The Neutrino: A Better Understanding Through Astrophysics

Final Report

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I Accomplishments

The field of neutrino physics is poised to make great advances in the coming years as a new generation of terrestrial neutrino experiments come online designed to answer such fundamental questions as the Dirac or Majorana nature of this fundamental particle, determine if there is CP violation, and much more. Theory support of these experiments is vital if they are to optimize their scientific potential. There exists a ready audience for the results of these experiments among astrophysicists who need to know the properties of the neutrino if they are to understand multiple astrophysical phenomena such as supernovae, the mergers of compact objects, and the early Universe. But the flow of information about neutrinos is not one way from experimentalists to astrophysicists: there exist environments in the cosmos where the conditions are beyond the reach of any terrestrial experiment allowing us to probe the properties of the neutrino at the extremes of density, temperature, magnetic fields etc. Indeed, astrophysical neutrinos have historically often provided the first indications of new, uncharted, physics such as new flavors and neutrino oscillations. Astrophysical neutrinos also can act as messenger particles from such systems carrying information about the conditions that produced them. The overarching goal of the research funded by this award was to exploit this potential of astrophysics as a probe of neutrino properties and neutrinos as astrophysical messengers. The original proposal set out a number of goals that were grouped into five main areas:

- to construct new theoretical approaches to the problem of neutrino propagation in media including where neutrino-neutrino interactions are important,
- to pioneer the use of new approaches, including super-scattering operators, for the evolution of neutrino thermal and statistical ensembles
- to implement these new approaches in computer codes to study neutrino evolution in supernovae and other hot, dense environments,
- to increase the realism of simulated signals of a Galactic supernovae neutrino burst in current and future neutrino detectors,
- to study the simulated signals to determine the ability to extract information on the missing neutrino mixing parameters and the dynamics of the supernova explosion.

As the projects progressed it was decided to add to this list

- to study sterile neutrinos and non-standard interactions of neutrinos in supernova and their effect upon the signal.

Accomplishments were made in all areas. Below is a description of the various projects undertaken by the P.I. and his group.

New theoretical approaches to the problem of neutrino propagation

The major focus of any project computing supernova or compact object neutrino signals is to determine how the neutrinos propagate through the hot, dense environment. The general problem is to solve for the evolution in time of an arbitrary N flavor neutrino created at some initial time t_1 in an arbitrary state - represented by a column vector - which has been decomposed into a sum of the N states of some basis (X). The neutrino evolves to time t_2 and at which we point we decompose the state in terms of the N states of a possibly different basis (Y). The evolution from t_1 to t_2 is described by a matrix $S^{(YX)}(t_2, t_1)$ and the transition probabilities are the set of probabilities that the system in a given initial state x of (X) at t_1 is detected in the state y of (Y) at t_2. These transition probabilities are denoted by $P_{yx}^{(YX)}(t_2, t_1)$ and are related to the elements of $S^{(YX)}$ by $P_{yx}^{(YX)} = |S_{yx}^{(YX)}|^2$. In most cases the bases (X) and (Y) are the same but there are circumstances - supernovae and compact object mergers being an example - where knowing the evolution from one basis to a different basis is useful. In some generic basis (Z) the evolution matrix $S^{(ZZ)}$ can be found by solving the Schrodinger equation

$$\imath \frac{dS^{(ZZ)}}{dt} = H^{(Z)}\, S^{(ZZ)} \tag{1}$$

where $H^{(Z)}$ is the Hamiltonian in the basis (Z). In a hot dense environment the Hamiltonian $H^{(Z)}$ will be composed of several terms including: a) the vacuum contribution, b) the effect of matter [5; 6] and c) neutrino-neutrino self interaction [1; 2]. In the past the P.I. has focused a great deal of attention upon the case of the effect of matter otherwise known as the Mikheyev-Smirnov-Wolfenstein (MSW) effect. The first major goal of the proposal was to construct new theoretical tools which could be used to more efficiently to compute neutrino evolution when other terms in the Hamiltonian were present.

Self-Interaction

The first project in this vein was neutrino evolution including neutrino collective effects in order to a) move the theoretical understanding of the phenomenon out of the flavor basis where it was stuck, and b) to use the new insights into the problem one gains from the view-point of other bases to improve the efficiency of the calculations. The difficulties of moving away from the flavor basis where the problem of collective effects was first transcribed were solved by the P.I. and collaborators Cristina Volpe (IPN Orsay) and Sebastien Galais (IPN Orsay). This work is published as 'The neutrino-neutrino interaction effects in supernovae: the point of view from the matter basis', Galais, Kneller & Volpe, Journal of Physics G **39**, 035201 (2012). The major accomplishments of that work appear in the first half of the paper where a number of analytical results were presented. It was shown a) how to efficiently compute the elements of the unitary matrix U that diagonalizes an arbitrary Hamiltonian H once the eigenvalues have been computed, b) that the evolution of the eigenvalues could be written in terms of the elements of U and the derivatives of H, and c) how to obtain the elements of the Hamiltonian in what is known as the 'matter' basis also known as the 'instantaneous eigenstate' basis. These results were then combined to define the generalizations of the diabaticity parameters that had been previously introduced by the P.I. and Gail McLaughlin [4]. The work is significant and useful because it is valid for arbitrary Hamiltonians and arbitrary number of flavors. The results from this project were exploited in many later projects.

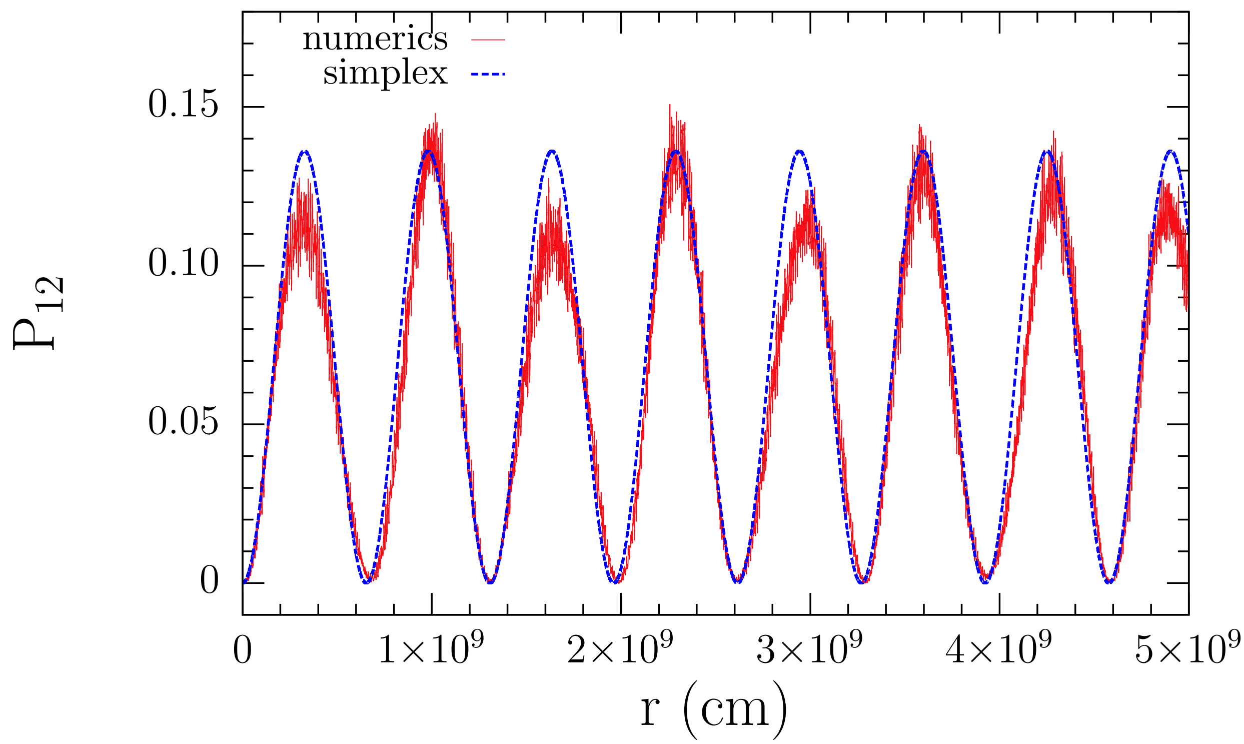

Figure 1: The agreement between numerical and analytic (labeled 'simplex') solutions for the effect of turbulence upon the neutrino transition probability P_{12}. This figure is taken from Patton, Kneller & McLaughlin, Phys. Rev. D, **89**, 073022 (2014).

Applying time-dependent perturbation theory approach to neutrino oscillations

The next problem tackled was in collaboration with Gail McLaughlin (NC State) and Kelly Patton (NC State) on the effect of sinusoidal density profiles upon neutrinos. The paper describing this work is 'Stimulated neutrino transformation in supernovae', Kneller, McLaughlin & Patton, Journal of Physics G, **40**, 055002 (2013). In that paper the P.I. and collaborators reframed the problem of neutrino propagation through the sinusoidal profile as propagation through some smooth, non-oscillatory profile and then the effect of the oscillatory component was recast as a perturbation. They showed the external, time-dependent perturbing potential acting upon the neutrino can lead to transitions between its eigenstates which oscillate in time and, using the Rotating Wave Approximation (RWA), a solution was found which very closely matched the numerical results even when the effect of the perturbation was large.

The P.I., Gail McLaughlin and Kelly Patton then generalized the approach to tackle the problem of density profiles built from multiple sinusoidal components. This allowed them to consider the case of neutrino propagation through turbulence which is regarded as a major unsolved problem in supernova neutrinos. The paper detailing this project is 'Stimulated neutrino transformation through turbulence', Patton, Kneller, and McLaughlin, Phys. Rev. D, **89**, 073022 (2014). In that paper a number of analytical results are presented and their validity was tested against numerical solutions. The paper contains two surprising results. First, even though the Hamiltonian governing the neutrino evolution was aperiodic, it was found the transition probability P between the neutrino states evolved quasi-sinusoidally, i.e. as $P \sim \sin^2(Qr)$ with Q a wavenumber and r distance. This result is shown in figure (1) which compares the analytical RWA solution with the numerical solution for the transition probability of a neutrino propagating through turbulence. The expression for the wavenumber Q was dominated by whichever sinusoidal mode in the perturbation matched the splitting between the eigenvalues of the unperturbed Hamiltonian, i.e. whichever mode was closest to resonance, but also involved a contribution from every other mode. The second surprise was that it was possible for the non-resonant modes to overwhelm the resonant one and suppress the transitions between the neutrinos states.

Most recently the P.I., a graduate student Yue Yang (NC State) and an undergraduate Kennedy Perkins (NC State), revisited this approach to neutrino evolution further generalizing the theory to arbitrary number of eigenstates of the system and arbitrary structure of the perturbing Hamiltonian, the number of Fourier modes, their amplitude and their wavenumbers. They found new terms appear in the results indicating new avenues by which the frequencies and amplitudes of the modes may affect the transition probabilities. Then they considered two applications of the theory to neutrino flavor transformation through matter. The first is the effect of two sinusoidal density fluctuations upon a three flavor neutrino where they found the phenomenon of Induced Transparency and a new effect they called Restored Opacity. The new effect of Restored Opacity has an analytical explanation very similar to Induced Transparency even though the effect appears to be the complete opposite. The second test case they considered is the case of a mono-energetic, neutrino self-interaction Hamiltonian with constant coupling. They demonstrated how the analytic solutions are able to match the amplitude and wavenumber of the numerical results to within a few percent. A paper 'Stimulated transitions due to arbitrary, Fourier decomposed, perturbing Hamiltonians', Yang, Kneller, & Perkins, arXiv:1510.01998, describing these results has been submitted to Physical Review D.

Implement new approaches to neutrino propagation

The second major goal of the proposal was to take the theoretical tools developed by the P.I. and his team and implement them into codes that could be used to study neutrino evolution in supernovae and above compact object merger disks.

The results found in Galais, Kneller & Volpe were used by P.I. to build codes for both two and three neutrino flavors that included neutrino self-interaction. It was quickly realized that there was a significant stumbling block to their implantation that had to be overcome first: to make the calculation efficient the codes aim to solve for the S matrix in the instantaneous eigenstate basis. In order to do that the Hamiltonian H in the flavor basis has to be found first and this Hamiltonian can only be computed if the matrix U which relates the matter and flavor basis is known. But in order to compute the matrix U it is necessary to already know H thus the logic of how to go about the computation involves a circular argument that has to be broken. One possible solution is to evolve H and S simultaneously so that H is always known when needed. This solution was attempted by the P.I. however, it was found that the solution for H suffers from instabilities that could not be cured and so the project was put on hold until better ideas were found. These emerged from the separate work of the P.I. in collaboration with Gail McLaughlin and Kelly Patton described above. The P.I. realized the neutrino collective effects could also be treated as a perturbation and that by doing so the circular logic problem previously identified could be bypassed. A collective effects code adopting the new approach was written and was found to be stable. The increase in efficiency of the new code is dramatic: a speed up of a factor between 50 and 100 compared to pure flavor basis codes was typical. This new code formed the foundation of multiple projects completed during the lifetime of the proposal.

Neutrino flavor transformation above accretion disks

The first project to use the new code was a study of the neutrino flavor evolution above accretion disks. This project was undertaken by the P.I. in collaboration with a postdoc Annie Malkus (NC State), Gail McLaughlin, and Rebecca Surman (Notre Dame). Black hole accretion disks can form through the collapse of rotating massive stars and these disks produce large numbers of neutrinos and antineutrinos of electron flavor that can influence energetics and nucleosynthesis. Neutrinos are produced in sufficient numbers that, after they are emitted, they can undergo flavor transformation facilitated by the neutrino self interaction. In this project it was shown that some of the neutrino flavor transformation phenomenology for accretion disks is similar to that of the supernova case, but also, it was found that the disk geometry lends itself to new transformation behaviors that were later called Matter Neutrino Resonances (MNR). Two types of MNR were found and these transformations strongly influence the nucleosynthetic outcome of disk winds. The paper describing this work is 'Neutrino oscillations above black hole accretion disks: disks with electron-flavor emission', Malkus, Kneller, McLaughlin and Surman, Phys. Rev. D, **86**, 085015 (2012).

The effect of turbulence upon neutrinos

A second set of projects looked at the effect of turbulence upon neutrinos in supernovae. The first paper in this set is 'Consequences of large θ_{13} for the turbulence signatures in supernova neutrinos', Kneller and Mauney, Phys. Rev. D, **88**, 025004 (2013). The transition probabilities for a single neutrino emitted from a point proto-neutron source after passage through a turbulent supernova density profile had been found to be random variates drawn from parent distributions whose properties depend upon the stage of the explosion, the neutrino energy and mixing parameters, the observed channel, and the properties of the turbulence such as the amplitude $C_\star$. In this project the P.I. and Alex Mauney (NC State) examined the consequences of the recently measured mixing angle θ_{13} upon the neutrino flavor transformation in supernova when passing through turbulence, in order to provide some clarity as to what one should expect in the way of turbulence effects in the next supernova neutrino burst signal. The P.I. and Mauney found that the measurements of a relatively large value of θ_{13} means the neutrinos are relatively immune to small, $C_\star \lesssim 1\%$, amplitude turbulence but as $C_\star$ increases the turbulence effects grow rapidly and spread to all mixing channels. For $C_\star \gtrsim 10\%$ the turbulence effects in the high density resonance mixing channels are independent of θ_{13} but nonresonant mixing channels are more sensitive to turbulence when θ_{13} is large.

The transition probabilities describing the evolution of a neutrino with a given energy along some ray through a turbulent supernova profile are random variates unique to each ray. If the proto-neutron-star source of the neutrinos were a point, then one might expect the evolution of the turbulence would cause the flavor composition of the neutrinos at Earth to vary in time i.e. the flavor would scintillate. But in reality the proto-neutron star is not a point source - it has a size of order $\sim$10 km - so the neutrinos emitted from different points at the source will each have seen different turbulence. The finite source size will reduce the correlation of the flavor transition probabilities at Earth and reduce the magnitude of the flavor scintillation. This same argument about the presence or absence of scintillation in an observation is used often by astronomers to obtain rough estimates for the size of an astrophysical source. To determine whether the finite size of the proto-neutron star will preclude flavor scintillation, the P.I. and Alex Mauney calculated the correlation of the neutrino flavor transition probabilities through turbulent supernova profiles as a function of the separation δx between the emission points. The correlation will depend upon the power spectrum used for the turbulence, and they considered two cases: when the power spectrum is isotropic, and the more realistic case of a power spectrum which is anisotropic on large scales and isotropic on small. Although it is dependent on a number of uncalibrated parameters, they showed the supernova neutrino source is not of sufficient size to significantly blur flavor scintillation in all mixing channels when using an isotropic spectrum, and this same result holds when using an anisotropic spectrum, except when they greatly reduced the similarity of the turbulence along parallel trajectories separated by $\sim$10 km or less. This project is published as 'Does The Finite Size of the Proto-Neutron Star Preclude Supernova Neutrino Flavor Scintillation Due to Turbulence?', Kneller and Mauney, Phys. Rev. D, **88**, 045020 (2013)

The P.I. Kelly Patton and Gail McLaughlin also looked at turbulence in supernovae using the model of stimulated neutrino transitions they developed and described above. This work is published in 'Stimulated neutrino transformation through turbulence on a changing density profile and application to supernovae', Patton, Kneller, and McLaughlin, Phys. Rev. D, **91**, 025001 (2015). In that paper the P.I. Patton and McLaughlin described a method to predict the location of large amplitude transitions and demonstrate the effectiveness of this method by comparing to numerical calculations using a model supernova (SN) profile. The important wavelength scales of turbulence, both those that stimulate neutrino transformations and those that suppress them, were presented and then they examined the effects of changing the parameters of the turbulent spectrum, specifically the root-mean-square amplitude and cutoff wavelength, and showed how the stimulated transitions model offers an explanation for the increase in both the amplitude and number of transitions with large amplitude turbulence, as well as a suppression or absence of transitions for long cutoff wavelengths. The method was also found to predict the location of transitions between antineutrino states which, in the normal hierarchy they used, will not undergo Mikheev-Smirnov-Wolfenstein transitions. Finally, the stimulated neutrino transitions method was applied to a turbulent 2D supernova simulation and explained the minimal observed effect on neutrino oscillations in the simulation as being due to excessive long wavelength modes suppressing transitions and the absence of modes that fulfill the parametric resonance condition.

Finally, the P.I. and Neel Kabadi (NC State) considered how the turbulence effect upon supernova neutrinos, and the correlation between pairs of neutrinos, exhibited sensitivity to the power spectrum of the turbulence. An analysis of the turbulence in a two-dimensional hydrodynamical simulation of a core-collapse supernova that was published around this time had indicated the power spectrum may not be the Kolmogorov 5 /3 inverse power law as had been previously assumed. In this project the P.I. and Kabadi studied the effect of non-Kolmogorov turbulence power spectra upon neutrinos from a point source as a function of neutrino energy and turbulence amplitude at a fixed postbounce epoch. The P.I. and Kabadi found the two effects of turbulence upon the neutrinos - the distorted phase effect and the stimulated transitions - both possess strong and weak limits in which dependence upon the power spectrum is absent or evident, respectively. Since neutrinos of a given energy will exhibit these two effects at different epochs of the supernova each with evolving strength, the P.I. and Kabadi found there is sensitivity to the power spectrum present in the neutrino burst signal from a Galactic supernova. This work is published as 'Supernova neutrinos and the turbulence power spectrum: point source statistics', Kneller and Kabadi, Phys. Rev. D **92**, 013009 (2015)

Neutrino Signals From Supernovae

Another major plank of the proposal was to construct neutrino signals from Galactic supernovae in order to determine how the various transformation effects manifested themselves in the neutrino flux at Earth, the sensitivity of various current and next-generation detectors to these features, and how one might go about extracting the information in the signal that could determine both neutrino properties and supernova dynamics.

Core-Collapse

In order to decode the neutrino burst signal from a Galactic core-collapse supernova (ccSN) and reveal the complicated inner workings of the explosion we need a thorough understanding of the neutrino flavor evolution from the proto-neutron star outwards. The flavor content of the signal evolves due to several effects which can lead to a highly interesting interplay and distinctive spectral features. A postdoc Tina Lund (NC State) and the P.I. investigated the supernova neutrino flavor evolution in three different progenitors and included collective flavor effects, the evolution of the Mikheyev, Smirnov & Wolfenstein conversion due to the shock wave passage through the star, and the impact of turbulence. They considered both normal and inverted neutrino mass hierarchies and used a value of θ_{13} close to the current experimental measurements. In the Oxygen-Neon-Magnesium (ONeMg) supernova they found that the impact of turbulence is both brief and slight during a window of 1-2 seconds post bounce. This is because the shock races through the star extremely quickly and the turbulence amplitude is expected to be small, less than 10%, since these stars do not require multidimensional physics to explode. Thus the spectral features of collective and shock effects in the neutrino signals from Oxygen-Neon-Magnesium supernovae may be almost turbulence free making them the easiest to interpret. For the more massive progenitors they again found that small amplitude turbulence, up to 10%, leads to a minimal modification of the signal, and the emerging neutrino spectra retain both collective and MSW features. However, when larger amounts of turbulence was added, 30% and 50%, which was justified by the requirement of multidimensional physics in order to make these stars explode, the features of collective and shock wave effects in the high (H) density resonance channel are almost completely obscured at late times but, simultaneously, they observed other mixing channels - such as the low (L) density resonance channel and the nonresonant channels - began to develop turbulence signatures. Large amplitude turbulent motions in the outer layers of more massive, iron core-collapse supernovae may obscure the most obvious fingerprints of collective and shock wave effects in the neutrino signal but cannot remove them completely, and additionally bring about new features in the signal. The long paper describing these results is 'Combining collective, MSW, and turbulence effects in supernova neutrino flavor evolution', Lund and Kneller, Phys. Rev. D, **88**, 023008 (2013) and the numerical results have been passed to the DUNE, HALO and HyperK collaborations to be used to simulate a supernova burst event.

In addition, Tina Lund collaborated with Georg Raffelt (MPI Germany), Thomas Janka (MPA Germany), Ewald Müller (MPA Germany) and Annop Wongwathanarat (MPA Germany), on the observability in the IceCube detector of predicted neutrino signals from hydrodynamical supernova simulations made by the Garching group. The paper containing their results is 'Fast time variations of supernova neutrino signals from 3-dimensional models', Lund, Wongwathanarat, Janka, Müller, & Raffelt, Phys. Rev. D, **86**, 105031 (2012). The project used Fourier analysis to identify characteristic features in the supernova neutrino signal and is an extension of a previous project, which treated neutrino signals from 2D numerical supernova models, to investigate the neutrino signals from recent 3D numerical models. For 2D models the imprint of the Standing Accretion Shock Instability (SASI) on the neutrino flux was easily identified. The SASI is significantly weaker in 3D and thus the characteristic features in the neutrino signal are now observable only with at supernova at a much shorter distance.

Thermonuclear Supernovae

It has long been recognized that the neutrinos detected from the next core-collapse supernova in the Galaxy have the potential to reveal important information about the dynamics of the explosion and the nucleosynthesis conditions as well as allowing us to probe the properties of the neutrino itself. The neutrinos emitted from thermonuclear - Type Ia - supernovae also possess the same potential, although these supernovae are dimmer neutrino sources. In a paper published by Physical Review D, postdoc Warren Wright (NC State), the P. I., Gautam Nagaraj (NC State), Kate Scholberg (Duke) and Ivo Seitenzahl (ANU Australia) calculated the time, energy, line of sight and neutrino-flavor-dependent features of the neutrino signal expected from a three-dimensional delayed-detonation explosion simulation, where a deflagration-to-detonation transition (DDT) triggers the complete disruption of a near-Chandrasekhar mass carbon-oxygen white dwarf. They calculated the neutrino flavor evolution along eight lines of sight through the simulation as a function of time and energy using the transformation code built at NC State and identified a characteristic spectral peak at ~ 10 MeV as a signature of electron captures on copper. This peak is a potentially distinguishing feature of explosion models since it reflects the nucleosynthesis conditions early in the explosion. They then went on to simulate the event rates in the Super-K, Hyper-K,

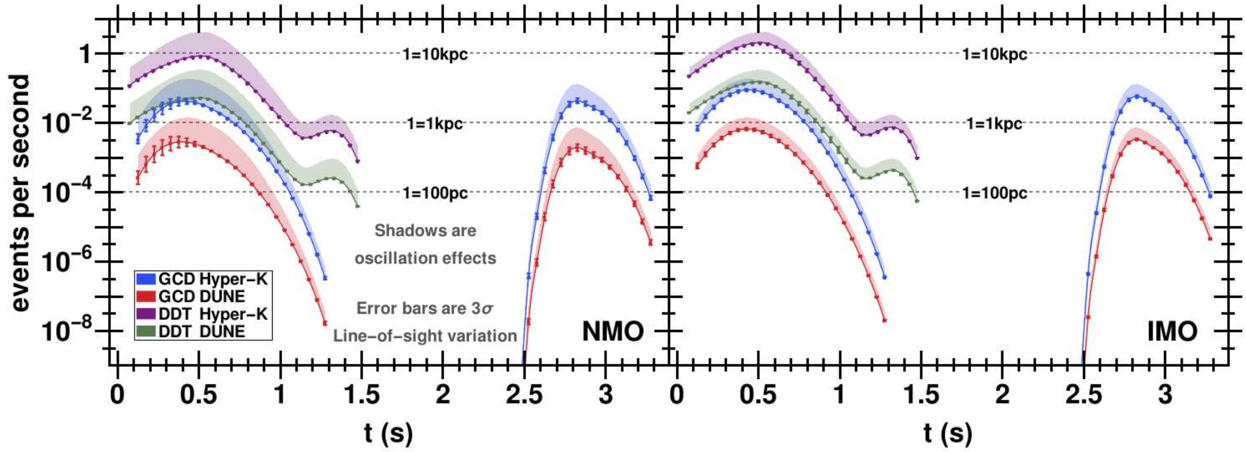

Figure 2: The time evolution of the event rate in Hyper-K and DUNE for DDT and GCD simulations of a SN Ia at 10 kpc taken from Wright *et al.* arXiv:1609.07403. The shaded regions represent the effects of neutrino oscillation such that the top of each shadowed region represents the associated un-oscillated event rate. The lines represent the mean event rate across all neutrino trajectories considered. Similarly, the error bars represent the 3σ deviation due to line-of-sight variations in the event rates. The left (right) plot is for normal (inverted) mass ordering. The horizontal lines show how the event rate would change if the supernova occurred at a closer distance.

JUNO, and DUNE neutrino detectors with the SNOwGLoBES event rate calculation software - which had input from the P.I. - and also computed the IceCube signal. They found Hyper-K will be able to detect neutrinos from the model out to a distance of $\sim$ 10 kpc. At 1 kpc, IceCube, JUNO, Super-K, and DUNE would register a few and Hyper-K several tens of events. This project represents a huge leap in the sophistication of the simulation of neutrino signals from thermonuclear supernovae. The long paper describing this project can be found in Wright, Nagaraj, Kneller, Scholberg, & Seitenzahl, Phys. Rev. D **94**, 025026 (2016).

More recently a similar group consisting of the P.I. postdoc Warren Wright, Sebastian Ohlmann (Heidelberg), Fritz Roepke (Heidelberg), Kate Scholberg, and Ivo Seitenzahl, tackled the case of a Gravitationally Confined Detonation (GCD) explosion scenario for a SN Ia. They showed how the flux at Earth contains features in time and energy unique to this scenario and then they calculated the expected event rates in the Super-K, Hyper-K, JUNO, DUNE, and IceCube detectors. They found both Hyper-K and IceCube would see a few events for a GCD supernova at 1 kpc or closer, while Super-K, JUNO, and DUNE would see a events if the supernova were closer than $\sim$0.3 kpc. The distance and detector criteria needed to resolve the time and spectral features arising from the explosion mechanism, neutrino production, and neutrino oscillation processes were also discussed.

The neutrino signal from the GCD was then compared with the signal from the DDT explosion model computed previously. They found the overall event rate is the most discriminating feature between the two scenarios followed by the event rate time structure. Using the event rate in the Hyper-K detector alone, the DDT can be distinguished from the GCD at 2σ if the distance to the supernova is less than 2.3 kpc for a normal mass ordering and

3.6 kpc for an inverted ordering. The most important figure from this work is shown in figure (2) where one sees the number of events in HyperK and DUNE as a function of time for the two types of explosion scenario and both neutrino mass orderings when the supernova is placed at a distance of 10 kpc. A preprint entitled 'Neutrinos from Type Ia Supernovae: The Gravitationally Confined Detonation Scenario', by Wright, Kneller, Ohlmann, Roepke, Scholberg, and Seitenzahl, is available at arXiv:1609.07403

Sterile neutrinos and non-standard interactions of neutrinos in supernova

Non-standard neutrino interactions in supernovae

Finally, Non Standard Interactions (NSI) of neutrinos with matter can significantly alter neutrino flavor evolution in supernovae with the potential to impact explosion dynamics, nucleosynthesis and the neutrino signal. In this project the P.I., collaborator Gail McLaughlin, postdoc Däavid Väänänen (NC State), graduate student Charles Stapelford (NC State) and undergraduate student Brandon Shapiro (Brandeis) explored, both numerically and analytically, the landscape of neutrino flavor transformation effects in supernovae due to NSI and found new, heretofore unseen transformation processes can occur. These new transformations can take place with NSI strengths well below current experimental limits. Within a broad swathe of NSI parameter space they observed Matter-Neutrino Resonances for supernovae neutrinos, a transformation effect previously only seen in compact object merger scenarios; in another region of the parameter space they found the NSI can induce neutrino collective effects in scenarios where none would appear with only Standard Model physics; and in a third region the NSI can lead to the disappearance of the high density Mikheyev-Smirnov-Wolfenstein resonance. Using a variety of analytical tools they were able to describe quantitatively the numerical results allowing them to partition the NSI parameter according to the transformation processes observed. The results indicate Non Standard Interactions of supernova neutrinos provide a sensitive probe of Beyond the Standard Model physics complementary to present and future terrestrial experiments. The paper describing this work is Stapleford, Väänänen, Kneller, J. P., McLaughlin, & Shapiro, (arXiv:1605.04903) and has been submitted to Physical Review D.

II Bibliography and References Cited

[1] Duan, H. and Kneller, J.P., J. Phys. G **36** 113201 (2009)

[2] Duan, H., Fuller, G. M., & Qian, Y.-Z. Annual Review of Nuclear and Particle Science **60** 569 (2010)

[3] J. P. Kneller and G. C. McLaughlin, Phys. Rev. D **73** 056003 (2006)

[4] J. P. Kneller and G. C. McLaughlin, Phys. Rev. D **80**, 053002 (2009)

[5] S. P. Mikheev and A. I. Smirnov, Nuovo Cimento C **9** 17 (1986)

[6] L. Wolfenstein, Phys. Rev. D **17** 2369 (1978)

(i) Student Training

Two graduate students at NC State have been supported through this award: Howard Whittle who is now in the fifth year of his PhD, and Yue Yang who is in the fourth year of his PhD.

Participant	**Publications**	**Preprints/ Submitted**	**Conference Proceedings**	**Other Reports**	**Invited Talks**
James P. Kneller	11	3	10	1	17
Tina Lund	2		3		8
Warren Wright	1	1			1
Yue Yang		1			
Total	12	3	10	1	26

Table 1: Publications, Proceedings, Reports, and Invited Talks

III Work to be Accomplished

At the present time the P.I., his students, postdocs and collaborators have several projects that were started during this award in various stages of completion. These projects will be carried forward supported by other funding sources. Of these projects the four closest to completion are:

- neutrino signals from pair-instability supernovae,
- the effect of sterile neutrinos in supernovae,
- the effect of turbulence during the accretion epoch of a core-collapse supernova
- the effect of supernova turbulence upon neutrino self-interactions.

At the present time another project related to neutrino signals, this time from pair-instability (PI) supernovae, is underway undertaken in collaboration with Carla Frölich (NC State) and her graduate student Matthew Gilmer (NC State). The simulation of the supernova is almost complete and once finished, snapshots will be analyzed using the same data pipeline as for the thermonuclear supernova calculations in order to generate the signal. The expected time to completion of this project is 3 months once the simulation data is available.

The project involving the P.I. and graduate student Howard Whittle (NC State) looking at the effect of sterile neutrinos in supernovae has been making slow progress. The flavor oscillation part of the code is now settled, the issues are all related to the part related to the calculation of the electron fraction. The calculations are intended to be used with supernova simulations provided by Tonias Fischer but at the present time the oscillation-free calculations are not able to reproduce the electron fraction of Fischer's simulation. It is not clear what Fischer *et al.* used for the neutron-proton weak cross sections, the values of various parameters they used, and other details. Recently it was discovered there may be an error in the algorithm used by Fischer *et al.* to compute the rates and this possibility is presently being investigated. Once settled the calculations for this project are straight forward.

A project involving the P.I. undergraduates Mithi des los Reyes (NC State) and Tia Alliy (Smith), and Hubble Fellow Evan O'Connor (NC State) is looking at the effect of turbulence during the accretion epoch of a core-collapse supernova may have upon neutrinos streaming from the proto-neutron star. It was shown by Kneller & Kabadi - described previously in this report - that turbulence can alter the neutrino flavor composition in two different ways and both effects can be understood theoretically. This theoretical understanding is being applied to the turbulence found during the accretion epoch of core-collapse supernova and then verified against numerical calculations. The project is approximately 3/4 complete with just the the numerical verification part missing. A paper describing this project is also approximately 3/4 complete. The expected time to submission is 3-6 months.

Finally, the increased efficiency of the single-angle self-interaction codes described earlier led the P.I. to write a more exact, multi-angle neutrino evolution code for supernovae. The code is efficient because it relies upon the analytic results in Galais, Kneller & Volpe where the expressions of matter mixing matrices and adiabatic Hamiltonians where generalized to arbitrary numbers of neutrinos. A graduate student Yue Yang is modifying the code to include turbulence and the goal is to study the effect of the turbulence upon the neutrino self-interactions.

(i) Publications

Bold faced indiactes individuals supported by this award.

Peer Reviewed Journals

1. 'Neutrinos from Type Ia Supernovae: The Gravitationally Confined Detonation Scenario'
   Wright, W. P., Nagaraj, G., **Kneller, J. P.**, Scholberg, K. and Seitenzahl, I. R.
   Phys. Rev. D, **94**, 025026 (2016)
   (arXiv:1605.01408)

2. 'Supernova neutrinos and the turbulence power spectrum: point source statistics'
   J. P. Kneller and N. V. Kabadi
   Phys. Rev. D, **92**, 013009 (2015)
   (arXiv:1410.5698)

3. 'Stimulated neutrino transformation through turbulence on a changing density profile and application to supernovae'
   K. Patton, **J. P. Kneller** and G. C. McLaughlin
   Phys. Rev. D, **91**, 025001 (2015)
   (arXiv:1407.7835)

4. 'Stimulated neutrino transformation through turbulence'
   K. Patton, **J. P. Kneller** and G. C. McLaughlin
   Phys. Rev. D, **89**, 073022 (2014)
   (arXiv:1310.5643)

5. 'Does The Finite Size of the Proto-Neutron Star Preclude Supernova Neutrino Flavor Scintillation Due to Turbulence?'
   J. P. Kneller and A. W. Mauney
   Phys. Rev. D, **88**, 045020 (2013)
   (arXiv:1302.6601)

6. 'Consequences of large θ_{13} for the turbulence signatures in supernova neutrinos'
   J. P. Kneller and A. W. Mauney
   Phys. Rev. D, **88**, 025004 (2013)
   (arXiv:1302.3825)

7. 'Combining collective, MSW, and turbulence effects in supernova neutrino flavor evolution'
   T. Lund and **J. P. Kneller**
   Phys. Rev. D, **88**, 023008 (2013)
   (arXiv:1304.6372)

8. 'Stimulated Neutrino Transformation with Sinusoidal Density Profiles'
   J. P. Kneller, G. C. McLaughlin and K. Patton

Journal of Physics G Nuclear Physics, **40**, 055002 (2013)
(arXiv:1202.0776)

9. 'Neutrino oscillations above black hole accretion disks: disks with electron-flavor emission'
A. C. Malkus, **J. P. Kneller**, G. C. McLaughlin and R. Surman
Phys. Rev. D, **86**, 085015 (2012)
(arXiv:1207.6648)

10. 'The neutrino-neutrino interaction effects in supernovae: the point of view from the matter basis'
S. Galais, **J. P. Kneller** and C. Volpe
J. Phys. G, **39**, 035201 (2012)
(arXiv:1102.1471)

11. 'Fast time variations of supernova neutrino signals from 3-dimensional models'
Lund, T., Wongwathanarat, A., Janka, H.-T., Müller, E. and Raffelt, G.
Phys. Rev. D, **86**, 105031 (2012)
(arXiv:1208.0043)

Papers Submitted

1. 'Neutrinos from Type Ia Supernovae: The Gravitationally Confined Detonation Scenario' **Wright, W. P.**, **Kneller, J. P.**, Ohlmann, S. T., Roepke, F. K., Scholberg, K. and Seitenzahl, I. R.
(arXiv:1609.07403)

2. 'Non-Standard Neutrino Interactions in Supernovae'
Stapleford, C. J., Väänänen, D. J., **Kneller, J. P.**, McLaughlin, G. C. and Shapiro, B. T.
(arXiv:1605.04903)

3. 'Stimulated transitions due to arbitrary, Fourier decomposed, perturbing Hamiltonians'
Yang, Y., **Kneller, J. P.** and Perkins, K. M.
(arXiv:1510.01998)

Conference Proceedings

1. 'The Physics of Supernova Neutrino Oscillations'
J. P. Kneller
Ppublished in 12TH Conference on the intersections of particle and nuclear physics: (CIPANP 2015). ed. B. Fleming & W. Haxton
(arXiv:1507.01434)

2. 'Neutrino oscillation above a black hole accretion disk'
A. Malkus, **J. P. Kneller**, G. C. McLaughlin, and R. Surman
AIP Conference Proceedings, **1663**, 050004 (2015)

3. 'Neutrino Flavor Evolution in Turbulent Supernova Matter'
T. Lund and **J. P. Kneller**
Physics Procedia, **61**, 729 (2015)

4. 'Flavor evolution of supernova neutrinos in turbulent matter'
T. Lund and **J. P. Kneller**
AIP Conference Proceedings, **1604**, 225 (2014)

5. 'Turbulence and its effects upon neutrinos'
J. P. Kneller, G. C. McLaughlin and K. Patton
American Institute of Physics Conference Series, **1604**, 204 (2014)

6. 'Stimulated neutrino transformation in supernovae'
J. P. Kneller, G. C. McLaughlin and K. Patton
11TH Conference on the intersections of particle and nuclear physics: (CIPANP 2012). ed. B. Fleming, AIP Conference Proceedings, **1560**, 176 (2013)

7. 'ν propagation in turbulent supernova matter'
T. Lund and **J. P. Kneller**
11TH Conference on the intersections of particle and nuclear physics: (CIPANP 2012). ed. B. Fleming, AIP Conference Proceedings, **1560**, 333 (2013)

8. 'νs and nucleosynthesis from accretion disks'
A. C. Malkus, **J. P. Kneller**, G. C. McLaughlin and R. Surman
11TH Conference on the intersections of particle and nuclear physics: (CIPANP 2012). ed. B. Fleming, AIP Conference Proceedings, **1560**, 336 (2013)

9. 'Turbulence and Supernova Neutrinos'
J. P. Kneller
Proceedings of the Hamburg neutrinos from supernova explosions 2011, DESY Proceedings Series, eds A. Mirizzi, P. Serpico, and G. Sigl, (2011)

10. 'The effect of turbulence upon supernova neutrinos'
J. P. Kneller
Nucl. Phys. Proc. Suppl. **217** 118 (2011)

Technical Reports

1. 'SNOwGLoBES: SuperNova Observatories with GLoBES'
A. Beck *et al.*
`http://www.tapir.caltech.edu/~cott/CGWAS2013/snowglobes_1.1.pdf`

Conferences and Workshops

1. **W. P. Wright** 'Measuring the Size of Proto-Neutron Stars Using Neutrino Intensity Interferometry'
   Invited Talk
   Neutron Stars in the Multi-Messenger Era
   Athens, OH, USA, May 26, 2016

2. **J. P. Kneller** 'The Effect Upon Neutrinos of Turbulence in Core-Collapse Supernovae During the Accretion Phase'
   Invited Talk
   Neutron Stars in the Multi-Messenger Era
   Athens, OH, USA, May 26, 2016

3. **J. P. Kneller** 'Stimulated Transitions and Self Interactions'
   Invited Talk
   Neutrino Astrophysics and Fundamental Properties
   Seattle, WA, USA, June 16, 2015

4. **J. P. Kneller** 'The Physics of Supernova Neutrinos'
   Invited Review Talk
   Twelfth Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2015)
   Vail, CO, USA, May 20, 2015

5. **J. P. Kneller** 'Sterile neutrinos and supernova turbulence'
   Invited Talk
   'Neutrinos and nucleosynthesis in hot and dense matter' DOE Topical Collaboration Meeting

   Berkeley, CA, USA, February 28, 2015

6. **T.Lund** 'Identifying emitted supernova neutrino parameters'
   Invited Talk
   'Neutrinos and nucleosynthesis in hot and dense matter' DOE Topical Collaboration Meeting
   Raleigh, NC, USA, May 1, 2014

7. **J. P. Kneller** 'Sterile neutrinos and supernova turbulence'
   Invited Talk
   'Neutrinos and nucleosynthesis in hot and dense matter' DOE Topical Collaboration Meeting
   Berkeley, CA, USA, February 28, 2015

8. **J. P. Kneller**'Neutrino signals from core-collapse supernovae'
   Invited Talk
   Multi-Messengers from Core-Collapse Supernovae (MMCOCOS) 2013 Workshop
   Fukuoka, Japan, December 3, 2013

9. **T. Lund** 'Supernova neutrinos flavor evolution and signals'
   Contributed Talk
   INFO13
   Santa Fe, NM, USA, August 28, 2013
10. **J. P. Kneller** 'TBD: Turbulence better determined'
    Invited Talk
    INFO 13
    Santa Fe NM, USA, August 28, 2013
11. **T. Lund** 'Flavor evolution of supernova neutrinos and their signals'
    Invited Talk
    CETUP* 2013
    Lead, SD, USA, July 22, 2013
12. **J. P. Kneller** 'Supernova turbulence and its effects upon neutrinos'
    Invited Talk
    CETUP* 2013
    Lead, SD, USA, July 17, 2013
13. **T. Lund** 'Neutrino flavor evolution in turbulent supernova matter'
    Invited Talk
    Fifty-One Ergs
    Raleigh, NC, USA, May 16, 2013
14. **J. P. Kneller** 'Supernova turbulence and its effects upon neutrino transition probabilities'
    Invited Talk
    New Directions in Neutrino Physics
    Aspen, CO, USA, February 4, 2013
15. **J. P. Kneller** 'Neutrino oscillations in supernova'
    Invited Talk
    'Neutrinos and nucleosynthesis in hot and dense matter' DOE Topical Collaboration Meeting
    Seattle, WA, USA, January 16, 2013
16. **T. Lund**, 'Traveling through turbulence'
    Invited Talk
    INT program 12-2a 'Core-Collapse Supernovae: Models and Observable signals'
    INT, University of Washington, Seattle, WA, USA, July 20, 2012
17. **T. Lund**, 'Neutrino Signatures of Supernova SASI'
    Invited Talk
    INT program 12-2a 'Core-Collapse Supernovae: Models and Observable signals'
    INT, University of Washington, Seattle, WA, USA, July 23, 2012

18. **T. Lund**, ‘Traveling through turbulence’
Contributed Talk
Eleventh Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2013)
CIPANP, St. Petersburg, FL, USA May 31, 2012

19. **J. P. Kneller** ‘Stimulated neutrino transformation in supernovae’
Contributed Talk
Eleventh Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2013)
St Petersburg FL, USA, May 29, 2012

20. **J. P. Kneller** ‘Stimulated neutrino transformation in supernovae’
Invited Talk
‘Neutrinos and nucleosynthesis in hot and dense matter’ DOE Topical Collaboration Meeting
San Diego CA, USA, February 17, 2012

21. **J. P. Kneller** ‘Turbulence and supernova neutrinos’
Invited Talk
HAνSE: HAmburg neutrinos from Supernova Explosions
Hamburg, Germany, July 19-23, 2011

22. **T. Lund** ‘Neutrino Signatures of Supernova SASI - now in 3D’
Contributed Talk
HAνSE: Hamburg neutrinos from Supernova Explosions
Hamburg, Germany, July 19-23, 2011

Colloquia and Seminars

1. **J. P. Kneller** ‘The physics of supernova neutrinos’
High Energy Physics Seminar
University of Virginia, Charlottesville, VA, USA, October 28, 2015

2. **J. P. Kneller** ‘The neutrino signal from the next Galactic supernova’
Physics Department Colloquium
Ohio University, Athens OH, USA, October 9, 2015

3. **J. P. Kneller** ‘The neutrino message from the next Galactic supernova’
Physics Department Colloquium
University of North Carolina at Wilmington, Wilmington, NC, USA, October 24, 2014

4. **T. Lund** ‘Supernova neutrinos flavor evolution and signals’
Astro Seminar
Aarhus University, Aarhus, Denmark, December 19, 2013.

5. **T. Lund** 'Supernova neutrinos flavor evolution and signals'
   TAPIR Seminar
   Caltech, Pasadena, CA, USA, November 15, 2013

6. **J. P. Kneller** 'Understanding the next Galactic supernova neutrino signal'
   Physics Department Colloquium
   East Carolina University, Greenville, NC, USA, October 11, 2013

7. **T. Lund**, 'Neutrino propagation through turbulent supernova matter'
   Joint HEP/Theory Seminar
   Duke University, Durham, NC, USA, November 1, 2012

8. **J. P. Kneller** 'Get the message? Understanding the next Galactic supernova neutrino signal'
   Physics Department Colloquium
   Virginia Tech University, Blacksburg, VA, USA, March 1, 2012

Posters

1. **Tina Lund** 'Neutral current events from supernova neutrinos', Neutrino 2014, Boston, MA, USA, June 2-7, 2014

2. **Tina Lund** 'Neutrino flavor evolution in turbulent supernova matter', TAUP 2013, Asilomar, CA, USA, September 8-13, 2013

IV Participants and Collaborators

In addition to the P.I. the participants at NC State University directly supported by this project are:

- Dr. Tina Lund, a postdoctoral fellow,
- Dr. Warren Wright, a postdoctoral fellow,
- Howard H. Whittle, a graduate student,
- Yue Yang, a graduate student.

The P.I. and participants in this award have collaborated significantly with many others. The list of names and current institution are:

- Dr. Gail McLaughlin, NC State University,
- Dr. Carla Frölich, NC State University,
- Dr. Rebecca Surman, Notre Dame,
- Dr. Kate Scholberg, Duke,
- Dr. Evan O'Connor, NC State University,
- Dr. Däavid Väänänen, NC State University,
- Dr. Annie Malkus, University of Wisconsin,
- Dr. Kelly Patton, INT, University of Washington,
- Dr. Sebastian Ohlmann, Heidelberg,
- Dr. Fritz Roepke, Heidelberg,
- Dr. Georg Raffelt, MPI Germany,
- Dr. Thomas Janka, MPA Germany,
- Dr. Ewald Müller, MPA Germany,
- Dr. Annop Wongwathanarat, MPA Germany,
- Dr. Ivo Seitenzahl, Australian National University,
- Dr. Sebastien Galais, IPN Orsay,
- Dr. Cristina Volpe, APC Paris,
- Charles Stapelford, NC State University,
- Matthew Gilmer, NC State University,

- Neel Kabadi, MIT,
- Alex Mauney, Columbia,
- Mithi des los Reyes, Cambridge,
- Brandon Shapiro, Brandeis,
- Tia Alliy, Smith College,
- Gautam Nagaraj, NC State.

(i) Graduate Student Tracking Information

Name of Student	Entered Grad. School	Joined Group	Degree Program	Expected Graduation	Adviser
Howard Whittle	August 2012	August 2012	PhD	August 2018	James P. Kneller
Yue Yang	August 2013	January 2015	PhD	August 2018	James P. Kneller

Table 2: Graduate Student Tracking Information