New Aspects and Boundary Conditions of Core-Collapse Supernova Theory

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Core-collapse supernovae are among Nature's grandest explosions. They are powered by the energy released in gravitational collapse and include a rich set of physical phenomena involving all fundamental forces and many branches of physics and astrophysics. We summarize the current state of core-collapse supernova theory and discuss the current set of candidate explosion mechanisms under scrutiny as core-collapse supernova modeling is moving towards self-consistent three-dimensional simulations. Recent work in nuclear theory and neutron star mass and radius measurements are providing new constraints for the nuclear equation of state. We discuss these new developments and their impact on core-collapse supernova modeling. Neutrino-neutrino forward scattering in the central regions of core-collapse supernovae can lead to collective neutrino flavor oscillations that result in swaps of electron and heavy-lepton neutrino spectra. We review the rapid progress that is being made in understanding these collective oscillations and their potential impact on the core-collapse supernova explosion mechanism.

1 Overview: Core-Collapse Supernova Theory

The ultimate goal of core-collapse supernova theory is to understand the mechanism driving supernova explosions in massive stars, connect initial conditions to the final outcome of collapse, and make falsifiable predictions of observable signals and explosion features. These include neutrino, gravitational wave, and electromagnetic signals, nucleosynthetic yields, compact remnant masses, explosion morphologies, and pulsar kicks, spins, and magnetic fields.

Baade and Zwicky, in their seminal 1934 article [1], first hypothesized that a "supernova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons." This basic picture still holds today and the road to its refinement has been, at best, meandering and bumpy. When the nuclear fuel at the core of a massive star is exhausted, the core becomes electron degenerate and, upon reaching its effective Chandrasekhar mass, undergoes dynamical collapse. Electron capture on free protons and protons bound in heavy nuclei reduces the electron fraction (Y_e; the number of electrons per baryon) and accelerates the collapse of the inner core. When the latter reaches nuclear density, $\rho_{\rm nuc} \approx 2.7 \times 10^{14}\,{\rm g\,cm^{-3}}$, the nuclear equation of state (EOS) stiffens[1], leading to core bounce and the formation of the bounce shock

[1]The stiffening of the EOS near $\rho_{\rm nuc}$ is due to the repulsive effect of the strong force at small distances and $\Gamma = d\ln P/d\ln\rho$ jumps from $\sim$4/3 to $\gtrsim 2$. Neutron degeneracy, which is non-relativistic at bounce, only gives $\Gamma \approx 5/3$.

at the interface of inner and outer core. The shock initially rapidly propagates out in radius and mass coordinate, but the work done to break up infalling heavy nuclei and energy losses to neutrinos quickly sap its might. The shock stalls within tens of milliseconds of bounce and turns into an accretion shock at a radius of $\sim 100 - 200\,\mathrm{km}$ [2].

Core collapse liberates $\sim 3 \times 10^{53}\,\mathrm{erg} = 300\,\mathbf{B}ethe$ of gravitational binding energy of the neutron star, ~99% of which is radiated in neutrinos over tens of seconds. The *supernova mechanism* must revive the stalled shock and convert ~1% of the available energy into energy of the explosion, which must happen within less than $\sim 0.5 - 1\,\mathrm{s}$ of core bounce in order to produce a typical core-collapse supernova explosion and leave behind a neutron star with the canonical neutron star gravitational mass of $\sim 1.4\,M_\odot$ [3, 4].

The *neutrino mechanism* [2, 5] for core-collapse supernova explosions relies on the deposition of net neutrino energy (heating > cooling) in the region immediately behind the stalled shock, heating this region and eventually leading to explosion (for details, see the excellent discussion in [6]). While having great appeal and being most straightforward, given the huge release of neutrino energy in core collapse, the simplest, spherically-symmetric form of this mechanism fails to revive the shock in all but the lowest-mass massive stars (O-Ne cores) [7–10].

Indications are strong that multi-dimensional effects, principally turbulent convective overturn and the standing-accretion-shock instability (SASI, e.g., [11, 12] and references therein) increase the efficacy of the neutrino mechanism by boosting neutrino heating [13–16] or, as suggest by [6], by reducing neutrino cooling. This is generally borne out by recent fully self-consistent axisymmetric (2D) neutrino radiation-hydrodynamics simulations with an energy-dependent treatment of neutrinos, but their detailed results vary significantly from group to group and a clear picture has yet to emerge. Marek *et al.* [17] reported the onset of explosions in a nonrotating 11.2-$M_\odot$ (at zero-age main sequence [ZAMS]) and in a slowly spinning 15-$M_\odot$ star, setting in at ~200 ms and ~600 ms after bounce, respectively, and the estimate explosion energies are on the lower side of what is expected from observations. The exploding simulations used the softest variant of the EOS by Lattimer & Swesty (LS) [18] and included a stronger quasi-relativistic monopole term in the gravitational potential. A similar, so far unpublished [19], calculation of core collapse in a 11.2-$M_\odot$ star with the stiffer EOS of H. Shen *et al.* [20] also produced an explosion while simulations with the very stiff EOS by Hillebrand & Wolff [21] did not. Bruenn *et al.* [22], also using the softest LS EOS variant and quasi-relativistic gravity, found strong explosions setting in within ~250 ms after bounce in progenitors with ZAMS masses of (12, 15, 20, and 25) $M_\odot$. Suwa *et al.* [23], using Newtonian gravity and the soft LS EOS variant, found early, but weak explosions in a 13-$M_\odot$ progenitor star. Ott *et al.* [24] and Burrows *et al.* [25, 26], on the other hand, who performed purely Newtonian calculations using the stiffer H. Shen EOS, did not find neutrino-driven explosions in progenitors of $11.2 - 25\,M_\odot$.

Given that Nature has a way to robustly (without fine tuning) explode at least a significant fraction, but probably most stars with ZAMS masses of $\sim 10 - 20\,M_\odot$ [27, 28], the large range of differing and sometimes disagreeing results of 2D simulations is dissatisfactory, if not disturbing.

There are essentially three possible ways out:

(*1*) The neutrino mechanism, while getting much closer to being viable in 2D than in 1D, may still not be reaching its full efficacy. In 3D, an additional fluid motion degree of freedom is available and the nature of turbulence changes[2]. This may allow accreting material to stay even longer in the region of net heating, resulting in a greater heating efficiency and, thus,

[2] Provided that the turbulent cascade is resolved, turbulent power will cascade towards small scales in 3D while it cascades to large scales in 2D, which is unphysical.

potentially make the neutrino mechanism robust. Results to this effect have been obtained by Nordhaus *et al.* [29] who performed 1D, 2D, and 3D calculations with parameterized neutrino heating and cooling using spherical Newtonian gravity and the H. Shen EOS. This work confirmed the results of [13] for the 1D→2D case and found another big increase in efficacy when going from 2D to 3D. However, a similar parameterized study, carried out by Hanke *et al.* [16], found no significant difference between 2D and 3D. The debate thus remains open and more work will be needed before the final word on the neutrino mechanism can be spoken. For this, fully self-consistent 3D simulations with reliable energy-dependent neutrino transport will be necessary. The first steps towards such self-consistent 3D models have already been taken [30, 31] and their results, while not definite, are encouraging.

(*2*) If dimensionality is not the key to robust neutrino-driven core-collapse supernova explosions, then could there be physics missing from current 1D and 2D simulations that, once included, could render 2D, or perhaps even 1D, neutrino-driven explosions robust? A key example for this are self-induced (by ν-ν scattering) collective neutrino oscillations and we will discuss their potential effect on the neutrino mechanism in §3.

(*3*) If 3D and/or new physics cannot save the neutrino mechanisms, alternatives must be sought. Potential ones include the *magnetorotational mechanism* (e.g., [32]), the *acoustic mechanism* [25, 26, 33], and the *phase-transition-induced* mechanisms [34]. The *magnetorotational mechanism* requires very rapid rotation in combination with non-linear magnetic field amplification after bounce by the magnetorotational instability (e.g., [32, 35]). Pulsar birth spin estimates [36] and stellar evolution calculations that take into account magnetic fields (e.g., [37]) suggest that it may be active in no more than $\sim$1% of massive stars that produce very energetic explosions and are related to the hyper-energetic core-collapse supernova explosions associated with a growing number of long gamma-ray bursts [38–40].

The *acoustic mechanism*, proposed by [25, 26], relies on the excitation of protoneutron star pulsations by turbulence and SASI-modulated accretion downstreams. These pulsations reach large amplitudes at $600-1000$ ms after bounce and damp via the emission of strong sound waves that steepen to secondary shocks as they propagate down the radial density gradient in the region behind the stalled shock. They dissipate and heat the postshock region, robustly leading to explosions, which, however, tend to be weak and occur late. This mechanism has not been confirmed by other groups, has been studied only in 2D simulations, and, most importantly, [41] have shown via non-linear perturbation theory that a parametric instability between the main mode of pulsation and abound higher-order modes, which are not resolved by the numerical models of [25, 26], is likely to limit the mode amplitude to dynamically negligible magnitudes.

The *phase-transition-induced mechanism* (e.g., [34, 42]) requires a hadron-quark phase transition occurring within the first few 100 ms after core bounce (hence, at moderate protoneutron-star central densities). This phase transition leads to an intermittent softening of the EOS, a short collapse phase followed by a second bounce launching a secondary shock wave that runs into the stalled shock and launches an explosion even in spherical symmetry. However, the needed early onset of the phase transition requires fine tuning of the quark EOS and leads to maximum cold neutron star gravitational masses inconsistent with observations [3, 43].

In the remainder of this contribution to the proceedings of the HAmburg Neutrinos from Supernova Explosions 2011 (HAνSE 2011) conference, we discuss, in §2, new boundary conditions of core-collapse supernova theory set by neutron star mass and radius constraints, and, in §3, we summarize the recent rapid progress made by studies considering the potential effect of collective neutrino oscillations on the core-collapse supernova mechanism. In §4, we cricially

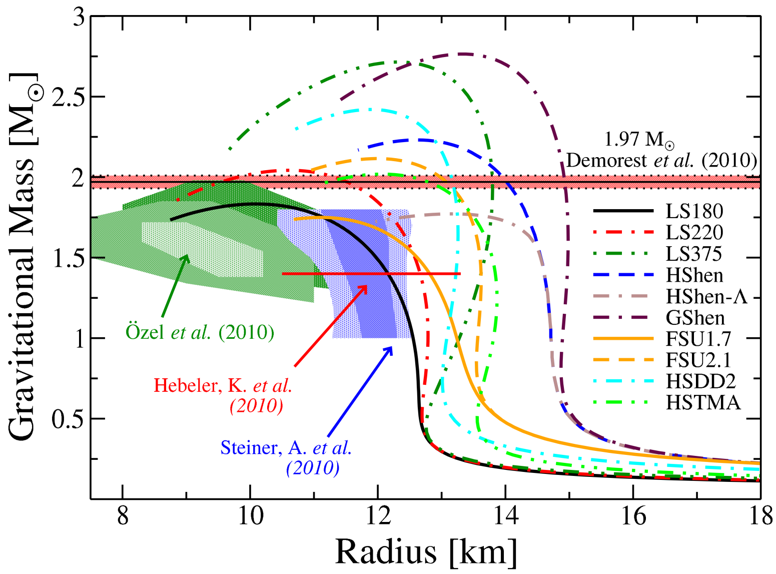

Figure 1: (color online) Mass-radius relations for 10 publically available finite-temperature EOS along with several constraints. The EOS are taken from [18, 44–48] and the Tolman-Oppenheimer-Volkoff equation is solved with $T = 0.1\,\text{MeV}$ and neutrino-less β-equilibrium imposed. The family of LS EOS is based on the compressible liquid-droplet model [18] while all other EOS are based on relativistic mean field theory. The nuclear theory constraints of Hebeler *et al.* [49] assume a maximum mass greater than $2\,M_\odot$ and do not take into account a crust (which would increase the radius by $\sim$400 m). EOS that do not support a mass of at least $1.97 \pm 0.04\,M_\odot$ are ruled out [3, 43]. Özel *et al.* [50] analyzed three accreting and bursting neutron star systems and derived mass-radius regions shown in green. Steiner *et al.* [51] performed a combined anaylsis of six accreting neutron star systems, shown are 1-σ and 2-σ results in blue.

summarize our discussion and highlight the new frontiers of core-collapse supernova theory.

2 New Constraints on the Supernova Equation of State

An important ingredient in any core-collapse supernova model is the nuclear EOS. It provides the crucial closure for the set of (magneto-)hydrodynamics equations used to describe the evolution of the collapsing stellar fluid and strongly influences the structure of the protoneutron star and the thermodynamics of the overall problem. Nuclear statistical equilibrium (NSE) prevails above temperatures of $\sim$0.5 MeV, which corresponds to densities above $\sim 10^7\,\text{g}\,\text{cm}^{-3}$ in the core-collapse supernova problem. In this regime, the EOS is derived from the Helmholtz free energy and thus is expressed as a function of density ρ, temperature T, and electron fraction Y_e. The NSE part of the core-collapse supernova EOS must cover tremendous ranges of density ($10^7 - 10^{15}\,\text{g}\,\text{cm}^{-3}$), temperature ($0.5 - 100\,\text{MeV}$), and electron fraction (0–$\sim$0.6). Constraints from experimental nuclear physics on the nuclear EOS are few and generally limited to only small regions of the needed (ρ, T, Y_e) space (see the discussions in [47, 52]).

A stringent constraint on the nuclear EOS is set by precision mass measurements of neutron stars in binary systems. The 2-$M_\odot$ ($[1.97 \pm 0.04]\,M_\odot$) neutron star of Demorest *et al.* [43] rules out a large range of soft hadronic, mixed hadronic-exotic, and strange-quark matter EOS [3, 53].

Recently, Hebeler *et al.* [49] have carried out chiral effective field theory calculations of neutron-rich matter below nuclear saturation density, strongly constraining the $P(\rho)$ relationship in this regime. They derived a radius constraint for a 1.4-$M_\odot$ neutron star of $10.5\,\mathrm{km} \lesssim R \lesssim 13.3\,\mathrm{km}$ (these numbers would be shifted up by $\sim$400 m if a detailed crust treatment was included) by requiring that all EOS support neutron stars with mass $\gtrsim 2\,M_\odot$ and pass through the $P(\rho)$ range allowed by their calculations.

Steiner *et al.* [51] and Özel *et al.* [50] analyzed observations from accreting and bursting neutron stars to obtain neutron star mass-radius constraints. Such observations and their interpretations should be taken with a grain of salt, since large systematic uncertainties are attached to the models that are required to infer mass and radius and to the assumptions made in their statistical analysis. For example, [51] and [50], starting with different assumptions, derive rather different 2-σ mass-radius constraints from the same set of sources.

In Fig. 1, we contrast the various observational constraints on the neutron star mass and radius with a range of EOS used in core-collapse supernova modeling. The LS family of EOS is based on the compressible liquid droplet model [18], while all other EOS (drawn from [44–48]) are based on relativistic mean field (RMF) theory. The details of the $M - R$ curves depend on multiple EOS parameters such as nuclear incompressibility, symmetry energy and their derivatives and we must refer the reader to [47] and to the primary EOS references for details for each EOS. Fig. 1 shows that none of the current set of available EOS allow for a 2-$M_\odot$ neutron star while at the same time being consistent with the current mass-radius constraints from observations. The crux is that the EOS needs to be sufficiently stiff to support 2-$M_\odot$ neutron stars *and* at the same time sufficiently soft to make neutron stars with moderate radii in the canonical mass range. This balance appears to be difficult to realize. The stiff set of RMF EOS produce systematically too large neutron stars. The soft compressible liquid-droplet LS180 EOS [18] agrees well with the mass-radius constraints, but is ruled out by its failure to support a 2-$M_\odot$ neutron star. Closest to satisfying all constraints are the LS220 EOS of [18] and the yet unpublished HSDD2 EOS of [48] based on the RMF model of [54].

The stiffness of the nuclear EOS at high and intermediate densities has important consequences for the postbounce evolution of core-collapse supernovae. In simple terms: the stiffer the EOS, the more extended the protoneutron star and the larger the radius and the lower the matter temperature at which neutrinos decouple from the protoneutron star matter. Assuming a Fermi-Dirac spectrum with zero degeneracy, the mean-squared energy of the emitted neutrinos is approximately given by $\langle \epsilon_\nu^2 \rangle \approx 21 T_\nu^2$ [55], where T_ν is the matter temperature (in units of MeV) at the neutrinosphere (where the optical depth $\tau \approx 2/3$). Hence, a softer EOS will lead to systematically harder neutrino spectra than a stiffer EOS (as born out by the simulations of [17]). Since the charged-current neutrino heating rate Q_ν^+ scales $\propto \langle \epsilon_\nu^2 \rangle$, a soft EOS leads to a higher neutrino heating efficiency than a stiff EOS. This is at least part of the explanation why some published 2D simulations using the soft, now ruled-out LS180 EOS have shown neutrino-driven explosions [17, 22, 23] while simulations with stiffer EOS have generally failed to yield such explosions in stars more massive than $\sim$11 $M_\odot$ [17, 19, 25].

3 New Physics: Collective Neutrino Oscillations

Neutrinos and antineutrinos of all three flavors are produced in core-collapse supernovae and can oscillate from one flavor to another. ν_e and $\bar{\nu}_e$ are made and interact via charged-current and neutral-current interactions, while ν_μ and ν_τ and their antineutrinos experience only neutral-current processes, since no muons or tauons are present in the core-collapse supernova environment. Hence, their interaction cross sections are very similar and one generally lumps them together as $\nu_x = \{\nu_\mu, \nu_\tau\}$ and $\bar{\nu}_x = \{\bar{\nu}_\mu, \bar{\nu}_\tau\}$.

The oscillations between ν_e and ν_x or $\bar{\nu}_e$ and $\bar{\nu}_x$ are driven by their mass differences, forward scattering off background electrons, and forward scattering off other neutrinos and antineutrinos. These limiting regimes are called neutrino oscillations in vacuum [56], matter-enhanced oscillations through the MSW effect [57], and collective oscillations [58], respectively. Quantitatively, the nature of neutrino flavor conversions depends on an interplay of vacuum neutrino oscillation frequency $\omega = \Delta m^2/(2E)$ with the matter potential $\lambda = \sqrt{2}G_F n_e$ due to background electrons (where n_e is the electron number density) and with the collective neutrino potential $\mu \sim \sqrt{2}G_F(1-\cos\theta)n_{\nu+\bar{\nu}}$ generated by the neutrinos themselves (where $n_{\nu+\bar{\nu}}$ is the neutrino and antineutrino number density). In a typical core-collapse supernova environment, the matter potential falls off with radius as $n_e \propto 1/r^3$, whereas the collective potential falls off faster with $n_{\nu+\bar{\nu}}\langle 1-\cos\theta\rangle \propto 1/r^4$. So, when the neutrinos travel outward from the core, they generally first experience collective effects and then matter effects, which may be modified by shock wave effects [59]. After they leave the star, the mass eigenstates travel independently and are detected on Earth as an incoherent superposition. There can be distinctive effects due to additional conversions during propagation inside the Earth (e.g., [60]).

3.1 Collective Oscillations due to ν-ν Interactions

The neutrino density creates a potential that is not flavor diagonal [58]; $n_\nu, n_{\bar{\nu}}$ are density matrices in flavor space and depend on the flavor composition of the entire neutrino ensemble! Flavor evolution of such dense neutrino gases [61] can be understood to good accuracy without considering many-particle effects [62]. Calculations in spherical symmetry showed that the collective oscillations can affect neutrino flavor conversions substantially [63, 64]. The main features observed were large flavor conversions for inverted hierarchy (neutrinos masses $m_1, m_2 > m_3$), and a surprisingly weak dependence on the mixing angle and the matter density.

These features can be understood analytically. A dense gas of neutrinos displays collective flavor conversion [65], i.e., the flavor oscillations of all neutrinos and antineutrinos become coupled to each other and all of them undergo flavor conversion together. Neutrinos of all energies oscillate almost in phase, through synchronized [66]/parametrically resonant [67]/bipolar oscillations [68, 69]. The effect of the bipolar oscillations with a decreasing collective potential μ is a partial or complete swap of the energy spectra of two neutrino flavors [70, 71]. The "$1-\cos\theta$" structure of weak interactions can give rise to a dependence of flavor evolution on the neutrino emission angle [64] or even flavor decoherence, i.e., neutrinos acquire uncorrelated phases, and the neutrino fluxes for all flavors become almost identical [72]. For a realistic excess of ν_e, compared to $\bar{\nu}_e$ fluxes, such angle-dependent effects are likely to be small [73, 74]. Even non-spherical source geometries can often be captured by an effective single-angle approximation [75] in the coherent regime. While most of these results were obtained for neutrino oscillations between two flavors, it was shown that with three flavors one can usually treat the oscillation problem by factorizing it into simpler two-flavor oscillation problems, since the masssquared differences between the mass eigenstates obey $\Delta m_{12}^2 \ll |\Delta m_{13}|$ and the mixing angle $\theta_{13} \ll 1$ [76], and the previous results are easily generalized. Effects of potential CP violation are expected to be small with realistic differences between μ and τ neutrino fluxes [77]. On the other hand, similar realistic departures are sufficient to trigger collective effects even for a vanishing mixing angle [78, 79].

3.2 Results obtained with Core-Collapse Supernova Toy-Models

Although the inherent nonlinearity and the presence of multi-angle effects make the analysis rather complicated, the final outcome for the neutrino fluxes turns out to be rather straightforward, at least in the spherically symmetric scenario. Synchronized oscillations with a frequency $\langle\omega\rangle$ take place just outside the neutrinosphere at $r \sim 10 - 40$ km. These cause no significant flavor conversions since the mixing angle, which determines the extent of flavor conversion, is highly suppressed by the large matter potential due to the high electron density in these inner regions [80, 81]. A known exception occurs for the ν_e burst phase in low-mass progenitor stars that have a very steep density profile [82]. In such a situation, neutrinos of all energies undergo MSW resonances *before* collective effects become negligible [83, 84]. At larger radii, $r \sim 40-100$ km, bipolar or pendular oscillations $\nu_e \leftrightarrow \nu_x$ with a higher frequency $\sqrt{2\omega\mu}$ follow. These oscillations are instability-driven and thus depend logarithmically [68] on the mixing angle, occurring where the fluxes for the two flavors are very similar [71]. As μ decreases, so that $\langle\omega\rangle \sim \mu$, neutrinos near this instability may relax to the lower neutrino mass (energy) state. As a result, one finds one or more spectral swaps demarcated by sharp discontinuities or "spectral splits" in the oscillated flux.

These simple explanations do not take into account the fact that neutrinos are emitted at different angles from the neutrinosphere. As a result, radial neutrinos take a shorter path (while tangentially emitted neutrinos take a longer path), and thus experience less (more) background potentials from the electrons and from other neutrinos leading to an emission angle-dependent flavor evolution. These sort of effects are called *multi-angle effects*, and can suppress or delay flavor conversions either through multi-angle matter effects [85], or through multi-angle neutrino-neutrino interactions themselves [86].

3.3 Results obtained with more realistic Models

The observations outlined in the previous section 3.2 were mostly based on toy models of core-collapse supernova neutrino fluxes and background densities. Recently, several groups have tried to perform semi-realistic calculations of the oscillation physics, by injecting the output neutrino fluxes from supernova simulations into oscillation calculations [87–89]. Interesting results have also been obtained by performing a linear stability analysis of the equations used for calculating the flavor conversion, with the initial conditions taken from simulations [90, 91].

The simple picture given in §3.2 has therefore undergone further changes. Firstly, it has been recognized that matter effects suppress collective oscillations even in the bipolar regime through multi-angle effects as explained before [87, 88] (see also §3.4). This is most effective in the pre-explosion accretion phase, when the matter density is large in the region behind the stalled shock. In this case, it appears that one can simply ignore collective effects and only include the MSW effects which take place at larger radii. Of course, the result depends on details of the matter density and ratios of neutrino fluxes. In particular, for fluxes that are either highly symmetric in neutrinos and antineutrinos [89], or include flavor dependent angular

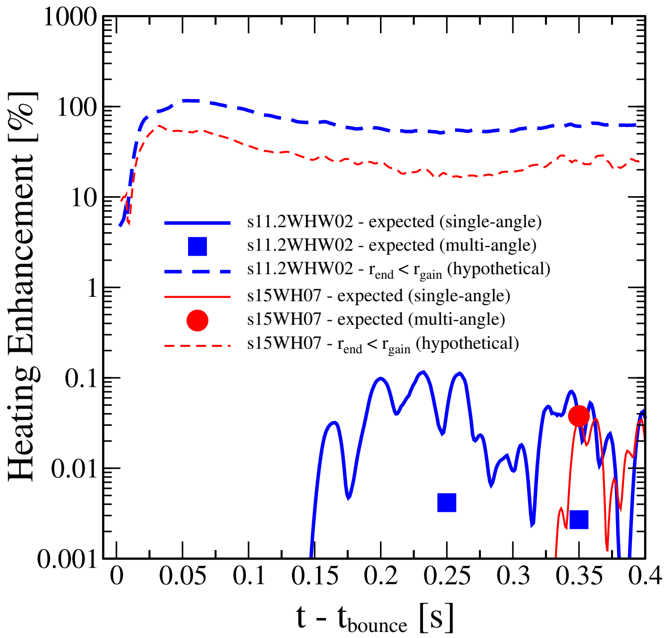

Figure 2: (color online) Time evolution (as a function of time after core bounce) of the potential percentage increase in the heating rate due to collective neutrino oscillations based on our recent simulations [89], in which we considered 11.2-$M_\odot$ and 15-$M_\odot$ progenitors. The dashed lines assume the naive case of complete conversion already below the gain radius where heating begins to dominate over cooling. This is the case assumed by by Suwa *et al.* [95]) and leads to an enhancement of up to 100%. In the our detailed oscillation calculations, conversion does not occur before the gain radius and our more realistic estimate of the heating enhancement is much lower and shown in solid lines. The points, blue squares for the 11.2-$M_\odot$ model and red circles for the 15-$M_\odot$ model, represent our estimate of the heating enhancement if multi-angle oscillation effects are included, which further increase the radii at which collective oscillations occur and thus decrease the heating enhancement even further, in general agreement with [87, 88]. This figure corresponds to Fig. 7 of [89].

emission that leads to an angular instability [89, 92], one finds the matter suppression to be less effective. Secondly, in the cooling phase of the explosion, $\nu_x/\bar{\nu}_x$ fluxes may be larger than $\nu_e/\bar{\nu}_e$ fluxes. This can lead to additional instabilities which cause multiple spectral splits [71]. These features survive multi-angle effects in general, and with the inclusion of three-flavor effects can lead to a rich and complex phenomenology [93, 94].

The understanding of collective neutrino oscillations is still evolving, and we expect that more accurate numerical calculations and improved analytical understanding will yield new surprises and insights into the existing results we have summarized here.

3.4 Effect of Collective Oscillations on Neutrino-driven Explosions

From the core-collapse supernova theory point of view, the most intriguing result of collective oscillations is the almost complete exchange of ν_e and ν_x and $\bar{\nu}_e$ and $\bar{\nu}_x$ spectra in the inverted mass hierarchy. The ν_x and $\bar{\nu}_x$ are emitted by thermal processes deep inside the core and their spectra are much harder than those of their electron-flavor counterparts. Due to the ϵ_ν^2-dependence of the charged-current absorption cross section, a swap of $\nu_x/\bar{\nu}_x$ and $\nu_e/\bar{\nu}_e$ spectra could dramatically enhance neutrino heating and may be the crucial ingredient missing in core-collapse supernova models, provided that the oscillations occur at sufficiently small radii to have an effect in the region behind the shock. To our knowledge, this point, in the context of collective oscillations, was first made by one of us [96].

Suwa *et al.* [95] recently performed a set of 1D and 2D core-collapse supernova simulations in which they considered *ad-hoc* spectral swaps above 9 MeV for neutrinos and antineutrinos occurring at a fixed radius of 100 km, which is close to the gain radius (where heating begins to dominate over cooling) in their simulations. They considered a range of progenitor models and found that the heating enhancement by collective oscillations can indeed turn duds into explosions. This result was corroborated in a semi-analytic study by Pejcha *et al.* [97] in which the authors also considered different radii for the oscillations to become effective.

Chakraborty *et al.* [87, 88] carried out the first multi-angle single-energy neutrino oscillations based on realistic neutrino radiation fields from 1D core-collapse supernova simulations. They discovered that the rather high matter density between protoneutron star and stalled shock strongly suppresses collective neutrino oscillations in the pre-explosion phase when multi-angle effects are taken into account. Hence, the authors excluded any impact of collective oscillations on neutrino heating.

In Dasgupta *et al.* [89], we carried out single-angle multi-energy and multi-angle single-energy oscillation calculations based on neutrino radiation fields from 2D core-collapse supernova simulations performed with the `VULCAN/2D` code [26]. In 2D, convection and SASI lead to complicated flow patterns and large-scale shock excursions not present in 1D simulations. Even in our single-angle calculations and in the most optimistic case, we find that collective oscillations do not set in at radii sufficiently deep in the heating region to have a significant effect on neutrino heating. When including multi-angle effects, we also observe a suppression of collective oscillations, though not at the level argued for by [87, 88], who made different assumptions about the angular distribution of the neutrino radiation fields emitted from the neutrinosphere (ours are based on the angle-dependent neutrino transport results of [24]).

As depicted by Fig. 2, we find that the heating enhancement due to collective oscillations, if present at all, stays below $\sim$0.1% at all times in both considered progenitor models when oscillation radii from full oscillation calculations are taken into account. This shows, in agreement with [87, 88], that the strong positive effect on the neutrino mechanism reported by Suwa *et al.* [95] is artificial and due primarily to their ad-hoc choice of a small oscillation radius.

3.5 Collective Oscillations after the Onset of Explosion

In Dasgupta *et al.* [89], we studied the suppression of collective oscillations by multi-angle effects at high matter density using multi-angle single-energy oscillation calculations for select simulation snapshots of the pre-explosion phase in 11.2-$M_\odot$ and 15-$M_\odot$ progenitors. We also, in a more heuristic approach, studied the potential for suppression of collective oscillations by comparing the MSW potential $\lambda(r)$ with the expression $\lambda_{\rm MA} = 2\sqrt{2}G_F\Phi_{\nu,\bar{\nu}}(R_{\nu_e}^2/r^2)\mathcal{F}_-$,

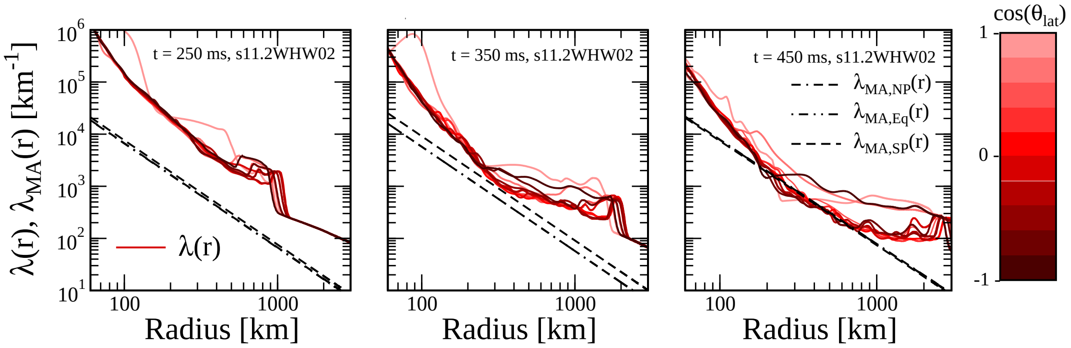

Figure 3: (color online) The MSW potential $\lambda(r)$ along various directions (solid lines, 10 rays equally spaced in $\cos[\theta_{\rm lat}]$), in comparison to the minimum $\lambda(r)$ needed for multi-angle suppression, $\lambda_{\rm MA} = 2\sqrt{2}G_F\Phi_{\nu,\bar{\nu}}(R^2_{\nu_e}/r^2)\mathcal{F}_-$. Dot-dashed-dashed, dot-dot-dashed, and dashed lines, indicated $\lambda_{\rm MA}$ taken along the North pole (NP), equator (Eq), and South pole (SP), respectively. The steep rise in the $\lambda(r)$ profiles at 250 ms and 350 ms occurring around $r \sim 1000$ km and $r \sim 2000$ km, respectively, is the location of the shock. At 450 ms the shock is close to 3000 km.

where $\Phi_{\nu,\bar{\nu}}$ is the neutrino number density at the ν_e neutrino sphere radius R_{ν_e} and $\mathcal{F}_- = (\Phi_{\nu_e} - \Phi_{\bar{\nu}_e})/(\Phi_{\nu_e} + \Phi_{\bar{\nu}_e} + 4\Phi_{\nu_x})$ is the relative lepton asymmetry of the neutrinos. If $\lambda \gg \lambda_{\rm MA}$, collective oscillations are suppressed [85].

In [89], we compared λ and $\lambda_{\rm MA}$ at various pre-explosion times, radii, and spatial angular directions in our simulations using 11.2-$M_\odot$ and 15-$M_\odot$ progenitors. Based on this, we concluded, in agreement with [87, 88], that suppression of collective oscillations is likely highly relevant in the pre-explosion phase and must be carefully studied even in relatively low-mass progenitors with steep density profiles such as the 11.2-$M_\odot$ progenitor model.

The situation after the onset of explosion, however, may be quite different: The explosion rarefies the region behind the expanding shock and shuts off the large $\nu_e/\bar{\nu}_e$ accretion luminosity, changing the neutrino flux asymmetry. Extending our previous results to the explosion phase, we have repeated our simulations for the 11.2-$M_\odot$ progenitor, but included an additional neutrino heating term in order to drive an early explosion. The heating term is equivalent to the prescription used in [13] with $L_{\nu_e} = L_{\bar{\nu}_e} = 0.5 \times 10^{52}$ ergs/s.

In Figure 3, we compare the MSW potential $\lambda(r)$ along multiple angular directions with $\lambda_{\rm MA}$. As the explosion clears out the region behind the shock, the MSW potential decreases in strength. In this model, within a few 100 ms of the onset of the explosion, the MSW potential becomes comparable to $\lambda_{\rm MA}$, which indicates that the suppression is lifted and collective oscillations may now occur at radii as small as ~200 km. At this point, the core-collapse supernova explosion has already been launched, but collective neutrino oscillations may still affect the evolution and various observable features, for example, via the neutrino-driven wind from the protoneutron star and r-process nucleosynthesis [98, 99].

4 Summary and Outlook

In this contribution to the proceedings of the HAmburg Neutrinos from Supernova Explosions (HAνSE) 2011 conference, we have summarized the recent rapid progress in various aspects of core-collapse supernova theory. While 2D simulations continue to be perfected [22, 24, 100, 101], self-consistent 3D simulations with energy-dependent neutrino radiation hydrodynamics are now the frontier of core-collapse supernova modeling [30] and are made possible by the first generation of petascale supercomputers. General relativity is also beginning to be included in 2D [100–102] and 3D simulations [103, 104], which will eventually allow for first-principles studies of multi-D black hole formation and the relationship between massive star collapse and long gamma-ray bursts. Also, open-source codes and microphysics inputs (EOS, neutrino opacities) are gaining traction [48, 105–112]. They allow for code verification and physics benchmarking and are lowering the technological hurdle for new groups with new ideas trying to enter core-collapse supernova modeling.

After ten years with little activity, improved modeling capabilities, faster computers, and the discovery of the 2-$M_{\odot}$ neutron star, have spawned a flurry of activity in the nuclear EOS community, which has already resulted in multiple new finite-temperature EOS for core-collapse supernova modeling [44–47].

The realization that collective neutrino oscillations may occur in the core-collapse supernova environment [63, 64, 68] has led to a plethora of work since $\sim$2005. As we have outlined in this article, the current state of affairs is that collective oscilations are unlikely to be dynamically relevant in driving the explosion, but their effects are crucial in predicting and understanding the neutrino signal that will be seen in detectors from the next nearby core collapse event. The current frontier of oscillation calculations in the core-collapse supernova context is marked by detailed multi-energy multi-angle calculations that take their input spectra and angular distributions from core-collapse supernova models. Significant progress towards this has recently been made [87–89, 113], but more will be needed to assess the potentially strong impact of neutrino-matter interactions and only partially-decoupled neutrino radiation fields in the oscillation regime.

The broad range of current and near-future advances in theory will be matched and tested by observations of the next galactic (or Magellanic-cloud) core-collapse supernova. This event will most likely be observed in electromagnetic waves, neutrinos, and, with the upcoming advanced generation of gravitational-wave observatories, for the first time also in gravitational waves. Gravitational waves carry dynamical information on the intricate multi-D processes occuring in the supernova core [114, 115] and will complement the structural and thermodynamic information carried by neutrinos. Together, neutrinos and gravitational waves may finally shed observational light on the details of the core-collapse supernova mechanism.

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References

[1] W. Baade and F. Zwicky. *Proc. Nat. Acad. Sci.*, 20:259, 1934.

[2] H. A. Bethe. *Rev. Mod. Phys.*, 62:801, 1990.

[3] J. M. Lattimer and M. Prakash. What a Two Solar Mass Neutron Star Really Means. In S. Lee, editor, *From Nuclei to Stars: Festschrift in Honor of Gerald E. Brown. arXiv:1012.3208*. World Scientific Publishing, UK, 2011.

[4] E. O'Connor and C. D. Ott. *Astrophys. J.*, 730:70, 2011.

[5] H. A. Bethe and J. R. Wilson. *Astrophys. J.*, 295:14, 1985.

[6] O. Pejcha and T. A. Thompson. *Submitted to ApJ. arXiv:1103.4865*, 2011.

[7] T. A. Thompson, A. Burrows, and P. A. Pinto. *Astrophys. J.*, 592:434, 2003.

[8] M. Liebendörfer, M. Rampp, H.-T. Janka, and A. Mezzacappa. *Astrophys. J.*, 620:840, 2005.

[9] R. Buras, M. Rampp, H.-T. Janka, and K. Kifonidis. *Astron. Astrophys.*, 447:1049, 2006.

[10] F. S. Kitaura, H.-T. Janka, and W. Hillebrandt. *Astron. Astrophys.* , 450:345, 2006.

[11] J. M. Blondin, A. Mezzacappa, and C. DeMarino. *Astrophys. J.*, 584:971, 2003.

[12] L. Scheck, H.-T. Janka, T. Foglizzo, and K. Kifonidis. *Astron. Astrophys.* , 477:931, 2008.

[13] J. W. Murphy and A. Burrows. *Astrophys. J.*, 688:1159, 2008.

[14] R. Fernández and C. Thompson. *Astrophys. J.*, 703:1464, 2009.

[15] J. W. Murphy and C. Meakin. *Astrophys. J.*, 742:74, 2011.

[16] F. Hanke, A. Marek, B. Müller, and H.-T. Janka. *Submitted to the Astrophys. J., arXiv:1108.4355*, 2011.

[17] A. Marek and H.-T. Janka. *Astrophys. J.*, 694:664, 2009.

[18] J. M. Lattimer and F. D. Swesty. *Nucl. Phys. A*, 535:331, 1991.

[19] H.-T. Janka. private communication, 2011.

[20] H. Shen, H. Toki, K. Oyamatsu, and K. Sumiyoshi. *Prog. Th. Phys.*, 100:1013, 1998.

[21] W. Hillebrandt and R. G. Wolff. Models of Type II Supernova Explosions. In W. D. Arnett and J. W. Truran, editors, *Nucleosynthesis : Challenges and New Developments*, page 131, 1985.

[22] S. W. Bruenn, A. Mezzacappa, W. R. Hix, J. M. Blondin, P. Marronetti, O. E. B. Messer, C. J. Dirk, and S. Yoshida. Mechanisms of Core-Collapse Supernovae and Simulation Results from the CHIMERA Code. In G. Giobbi, A. Tornambe, G. Raimondo, M. Limongi, L. A. Antonelli, N. Menci, and E. Brocato, editors, *AIP Phys. Conf. Ser.*, volume 1111 of *AIP Phys. Conf. Ser.*, page 593, 2009.

[23] Y. Suwa, K. Kotake, T. Takiwaki, S. C. Whitehouse, M. Liebendörfer, and K. Sato. *Pub. Astr. Soc. Jap.*, 62:L49, 2010.

[24] C. D. Ott, A. Burrows, L. Dessart, and E. Livne. *Astrophys. J.*, 685:1069, 2008.

[25] A. Burrows, E. Livne, L. Dessart, C. D. Ott, and J. Murphy. *Astrophys. J.*, 640:878, 2006.

[26] A. Burrows, E. Livne, L. Dessart, C. D. Ott, and J. Murphy. *Astrophys. J.*, 655:416, 2007.

[27] N. Smith, W. Li, A. V. Filippenko, and R. Chornock. *Mon. Not. Roy. Astron. Soc.* , 412:1522, 2011.

[28] S. J. Smartt. *Ann. Rev. Astron. Astroph.* , 47:63, 2009.

[29] J. Nordhaus, A. Burrows, A. Almgren, and J. Bell. *Astrophys. J.*, 720:694, 2010.

[30] T. Takiwaki, K. Kotake, and Y. Suwa. *Submitted to the Astrophys. J., arXiv:1108.3989*, 2011.

[31] C. L. Fryer and M. S. Warren. *Astrophys. J. Lett.*, 574:L65, 2002.

[32] A. Burrows, L. Dessart, E. Livne, C. D. Ott, and J. Murphy. *Astrophys. J.*, 664:416, 2007.

[33] C. D. Ott, A. Burrows, L. Dessart, and E. Livne. *Phys. Rev. Lett.*, 96:201102, 2006.

[34] I. Sagert, T. Fischer, M. Hempel, G. Pagliara, J. Schaffner-Bielich, A. Mezzacappa, F.-K. Thielemann, and M. Liebendörfer. *Phys. Rev. Lett.*, 102:081101, 2009.

[35] M. Obergaulinger, P. Cerdá-Durán, E. Müller, and M. A. Aloy. *Astron. Astrophys.* , 498:241, 2009.

[36] C. D. Ott, A. Burrows, T. A. Thompson, E. Livne, and R. Walder. *Astrophys. J. Suppl. Ser.*, 164:130, 2006.

[37] A. Heger, S. E. Woosley, and H. C. Spruit. *Astrophys. J.*, 626:350, 2005.

[38] S.-C. Yoon, N. Langer, and C. Norman. *Astron. Astrophys.* , 460:199, 2006.

[39] S. E. Woosley and A. Heger. *Astrophys. J.*, 637:914, 2006.

[40] M. Modjaz. *Astron. Nachr.*, 332:434, 2011.

[41] N. N. Weinberg and E. Quataert. *Mon. Not. Roy. Astron. Soc.* , 387:L64, 2008.

[42] N. A. Gentile, M. B. Aufderheide, G. J. Mathews, F. D. Swesty, and G. M. Fuller. *Astrophys. J.*, 414:701, 1993.

[43] P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts, and J. W. T. Hessels. *Nature*, 467:1081, 2010.

[44] H. Shen, H. Toki, K. Oyamatsu, and K. Sumiyoshi. *Submitted to Astrophys. J., arXiv:1105.1666*, 2011.

[45] G. Shen, C. J. Horowitz, and S. Teige. *Phys. Rev. C*, 83:035802, 2011.

[46] G. Shen, C. J. Horowitz, and E. O'Connor. *Phys. Rev. C*, 83:065808, 2011.

[47] M. Hempel, T. Fischer, J. Schaffner-Bielich, and M. Liebendörfer. *ArXiv:1108.0848*, 2011.

[48] M. Hempel. URL `http://phys-merger.physik.unibas.ch/~hempel/eos.html`. Matthias Hempel's EOS webpage.

[49] K. Hebeler, J. M. Lattimer, C. J. Pethick, and A. Schwenk. *Phys. Rev. Lett.*, 105:161102, 2010.

[50] F. Özel, G. Baym, and T. Güver. *Phys. Rev. D.*, 82:101301, 2010.

[51] A. W. Steiner, J. M. Lattimer, and E. F. Brown. *Astrophys. J.*, 722:33, 2010.

[52] F. J. Fattoyev, C. J. Horowitz, J. Piekarewicz, and G. Shen. *Phys. Rev. C*, 82:055803, 2010.

[53] F. Özel, D. Psaltis, S. Ransom, P. Demorest, and M. Alford. *Astrophys. J. Lett.*, 724:L199, 2010.

[54] S. Typel, G. Röpke, T. Klähn, D. Blaschke, and H. H. Wolter. *Phys. Rev. C*, 81:015803, 2010.

[55] H.-T. Janka. *Astron. Astrophys.* , 368:527, 2001.

[56] B. Pontecorvo. *Sov.Phys.JETP*, 26:984, 1968.

[57] S.P. Mikheev and A.Yu. Smirnov. *Sov.J.Nucl.Phys.*, 42:913, 1985.

[58] J. T. Pantaleone. *Phys. Lett. B.*, 287:128, 1992.

[59] R. C. Schirato and G. M. Fuller. *astro-ph/0205390*, 2002.

[60] M. Cribier, W. Hampel, J. Rich, and D. Vignaud. *Phys. Lett. B*, 182:89, 1986.

[61] G. Sigl and G. Raffelt. *Nucl. Phys. B*, 406:423, 1993.

[62] A. Friedland and C. Lunardini. *Phys. Rev. D.*, 68:013007, 2003.

[63] H. Duan, G. M. Fuller, and Y.-Z. Qian. *Phys. Rev. D.*, 74(12):123004, 2006.

[64] H. Duan, G. M. Fuller, J. Carlson, and Y.-Z. Qian. *Phys. Rev. D.*, 74(10):105014, 2006.

[65] V. A. Kostelecky and S. Samuel. *Phys. Rev. D.*, 52:621, 1995.

[66] S. Pastor, G. G. Raffelt, and D. V. Semikoz. *Phys. Rev. D.*, 65:053011, 2002.

[67] G. G. Raffelt. *Phys. Rev. D.*, 78:125015, 2008.

[68] S. Hannestad, G. G. Raffelt, G. Sigl, and Y. Y. Y. Wong. *Phys. Rev. D.*, 74(10):105010, 2006.

[69] H. Duan, G. M. Fuller, J. Carlson, and Y.-Z. Qian. *Phys. Rev. D.*, 75:125005, 2007.

[70] G. G. Raffelt and A. Y. Smirnov. *Phys. Rev. D.*, 76:081301, 2007.

[71] B. Dasgupta, A. Dighe, G. G. Raffelt, and A. Y. Smirnov. *Phys. Rev. Lett.*, 103:051105, 2009.

[72] G.G. Raffelt and G. Sigl. *Phys. Rev. D.*, 75:083002, 2007.

[73] A. Esteban-Pretel, S. Pastor, R. Tomas, G. G. Raffelt, and G. Sigl. *Phys. Rev. D.*, 76:125018, 2007.

[74] G. L. Fogli, E. Lisi, A. Marrone, and A. Mirizzi. *JCAP*, 0712:010, 2007.

[75] B. Dasgupta, A. Dighe, A. Mirizzi, and G. G. Raffelt. *Phys. Rev. D.*, 78:033014, 2008.

[76] B. Dasgupta and A. Dighe. *Phys. Rev. D.*, 77:113002, 2008.

[77] J. Gava and C. Volpe. *Phys. Rev. D.*, 78:083007, 2008.

[78] M. Blennow, A. Mirizzi, and P. D. Serpico. *Phys. Rev. D.*, 78:113004, 2008.

[79] B. Dasgupta, G. G. Raffelt, and I. Tamborra. *Phys. Rev. D.*, 81:073004, 2010.

[80] L. Wolfenstein. *Phys. Rev. D.*, 17:2369, 1978.

[81] S. P. Mikheev and A. Y. Smirnov. *Yad. Fiz.*, 42:1441, 1985.

[82] H. Duan, G. M. Fuller, J. Carlson, and Y.-Z. Qian. *Phys. Rev. Lett.*, 100:021101, 2008.

[83] H. Duan, G. M. Fuller, and Y.-Z. Qian. *Phys. Rev. D.*, 77:085016, 2008.

[84] B. Dasgupta, A. Dighe, A. Mirizzi, and G. G. Raffelt. *Phys. Rev. D.*, 77:113007, 2008.

[85] A. Esteban-Pretel, A. Mirizzi, S. Pastor, R. Tomàs, G. G. Raffelt, P. D. Serpico, and G. Sigl. *Phys. Rev. D.*, 78:085012, 2008.

[86] H. Duan and A. Friedland. *Phys. Rev. Lett.*, 106(9):091101, 2011.

[87] S. Chakraborty, T. Fischer, A. Mirizzi, N. Saviano, and R. Tomàs. *Phys. Rev. Lett.*, 107:151101, 2011.

[88] S. Chakraborty, T. Fischer, A. Mirizzi, N. Saviano, and R. Tomàs. *Phys. Rev. D.*, 84:025002, 2011.

[89] B. Dasgupta, E. P. O'Connor, and C. D. Ott. *Submitted to Phys. Rev. D., arXiv:1106.1167*, 2011.

[90] A. Banerjee, A. Dighe, and G. Raffelt. *Phys. Rev. D.*, 84:053013, 2011.

[91] S. Sarikas, G. G. Raffelt, L. Hudepohl, and H.-T. Janka. *arXiv:1109.3601*, 2011.

[92] A. Mirizzi and P. D. Serpico. *arXiv:1110.0022*, 2011.

[93] A. Friedland. *Phys. Rev. Lett.*, 104:191102, 2010.

[94] B. Dasgupta, A. Mirizzi, I. Tamborra, and R. Tomas. *Phys. Rev. D.*, 81:093008, 2010.

[95] Y. Suwa, K. Kotake, T. Takiwaki, M. Liebendörfer, and K. Sato. *Astrophys. J.*, 738:165, 2011.

[96] C. D. Ott. Talk at the Joint Indo-German Supernova Astroparticle Physics Workshop (JIGSAW) 2010 at TIFR, Mumbai, India, 2010. URL `http://theory.tifr.res.in/~jigsaw10/talks/ott.pdf`.

[97] O. Pejcha, B. Dasgupta, and T. A. Thompson. *Submitted to the Astrophys. J., arXiv:1106.5718*, 2011.

[98] H. Duan, A. Friedland, G. C. McLaughlin, and R. Surman. *J. Phys. G Nuc. Phys.*, 38:035201, 2011.

[99] R. Surman, G. C. McLaughlin, A. Friedland, and H. Duan. *Nuc. Phys. B Proc. Suppl.*, 217:121, 2011.

[100] B. Müller, H.-T. Janka, and H. Dimmelmeier. *Astrophys. J. Supp. Ser.* , 189:104, 2010.

[101] P. Cerdá-Durán, J. A. Font, L. Antón, and E. Müller. *Astron. Astrophys.* , 492:937, 2008.

[102] Y. Sekiguchi and M. Shibata. *Astrophys. J.*, 737:6, 2011.

[103] C. D. Ott, H. Dimmelmeier, A. Marek, H.-T. Janka, I. Hawke, B. Zink, and E. Schnetter. *Phys. Rev. Lett.*, 98:261101, 2007.

[104] C. D. Ott, C. Reisswig, E. Schnetter, E. O'Connor, U. Sperhake, F. Löffler, P. Diener, E. Abdikamalov, I. Hawke, and A. Burrows. *Phys. Rev. Lett.*, 106:161103, 2011.

[105] M. Liebendörfer. URL `http://www.physik.unibas.ch/~liebend/download/index.html`. Numerical Algorithms for Supernova Dynamics.

[106] URL `http://www.stellarcollapse.org`. `stellarcollapse.org`: A Community Portal for Stellar Collapse, Core-Collapse Supernova and GRB Simulations.

[107] E. O'Connor and C. D. Ott. *Class. Quantum Grav.*, 27:114103, 2010.

[108] F. Timmes. URL `http://cococubed.asu.edu/code_pages/codes.shtml`. Cococubed – Astronomy Codes.

[109] URL `http://www.einsteintoolkit.org`. EinsteinToolkit: A Community Toolkit for Numerical Relativity.

[110] F. Löffler, J. Faber, E. Bentivegna, T. Bode, P. Diener, R. Haas, I. Hinder, B. C. Mundim, C. D. Ott, E. Schnetter, G. Allen, M. Campanelli, and P. Laguna. *ArXiv:1111.3344*, 2011.

[111] H. Shen. URL `http://physics.nankai.edu.cn/grzy/shenhong/EOS/index.html`. Homepage of Relativistic EOS Table.

[112] G. Shen. URL `http://cecelia.physics.indiana.edu/gang_shen_eos/`. Gang Shen's EOS webpage.

[113] H. Duan, G. M. Fuller, and Y.-Z. Qian. *Ann. Rev. Nuc. Part. Sc.*, 60:569, 2010.

[114] C. D. Ott. *Class. Quantum Grav.*, 26:063001, 2009.

[115] K. Kotake. *submitted to a special issue of Comptes Rendus Physique "Gravitational Waves (from detectors to astrophysics)", ArXiv:1110.5107*, 2011.