JINA-CEE

Center for the Evolution of the Elements

December 2021

A note from the Director, Hendrik Schatz

Dear JINA-CEE Collaborators and Friends,

These are exciting times in nuclear astrophysics with rapid developments in experiment, observations, theory and computation, some of them reflected in this newsletter. At the same time, the range of sub-disciplines and areas of expertise that need to be integrated continues to increase. The IReNA network of networks, supported through the NSF AccelNet program that connects JINA-CEE with other networks around the world, aims at facilitating the necessary interdisciplinary connections. We are especially happy to welcome the new IReNA partner networks BRIDGCE (UK), CanPAN (Canada) and ChETEC-INFRA (Europe). This expansion offers many new opportunities for international collaboration and for taking advantage of complementary infrastructure and expertise. I encourage the JINA-CEE community to take advantage of these opportunities and explore the IReNA website irenaweb.org, which also includes information on how to join IReNA and how to participate. In particular, I encourage young researchers who may be new to nuclear astrophysics to join the new IReNA Young Researcher Organization. Please contact myself or Ana Becerril with any questions you may have.

I wish you all happy holidays and hope that you find some time to take a real break and recharge after another challenging year.

Inside this issue

The Status and Future of Direct Nuclear Reaction Measurements for Stellar Burning

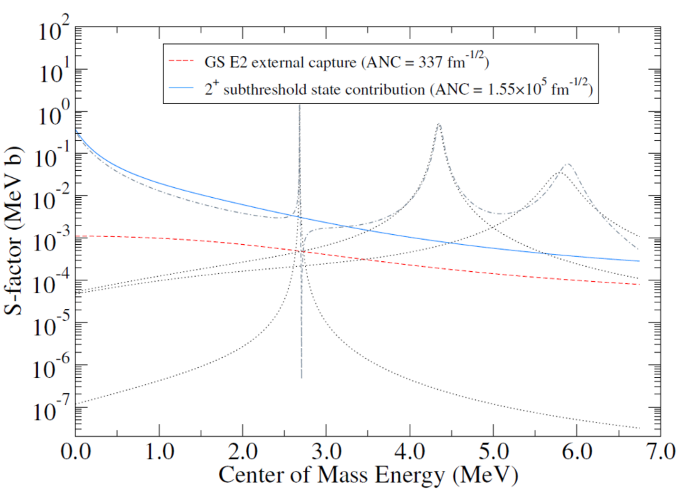
Contributed by Zach Meisel (Ohio University, USA)

The study of stellar burning began just over one-hundred years ago, when Eddington posited that the Sun is powered by the conversion of hydrogen to helium. Since that time, a coherent picture has emerged for nuclear reactions in stars. We know that hydrogen is converted to helium, helium to carbon and oxygen, and, for massive stars, elements are synthesized all the way up to the iron region. We know that stellar burning scenarios can lead to prolific neutron production, synthesizing elements all the way up to lead.

However, we still lack a detailed picture of stellar burning and many questions remain. What is the carbon/oxygen ratio produced by helium burning and, consequently, where should the upper-mass gap in the black-hole mass distribution be located? What is the rate of carbon-carbon fusion, which has downstream implications for type-1a supernova nucleosynthesis and the fate of stars in the 8-10 solar mass range? How strong are the neutron sources and sinks within stellar burning and how precisely can neutron-capture yields constrain stellar burning conditions? Answering these and many more questions requires dedicated efforts in experiment and theory using state-of-the-art tools across multiple research networks.

In recent years, several devices and facilities have been developed that are dedicated to measuring nuclear reactions at or near the energies relevant to stars and stellar explosions. Deep underground laboratories shelter experiments from cosmic-ray induced backgrounds, boosting signal-to-noise ratios. Recoil separators and storage rings approach the problem from inverse kinematics, where measurements focus on detecting the heavy recoil nucleus emerging from the reaction. Neutron beams enable measurements of neutron-captures on stable and long-lived nuclides. Photon beams can shed light on stellar photodisintegration reactions, but more often provide unique indirect probes.

The Reaction Rates focus area in the International Research Network for Nuclear Astrophysics (IReNA, irenaweb.org), of which JINA-CEE is a core network, recently published a whitepaper [1] highlighting some of the aforementioned open questions and the experimental developments of the recent past and near future that will help address them. The international team involved 25 researchers from 23 institutions based in 9 countries. The whitepaper was featured by the Physics World Weekly podcast from IOP Publishing in a recent interview [2] with Zach Meisel, JINA-CEE member from Ohio University.



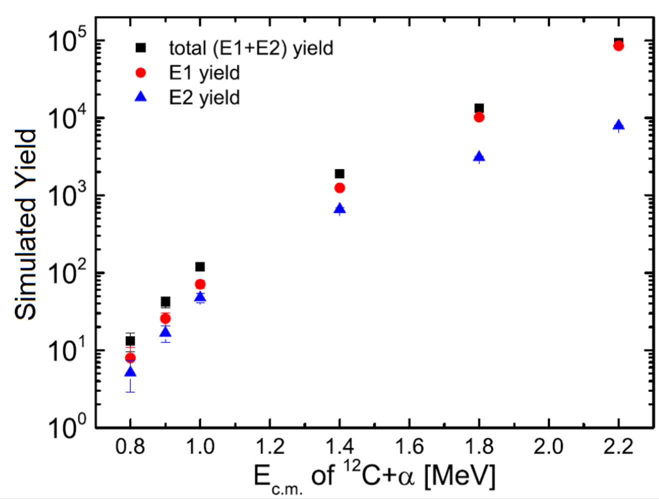


Figure 1. $^{12}C(\alpha,\gamma)^{16}O$ is one of many reactions that play an important role in stellar burning. The left panel shows calculation results from the JINA-CEE code AZURE2 for the E2 component of $^{12}C(\alpha,\gamma_0)^{16}O$. The right panel shows simulation results for the anticipated yield of $^{16}O(\gamma,\alpha)^{12}C$ at ELI-NP. Figures are from [1].

References

[1] M Aliotta *et al* 2022 *J. Phys. G: Nucl. Part. Phys.* **49** 010501

[2] Physics World Podcast

State-of-the-Art i-process Simulations and the Quest for the i-process Site

Contributed by Pavel Denisenkov and Falk Herwig (University of Victoria, Canada)

A JINA-CEE collaboration between UVic, CMU, MSU and UMinn, has developed a new advective (the transport of a substance by bulk motion of a fluid) two-stream model that allows large-network nucleosynthesis post-processing of 3D hydrodynamic simulations (Fig. 1) of the convective-reactive i process in rapidly accreting white dwarfs (RAWD) [1]. The model revealed significant differences between the upstream and downstream abundance profiles of unstable species and allows a more accurate nucleosynthesis calculation in violent events.

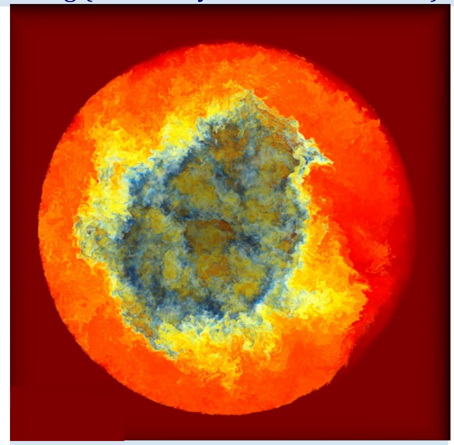


Figure 1: H-rich material (red-yellow-blue) concentration in a 3D hydro simulation of H ingestion into the He-shell flash convection of an accreting white dwarf.

Monte Carlo simulations of the i-process nucleosynthesis with randomly varied neutron-capture rates of 164 unstable isotopes from ^{131}I to ^{189}Hf, with their variation limits constrained by Hauser-Feshbach model computations, were performed to study the impact of those uncertainties on predicted abundances of 18 elements from Ba to W enhancements of which are observed in carbon-enhanced metal-poor stars with enhanced s-process and r-process material (CEMP-r/s stars) [2]. Those post-processing simulations used a one-zone model with two constant neutron densities, N_n = 3.16×10^{13} cm^{-3} and 3.16×10^{14} cm^{-3}, and a more realistic multi-zone model based on the stellar evolution simulation of H entrainment by He-shell convection in the RAWD model G from [3]. Two neutron-capture reactions with the strongest correlations between their rate variations and the predicted abundances were identified for each of the 18 elements. It was found that the discrepancies between the observed and predicted abundances of Ba and Pr in the CEMP-r/s star CS31062-050 could be significantly reduced if the rate of neutron capture by ^{137}Cs were decreased and the rates of neutron captures by ^{141}Ba or ^{141}La were increased. It was also shown that the model of i-process nucleosynthesis in RAWDs could better explain the heavy-element abundance enhancements in CEMP-r/s stars than a model of low-mass low-metallicity AGB stars [4], in which i-process nucleosynthesis occurs when convection driven by a He-burning shell thermal pulse entrains H from the outer layers of the star (see Fig. 2).

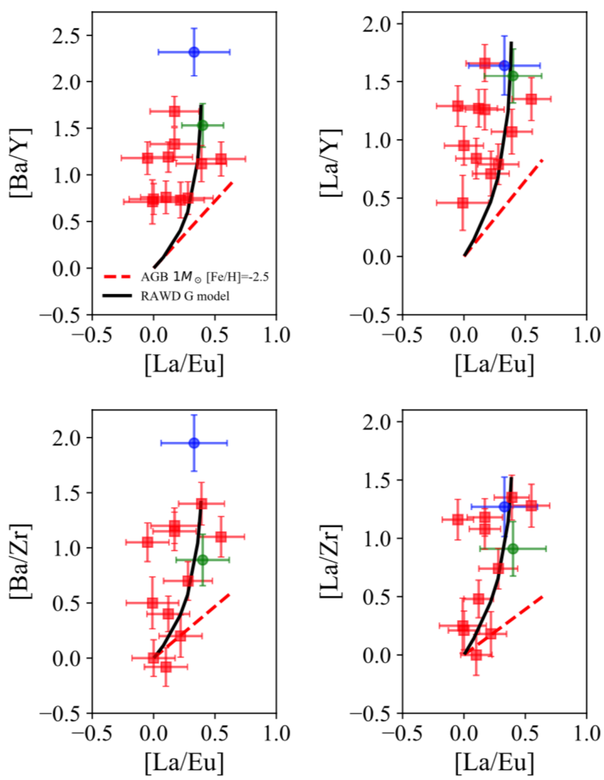


Figure 2: i-process produced element ratios vs the La to Eu elemental abundance ratios in the CEMP-r/s stars from [4] (red squares with error bars) and in the CEMP-r/s stars CS31062-050 and HE2148-1247 studied in [2] (blue and green circles) are compared with the abundance dilution curves for the i-process nucleosynthesis yields from the RAWD model G (black) and an AGB model from [4] (dashed red).

References:

[1] D. Stephens et al., MNRAS 504, 744 (2021)
[2] P. Denissenkov et al., MNRAS 503, 3913 (2021)
[3] P. Denissenkov et al., MNRAS 488, 4258 (2019)
[4] D. Karinkuzhi et al., A&A 645, 61 (2021)

Reconstructing Supernova Explosions with Physics-Based Machine-Learning Models

Contributed by Jack O'Brien and Wolfgang Kerzendorf (Michigan State University, USA)

Type Ia supernovae, the thermonuclear disruption of white-dwarfs in binary systems, have long been powerful tools for astronomers in understanding the evolution of the universe. Most famously they have served as powerful cosmic distance indicators leading to the Nobel-prize-winning discovery of Dark Energy. Despite their significance, the nature of their explosions remains a mystery. How and why a white-dwarf suddenly erupts into an explosion brighter than all of the stars in its host galaxy has been a matter of intense debate. Many progenitor scenarios have been proposed in order to explain the observed properties of Type Ia supernovae. We have developed a methodology and applied it to data that can discriminate between the progenitor scenarios.

Radiation-transport simulations are used to simulate observations of spectra which are then compared to real data. These models contain dozens of input parameters and detailed physics resulting in a highly complex parameter space. There may exist multiple solutions that produce similar looking synthetic spectra varying over orders of magnitude in parameters such as composition, temperature, and density. Getting a full picture of the space of all possible models that can describe an observation requires exploring millions of possible parameter combinations. Radiation-transport models take 10s of minutes to evaluate these parameters, making this problem computationally intractable, until now.

We have trained a machine-learning algorithm to run these radiative-transport simulations for us, substantially speeding up model evaluation. Our technique has reduced each parameter evaluation step from 10 minutes to fractions of a millisecond. Thus, the time required to perform the entire analysis has been reduced from 20 years to only 10 minutes! Exploring the relative likelihood of solutions in this space has revealed a complex and multi-modal parameter distribution. Some parameter combinations produce degenerate solutions and some elements can vary over orders of magnitude in relative abundance with little change on the resulting spectrum. Comparing our reconstruction of the Type Ia supernova SN2002bo to hydrodynamic simulations has revealed that the explosion best matches with a supersonic nuclear burning front, effectively ruling out the older turbulent models. Further constraining the possible scenarios for Type Ia supernovae will have profound implications on our understanding of their role in the evolution of the universe.

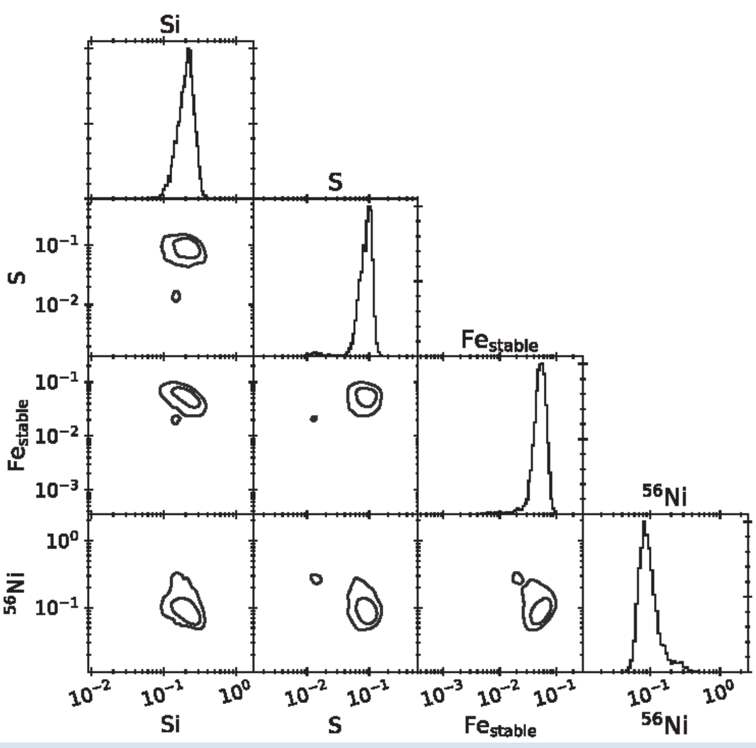


Figure 1. The probability distributions of radiative-transfer parameters that best model the Type Ia supernova SN2002bo are complex and multi-modal. Shown above are posterior probability distribution of the elemental abundances of silicon, sulfur, stable iron, and ^{56}Ni. Contours show 68% and 95% confidence intervals of the Gaussian kernel density estimation (KDE) over the joint distribution of each parameter.

Further reading:

John T. O'Brien *et al* 2021 *ApJL* **916** L14

Urca Cooling in Neutron Star Crusts and Oceans: Effects of Nuclear Excitations

Contributed by Yang Sun (Shanghai Jiao Tong University, China)

Stars end their lives in various ways leaving very different very compact objects as remnants: white dwarfs, black holes, or neutron stars. Studying these remnants sheds light on important open questions such as the origin of the elements. Neutrinos play crucial roles in these phenomena by various mechanisms. For example, neutron stars and white dwarfs can be cooled effectively by the nuclear Urca process.

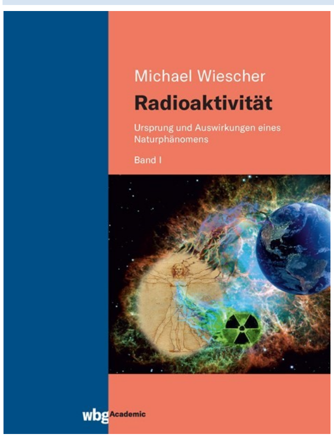
In the Urca process, a pair of nuclear species —in which one is the beta-decay daughter of the other— with a mass difference close to the electron Fermi energy undergoes repeated back-and-forth electron capture and beta-decay. Each step creates a neutrino that carries away energy; this is one of the major cooling mechanisms of neutron stars. This recent work scrutinizes a simplification in the half-century-old standard calculation of the Urca process of neutrino cooling in neutron stars.

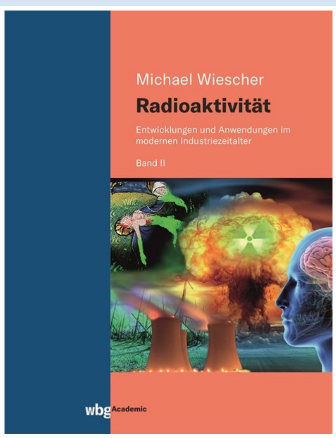
In the original treatment, only the ground states of the nuclei were considered to decay or capture electrons, but this work discovered that thermally populated low-lying excited states can dramatically change the neutrino cooling rate in many Urca pairs. The authors computed an overall effect of a large increase (factor of a few) in the rate of neutron star Urca cooling.

These results amend understanding of neutron star cooling. This impacts many related studies, including cooling of the neutron star remnant of a core-collapse supernova and observations of X-ray bursters. It is anticipated that the findings will have significant implications and stimulate research across subfield boundaries, including astrophysics, nuclear physics, and neutrino physics. The new results for Urca cooling will motivate new research in network simulations and supernova modeling, and it will encourage new measurements of weak interaction rates for excited states in a wide range of nuclei.

Further reading: Wang, L-J, et al. Phys. Rev. Lett., 127, (2021) 172702

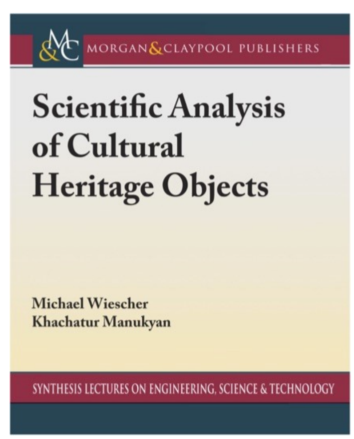
Michael Wiescher Publishes New Textbooks





JINA's first director and current co-PI of JINA-CEE, Michael Wiescher, published two new textbooks earlier this year that will certainly be of interest for the nuclear astrophysics community:

Radioactivity Volumes I and II: After a summary of the history of its discovery, the first part describes its physical and biological laws. The second part deals with radioactivity as a natural phenomenon. These are both currently available in German, and an English translation is in preparation. Published by WBG Academic.



Scientific Analysis of Cultural Heritage Objects:
Coauthored with Khachatur Manukyan, research assistant professor at the University of Notre Dame, this textbook summarizes scientific methods that are currently used to characterize objects of cultural heritage and archaeological artifacts. Published by Morgan & Claypool Publishers.

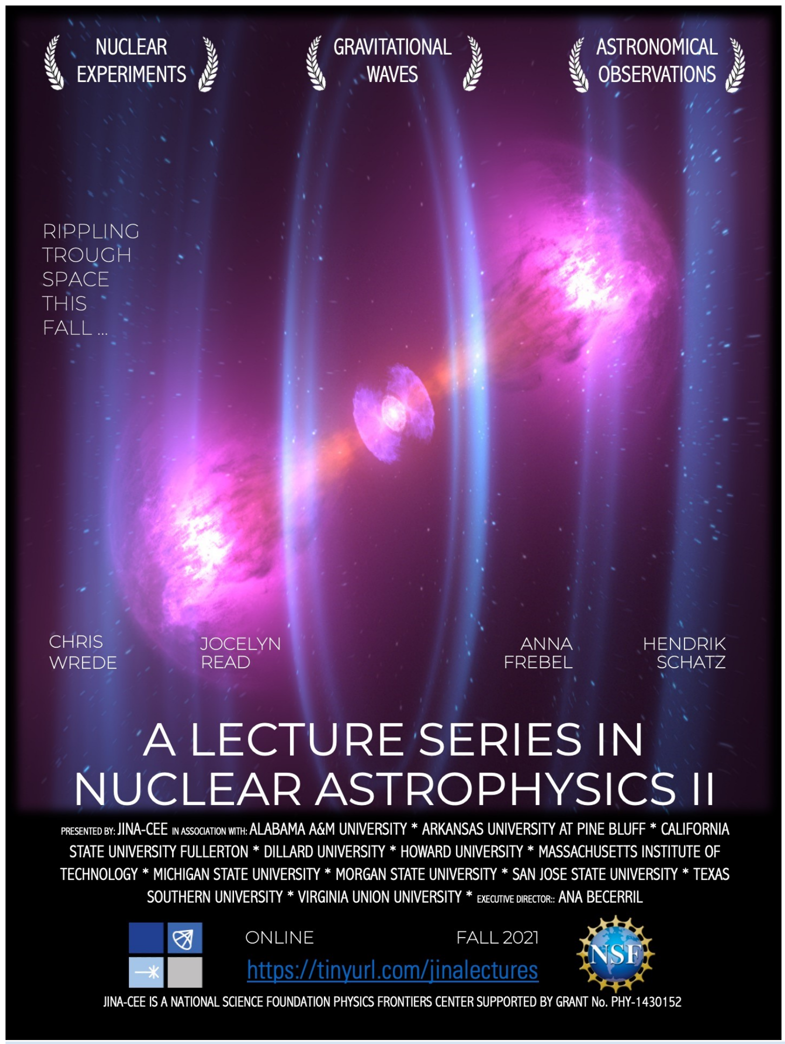
Second JINA-CEE Lecture Series in Nuclear Astrophysics for Minority Serving Institutions Now Publicly Available

The JINA-CEE program to introduce and attract students from Minority Serving Institutions (MSIs) to the field of nuclear astrophysics continues to grow. This year we welcomed three new partner institutions: Morgan State, San Jose State and California State Fullerton.

Following the success of the first introductory lecture series offered in the fall of 2020, a second lecture series was prepared for this fall. Students and faculty members from all nine MSIs involved joined these online conversations, and in some cases the lectures were embedded into the class curriculum. The 2021 lecture series focused on how the first observations of a neutron star merger in both gravitational waves and light have changed the way the study the cosmos. Our goal was to show students that given the new ability to detect the various signals (i.e. multi-messengers) from astrophysical phenomena, combined with new and more sophisticated measurements of the short-lived isotopes that take part in them, we are now much closer than ever to understand the most extreme environments in the cosmos. The lecture series showcases JINA-CEE research, stimulates appreciation of fundamental science, and encourages students interested in nuclear physics or astrophysics to pursue research experiences, for example as part of the JINA-CEE community. The 2021 lecture series has a dedicated website where you can learn more, and the recorded lectures are available on our YouTube channel.

Anna Frebel, Jocelyn Read, Hendrik Schatz and Chris Wrede each taught one of the four lectures of the series. They accompanied their stories with engaging audiovisuals that portrayed the very big and the very small scales in sizes and energies involved. Polls sprinkled throughout each lecture helped make each session more interactive and prompted attendees to reflect on the implications of the research they were learning about. Lecturers also provided information about graduate studies and research opportunities available at their institutions, and other career relevant information.

Chris Wrede from MSU kicked off the series by guiding the audience through rare-isotope research and the connection between atomic nuclei and stars like our sun and transient events such as pulsars. Jocelyn Read from Fullerton explained how gravitational waves are produced and detected and how they can help us understand neutron stars and neutron star mergers. Anna Frebel from MIT briefly reviewed the history of the universe in terms of chemical evolution in order to explain how the study of the oldest stars can provide clues about heavy element nucleosynthesis in neutron star mergers. Hendrik Schatz from MSU closed the series by reviewing what we know and what we don't know about the origin of the elements, and introduced some of the exciting mysteries that FRIB may soon help to unlock.



Poster used to advertise the lecture series to students at participating MSIs

JINA-CEE Faces:
Interview with Sanjana Curtis

Sanjana Curtis
University of Amsterdam
and UC Santa Cruz

A passionate science communicator and advocate for underrepresented groups in science, Sanjana Curtis shares with us details about her scientific journey and gives us a glimpse into her work in theoretical astrophysics. She is a postdoctoral researcher at the University of Amsterdam, but is currently based in sunny California where she is a research fellow at the University of California Santa Cruz.

How did you decide to pursue a career in science?
-I was always driven by an innate curiosity to figure out how things worked, but growing up I wasn't aware of physics as a career. I went to college to study electrical engineering and it was during that time when I realized that what I really wanted to do was physics. My mission was then to find a graduate program that would accept someone with a bachelor degree that wasn't physics. After graduating from PES University in India, I moved to the US to study my PhD at North Carolina State University. While in grad school, I tried a few different things but astrophysics was the one that really captured my attention, and decided to join Carla Fröhlich's group to do research on core collapse supernovae.

How do you interact with JINA-CEE?
-Carla introduced me to JINA when I was a student, and since then, I have participated in multiple conferences, workshops, and seminars, for some of which I received JINA travel support. These have facilitated interactions with collaborators considerably. I have also contributed science highlights to the Newsletter. All these have been great resources for me in the sense of community forming and professional development.

What is the focus of your research?
- Connecting the results of calculations to observations of very complex, multi-physics systems like core collapse supernovae, or neutron star mergers, or disks around black holes. I make these connections to observations by predicting nucleosynthesis yields and electromagnetic emission that one would expect to observe.

What's your favorite part of your job?
- I think that what makes my job unique is the fact that I get to think very intensely about topics that are interesting just for the sake of understanding how the universe operates on a fundamental level. Also, I like the fact that there are people around me who care about thinking intensely about these topics as well, and we can talk about them and work together.

What do you consider has been your most important scientific finding so far?
- Early in my PhD we were looking at the material that is ejected from core collapse supernovae, and by carefully studying how neutrinos interact with this material we were able to understand that the neutrinos can change the proton to neutron ratios, which in turn changes the isotopes produced by the explosion. I thought it was very interesting and compelling to be able to show that carefully accounting for the neutrino physics led to yields from theory matching observations better, and across a large sample of simulations.
- A second one is my most recent paper about outflows of highly magnetized neutron stars. These ejecta could help us understand the blue component of the observed electromagnetic emission from a neutron star merger like GW170817, and how future observations would look.

What advice can you give to junior researchers?
- I think it is important that you work with people who are supportive, which applies not only to your PhD advisor but also to collaborators and peers. It makes for a much more joyful experience to work with people who care about you and who want your success. As a student, I think this is more important than the topic you chose to work on. Also, it is OK to be yourself in the sense that you don't need to fit a particular mold of what other people think a scientist should be. This can be difficult, at times it can feel like you don't belong or that you can't be successful but you have to remember that there is more to life than a very linear path to a successful career.

What do you do when you are not doing physics?
- I have plenty of hobbies, most of which I enjoy outdoors, like running, hiking and roller skating. I also enjoy painting in watercolors. I am also very active in science communication and have exciting projects coming out soon!

Awards for JINA-CEE Members

Erika Holmbeck
Carnegie Observatories

Erika Holmbeck receives the 2022 APS Dissertation Award in Nuclear Physics

NASA Hubble Fellow Erika Holmbeck is being recognized for her doctoral thesis research of outstanding quality and achievement in nuclear physics. Holmbeck gave an invited talk at the 2021 APS Division of Nuclear Physics Meeting in October, where she received the award. Her dissertation was chosen "For elucidating the nature of the rapid neutron-capture process, including actinide production in the early Universe, with an innovative combination of nuclear network calculations and spectroscopic observations of metal-poor stars in the Milky Way."

Holmbeck became a JINA-CEE member while working on her PhD at the University of Notre Dame. After graduating in 2020 she joined the Rochester Institute of Technology as a postdoctoral researcher. In 2021 she was selected a NASA Hubble Fellow, and joined the Observatories of the Carnegie Institution for Science in Pasadena, CA.

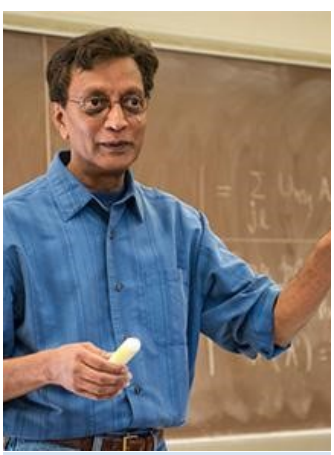
Artemis Spyrou
Michigan State University

Artemis Spyrou Selected as a Fellow of the American Physical Society

Professor of physics at FRIB and Michigan State University's Dept. of Physics and Astronomy Artemis Spyrou was selected Fellow of the American Physical Society, a distinction recognizing researchers for significant and innovative contributions to physics. APS Fellowship is restricted to just 0.5% of the APS membership in a given year.

Spyrou was nominated by the Division of Nuclear Physics, and is being recognized "For studies using total absorption spectroscopy and the beta-Oslo technique to determine neutron-capture rates for astrophysical modeling, and for dedication to communicating science to the general public." In the materials nominating Spyrou, her colleagues described her as an “unstoppable force” in nuclear physics research and outreach.

Spyrou received her PhD from the National Technical University of Athens, and has been a JINA member since joining the NSCL as a postdoctoral researcher in 2007.



Madappa Prakash
Ohio University

Madappa Prakash is Awarded the 2022 APS Bethe Prize

Professor Madappa Prakash, faculty member at Ohio University and long-time member of JINA, was awarded the 2022 American Physical Society Hans A. Bethe Prize. Each year the prize is awarded to recognize outstanding work in theory, experiment, or observation in nuclear astrophysics. Prakash’s citation reads “*for fundamental contributions to the physics of hot and dense matter, and their implications for heavy ion collisions and multi-messenger observations of neutron star structure and evolution*”.

Prakash’s research program operates at the interface between nuclear physics and astrophysics, including pivotal works on the neutron star equation of state and neutron star cooling. His recent work has directly informed interpretations of multi-messenger data from neutron stars, including observations from the NICER X-ray telescope and the LIGO and VIRGO gravitational wave observatories. Prakash has been a dedicated research mentor over his career, advising 14 PhD students and over 30 undergrads.

JINA-CEE Institutions

JINA-CEE Core Institutions:

Michigan State University, Physics and Astronomy Department, FRIB
University of Notre Dame, Department of Physics, ISNAP
Arizona State University, SESE
University of Washington, INT

JINA-CEE Associated Institutions:

Alabama A&M University, Anton Pannekoek Institute for Astronomy University of Amsterdam, Netherlands, Argonne National Laboratory, Arkansas University At Pine Bluff, Central Michigan University, California State University Fullerton, ChETEC, CNA Shanghai Jiao Tong University China, Dillard University, EMMI-GSI Helmholtz Gemeinschaft Germany, Florida State University, Howard University, INPP Ohio University, Los Alamos National Laboratory / LANSCE-3 / T2, Massachusetts Institute of Technology, McGill University Canada, MoCA Monash University Australia, Morgan State, National Astronomical Observatory of Japan, North Carolina State University, NUCLEI LANL, Ohio State University, Rutgers University, San Jose State, Texas Southern University, TRIUMF Canada, University of Chicago, University of Hull UK, University of Minnesota, University of Oslo Norway, University of Victoria Canada, Virginia Union University, Western Michigan University.

JINA-CEE also has participants from:

Bucknell University, California Institute of Technology, Gonzaga University, Al-Balqa Applied University Jordan, LBNL, Louisiana State University, MPI for Extraterrestrial Physics Germany, ORNL, UNAM Mexico, Stony Brook University, TU Darmstadt Germany, University of Illinois, University of Michigan and Wayne State University.

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