Research Statement

Research Interests

My primary research interests are in neutrino astrophysics. I have focused most of my work on the role of neutrinos in core-collapse supernovae (CCSNe), working with neutrino transport and neutrino flavor transformation in this environment. My most significant work has been to self-consistently couple neutrino oscillations into the classical neutrino transport model in a computationally efficient manner.

I am also interested in exploring other areas of neutrino astrophysics. Neutron star mergers (NSMs) and other compact object collision events are another very interesting environment where neutrinos play a significant role, and where my experience with supernovae simulations would be directly applicable. Understanding the neutrino signal from a CCSN or NSM could allow us to gather vital information on the nuclear equation of state within these environments. Neutrino Oscillations also provide an excellent mechanism to search for physics beyond the standard model, with any such interactions having potential effects on the resulting flavor composition of the neutrinos.

Research Projects

Nonstandard Neutrino Interactions

In one of my first research projects as a Ph.D. student, My collaborators and I sought to examine how the presence of physics beyond the standard model (BSM) may impact the neutrino flavor composition in the core of a CCSN. The non-linear effects of the neutrino-neutrino interaction present in extreme environments like CCSN can amplify any small perturbation that BSM physics might produce. Our goal was to observe how significant a change in the neutrino flavor composition the presence of an NSI of various strengths could have, and how deep within the core such flavor transformation might occur.

By applying constraints from solar neutrino observations, as well as a few simplifying assumptins, I reduced our generalized NSI model from nine free parameters down to just two. I then wrote and ran a code to calculate the neutrino flavor transformation for hundreds of combinations of these two NSI parameters. I then analyzed the output of these runs to determine what flavor mixing effects we observed as well as how the NSI caused this behavior.

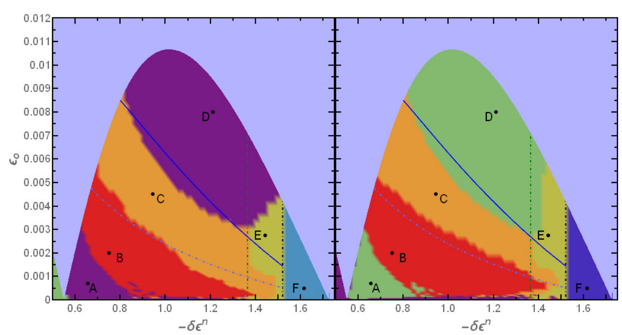

Figure 1: NSI Parameter Space from Stapleford, et. al. (2016). We categorize the NSI parameter space according to the oscillations that occur in the Normal Hierarchy (left) and Inverted Hierarchy (right). The labeled points correspond to specific examples from the paper.

The results from this analysis were published in Stapeford, et. al. (2016), and are summarized in figure 1 from that paper. The NSI parameter space was divided into regions based on the flavor transformation that was occurred. The principle change that spawned most of the observed phenomena was the presence of an MSW-like conversion known as the I-resonance which is entirely a result of the NSI. This resonance drives flavor conversion within a few 10's of km from the neutrinosphere. This flavor transformation then causes additional effects such as the appearance of the collective (bipolar) instability in the normal hierarchy instead of the inverted hierarchy (purple/green), the presence of the matter-neutrino resonance (red/orange), and more complicated chaotic behaviors at large values of $\delta\epsilon^n$.

The findings we presented have potentially significant implications for CCSNe. The change in flavor composition will directly affect the observed neutrino signal at earth, and potentially provide new constraints on BSM physics.

Additionally, this mixing of neutrino flavors from so close to the surface of the proto-neutron star would affect both the neutrino heating which depends primarily on the electron flavor (anti)neutrinos, as well as the proton-neutron ratio of the ejected material, which will change the yields of various isotopes made during the explosive nucleosynthesis.

Hybrid (Classical-Quantum) Neutrino Transport

The main focus of my Ph.D. work was to develop a method to self-consistently apply neutrino oscillations with classical neutrino radiation transport. Modern simulations of CCSNe treat the neutrino as a classical particle with definite mass and flavor. This simplifying assumption allows neutrino transport in these simulations to be done using the classical Boltzmann equation. The existence of neutrino flavor mixing has been well established, and recent work with 'fast flavor' collective oscillations and NSI induced resonances have directly challenged the assumption of flavor conservation in CCSNe. To completely incorporate the quantum nature of the neutrino into neutrino transport would require solving the quantum kinetic equations (QKEs); however, this exceeds the current computational abilities for 3D simulations which already require $\sim$millions of CPU hours on advanced supercomputer systems.

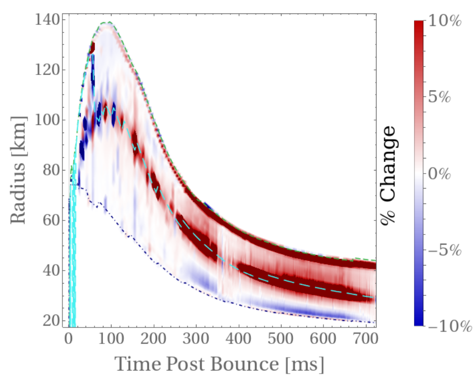

Figure 2: The percent change in the net neutrino heating rate due to neutrino oscillations from Stapleford et. al. (2019).

My goal was the develop a computationally efficient method to couple neutrino oscillations with classical transport to self-consistently examine the feedback between flavor mixing and supernova dynamics. To achieve this I combined the 1D supernova hydrodynamics and neutrino transport code `Agile-BOLTZTRAN`, written in Fortran, with `SQA` a free-streaming neutrino flavor oscillation code, written in C++. The use of a 1D supernova code was necessary to reduce the complexity of the supernova problem and allow for the addition of the oscillation calculations. The computational challenge of combining these codes written in different languages was the different domains and resolutions they required. For instance, the oscillation calculation was only relevant over a small portion of the supernova spatial domain, but required significantly greater energy resolution compared to the neutrino transport.

The hybrid classical-quantum transport method was implemented by introducing an oscillation source term (OST) within the transport equations. Oscillations are treated as an effective emissivity/opacity with the emission in one flavor linked to the absorption in another to conserve neutrino number. Neutrino oscillations are periodically updated by supplying the current hydro and neutrino states to `SQA`. The neutrino transition probabilities are then used to determine the effective oscillation opacity used by `BOLTZTRAN` for the next time steps. Unlike other methods, the OST allows the neutrino distribution function and hydrodynamics to self-consistently evolve toward a solution that includes flavor mixing. The OST is also consistent with the QKEs which also adds a neutrino flavor mixing term to the collision terms. This consistency will allow for direct comparison between these methods when full QKE calculations become computationally feasible.

As a first test for this new method we considered the effects of standard oscillation phenomenon (no inclusion of NSI or 'fast-flavor' oscillations) on a supernova explosion. These results were published in Stapleford, et. al. (2019), with figure 2 showing the percent change in the net neutrino heating rate due to neutrino oscillations compared to classical Boltzmann transport. While the effects immediately after bounce are small, starting at around 300 ms post bounce we see that neutrino oscillations produce an overall increase in heating of $\sim$4%. While this additional heating was insufficient to overcome the difficulties of exploding supernovae in 1D, this could be much more significant in multi-D where neutrino heating is amplified non-linearly due turbulence and other hydrodynamic effects.

As a postdoc I have continued working on this hybrid transport. While the 'standard' oscillation scenario presented in my second paper had a negligible effect consistent with previous literature, we now seek to revisit the oscillation phenomenon that may occur deep within CCSNe such as NSI resonances and 'fast-flavor' oscillations. By implementing a large transition probability into our OST close to the PNS surface, we will simulate the effects of these transitions, and examine their potential effects on supernovae.

High Performance Computing

As a postdoc I have focused on high performance computing in astrophysical simulations. My primary project has been to contribute to the development of `Flash-X` as part of the Exascale Computing Project: ExaStar. I was responsible for using my experience and expertise with the `BOLTZTRAN` code to test and validate the neutrino transport module of `Flash-X` and `Weaklib`, a library of weak physics interactions. I would coordinate runs of the two codes for identical scenarios and compare the simulation results of the new code with the well established and reliable `BOLTZTRAN` output to ensure consistent and accurate results for the new code.

My secondary project has been upgrading the `Agile-BOLTZTRAN` code to prepare for releasing an open-source version. I have gained significant insight, understanding, and experience into programming for high performance computing. During this project I have utilized various methods for code optimization, shared memory parallelism with OpenMP, and distributed memory parallelism with MPI. This work has already yielded seen significant improvement in code performance, and we are considering the benefits of further improvement by utilizing GPU acceleration.

Future Research

Astrophysical events such as core-collapse supernovae and compact object mergers remain one of the most interesting challenges in computational and nuclear astrophysics. The role of neutrinos in these environments is well established, but still not fully understood. The hybrid transport method I developed has opened the door to better understanding the interactions in the decoupling region where neutrinos transition from being optically trapped to free-streaming. Understanding the neutrino physics in this region will be essential for understanding the dynamics and ejecta from these high energy events.