Snowmass2021 - Letter of Interest

Neutrinos from Supernovae

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
□ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
□ (NF7) Applications
■ (NF8) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
□ (NF10) Neutrino detectors
□ (Other) *[Please specify frontier/topical group(s)]*

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Abstract: The authors use this letter to highlight some aspects of neutrino emission from core-collapse supernovae that need development, as well as key-points related to neutrino physics that may be explored in the detection of the next galactic supernova.

Flavor Conversion in Supernovae

Understand the neutrino flavor conversion mechanism and propagation inside a supernova is necessary to predict and extract information from the signal detected from galactic supernova and DSNB. However, our understanding of this mechanism is not established yet, mostly due to the effects of neutrino-neutrino SM interactions. In high-density neutrinos environment, such as in supernovae, these interactions could lead to a neutrino evolution difficult to solve, where the Hamiltonian depends on the neutrino density matrix, i.e., it depends on the state of the neutrinos in the environment, making the problem non-linear. Different from the common matter MSW effect[1;2], the neutrino-neutrino interaction contributes with off-diagonal elements, as point out by J. Pantaleone[3;4]. Furthermore, it depends on the neutrino interaction angle, which may play an important role in a non-isotropic neutrino environment, such as in supernovae. Although there are no exact solutions to the problem, it is possible to find numerical solutions and solutions to simplified evolution equations[5;6], e.g., imposing symmetries (Bulb Model), which show that collective effects may arise in a supernova environment. Some of these effects are listed below, where most of them realized in the two neutrino families scenario and using simplified toy models.[1]

-**Synchronized Oscillations**: It is the regime where all neutrinos modes oscillate with the same frequency. In the polarization vector picture, this is represented by all neutrinos vectors coupled to the sum of them, which then oscillates around the Hamiltonian polarization vector (slow-oscillations)[9;10]. This synchronized regime may occur at high neutrino densities and with high flux hierarchy among the flavors so that the total polarization vector has a significant strength. In supernovae, this regime is believed to dominate near the proto-neutron star (PNS), where the neutrino density is high enough[11].

-**Bipolar Oscillations**: When the neutrino system is composed of two opposite polarization vectors, e.g., neutrino-antineutrino, they form a bipolar system. As the neutrino density decreases, the total polarization vector tends to align with the Hamiltonian polarization vector. This may lead to a total flavor $\nu_e\bar{\nu}_e \rightarrow \nu_x\bar{\nu}_x$ conversion for IH and none for NH[10;11]. In analogy to a gyroscope precession, the NH represents the stable initial position pointing downwards, and the IH represents the unstable initial position pointing upwards. In supernovae, this regime is believed to dominate right above the synchronized region, where the neutrino density became smaller[11].

-**Spectral Swap and Split**: As a consequence of bipolar pair conversion, there may be spectral swaps among the flavors depending on the mass hierarchy. Moreover, one characteristic of the evolution is the conservation of flavor asymmetry, so that partial swap occurs in one of the neutrinos type, normally the neutrino, due to the flux hierarchy[8]. This partial swap would appear as a characteristic split in the neutrino spectrum, which would be a signature of collective neutrino oscillations in the detection. Although this behavior is related to bipolar oscillations, when considering more general situations, such as multi-angle effects and three neutrino families, there may be multiple spectral swaps for both neutrino mass hierarchies (See[8] Sec. 4.7).

Although the effort, the field is still under development, with several open questions and new phenomena appearing during the years. As many neutrino detectors (DUNE, Super-Kamiokande, JUNO) have in their program the possible detection of galactic supernova neutrinos and DSNB, it is necessary to understand the process of neutrino flavor conversion from its emission to its detection. That is necessary not just to explore neutrino physics but also to explore the supernova explosion mechanisms and its results, such as elements production. Therefore, we see as necessary the study of neutrino evolution containing neutrino-neutrino interactions as part of the program to detect supernova neutrinos.

[1] See[7;8] for reviews.

Neutrino Properties from Supernovae

The detection of supernova neutrinos can bring information about neutrino properties. Although the mechanism of flavor evolution still in development, due to the collective (self-induced) effects complications, there are some ways around this problem. One way to explore neutrino properties without worrying about the collective effects is to use the neutronization peak/burst. Due to the large excess of ν_e compared to other flavors, the collective effects are not present (suppressed, and the only active flavor conversion mechanism is the well-known MSW effect[8]. The last one is sensible to mass hierarchy, where ν_e will reach Earth as ν_2 for NH and as ν_3 for IH. Therefore, a ν_e suppression at the detector would indicate NH, and its detection would indicate IH[8;12;13]. However, it has been shown that[14] BSM neutrino decay could mimic this behavior. Another feature sensible to the mass hierarchy is the spectrum swap, although it is dependent on our understanding of the flavor conversion mechanism.

The supernova neutrino detection can also be used to impose limits on the neutrino absolute mass. The inertia from non-zero mass leads to a time delay compared to massless particles, which would be significant in the distance scales of supernovae. In a model-independent way, this delay needs to be less or equal to the total detection time, which imposes a limit in the neutrino mass ([15] Sec. 15.5). However, using some model for the neutrino signal, it is possible to impose stronger limits, as already shown for the SN1987A[16].

Therefore, we conclude that the field of supernova neutrinos still rich in the capability of exploring neutrino properties, even without a final answer in the topic of collective effects. For example, using the neutronization burst. However, to extract information from future galactic supernova detection, it still necessary to develop our knowledge on the topic.

Decoherence

The treatment of the evolution of a quantum subsystem in contact to the environment is an invitation to quantum dynamical semigroups and can be approached through open quantum systems formalism[17–19]. This extension of quantum mechanics has the neutrino physics as an obvious source of investigation[20]. The effects of this treatment is expected to lead a loss of coherence and consequent impact on the neutrino mixing in different sources. Several analysis in order to include limits on this phenomena were made for atmospheric[21], accelerator[22;23] and solar[24–26] neutrinos.

In different astrophysical sources such as the solar one, neutrinos are created as a complete incoherent admixture of mass eigenstates, nevertheless in the open system formalism, a relaxation effect could change neutrino mixing[26]. Supernova neutrinos is another important source in which the impact of this phenomena could emerge. However the inclusion of such effects in the complex combination of several already cited features in neutrino emission and evolution in this source, generates a very challenging framework and we see as an open question that needs to be investigated.

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