhaps 1 neutrino per year from galaxies out to several Mpc [13].

One classic method to estimate our galaxy’s SN rate is to scale from external galaxies. Another classic approach is to extrapolate the five historical SNe of the past millenium to the entire galaxy, leading to a larger but more uncertain estimate. The most recent estimate derives from the γ-rays emitted by $^{26}$Al (half-life $7.2 \times 10^5$ years) that is produced in massive stars. Finally, the non-observation of a galactic neutrino burst since 30 June 1980 when the Baksan Scintillator Telescope (BST) took up operation, and the almost complete coverage of the neutrino sky by different detectors since then, provides the upper limit shown in Table 1.

Therefore, one expects 1–3 core-collapse SNe per century in our galaxy and its satellites. With a megatonne-class detector one would reach Andromeda (M31) and its immediate neighbors such as Triangulum (M33), roughly doubling the expected rate. On the other hand, the last SN from that region was observed in 1885! However, we also note that SNe can be quite frequent in some galaxies. The record holders are NGC 6946 with SNe 1917A, 1939C, 1948B, 1968D, 1969P,

| Method                          | Rate    | Authors                        | Refs.  |
|---------------------------------|---------|--------------------------------|--------|
| Scaling from external galaxies  | 2.5 ± 0.9 | van den Bergh & McClure (1994) | [14, 17] |
|                                 | 1.8 ± 1.2 | Cappellaro & Turatto (2000)    | [15, 16] |
| Gamma-rays from galactic $^{26}$Al | 1.9 ± 1.1 | Diehl et al. (2006)            | [17]    |
| Historical galactic SNe (all types) | 5.7 ± 1.7 | Strom (1994)                   | [18]    |
|                                 | 3.9 ± 1.7 | Tammann et al. (1994)          | [19]    |
| No neutrino burst in 25 years$^a$| < 9.2 (90% CL) | Alekseev & Alekseeva (2002)    | [20]    |

$^a$We have scaled the limit of Ref. [20] to 25 years of neutrino sky coverage.
1980K, 2002hh and 2004et and the galaxy NGC 5236 (M83 or Southern Pinwheel) with SNe 1923A, 1945B, 1950B, 1957D, 1968L and 1983N [21]. These time sequences provide a healthy lesson in Poisson statistics: even if the average rate is quite large, one may still wait for a long time for the next SN, or conversely, we could be lucky and observe one soon, even if the average rate is as small as suggested by Table I.

What would be a typical distance for a SN in our own galaxy? Core-collapse marks the final evolution of massive stars and thus must occur in regions of active star formation, i.e., in the spiral arms. As proxies for the distribution one can use either observations in other galaxies or in our galaxy the distribution of pulsars, SN remnants, molecular and ionized hydrogen, and OB-star forming regions [22]. All of these observables are consistent with a deficit of SNe in the inner galaxy and a maximum at 3.0–5.5 kpc galactocentric distance. Small regions of high star-forming activity have been found within 50 pc from the galactic center that may contribute up to 1% of the galactic star-formation rate [23], although this finding does not seem to contradict the overall picture of a reduced SN rate in the inner galaxy.

As a representative example we follow Ref. [24] and consider a common parametrization for the galactic surface density of core-collapse (cc) events,

\[
\sigma_{cc}(r) \propto r^\xi \exp\left(-\frac{r}{u}\right),
\]

(1)

where \( r \) is the galactocentric radius. For the birth location of neutron stars, a fiducial distribution of this form was suggested with the parameters \( \xi = 4 \) and \( u = 1.25 \) kpc [25]. They are consistent with several SN-related observables, even though large uncertainties remain. Thermonuclear SNe, that are believed to originate from old stars in binary systems, more closely follow the matter distribution. It can be parameterized as [22]

\[
\sigma_{Ia}(r) \propto \exp\left(-\frac{r}{4.5 \text{ kpc}}\right).
\]

(2)

We show the SN distance distributions corresponding to these models in Fig. 1. The tails at large distances are unphysical due to a complete lack of data.

The average distance for the assumed distribution is \( \langle d_{cc} \rangle = 10.7 \) kpc with a rms dispersion of 4.9 kpc. This agrees with the fiducial distance of 10 kpc that is frequently assumed in the literature. On the other hand, the dispersion is very large so that the number of neutrinos detected even from a “typical” galactic SN can vary by more than an order of magnitude.

![Figure 1](image.png)

**Figure 1.** Distance distribution of core-collapse (solid) and thermonuclear SNe (dotted) according to the assumed galactic surface distributions of Eqs. (1) and (2), respectively [24].
3. Basic lessons from a SN neutrino observation

3.1. Early warning, distance and direction

Turning to the many uses of a SN neutrino observation, we first note that it occurs several hours before the optical explosion, allowing one to issue an alert. The Supernova Early Warning System (SNEWS) provides this service to the neutrino and astronomy communities [28].

Most galactic SNe are optically obscured. While it is implausible that the SN will remain invisible in the entire electromagnetic spectrum, it is interesting if it can be located by its neutrinos alone [29, 30]. The best existing pointing capability is provided by $\nu + e \rightarrow \nu + e$ scattering in Super-K where an accuracy of about 8° (95% CL half-cone opening angle) can be achieved. If neutron tagging becomes possible by adding gadolinium [31], the accuracy increases to about 3°. For a megatonne-class detector with 30 times the Super-K fiducial volume, these numbers improve to 1.4° (no neutron tagging) and 0.6° (90% tagging efficiency).

The distance of SN 1987A, besides its obvious association with the Large Magellanic Cloud, could be directly determined with light echoes from its inner ring [32, 33]. If the next galactic SN is obscured, nothing of the sort may be possible and one may actually have to rely on the neutrinos to estimate its distance. However, SNe are no good neutrino standard candles. The total emitted energy depends on the poorly known nuclear equation of state as well as the total mass of the progenitor star. The signal registered by the standard $\bar{\nu}_e + p \rightarrow n + e^+$ reaction is also subject to details of the flavor-dependent neutrino emission and on flavor oscillations. Altogether, one could probably estimate the distance within a factor of two or so.

The prompt $\nu_e$ burst, on the other hand, comes close to being a standard candle [34, 35, 36]. Here the problem is that the world lacks a big $\nu_e$ detector because in water-Cherenkov and scintillator detectors the main channel is inverse beta decay. In a large liquid Argon TPC the charged-current absorption $\nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K} + e^-$ would provide an exquisite $\nu_e$ signal [37]. In a megatonne water-Cherenkov detector with neutron tagging, the signal from $\nu + e$ scattering could be isolated and a distance determination within 5–10% may become possible, in particular if the neutrino mass hierarchy and the 13-mixing angle were known [36].

3.2. Neutrino spectrum

The SN 1987A neutrino observations provided a unique confirmation of the overall picture of core-collapse and neutron-star formation. The signal lasted for about ten seconds, a time scale predicted by the diffusive neutrino energy transport in a nuclear-density hot compact star. The energies in the ten MeV range, representative of the temperature at the “neutrino sphere,” roughly agrees with expectations. (The physics of core-collapse phenomena was presented by H.-T. Janka at this conference; for a recent review see [27].)

In detail, however, the $\bar{\nu}_e$ energies implied by Kamiokande-II [1, 2] and IMB [3, 4] do not agree well with each other or with expectations. In particular, the Kamiokande-II energies are significantly lower than expected [38, 39, 40, 41]. To interpret the SN 1987A data in any useful way one must make a prior assumption about the spectral shape [40]. The tension in the data and with theoretical models may well be a fluke of small-number statistics, but a serious comparison of the neutrino spectrum with theory for sure requires better data. Even a low-statistics signal of a few tens of events from a SN in Andromeda in a megatonne detector would provide valuable information. Without better data one has to rely on theoretical models, for example, to interpret future measurements of the cosmic Diffuse Supernova Neutrino Background (DSNB) from all past SNe (see C. Lunardini’s presentation at this conference [42]).

A large detector might reveal new subdominant spectral components. A few 100–200 MeV events contemporaneous with the ordinary burst could reveal that energy leaks out directly from the inner core in some novel form of radiation. For example, right-handed neutrinos produced in the SN core could decay into active ones [43] or neutrinos with Dirac magnetic moments could escape from the SN interior and spin-precess into active ones on the way to us [44, 45].
3.3. Signal duration

The signal duration of the SN 1987A burst agrees well with expectations. This observation is the basis for perhaps the most useful particle-physics lesson from SN 1987A: apparently there was no other energy-loss channel but the ordinary neutrinos \([46, 47, 48, 49]\). This “energy-loss argument” has been applied to a large number of cases, notably axions, Majorons, right-handed neutrinos, and Kaluza-Klein gravitons, often providing the most restrictive limits on the underlying particle-physics model. Extensive reviews are Refs. \([50, 51, 52]\) and some more recent applications are discussed in Refs. \([53, 54, 55, 56]\).

Far-reaching conclusions about fundamental physics are here based on a sparse sample of data. Even a relatively low-statistics observation would be enough to remove any lingering doubt if these energy-loss limits are actually correct. Beyond a general confirmation, a high-statistics observation would not improve such limits very much because their uncertainties are typically dominated by physics in the SN core. This includes uncertainties about the temperature, density and composition of the medium as well as uncertainties of how to calculate interaction and emission rates in a nuclear medium.

3.4. High-statistics light curve

If one were to observe a high-statistics neutrino light curve, crucial details of the core-collapse paradigm could be tested. In particular, one could probably separate the early accretion phase from the later Kelvin-Helmholtz cooling phase after the explosion has been launched. If the standard delayed-explosion scenario is indeed correct, one could probably see the different phases in the neutrino light curve and confirm or refute this scenario \([57]\). Besides Super-K, the IceCube detector would be well suited to this task even though it does not provide spectral information, but a high-statistics “bolometric” neutrino light-curve that reflects the time-structure of the burst with high significance.

A detailed cooling profile would allow one to test the theory behind neutrino transport in a hot nuclear medium. Moreover, one may be able to detect short-term time variations that are caused by the large-scale convection pattern during the accretion phase. A sudden termination would reveal late black-hole formation. Of course, there could be completely unexpected features.

Even a high-statistics signal has only limited time-of-flight sensitivity to neutrino masses. Even the most ambitious forecasts do not seriously go below 1 eV \([58, 59, 60]\), not good enough in the light of cosmological limits \([61, 62]\) and the expected sensitivity of the KATRIN tritium decay experiment \([63]\). A few tens of events from a SN in Andromeda would also provide a sensitivity of about 1 eV. One man’s trash is another man’s treasure: we now expect the time-of-flight dispersion caused by neutrino masses to be so small that fast time variations at the source will faithfully show up at the detector.

4. Neutrino flavor oscillations

4.1. Ordinary MSW oscillations

Since SN 1987A, many of the “simple” questions about neutrinos have been answered, but more challenges lie ahead. The observation of a galactic SN burst may help us to address some of them. The neutrinos pass through the mantle and envelope of the progenitor star and encounter a vast range of matter densities, implying two MSW resonances. One of them corresponds to the “atmospheric mass difference” (H-resonance), the other, at lower density, to the “solar mass difference” (L-resonance). Of particular interest is the MSW effect at the H-resonance driven by the unknown 13-mixing angle. This resonance occurs in the neutrino sector for the normal mass hierarchy, and among anti-neutrinos for the inverted hierarchy. It is adiabatic for \(\sin^2 \Theta_{13} \gtrsim 10^{-3}\) and non-adiabatic for \(\sin^2 \Theta_{13} \lesssim 10^{-5}\). Therefore, the neutrino burst is, in principle, sensitive to the mass hierarchy and the 13-mixing angle \([64, 65]\).
One important simplification is that the neutrino energies are far below the \( \mu \) and \( \tau \) mass thresholds. Therefore, the species \( \nu_\mu, \bar{\nu}_\mu, \nu_e, \) and \( \bar{\nu}_e \) have only neutral-current interactions. Their fluxes and spectra emerging from the SN and their detection cross sections are the same. They are collectively denoted as \( \nu_x \) or equivalently \( \bar{\nu}_x \). On the other hand, \( \nu_e \) and \( \bar{\nu}_e \) have charged-current interactions, notably with protons, neutrons and nuclei with different abundances so that we finally need to distinguish between the three species \( \nu_e, \bar{\nu}_e \) and \( \nu_x \). Oscillation effects can be summarized in terms of the energy-dependent \( \nu_e \) survival probability \( p(E) \) as

\[
F_{\nu_e}(E) = p(E)F^0_{\nu_e}(E) + [1 - p(E)]F^0_{\bar{\nu}_e}(E),
\]

where the superscript zero denotes the primary fluxes. An analogous expression pertains to \( \bar{\nu}_e \) with the survival probability \( \bar{p}(E) \). Table 2 summarizes the survival probabilities for different mixing scenarios where \( \Theta_\odot \) refers to the “solar” mixing angle \( \Theta_\odot [64, 65] \).

The most pronounced and most robust flavor-dependent structure of a SN neutrino signal is the prompt \( \nu_e \) burst. Unfortunately, the main detection channel in all existing and near-future detectors is \( \bar{\nu}_e + p \rightarrow n + e^+ \). In Super-K, the prompt \( \nu_e \) burst would generate of order 10 events from \( \nu_e \) scattering so that the burst perhaps could be just barely detected. Of course, in a megatonne water-Cherenkov detector with neutron tagging, the \( \nu_e \) burst would be an extremely useful tool both for studying flavor oscillations and determining the SN distance [30]. Likewise, a large liquid Argon TPC would be a powerful and useful \( \nu_e \) detector [37].

For the time being, inverse beta decay will provide the dominant signal. Oscillation effects are more subtle in this channel because the primary spectra and fluxes of \( \bar{\nu}_e \) and \( \bar{\nu}_x \) are probably more similar than had been thought until recently [66, 67]. Moreover, the relative spectral energies and fluxes change during the accretion and cooling phases. At present, reliable predictions for the time-dependent quantities \( \langle E_{\nu_e} \rangle/\langle E_{\bar{\nu}_e} \rangle \) and \( F_{\nu_e}/F_{\bar{\nu}_e} \) are not available and in fact may differ for different SNe because the progenitor mass may play some role.

Therefore, one must focus on model-independent signatures. One is the matter regeneration effect if the neutrinos are observed through the Earth. Flavor oscillations would manifest themselves by characteristic energy-dependent signal modulations [68, 69, 70, 71, 72, 73], an effect that would be especially apparent in a large scintillator detector because of its superior energy resolution. One could also compare the signals of different detectors if one of them sees the SN shadowed and the other not [70]. We have provided an online tool that allows one, for chosen detector locations, to calculate the probability for the next galactic SN to be shadowed in none, one, or both detectors [24]. Both for SN and geo-neutrino detection, several big scintillator detectors in different locations would be more useful than one large detector such as the proposed LENA [24] in a single location.

Another characteristic signature of flavor oscillations could be a pronounced dip or double-dip feature in the late neutrino signal caused by shock-wave propagation. When the shock wave passes the H-resonance region, the MSW adiabaticity is temporarily broken. Moreover, for some time several H-resonances obtain because the density profile is not monotonic. If one were to

### Table 2.
Survival probabilities for neutrinos, \( p \), and antineutrinos, \( \bar{p} \), in various mixing scenarios. The channels where one expects Earth effects, shock-wave propagation effects, and where the full \( \nu_e \) burst is present or absent are indicated.

| Scenario | Hierarchy | \( \sin^2 \Theta_\odot \) | \( p \) | \( \bar{p} \) | Earth effects | Shock wave | \( \nu_e \) burst |
|----------|-----------|----------------|------|------------|-------------|-----------|----------|
| A        | Normal    | \( \gtrsim 10^{-3} \) | 0    | \( \cos^2 \Theta_\odot \) | \( \bar{\nu}_e \) | \( \nu_e \) | absent  |
| B        | Inverted  | \( \gtrsim 10^{-3} \) | \( \sin^2 \Theta_\odot \) | 0    | \( \nu_e \) | \( \bar{\nu}_e \) | present |
| C        | Any       | \( \lesssim 10^{-5} \) | \( \sin^2 \Theta_\odot \) | \( \cos^2 \Theta_\odot \) | \( \nu_e \) and \( \bar{\nu}_e \) | —         | present |
observe such features, they could serve as a diagnostic both for neutrino oscillation parameters and the astrophysics of shock-wave propagation [75, 76, 77, 78].

The SN matter profile need not be smooth. Behind the shock-wave, convection and turbulence can cause significant stochastic density variations that tend to wash out the neutrino oscillation signatures [79, 80]. The quantitative relevance of this effect remains to be understood.

4.2. Collective neutrino oscillations

The trapped neutrinos in a SN core as well as the neutrinos streaming off its surface are so dense that they provide a large matter effect for each other. The nonlinear nature of this neutrino-neutrino effect renders its consequences very different from the ordinary matter effect in that it results in collective oscillation phenomena [81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93] that can be of practical interest in the early universe [94, 95, 96, 97] or in core-collapse SNe [98, 99, 100, 101, 102, 103, 104, 105, 106, 107]. The crucial importance of “bipolar oscillations” for SN neutrinos was first recognized in Refs. [104, 105, 106] and some of their salient features explained in Ref. [107].

What are the conditions for neutrino-neutrino matter effects to be relevant? Considering for simplicity a two-flavor situation, vacuum oscillations are driven by the frequency $\omega = \Delta m^2 / 2E$. The ordinary matter effect is important when $\lambda \gtrsim \omega$ where $\lambda = \sqrt{2}G_F n_e$. Neutrino-neutrino effects are important when $\mu \gtrsim \omega$ where $\mu = \sqrt{2}G_F n_\nu$. It is crucial to note that ordinary matter effects do not override neutrino-neutrino effects. As stressed in Ref. [104], it is a misconception that neutrino-neutrino effects would be negligible when $\lambda \gg \mu$.

The low-energy weak-interaction Hamiltonian is of current-current form so that the interaction energy between two particles of momenta $p$ and $q$ is proportional to $(1 - v_p \cdot v_q)$ where $v_p = p / E_p$ is the velocity. In isotropic media the $v_p \cdot v_q$ term averages to zero. On the other hand, collinear-moving relativistic particles produce no weak potential for each other. For neutrinos streaming off a SN core, the $(1 - v_p \cdot v_q)$ term implies that the neutrino flux declines not only with the geometric $r^{-2}$ factor, but the average interaction energy $\mu$ has another $r^{-2}$ factor that accounts for the increasing collinearity of the neutrino trajectories with distance from the source [99]. Considering the atmospheric mass difference of $1.9 - 3.0 \times 10^{-3}$ eV$^2$ and using a typical energy of 15 MeV, we may use $\omega = 0.3$ km$^{-1}$ as a typical value, where we here express frequencies and energies in km$^{-1}$ that is a useful unit in the SN context. Moreover, if we use $10^{51}$ erg s$^{-1}$ as a typical neutrino luminosity, and if we use 10 km as the neutrino-sphere radius, we may use $\mu = 0.3 \times 10^5$ km$^{-1}$ at the neutrino sphere so that indeed $\mu \gg \omega$. With the $r^{-4}$ scaling of the effective $\mu$, collective neutrino oscillations will be important out to a radius of about 200 km.

There are two extreme cases of collective oscillation effects that have been discussed in the literature. Synchronized oscillations occur when the neutrino-neutrino interaction “glues” the neutrino flavor polarization vectors together enough so that they evolve the same. In other words, even though the vacuum oscillation frequency $\Delta m^2 / 2E$ is different for different modes, they all oscillate with the same “synchronized frequency” that is an average of the vacuum or in-medium frequencies (“self-maintained coherence”). Of course, if the vacuum or in-medium mixing angle is small, this synchronization effect has no macroscopic significance.

The generic case of bipolar oscillations occurs in a neutrino gas with equal densities of, say, $\nu_e$ and $\bar{\nu}_e$. In an inverted-mass situation with a small mixing angle, the ensemble will undergo oscillations of the sort $\nu_\mu \bar{\nu}_e \rightarrow \nu_\mu \nu_\mu \rightarrow \nu_\mu \nu_e \rightarrow \ldots$, approximately with the “bipolar frequency” $\kappa = \sqrt{2\omega \mu}$ that is much faster than the vacuum oscillation frequency. The period of this phenomenon depends logarithmically on the mixing angle, explaining why this phenomenon is not much affected by the presence of ordinary matter [104, 105, 107]. For the normal hierarchy, the ensemble performs small-amplitude harmonic oscillations with the frequency $\kappa$ so that macroscopically “nothing” happens.
The next complication are “multi-angle effects,” probably first stressed in Ref. [92] and numerically explored in Ref. [105]. In a non-isotropic neutrino gas, the self-term is not the same for all modes because of the \((1 - \mathbf{v}_p \cdot \mathbf{v}_q)\) factor. The result is an instability that causes a neutrino gas with equal densities of \(\nu\) and \(\bar{\nu}\) to de-cohere kinematically in flavor space between different directions of motion. Independently of the mass hierarchy and with the smallest initial anisotropy, complete flavor equipartition obtains. The time scale, again, is set by the bipolar frequency \(\kappa\). The overall time to achieve equilibrium depends logarithmically on the mixing angle and the initial anisotropy [93].

Bipolar oscillations are a collective pair-conversion effect; there is no enhanced flavor conversion. For equal densities of \(\nu_e\) and \(\bar{\nu}_e\), the net electron lepton number vanishes. “Pair oscillations” do not change of overall flavor lepton number. One requirement is that there is a sufficient “pair excess” in some flavor. This is not the case in the interior of a SN core where all neutrinos are in thermal equilibrium, and only the \(\nu_e\) have a large chemical potential that increases the number density of \(\nu_e\) (relative to \(\nu_\mu\) or \(\nu_\tau\)) while at the same time suppressing the \(\bar{\nu}_e\) density. Therefore, bipolar oscillations do not seem to be relevant in the interior of a SN core. Synchronized oscillations will occur, but with an extremely small in-medium mixing angle.

On the other hand, there is an excess of both \(\nu_e\) and \(\bar{\nu}_e\) in the neutrinos streaming off a SN core, where generically \(F_{\nu_e} > F_{\bar{\nu}_e}\). If this asymmetry is too large, the oscillations are still of the synchronized type, even though there is a pair excess. Bipolar conversions will begin playing a role beyond a radius where the effective \(\mu\) is small enough that the asymmetry no longer prevents them. The critical region is between a few tens of km above the neutrino sphere and about 200 km. Without the “multi-angle effect,” the outcome would be generic in that complete pair-conversion \(\nu_e\bar{\nu}_e \rightarrow \nu_x\bar{\nu}_x\) would occur for the inverted mass hierarchy, and essentially nothing new would happen for the normal hierarchy. Including multi-angle effects, the outcome does not seem generic but rather depends on details [105].

As for observable flavor oscillation effects from the next galactic SN, the deleptonization burst likely remains unaffected because it is characterized by an excess of \(\nu_e\) and a suppression of \(\bar{\nu}_e\). During the accretion phase, some degree of flavor-swapping may occur and since the relevant region is within the stalled shock wave, one may speculate if some effect on the SN dynamics itself obtain in the spirit of Ref. [108]. After a successful explosion, nucleosynthesis in the neutrino-driven wind above the neutron star may well be affected, a possibility that was the main motivation for the exploratory study of Ref. [105, 109]. Possible modifications of what will be observed in the neutrino signal of the next galactic SN have not yet been studied. Some interesting work remains to be done!

5. Summary
Twenty years after SN 1987A we are well prepared for the observation of another neutrino burst from a collapsing star. The scientific harvest would be immense. Without any doubt, neutrinos would be excellent astrophysical messengers and allow us to follow stellar collapse and many of its details “in situ.” From the particle-physics perspective, many of the unique lessons from SN 1987A could be corroborated. In principle, the neutrino burst also holds information about the neutrino mass hierarchy that is extremely difficult to determine in the laboratory. On the other hand, collective neutrino oscillation effects that had not been fully appreciated may change some of the previous paradigm. In preparation for the next galactic SN burst, both theorists and experimentalists have more work to do than just wait!

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