The Origin of Chemical Elements: Connecting Laboratory Nuclear Astrophysics with Astronomical Observations through Nucleosynthesis Modeling

Final report

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1 Accomplishments

Nuclear astrophysics is a field at the frontier of nuclear science which continues to enjoy significant progress and exciting prospects for the future. It addresses the fundamental question of where and how the chemical elements are made. Except for hydrogen and helium, all other chemical elements are made either in stars or in cosmic explosions such as supernovae or neutron star mergers. To understand the formation of elements we need to understand the relevant nuclear physics processes that govern the interaction between nuclei. We need to understand the conditions in the star or the explosion under which these nuclear processes take place. And we need to understand how individual events of element formation contribute to the overall chemical enrichment of our Galaxy over time. Experimental facilities allow for terrestrial experiments on the nuclear physics governing the element synthesis. Earth-based and space-based telescopes probe the Galaxy around us and provide information about the conditions in stars and supernovae, and about the chemical element enrichment of these different environments. Numerical simulations of stars, supernovae, and other astrophysical phenomena allow us to probe the conditions of extreme densities and temperatures required for element synthesis. Nucleosynthesis research is ideally posed to integrate advances from all three of these areas and advance our understanding of how and where elements are made. Nucleosynthesis research provides theory support for experiments and observations. And it makes predictions that can be tested in nuclear physics experiments and astronomical observations.

The goals of this award were in three main areas:

- Develop and implement an effective core-collapse supernova model that is computationally efficient and that captures the relevant physics for the scientific questions of interest
- Advance our understanding of the synthesis of the lightest heavy elements
- Increase the realism of supernova nucleosynthesis and determine its dependence on the properties of the exploding star

As the projects progressed, an additional focus was added to this list:

- Study the explosion properties and the signals from the most massive stars.

Accomplishments were made in all areas. The various projects undertaken by the PI and her group are described below.

Effective core-collapse supernova models

Core-collapse supernovae (CCSNe) are key players in the evolution and chemical enrichment of galaxies. They synthesize and eject a wide range of chemical elements: carbon and oxygen, intermediate-mass elements such as magnesium and calcium, iron-group elements (from titanium to iron, nickel, and zinc), and even some elements heavier than iron (mostly Sr, Y, Zr). Core-collapse supernovae leave behind neutron stars (for successful explosions) or black holes (for failed explosions). However, despite their importance in astrophysics the explosion mechanism is still not fully understood. The modeling of CCSN explosions is a computationally expensive problem that requires general relativity, a nuclear equation of state, neutrino transport, nuclear reactions, and (ideally) three spatial dimensions. The situation is further complicated by the range of length scales (proto-neutron star radius is ~ 15 km; the stellar radius is $\sim 10^8$ km) and time scales. The problem is complex enough that for the foreseeable future we will continue to be limited to a few simulations when performed in 2D and in 3D.

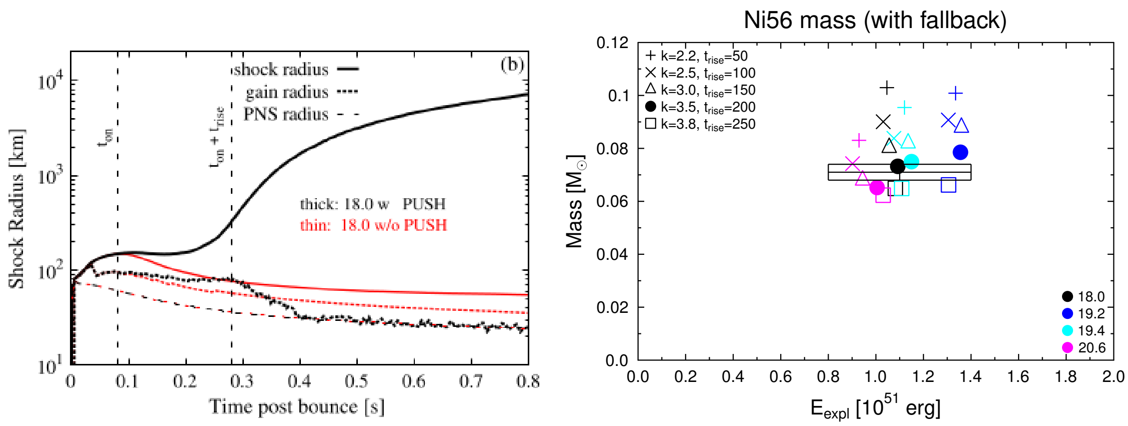

Figure 1: Left: Shock radius as function of time as indicator of a successful explosion (with PUSH; black) and unsuccessful explosion (without PUSH; orange). Right: ^{56}Ni yields for different progenitor models and parameter settings, in comparison to the observed values for SN 1987A. Our "best fit" to SN 1987 is shown as solid black circle. Figure taken from Astrophysical Journal 806, 275 (2015).

The PUSH method for core-collapse supernovae

The first project in this vain was to explore the possibility of (artificially) triggering a supernova explosion in spherically symmetric models while allowing for a consistent treatment of all microphysics and neutrino physics processes critical to nucleosynthesis. This thrust emerged from our earlier work where we showed that the interaction between neutrinos and the ejecta is critical in setting the conditions for nucleosynthesis. Our investigations are based on the neutrino-heating mechanism where electron neutrinos and antineutrinos are believed to deposit energy in the heating region — the region behind the shock where neutrino absorption reactions dominate over their inverse reactions — to revive the stalled shock and launch an explosion.

The approach we chose was to mimic the enhanced neutrino-heating seen in multi-D simulations in our effective 1D model by depositing a small amount of additional energy in the heating region. The additional heating is chosen to spatially and temporally only occur when electron flavor neutrinos and antineutrinos already deposit energy. The additional energy is provided by the heavy-flavor neutrinos though an artificial coupling with matter. The additional energy deposition is given by the local heating term

$$Q^+_{\rm push}(t,r) = 4\,\mathcal{G}(t)\int_0^\infty q^+_{\rm push}(r,E)\,dE, \tag{1}$$

where

$$q^+_{\rm push}(r,E) \equiv \sigma_0\,\frac{1}{4\,m_b}\left(\frac{E}{m_e c^2}\right)^2\frac{1}{4\pi r^2}\left(\frac{dL_{\nu_x}}{dE}\right)\mathcal{F}(r,E). \tag{2}$$

The term $(dL_{\nu_x}/dE)/(4\pi r^2)$ is the spectral energy flux for any single ν_x neutrino species with energy E, σ_0 the typical neutrino cross-section, and $m_b \approx 1.674\times10^{-24}$g an average baryon mass. The function $\mathcal{G}(t)$ (which contains the two free parameters $k_{\rm push}$ and $t_{\rm rise}$) controls the temporal evolution of PUSH. The spatial dependence of PUSH is described by

$$\mathcal{F}(r,E) = \begin{cases} 0 & \text{if} \quad r > R_s \quad \text{or} \quad \dot{e}_{\nu_e,\bar{\nu}_e} < 0 \\ \exp(-\tau_{\nu_e}(r,E)) & \text{otherwise} \end{cases}\;, \tag{3}$$

where R_s is the shock radius, $\dot{e}_{\nu_e,\bar{\nu}_e}$ the net specific energy deposition rate due to electron neutrinos and anti-neutrinos, and τ_{ν_e} is the optical depth for electron neutrinos. The free parameters of the method need to be set, either by comparison to multi-dimensional simulations and/or from calibration to observational constraints. This work is published as 'PUSHing CCSNe to Explosions in Spherical Symmetry I: Model and SN1987A' in the Astrophysical Journal 806, 275 (2015) by the PI, postdoc Casanova, and collaborators. In this paper we demonstrated the feasibility of the method: otherwise non-exploding models in spherical symmetry can be exploded and exhibit properties consistent with observations. In particular, we showed that for a suitable progenitor model the PUSH method results in explosion properties and nucleosynthesis yields consistent with the observations of SN 1987A. In addition, we were able to make a prediction for the mass of the yet to be observed neutron star in SN 1987A.

This work is significant and useful as it allows to tackle many timely open question related to core-collapse supernovae that require hundreds of simulations, such as: what is the connection between the progenitor and the remnant of the CCSN, or, how do nucleosynthetic yields depend on the progenitor. The results from this project laid the foundation for many later projects.

Explodability of massive stars: the progenitor-remnant connection

The next problem tackled was to extend the PUSH method from a single progenitor model (for SN 1987A) to a general method that can be applied to any CCSN progenitor across the entire mass range of potential CCSN progenitors. The key here was to extend the method in a way that allows true predictions within our model. This work was done with Kevin Ebinger (NC State University) and members of the PUSH collaboration. In this project, we generalized the calibration of the PUSH method by characterizing the CCSN progenitors by their compactness (essentially describing the innermost ~ 2 $M_\odot$). This allowed us to find a prescription for the main free parameter of the PUSH method ($k_{\rm push}$) that can be applied to any model across the entire stellar mass range without any additional fitting. The first key result of the project was to show that the generalization is possible and gives results consistent with observations of CCSNe. We also determined the dependence of our results on the specific choices we made in this generalization.

This result put us in an ideal position to turn to systematic studies with the PUSH method: We explored two sets of CCSN progenitors to predict the outcome of the collapse (successful explosion or black hole), explosion properties of the successful explosions, and the remnant properties (neutron star and black hole masses) for all the progenitor models. The key results are: Our predicted outcomes are consistent with observations of CCSNe across the mass range. For the successful explosions, we simultaneously reproduce explosion energies and Ni-ejecta of observed supernovae. In addition, we were able to predict neutron-star masses that are consistent with observed distributions. All these results are published in the paper 'PUSHing Core-Collapse Supernovae to Explosions in Spherical Symmetry II: Explodability and Global Properties', Ebinger, Curtis, Fröhlich and the PUSH collaboration, arXiv:1804.03182.

Synthesis of the lightest heavy elements

The origin of the elements heavier than iron is a long-standing open question. One of the promising sites are neutrino-driven winds from supernovae. However, there are uncertainties in the conditions of the neutrino-driven wind as well as in the relevant nuclei and reactions. We have tackled a series of projects in this realm to identify critical inputs and to improve the inputs to neutrino-driven wind nucleosynthesis calculations.

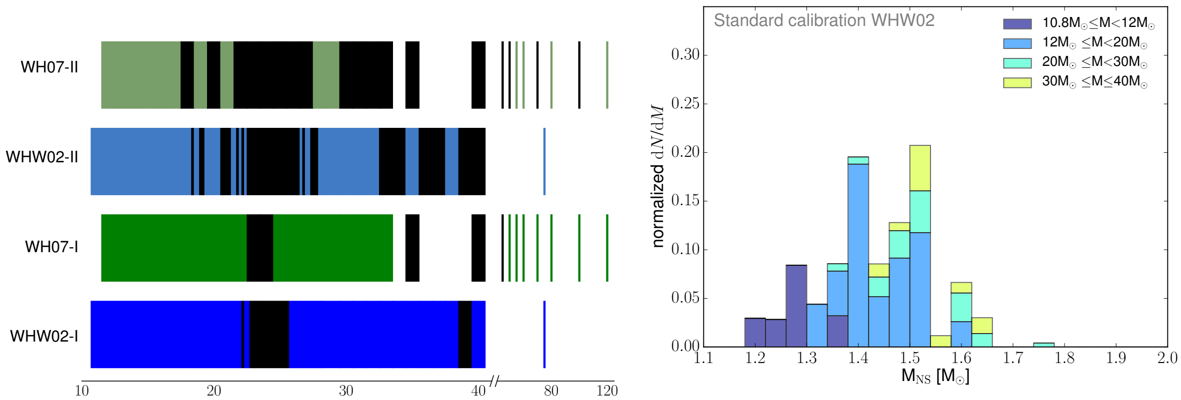

Figure 2: Left: Explodability study for two engines (dark and light colors) and two sets of CCSN progenitors (blue and green). Right: Predicted mass distribution for one of the combinations. Figure is taken from Ebinger, Curtis, Fröhlich *et al*, arXiv:1804.03182.

Conditions in the neutrino-driven wind

With undergraduate students Banerjee, Samulski, and Lineberry we performed a pilot study to systematically look at the nucleosynthesis in neutrino-driven winds taking into account the range of conditions found in supernova simulations from various groups. The key result from this study is that we determined feasibility and the associated uncertainties of such nucleosynthesis calculations.

r-process nuclei near $A = 80$ and $A = 160$

The r-process occurs under neutron-rich conditions. It has long been speculated that such conditions can be found in neutron-rich neutrino driven winds from supernovae and/or in the ejecta of neutron star mergers. In addition to the unknown site, most of the nuclei involved in the r-process are only theoretically known. With collaborators McLaughlin (NC State University), Shafer and Engel (UNC) and Mumpower and Surman (Notre Dame), we performed sensitivity studies to identify critical nuclei betwen $A = 80$ and $A = 160$ for the r-process. These sensitivity studies then guided the calculations by Shafer and Engel who used the Skyrme finite-amplitude method to calculate β-decay half-lives. Finally, Mumpower and Surman performed impact studies using the new β-decay half-lives. The key finding was that modern QRPA calculations are converged within a factor of two to each other. However, often in astrophysical simulations older calculations are still being used, increasing the uncertainty of the results. The paper describing this work is 'β decay of deformed r-process nuclei near $A = 80$ and $A = 160$, including odd-A and odd-odd nuclei, with the Skyrme finite-amplitude method', Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman, Physical Review C 94, 5802 (2016).

The νp-process and nuclear physics

The νp-process which occurs in proton-rich neutrino-driven winds from supernovae contributes to the synthesis of the lightest elements heavier than iron. For this project, we worked closely with experimental groups to identify critical reactions that help prioritize experimental campaigns and to test new experimental results in nucleosynthesis calculations. We performed nucleosynthesis calculations for new mass measurements that were performed at the Lanzhou facility in China. The results from this study are published in Physics Letters B 781, 358 (2018). We have also

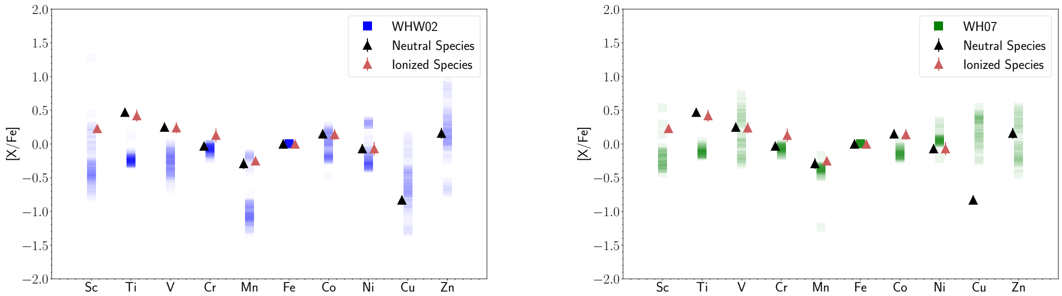

Figure 3: Iron group yields for two sets of CCSN progenitors. The figure is taken from Curtis *et al*, arXiv:1805.00498.

extended earlier work on identifying critical reactions in the νp-process by performing a systematic variation study of all (n,p), (p,γ), and (n,γ) reactions in the νp-process. This study has found the following key results: (i) We confirmed our earlier findings that the reaction ^{56}Ni(n,p)^{56}Co has a very strong impact on the strength of the νp-process. (ii) We have identified additional reactions that impact the νp-process abundances. Our work on this project has also led to two upcoming experimental campaigns (one at the National Superconducting Cyclotron Laboratory and one at the LANSCE facility at Los Alamos National Laboratory).

Realistic supernova nucleosynthesis calculations

For this project, we capitalized on another aspect of the PUSH method: It includes consistent interactions of (electron-flavor) neutrinos with matter as well as having a mass cut that emerges consistently from the simulation (ie. it is not an additional free parameter). Both aspects are crucial for the conditions in the innermost ejecta, as the PI has demonstrated in earlier work. These are the layers were the traditional methods (e.g. piston or thermal bomb) have well-known short comings, which directly affect the iron group yields. We have applied the PUSH method to two sets of progenitor models (combined a total of 111 models at solar metallicity between 10.8 $M_\odot$ and 120 $M_\odot$). We have computed complete isotopics yields for all layers from the mass cut to the He-layer. We analyzed these results for correlations among yields of different elements and of the yields with explosion and progenitor properties. There are several key results from this study: (i) The details of the CCSN progenitor, e.g. size of the nuclear reaction network used, matter for the nucleosynthesis predictions. The iron-group nuclei are most strongly affected by this (within the iron group, the yields of manganese are most strongly impacted). (ii) ^{44} Ti yields are higher than in previous 1D calculations, which is a long-standing puzzle. However, even our increased yields are still too low compared to observational values from SN 1987A and Cas A. (iii) The yields of zinc span a wide range of almost 2 dex. This is a very intriguing result as similar trends have started to emerge from observations of very metal-poor stars. This issue calls for further investigation. (iv) Our predicted yields are consistent with the most modern abundance determination in extremely metal-poor stars. The broader impact of our results are that all our yields are available to the community. In particular, the field of galactic chemical evolution is in dire need of such yield predictions. The paper describing this work is 'PUSHing Core-Collapse Supernovae to Explosions in Spherical Symmetry III: Nucleosynthesis Yields', Curtis, Ebinger, Fröhlich and the PUSH collaboration, arXiv:1805.00498, accepted to The Astrophysical Journal.

Explosions of the most massive stars: pair-instability supernovae

Very massive stars (stars with initial mass greater than 100 $M_\odot$) are too massive to reach an iron core and end their lives as core-collapse supernovae. Instead, they are susceptible to a different instability which leads to explosion and complete disruption of the star. The carbon-oxygen cores of these stars are supported by radiation pressure (due to their relatively low density and high temperature). At these conditions, pair-production from high-energy photons ($\gamma \rightarrow e^- + e^+$) is favorable, which reduces the radiation pressure and hence the adiabatic index Γ. Once $\Gamma < 3/4$, the core becomes unstable and begins to collapse. The resulting increase in density and temperature initiates explosive oxygen burning. The energy release from this explosive burning reverts the collapse and completely disrupts the star. Due to the large stellar mass, these explosions can produce up to two orders of magnitude more radioactive nickel (^{56}Ni) than ordinary core-collapse supernovae, resulting in very bright transients. These very massive stars are thought to be much more common in the early universe, however they are predicted to exist up to a metallicity of $Z < Z_\odot/3$. In the local universe, a few superluminous supernovae (PTF12dam and OGLE14-073) may be explained by pair-instability supernovae. In the early Universe the prospects are much brighter: The James Webb Space Telescope may observe 5-10 pair-instability supernovae through its lifetime and WFIRST could possibly observed up to 10^3 per year.

Explosion properties in multi-dimensional simulations

In this project, the PI and graduate student Matthew Gilmer (NC State University) performed the first-ever published hydrodynamical simulations of pair-instability supernovae in three spatial dimensions as well as one-dimensional and two-dimensional simulations for comparison purposes. We found consistent explosion properties (explosion energy and bulk yields) in all our simulations, independent of the spatial dimensions used. We could not confirm the predicted "Ni-bubble effect" (significant outward mixing of Ni) which would affect the rise time of the light curve. However, we found heretofore unseen amounts of mixing at the composition interfaces in 3-dimensional simulations. This is was an unexpected but highly important results. This requires further investigation as it is expected to impact the spectral signature of pair-instability supernovae. The work for this project has been performed by PI and graduate student Gilmer (hydrodynamical simulations of the PISN explosions) together with collaborators Hirschi and Yusof (stellar evolution calculations), and collaborator Kozyreva (light curve calculations). The paper describing this work is 'Pair-instability Supernova Simulations: Progenitor Evolution, Explosion, and Light Curves', Gilmer, Kozyreva, Hirschi, Fröhlich & Yusof ApJ 846, 100 (2017).

Observable signals from pair-instability supernovae

The next focus in this topic was to predict different observable signals from these pair-instability supernova models. With collaborator Kozyreva (Tel Aviv University), we computed broad-band light curves from the hydrodynamic simulations presented in Gilmer *et al*, ApJ 846, 100 (2017). Our key results were that the light curves from the lightest pair-instability supernova progenitors are very different from the light curves of the most massive members of this class. They appear very similar to normal type II or type Ib supernovae. Only the most massive progenitors reach superluminous brightness. This is a timely result that is relevant for current and future transient surveys that require light curve templates for all types of transients for initial classification. The paper describing these results is Kozyreva, Gilmer, Hirschi, Fröhlich, *et al*, Monthly Notices of the Royal Astronmical Society 464, 2854 (2017).

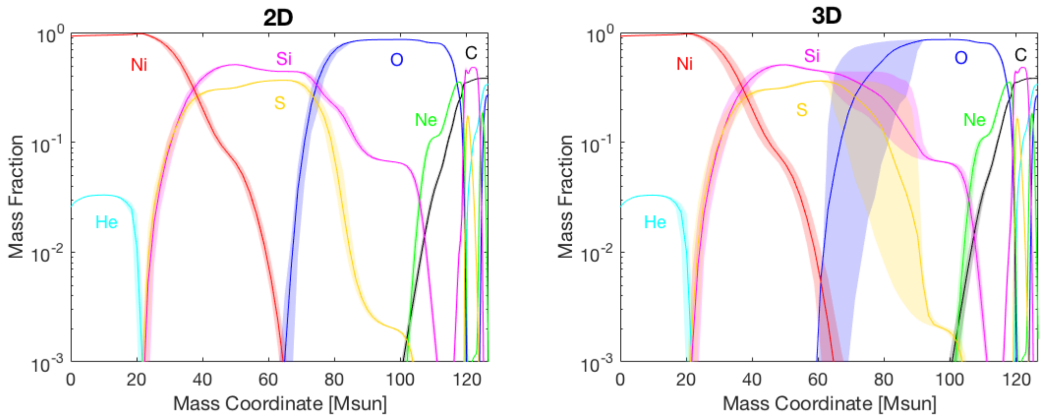

Figure 4: Angular-averaged mass fraction profiles for the high resolution (3.25×10^7 cm) simulations in 2D (left) and 3D (right). The shaded bands indicate the regions with mixing. Figure is taken from Gilmer, Kozyreva, Hirschi, Fröhlich & Yusof ApJ 846, 100 (2017).

In collaboration with James Kneller (NC State University) and his postdoc Warren Wright, we have predicted the neutrino signal pair-instability supernovae. These results are presented in Wright, Gilmer, Frḧlich and Kneller, 'The Neutrino Signal From Pair Instability Supernovae', Physical Review D, 96, 3008 (2017).

2 Work to be accomplished

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

- spectra from pair-instability supernovae
- nucleosynthesis from pair-instability supernovae
- Explosion properties and nucleosynthesis yields for low-metallicity CCSN progenitors

At the present time, two projects related to pair-instability supernova are underway in collaboration with Gilmer (now at LANL), Chatzopoulos (LSU), and Miles (NC State University). For both projects, we make use of the hydrodynamical simulations performed and presented in Gilmer *et al* ApJ 846, 100 (2017). The expected time to submission is 3–6 months.

Finally, with graduate students Curtis and Ghosh (NC State University) and Ebinger (now at GSI) we are applying the PUSH method to additional sets of CCSN progenitors. As a first step, we focus on low and zero metallicity progenitors which experience less mass loss and hence are more massive at collapse than their solar-metallicity counterparts. These low-metallicity progenitors are thought to be the origin of the stellar mass black holes observed by LIGO/VIRGO. The expected time to submission for this project is 9–12 months.

3 Student Training

Three graduate students (2 PhD and 1 Master) at NC State have been supported though this award. Two have graduated during the award period (Erb: MS 2015; Gilmer: PhD 2018) and one (Curtis) is expected to graduate in August 2020. In addition, one undergraduate student was supported. Graduate students supported on this award are listed in Table 1.

Name of Student	**Entered Graduate School**	**Joined Group**	**Program**	**Graduation (Actual/ Expected)**	**Advisor**
Matthew Gilmer	Aug. 2012	Sep. 2012	PhD	May 2018	Fröhlich
Jonathan Erb	Aug. 2012	Jan. 2014	MS	August 2015	Fröhlich
Sanjana Curtis	Aug. 2013	Feb. 2015	PhD	August 2020	Fröhlich

Table 1: Student Tracking Information

4 Publications

Individuals support by this grant are indicated in bold face. Undergraduate students are underlined.

Participant	**Peer reviewed Publications**	**Preprints/ Submitted**	**Conference Proceedings**	**Invited Talks**
Carla Fröhlich	10	2	12	27
Jordi Casanova	1			
Kevin Ebinger		2	1	
Sanjana Curtis		2	3	
Matthew Gilmer	3		2	
Total	10	2	12	27

Table 2: Publications, Proceedings, and Invited Talks

Peer Reviewed Articles

1. "Mass measurements of neutron-deficient Y, Zr, and Nb isotopes and their impact on rp and νp nucleosynthesis processes", Y.M. Xing, Li, Zhang, Zhou, Wang, Litvinov, Blaum, K. Wanajo, Kubono, Martínez-Pinedo, Sieverding, Chen, Shuai, Fu, Yan, Huang, Xu, Tang, Xu, Bao, Chen, Gao, He, Lam, Li, Liu, Ma, Mao, Si, Sun, Tu, Wang, Yang, Yuan, Zeng, Zhang, Zhou, Zhan, Litvinov, Audi, Uesaka, Yamaguchi, Yamaguchi, Ozawa, **C. Fröhlich**, Rauscher, Thielemann, Sun, Sun, Dai, Xu,; Physics Letters B **781**, 358 (2018) doi:10.1016/j.physletb.2018.04.009

2. "The Neutrino Signal From Pair Instability Supernovae", W. P. Wright, **M. Gilmer**, **C. Fröhlich**, and J. P. Kneller; Physical Review D, **96**, 103008 (2017)
doi:10.1103/PhysRevD.96.103008

3. "Pair-instability Supernova Simulations: Progenitor Evolution, Explosion, and Light Curves", **M. Gilmer**, A. Kozyreva, R. Hirschi, **C. Fröhlich**, N. Yusof; Astrophysical Journal, **846**, 100 (2017)
doi:10.3847/1538-4357/aa8461

4. "Fast evolving pair-instability supernova models: Evolution, explosion, light curves", A. Kozyreva, **M. Gilmer**, R. Hirschi, **C. Fröhlich**, S. Blinnikov, R. T. Wollaeger, U. M. Noebauer, D. R. van Rossum, A. Heger, W. P. Even, R. Waldman, A. Tolstov, E. Chatzopoulos, E. Sorokina; Monthly Notices of the Royal Astrononmical Society, **464**, 2854 (2017)
doi:10.1093/mnras/stw2562

5. "β decay of deformed r-process nuclei near $A = 80$ and $A = 160$, including odd-A and odd-odd nuclei, with the Skyrme finite-amplitude method", T. Shafer, J. Engel, **C. Fröhlich**, G. C. McLaughlin, M. Mumpower, R. Surman; Physical Review C, **94**, 5802 (2016)
doi:10.1103/PhysRevC.94.055802

6. "White paper on nuclear astrophysics and low energy nuclear physics Part 1: Nuclear astrophysics," A. Arcones *et al.*, Progress in Particle and Nuclear Physics, **94**, 1 (2017)
doi:10.1016/j.ppnp.2016.12.003

7. "PUSHing CCSNe to Explosions in Spherical Symmetry I: Model and SN1987A", A. Perego, M. Hempel, **C. Fröhlich**, K. Ebinger, M. Eichler, J. Casanova, M. Liebendörfer, F.-K. Thielemann; Astrophysical Journal, **806**, 275 (2015)
doi:10.1088/0004-637X/806/2/275

8. "Supernovae, neutrinos, and nucleosynthesis", **C. Fröhlich**; Journal of Physics G, **41**, 044003 (2014)
doi:10.1088/0954-3899/41/4/044003

9. "Constraining the astrophysical origin of the p-nuclei through nuclear physics and meteoritic data", T. Rauscher, N. Dauphas, I. Dillmann, **C. Fröhlich**, Zs. Fülöp, Gy. Gyürky; Reports on Progress in Physics, **76**, 066201 (2013)
doi:10.1088/0034-4885/76/6/066201

10. "Systematic study of (p,γ) reactions on Ni isotopes", A. Simon, A. Spyrou, T. Rauscher, **C. Fröhlich**, S. J. Quinn, +21 *authors in alphabetical order*; Physical Review C, **87**, 055802 (2013)
doi:10.1103/PhysRevC.87.055802

Papers Submitted

1. "PUSHing CCSNe to Explsions in Spherical Symmetry III: Nucleosynthesis Yields", **S. Curtis**, **K. Ebinger**, **C. Fröhlich**, M. Hempel, A. Perego, M. Liebendörfer, F.-K. Thielemann; Submitted to The Astrophysical Journal

2. "PUSHing CCSNe to Explsions in Spherical Symmetry II: Explodability and the faint supernova branch", **K. Ebinger**, **S. Curtis**, **C. Fröhlich**, M. Hempel, A. Perego, M. Liebendörfer, F.-K. Thielemann; Submitted to The Astrophysical Journal

Conference Proceedings

1. B. Wehmeyer, **C. Fröhlich**, M. Pigantari, F.-K. Thielemann; "Inhomogeneous Chemical Evolution of r-process Elements in the Galactic Halo", Proceedings for Nuclei in the Cosmos XV, Gran Sasso, Italy (2018)

2. J.P. Kneller, **C. Fröhlich**, **M. Gilmer**, W. Wright; Neutrinos from Pair-Instability Suprenovae", Proceedings for Nuclei in the Cosmos XV, Gran Sasso, Italy (2018)

3. **C. Fröhlich**, **S. Curtis**, **K. Ebinger**, M. Hempel, M. Liebendörfer, A. Perego, F.-K. Thielemann; "Nucleosynthesis in Core-collapse Supernovae", Proceedings for Nuclei in the Cosmos XV, Gran Sasso, Italy (2018)

4. "PUSHing Core-Collapse Supernovae to Explosions in Spherical Symmetry: Nucleosynthesis Yields", **S. Sinha**, **C. Fröhlich**, K. Ebinger, A. Perego, M. Hempel, M. Eichler, J. Casanova, M. Liebendörfer, F.-K. Thielemann; Proceedings of the 14th International Symposium on Nuclei in the Cosmos (NIC2016), id.020608 (2016)
   doi:10.7566/JPSCP.14.020608

5. "Effects of Dimensionality on Pair-Instability Supernova Explosions", **M. S. Gilmer**, A. Kozyreva, R. Hirschi, **C. Fröhlich**; Proceedings of the 14th International Symposium on Nuclei in the Cosmos (NIC2016), id.020601 (2016)
   doi:10.7566/JPSCP.14.020601

6. "Explosion Dynamics of Parametrized Spherically Symmetric Core-Collapse Supernova Simulations" K. Ebinger, **S. Sinha**, **C. Fröhlich**, A. Perego, M. Hempel, M. Eichler, J. Casanova, M. Liebendörfer, F.-K. Thielemann; Proceedings of the 14th International Symposium on Nuclei in the Cosmos (NIC2016), id.020611 (2016)
   doi:10.7566/JPSCP.14.020611

7. "Nuclear Reactions and the νp-process", **C. Fröhlich**, D. W. Hatcher, G. Perdikakis, S. Nikas; Proceedings of the 14th International Symposium on Nuclei in the Cosmos (NIC2016), id.010505 (2016)
   doi:10.7566/JPSCP.14.010505

8. "Investigating the Role of νp-Process: Preparations for the Measurement of the ^{56}Co(p,n)^{56}Ni Reaction", P. Gastis, G. Perdikakis, **C. Fröhlich**, +14 *authors in alphabetical order*; Proceedings of the 14th International Symposium on Nuclei in the Cosmos (NIC2016), id.020511 (2016)
   doi:10.7566/JPSCP.14.020511

9. "Influence of nuclear reaction rates on the nucleosynthesis in neutrino-driven winds", **C. Fröhlich** and D. W. Hatcher; CGS15 - Capture Gamma-Ray Spectroscopy and Related Topics, Dresden, Germany, Edited by Schwengner, R.; Zuber, K.; EPJ Web of Conferences, Volume 93, id.03008 (2015)
   doi:10.1051/epjconf/20159303008

10. "Parametrized Spherically Symmetric Core Collapse Supernova Simulations: Push", K. Ebinger, A. Perego, M. Hempel, **C. Fröhlich**, M. Eichler, **J. Casanova**, M. Liebendörfer, F.-K. Thielemann; Proceedings of XIII Nuclei in the Cosmos (NIC XIII). 7-11 July, 2014. Debrecen, Hungary.
    Online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=204, id.90

11. "Neutrinos and nucleosynthesis in core-collapse supernovae", **C. Fröhlich**, **J. Casanova**, M. Hempel, M. Liebendörfer, C. A. Melton, A. Perego; AIP Conference Proceedings, Volume 1604, Issue 1, p.178-184 (2014)
doi:10.1063/1.4883428

12. "Origin of the Elements", A. Heger, J. W. Truran, **C. Fröhlich**; Planets, Asteroids, Comets and The Solar System, Volume 2 of Treatise on Geochemistry (Second Edition). Edited by Andrew M. Davis. Elsevier, 2014., p.1-14 (2014)

Conferences and Workshops

1. **C. Fröhlich**: "PUSHing CCSNe to Explosion: Method, Global properties, Nucleosynthesis", *Contributed talk*, Core-collapse Supernovae in the Multi-Messenger Era Workshop, L'Aquila, Italy (July 2018)

2. **C. Fröhlich**: "Nucleosynthesis in core-collapse supernovae", *Contributed talk*, International Symposium on Nuclei in the Cosmos NIC-XV, Gran Sasso, Italy (June 2018)

3. **C. Fröhlich**: "CCSN nucleosynthesis yields across the mass range", *Contributed talk*, Supernovae - From Simulations to Observations and Nucleosynthetic Fingerprints, Bad Honnef, Germany (Jan 2018)

4. **C. Fröhlich**: "Yields from Core-Collapse Supernovae and EMP Stars", ***Invited talk***, International conference "Stellar evolution, Supernovae, and Nucleosynthesis Across Cosmic Times", Tokyo, Japan, September 2017

5. **C. Fröhlich**: "Overview: Nucleosynthesis in Core-Collapse Supernovae", ***Invited talk***, INT Program Electromagnetic Signatures of r-Process Nucleosynthesis in Neutron Star Binary Mergers, Seattle, WA, July 2017

6. **C. Fröhlich**: "Nuclear Astrophysics", ***Invited lectures***, Exotic Beams Summer School, Argonne National Laboratory, Chicago, IL, July 2017

7. **C. Fröhlich**: "Nucleosynthesis yields from CC supernovae", *Contributed talk*, JINA-CEE Workshop "Forging Connections: From Nuclei to the Cosmic Web", Michigan State University, Lansing, MI (June 2017)

8. **K. Ebinger**: "PUSHing core-collapse supernovae to explosion in spherical symmetry II: Explodability and hte fiant supernova branch", *Contributed talk*, Fifty-One Ergs: Third International Conference on the physics and observations of supernovae, supernova remnants, and other explosive phenomena" Corvalis, OR (June 2017)

9. **S. Curtis**: "PUSHing Core-Collapse Supernovae to Explosions in Spherical Symmetry: Nucleosynthesis Yields", *Contributed talk*, Fifty-One Ergs: Third International Conference on the physics and observations of supernovae, supernova remnants, and other explosive phenomena" Corvalis, OR (June 2017)

10. **C. Fröhlich**: "Nucleosynthesis in Core-Collapse Supernovae: What we know and what we do not know", ***Invited talk***, Princeton Workshop "A Definitive Investigation of Core-Collapse Supernova Cassiopeia A", Princeton, NJ, April 2017

11. **S. Curtis**: "PUSHing Core-Collapse Supernovae to Explosions in Spherical Symmetry: Explodability and Nucleosynthesis Yields", *Contributed talk*, APS April Meeting 2017, Washington DC, January 2017
12. **C. Fröhlich**: "PUSH Method and Nucleosynthesis", ***Invited talk***, Brainstorming & Fun Workshop, Basel, Switzerland, September 2016
13. **C. Fröhlich**: "Nucleosynthesis in Supernovae: Challenges and Recent Developments", ***Invited talk***, Conference "Many Riddles of Supernovae", Tokyo, Japan, June 2016
14. **C. Fröhlich**: "Nuclear reactions and the νp Process", *Contributed talk*, International Symposium on Nuclei in the Cosmos XIV, Niigata, Japan (June 2016)
15. **C. Fröhlich**: "Setting the Stage: Nucleosynthesis", ***Invited review talk***, Conference "Microphysics in Computational and Relativistic Astrophysics (MICRA)", Stockholm, Sweden, August 2015
16. **C. Fröhlich**: "Nucleosynthesis of light neutron-capture elements: Clues from stars and simulations", *Contributed talk*, International Symposium on Nuclei in the Cosmos XIII, Debrecen, Hungary (June 2015)
17. **C. Fröhlich**: "The νp-Process: Production of p-Nuclei and the impact of nuclear reaction uncertainties", ***Invited review talk***, p-Process Workshop, Limassol, Cyprus, June 2015
18. **C. Fröhlich**: "PUSHing CCSNe to explosion: Model and SN1987A", *Contributed talk*, Nuclei Physics in Astrophysics VII, York UK (May 2015)
19. **C. Fröhlich**: "PUSHing core-collapse supernovae to explosion", ***Invited talk***, Neutrinos and Nucleosynthesis Workshop, Berkeley, CA, February 2015
20. **C. Fröhlich**: "Core-collapse supernovae and nucleosynthesis", ***Invited talk***, 4^{th} Joint Meeting of the APS and JPS, Waikoloa Village, HI, October 2014
21. **C. Fröhlich**: "Critical nuclear physics in neutrino-driven wind nucleosynthesis", ***Invited talk***, 15^{th} International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics (CGS15), Dresden, Germany, August 2014
22. **C. Fröhlich**: "The νp-process: A LEPP candidate", ***Invited talk***, INT Program on Nucleosynthesis and Chemical Evolution, Seattle WA, August 2014
23. **C. Fröhlich**: "Neutrino interactions and Nucleosynthesis", ***Invited lectures***, HIPACC Summer School: Neutrinos and Nuclear Astrophysics, San Diego, CA, July 2014
24. **C. Fröhlich**: "Nucleosynthesis signatures in metal-poor stars", *Contributed talk*, 17th Ringberg Workshop on Nuclear Astrophysics, Ringberg, Germany (April 2014)
25. cfbf: "Neutrinos and supernova nucleosynthesis", ***Invited talk***, ECT Workshop on Simulation the Supernova Neutrinosphere with Heavy Ion Collisions, Trento, Italy, April 2014
26. **C. Fröhlich**: "Microphysics in Supernova Nucleosynthesis", *Contributed talk*, Microphysics in Computational Relativistic Astrophysics MICRA, Trento, Italy (Sept 2013)
27. **C. Fröhlich**: "Nucleosynthesis and neutrinos in core-collapse supernovae", ***Invited talk***, INFO13: Implications of Neutrino Flavor Oscillations, Santa Fe, NM, August 2013

28. **C. Fröhlich**: "Neutrinos and Nucleosynthesis in Core-collapse Supernovae", ***Invited talk***, CETUP* Workshop on Neutrinos and Astrophysics, Lead, SD, USA (July 2013)

Colloquia and Seminars

1. **C. Fröhlich**: "Explosive Yields from Massive Stars", *Astrophysics Seminar*, Observatoire de Geneve, Geneva, Switzerland (May 2018)
2. **C. Fröhlich**: "Modelling Stellar Explosions and Nucleosynthesis", *High Energy Density Science Seminar*, Lawrence Livermore National Laboratory (Feb 2018)
3. **C. Fröhlich**: "Modern Core-Collapse Supernova Nucleosynthesis", *Astrophysics Seminar*, INAF, Rome, Italy (Jan 2018)
4. **C. Fröhlich**: "^{56}Ni in Supernovae: Nuclear Physics, Explosion Properties, and Light Curves", *Nuclear Data Seminar*, Los Alamos National Laboratory, Los Alamos, NM, December 2016
5. **C. Fröhlich**: "Supernovae of massive and very massive stars", *Physics Department Colloquium*, Wake Forest University, Greensboro, NC, October 2016
6. **C. Fröhlich**: "Heavy elements: The relics of stars and supernovae", *Physics Department Colloquium*, Eastern Carolina University, Greenville, NC, February 2015
7. **C. Fröhlich**: "Challenges in core-collapse supernova nucleosynthesis", *Physics Department Colloquium*, University of Notre Dame, South Bend, IN, November 2014
8. **C. Fröhlich**: "Supernovae and nucleosynthesis", *TUNL Seminar*, Duke University, Durham, NC, June 2014
9. **C. Fröhlich**: "Supernovae, neutrinos, and nucleosynthesis", *Astrophysics Seminar*, Keele University, Keele, UK, October 2013
10. **C. Fröhlich**: "On the Origin of Light neutron-capture Elements", *Nuclear, Astro, and Particle Physics Seminar*, University of Basel, Switzerland (October 2013)
11. **C. Fröhlich**: "Supernovae, neutrinos, and nucleosynthesis", *Astrophsyics Seminar*, Technische Universität Darmstadt, Darmstadt, Germany, October 2013

Posters

1. **B. Miles**, **M. Gilmer**, **C. Fröhlich**. "Detailed Nucleosynthesis Calculations from Pair-Instability Supernovae" International Symposium on Nuclei in the Cosmos XV, Gran Sasso, Italy (2018)
2. **S. Curtis**, **K. Ebinger**, **C. Fröhlich**, M. Hempel, A. Perego, M. Liebendörfer, F.-K. Thielemann. "PUSHing Core-Collapse Supernovae to Explosions in Spherical Symmetry: Nucleosynthesis Yields", International Symposium on Nuclei in the Cosmos XV, Gran Sasso, Italy (2018)
3. **S. Curtis**, **K. Ebinger**, **C. Fröhlich**, et al. "PUSHing Core-Collapse Supernovae to Explosions in Spherical Symmetry: Nucleosynthesis Yields", International Symposium on Nuclei in the Cosmos, Niigata XIV, Japan (June 2016)

4. **M. Gilmer**, A. Kozyreva, R. Hirschi, **C. Fröhlich**. "Mixing of ^{56}Ni in Multi-dimensional Pair-Instability Supernova Simulations", International Symposium on Nuclei in the Cosmos XIV, Niigata, Japan (June 2016)

5. T. Garnowski & **C. Fröhlich**. "Core-collapse Supernovae in Spherical Symmetry", 30^{th} Annual National Conference on Undergraduate Research, Asheville, NC (May 2016)

6. D. Hatcher & **C. Fröhlich**. "Nuclear reaction rates and their influence on nucleosynthesis in the neutrino-p-process", Conference Experience for Undergraduates (CEU), APS Division of Nuclear Physics Meeting, Santa Fe, NM (Oct 2015)

7. D. Hatcher & **C. Fröhlich**. "Comparison of nucleosynthesis simulations to abundances in metal-poor stars: the impacts of nuclear physics inputs", Fifty-One Ergs II, Raleigh, NC (June 2015)

8. A. Mahler & **C. Fröhlich**. "r-Process Approximation Nucleosynthesis: A Case Study", Fifty-One Ergs II, Raleigh, NC (June 2015)

9. S. Seadrow, **C. Fröhlich**, H. Duan, A. Friedland, G. McLaughlin, J. Keohane. "The Effects of Collective Neutrino Oscillations on Supernova Nucleosynthesis", AAS January Meeting, Washington, DC, USA (Jan 2014)

10. C. Melton & **C. Fröhlich**. "Core-collapse Supernova Nucleosynthesis of promptly Ejected Material", Conference Experience for Undergraduates (CEU), APS Division of Nuclear Physics Meeting, Newport News VA, USA (Oct 2013)

11. O. Banerjee & **C. Fröhlich**. "Nucleosynthesis at Low Metallicity", Fifty-One Ergs I, Raleigh NC, USA (May 2013)

12. C. Melton & **C. Fröhlich**. "Asymmetry in the νp-Process", Fifty-One Ergs I, Raleigh NC, USA (May 2013)

13. **M. Gilmer**, **J. Casanova**, **C. Fröhlich**, A. Perego, M. Hempel, K. Ebinger, M. Liebendörfer. "Towards Core-collapse Supernova Models for Nucleosynthesis", Fifty-One Ergs I, Raleigh NC, USA (May 2013)

5 Participants and Collaborators

Participants directly supported on this project are (in addition to the PI):

- Dr. Jordi Casanova (postdoctoral fellow)
- Dr. Kevin Ebinger (postdoctoral fellow)
- Dr. Broxton Miles (postdoctoral fellow)
- Sanjana Curtis (graduate student)
- Matthew Gilmer (graduate student)
- Jonathan Erb (graduate student)
- Aaron Mahler (undergraduate researcher)

The PI and the participants in this award have collaborated significantly with many others. They are listed below with their current institution:

- Dr. J. P. Kneller (NC State University)
- Dr. G. McLaughlin (NC State Univeristy)
- Dr. E. Chatzopoulos (LSU)
- Dr. J. Engel (UNC)
- Dr. R. Hirschi (Keele University, UK)
- Dr. M. Liebendoerfer (University of Basel, Switzerland)
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- Dr. M. Eichler (TU Darmstadt, Germany)
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- Dr. A. Perego (INFN Italy)
- Dr. S. Richers (NC State University)
- Dr. B. Wehmeyer (NC State University)
- Dr. W. Wright (NC State University)
- O. Banerjee Ohio State Univeristy)
- T. Garnowksi (University of Tübingen, Germany)
- P. Gastis (CMU)
- D. Hatcher (CMU)
- J. Lineberry (APS)
- C. Melton (NC State University)
- S. Nikas (CMU)
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- H. Stephens (NC State University)