Section A - Executive Summary

Research Hub for Fundamental Symmetries, Neutrinos, and Applications to Nuclear Astrophysics: The Inner Space/Outer Space/Cyber Space Connections of Nuclear Physics

Intellectual Merit: The first goal of this proposal is to create a coordinated NSF national theory effort at the nuclear physics core of three of the most exciting "discovery" areas of physics:

- *Neutrino Physics:* Beyond-the-standard model (BSM) physics of neutrinos, including their mixing phenomena on earth and in extreme astrophysical environments; the absolute mass scale and the eigenstate behavior under particle-antiparticle conjugation, and the implication of mass and lepton number violation for cosmological evolution; and the relevance of neutrinos to astrophysics both in transporting energy and lepton number, and as a probe of the otherwise hidden physics that governs the cores of stars and compact objects.
- *Dense Matter:* The recent start of Advanced LIGO Run 1 could well lead to the observation of the gravitational wave signatures from neutron star (NS) mergers by the end of the decade. This follows the observation of a NS of nearly two solar masses by Shapiro delay, and of "black-widow" systems hinting of even higher masses. Current and anticipated observations provide unprecedented opportunities to determine nuclear matter properties at densities and isospins not otherwise reachable, and to relate them to those we measure in laboratory nuclei.
- *Dark Matter:* Definitive evidence that dark matter (DM) dominates our universe is the second demonstration of BSM physics. Nuclear physics can play an important role in this field by helping direct-detection experimenters understand the variety and nature of the possible responses of their nuclear targets, by connecting the stellar processes we study to the feedback mechanisms that can alter galactic structure, and by contributing to the understanding of composite dark matter in cases where lattice QCD methods are relevant.

These problems pose a common challenge to nuclear physics: the description of fundamental weak interactions in nuclei and nuclear matter, and their embedding in exotic astrophysical environments - the Big Bang, supernovae (SNe), and NSs – where nuclear microphysics governs the evolution, cooling, transport, and nucleosynthesis. The Hub proposed here will position nuclear physics to play a prominent and also very necessary role in these three discovery areas over the next five years.

Astrophysical environments are not only governed by fundamental microphysics, but often provide unique laboratories for probing otherwise untestable aspects of interactions. The first evidence for neutrino oscillations came from models of the Sun. The solar MSW mechanism, the phenomenon fixing the order of two neutrino mass eigenstates, exhibits many new aspects at higher density, influencing all flavors and driving novel nonlinear phenomena in SNe. Sterile neutrinos barely coupled to the known neutrinos can have enormous consequences for Big Bang nucleosynthesis. Phases of nuclear matter otherwise inaccessible may influence the properties of NS cores. There is the possibility of determining both the neutrino absolute mass scale and hierarchy from cosmology – with the concordance of the results with future laboratory determinations a matter of exceptional importance. FRIB's exotic nuclei, so difficult to produce on earth, are present in the ground states of the hot nuclear matter ejected in SNe, and control novel nucleosynthesis.

The inner space/outer space/cyber space theme of the proposed Hub describes the synthesis we think can be achieved. Quantitative connections between fundamental symmetries and laboratory tests of those symmetries (inner space), and astrophysical observables such as the electromagnetic and nucleosynthetic signals from a core-collapse (CC) SN or NS merger (outer space), require sophisticated numerical modeling (cyber space). Team organization was guided in part by the desire to be at the forefront of the needed modeling. The proposed Hub includes experts associated with 1) SciDAC efforts in Green's function Monte Carlo and Lanczos shell model (SM) developments; 2) code suites such as CASTRO/Sedona suitable for integrating CCSNe out to late times; 3) the most advanced nucleosynthesis networks; 4) electroweak nuclear response codes; and 5) stellar evolution codes such as Kepler, MAESTRO, and the Princeton Standard Solar Model, with capabilities that include convection and accretion. Early career researchers affiliated with this proposal are involved in simulating mergers and their gravitational wave signals. We have partnerships with the computational science groups at LBL, ORNL, ANL, and UCSD, hold INCITE grants, and have experience with machines such as Cori, Edison, Titan, Mira, Vulcan, and BlueWaters. Some of the group's codes are in the current DOE ASCR competition for exascale development.

The Hub's focus will complement, not duplicate, similar collaborations. The DOE is establishing a fundamental symmetries topical collaboration that will focus on matrix element calculations for neutrinoless double beta decay, extracting constraints on CP-violation from electric dipole moment (edm) measurements, and hadronic parity nonconservation (HPNC), work important to $\beta\beta$ decay experiments, the HPNC program at the SNS, and nedm. The DOE SciDAC3 porfolio includes two very relevant projects, the lattice QCD collaboration CalLAT (HPNC in few-nucleon systems) and the USQCD/BSM collaboration (lattice methods for QCD-like composite DM theories). Our physics focus and experimental connections are largely distinct: FRIB (neutron rich nuclei in explosive nucleosynthesis), JLab (including the PREX/CREX test of the nuclear symmetry energy), and proposed neutrino beam experiments (including the DUNE target response, the DUNE SN program, and proposed low-energy solar and coherent neutrino scattering experiments). The Hub's numerical efforts on modeling SNe, NS mergers, and associated nucleosynthesis fill a gap in the current SciDAC3 nuclear physics portfolio. The Hub can be viewed as the missing piece in a puzzle, that when added, will complete the overall picture. Because Hub members have connections to these other projects, our work will enrich their efforts, and conversely.

Many early career researchers are attracted to problems in fundamental symmetries and nuclear astrophysics. The second goal of our Hub is to draw new talent into the field, enhance the nuclear physics training experience through collaborations not normally available to postdocs attached to a single institution, and provide opportunities for interdisciplinary interactions that are often crucial to further advancement. The Hub's "graduating" postdoctoral fellows will not only be expert in their immediate research area, but confident in their ability to interact across boundaries with experimentalists, observers, particle and astrophysics theorists, and computational physicists – and thus to become valued faculty members in a broad-based physics department.

Broader Impacts: Essentially all of the Hub's resources will be focused on postdoctoral training and career enhancement. The Hub's design borrows ideas from two very successful efforts, the INT and the Einstein Fellows. The INT has a reputation for producing independent, broadly educated postdocs: its programs provide exposure to a diverse set of subjects and ideas. The NASA Einstein (and Hubble) programs empower postdocs by allowing them to decide where to spend their fellowships, encouraging independence and scientific initiative.

The Hub will couple eight sites with three centers, organized to provide a three-year postdoctoral fellow program offering two years of in-depth training at a site followed by a third in an interdisciplinary center. The eight sites – Kentucky (Gardner), LANL (Carlson, Cirigliano, Gandolfi), Minnesota (Qian), NC State (McLaughlin), Northwestern (DeGouvea), Notre Dame (Surman) , Ohio U (Phillips, Prakash), and Wisconsin (Balantekin) – are prominent nationally in fundamental symmetries and nuclear astrophysics. The three centers – UC Berkeley (Haxton, Kasen), UC San Diego (Fuller), and U. Washington/INT (Reddy, Lattimer) – are major research centers with fundamental symmetries/nuclear astrophysics programs imbedded in broader organizations. The associated coPIs play prominent roles in UCSD's Center for Astrophysics and Space Science, Berkeley's Theoretical Astrophysics Center (campus) and Institute for Nuclear and Particle Astrophysics (LBNL), and the Institute for Nuclear Theory.

The Hub Fellow applicants will be asked to specify three sites of interest to them, and to indicate their preferences for the third year at a center. Postdoc selection will be done by the full group of coPIs. The site of most interest to the candidate will lead the interview process, with the candidate's seminar broadcast to other sites. We believe a selection process in which the entire group of coPIs participates will help to generate broadest and most diverse pool of candidates, from which the strongest would be selected. When an offer is made to a candidate, the candidate will be allowed to choose from among the available sites. This will allow the candidate to consider family issues, such as child care facilities and spousal opportunities, that may vary among the Hub's various sites. Over the five year cycle each site should have an opportunity to host a Fellow.

Each Fellow will have two mentors, one local and one residing at a second site or center, an arrangement designed to encourage the Fellows to function as a member of a collaboration, rather than a postdoc for a local site. These pairings will be arranged in partnership with the Fellow: the second mentor might be a coPI from the center the Fellow will join in the third year, or a member from another site with shared scientific interests. The Fellows will be provided with travel support that can be used to facilitate multi-site collaborative work. As our goal over five years is to train eight postdocs, the plan should keep each coPI engaged as a mentor for the Hub's duration, even if a given site may host a Fellow for only two years. The collaboration includes three women coPIs who lead aspects of our program on nucleosynthesis, neutrinos, and DM. They will be available as mentors and will implicitly serve as role models. Long-distance collaborations and mentor-Fellow interactiions will be facilitated by the electronic communications facilities available at Hub institutions, some of which are quite advanced.

The mentors will provide scientific and professional guidance as well as advocacy, identifying opportunities, such as seminars or convener roles, to advance the Fellow's professional development. The mentors for each Fellow will caucus twice each year, to discuss the Fellow's progress as well as opportunities for effective mentoring, providing feedback to the Fellow and a progress report to the PI. This proposal describes plans to utilize existing community funding/facilities for relevant workshops – Hub members will make proposals for INT and KITP programs, for the LBNL summer school, for TALENT, etc. The Hub will also sponsor its own annual workshop/collaboration meeting. The Fellows will play leading roles in these activities.

The Centers will have a special responsibility as the third-year hosts. At this point the Fellows will be fully integrated into the Hub collaborations, with a record of associated publications. The Centers provide interactive, interdisciplinary environments, each with a special character, with abundant seminars, lively visitor programs, etc. We view the third year as an opportunity to help each Fellow integrate his/her work into a broader physics context, possibly leading to new collaborations at the boundaries of nuclear physics. The Center coPIs will be part of the mentoring team advising the Fellow on job searches, including opportunities to step up to the faculty level.

Section B - Results from Prior NSF support:

A. B. Balantekin

1. (a) *NSF award numbers:* PHY-1205024 and PHY-1514695
   Amounts: $380,000 and $300,000
   Award periods: 05/01/12-04/30/16 and 08/01/15-07/31/18

   (b) *Titles:* Research in Theoretical Nuclear and Neutrino Physics
   Research Topics in Theoretical Nuclear and Neutrino Physics

   (c) *Summary of results: Merit:* These grants support the main theoretical research activity of Balantekin at the interface of nuclear, particle physics and astrophysics. This research led to i) previously unknown symmetries of collective neutrino oscillations and exploration of their consequences in CCSNe; ii) limits on neutrino magnetic moments; iii) elaboration of the impact of the physics beyond the standard model (including neutrino magnetic moments) on BBN; iv) calculation of the neutrino-^{13}C cross sections, crucial for achieving a high precision in scintillator based experiments; and v) inclusion of plasma effects on astrophysical reaction rates. *Broader Impacts:* Virtually all of the work involves collaborations with graduate students that helped them to develop professionally as independent researchers.

   (d) *Publications resulting from the NSF award:* So far 39 publications resulted from those grants within the last five years. Representative publications include:

   - N. Vassh, E. Grohs, A. B. Balantekin and G. M. Fuller, Phys. Rev. D **92**, 125020 (2015) (Majorana Neutrino Magnetic Moment and Neutrino Decoupling in Big Bang Nucleosynthesis [arXiv:1510.00428]).
   - Y. Pehlivan, A. B. Balantekin and T. Kajino, Phys. Rev. D **90**, no. 6, 065011 (2014) (Neutrino Magnetic Moment, CP Violation and Flavor Oscillations in Matter [arXiv:1406.5489]).
   - A. B. Balantekin and N. Vassh, Phys. Rev. D **89**, no. 7, 073013 (2014) (Magnetic moments of active and sterile neutrinos [arXiv:1312.6858]).

2. (a) *NSF award numbers:* PHYS-1239053, PHYS-1342611, and PHY-1523395
   Amounts: $12,000, $12,000, and $12,000
   Award periods: 8/15/2012-7/3/2013, 6/1/2013-7/31/2014, and 03/01/15-02/29/16

   (b) *Titles:* Summer Program at CETUP*
   Center of Theoretical Underground Physics and Related Areas
   2015 Summer Program at Center for Theoretical Underground Physics and Related Areas (CETUP*)/PPC in Lead/Deadwood, SD

   (c) *Summary of results: Merit:* CETUP* is intended to be the central collaboration point for long term, intermediate, and programmatic functions for physics and related fields that deal directly with the experimental work being conducted at the underground laboratories. CETUP* is conceived as a forum to get together, to exchange ideas, to discuss recent theoretical results, and debate experimental results and projects. *Broader Impacts:* Balantekin helped start CETUP* and organized (along with with B. Szczerbinska) all the CETUP* programs that took place at Lead, South Dakota every year since its conception in 2011. The programs have helped professional physicists, including early career scientists, to develop the scientific connections they need to be successful in this interdisciplinary and rapidly expanding field.

   (d) *Publications resulting from the NSF award:* Two proceedings were published resulting form this activity with a third one in preparation.

George Fuller

1. (a) *NSF award numbers:* PHY13-07372 and PHY09-7006
   Amounts: $559,633 and $523,199
   Award periods: 09/01/13-08/30/16 and 08/01/10-09/01/13
   (b) *Title:* Nuclear, Particle, and Weak Interaction Physics of the Big Bang and Stellar Collapse
   (c) *Summary of results: Merit:* These grants support the main theoretical research activity of Fuller at the interface of nuclear and particle physics and cosmology. Key advances from this work include: 1) derivation from first principles of the quantum kinetic equations that provide a complete description of neutrino spin and flavor evolution in dense matter; 2) discovery of a MSW-like level crossing for the neutrino-antineutrino channel, causing significant conversion; 3) construction of the BURST code that, for the first time, can couple a full BBN nuclear reaction network with a full Boltzmann multi-energy-bin neutrino transport calculation; and 4) studies of the subtle effects of neutrino mass ionization equilibrium freezeout at the CMB photon decoupling epoch. *Broader Impacts:* The PI's research effort is built around the training of students. He has participated in, and organized, summer schools targeting nuclear, particle, and astrophysics graduate students: lectured in the 2012 National Nuclear Physics Summer School, organized (with W. Haxton) the TAUP Summer School at Asilomar in 2013; lectured in and helped organize the 2014 TALENT Summer School at MSU; organized (with J. Primack UCSC) and raised funds for "Neutrino and Nuclear Astrophysics," the 2014 International Summer School on AstroComputing at the San Diego Supercomputer Center/UCSD. Additionally, the PI is the Chair of the International Advisory Committee for the Center for Nuclear Astrophysics (CNA) at Shanghai Jiao Tong University and helped organize a summer school there. As Director UCSD's CASS, the PI coordinated the hiring of an Academic Coordinator for Outreach, Karen Flammer. Adam Burgasser (UCSD) and the PI worked with Willie Rockward (Morehouse College) to create the Morehouse-UCSD Bridge Program in Physics, which provides Morehouse students with summer internships at UCSD. The PI supervised one of these students, Jeremy Ariche, in 2014. The PI supervised four successful PhD candidates during the grant period (J. Cherry, W. Misch, A. Vlasenko, E. Grohs), and helped four others start their research careers (Amol Patwardhan, Luke Johns, James Tian, Jung-Tsung Li).

   (d) *Publications resulting from the NSF award:* As of this date, 43 publications have resulted from the work: the length of the publication list precludes its inclusion here, but all of the publications are available on the arXiv. The publications in refereed journals include: Physical Review Letters (1), Physics Letters B (1), Physical Review D (13), Journal of Cosmology and Astroparticle Physics (JCAP) (2), Physical Review C (2), Annual Review of Nuclear and Particle Science (1), Astroparticle Physics (1), Progress in Particle and Nuclear Physics (2), Modern Physics Letters (2), and Journal of Low Temperature Physics (1). Recent representative publications include:

   ◦ N. Vassh, E. Grohs, A. B. Balantekin and G. M. Fuller, Phys. Rev. D **92**, 125020 (2015) (Majorana Neutrino Magnetic Moment and Neutrino Decoupling in Big Bang Nucleosynthesis [arXiv:1510.00428]).

   ◦ E. Grohs, G. M. Fuller, C. T. Kishimoto, and M. W. Paris, Phys. Rev. D **92** (2015) 125027 [arXiv:1412.6875]

   ◦ A. Vlasenko, G. M. Fuller, and V. Cirigliano, "Neutrino Quantum Kinetics," Phys. Rev. D **89** (2014) 105004 [arXiv:1309.2628]

W. C. Haxton

1. (a) *NSF award number:* PHY-1343814
   Amount: $20K
   Award period: 7/15/13-6/30/14
   (b) *Title:* School on Astroparticle and Underground Science
   (c) *Summary of results: Merit:* The grant provided partial support for the School on Astroparticle and Underground Science that was coordinated with TAUP2013, the major international conference in this field. Fifty-seven research students heard lectures from some of the world's leading experts on nuclear and particle astrophysics, cosmology, and gravitation. *Broader Impacts:* The school made important contributions to the education of the student participants, and allowed them to meet colleagues of similar age and experience, part of future community building. The concluding poster session, scheduled at the start of the TAUP conference, gave the students an opportunity to present their work to the world-wide community.
   (d) *Publications resulting from the NSF award:* The students were invited to submit written versions of their papers to the conference proceedings, which were published in the online journal Physics Procedia. The proceedings can be found at `http://www.sciencedirect.com/science/journal/18753892/61`.
   (e) *Research products and their availability:* All records from the school are preserved electronically, including the lectures. The materials can be found at `https://commons.lbl.gov/display/TAUP2013/School+Program+and+Schedule`.

2. (a) *NSF award number:* PHY-1063090 AM004
   Amount: $293.8K
   Award period: 3/1/11-2/28/16
   (b) *Title:* National Nuclear Physics Summer School
   (c) *Summary of results: Merit:* This long-standing nuclear physics summer school is held yearly, supported by the NSF, APS Division of Nuclear Physics, and the INT. Typically 40-60 students attend, hearing lectures from approximately 10 lecturers chosen from among the community's leading researchers and teachers. *Broader Impacts:* The school is designed to expose advanced graduate students and beginning postdoctoral researchers to the full breadth of nuclear physics (both theory and experiment), and to help the participants build connections with one another, as part of the process of establishing a new generation of nuclear physicists.
   (d) Publications resulting from the NSF award: None.
   (e) Research products and their availability: School records, including electronic versions of the lectures, for the schools covered by this grant as well as for those supported under previous grants are archived by the INT. The link can be found on the INT home page, `http://www.int.washington.edu`. These lectures have proven to be an important resource for the entire community.

D. Kasen

1. (a) *NSF award number:* AST-1109896
   Amount: $309k
   Award period: 08/01/11-7/31/2016
   (b) *Title:* Explaining Peculiar Thermonuclear SNe

(c) *Summary of results: Merit:* This project involved theoretical studies of peculiar SNe believed to be the result of thermonuclear explosions in, e.g., degenerate white dwarf (WD) stars. We carried out simulations of several different scenarios, including models of Type Ia SNe from the merger of two WDs, and the nature of rapidly evolving transients thought to be related to partial explosions of WDs. Our method involved simulating the hydrodynamics and nucleosynthesis in stellar explosions, and modeling the observable light curves and spectra with the radiation transport code SEDONA. Our results have helped clarify the physical origin of both normal and unusual Type I SNe. *Broader Impacts:* The grant was largely used to support graduate and undergraduate students and postdocs, furthering the training of early career scientists. The PI was co-director of the UC High Performance AstroComputing Center Summer School in 2011, which presented material related to this project. The PI recently had a popular article accepted for publication in *Scientific American*, which describes some of the topics studied under this project, and has also written a related pedagogical chapter on "Peculiar Supernovae" to appear in the *Supernova Handbook*, a book aimed at helping graduate students entering the field.
(d) *Publications resulting from the NSF award:* So far 10 refereed publications have resulted from this grant. Representative publications include:

- J. Bloom, D. Kasen, et al.,"A compact degenerate primary-star progenitor of SN 2011fe", Astrophysical Journal, p. 17, vol. 744, (2012).
- K. Shen, L. Bildsten, D. Kasen and E. Quataert, "The long term evolution of double white dwarf mergers", Astrophyiscal Journal, p. 35, vol. 748, (2012).
- C. Raskin, D. Kasen et al., "Type Ia Supernovae from Merging White Dwarfs. II. Post-merger Detonations?, ApJ, 788, 75 (2014).

M. Prakash

1. (a) *NSF award number:* AST - 0708284
   Amount: $270,063
   Award period: 09/01/2007 - 08/31/2011 (3 year award - 1 year no cost extension)
   (b) *Title:* The Hydrodynamical Histories of Elliptical Galaxies
   (c) *Summary of results: Merit:* The PI replaced astronomer T. S. Statler during the period he was NSF program officer. Projects goals focused on achieving a better understanding of the effects of the energetics of supermassive black holes in the centers of galaxies on galaxy evolution and galaxy properties. The evolution of isolated elliptical galaxies, interacting elliptical galaxies, and merging spiral galaxies were simulated, employing different models for black hole energetics in order to access their consequences for galactic structure. *Broader Impacts:* The grant supported the doctoral dissertation work of a graduate student, who concentrated on the gas-dynamical simulations described above. The supported student had a change of career goals late in the period of support, finishing with a Master's degree.
   (d) *Publications resulting from the NSF award:*

- Diehl, S. *et al.*, "Generating Optimal Initial Conditions for Smooth Particle Hydrodynamics Simulations", Publications of the Astronomical Society of Australia (2015); arXiv: 1211.0525v2
- Statler, T. S. 2012, "Hot Gas Morphology, Thermal Structure, and the AGN Connection in Normal Elliptical Galaxies," in "Hot Interstellar Matter in Elliptical Galaxies," ed. D.-W. Kim and S. Pellegrini, Springer ASSL series #378, pp. 207 - 234.

Section C - Hub Description

Overview: The Hub research program will position nuclear physics to play an important and necessary role in three of the most exciting discovery areas in fundamental physics, the novel flavor physics of neutrinos, the nature of the dense nuclear matter that governs the structure of NSs and the core bounce of SNe, and the nature of the DM that dominates our universe. The nuclear physics of these three problems involves a common theme, the description of fundamental weak interactions in nuclei and nuclear matter, and their embedding in exotic astrophysics environments, where they control the cooling, the transport of energy and lepton number, and the nucleosynthesis. Hub research will connect the nuclear microphysics to the astrophysics, further developing the numerical tools required to treat weak interactions under extreme conditions as well as those needed to model the astrophysical environments producing those conditions. By engaging young researchers in this program, we hope to produce a new generation of researchers who are both deep and broad – skilled in the nuclear microphysics, while aware of its relevance to a range of astrophysical problems.

The physics flows in both directions: a SN cannot explode unless microscopic processes transport the energy released in CC preferentially to the mantle, allowing ejection of material that was previously bound. Hydrodynamic compression, shock creation and propagation, storage of gravitational energy in a leptonic sea, and transport of that energy by neutrino processes all play key roles in one of Nature's most important nucleosynthetic factories. Decades of work have led to the present state of the art, high fidelity 3D calculations with realistic microphysics that can follow dynamic explosions out to times of ~ 1 sec. A theme of our Hub will be to connect the conditions at 1 sec to the electromagnetic and nucleosynthetic observables from much later times – which requires a different set of radiative transport codes of the type members of our Hub have developed. Conversely, the conditions Nature generates in such an explosion are so exotic that they depend on aspects of fundamental physics that may otherwise be hidden from us. Perhaps the most extraordinary example is DM – the gravitational "glue" through which structure forms, so far detected only via its critical role in shaping our universe, and without which we would not have a Milky Way to study. The neutrino physics which led to this year's Nobel Prize – which requires extensions of our standard model to include massive neutrinos and their flavor mixing – becomes far more exotic at the core of a SN, where novel nonlinear phenomena can radically alter both flavor and lepton number. One also encounters extremes in the hadronic physics. Our FRIB experimental colleagues are working diligently to approach the neutron drip line, where they will be rewarded by the opportunity to study rare isotopes, but only for the instant before they retreat to the valley of stability. But in high-density astrophysics, neutron-dominated matter is often the ground state, allowing us to study over long times the consequences of isospins and densities unreachable on earth. Already observations of NS masses have greatly constrained the nuclear equation of state; with the recent discovery and the continued monitoring of binary pulsars, and the anticipated merger signals that Advanced LIGO might detect, a great deal more may be learned.

This confluence of inner and outer space, which can be quantitatively linked in our theoretical work because of the power of modern computer simulations, is the theme of our Hub. We see this as a marvelous area for training postdocs, who can develop a "toolbox" of specific nuclear physics skills that can then be applied to a variety of important, interdisciplinary astrophysical problems. As Fig. 1 conveys, a postdoc who learns state-of-the-art nuclear structure techniques to evaluate electroweak responses important to neutrino-driven nucleosynthesis in a SN, for example, can pivot in a moment to calculate DM direct-detection scattering cross sections. In fact, our much more mature understanding of the former may allow that postdoc to make important conceptual contri-

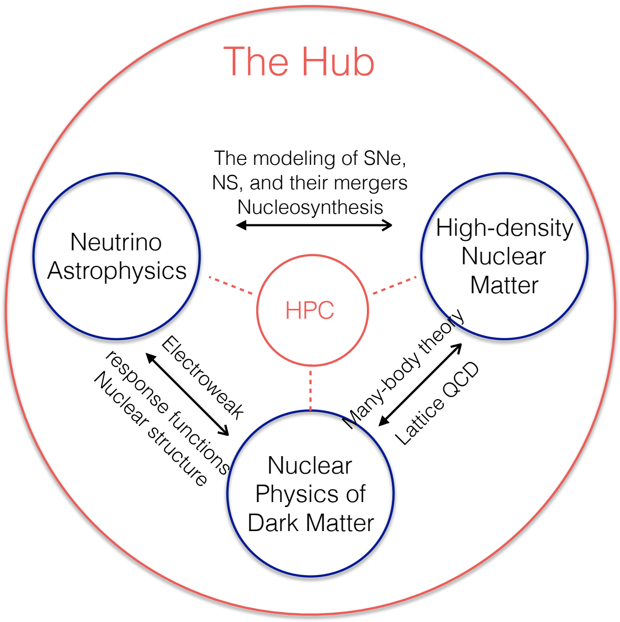

Figure 1: Qualitative illustration of the connections between the areas that come together in understanding the astrophysics of compact objects and the associated nucleosynthesis. High performance computing (HPC) plays an important role, establishing the link between the underlying fundamental physics and astrophysical observables.

butions to the latter. Working in partnership with others, he/she will be able to able to model the coupled neutrino and hadronic physics, and its nucleosynthetic consequences, in CCSNe – or in NS mergers, disks, etc. The Hub has been designed to create a "collaboratory" environment in which postdocs will be drawn into problems that use their skills in a variety of ways, so that in their future careers they will continue to look for opportunities to stretch their horizons, as well as our field.

The Hub's People: As described elsewhere in this proposal, the postdocs will spend two years at one of our eight sites, followed by one year at one of the three Hub centers. The supplementary documentation includes short descriptions of each senior investigator's envisioned role in the Hub. In a briefer format, here we list the sites, their senior personnel, and the principal areas of interest of the investigators:

Kentucky	Susan Gardner	Dark Matter, Neutrinos
Los Alamos	Joe Carlson	Dense Matter, Neutrinos
	Vincenzo Cirigliano	Dark Matter, Neutrinos
	Stefano Gandolphi	Dense Matter, Neutrinos
Minnesota	Yong − Zhong Qian	Nucleosynthesis, Neutrinos
North Carolina State	Gail McLaughlin	Nucleosynthesis, Neutrinos
Notre Dame	Rebecca Surman	Nucleosynthesis, Neutrinos
Northwestern	Andre DeGouvea	Neutrinos (Models)
Ohio U.	Madappa Prakash	Dense Matter, Neutrinos
	Daniel Phillips	Dense Matter (EFT)
Wisconsin	A. Baha Balantekin	Neutrinos, Nucleosynthesis

The Hub centers are

Berkeley	Wick Haxton	Dark Matter, Neutrinos
	Dan Kasen	Nucleosynthesis, SN/NS Modeling
San Diego	George Fuller	Neutrinos, Nucleosynthesis
Washington	Jim Lattimer	Dense Matter, Neutrinos
	Sanjay Reddy	Dense Matter, Neutrinos

One of the roles of the centers is to give postdocs an opportunity to work in groups with especially active visitor programs, so that they will have opportunities to form collaborations across boundaries, if so inclined. The three centers have somewhat different characters. Berkeley has a large Theoretical Astrophysics Center (16 faculty) and a great deal of activity there and at LBL in high performance computing applications to astrophysics and cosmology. The San Diego center will be part of CASS, the Center for Astrophysics and Space Sciences, a multidisciplinary campus unit involved in several high-profile observational efforts; there are connections to the San Diego SuperComputer Center, as well. Washington, because of the INT, is the most active nuclear theory visitor center in the US, and can provide Hub postdocs with opportunities to interact with other segments of our field and to take part in INT programs.

Several of our colleagues have agreed to be "affiliated scientists" of the Hub, not responsible for the Hub's proposed research, but available as long-time collaborators of the senior investigators, to share their expertise with the postdocs. They include Ann Almgren and John Bell, LBL (applied mathematicians involved in the development of the MAESTRO/Castro/Sedona suite for SN physics); Francois Foucart, Philipp Moesta, and Sasha Tcheckhovskoy, Berkeley/LBL (Einstein Fellows involved in numerical simulations of mergers and related numerical astrophysics); Alexander Heger, Monash University (stellar evolution with Kepler); Calvin Johnson, San Diego State and CASS (developer of the highly parallelized SM code Bigstick); Matt Kistler, KIPAC/SLAC (DM indirect signals); Gabriel Martinez-Pinedo, TU-Darmstadt (nuclear reaction input for the r-process); Bernhard Muller, Queen's University, Belfast (3D SN simulations); Filomena Nunes, MSU (FRIB theory users group, reactions); Achim Schwenk, TU Darmstadt (DM nuclear response functions); Aldo Serenelli, Barcelona (standard solar model); Fridolin Weber, San Diego State and CASS (NS structure); and Pavlos Vranas (LLNL) and Andre Walker-Loud (LBL) (lattice QCD theorist connected with the fundamental symmetries efforts of the USQCD/BSM and CalLAT collaborations). Further information is given in Sections F and G. Most of these individuals are connected with one of the three Hub centers, where they might become involved in collaborations involving the Hub postdocs.

Resources available: The nuclear physics groups involved in this proposal can accommodate the day-to-day needs of theorists, e.g., office space, visitor accommodations, local computing clusters, etc. As noted previously, several members are involved in SciDAC/INCITE collaborations: the group's access to high performance computing and supporting computer science is outstanding, due to facilities such as NERSC and SDSC, LANL computing, etc. We have access to modern high-definition video streaming equipment. This will not only be used in site-to-site collaborations, but will also allow us to broadcast seminars. Our plan is to try to schedule e-seminars once a month, as a way to make sure the entire group gathers regularly to hear about progress, and to plan further steps.

Interactions with other groups: Our group includes two members that are also involved with the recently created Topical Collaboration on double beta decay matrix elements and fundamental symmetries (particularly, electric dipole moment measurements). While the work proposed here and by the TC membership has little direct overlap, there are important underlying themes– neutrino mass, lepton number, CP violation – connecting the two efforts. The workshops we will host at the time of our annual meeting will provide a good opportunity to engage members of the TC.

We have close connections to the two lattice QCD efforts most relevant to symmetries. The BSM group – which works on topics such as the structure of composite DM and the neutron edm – is led by one of our affiliates, P. Vranas, and includes participants from Berkeley and Los Alamos. The Berkeley/LBL/LLNL CalLAT group's work focuses on hadronic parity violation, but includes topics like the form factor dependence of $g_A(q^2)$ relevant to our work on weak responses. Our members interact frequently with both collaborations, and the Hub will seek their participation in our annual meeting.

NSF supports a Theoretical and Computational Astrophysics Network (TCAN) with major nodes at the California Institute of Technology, Syracuse University, Cornell University, and the University of Washington, one of our Hubs. Reddy is the UW lead. The Network's goal is to advance the theory of merging compact-object binaries and stellar collapse. Gravitational waves from these types of events are expected to be detected by Advanced LIGO in coming years. The network team's goals are to develop the theoretical and computational tools needed to extract the equation of state of dense nuclear matter from gravitational wave and electromagnetic observations, and to determine the impact of compact-object mergers on the synthesis of light and heavy elements. This project has perhaps the most direct connection to the Hub's goal. Its goals include (1) development of an open-source, next-generation relativistic astrophysics computation framework; (2) improvements in the theoretical understanding of the nuclear equation of state; (3) improvements in the computational treatment of nuclear reactions in merger and collapse simulations; and (4) developing strategies for extracting EoS information from multi-messenger observations. There are abundant opportunities for collaboration between the Hub and TCAN.

Hub Science

Neutrinos and Nucleosynthesis - Overview: Three of the most exciting developments in physics and astrophysics have converged to make neutrino physics an extraordinarily exciting discovery area. First, solar and atmospheric neutrino discoveries, now augmented by a new generation of laboratory and accelerator beam experiments, revealed that our standard model of elementary physics was incomplete, opening up a series of new questions about neutrino mass, flavor, and CP properties. Second, recent and anticipated advances in the capabilities of electromagnetic, neutrino, and gravitational wave ("multi-messenger") probes of compact objects and cosmology have given us a new set of neutrino laboratories, ones creating extremes of density, temperature, lepton number, and isospin impossible to realize on earth. Third, the rapid advance to exascale computing has given us the tools we need to connect astrophysical events to the underlying microphysics, including fundamental neutrino properties.

Neutrinos are inordinately important in astrophysics, transporting most of the energy, entropy, and lepton number in environments like collapsing SN cores, merging NSs, and the early universe, while controlling the isospin of the matter through conversions between protons and neutrons. The specific p/n ratio neutrinos imprint on the matter is crucial to subsequent nucleosynthesis, which terminates at elements just above He in the high-entropy proton-rich gas of the Big Bang, but extends to the transuranic elements in the high-entropy neutron-rich wind blowing off the surface of a nascent NS. The life cycles of massive stars are governed by the interplay of gravity and neutrino emission, and their terminal SN CCs are the most prodigious sources of neutrinos in our galaxy, producing $\sim 10^{58}$ neutrinos of all kinds. While the kinetic and optical displays from such an event are impressive, the energy emitted in neutrinos is 100 times larger.

Neutrino properties are potentially crucial to our understanding of BSM physics. Unlike the charged fermions, the absence of any obvious "charge" label for neutrinos allows them to carry two kinds of mass: this freedom provides a natural explanation for the anomalous mass scale of the neutrinos in the seesaw mechanism, which naively suggests neutrino mass is connected to physics near the GUT scale [1]. The open questions in neutrino mass – the absolute mass scale, the hierarchy, the Majorana/Dirac character – are being attacked both through cosmology and in the laboratory, via a new generation of tritium endpoint, double beta decay, and long-baseline oscillation experiments [2]. Indeed, existing oscillation experiments have established a lower bound for the cosmological neutrino mass of ~ 56 meV, a value within the grasp of next-generation cosmological surveys of various types. While the mixing angles of the three light neutrinos have been measure to good accuracy, the three CP phases have not. One of these will be probed in LBNF, while the two remaining Majorana phases are likely to remain a source of uncertainty in interpreting future ton-scale double beta decay results. The possibility of large CP invariants could help us make progress in understanding the matter-antimatter asymmetry of our universe.

And are there just three neutrinos? As see-saw models introduce heavy neutrinos to engineer light ordinary "active" neutrinos, the expected answer is no. There are several discrepancies in neutrino experiments – the MiniBOONe experiment, the source calibrations of the Ga solar neutrino detectors, the reactor neutrino anomaly – that some argue provide evidence of new, light, but very weakly coupled neutrinos: sterile neutrinos with new mixing angles and CP phases.

Astrophysical neutrinos are valuable for another reason: with typical energies of 100 MeV or less, we understand their interactions with nuclei. The responses are calculable with the standard tools of nonrelativistic nuclear structure, including quantum Monte Carlo (QMC) and the configuration-interaction SM. They are also measurable, using weak interactions in the laboratory, or approximately through surrogate reactions, like forward-angle (p,n) to measure the Gamow-Teller (GT) strength. With facilities like FRIB, such measurements can be extended even to parts of the r-process path. This means that the connection between astrophysical environments and the underlying weak interaction physics can be made with some degree of confidence, a necessary condition if we are to learn new fundamental physics from those environments.

Neutrino scattering and nuclear weak interactions: One goal of the Hub will be to take advantage of modern computational capabilities to advance our understanding of semi-leptonic weak interactions in both low entropy nuclear matter, relevant for compact object mergers and SNe, and high entropy environments characteristic of the early universe. As discussed above, the weak interaction governs stellar evolution, the explosive environments found in CC and NS mergers, and most nucleosynthesis pathways. These environments pose new challenges to theory: Nuclei in extreme environments can be in highly excited, thermally-populated states. Conventional approaches to response functions are not easily adapted to such conditions. Consequently, looking "under the hood" of many stellar evolution codes like Mesa and Kepler, one finds tables of weak rates and neutrino response functions of a variety of vintages, poorly documented, and often in conflict with experiment when extrapolated to known laboratory conditions. Although the modernization of such input could be considered "yeomans work," improvements in such data bases are as important to nuclear astrophysics as a foundation is to a well-constructed building.

The theory and computational issues are not routine. Bigstick [3], which was developed cooperatively by the SciDAC2 UNEDF collaboration and members of our team under SciDAC3, is capable of untruncated SM calculations through most of the $g_{7/2}sdh_{11/2}$ space. We now have highly tuned and remarkably predictive effective interactions that, if used in untruncated spaces, give reliable low-momentum representations of wave functions. An example of the state-of-the-art is GCN5082 [4]. Just as zero-temperature inclusive responses can be calculated using Lanczos moments methods (thus avoiding impractical state-by-state summations), there exist finite-temperature extensions of these methods – though some of the approaches, developed in other subfields [5], have not yet been employed in nuclear physics. The theoretical issues connected with properly defining the partition function are nontrivial: the SM Slater determinant basis, despite its compactness, is in principle complete, so double-counting issues arise if that response is combined naively with those for continuum states such as $(A-1, Z)+n$, for example. Finally, the computer science issues are interesting, due to the combination of SM capabilities allowing full-space calculations, interactions like GCN5082 that are applicable to large libraries of nuclei without nucleus-by-nucleus tuning, and density matrix techniques to extract from the SM results just that information needed to evaluate one-body operators. It should be possible to automate calculations, so that the theorist's time can be invested in the high-level conceptual issues listed above, instead of tedious input-file preparation.

The moments technique is immediately applicable to allowed and first-forbidden operators that dominate nuclear responses for neutrino energies typical of SNe, where $T_\nu \lesssim 6-8$ MeV ($E_\nu \sim 3T_\nu$). A method for treating the full momentum transfer dependence of response functions has been developed [6], should we decide such an extension is necessary. One needs, in addition to charged and neutral-current neutrino reactions important for ν- and $r-$process nucleosynthesis, β decay and free- and bound-electron capture rates, as well as neutral current (neutrino pair) decay of excited nuclei. Past experience shows that improved weak rates can have a significant effect on SN quantities such as the trapped lepton fraction and mass of the homologous core [7, 8].

Neutrino flavor (and spin) evolution in dense matter: The proper treatment of neutrino flavor and spin evolution in explosive astrophysical environments requires the solution of quantum kinetic equations (QKEs) [9, 10, 11, 12, 13]. As general QKE solutions in multi-D environments are currently impractical, researchers have followed an apparently reasonable procedure: separation of regimes and techniques, with 1) Boltzmann neutrino transport at high density (e.g., below the neutrino sphere) where scattering-induced de-coherence dominates and neutrino oscillations are neglected, and 2) coherent, flavor evolution treatment at lower density. In the latter case, a system of $\sim 10^8$ nonlinearly-coupled Schrödingier-like equations can be solved on a supercomputer, with the nonlinearity stemming from the neutrino-neutrino forward scattering contribution to the potential governing flavor transformation. The results are startling: collective neutrino flavor oscillations and their manifestations like the swap/split occurring for a host of conditions potentially relevant for the SN signal and nucleosynthesis [14, 15, 16, 17, 18, 19, 20, 21].

However, this separation of coherent, flavored evolution and incoherent Boltzmann regimes is not valid [22] in some SN epochs, such as the shock breakout neutronization pulse and the iron core CC accretion phase. Even a small amount of direction-changing scattering, e.g., one neutrino in 10^3, can completely alter flavor evolution, converting the flavor evolution problem from an initial value problem into something more akin to a boundary value problem, with scattering facilitating quantum flavor information propagating downward from higher radii. This "halo" of scattered neutrinos (see Fig. 2) also renders flavor evolution dependent on nuclear composition, as coherent neutrino-nucleus scattering varies as the square of the nuclear mass number. This couples flavor evolution to nuclear equation of state physics in a new way. This result led to a derivation of the full QKEs from first principles and the discovery of a surprising way that Majorana neutrinos and antineutrinos can transform into each other (spin flip) in anisotropic media [24, 25, 26, 27, 28].

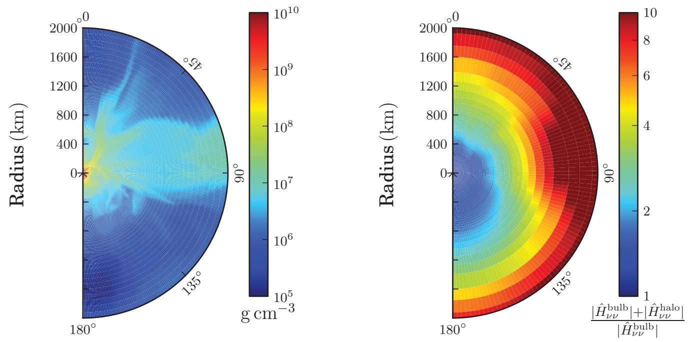

Figure 2: Left: The color scale indicates the density during the accretion epoch for a $15\,\mathrm{M}_\odot$ progenitor CC SN 500 ms after core bounce [23]. Right: Effect of the scattered neutrino halo for the matter distribution to the left. The color scale indicates the ratio of the sum of the maximum (no phase averaging) magnitudes of the constituents of the neutrino-neutrino Hamiltonian, $|\hat{H}^{\rm bulb}_{\nu\nu}| + |\hat{H}^{\rm halo}_{\nu\nu}|$, to the contribution from the neutrinosphere $|\hat{H}^{\rm bulb}_{\nu\nu}|$.

Neutrinos can transform their flavors and/or spins via medium-affected coherent neutrino oscillations, and they can do this through scattering as well. Insight into the QKE's may help with two related issues: (1) Sound waves, shocks, and turbulence can induce non-adiabatic jumps in neutrino flavor survival probability [29] or flavor de-polarization [30, 31, 32, 33, 34]; and (2) Coherent treatments of the neutrino flavor field suggest that there may be no steady state solutions [35, 36, 37]. While solving for neutrino flavor/spin evolution is difficult, solutions are necessary to make contact with important observables such as the CCSN neutrino signal in DUNE and SN nucleosynthesis. Another important goal is a full QKE treatment of the early universe, to make contact with BBN and CMB neutrino physics constraints.

Nucleosynthesis: The SN neutrino-driven wind is thought to be an important galactic source of nuclei above the iron group. The quantity that most directly determines the resulting nucleosynthesis is the neutron-to-proton ratio, set by weak interactions in the wind. As the proto-NS deleptonizes, electron neutrino emission dominates first, initially driven the material to the proton-rich side. These early neutrino-driven winds are thus an attractive potential site for the νp-process [38, 39, 40, 41]. At somewhat later times ($\sim$ seconds), the proto-NS cools via emission of roughly equal numbers of neutrinos in all flavors. If the electron antineutrinos emerge from deeper within the proto-NS and thus at higher energies than the neutrinos, the material can become (modestly) neutron rich. Early calculations suggested the neutrino heating could produce entropies sufficient to sustain a vigorous r-process [42, 43], though problems with this conclusion quickly emerged [44, 45, 46]. While conditions producing the heaviest r-process nuclei are not found in modern simulations [47, 48, 49, 50, 51], the inclusion of new neutrino physics can alter this conclusion [52, 53, 54, 55]. In any event, as the SN neutrino-driven wind is expected to eject $\sim 10^{-3}$ solar masses of material per event to the interstellar medium [56], its composition is of great importance to galactic chemical evolution and nucleosynthesis studies. Our calculations of neutrino transport, oscillations, and nucleosynthesis will not only provide the state-of-the-art characterization, but also an estimate of the error bar on electron fraction, the quantity that most directly determines the various nuclear yields.

Additional proposed sites for neutron-rich nucleosynthesis [57] include NS mergers and black hole (BH) accretion disk outflows. The material promptly ejected in the tidal tails of a NS merger has long been recognized [58, 59, 60] as a potential r-process site. Recent simulations [61, 62, 63] seem to confirm that this very neutron-rich, mildly heated material produces a robust r-process with fission recycling. The ejected masses may be sufficient to account for the net galactic r-process abundances (even if the timescale for production does not entirely fit observations [64, 65]). These simulations, however, do not carefully treat weak interactions in the outflows, and early attempts to add neutrino interactions [66, 67] show both a dramatic decrease in the resulting neutron richness and an r-process reaction flow significantly closer to stability. Thus, an important Hub goal is the completion of realistic neutrino transport and neutrino reaction studies to determine the neutron richness and amount of synthesized material in the merger outflow.

BH accretion disks (AD-BH) can result from NS-NS/BH-NS mergers or the collapse of massive, rotating stars ("collapsars"); some portion of the AD-BH is expected to be ejected in neutrino-driven or viscous outflows, e.g., [68, 69, 70]. The element synthesis in the outflows depends on the AD-BH neutrino emission [71, 72, 73, 74] and oscillations [75, 76, 77]. We will conduct a special study of this environment. As the astrophysical conditions differ significantly from those found in the SN neutrino wind and NS merger tidal tails, AD-BH nucleosynthesis should be distinctive, with different sensitivities to the flavor physics.

The dense matter and neutrino flavor transformation calculations pursued by Hub investigators will provide needed clarification of the range of nucleosynthesis possibilities in such explosive environments. The work could help focus experimental activity on the pathways of most interest, ranging from the proton-rich νp-process to the most neutron-rich, fission-recycling r-process. Our lack of information on the masses and decay properties [78, 79] of the relevant unstable nuclei is a driver for FRIB and similar rare isotope facilities [80]. Because cost and available beam time will limit the number of new experiments that can be done, it is important for theory to provide some guidance. Hub work will provide the best possible characterization of the relevant pathways for the processes of interest, while identify those uncertainties in nuclear masses, decay properties, and reaction rates that, if reduced, will have the greatest impact on our understanding of nucleosynthesis.

Multi-Messenger Observations: In explosive astrophysical environments like CCSNe and NS mergers, hydrodynamics, neutrino flavor physics, and nucleosynthesis are coupled in complex ways. This raises the bar for theory, requiring sophisticated modeling of shock wave production and propagation, complex flavor physics that can affect energy deposition and transport, and nuclear reaction networks. The validation of complex models requires data – do the model reproduce observations? We are fortunate that the field is entering a time when our opportunities to observe transient explosive events are rapidly expanding.

Current and future neutrino detectors like SuperKamiokande, IceCube, and DUNE will record future galactic SN with high statistics - typically 10^4 events would be expected in SuperKamiokande, were a SN to occur 10 kiloparsecs from earth. The neutrino light curve could be followed for several tens of seconds, free of background. The neutrinos come to us from the SN's outer core, decoupling at a density $\sim 10^{12}$ g/cm^3. A comparison of a detected neutrino burst signal with our calculations of the flavor evolution could provide information on the neutrino flavor histories, density profiles, and geometry of the dense supernova environment. This includes dynamical information. During neutrino emission, SN conditions change. Accretion influences some of the early neutrino emission. As the emission continues, the core lepton number is reduced, potentially triggering a change in the nuclear-matter phase or even a delayed collapse to a BH. At late times the shock wave may pass through the first MSW resonance, altering the density and thus the flavor conversion. It has also been shown that convection driven by hydrodynamic instabilities - the SASI mode – can imprint high frequency (few msec) fluctuations [81] on the neutrino flux, potentially detectable by comparing two high-statistic detectors (SuperKamiokande/IceCube/DUNE). Thus, in addition to the information about the global properties of the SN – the total energy and lepton number radiated – the neutrino flux carries a great deal of information about SN dynamics.

Though we think of the neutrino burst as prompt, future observations will continue far beyond the times modeled in our most advanced 3D explosion codes. Typically simulations extend to $\sim$ 1 sec after core bounce, when it may become apparent that a successful explosion has been launched. Our main interest in multi-messenger SN physics – what we find missing – is the bridge from 1 sec to the late time observables, which includes the long time development of the neutrino burst, but also the much later electromagnetic and nucleosynthetic signals. The Hub program we envision – some of this issues are relevant to NS merger outflows, as well – is the use of sophisticated radiative transport codes like Sedona to establish this bridge. Such codes can accept results from an explosion calculation as initial conditions, propagating the explosion forward in a less detailed but more efficient way. Important questions might then be answered. How does mantle ejection reflect the strength of the explosion at 1 sec? What determines the strength and duration of the kinetic and optical displays? What connection exists between early convection and the inhomogeneous distribution of elements like Ni and Ti in the ejecta?

One of the most important clues we have about the origin of the nuclei in our galaxy comes from the fossil evidence of early nucleosynthetic events, preserved on the surfaces of old, metal-poor halo stars. These "museums" are an important part of the multi-messenger story because they preserve data from a time when the galaxy was unmixed – data on the contributions of individual events to the r-process. We know from such stars that r-process nucleosynthesis was already underway when the galaxy contained only 0.01% of the metals it has today. The similarity of the r-process patterns seen in these stars to that seen in the sun is striking. Part of the r-process puzzle is to explain these early events – forensic evidence suggests a SN association – in view of our difficulties in producing a robust r-process in current SN explosion models. One idea Hub members have pursued is a SN r-process that is successful only at low metallicity: a weak neutron source can then drive an r-process, since the critical parameter is the neutron/seed ratio, and there are few seeds. A neutrino-driven mechanism has been identified in the He zones of metal poor stars [82].

While such a mechanism might account for the metal-poor star data, other more robust mechanisms would need to account for the bulk of galactic metal. NS mergers may be the major source for heavy elements with mass numbers above 130 including the actinides. The decay of the radioactive progenitors for these elements can power a unique infrared light curve that might have been observed – if confirmed, this "kilonova" would be the first direct evidence identifying an r-process site [83]. In addition, NS mergers are also the leading candidate for producing short gamma-ray bursts. The accretion disks in these events may contribute additional elements with mass numbers below 130. Last but not the least, NS mergers are a major source for gravitational waves. The wave form may help constrain the equation of state of dense matter, which is crucial in determining the amount of material dynamically ejected with freshly-synthesized nuclei during the merger.

The Near-Field Cosmology Connection: The standard cosmology based on cold dark matter (CDM) and dark energy explains a wide range of observational data, including structures on scales of galaxy clusters and larger. However, difficulties arise at the galactic scale. As a result of hierarchical structure formation, the CDM halo associated with a main galaxy has many sub-halos. In principle, this can account for the dwarf satellite galaxies orbiting the Milky Way. However, the number of observed satellite galaxies is far below that predicted in simulations, leading to the "missing satellite" problem. In addition, the largest sub-halos appear unsuitable for hosting the brightest Milky Way satellites because of incompatible mass distributions - the so-called "too big to fail" problem.

These problems may reflect an incomplete treatment of baryons and the associated gas dynamics in CDM simulations, issues closely connected to the nucleosynthesis and chemical evolution studies of the Hub: baryonic processes are expected to alter the CDM distribution through various feedback mechanisms, especially the redistribution of gas, and hence CDM via gravitational interaction, by SN explosions. However, an *ab initio* treatment of the feedback in simulations is daunting if not impossible because the relevant gas physics is both complicated and poorly understood. Consequently, various empirical approaches are taken in simulations to describe gas accretion by CDM halos, cooling and condensation of gas to form stars, conversion of cold into hot gas by radiation and SN explosions, and gas expulsion from halos. These processes also determine the mixing and chemical enrichment of gas. Consequentially, the chemical evolution of dwarf galaxies, reflected in the elemental abundances of the stars that have formed through today, in principle constraint any approximate treatment of the gas and baryons.

Nuclear physicists, by understanding the nuclear processes that drive chemical evolution, are making important contributions to our understanding of standard CDM cosmology. Star formation histories and elemental abundances in MW satellite galaxies have become the major objectives of observational near-field cosmology. Available data have already provided important insights into the gas dynamics and chemical enrichment of these systems. By combining our understanding of nuclear microphysics at the stellar scale with observations at the galactic scale, major advances can be made in understanding the TBTF problem in particular and galaxy formation and evolution in general.

Solar Neutrinos: Our much improved understanding of neutrino flavor physics allows us to return to the question that started neutrino astrophysics: can we use neutrinos to test our understanding of our nearest star? Next-generation solar neutrino experiments are envisioned with counting rates of tens of thousands of events per year and extraordinary radio-purities, mounted at depths of two kilometers. Important open questions could be addressed:

1. The most precisely known spectrum of neutrinos in Nature are those from solar p+p β decay, known to a precision of $\sim 0.4\%$ [84, 85]. Main sequence stellar evolution is based on the assumption of hydrostatic equilibrium, though physics allows secular variations in stars on the Kelvin timescale. The most direct test of this assumption would come from a comparison of the (instantaneous) p+p neutrino flux with the (delayed) surface photon luminosity. Equivalence of these two fluxes would test solar variability of potential interest to long-term climate change, as well as any candidate BSM stellar cooling mechanism.
2. A second fundamental assumption of the standard solar model (SSM), a homogeneous zero-age Sun, is in question. This assumption comes from the predicted convective mixing of the collapsing gas cloud in the pre-solar Hayashi phase. However, the "solar metallicity problem,"

the large (30%) discrepancy between helioseismic determinations of solar core metallicity and photospheric absorption line determinations of surface metallicity [86], has led to suggestions that homogeneity was later broken by the large-scale segregation of metals during planetary formation [87]. The associated accretion of disk gas, scrubbed of its metals, onto the Sun could dilute the convective zone. This scenario also accounts for other anomalies that involve chemical comparisons of the Sun with nearby "solar twins" with and without exoplanets [88].

Tests of hydrostatic equilibrium and zero-age homogeneity could be made in next-generation measurements of low energy solar neutrinos. In particular, core metallicity can be determined precisely and directly from a measurement of the CN solar neutrinos – a direct test of interior composition that would be unique in astrophysics.

What is needed to motivate a new-generation solar neutrino experiment? In the early 1960s Bahcall, Iben, and Sears built the theoretical foundation for Davis's experiment by developing the SSM. A solar metallicity problem is one of several that suggest links between the astrochemistry of the Sun and its planets, and the dynamics that led to their formation from a collapsing gas cloud. Just as the SSM tests our general theory of main sequence stellar evolution, the creation of a standard solar system model (SSSM) could provide a template for our understanding of extra-solar systems. Our Hub includes individuals who have developed self-consistent SSMs with accretion, and we see opportunities to use other numerical tools to greatly advance existing gas cloud collapse modeling [89]. This is a grand-challenge problem that our Hub could build toward, and that some finishing postdoc might then carry forward into the next stage of his/her career.

Dense Matter for Fundamental Astrophysics: Advances in theory and simulations have revealed that a quantitative theory of dense neutron-rich matter is essential for: (i) predicting flavor-dependent neutrino signals from a galactic SN in detectors such as Super-Kamiokande, IceCube and DUNE [90, 91, 92, 93]; (ii) interpreting the anticipated gravitational waves signals in advanced LIGO [94, 95] and their associated electromagnetic counterparts [96, 97]; (iii) determining the site(s) of heavy element nucleosynthesis and understanding the diversity of nucleosynthetic yields from SNe [98, 99] and NS mergers [66]; and (iv) exploring the influence of weakly interacting DM candidates on NSs, mergers, and SNe and identifying observables that might constrain their properties [100, 101, 102, 103, 104]. The overarching goals of the Hub's dense matter research are to advance calculations of the equation of state (EoS), transport properties, and low-energy response functions of dense matter relevant to large nuclei, NSs, SNe and NS mergers, facilitate their incorporation into simulation codes, identify relevant observable signatures, and explore connections to laboratory experiments. We believe the NSF Hub uniquely combines the necessary expertise in nuclear, neutrino and NS phenomenology, many-body theory, nucleon-nucleon interactions, effective field theory (EFT), computational astrophysics, and error analysis to accomplish these goals.

We propose to meld ongoing efforts at UW, LANL, and OU to improve calculations of the EoS and neutrino-mater interaction rates in dense matter, with the computational astrophysics effort at UC Berkeley, and the neutrino oscillation effort in extreme environments at UC San Diego, U Wisconsin, and NCSU. The three key research thrusts, which will involve UW, LANL and OU and the postdoctoral researchers shared between these locations, are:

1. *EoS of cold dense matter, NS radius and maximum mass:* The transition from net attraction at sub-nuclear density to repulsion at supra-nuclear density in neutron-rich matter plays a key role in determining the radius and maximum mass of NSs. Three-nucleon forces play an important

role [105, 106, 107]. We will build on recent efforts to include chiral EFT two- and three-nucleon potentials into QMC calculations of neutron matter [108, 109, 110], exploring their influence on the properties of NSs (radii, maximum mass, crust thickness, tidal polarizability, etc.). These calculations will be combined with constraints from measurements of the neutron skin thickness [111, 112, 113], dipole polarizability [114], nuclear masses, and the range of observed NS radii as determined in a Bayesian framework (see also below) [115]. All of this information will be used to develop a minimal Hamiltonian with density dependent effective two-body interactions with a finite range for use in astrophysics. The work will also inform density functional theories of heavy nuclei [116]. We will develop a hybrid model based on second-order perturbation theory where the parameters of this simpler Hamiltonian are determined to reproduce the EoS of pure neutron matter, its spin and isospin susceptibilities obtained from ab intio QMC calculations with realistic two- and three-body forces, and the empirical properties of symmetric nuclear matter. We will use the Bayesian formalism developed in Refs. [117, 115] to obtain intervals for the parameters in the effective interaction (and correlations between them) that reflect the uncertainties of input observables used in the fitting. We will therefore be able to use the effective interaction to propagate uncertainties in, e.g., the EoS, to any quantity computed within our framework. This approach will complement ongoing efforts to develop an EoS of isospin asymmetric matter based on many body perturbation theory and chiral EFT interactions [118, 119]. The approach should more cleanly isolate those aspects of the nucleon-nucleon (NN) interaction most relevant to the thermodynamic properties of astrophysical dense matter.

Although the discovery of two massive NSs with masses $M \gtrsim 2M_\odot$ [120, 121] disfavors strong first-order phase transitions at supra-nuclear density, it remains likely that non-nucleonic degrees of freedom will emerge well above saturation density. With an improved EoS of neutron-rich matter that extrapolates to high density [122], we can explore correlations between the NS radii, the maximum mass, slope of the mass-radius curve for canonical NS masses in the range 1.2-1.4 $M_\odot$, deriving quantitative constraints on possible phase transitions at high density.

2. *Thermal properties of dense matter:* In SNe and NS mergers, the temperature is controlled by the specific heat of dense, partially degenerate matter. The temperature in turn influences many aspects of the evolution as neutrino and weak interaction rates are strong functions of the ambient temperature [123]. EoSs in current use are based on mean field approaches that neglect important contributions to the specific heat from correlations and fluctuations. We propose two new approaches. First, we will extend the hybrid approach discussed earlier to finite temperatures to build a new EoS for astrophysics which naturally incorporates some of these effects. Second, we will study a series of effects known to strongly influence the specific heat of interacting Fermi systems, including the enhancement of the nucleon effective masses at the Fermi surface, coupling between quasi-particles and collective excitations, and the non-analytic behavior of the nucleon self-energy [124, 125]. Some of these effects have been studied using many-body perturbation theory and self-consistent Green's Function methods in recent years [126, 127, 118, 128, 129, 130]. The proposed research will improve the state of the art by: (i) developing Monte Carlo techniques for nuclear systems at finite temperature; (ii) using Fermi liquid theory with $l = 0, 1$ Fermi liquid parameters calculated from ab initio methods to estimate the non-analytic $T^3 \log T$ contribution to the specific heat at low to intermediate temperatures which are known to play a role in ^{3}He [124, 131]; (iii) investigating the role of thermal pions; and (iv) including collective excitations at very low temperatures where the single-particle degree of freedom is frozen due to BCS pairing and/or strong Coulomb correlations between ions [132].

3. *Bremsstrahlung, neutrino scattering and absorption, and related processes in dense matter:* In dense matter, the thermal production of μ and τ neutrinos, as well as axions, dark photons and other DM candidates, is dominated by NN bremsstrahlung; the inverse processes are important for neutrino pair absorption and inelastic neutrino scattering [133]. Most calculations of these rates are either based on a simplified treatment of the NN interaction [134] or on the soft-radiation approximation [135]. Building on recent work in Refs. [136, 137] and using chiral EFT potentials and associated two-body currents, we will go beyond the soft-radiation approximation. We will study screening due to long-range correlations and the Landau-Pomeranchuk-Migdal suppression of soft-neutrino emission due to finite quasi-particle lifetimes [138, 139, 140, 141]. This work will give us more reliable estimates of the thermal production of weakly interacting particles.

   We will pursue a novel approach to the low-energy nuclear response functions relevant to neutrino scattering and absorption in hot and dense matter. Building on earlier work based on Landau's Fermi liquid theory and the Random Phase Approximation [142, 143, 144, 145, 146], the energy dependence of response functions will be represented by well-motivated parameterized forms that can be adjusted to fit exact QMC results for the imaginary time response and sum rules as outlined in Ref. [147]. This will allow us to incorporate contributions from single- and multi-particle excitations, as well as from collective modes in the low-energy spectrum.

The improved microphysics will be incorporated into codes being developed to model NS mergers and SNe at UC Berkeley, providing a starting point for more realistic treatments of neutrino flavor transformations in these extreme environments by Hub members at UC San Diego, U of Wisconsin and NCSU. Jointly, we will design a suite of simulations to address how microphysics influences the GW emission, composition of the ejecta, and electromagnetic emissions from NS mergers, and neutrino emission from SNe.

The low-energy response of nuclear matter is also relevant in the context of DM interactions with large finite nuclei and aligns well with other DM research at UC Berkeley and at the U of Kentucky [148]. Issues relating to two-particle-hole excitations and axial two-body currents which play a role in bremsstrahlung processes, and possibly in the quenching of the axial charge, are of interest also to neutrino-nucleus reactions[149, 150, 151] and to double beta-decay [152, 153], and can play a role in inelastic DM nucleus scattering.

Understanding and estimating errors associated with the EoS and weak interaction rates will be a major component of all three dense matter research thrusts. Using a Bayesian framework and, where appropriate, EFT [117, 154] as a guide, we will evaluate the impact of uncertainties on EoS, neutrino opacities, emissivities *etc.*, while also delineating the mapping from correlated observables and their uncertainties to model parameters.

Dark Matter in Nuclear Physics: Various observations establish that most of the matter in our universe is dark, long-lived or stable, warm or cold, gravitationally active, and without strong interactions with ordinary matter [155, 156, 157]. DM represents new physics, beyond the standard model, with candidates including new weakly interacting massive particles (WIMPs), axions, sterile neutrinos with keV-MeV masses, and hidden-sector composites that might be dark analogs of pions or nucleons.

The Hub investment in this area is driven by our concern that DM astrophysics is inextricably part of coupled galaxy/nucleosynthesis/explosive astrophysics/microphysics issues discussed so far in this proposal, and that the absence of adequate nuclear physics involvement is holding back the field's development. One issue – the critical role nuclear physics likely plays in the dynamics of gas and baryons important to near-field cosmology – has already been described. Another is the potential importance of nuclear-physics-inspired lattice QCD methods, were the DM shown to be composite, e.g., dark pions or dark nucleons. Two additional issues, connected with the importance of nuclear theory and nuclear facilities to direct DM searches, are described below, and will comprise an important part of the Hub's collaborative efforts among Berkeley, Kentucky, and LANL.

Dark-Matter-Particle Direct Detection: Experimentalists are working diligently to detect DM particles through elastic scattering off nuclear targets, especially DM candidates in the 1 GeV - 1 TeV mass range [158]. In the past the selection of new direct-detection (DD) experiments has been largely predicated on simple models of DM, such as a massive Majorana neutrino. However, many classes of BSM theories that can accommodate DM, with very different consequences for DD experiments. The challenging problem, then, is to find a procedure for mapping the full range of ultraviolet theories into simpler but complete low-energy effective theories, thereby defining the full range of DD responses. This determines what information can be obtained from DD experiments, and how many independent experiments are needed.

Efforts began a few years back to treat this problem in the framework of EFT [148, 159]. The reduction to low energies is done in two steps, the construction of the most general WIMP-nucleon effective theory, and then the further reduction to the effective operators for nuclear elastic scattering. The results show that DD experiments are far more interesting than one would have concluded based on the naive point-nucleus spin-independent/spin-dependent (SI/SD) treatment [160]. The EFT analysis shows that DD experiments are sensitive to interactions to which they were previously thought to be "blind," such as those with derivative couplings, which produce familiar nuclear operators such as the orbital angular momentum, $\vec{\ell}(i)$. The experimental community has been receptive to these advances, upgrading their analysis tools to incorporate the EFT formulation.

We see great benefit in training Hub fellows who can work with DM experimentalists, developing the EFT framework and guiding experimental analyses:

- The EFT responses functions are closely related to those governing neutrino-nucleus scattering, and thus provide a second motivation for the microphysics developments described previously.
- A "best practices" nuclear structure program for DM and neutrinos is essential identical. For example, untruncated SM calculations for the leading experiment LUX/LZ require modern, highly tuned interactions and codes capable of handling bases of $\sim 10^{10}$ – now possible with Bigstick.
- A comprehensive EFT analysis of approximately 12 elastic scattering experiments, using state-of-the-art nuclear methods, is not available. Completion of this task will advance our understanding of the relationship among competing experiments, revealing any "blind spots."
- The EFT extension to inelastic scattering has not been completed, but could be very important, as excited states in Ge (CDMS) and Xe (LZ) are found just above detector energy thresholds. Only a single paper limited to the SD interaction exists [161]. The tentative observation [162] at ATLAS/CMS of the decay of a ~ 0.75 TeV boson into two photons has generated great interest in heavy scalar DM candidates. Elastic scattering is blind to two of the four relevant candidate EFT interactions, but not inelastic scattering.
- A mapping of candidate ultraviolet theories onto the DD EFT is essential to any meaningful analysis that combines direct detection, indirect detection, and collider constraints. A complete mapping of quark-WIMP operators onto nucleon-WIMP operators is not available, but could be undertaken. The inclusion of electroweak renormalization group running will likely have a

significant impact, as it mixes SD and SI operators in the simple "two-responses" framework [163].

New Fixed-Target Probes of Dark Forces: In so-called beam-dump experiments, such as the Seaquest experiment at Fermilab [164], detectors are mounted downstream of a particle beam stop. Such experiments serve as sensitive probes of hidden-sector gauge particles, that can mix with SM degrees of freedom. This mixing can occur via mass-dimension-four operators, so that their appearance need not require the inclusion of additional new physics to be theoretically consistent at high energy scales, such as in the case of dark photons [165, 166, 167]. With the possibility of downstream pion detection, the experiment opens windows on leptophobic gauge bosons and thus non-Abelian hidden sector interactions. It is possible that the coupling of the hidden-sector gauge boson to SM fermions breaks parity, giving rise to a "dark Z" [168]. The use of polarized proton beams opens the possibility of a direct window on the dark Z, as parity-violation in the coupling to SM fermions makes a parity-violating asymmetry in the transmission of the dark gauge bosons through the beam dump possible [164]. We would like to compute the dark-bremsstrahlung production cross section and parity-violating asymmetry for different dark gauge boson models, both with proton and electron beams. The development of a polarized proton beam is planned at Fermilab, but polarized electron beams are a strength of JLab, giving nuclear experimentalists a unique opportunity in this field. Our Hub work will frame the arguments for a JLab proposal.

Our Cyber Space Connections: Recent advances in high-performance computing have enabled scientific breakthroughs in several domains of nuclear theory, with the future promise of addressing long-standing questions in physics and nuclear astrophysics. A National Strategic Computing Initiative has called for accelerating the delivery of an exascale computing system, with approximately 100 times the performance of current 10 petaflop systems. The 2015 Long Range Plan for Nuclear Science recommends "new investments in computational nuclear theory that exploit the U.S. leadership in high-performance computing."

A key goal of our Hub is to connect new insights into weak interactions and dense-matter microphysics ("inner-space") to our understanding of macroscopic astronomical phenomena and the sites of nucleosynthesis ("outer-space"). This requires embedding computations of inner-space microphysics within multi-physics simulations of explosive environments such as SNe and NS mergers.

Nuclear structure and weak nuclear responses: The "work horse" code is the Open MP/MPI SM code Bigstick, which is based on a novel scheme for partially storing and partial recalculating interaction matrix elements on the fly, in order to overcome the communications bottlenecks that often plague iterative diagonalization methods based on the Lanczos algorithm. In its most recent version, a collaborative effort of San Diego State, Berkeley, and LBL, the code continues to perform efficiently for SM spaces of dimension $\sim 2 \times 10^{10}$ [3]. Further improvements appear possible. At its current level the code can handle, for example, all of the DM direct detection (or $\beta\beta$ decay) isotopes in the $sdg_{7/2}h_{11/2}$ shell (e.g., Xe, Te, Cs) without truncation. Bigstick generates one-, two-, and certain three-body density matrices from the SM output, for easy evaluation of operators.

Berkeley maintains a suite of weak interaction response codes that can be used in combination with Bigstick. These are based on standard multipole expansions, such as those developed by Walecka [169], that include the full momentum dependence of interactions.

Dense matter and QMC: The microscopic modeling of dense matter requires the treatment of an ensemble of nucleons interacting through potentials that are nonperturbative and have a complex spin and isospin structure. The technique used to solve this problem is QMC. QMC calculations of dense matter typically involve solutions for 50-150 nucleons in periodic boundary conditions. Today these codes scale very efficiently to one hundred thousand cores or more, and calculations of the zero-temperature EoS as a function of density and proton fraction for different models are fairly routine. While extensions of path integral simulations to weak responses in dense matter are more challenging, they should become within reach as available computing resources move towards the exascale.

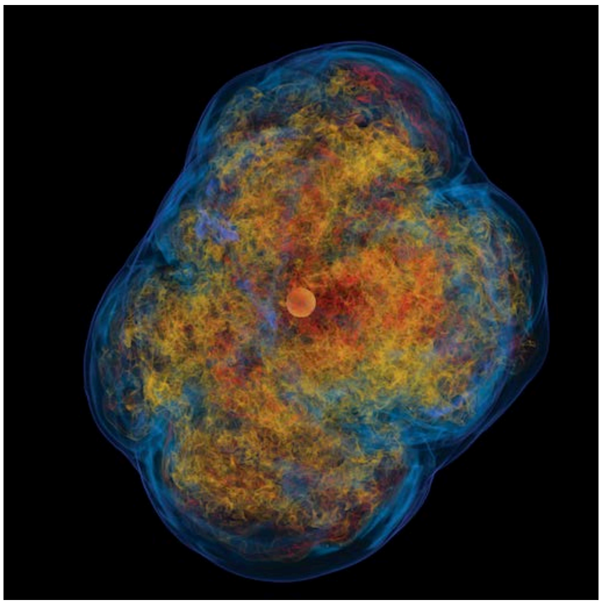

Figure 3: Three-dimensional simulation of a core collapse supernova explosion, calculated using the CASTRO code. The orange sphere at the center is the proto-neutron star, which irradiates the surroundings with neutrinos, driving the explosion shock wave and controlling the n/p ratio important to nucleosynthesis. From [170].

Astrophysics: Simulations of stellar explosions ideally couple high-resolution hydrodynamics in three spatial dimensions with general relativistic (GR) gravity, an accurate treatment of neutrino transport, a realistic dense-matter EoS, and thermonuclear kinetic networks including large numbers of isotopes. Our collaboration fields a number of codes that treat various aspects of the problem at state-of-the-art levels of accuracy.

Over the last decade, computer scientists and astrophysicists at Berkeley have developed a suite of petascale codes based on the BoxLib block-structured adaptive-mesh refinement (AMR) library. The CASTRO code solves the equations of multi-group radiation hydrodynamics with arbitrary EoS and nuclear reaction networks for simulation of CC and thermonuclear SNe. The MAESTRO code solves a low-Mach number formulation of hydrodynamics, suitable for modeling the convective stages that precede or follow explosive events. The SEDONABox code uses Monte Carlo radiation transport methods to synthesize the post-explosion emergent photon and neutrino radiation. Taken together, these three codes form a pipeline for end-to-end simulations from the stellar preSN phase to the final observable light curves, spectra, and nucleosynthetic output of stellar explosions.

The Spectral Einstein Code (SpEC) has been used at UCB to study the dynamics and GW emission of NS mergers. It evolves Einstein's equations of GR using pseudospectral methods, coupled to finite volume methods for solving the GR equations of magnetohydrodynamics and of gray neutrino transport. A next generation GR code Spectre is currently being developed under an NSF TCAN project (co-I Reddy) which will improve scalability and permit the inclusion of more detailed microphysics. Other codes in use by scientists at UCB include Flash for modeling the dynamics of CCSNe and the post-merger phase of NS mergers, and GRHydro for studying the GR magneto-hydrodynamics of rotating CCSNe.

Hub collaborators at Minnesota frequently use the 1D multi-zone hydro code Kepler to involve progenitors, and to do survey explorations of nucleosynthesis in CC, for explosions modeled as a piston driven into the core.

Section D - Human Resources and Diversity

The primary goal of the Hub is to engage postdoctoral fellows in the study of fundamental interactions, advancing the science while helping to create a needed new generation of researchers. This growing importance of this subfield in nuclear physics in apparent from the 2007 LRP's 14 questions, six of which address fundamental physics/astrophysics:

- What is the nature of NSs and dense nuclear matter?
- What is the origin of the elements in the cosmos?
- What are the nuclear reactions that drive stars and stellar explosions?
- What is the nature of the neutrinos, what are there masses, and how have they shaped the evolution of the universe?
- Why is there now more visible matter than antimatter in the universe?
- What are the unseen forces that were present at the dawn of the universe but disappeared from view as the universe evolved?

The experimental program has grown significantly over the last decade. Five of nine "demonstrator" scale $\beta\beta$ experiments have US agency support. JLab's 12 GeV electroweak program includes the PREX/CREX neutron skin measurements important to NS structure, precise PNC electron scattering measurements of Q_{weak}, a Møller scattering 0.1% measurement of the weak mixing angle, and a search for heavy photons, a DM candidate. FRIB will soon produce a wealth of new data on the nuclei that mediate nucleosynthesis in SNe and NS mergers. The first major experiment (NPDGamma) has been completed at the new SNS cold neutron beam line. A significant R&D program has been established to support a next-generation, US-led neutron edm experiment; nuclear edm experiments using trapped atoms have been initiated, precursors to a future FRIB program.

Theory has not been able to keep pace with the experimental buildup, despite the demanding nuclear theory needs of the subfield, which include a deep understanding of electroweak physics, state-of-the-art nuclear structure, and astrophysical modeling using our most advanced HPC platforms. Limited resources have allowed only selected investments. Under SciDAC3 the DOE was able to start a lattice QCD/nuclear structure effort in support of NPDGamma and edm experiments, but at the cost of discontinuing CCSN/NS modeling efforts important to FRIB astrophysics. A Topical Collaboration primarily focused on $\beta\beta$ decay nuclear matrix elements is about to start, but one on neutrino physics has ended.

The present NSF call for establishing a Hub focused on postdoctoral training is particularly appropriate for helping theory, due to the nature of the subfield:

- The subfield's major themes – fundamental neutrino physics, NSs and their mergers, and DM – excite young researchers.
- Because the subfield shares boundaries with astrophysics and particle physics, the pool of potential recruits is large. New talent can be brought *into* nuclear physics. Two recent neutrino Nobel Prizes have given the subfield special prominence.

- Postdocs who are trained in the subfield compete well for positions in universities, as the science they do connects to issues in particle physics, astrophysics, etc.

But these advantages have been negated by a restricted pipeline: there are only a few programs training postdocs. The lack of postdoctoral opportunities limits the capacity to take on students, despite great student interest. It also negates the subfield's advantage at the entering faculty level. A compounding problem is that our programs are often just a single investigator, making it difficult for postdocs to acquire the breadth they need to take advantage of faculty opportunities. These considerations lead to following human resources plan for the Hub:

- Form a group of strong coPIs – exciting science, established mentoring records – who will work together to recruit from the broadest possible pool the most deserving postdocs.
- Allow the postdocs flexibility in selecting their site (first two years), mentors, and Hub center (third year), allowing them to optimize scientific training and family or personal needs.
- View training as a collaboration responsibility, with each postdoc connected to a collaboration project of his/her choosing, and having both an on-site and off-site mentor.
- In the third year, exploit the environments of the three Hub centers (UCSD/CASS, UCB/TAC, UW/INT) to help develop Fellow breadth, including an appreciation of connections to experiment, observation, and sister disciplines such as astrophysics and particle physics.
- Stretch Hub resources, so that eight 3-year postdoctoral Fellows are trained in 5 years.
- Be proactive in proposing workshops/programs utilizing existing community resources (INT, KITP, Fine, ECT*, TALENT, NNPSS), to generate additional opportunities for the Fellows.

Diversity issues: Important components in building diversity in physics are the selection process, designed here to maximize the Fellow candidate pool, and the placement process, designed here to give the successful candidates maximum flexibility in selecting the site and Hub center meeting their needs. A candidate might feel that site A provides the best science match to her interests, but site B provides the best mentor and role model. The Hub's plan of dual mentors was designed in part to address such cases. Postdocs often have partners with dual careers. The Hub has the flexibility to complete a hire, while allowing multiple site possibilities to remain open, giving a couple time to identify the optimal dual-career choice. We have addressed other barriers than can limit participation through our budgeting, providing portable health care benefits through UC and dislocation allowances both initially and at the time of the 3rd year move.

There are many resources available through our institutions to address postdoc day-to-day needs (social, housing, etc.), promote equity and inclusion, and provide opportunities for career development. This information, displayed on the Hub's web site indexed by institution, will be an important tool in building a diverse candidate pool. We use Berkeley to illustrate the content. The Berkeley Postdoctoral Association website describes social orientation activities, the Postdoctoral Teaching Opportunities Program, Community Resources for Science (recruitment, preparation, and placement of young scientists in Bay Area classrooms, volunteer work promoting greater inclusion in STEM), and community outreach through science centers (volunteer opportunities at the California Academy of Science and the Lawrence Hall of Science). The Physics Department's Equity and Inclusion and campus Berkeley Diversity web pages provide links to LGBT support groups, STEM professional development, diversity initiatives, career connections – a vast network of faculty, postdocs, students, industry leaders, and community educators. Some of the initiatives will be highlighted as of particular importance to our program, e.g., UC President's and Chancellor's Postdoctoral Fellowships, which many of our candidates should apply for (they can be combined with Hub support). They are awarded to applicants whose research, teaching, and service will contribute to diversity and equal opportunity, and include future hiring incentives to help recipients move on to faculty positions. The Society of Women in the Physical Sciences web page is another important site serving both students and postdoctoral researchers. We will include information on ADA compliance of the buildings the Fellows will use, with links to the offices charged with ensuring equal physical access.

Section E - Shared Facilities

Relevant Hub shared facilities – because the project supports early-career theory postdocs – are largely limited to workshop/program facilities and computing infrastructure.

Workshops: Workshop and program activities, while important to interactions among the coPIs and Hub Fellows, are primarily envisioned as mechanisms to engage the broader nuclear physics community in our program, including experimentalists and observers doing related work. We intend to make use of shared community venues in proposing and organizing occasional workshops. The collaboration has direct connections to two major visitor centers, the INT (Reddy, Haxton) and the Fine Theoretical Physics Institute (Qian), both of which sponsor regular workshops, providing local support to participants and professional staff assistance to organizers. The FTPI selects its workshops internally: we have confirmed with the Director that a proposal from our group would be viewed favorably.

The INT selects workshops and longer programs through competitive review of proposals, conducted by its National Advisory Committee. Members of our group have long connections to the INT, and in fact have organized recent activities relevant to this proposal. These include the 2014 programs on "Nucleosynthesis and Chemical Evolution" (Qian) and "Binary Neutron Star Coalescence as a Fundamental Physics Laboratory" (Reddy); the 2014 workshops on "The r-process" (Qian, Reddy) and "Nuclear Aspects of Dark Matter Searches" (Haxton); the 2015 programs "Neutrino Astrophysics and Fundamental Properties" (Haxton) and "Intersections of BSM Phenomenology and QCD for New Physics Searches" (Gardner); and the 2015 INT-sponsored TALENT school "Nuclear Physics of Neutron Stars and Supernovae" (Reddy). We are already involved as organizers of approved INT programs and workshops through 2017, including the 2016 workshop on "Flavor Observations with Supernova Neutrinos" (Reddy); and the 2017 programs on "Neutrinoless Double Beta Decay" (Carlson, Cirigliano) and "Electromagnetic Signatures of r-process Nucleosynthesis in Neutron Star Binary Mergers" (Kasen). Indeed, our group appears to have been involved in nearly all of the successful proposals in fundamental interaction and nuclear astrophysics, over the past decade. This involvement will continue for the duration of the Hub.

Though the KITP, with its broader mandate, sponsors nuclear physics activities less frequently, we are also involved in organizing the 2016 KITP workshop"Symmetry Tests in Nuclei and Atoms" and associated program (Gardner, Haxton).

We will continue working with established venues such as the INT, KITP, and FTPI in proposing, organizing, and participating in workshops and programs that support Hub goals. Participation in such activities can be an exceptional experience for postdocs, putting them in contact with international leaders of the field, and providing opportunities to showcase their research and form new collaborations. We will strongly urge all Hub Fellows to take advantage of these opportunities. As co-participants, we can help introduce them to the community.

Our annual meeting and advisory committee meeting, activities discussed in part Section H, will often be coordinated with activities such as those above. The advantages including minimizing travel costs, encouraging outside participation in our annual meeting, and extending the time periods group members have for face-to-face collaboration.

Computing: While the Hub's research involves state-of-the-art computational physics, the collaboration's needs will be addressed through shared community resources and associated time allocations, which are done competitively. Members of our group head two of the three Nuclear Physics SciDAC3 collaborations, one focused exclusively on symmetries (CalLAT) and the other with important symmetries and nuclear astrophysics components (NUCLEI). Hub members hold several current INCITE allocations. We run on most of the leadership class machines – NERSC's Cori and Edison, Titan, Mira, Vulcan, BlueWaters – and have access to advanced GPU clusters. We have institutional and personal collaborative relationships with the Computational Research Division (LBNL), the San Diego SuperComputer Center, and the Ohio SuperComputer Center.

Consequently we can address postdoc computational needs using existing shared infrastructure. Because of NERSC and SDSC, Hub Fellows who have or develop HPC codes will be able to optimize their HPC opportunities by choosing either Berkeley or San Diego as their third-year choices.

Most of our institutions have advanced distance collaboration and webcasting facilities, with HD screens, etc. We will use these for collaboration broadcasts of regular Hub seminars (including candidate seminars) as well as in our collaborative research activities.

Section F - Collaboration with Sectors

This section describes collaborative relationships between the Hub or Hub members and others.

1. *Senior Participating Investigators*: The collaboration includes the DOE National Laboratory group of Joe Carlson, Vicenzo Cirigliano, and Stefano Gandolfi as participating senior investigators. They will act as senior members of the Hub, helping in the areas of dense matter and DM, and mentoring a postdoc that they will host as a LANL visitor. The LANL group will collaborate with UW and OU collaborators to improve calculations of the EoS and neutrino-matter interaction rates in dense matter, and explore the consequences of these improvements in collaboration with the computational astrophysics group at Berkeley. Their collaboration agreements are included among the supplemental documents. We will seek Visiting Scholar appointments for the group at either the UW or Berkeley, to facilitate interactions.
2. *Affiliated scientists:* Affiliated scientists include colleagues and collaborators who are interested in Hub research, but not directly involved in the Hub research program. We hope many of the affiliates will take part in our annual meeting and presenttalks abut their interests:
   - *Francois Foucart, Phillip Moesta, Sasha Tcheckhovskoy, Berkeley and LBL*: These three Einstein Fellows are associated with the Berkeley group and involved in various aspects of general relativistic simulations of mergers, which include in some cases relatively sophisticated treatments of the nuclear EoS and neutrino transport. They form a potential link between Hub efforts on the EoS, and gravitational wave form calculations of interest to LIGO.
   - *Evan O'Connor, NC State:* Evan is a Hubble Fellow who works on simulations of CCSNe, with particular emphasis on understanding the neutrino signals from these events.

- ◦ *Calvin Johnson and Fridolin Weber, San Diego State University*: Both are members of CASS, and thus will be connected to the collaboration through UCSD. Johnson is one of the developers of Bigstick, a Lanczos engine for very large scale (bases $\gtrsim 10^{10}$) SM calculations of the type needed for dark matter and neutrino responses, and is connected to Berkeley efforts through the DOE Topical Collaboration on double beta decay. Weber's specialty is NS structure.
- ◦ *Matt Kistler, SLAC*: Matt is a postdoc at the Kavli Institute for Particle Astrophysics and Cosmology, and is interested in indirect astrophysical constraints on dark matter.
- ◦ *Filomena Nunes, MSU*: Filomena has played a leadership role in the FRIB Theory Users Group, and has agreed to be our collaboration liaison with FRIB, helping us interact with the experimentalists who are planning the FRIB program.
- ◦ *Pavlos Vranas, LLNL*: Pavlos leads the BSM/USQCD group that is exploring strongly interacting composite models of dark matter (dark pions, dark nucleons), evaluating their properties using lattice gauge theory.
- ◦ *Andre Walker-Loud, Nuclear Science Division, LBNL*: Andre is a member of the CalLat SciDAC3 group that is applying lattice QCD to the calculation of PNC NN scattering in the isovector and isotensor channels
- ◦ *Ann Almgren and John Bell, Computing Research Division, LBNL*: Co-developers with Kasen and others of the MAESTRO/CASTRO/SEDONA pre-SN and SN code suite based on BoxLib adaptive mesh refinement.

3. *Major collaborations:* We have direct collaborative connections to the DOE Topical Collaboration on Nuclear Theory for $\beta\beta$ Decay and Fundamental Symmetries, the CalLAT LQCD effort on hadronic parity violation, the USQCD/BSM DM program, and the Caltech/Syracuse/Cornell/ Washington Theoretical and Computational Astrophysics Network (which focuses on relativistic simulations of compact-object binaries, an effort that could help link Hub EoS work to gravitational wave and electromagnetic observations of mergers). In our view the proposed Hub is in fact a hub that sits at the nexus of these other, related efforts. We will invite each of these collaborations to send one or more members to attend our annual meeting and workshop.

Section G - International Collaborations

Here we note international collaborations of our members that we anticipate could support Hub research goals. Some connections involve numerical tools that have been developed collaboratively.

1. *Alexander Heger, Monash University, Australia*: Heger has worked with the Minnesota group and others on the development of Kepler, a 1-D multizone hydrodynamics code useful for generating libraries of SN progenitors, and for simulating SN explosions and associated nucleosynthesis using a piston model. Kepler, and several other similar codes, uses libraries of electroweak reaction cross sections that are far from state of the art, and could be updated as a result of planned Hub work of electron capture, β decay, and neutrino reactions
2. *Aldo Serenelli, Institute of Space Sciences, Barcelona*: Serenelli has continued the development of the Princeton Standard Solar Model, including a series of collaborations with the Berkeley group treating early accretion self-consistently. This code provides the theoretical baseline for almost all solar neutrino analyses, and would be the starting point for any future code developments treating the coupled problem of proto-solar and planetary disk evolution.

3. *Bernhard Muller, Queen's University, Belfast*: Muller collaborates with the Minnesota and Monash groups on multi-D pre-SN evolution, SN explosion, and nucleosynthesis calculations.
4. *Gabriel Martinez-Pinedo, TU-Darmstadt*: Martinez-Pinedo has collaborated with several of the Hub's co-PIs in developing optimized nuclear reaction input for nucleosynthesis studies, particularly fission important in many r-process scenarios. His expertise complements that of our Notre Dame group.
5. *Achim Schwenk, TU-Darmstadt*: Involved in an ongoing collaboration with the Berkeley group, supported by the Humboldt Foundation, on nuclear structure issues in dark matter direct detection experiments.

Section H - Management

The budgeting for the project will be managed centrally, through UC Berkeley, which will handle Fellow salaries and benefits; Fellow interview, travel, and relocation costs; and annual meeting costs. The project is designated as an off-campus one for purposes of indirect costs. Berkeley and the PI will be responsible for the administrative tasks connected with the project's budget and personnel functions, and for the associated reporting to the NSF. Berkeley will be also responsible for the construction and maintenance of the web site, though current plans are to work with the University of Washington on this task.

Postdoc Selection and Mentoring: Project decisions affecting Fellows and science will be made jointly by the group of 12 coPIs and three senior National Laboratory investigators. The paramount responsibility of the group is in selecting, training, and mentoring the Hub postdocs. As described elsewhere in this proposal, candidates will learn about the Hub Fellows program through the web site, to which they will be directed by various job clearinghouses, such as Academic Jobs Online. The site will describe the positions – two years located at one of eight sites, and one at one of the three Hub centers. At the time of application, candidates will be asked to indicate the sites and Hub centers of most interest, a selection they will make based on the posted information (which will include descriptions of our collaboration goals, special expertise resident at each site, and relevant human resources/diversity characteristics of the sites, as described in Section F). This selection process is designed to achieve the largest possible pool of candidates, to give candidates choices, and to ensure that Fellow selections are based on the collective wisdom of the group, and not dominated by local site interests.

Once the leading candidates are identified, the site and Hub center that the candidate finds of most interest will lead the interview process. The candidate will be ask to give a seminar at the site, which will be broadcast to other sites: all members of our group will be expected to "attend" the seminar. The Hub center visit that will follow will be informative, providing the candidate with an overview of the resources and people available. At the conclusion of interviews, offers will be made.

The offers are from the group: once a candidate has been named a Hub Fellow, he/she is free to select any site and any center, regardless of the initial choice made at the time of application. As noted elsewhere, a variety of physics and family issues can affect the final decision. Candidate wishes will also be paramount in selecting the on-site/off-site mentor pair.

Our intent is to hire three sets of Fellows, staggered as shown in Fig. 4. There is some flexibility in this plan: if in a given year we do not identify three candidates who meet the selection thresholds, we will delay one of those appointments for a year.

Each site will have an opportunity to host a Fellow. In the second (third) year, the number of site choices for the new set of candidates would be reduced to five (three). Even in year three, some flexibility to optimize the placement of Fellows with sites would remain. In practice, the site choice is not crucial, as all Hub collaborations extend over multiple institutions, and the Fellows will have opportunities to travel. Fellows are Hub Fellows, not site Fellows.

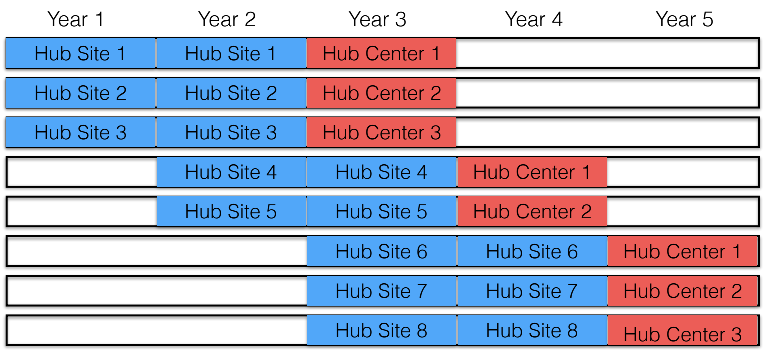

Figure 4: Hub fellow hiring plan, illustrating the cycle of appointments, and the plan to combined two years at Hub sites with a finishing year at one of the three Hub centers

Division of Tasks: The group of coPIs and senior investigators will divide the tasks that arise each year. Key tasks include the search committee (charged with initial review, initial cuts, and organizing collaboration discussions about short-listed candidates); the workshop/program/school committee, charged with identifying and acting on opportunities at venues like INT, KITP, and the Fine Institute; the mentoring committee (charged with reviewing the annual mentor's reports, and offering advice if issues are identified); annual meeting committee (charged with identifying dates and venues, arranging the program, and inviting non-collaboration participants); and the professional development committee (charged with keeping the Fellows abreast of teaching and outreach opportunities, and faculty openings and named fellowships application due dates). This last committee will also conduct exit interviews with Fellows and track future progress.

Advisory Committee: A six-person Advisory Committee will meet annually, on the day preceding or following the annual meeting, to review Hub science; recruitment and mentoring, outreach and other professional development activities; participation in and initiation of workshops, programs, and schools; and quality of interactions with the broader nuclear physics community (including those with other initiatives, such as Topical and SciDAC collaborations). The following colleagues were invited to join the Advisory Committee as inaugural members and have agreed to serve,

- *Gordon Baym, University of Illinois*
  Nuclear theorist. Interests: dense matter, NS structure, RHIC physics
- *Anna Frebel, MIT*
  Observer. Interests: metal poor stars, r-process; active in outreach
- *Boris Kayser, FermiLab*
  Neutrino phenomenologist. Formerly headed theory for NSF Physics
- *Michael Thoennessen, MSU*
  FRIB nuclear experimentalist. Co-covenor for workforce, education and outreach, 2015 LRP

If our proposal is selected, two additional members will be added and a rotation established, after group discussions about scientific balance.

References

[1] "Neutrinos," Community Summer Study Intensity Frontier Neutrino Working Group, arXiv1310.4340

[2] "Neutrino oscillations," A. B. Balantekin and W. C. Haxton, Progress in Nuclear and Particle Physics , **71** 150 (2013)

[3] "Parallel implementation and performance optimization of the configuration-interaction method," H. Shan, S. Williams, C. Johnson, K. McElvain, and W. Erich Ormand, paper presented at SuperComputing 2015

[4] "The influence of pairing on the nuclear matrix elements of the neutrinoless $\beta\beta$ decays," E. Caurier, J. Menendez, F. Nowacki, and A. Poves, Phys. Rev. Lett. **100**, 052503 (2008); "Disassembling the matrix elements of the neutinoless $\beta\beta$ decay," J. Menendez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A **818**, 139 (2009)

[5] "Ground state and finite temperature Lanczos methods," P. Prelovsek and J. Bonca, in *Numerical Methods for Strongly Correlated Systems*, vol **176**, 1 (2013)

[6] "Piecewise moments method: Generalized Lanczos technique for nuclear response functions," W. C. Haxton, K. M. Nollett, and K. M. Zurek, Phys. Rev. C **72**, 065501 (2005)

[7] "Stellar weak interaction rates for intermediate mass nuclei:II A=21 to A=60," G. M. Fuller, W. A. Fowler, and M. J. Newman, Astrophys. J. **252**, 715 (1982)

[8] "Nuclear weak interaction processes in stars," K. Langanke and G. Martinez-Pinedo, Reviews of Modern Physics **75**, 819 (2003)

[9] "Refraction and oscillations of neutrinos in the early universe," K. Enqvist, K. Kainulainen, J. Maalampi, Nuclear Physics B **349**, 754 (1991)

[10] "General kinetic description of relativistic mixed neutrinos," G. Sigl and G. Raffelt, Nuclear Physics B **406**, 423 (1993)

[11] "Oscillating neutrinos in the early Universe," B. H. J. McKellar and M. Thomson, Phys. Rev. D **49**, 2710 (1994)

[12] "Multiangle instability in dense neutrino systems," R. Sawyer, Phys. Rev. D **79**, 105003 (2009)

[13] "Generalized Boltzmann formalism for oscillating neutrinos," P. Strack and A. Burrows, Phys. Rev. D **71**, 093004 (2005)

[14] "Collective neutrino oscillations," H. Duan, G. M. Fuller, Y.-Z. Qian, Annual Review of Nuclear and Particle Science **60**, 569 (2010)

[15] "Monte Carlo neutrino oscillations," J. P. Kneller and G. C. McLaughlin, Phys. Rev. D **73**, 056003 (2006)

[16] "Neutrino mixing and nucleosynthesis in core-collapse supernovae," A. B. Balantekin and H. Yüksel, New Journal of Physics **7**, 1 (2005)

[17] "Self-induced conversion in dense neutrino gases: Pendulum in flavor space," S. Hannestad, G. Raffelt, G. Sigl, and Y. Y. Y. Wong, Phys. Rev. D **74**, 105010 (2006)

[18] "Adiabaticity and spectral splits in collective neutrino transformations," G. Raffelt and A. Yu. Smirnov, Phys. Rev. D **76**, 125008 (2007)

[19] "Supernova neutrinos and antineutrinos: ternary luminosity diagram and spectral split patterns," G. Fogli, E. Lisi, A. Marrone, and I. Tamborra, Journal of Cosmology and Astroparticle Physics **2009**, 1 (2009)

[20] "Decoherence in supernova neutrino transformation suppressed by deleptonization," A. Esteban-Pretel, S. Pastor, R. Tomas, G. Raffelt, G. Sigl, Phys. Rev. D **76**, 125018 (2007)

[21] "Multiple spectral splits of supernova neutrinos," B. Dasgupta, A. Dighe, G. Raffelt, and A. Yu. Smirnov, Phys. Rev. Lett. **103**, 051105 (2009)

[22] "Neutrino scattering and flavor transformation in supernovae," J. F. Cherry, J. Carlson, A. Friedland, G. M. Fuller, and A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012)

[23] "2D and 3D core-collapse supernovae simulation results obtained with the CHIMERA code," S. Bruenn, A. Mezzacappa, W. R. Hix, J. M. Blondin, P. Marronetti, O. E. B. Messer, C. J. Dirk, and S. Yoshida, Journal of Physics: Conference Series **180**, 012018 (2009)

[24] "Neutrino quantum kinetics," A. Vlasenko, G. M. Fuller, V. Cirigliano, Phys. Rev. D **89**, 105004 (2014)

[25] "Extended evolution equations for neutrino propagation in astrophysical and cosmological environments," C. Volpe, D. Väänänen, and C. Espinoza, Phys. Rev. D **87**, 1130 (2013)

[26] "A new spin on neutrino quantum kinetics," V. Cirigliano, G. M. Fuller, A. Vlasenko, Phys. Lett. B **747**, 27 (2015)

[27] "Neutrino-antineutrino correlations in dense anisotropic media," J. Serreau and C. Volpe, Phys. Rev. D **90**, 125040 (2014)

[28] "Neutrino propagation in media: Flavor, helicity, and pair correlations," A. Kartavtsev, G. Raffelt, and H. Vogel, Phys. Rev. D **91**, 125020 (2015)

[29] "Connection between supernova shocks, flavor transformation, and the neutrino signal," R. C. Schirato and G. M. Fuller, arXiv:astro-ph/0205390

[30] "Neutrino oscillations in inhomogeneous matter," R. Sawyer, Phys. Rev. D **42**, 3908 (1990)

[31] "Effects of random density fluctuations on matter-enhanced neutrino flavor transitions in supernovas and implications for supernova dynamics and nucleosynthesis," F. Loreti, Y.-Z. Qian, A. B. Balantekin, and G. M. Fuller, Phys. Rev. D **52**, 6664 (1995)

[32] "Neutrino signatures of supernova turbulence," A. Friedland and A. Gruzinov, arXiv:astro-ph/0607244

[33] "Oscillation effects and time variation of the supernova neutrino signals," J. P. Kneller, G. C. McLaughlin, and J. Brockman, Phys. Rev. D **77**, 045023 (2008)

[34] "Shock waves in supernovae: New implications on the diffuse supernova neutrino background?," S. Galais, J. P. Kneller, C. Volpe, and J. Gava, Phys. Rev. D **81**, 053002 (2010)

[35] "Axial symmetry breaking in self-Induced flavor conversion of supernova neutrino fluxes," G. Raffelt, S. Sarikas, and D. de Sousa, Phys. Rev. Lett. **111**, 091101 (2013)

[36] "Mult-azimuthal-angle effects in self-induced supernova neutrino flavor conversions without axial symmetry," A. Mirizzi, Phys. Rev. D **88**, 073004 (2013)

[37] "Flavor instabilities in the multi angle neutrino lime model," A. Abbar, H. Duan, and S. Shalgar, Phys. Rev. D **92**, 065019 (2015)

[38] "Neutrino-induced nucleosynthesis of $A > 64$ nuclei: The νp process," C. Fröhlich, G. Martnez-Pinedo, M. Liebendoerfer, F.-K. Thielemann, E. Bravo, W. R. Hix, K. Langanke, and N. T. Zinner, Phys. Rev. Lett. **96**, 142502 (2006).

[39] "Nucleosynthesis in early supernova winds. II. The role of neutrinos," J. Pruet, R.D. Hoffman, S.E. Woosley, H.-Th. Janka, and R. Buras, Astrophys. J. **644**, 1028 (2006)

[40] "Uncertainties in the νp-process: Supernova dynamics versus nuclear physics," S. Wanajo, H.-Th. Janka, S. Kubono, Astrophys. J. **729**, 46 (2011)

[41] "Production of light-element primary process nuclei in neutrino-driven winds," A. Arcones, F. Montes, Astrophys. J. **731**, 5 (2011)

[42] "R-process nucleosynthesis in the high-entropy supernova bubble," B.S. Meyer, G.J. Mathews, W.M. Howard, S.E. Woosley, R.D. Hoffman, Astrophys. J. **399**, 656 (1992)

[43] "The r-process and neutrino-heated supernova ejecta," S.E. Woosley, J.R. Wilson, G.J. Mathews, R.D. Hoffman, B.S. Meyer, Astrophys. J. **433**, 229 (1994)

[44] "Nucleosynthesis in neutrino-driven winds from protoneutron stars II. The r-process," K. Takahashi, J. Witti, H.-Th. Janka, Astron. & Astrophys. **286**, 857 (1994)

[45] "Neutrino capture and supernova nucleosynthesis," G.M. Fuller, B.S. Meyer, Astrophys. J. **453**, 792 (1995)

[46] "Nucleosynthesis in neutrino-driven winds. II. Implications for heavy element synthesis," R.D. Hoffman, S.E. Woosley, and Y.-Z. Qian, Astrophys. J. **482**, 951 (1997)

[47] "Nucleosynthesis-relevant conditions in neutrino-driven supernova outflows. I. Spherically symmetric hydrodynamic simulations," A. Arcones, H.-Th. Janka, and L. Scheck, Astron. & Astrophys. **467**, 1227 (2007)

[48] "Nucleosynthesis in electron capture supernovae of asymptotic giant branch stars," S. Wanajo, K. Nomoto, H.-Th. Janka, F.S. Kitaura, and B. Muller, Astrophys. J. **695**, 208 (2009)

[49] "Protoneutron star evolution and the neutrino-driven wind in general relativistic neutrino radiation hydrodynamics simulations," T. Fischer, S. C. Whitehouse, A. Mezzacappa, F.-K. Thielemann, and M. Liebendoerfer,, Astron. & Astrophys. **517**, A80 (2010)

[50] "Neutrino signal of electron-capture supernovae from core collapse to cooling," L. Hüdepohl, B. Mueller, H.-T. Janka, A. Marek, and G. G. Raffelt, Phys. Rev. Lett. **104**, 251101 (2010)

[51] "Medium modification of the charged-current neutrino opacity and its implications," L. Roberts, S. Reddy, and G. Shen, Phys. Rev. C **86**, 065803 (2012)

[52] "An active sterile neutrino transformation solution for r process nucleosynthesis," G.C. McLaughlin, J.M. Fetter, A.B. Balantekin, and G.M. Fuller, Phys. Rev. C **59**, 2873 (1999)

[53] "Fission cycling in supernova nucleosynthesis: Active-sterile neutrino oscillations," J. Beun, G.C. McLaughlin, R. Surman, and W.R. Hix, Phys. Rev. D **73**, 093007 (2006)

[54] "Impact of eV-mass sterile neutrinos on neutrino-driven supernova outflows," I. Tamborra, G.G. Raffelt, L. Hüdepohl, and H.-Th. Janka, J. Cosmol. Astropart. Phys. **1**, 13 (2012)

[55] "Impact of neutrino flavor oscillations on the neutrino-driven wind nucleosynthesis of an electron-capture supernova," E. Pllumbi, I. Tamborra, S. Wanajo, H.-Th. Janka, and L. Hüdepohl, Astrophys. J. **808** 188 (2015)

[56] "Integrated nucleosynthesis in neutrino-driven winds," L. Roberts, S.E. Woosley, and R.D. Hoffman, Astrophys. J. **722**, 954 (2010)

[57] "The r-process of stellar nucleosynthesis: Astrophysics and nuclear physics achievements and mysteries," M. Arnould, S. Goriely, and K. Takahashi, Phys. Rep. **450**, 97 (2007)

[58] "Black-hole-neutron-star collisions," J.M. Lattimer and D.N. Schramm, Astrophys. J. **192**, L145 (1974)

[59] "Decompression of initially cold neutron star matter - A mechanism for the r-process?," B.S. Meyer, Astrophys. J. **343**, 254 (1989)

[60] "r-process in neutron star mergers," C. Freiburghaus, S. Rosswog, and F.-K. Thielemann, Astrophys. J. **525**, L121 (1999)

[61] "r-process nucleosynthesis in dynamically ejected matter of neutron star mergers," S. Goriely, A. Bauswein, and H.-Th. Janka, Astrophys. J. **738**, L32 (2011)

[62] "On the astrophysical robustness of the neutron star merger r-process," O. Korobkin, S. Rosswog, A. Arcones, and C. Winteler, MNRAS **426**, 1940 (2012)

[63] "Comprehensive nucleosynthesis analysis for ejecta of compact binary mergers," O. Just, A. Bauswein, R.A. Pulpillo, S. Goriely, and H.-Th. Janka, MNRAS **448**, 541 (2015)

[64] "Neutron star mergers versus core-collapse supernovae as dominant r-process sites in the early Galaxy," D. Argast, M. Samland, F.-K. Thielemann, and Y.-Z. Qian, Astron. & Astrophys. **416**, 997 (2004)

[65] "r-process calculations and galactic chemical evolution," S. Wanajo and Y. Ishimaru, Nucl. Phys. A **777**, 676 (2006)

[66] “Production of all the r-process nuclides in the dynamical ejecta of neutron star mergers,” S. Wanajo, Y. Sekiguchi, N. Nishimura, K. Kiuchi, K. Kyutoku, and M. Shibata, Astrophys. J. **789**, L39 (2014)

[67] “Impact of weak interactions of free nucleons on the r-process in dynamical ejecta from neutron star mergers,” S. Goriely, A. Bauswein, O. Just, E. Pllumbi, and H.-Th. Janka, MNRAS **452**, 3894 (2015)

[68] “Collapsars: Gamma-ray bursts and explosions in failed supernovae,” A.I. Mac Fadyen and S.E. Woosley, Astrophys. J. **524**, 262 (1999)

[69] “Black hole-neutron star mergers as central engines of gamma-ray bursts,” H.-Th. Janka, T. Eberl, M. Ruffert, and C.L. Fryer, Astrophys. J. **527**, L39 (1999)

[70] “Accretion models of gamma-ray bursts,” R. Narayan, T. Piran, and P. Kumar, Astrophys. J. **557**, 949 (2001)

[71] “Nucleosynthesis in the outflow from gamma-ray burst accretion disks,” R. Surman, G.C. McLaughlin, and W.R. Hix, Astrophys. J. **643**, 1057 (2006)

[72] “r-process nucleosynthesis in hot accretion disk flows from black hole-neutron star mergers,” R. Surman, G.C. McLaughlin, M. Ruffert, H.-Th. Janka, and W.R. Hix, Astrophys. J. **679**, L117 (2008)

[73] “On the conditions for neutron-rich gamma-ray burst outflows,” B.D. Metzger, T.A. Thompson, and E. Quataert, Astrophys. J. **676**, 1130 (2008)

[74] “The r-process in the neutrino-driven wind from a black-hole torus,” S. Wanajo and H.-Th. Janka, Astrophys. J. **746**, 180 (2012)

[75] “Neutrino oscillations above black hole accretion disks: Disks with electron-flavor emission,” A. Malkus, J.P. Kneller, G.C. McLaughlin, and R. Surman, Phys. Rev. D **86**, 085015 (2012)

[76] “Matter-neutrino resonance above merging compact objects,” A. Malkus, A. Friedland and G. C. McLaughlin, arXiv:1403.5797 [hep-ph]

[77] “Symmetric and standard matter-neutrino resonances above merging compact objects,” A. Malkus, G. C. McLaughlin and R. Surman, arXiv:1507.00946 [hep-ph]

[78] “Impact of supernova dynamics on the νp-process,” A. Arcones, C. Fröhlich, and G. Martínez-Pinedo, Astrophys. J. **750**, 18 (2012)

[79] “The impact of individual nuclear properties on r-process nucleosynthesis,” M. Mumpower, R. Surman, G.C. McLaughlin, and A. Aprahamain, Prog. Part. Nucl. Phys. **86**, 86 (2016)

[80] “Plans for the facility for rare isotope beams,” M. Thoennessen, Nucl. Phys. A **834**, 688 (2010)

[81] “Neutrino signature of supernova hydrodynamical instabilities in three dimensions,” I. Tamborra, F. Hanke, B. Mueller, H.-T. Janka, and G. Raffelt, Phys. Rev. Lett. **111**, 121104 (2013)

[82] “Long, cold, early r-process? Neutrino-induced nucleosynthesis in He shells revisited,” P. Banerjee, W. C. Haxton, Y.-Z. Qian, Phys. Rev. Lett. **106**, 201104 (2011); “New primary mechanisms for the synthesis of rare ^{9}Be in early supernovae,” P. Banerjee, Y.-Z. Qian, W. C. Haxton, and A. Heger, Phys. Rev. Lett. **110**, 141101 (2013)

[83] “Transient event from neutron star mergers,” L. Li and B. Paczynski, Ap. J. **507**, L59 (1998); “The effect of a high opacity on the light curves of radioactively powered transients from compact object mergers,” J. Barnes and D. Kasen, Ap. J. **775**, 18 (2013)

[84] “Solar fusion II,” Solar Fusion II Collaboration, Rev. Mod. Phys. **83** (2011) 195

[85] “Proton-proton weak capture in chiral effective field theory,” L. E. Marcucci, R. Schiavilla, and M. Viviani, Phys. Rev. Lett. **110** (2013) 192503

[86] See, e.g., “Solar heavy-element abundances: I. Constraints from stellar interiors,” F. Delahaye and M. Pinsonneault, Ap. J. **649** (2006) 529; “Solar heavy-element abundances: II. Constraints from stellar atmospheres,” F. Delahaye and M. Pinsonneault, Ap. J.**704** (2009) 1174

[87] “CN cycle solar neutrinos and the sun’s primordial core metallicity,” W. C. Haxton and A. M. Serenelli, Ap. J. **687** (2008) 678

[88] “Solar twins and possible solutions of the solar and Jupiter abundance problems,” A. Nordlund, arXiv:0908.3479 (2009); “The peculiar solar composition and its possible relation to planet formation,” J. Melendez, M. Asplund, B. Gustafsson, and D. Yong, Ap. J. **704** (2009) L66

[89] “The first million years of the sun: A calculation of formation and early evolution of a solar-mass star,” G. Wuchterl and R. S. Klessen, Ap. J. **560** (2001) L185

[90] “Neutrino signal of electron-capture supernovae from core collapse to cooling,” L. Hudepohl, B. Muller, H. T. Janka, A. Marek, and G. G. Raffelt, Phys. Rev. Lett. **104**, 251101 (2010), arXiv:0912.0260, [Erratum: Phys. Rev. Lett.105,249901(2010)].

[91] “Protoneutron star cooling with convection: The effect of the symmetry energy,” L. F. Roberts, G. Shen, V. Cirigliano, J. A. Pons, S. Reddy, and S. E. Woosley, Phys. Rev. Lett. **108**, 061103 (2012).

[92] “Evolution of a neutron star from its birth to old age,” M. Prakash, J. M. Lattimer, J. A. Pons, A. W. Steiner, and S. Reddy, Lect. Notes Phys. **578**, 364 (2001)

[93] “Evolution of proto-neutron stars,” J. A. Pons, S. Reddy, M. Prakash, J. M. Lattimer, and J. A. Miralles, Astrophys. J. **513**, 780 (1999).

[94] “Equation-of-state dependence of the gravitational-wave signature from the ring-down phase of neutron-star mergers,” A. Bauswein, H. T. Janka, K. Hebeler, and A. Schwenk, Phys. Rev. **D86**, 063001 (2012)

[95] “Matter effects on neutron star waveforms,” J. S. Read, L. Baiotti, J. D. E. Creighton, J. L. Friedman, B. Giacomazzo, K. Kyutoku, C. Markakis, L. Rezzolla, M. Shibata, and K. Taniguchi, Phys. Rev. **D88**, 044042 (2013)

[96] "Kilonova light curves from the disk wind outflows of compact object mergers," D. Kasen, R. Fernandez, and B. Metzger, Mon. Not. Roy. Astron. Soc. **450**, 1777 (2015)

[97] "The fate of the compact remnant in neutron star mergers," C. L. Fryer, K. Belczynski, E. Ramirez-Ruiz, S. Rosswog, G. Shen, and A. W. Steiner, Ap. J. **812**, 24 (2015)

[98] "Charge-current weak interaction processes in hot and dense matter and its impact on the spectra of neutrinos emitted from protoneutron star cooling," G. Martínez-Pinedo, T. Fischer, A. Lohs, and L. Huther, Phys. Rev. Lett. **109**, 251104 (2012)

[99] "Medium modification of the charge-current neutrino opacity and its implications," L. F. Roberts, S. Reddy, and G. Shen, Phys. Rev. C**86**, 065803 (2012)

[100] "Weakly interacting massive particles and neutron stars," I. Goldman and S. Nussinov, Phys. Rev. **D40**, 3221 (1989)

[101] "Nucleon spin fluctuations and the supernova emission of neutrinos and axions," H.-T. Janka, W. Keil, G. Raffelt, and D. Seckel, Phys. Rev. Lett. **76**, 2621 (1996)

[102] "Supernova bounds on the dark photon using its electromagnetic decay," D. Kazanas, R. N. Mohapatra, S. Nussinov, V. L. Teplitz, and Y. Zhang, Nucl. Phys. **B890**, 17 (2014)

[103] "Dark matter thermalization in neutron stars," B. Bertoni, A. E. Nelson, and S. Reddy, Phys. Rev. **D88**, 123505 (2013)

[104] "Nucleon-nucleon bremsstrahlung of dark gauge bosons and revised supernova constraints," E. Rrapaj and S. Reddy, (2015), arXiv:1511.09136.

[105] "Improved nuclear matter calculations from chiral low-momentum interactions," K. Hebeler, S. K. Bogner, R. J. Furnstahl, A. Nogga, and A. Schwenk, Phys. Rev. **C83**, 031301 (2011)

[106] "The maximum mass and radius of neutron stars and the nuclear symmetry energy," S. Gandolfi, J. Carlson, and S. Reddy, arXiv:1101.1921 (2011)

[107] "Neutron matter at next-to-next-to-next-to-leading order in chiral effective field theory," I. Tews, T. Krüger, K. Hebeler, and A. Schwenk, Phys. Rev. Lett. **110**, 032504 (2013)

[108] "Local chiral effective field theory interactions and quantum Monte Carlo applications," A. Gezerlis, , I. Tews, E. Epelbaum, M. Freunek, S. Gandolfi, K. Hebeler, A. Nogga, and A. Schwenk, Phys. Rev. **C90**, 054323 (2014)

[109] "Quantum Monte Carlo calculations of neutron matter with chiral three-body forces," I. Tews, S. Gandolfi, A. Gezerlis, and A. Schwenk, arXiv:1507.05561 (2015)

[110] "Chiral three-nucleon interactions in light nuclei, neutron-α scattering, and neutron matter," J. E. Lynn, I. Tews, J. Carlson, S. Gandolfi, A. Gezerlis, K. E. Schmidt, and A. Schwenk, arXiv:1509.03470 (2015)

[111] "Measurement of the neutron radius of ^{208}Pb through parity-violation in electron scattering," PREX Collaboration, Phys. Rev. Lett. **108**, 112502 (2012)

[112] "Weak charge form factor and radius of ^{208}Pb through parity violation in electron scattering," C. J. Horowitz, Z. Ahmed, C.-M. Jen, A. Rakhman, P. A. Souder, M. M. Dalton, N. Liyanage, K. D. Paschke, K. Saenboonruang, R. Silwal, G. B. Franklin, M. Friend, B. Quinn, K. S. Kumar, D. McNulty, L. Mercado, S. Riordan, J. Wexler, R. W. Michaels, and G. M. Urciuoli, Phys. Rev. C **85**, 032501 (2012)

[113] "Neutron skins of ^{208}Pb and ^{48}Ca from pionic probes," E. Friedman, Nucl. Phys. **A896**, 46 (2012)

[114] "Complete electric dipole response and the neutron skin in ^{208}Pb," A. Tamii, I. Poltoratska, P. von Neumann-Cosel, Y. Fujita, T. Adachi, C. A. Bertulani, J. Carter, M. Dozono, H. Fujita, K. Fujita, K. Hatanaka, D. Ishikawa, M. Itoh, T. Kawabata, Y. Kalmykov, A. M. Krumbholz, E. Litvinova, H. Matsubara, K. Nakanishi, R. Neveling, H. Okamura, H. J. Ong, B. Ozel-Tashenov, V. Yu. Ponomarev, A. Richter, B. Rubio, H. Sakaguchi, Y. Sakemi, Y. Sasamoto, Y. Shimbara, Y. Shimizu, F. D. Smit, T. Suzuki, Y. Tameshige, J. Wambach, R. Yamada, M. Yosoi, and J. Zenihir, Phys. Rev. Lett. **107**, 062502 (2011)

[115] "Bayesian parameter estimation for effective field theories," S. Wesolowski, N. Klco, R. J. Furnstahl, D. R. Phillips, and A. Thapaliya, arXiv:1511.03618 (2015)

[116] "Energy density functional for nuclei and neutron stars," J. Erler, C. J. Horowitz, W. Nazarewicz, M. Rafalski, and P. G. Reinhard, Phys. Rev. **C87**, 044320 (2013)

[117] "A recipe for EFT uncertainty quantification in nuclear physics," R. J. Furnstahl, D. R. Phillips, and S. Wesolowski, J. Phys. **G42**, 034028 (2015)

[118] "Nuclear chiral dynamics and thermodynamics," J. W. Holt, N. Kaiser, and W. Weise, Prog. Part. Nucl. Phys. **73**, 35 (2013)

[119] "Asymmetric nuclear matter based on chiral two- and three-nucleon interactions," C. Drischler, K. Hebeler, and A. Schwenk, arXiv:1510.06728 (2015)

[120] "Shapiro delay measurement of a two solar mass neutron star," P. Demorest, T. Pennucci, S. Ransom, M. Roberts, and J. Hessels, Nature **467**, 1081 (2010)

[121] "A massive pulsar in a compact relativistic binary," J. Antoniadis, P. C. C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, Marten H. van Kerkwijk, Michael Kramer, Cees Bassa, Vik S. Dhillon, Thomas Driebe, Jason W. T. Hessels, Victoria M. Kaspi, Vladislav I. Kondratiev, Norbert Langer, Thomas R. Marsh, Maura A. McLaughlin, Timothy T. Pennucci, Scott M. Ransom, Ingrid H. Stairs, Joeri van Leeuwen, Joris P. W. Verbiest, and David G. Whelan, Science **340**, no. 6131 (2013), http://www.sciencemag.org/content/340/6131/1233232.full.pdf.

[122] "Constraining and applying a generic high-density equation of state," M. G. Alford, G. F. Burgio, S. Han, G. Taranto, and D. Zappalà, Phys. Rev. D**92**, 083002 (2015)

[123] "Composition and structure of protoneutron stars," Madappa Prakash, I. Bombaci, Manju Prakash, P. J. Ellis, J. M. Lattimer, and R. Knorren, Phys. Rep.**280**, 1 (1997)

[124] "Specific heat of a normal fermi liquid. I. Landau-theory approach," C. J. Pethick and G. M. Carneiro, Phys. Rev. A **7**, 304 (1973)

[125] "On the nucleon effective mass in nuclear matter," J. Blaizot and B. Friman, Nuclear Physics A **372**, 69 (1981)

[126] "The Entropy of a correlated system of nucleons," A. Rios, A. Polls, A. Ramos, and H. Muther, Phys. Rev. **C74**, 054317 (2006)

[127] "Chiral three-nucleon forces and neutron matter," K. Hebeler and A. Schwenk, Phys. Rev. **C82**, 014314 (2010)

[128] "Thermal properties of supernova matter: The bulk homogeneous phase," C. Constantinou, B. Muccioli, M. Prakash, and J. M. Lattimer, Phys. Rev. **C89**, 065802 (2014)

[129] "Mean field extrapolations of microscopic nuclear equations of state," E. Rrapaj, A. Roggero, and J. W. Holt, arXiv:1510.00444 (2015)

[130] "Thermal properties of hot and dense matter with finite range interactions," C. Constantinou, B. Muccioli, M. Prakash, and J. M. Lattimer, Phys. Rev. C **92**, 025801 (2015)

[131] "Specific heat of normal liquid ^{3}He," D. S. Greywall, Phys. Rev. B **27**, 2747 (1983)

[132] "Low-energy collective excitations in the neutron star inner crust," N. Chamel, D. Page, and S. Reddy, Phys. Rev. **C87**, 035803 (2013)

[133] "Supernova neutrino opacity from nucleon-nucleon bremsstrahlung and related processes," S. Hannestad and G. Raffelt, Astrophys. J. **507**, 339 (1998)

[134] "Neutrino opacities in nuclear matter," A. Burrows, S. Reddy, and T. A. Thompson, Nuclear Physics A **777**, 356 (2006)

[135] "Neutrino and axion emissivities of neutron stars from nucleon-nucleon scattering data," C. Hanhart, D. R. Phillips, and S. Reddy, Physics Letters B **499**, 9 (2001)

[136] "Chiral effective field theory calculations of neutrino processes in dense matter," S. Bacca, K. Hally, C. J. Pethick, and A. Schwenk, Phys. Rev. **C80**, 032802 (2009)

[137] "Supernova matter at subnuclear densities as a resonant Fermi gas: Enhancement of neutrino rates," A. Bartl, C. J. Pethick, and A. Schwenk, Phys. Rev. Lett. **113**, 081101 (2014)

[138] "Nonequilibrium description of bremsstrahlung in dense matter (Landau-Pomeranchuk-Migdal effect)," J. Knoll and D. N. Voskresensky, Phys. Lett. **B351**, 43 (1995)

[139] "Classical and quantum many-body description of bremsstrahlung in dense matter," J. Knoll and D. N. Voskresensky, Annals Phys. **249**, 532 (1996)

[140] "Supernova neutrino scattering rates reduced by nucleon spin fluctuations: Perturbative limit," G. Raffelt, D. Seckel, and G. Sigl, Phys. Rev. **D54**, 2784 (1996)

[141] "Photon emission from quark gluon plasma: Complete leading order results," P. B. Arnold, G. D. Moore, and L. G. Yaffe, JHEP **12**, 009 (2001)

[142] "Effects of nucleon nucleon interactions on scattering of neutrinos in neutron matter," N. Iwamoto and C. J. Pethick, Phys. Rev. **D25**, 313 (1982)

[143] "Neutrino interactions in a dense plasma," C. J. Horowitz and K. Wehrberger, Physical Review Letters **66**, 272 (1991)

[144] "Effects of strong and electromagnetic correlations on neutrino interactions in dense matter," S. Reddy, M. Prakash, J. M. Lattimer, and J. A. Pons, Phys. Rev. C**59**, 2888 (1999)

[145] "Realistic neutrino opacities for supernova simulations with correlations and weak magnetism," C. J. Horowitz and M. A. Pérez-García, Phys. Rev. C**68**, 025803 (2003)

[146] "A unified approach to structure factors and neutrino processes in nucleon matter," G. I. Lykasov, C. J. Pethick, and A. Schwenk, Phys. Rev. **C78**, 045803 (2008)

[147] "Spin response and neutrino emissivity of dense neutron matter," G. Shen, S. Gandolfi, S. Reddy, and J. Carlson, Phys. Rev. **C87**, 025802 (2013)

[148] "The effective field theory of dark matter direct detection," A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, and Y. Xu, JCAP **1302**, 004 (2013)

[149] "Neutrino and antineutrino quasielastic interactions with nuclei," M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. **C81**, 045502 (2010)

[150] "Chiral effective field theory predictions for muon capture on deuteron and ^{3}He," L. E. Marcucci, A. Kievsky, S. Rosati, R. Schiavilla, and M. Viviani, Phys. Rev. Lett. **108**, 052502 (2012)

[151] "Electromagnetic and neutral-weak response functions of ^{4}He and ^{12}C," A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, and R. Schiavilla, Phys. Rev. **C91**, 062501 (2015)

[152] "Chiral two-body currents in nuclei: Gamow-Teller transitions and neutrinoless double-beta decay," J. Menendez, D. Gazit, and A. Schwenk, Phys. Rev. Lett. **107**, 062501 (2011)

[153] "Spin-dependent WIMP scattering off nuclei," J. Menendez, D. Gazit, and A. Schwenk, Phys. Rev. **D86**, 103511 (2012)

[154] "Quantifying truncation errors in effective field theory," R. J. Furnstahl, N. Klco, D. R. Phillips, and S. Wesolowski, Phys. Rev. **C92**, 024005 (2015)

[155] 'Particle dark matter: Evidence, candidates and constraints," G. Bertone, D. Hooper, and J. Silk, Phys. Rept. **405**, 279 (2005)

[156] "Dark Matter Candidates from Particle Physics and Methods of Detection," J. L. Feng, Ann. Rev. Astron. Astrophys. **48**, 495 (2010)

[157] "Dark Matter Studies Entrain Nuclear Physics," S. Gardner and G. Fuller, Prog. Part. Nucl. Phys. **71**, 167 (2013)

[158] See, for example, CDMS-II Collaboration, Phys. Rev. D**92**, 072003 (2015) and LUX Collaboration, arXiv:1512.03506 (2015)

[159] “Nonrelativistic effective theory of dark matter elastic scattering,” J. Fan, M. Reece, and L. T. Wang, JCAP **1011**, 042 (2010)

[160] “Weakly interacting massive particle-nucleus elastic scattering response,” N. Anand, A. Liam Fitzpatrick, and W. C. Haxton, Phys. Rev C**89**, 065501 (2014); for the more case of chiral EFT applied to S.D. interactions, see “Shining LUX on Isospin-Violating Dark Matter Beyond Leading Order,” V. Cirigliano, M. L. Graesser, and G. Ovanesyvan, JHEP **1210**, 025 (2012) and “Large scale nuclear structure calculations for spin-dependent WIMP scattering with chiral effective field theory currets,” J. Menendez, D. Gazit, and A. Schwenk, Phys. Rev D **88**, 083516 (2013)

[161] “Signatures of dark matter scattering inelastically off nuclei,” L. Baudis, G. Kessler, P. Klos, R. F. Lang, J. Menendez, S. Reichard, and A. Schwenk, Phys. Rev. D **88**, 115014 (2013)

[162] M. Kado, talk at ATLAS and CMS physics results from Run 2, CERN, 12/14/20015 [ATLAS Collaboration ATLAS-CONF-2015-081]; J. Olsen, talk at ATLAS and CMS physics results from Run 2, CERN, 12/14/20015 [CMS Collaboration CMS-PAS-EXO-15-004]

[163] “New Constraints on Dark Matter Effective Theories from Standard Model Loops,” A. Crivellin, F. D’Eramo and M. Procura, Phys. Rev. Lett. **112**, 191304 (2014)

[164] “New Prospects in Fixed Target Searches for Dark Forces with the SeaQuest Experiment at Fermilab,” S. Gardner, R. J. Holt, and A. S. Tadepalli, arXiv:1509.00050 (2015)

[165] “New Fixed-Target Experiments to Search for Dark Gauge Forces,” J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev. D **80**, 075018 (2009)

[166] “Exploring Portals to a Hidden Sector Through Fixed Targets,” B. Batell, M. Pospelov, and A. Ritz, Phys. Rev. D **80**, 095024 (2009)

[167] “Sensitivity to light weakly-coupled new physics at the precision frontier,” M. Le Dall, M. Pospelov, and A. Ritz, Phys. Rev. D **92**, 016010 (2015)

[168] “Muon $g2$, rare kaon decays, and parity violation from dark bosons,” H. Davoudiasl, H. S. Lee, and W. J. Marciano, Phys. Rev. D **89**, 095006 (2014)

[169] J. D. Walecka, “Semileptonic weak interactions in nuclei,” in Muon Physics, ed. V. Hughes and C.S. Wu, Vol. 2, Sec. 4; “Multipole operators in semi-leptonic weak interactions with nuclei: Harmonic oscillator single-particle matrix elements,” T. W. Donnelly and W. C. Haxton, At. Nucl. Data Tables **23**, 103 (1979)

[170] ”Dimensional dependence of the hydrodynamics of core-collapse supernovae,” J. C. Dolence, A. Burrows, J. W. Murphy, and J. Nordhaus, Ap. J. **765**, 110 (2013)