Project Summary

Overview: Nearly twenty years ago the influential report "From Quarks to the Cosmos" argued that the growing precision of astrophysical and cosmological measurements would make this field an increasingly important part of fundamental physics. Indeed, four monumental discoveries – massive neutrinos and their flavor mixing, dark matter, the accelerating universe, and gravitational waves – have confirmed this prediction. Astrophysics has given us extraordinary "multi-messenger laboratories" unlike any we can create on Earth, providing opportunities to test physics at it extremes – the Big Bang, supernova (SN) cores, merging neutron stars (NSs), black holes (BHs). Experimental progress has come through enormous effort: the LIGO discovery of the NS merger GW170817 came 20 years after the collaboration formed, and reflects the work of a team that grew to 1200 scientists and 100 institutions. To get value from these investments, it is critical that theory keep pace. To overcome the obstacles nuclear and neutrino astrophysics faces – its dispersion into small or single-investigator groups, inhibiting the coordinated efforts that the field now needs – senior theorists created N3AS, the Network for Neutrinos, Nuclear Astrophysics, and Symmetries.

Intellectual Merit: The multi-messenger theory challenges N3AS will address include

- The development of first-principles treatments of neutrino transport of energy, lepton number, entropy, and flavor in the high-density cores of SNe, in nascent NSs, and in NS mergers. Novel nonlinear flavor phenomena arise in these exotic environments.
- Understanding how the properties of exotic nuclear matter – matter at extremes of density, temperature, and isospin – are reflected in the structure of extreme astrophysical environments.
- Achieving a quantitative theory of the origin of the elements, allowing us to use nucleosynthesis as a forensic tool in transient events like kilonovae, and as a probe of long-term galactic evolution.
- Integration of this microphysics into state-of-the-art numerical simulations of SNe, mergers, and NSs, by developing algorithms that exploit the most advanced computing platforms.
- Establishment of a baseline understanding of the "extreme laboratories" Nature has created, giving us more confidence in our abilities to extract from these laboratories new constraints on dark matter and other weakly coupled exotic physics.

Broader Impacts: N3AS-PFC broader goals focus on strengthening the "human capital" investment in the field while increasing its diversity. A centerpiece of N3AS is its novel postdoctoral Fellows program, designed to help young researchers gain the competence and breadth they need to become leaders in multi-messenger astrophysics. N3AS-PFC will create new international connections through partnerships with the Centre Pierre Binètruy, RIKEN Berkeley Center (Astrophysics), and the European training efforts *HIDDeN*, *Elusives*, and *InvisiblesPlus*. It will train graduate students in the data science challenges of large astrophysical data sets. Beginning in 2020, N3AS will sponsor an annual summer school in multi-messenger astrophysics for advanced graduate students and beginning postdoctoral researchers (in theory, experiment, or observation), structured to convey the breadth and connectivity of multi-messenger astrophysics. The US has no regular school for such researchers. The participation of *HIDDeN*, *Elusives*, and *InvisiblesPlus* could help the US benefit from European efforts to work toward gender equality in astrophysics. N3AS will create a mentoring program for transfer students interested in astrophysics in three N3AS universities: by engaging newly arrived transfer students in astrophysics reading and research at an appropriate level, and by integrating them into a social environment that includes supportive faculty and peer mentors, the program will encourage students to persist in their major of choice.

3. N3AS-PFC Project Description

3a. Executive Summary

The Rationale for N3AS-PFC: The deep connections between precision astrophysics and fundamental properties of matter have been brought into sharp focus by a series of extraordinary discoveries in recent years. Neutrino mass and flavor mixing – themes that will drive the on-shore US particle physics program in the coming decade – emerged from the discovery that the Sun's weak luminosity in electron neutrinos did not match its electromagnetic luminosity in photons. The recognition that most of the matter in galaxies is dark, deduced initially from galaxy and cluster rotation velocities but now confirmed through a variety of astrophysical and cosmological measurements, provides our strongest evidence for new, weakly coupled particles beyond those of the standard model. The use of Type I SNe as standard candles revealed an accelerating universe, challenging physics to account for the scale of vacuum energy, to characterize its dynamics, and to connect it to other aspects of cosmology, such as inflation. The discovery of two-solar-mass NSs and the observation of the gravitational waves (GWs) from and electromagnetic afterglow of a neutron star merger – and the expectation that GW measurements will rapidly improve in sensitivity and frequency range – has opened up new opportunities to probe strongly interacting matter at extremes of density and isospin, and to test our quantitative understanding of the nucleosynthesis that accompanies billion-degree astrophysical explosions.

Continuing technological advances are rapidly opening up the universe in multiple wave lengths, extending our reach to earlier times, greater distances, and higher precision. The Webb telescope will provide a new window on the infrared universe, allowing us to see the formation of the first galaxies and the birth of stellar nucleosynthesis. Hyper-Kamiokande and DUNE will advance the scale of low-energy neutrino astronomy by an order of magnitude, enabling us to use neutrinos to map the cooling curves of galactic supernovae and other transient events out to very late times, and to monitor continuous solar, relic, and atmospheric fluxes. LIGO, Virgo, and KAGRA are the first steps in the new field of GW astronomy, enhanced by the growing coordination among and rapid slewing capabilities of optical instruments that can follow kilonovae and other associated transients. The extraordinary progress in CMB mappings since COBE has led us to CMB-S4, designed to measure the imprint of primordial gravitational waves on the CMB polarization anisotropy, constrain neutrino mass, and determine the possible contributions of light relic particles to the energy density of the early universe. Three G2 direct-detection dark matter experiments are currently being developed at the ton scale, and over the past few years an explosion of new experimental proposals for detecting alternative dark matter – from 10^{-22} eV bosons with kpc deBroglie wavelengths to "WIMPzillas" with masses at the GUT scale – are being implemented.

The field's visibility is reflected in the six physics Nobel Prizes so far earned in the new century: Big Bang cosmology (2019); GW detection (2017); solar and atmospheric neutrino oscillations (2015); the accelerating universe (2011); CMB black-body spectrum (2006); and neutrino astrophysics (2002). Talented and motivated students are drawn to astrophysics by the accelerating pace of discovery, and because the field's questions – the origin of matter, the mechanisms driving the universe's most cataclysmic explosions, the dominance of the dark universe – fire the imagination.

The promise inherent in connecting astrophysical observations to underlying fundamental physics was eloquently captured in the influential NRC report (now nearing its 20th anniversary) "From Quarks to the Cosmos" and in the eleven science challenges it posed for the new century. N3AS was formed in 2016 by a group of community astrophysics leaders with roots in nuclear physics who recognized that these challenges are rapidly evolving with the emergence of a new paradigm for the field, high-precision multi-messenger astrophysics. Observers and experimentalists have the culture and funding to create the large, international collaborations required to drive forward endeavors such as Advanced LIGO, Hyper-Kamiokande, and CMB-S4. In contrast, much of the relevant theory expertise needed to interpret multi-messenger signals is embedded in small groups and even individual investigators, dispersed over separated institutions. This situation inhibits the kinds of integration needed to meet the challenges of multi-messenger astrophysics: the current structure encourages individual investigators to focus on the specialty work that forms the core of their individual grants. In such environments students and postdocs will focus on local interests. Yet the field needs theorists who are broadly trained, cognizant of the broad range of experiment and observation, and adept at integrating observation into multi-physics models, to make connections to the underlying fundamental microphysics.

Potential science impacts: The merger of NSs was one example given in the 2016 N3AS Hub proposal to illustrate the urgent need for a more coherent approach to multi-messenger theoretical astrophysics. The governing physics includes the gravitational collapse and hydrodynamic ejection of neutron-rich material, the complex neutrino flavor physics that controls matter isospin and important energy deposition and transport, the coupled nuclear and atomic physics that governs the photon opacity, and the explosive nucleosynthesis that occurs within the expanding, cooling ejecta. The N3AS leadership includes the person who first suggested NS mergers as the site of the r-process; others who performed the first realistic calculation of the "kilonova" electromagnetic afterglow including how red and blue spectral components will depend on the heavy-element synthesis; several members who developed much of the theory of neutrino flavor physics in dense media; and other experts on the high-density nuclear equation-of-state (EoS) and nuclear structure along the r-process path. The N3AS-Hub proposal envisioned an integration of this microphysics into a state-of-the-art computational framework modeling the macrophysics - the GW signal, the afterglow, and the nucleosynthesis. The urgency of this program was underscored by the announcement of October 2017 that GW170817 had been observed in GWs and optically. This was the month N3AS Hub activities began, with the arrival of our first postdoctoral Fellows.

In nuclear physics the field's flagship facilities, RHIC, JLab, and FRIB, support large associated theory groups. In contrast, multi-messenger astrophysics and fundamental symmetries lack a natural institutional patron; furthermore, the challenging problems in this field tend to be interdisciplinary – a mixture of nuclear, particle, atomic, and astrophysics – creating further barriers to coherent organization. We believe N3AS-PFC, structured with the proper outward orientation to welcome the nuclear theory community as a whole, our colleagues in particle, atomic, and astrophysics, the international community, and experimental colleagues, would fill a great need.

NS mergers are just one of many examples where the pace of experimental discovery demands more coherence and sophistication in supporting theory. Other N3AS foci include

- *Neutrino Physics:* Understanding the properties of neutrinos, including mixing phenomena on earth and in extreme astrophysical environments; the absolute mass scale and hierarchy; their behavior under particle-antiparticle conjugation and implications for the matter-antimatter asymmetry; and the astrophysical roles of neutrinos in transporting energy, lepton number, flavor, and entropy, controlling physics hidden within the cores of stars and compact objects.
- *Nucleosynthesis:* How were the elements created, and how can we use nucleosynthesis to probe the evolution and structure of our galaxy and the objects within it?
- *Dense Matter:* The discovery of three NSs with masses $\sim 2\ M_\odot$ and the opportunities to deter-

mine masses and radii from future GW and optical observations of mergers, provide a window on matter at densities and isospins not otherwise reachable. Can we relate these properties to those deduced from laboratory nuclei, and ultimately understand the connections to QCD?

- *Modeling:* Integrate this physics into state-of-the-art computational frameworks utilizing the most advanced computing platforms, creating "standard models" of SNe, NSs, and their mergers.
- *Dark Matter:* Through such "standard models" of Nature's most extreme events, and by using nucleosynthesis to test our understanding of the evolution of galaxies and large-scale structure, help to make astrophysics a more quantitative laboratory for probing BSM physics.

Institutional Setting: The N3AS-PFC structure is a Berkeley center connected by spokes to 12 sites. Berkeley has exceptional strength in astrophysics and fundamental symmetries: it played major roles in the SNO discovery of solar neutrino oscillations, in the COBE measurement of the temperature anisotropy of the CMB, and in detecting the universe's acceleration, receiving a Breakthrough Prize and two Nobel Prizes for this work. Currently Berkeley is playing a important role in the Simons Array and in planning for the Simons Observatory, and its faculty are engaged with all three of the G2 dark matter direct detection experiments. In fundamental symmetries, Berkeley played leading roles on the KamLAND and Daya Bay experiments, efforts that led to Breakthrough, Panofsky, and Future Science Prize recognition for its faculty, and currently leads efforts on the DUNE near detector. It is the US lead institution for the double beta decay experiment CUORE. Berkeley's atomic physics group has a long history of precision measurements, including searches for electric dipole moments and atomic interferometry tests of dark energy models.

The twelve sites – UC San Diego, Kentucky, Los Alamos, Minnesota, New Hampshire, North Carolina State, Northwestern, Notre Dame, Ohio, Penn State, Washington and Wisconsin – include some of the strongest nuclear astrophysics programs in the US. In N3AS-PFC New Hampshire and Penn State, with newly hired junior faculty, have joined the ten original sites of N3AS-Hub.

Organization and Scope: N3AS has a PI and an executive committee consisting of the four co-PIs. However, in practice decisions are by consensus of the entire collaboration. N3AS administration was designed to be efficient and cost effective. All budgetary and personnel actions are handled by Berkeley; thus N3AS postdoctoral Fellows are Berkeley employees located off site, but covered by Berkeley benefits, with easy access to Berkeley's online travel and purchasing software. The arrangement greatly simplifies budget monitoring and agency reporting. It also allows Fellows to move to a second site seamlessly. Off-campus indirect costs rates apply, a significant cost savings.

The following elements define the scope of N3AS-PFC:

1. A physical center at Berkeley that will enable N3AS to host focused collaborations among our members, and to engage experimentalists, observers, and the broader nuclear and particle astrophysics community in our activities. Berkeley will remodel a 1600 sf area for the Center, contiguous to two existing collaboration areas; significant additional support will be provided by CNRS and RIKEN. We envision the Center as a community focal point for modeling and interpreting astrophysical phenomena, drawing US and international visitors.
2. Continuation of the innovative postdoctoral program begun under the N3AS-Hub which, as described in Sec. c, has provided N3AS Fellows with an enriching training experience, and also created a collaborating network of young researchers that will persist throughout their careers.
3. The establishment of an annual summer school for the community's advanced graduate students and beginning postdoctoral researchers, in theory and experiment, interested in multi-messenger

astrophysics. Though there are several such schools in Europe, none exists in the US.

4. Creating a modest graduate student effort focused on the data science challenges of multi-messenger astrophysics and the data sets it generates.
5. Creating an outreach program to support and mentor transferring undergraduates, to determine whether such mentoring can improve the success rate to the B.A. and, on graduation, the decision whether to pursue graduate study. The transfer student STEM failure rate is a significant issue in many of our public research universities. We seek to create a program whose success can be quantified, that can be progressively expanded to multiple sites, and that will persist beyond the duration of the PFC, due to its alignment with university and state goals. The program has significant potential to increase the diversity of the field.

Research and Educational Activities and their Integration: As described above and in more detail in Sec. c, the primary goal of N3AS – producing a stronger, more coherent, and more coordinated theory effort to better support the rapidly expanding experimental effort in multi-messenger astrophysics – inherently integrates research with education. The N3AS postdoctoral program was designed to give Fellows an unusual amount of freedom in pursuing their research goals, while at the same time creating a stronger mentoring framework and opportunities for growth through exposure to wider variety of physics. The collaborative networking among the postdocs, dispersed over but linked by N3AS, proved an added benefit of the program we designed. The tools we use include travel – Fellows have a generous budget and discretion in its use – weekly and other regular videoconferencing among collaboration subgroups, and full collaboration meetings twice yearly, featuring Fellow research. We have welcomed into these activities students and non-N3AS postdocs, supporting their participation in our meetings. N3AS-PFC will take these activities to a new level, with the creation of a collaboration space that can support a higher level of face-to-face interactions, and provide a venue for interacting with experimentalists and observers.

The summer school with be hosted by N3AS-Hub in 2020 and will continue annually thereafter, if N3AS-PFC is funded. Both N3AS faculty and “graduating” Fellows will be deeply involved, with the latter helping with discussion sessions and organizing student poster sessions. Our undergraduate “discovery experience” for transfer students includes partnerships with university professionals charged with community college recruitment, support of the recruited students by emersion in the N3AS network of graduate students, Fellows, and faculty, tangible support to encourage the transfers to ”stay the course,” and advice and support for those interested in the transition to graduate school. In all respects, the transfers will be members of N3AS and its research enterprises.

Outreach Activities and Diversity: N3AS is fortunate to have among its members several prominent women astrophysicists who provide excellent role models for students and postdocs. This in combination with the funding flexibility N3AS provides has already allowed us to provide one finishing student an ideal postdoctoral mentoring opportunity. N3AS-PFC will create partnerships with its European counterparts *HIDDeN*, *Elusives* and *InvisiblesPlus*, benefitting from and helping extend their efforts to reach gender equality in astrophysics.

Our transfer student undergraduate program was designed in collaboration with Colette Patt, Diversity Director for Mathematics and the Physical Sciences, UC Berkeley, because of the opportunity to provide badly needed support and encouragement to a group significantly more diverse than their four-year cohort. This diversity includes ethnicity, economic status, economic independence, age, and military status, as we will later describe.

3b. List of Participants

P.I. and co-P.I.s

Wick Haxton (P.I.)†	Univ. California, Berkeley	Dept. Physics
Baha Balantekin†	Univ. Wisconsin	Dept. Physics
George Fuller†	Univ. California, San Diego	CASS and Dept. Physics
Gail McLaughlin†	North Carolina State Univ.	Dept. Physics

Senior Investigators

Andre DeGouvea†	Northwestern Univ.	Dept. Physics
Francois Foucart	Univ. New Hampshire	Dept. Physics
Susan Gardner†	Univ. Kentucky	Dept. Physics
Dan Kasen†	Univ. California, Berkeley	Depts. Physics, Astronomy
Jim Lattimer†	Univ. Washington/Stony Brook	INT/Dept. Astronomy
Tongyan Lin	Univ. California, San Diego	Dept. Physics.
Katherine Mack	North Carolina State Univ.	Dept. Physics
Daniel Phillips†	Ohio Univ.	Dept. Physics
Madappa Prakash†	Ohio Univ.	Dept. Physics
Yong-Zhong Qian†	Univ. Minnesota	Dept. Physics
Eliot Quataert	Univ. California, Berkeley	Depts. Astronomy, Physics
David Radice	Pennsylvania State Univ.	Depts. Physics, Astronomy
Sanjay Reddy†,††	Univ. Washington	INT/Dept. Physics
Uros Seljak	Univ. California, Berkeley	Depts. Physics, Astronomy
Rebecca Surman†	Notre Dame Univ.	Dept. Physics

Senior Participating Investigators

Joseph Carlson†	Los Alamos National Laboratory	Theory Division
Vincenzo Cirigliano†	Los Alamos National Laboratory	Theory Division
Stefano Gandolfi†	Los Alamos National Laboratory	Theory Division

Collaborators

Tetsuo Hatsuda	RIKEN	iTHEMS (Director)
Shigehiro Nagataki	RIKEN	Astrophys. Big Bang Lab (Chief Scientist)
Silvia Pascoli	Univ. Durham	Co-ordinator, Horizon 2020 ITN *HIDDeN*
Colette Patt	Univ. California, Berkeley	MPS Division (Diversity Director)
Saul Perlmutter	Univ. California, Berkeley	Co-Director, Centre Pierre Binetruy
Radek Stompor	CNRS, Laboratoire APC	Co-director, Centre Pierre Binetruy

† Continuing member of N3AS

†† N3AS-Hub coPI, will resume this role on N3AS-PFC if his current PFC project (on which he is coPI) is not renewed

3c. Results from prior NSF support pertaining to current proposal

This section describes the progress of N3AS-Hub, which was approved by NSF in 2016, and welcomed its first Fellows in October, 2017. The recent N3AS midterm review concluded: "The Panel commends N3AS for its innovative approach to advancing theoretical nuclear physics by addressing key questions in Fundamental Symmetries, Neutrinos and Nuclear Astrophysics. N3AS is uniquely positioned to combine the expertise of the eleven network institutions to address exciting questions. It is identifying important, cutting-edge topics and is also filling in a scientific gap by attacking interdisciplinary questions while simultaneously training the future leaders in the field."

c.1 N3AS-Hub Science: Because we are proposing a transition from N3AS-Hub to N3AS-PFC, the science achievements of N3AS-Hub over the past 2.5 years are described in some detail in the MAs. Therefore here we give just a brief summary, with attention to the role the Fellows have played.

- GW170817 and its kilonova; accretion disk simulations; radioactive heating; neutrino energy transport; oscillations; and nucleosynthesis. The first quantitative description of a kilonova came from Kasen and collaborators, and over half of N3AS faculty have been involved in subsequent studies of GW170817. Kasen and others on the N3AS team were included on many of the most prominent publications associated with GW170817. Fellow Wang's work on nucleosynthesis links Notre Dame, Los Alamos, and NCSU.
- Collective neutrino oscillations in compact objects, including approaches based on quantum kinetics and on machine learning/neural networks. Fellows Patwardhan (Wisconsin/Washington) and Richers (NCSU/Berkeley) have been involved in this work. One important milestone established by Richers was the very first treatment of quantum decoherence near a NS's neutrinosphere, using the quantum kinetic equations. Regular telecons and in-person meetings link collaborators from Wisconsin, Washington, Los Alamos, San Diego, and Berkeley.
- Dark matter, including the core-cusp problem and the potential utility of r-process abundances in systems like Reticulum II as tracers of baryonic feedback; dark photons and other dark sector nuclear physics; light DM; and effective field theory treatments of direct detection. Regular "Dark Sector" Zoom meetings arranged by N3AS Fellow Grohs (LANL/Berkeley) include faculty and Fellows at Berkeley, Kentucky, Minnesota, NCSU, San Diego, Washington, and Wisconsin, and frequently other N3AS and non-N3AS members. N3AS work on effective theory applications to direct detection include some of the most cited theory papers in the field: the formalism has been adopted by almost all of the major experimental groups.
- Primordial nucleosynthesis and neutrino decoupling: a quantum kinetic framework was developed to follow oscillations and evaluate impacts on nucleosynthesis and N_{eff}, important to future Stage IV CMB and 30-m-telescope investigations. Fellows Rrapaj (Minnesota) and Grohs (LANL) are engaged in this work – one of several Fellow-to-Fellow collaborations across the Network – along with faculty at Minnesota and Washington.
- Dense matter equation of state (EoS). Fellow Han (Ohio University) has derived phenomenological constraints from NSs and NS mergers, while others at Berkeley and LANL are developing EoSs starting from chiral EFT, employing machine generation of the diagrams and sophisticated multi-dimensional Monte Carlo integrations. N3AS members have shown how future kilonova and GW measurements will determine the compactness of NSs and place important new constraints on the EOS.
- Neutrino properties under CP and neutrino electromagnetic moments. This is the main focus of a Midwest subset of N3AS that meets regularly at Fermilab or Madison for in-person

collaboration meetings. The group includes Fellows Patwardhan (Wisconsin/Washington), Sen (Northwestern), and Rrapaj (Minnesota).

The N3AS second-year progress report lists 73 publications from these efforts.

c.2 N3AS-Hub Background and Organization: N3AS-Hub was created as an NSF Focused Research Hub in Theoretical Physics. (NSF award 1630782 for $2.4M for five years; additional funding of $575K provided by the Heising-Simons Foundation.) FRHTPs are created to enhance significant breakthroughs at an intellectual frontier of physics by providing resources beyond those available to individual investigators, enabling collaborative problem solving. The proposing team included many of the leading nuclear theoreticians working in inner space/outer space/cyber space nexus of nuclear astrophysics and fundamental symmetries, e.g., three former APS Bethe Prize winners. The scientific focus is the use of astrophysical environments, such as NSs, mergers, SNe, and the Big Bang, to test fundamental interactions.

N3AS-Hub administration is centralized at Berkeley, which handles all appointments and other HR matters, purchasing, travel, and reporting. This arrangement streamlines accounting and budgeting, and also reduces costs, as an off-campus indirect cost rate applies. (Most Fellows resided off site.) Project participants have access to Berkeley's online administrative "toolbox" to request reimbursements for travel or purchases Requests are routed through the PI for single-click approval, then on to an administrator assigned to N3AS to check compliance with NSF and University rules. The arrangement provides greater accountability and uniformity than the more conventional arrangement of 10 subcontracts managed by 10 universities with differing rules.

This structure ensures that N3AS Fellow salaries, annual increases, and benefits are kept uniform across the Network. A Fellow can move to a second site at the beginning of the third year, as describe below, without any worries about reappointment or continuity of health care coverage. As discussed in c.4, the uniform treatment of Fellows as Berkeley postdocs reinforces the concept of collaboration membership, reducing distinctions between sites, facilitating Fellow placement.

c.3 N3AS-Hub Scope: The N3AS-Hub goals include:

1. Creating a stronger and more coherent national theory effort to support the expanding field of multi-messenger astrophysics. N3AS seeks to integrate state-of-the-art work in neutrinos, nucleosynthesis, and dense matter to produce more reliable "standard models" of SNe, NSs, and mergers, making such environments into more quantitative laboratories for new physics, while strengthening and coordinating interactions among the network of N3AS institutions;
2. Establishing an N3AS fellows program to enhance the number, productivity, and breadth of young nuclear astrophysicists, preparing them to step into faculty positions;
3. Involvement of the community through open workshops and a school. The school focuses on advanced graduate students and beginning postdocs, and seeks to broaden understanding of multi-messenger astrophysics while giving young researchers an opportunity to network; and
4. Establishing and leveraging new institutional partnerships, in the US and abroad, to enhance cooperation beyond the participating N3AS-Hub institutions.

c.4 Fellows program: The organization of the N3AS-Hub's Fellow program is illustrated in Fig. 1. During the first two years the Fellows are hosted by one of the institutions designated as "sites"; in the third year the Fellows move to one of the three "centers" (Berkeley, San Diego, Seattle). Fellows select their sites and centers and their associated faculty hosts/mentors, based on availability (sites currently hosting a Fellow are not eligible). The purpose of the move in year three is to ensure that Fellows do engage in cross-Network interactions, while also giving them an opportunity to benefit from the large, multi-disciplinary research programs connected to Center faculty (Theoretical Astrophysics Center, Berkeley; Center for Astrophysics and Space Science, UCSD; Institute for Nuclear Theory, Seattle). The centers can be helpful as "launching pads" as Fellows seek their next positions.

Fellow recruitment is done through Academic Jobs Online, utilizing AJO tools for group evaluation of candidates. All N3AS faculty participate in the initial evaluation and in the final selection, with candidate quality and capacity to contribute to N3AS paramount. We do not select Fellows based on an individual site's needs: our goal is to stimulate and optimize collaborative work, and not to support local groups and local grants. Final Fellow selection is by faculty vote, after short-listed candidates have all given seminars via Zoom. N3AS-Hub five-year funding allowed us to hire Fellows in each of the first three years (eight Fellows in total) for three-year terms.

In the first three years approximately 450 applications were received from prospective Fellows. Most of our first offers were accepted: we lost candidates to KIPAC (Stanford), FermiLab, and UCLA. While site choices diminished as the hiring process progressed – open sites are those which have not yet hosted a Fellow – we did not see any impact on applications or hiring success. We concluded that 1) our choice to hire all Fellows through Berkeley; 2) our efforts to make selection an N3AS-wide faculty process; 3) the generous funding of Fellow travel to enable cross-Network collaboration regardless of site; and 4) the opportunity to move in year three to a Center, combined to make the Network a success. Any perceived differences among the sites is secondary to the perception by Fellows that they are joining an outstanding collaboration.

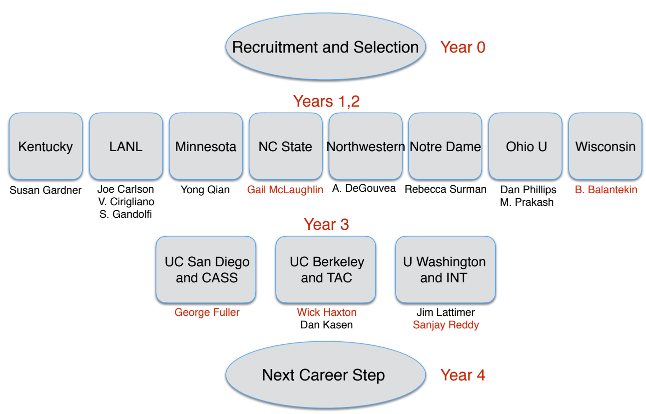

Figure 1: N3AS-Hub Fellows are chosen jointly by the N3AS faculty, becoming collaboration members. The Fellows spend two years at one of eight sites they select, then one additional year at one of three centers. The cycle provides the Fellows with multiple mentors and a strong base from which to take their next career steps.

c.5 Engagement of students and non-N3AS postdocs: N3AS projects have attracted participation from graduate students and from postdocs outside of N3AS. We have encouraged other beginning researchers to attend our Annual Meetings, inviting them to present and supporting their travel – helping N3AS-Hub grow as a community focal point, one of our NSF charges. N3AS groups have met by piggy-backing off community meetings at Santa Fe, KITP, and Palm Springs (CIPANP18), and N3AS has utilized both KITP and the INT as workshop hosts. Students and postdocs working with N3AS members but supported under individual grants, external to N3AS, have been encouraged to attend N3AS meetings, in order to interact with N3AS faculty, Fellows, and other students.

There is a need in the US – filled in other nuclear physics subfields by the major facilites, JLab, RHIC, and FRIB – to provide a focal point for students, making them feel a part of a larger scientific enterprise, and creating excitement. The key element of our outreach to the community's young researchers is the summer school N3AS-Hub will host in summer 2020. Approval of N3AS-PFC will allow us to continue the school annually thereafter, in locations distributed around the US. The school is being modeled on one in multi-messenger astrophysics that was organized by two members of the N3AS executive committee (Fuller, Haxton) at Asilomar, in conjuction with TAUP2013. That school included students from theory, experiment, and observation, and was inspirational because of the opportunities we created for the school's students to engage the senior researchers attending TAUP. Our plans to create similar opportunities under N3AS-PFC are discussed under MA7.

The senior members of N3AS have a long history of involvement in both schools and graduate education: a large fraction of the mid-career researchers in this field (some now in N3AS) were students of Balantekin, Fuller, Haxton, Lattimer, and Prakash. Our school experience includes one-time events such as the TAUP13 school, and annual events such as the National Nuclear Physics Summer School. Haxton led the creation of NNPSS in 1994 after an earlier effort failed, serving as PI for 20 years. N3AS member Sanjay Reddy then stepped into this role. Other N3AS faculty have served on the NNPSS Steering Committee.

c.6 Community workshops: With the help of partners, N3AS-Hub has hosted activities for the benefit of the broader physics community:

- The January 2018 N3AS workshop "Quantum Information: Condensed Systems to Neutrinos" dealt with quantum information transport, coherence and de-coherence, and quantum kinetics. Quantum kinetic treatments of the flavor evolution of trapped neutrinos have much in common with the large-scale condensed fermion simulations done by QI theorists.
- In March 2018 N3AS and the KITP, with NSF support, cosponsored a workshop on Hadronic Parity Nonconservation. Recent work involving N3AS members and based on large-N_c QCD had lead to a new classification of weak coupling (or Danilov) amplitudes, impacting the interpretation of cold-neutron experiments underway at the SNS. A followup workshop will be held in July 2020, cosponsored by the INT and N3AS.
- The planned school on Multi-messenger Astrophysics will be held Aug. 16-22, 2020, at UC Santa Cruz.

c.7 Institutional and international partnerships: PFCs are encouraged to "outreach to other institutions and scientists in the field, including international collaboration and cooperation."

The temptation to add members and scope can lead to "mile wide, inch deep" collaborations where resources are diluted to the point of becoming supplements to individual grants. N3AS has a three-pronged strategy for avoiding this trap: 1) create and maintain an intellectual core sized so that PFC support can have impact, enabling science beyond that possible with individual grants; 2) contribute to the broader community by organizing selected workshop and schools of general interest, using existing community venues like the KITP and INT when possible; and 3) selectively build scientific partnerships that leverage, rather than dilute, PFC resources.

The coordination with KITP and INT makes good use of the community's previous investments in visitor centers. We strive for similar coordination with other scientific collaborations: N3AS members are connected to the SciDAC astrophysics effort TEAMS, the lattice QCD collaboration CalLat, JINA, the Exascale Computing Project ExaStar, the Zwicky Transient Factory Theory Network, and the DOE Topical Collaboration on Fundamental Symmetries. These efforts are largely complementary to N3AS.

N3AS-Hub's creation led to two international partnerships that will leverage N3AS-PFC. Both

RIKEN and CNRS have agreed to establish visitor institutes at Berkeley that will be co-located with N3AS-PFC Berkeley Center. This three-way international partnership will create a critical mass of long-term visitors at the Berkeley Center at no salary cost to N3AS, making the Center a more visible focal point for the broader community. The RIKEN Berkeley Center (Astrophysics) will focus on explosive astrophysics, and includes connections to the Kamioka Laboratory, where Super-Kamiokande and KAGRA reside. The Centre Pierre Binétruy will focus on the CMB and GWs, and has ties to the CNRS Virgo data analysis team. The MOUs establishing the partnerships are in place. These institutes and the envisioned joint Berkeley PFC Center are discussed in MA6. These have significant international visibility: preliminary inaugural events held Berkeley were attended by RIKEN Executive Director Motoko Kotani and by the French Ambassador to the U.S., M. Philippe Etienne.

c.8 Broader impacts and diversity: An important part of the N3AS mission is to help young nuclear astro-theorists acquire the breadth and technical abilities needed in this rapidly evolving, highly collaborative, interdisciplinary field. The N3AS-Hub program was designed to speed the professional development of its Fellows by encouraging collaboration across a broad network of expert senior researchers. The circulation we require of Fellows gives them multiple mentors and varied experiences, without disrupting their research or professional relations. We encourage our Fellows to showcase their accomplishments by speaking at community meetings. We also help those who want to gain teaching experience connect with graduate students, e.g., Fellow Sherwood Richers is guiding the research of two NCSU graduate students interested in fast flavor oscillations and neutrino transport in supernovae and mergers.

An important diversity goal is to increase the representation of women in nuclear astrophysics. Among the faculty we have three excellent mid-career role models in Gardner, McLaughlin, and Surman. This has helped our Fellow recruitment efforts. We aspire to do better: a third international partnership could help us. In 2016, as NSF was approving N3AS, the EU launched two coordinated Horizon2020 programs with similar research and broader-impact goals – the Innovative Training Network *Elusives* [1] (recently renewed as *HIDDeN*) and the Research and Innovation Staff Exchange program *InvisiblesPlus* [2]. They share with N3AS a common motivation, to better coordinate theoretical support for multi-messenger astrophysics while growing the field through student and postdoctoral recruitment and mentoring. *Elusives/InvisiblesPlus* are exploiting an important European asset, a large contingent of senior women working in the field: most of the project leaders are female. Discussions are underway about exchanges that could help both sides make progress toward gender equality in multi-messenger physics, while simultaneously opening more opportunities for US-EU collaboration. Efforts will begin with the 2020 summer school, where N3AS will host several young researchers from *Elusives/InvisiblesPlus.* N3AS-Hub centers Berkeley/LBL and Washington are currently connected to both *Elusives* and *InvisiblesPlus* as partners: N3AS efforts will build on this existing relationship.

3d. Major Activities

Overview of the MAs: Nearly twenty years ago the influential report "From Quarks to the Cosmos" argued that the growing precision of astrophysical and cosmological measurements would make this field an increasingly important part of fundamental physics. Indeed in recent years four monumental discoveries – massive neutrinos and their flavor mixing, dark matter, the accelerating universe, and gravitational waves – have come from this field.

Astrophysics provides us with extraordinary "laboratories" unlike any we can create on Earth, providing opportunities to test physics at it extremes – e.g., the Big Bang, the core of a SN, merging NSs, and BHs. The experimentalists and observers probing these systems are now doing so in multiple channels and frequencies – electromagnetic, neutrino, gravitational, nucleosynthetic. Thus there are huge opportunities – provided we are up to the task of interpreting the measurements that are and will be made.

This is an extraordinary multi-physics challenge to theory. As an example, the physics governing core collapse includes hydrodynamic compression, shock creation and propagation, storage of gravitational energy in a leptonic sea, and transport of that energy by neutrino processes, creating a variety of conditions favorable to exotic forms of nucleosynthesis. The conditions in such an explosion are so exotic that they depend on aspects of fundamental physics that may otherwise be hidden from us. In the supernova core neutrinos repeatedly scatter off each other, generating novel nonlinear phenomena that can radically alter both flavor and lepton number. The hadronic physics is also pushed to extremes. 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 (~ 3 sec) the consequences of isospins and densities unreachable on earth. Already observations of NS masses and mergers have been used to place important new constraints on the nuclear equation of state. A great deal more will be learned from the coming flood of NS and merger data.

N3AS was organized by senior leaders in nuclear and neutrino astrophysics who became concerned that theory was not responding to the tremendous advances occurring in observational multi-messenger astrophysics. The supporting theory community was not growing significantly and its structure – dispersed over the US in small or single-investigator groups – inhibited the kind of coordinated efforts that the field now needs. GW170817, announced just as N3AS-Hub was starting, put an exclamation point on these concerns: an entirely new probe of the cosmos was at hand, the result of twenty years of development by an experimental team that grew to 1200 scientists and 100 institutions. There was no coordinated theory effort of remotely commensurate sophistication preparing to help this field exploit this new tool – a team that would bring together the expertise needed to understand the merger and its kilonova: modelers using state-of-the-art simulation to describe the event and its ejecta; experts in the nuclear EoS at finite temperature; neutrino physicists who can model the transport of energy, lepton number, entropy, and flavor; and experts in explosive nucleosynthesis who can relate the evolving kilonova to the radio-isotopes powering the event.

N3AS was created to address this challenge – to established a coordinated national theory effort to respond to and support the extraordinary discoveries occurring in multi-messenger astrophysics, enabled by a new generation of massive and highly sophisticated optical, gravitational wave, dark matter, and neutrino detectors. The scientific vision is summarized in the left panel of Fig. 2:

◦ Develop the theory and modeling capabilities to describe the propagation of neutrinos at

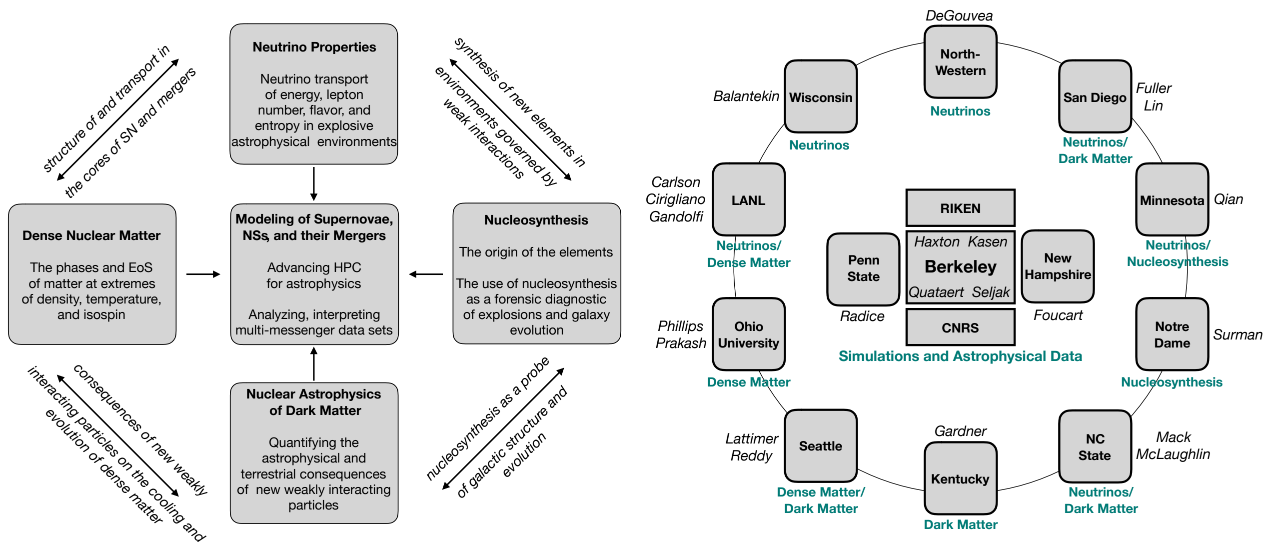

Figure 2: The left panel summarizes N3AS science and the challenge posed by multi-messenger astrophysics, the need to integrate the fundamental microphysics governing extreme astrophysical environments – neutrino transport, the phases and EoS of nuclear matter under exotic conditions, the creation of new metals and the use of nucleosynthesis as a forensic – into high fidelity, state-of-the-art simulations. To the extent that we can faithfully model such environments, they become powerful laboratories for new, dark-sector fundamental physics. The right panel shows the N3AS-PFC team we have formed to advance our science goals.

high density, where novel nonlinear flavor phenomenon arise. These neutrinos govern the transport of energy, lepton number, entropy, and flavor in the cores of supernovae, in nascent NSs, and in NS mergers.

- Probe the properties and phases of exotic nuclear matter – matter at extremes of density, temperature, and isospin – in both cold and hot astrophysical environments. These properties are reflected in the masses and cooling of neutron stars, in the core bounce of a supernova, and in the high-frequency dynamics of mergers.
- Develop a quantitative understanding of the origin of the elements. Utilize nucleosynthesis as a forensic tool in transient events like kilonovae, and as a probe of long-term galactic evolution, thereby constraining phenomena as diverse as the NS merger rate and the dark and visible matter halos of dwarf galaxies.
- Integrate these highly-coupled microphysics aspects of NSs and SNe into state-of-the-art numerical simulations that utilize the most advanced computing platforms. Test these “standard model” descriptions of exotic astrophysical environments against the increasingly detailed information experiment and observation are providing, learning from any discrepancies that arise.
- Establish a baseline understanding of the “extreme laboratories” Nature has created for us, given us more confidence in our abilities to deduce new constraints on dark matter and other weakly coupled exotic physics. Relate such constraints to those obtained in terrestrial labs.

This is the N3AS science program described below in MA1-MA5. The right panel of Fig. 2 shows the national collaboration we built to carry out this program, augmented from N3AS-Hub in important ways. The impact of GW170817 is seen in the addition of Penn State and New Hampshire as well as RIKEN's Astrophysical Big Bang Laboratory (ABBL), steps strengthening the team's simulation capabilities. Following a recommendation by the N3AS-Hub midterm review panel, we added two theorists (Lin, Mack) to help us build a stronger bridge between new-physics phenomena in astrophysics, and efforts in terrestrial laboratory to probe dark matter. These expansions brought four new assistant professors into N3AS. At Berkeley the addition of Quataert, Seljak, and collaborators from the Centre Pierre Binètruy give us great strength in the analysis of large data sets, including important ties to the Virgo/Lisa Pathfinder analysis teams, as well as greater depth in neutrino cooling, accretion, and galactic evolution. The N3AS-PFC team is capable of changing the landscape for US multi-messenger theoretical nuclear and neutrino astrophysics.

N3AS-PFC has broader goals, extending beyond our science, focused on strengthening the "human capital" investment in the field. In MA6, MA7, and Sec. e we describe efforts we will make to build a stronger community of young researchers. Our collaboration welcomes others into its workshops and other activities – we view N3AS as a catalyst for greater cooperation in nuclear astrophysics theory. A centerpiece of N3AS is its novel postdoctoral Fellows program, designed so that young researchers feel part of and benefit from an extended national collaboration. By integrating these young people into a multi-messenger, multi-physics environment, we help them acquire the breadth they need to take the next step in their careers. N3AS is structured to "showcase" these young researchers, providing them with exceptional opportunities to interact with others. N3AS-PFC will create new international connections for theoretical astrophysics, creating Joint Institute connections between N3AS and the newly established Centre Pierre Binètruy and RIKEN Berkeley Center (Astrophysics). This will make Berkeley an exciting focal point for N3AS – we do not have this capacity in N3AS-Hub – and for others in the community who would like to use Joint Institute facilities for collaboration meetings or other activities. We will experiment with a Network-oriented graduate student program focused on the data science challenges of large astrophysical data sets – the data science/domain science interface is hugely popular among young researchers – setting the stage for larger graduate student efforts in future years. This school will help N3AS connect to its European counterparts, *Elusives* and *InvisiblesPlus*, a connection that we anticipate will spur other collaborations while helping us make more rapid progress towards gender equality in astrophysics. Finally, over the next five years, we will create a mentoring program for transfer students interested in astrophysics in three N3AS universities: by engaging newly arrived transfer students in astrophysics reading and research at an appropriate level, and by integrating them into a social environment that includes supportive faculty and peer mentors, we hope to help these students succeed in their major of choice. The low success rate of transfer students in persisting to STEM majors is weakening programs that public research universities have implemented to maintain accessibility, in the face of diminished state funding. This in turn is undercutting an important opportunity to increase the diversity of the sciences. As our efforts have the support of university officials grappling with this issue, success of our program would likely lead to wider adoption of "discovery experiences" by university officials, to improve transfer student retention.

MA1 - Neutrino Properties in Astrophysics and Cosmology: [Balantekin, Cirigliano, de Gouvêa, Fuller, Gardner, Haxton, Kasen, McLaughlin, Qian, Quataert, Seljak, Surman; Centre Pierre Binétruy]

Overview of the Science: Neutrinos play extraordinary roles in physics, astrophysics, and cosmology. First, we know relatively little about the particle properties of these standard-model fermions: their absolute masses and mass ordering, their properties under particle-antiparticle conjugation (Dirac/Majorana character), their properties under charge conjugation and parity (CP), their electromagnetic moments, and whether they couple to sterile neutrino states beyond the standard model [3, 4]. In cosmology they make important contributions to the relativistic energy density driving the expansion of the early universe and have an outsized influence on the formation of large-scale structure as they transition from being relativistic, retarding the growth of structure, to non-relativistic. In astrophysics, neutrinos dominate the transport of energy and lepton number in many astrophysical objects — mergers, SNe, NSs — controlling their evolution and/or setting key conditions. Through weak interactions neutrinos determine the neutron-to-proton ratio (isospin) of the nuclear composition in the early universe and in many explosive and dense astrophysical environments, determining the path of any nucleosynthesis that occurs. The many open questions about neutrino properties have impact on astrophysics and cosmology, which opens wonderful opportunities to exploit astrophysical and cosmological environments as neutrino physics laboratories.

A classic example of this neutrino nexus of fundamental properties and astrophysics is the solar neutrino problem, the discrepancy between the Sun's photon and electron-neutrino (ν_e) luminosities, which provided the first credible evidence for neutrino oscillations, helping to motivate new-generation experiments like Super-Kamiokande and the Sudbury Neutrino Observatory. Subsequent measurements of the solar and atmospheric neutrino fluxes demonstrated that neutrinos are massive and oscillate among different flavors with surprisingly large mixing angles. Nearly simultaneous theory developments — the Mikheyev-Smirnov-Wolfenstein (MSW) mechanism and its interpretation in terms of adiabatic and non-adiabatic level crossings — proved crucial in understanding the measured distortions of the solar ν_e spectrum. Today our only constraint on the neutrino mass ordering remains that obtained from matter effects on solar neutrino oscillations.

We can probe many aspects of beyond-the-standard-model (BSM) physics with neutrinos. The absence of a neutrino "charge" allows two kinds of neutrino mass and the resulting seesaw mechanism potentially connects small neutrino masses to the Grand Unified Theory (GUT) scale [3]. The open questions of neutrino masses — their absolute scale, hierarchy, and Majorana/Dirac character — have stimulated a new generation of tritium endpoint, double beta decay, and long-baseline oscillation experiments [4, 5]. Oscillation results establish a lower bound of ~ 56 meV on the sum of neutrino masses $\sum m_\nu$, which is within the sensitivity of next-generation cosmological surveys. Three neutrino CP phases remain undetermined, though the Dirac phase can and is being probed in long-baseline experiments. The known mixing angles for neutrinos allow a large CP-violation invariant, suggesting links between neutrinos and the matter-antimatter asymmetry of our universe.

The track record of neutrino physics for making major scientific breakthroughs is perhaps unmatched: over the last 32 years discoveries in the field have been awarded the Nobel Prize four times. Experimental activity today is more intense than at any previous time. The main focus of the onshore US particle physics program over at least the next 15 years will be the Long-Baseline Neutrino Facility (LBNF), Fermilab's project to create world's most intense neutrino beam, and the associated mega-detector Deep Underground Neutrino Experiment (DUNE). In addition to serving as a beam neutrino detector, DUNE will act as an astrophysical neutrino observatory for transient Galactic events like SNe, mapping out their neutrino "light curves" for times well in excess of 10 sec, nearly free of background [6, 7]. The highest-priority new project in nuclear physics is a ton-scale neutrinoless double beta decay experiment to search for lepton number violation and determine the Majorana mass associated with the electron neutrino at a sensitivity set by the inverted mass hierarchy. A key goal of the Stage-4 Cosmic Microwave Background experiment (CMB-S4) is to map the power spectrum at high angular resolution to much higher precision as this portion of the spectrum is very sensitive to the number $N_{\rm eff}$ of effective relativistic species like neutrinos in the early universe. In addition, such data, especially in combination with other survey results, could determine $\sum m_\nu$ and might establish the neutrino mass hierarchy is normal. (In fact, CMB measurements and the long-baseline neutrino program could both reach conclusions on the hierarchy at about the same time, providing an important cross check.) In astrophysics, the kilonova accompanying the gravitational wave event GW170817 caused great excitement by providing the empirical evidence that heavy elements had been produced by rapid neutron capture, the r process, in the merger of two NSs. Properties of the associated kilonova suggest that neutrino interactions precluded an r process in other ejected material. As future GW observations improve in sensitivity and range, we will learn a great deal about the processes that govern the long-term chemical evolution of galaxies.

These experimental endeavors represent community investments that range from the few \$100M scale to a few \$1B or more. At the fundamental level theory provides the motivation. As noted above, neutrinos provide a window on some of the most profound open questions in physics, such as why we are here (why the universe contains matter instead of just radiation) and whether the anomalous mass scale of neutrinos is providing our first glimpse of grand unification. Perhaps more urgent, however, is whether the experiments and observations now underway (or soon to be) will realize their promises. Standard Model neutrinos count as $N_{\rm eff} = 3.046$ effective relativistic species in the early universe. How do known neutrino oscillations and possible mixing with sterile neutrinos change $N_{\rm eff}$? The most stringent constraints on $N_{\rm eff}$ and $\sum m_\nu$ will be obtained from careful analyses of CMB data in combination with other survey results. What is the best strategy to perform such analyses? The neutrino interactions in DUNE take place on a nuclear target well below the momentum scale where a simple partonic description would be valid. Can we characterize the complex nuclear response accurate enough to allow the kinds of precise constraints on neutrino properties desired by the experimentalists? When Hyper-Kamiokande or DUNE detects the next burst of Galactic supernova neutrinos, can we relate their light curve to the underlying neutrino physics of the explosion? (See Fig. 3.) This question is important, as there are aspects of neutrino oscillations that can be tested only in SNe or similar dense environments. How do we mine the experimental data to extract that physics? The current double beta decay program is motivated by rates estimated for a light Majorana neutrino exchange mechanism, but evidence is growing that the neutrino mass hierarchy is normal, in which case this mechanism can be suppressed. If this is the case, is there "discovery" potential remaining, and if so, what physics will the experiments probe and what are the implications for astrophysics and cosmology?

These are the kinds of questions that the N3AS collaboration formed to address. In most cases the required work is not a paper, but a program that requires the combined efforts of theorists with complementary backgrounds. If these programs can be executed, they will impact the interpretation of some of the most prominent neutrino and cosmological experiments and astrophysical observations of the next decade. In some cases they could affect how those experiments and observations are performed and analyzed. Specific examples are given below.

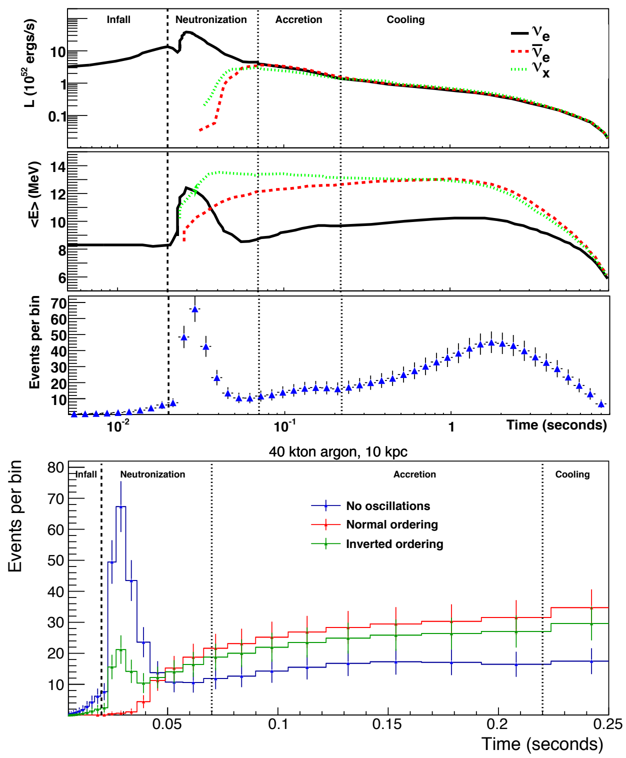

Figure 3: Recent work from the DUNE Collaboration [8]. The top two panels show the luminosity and average energy of the un-oscillated neutrinos from an electron-capture SN occurring 10kpc from earth. The third panel shows the DUNE event rate in the absence of oscillations, while the bottom panel includes standard MSW matter oscillations in the star's mantle. DUNE's sensitivity to ν_es allows reconstruction of the few-millisecond deleptonization pulse associated with shock wave passage through the outer iron core. While there appears to be good sensitivity to the mass hierarchy because of this pulse, the relationship of the simulations to reality is hard to estimate because all of the "new" physics that takes place in the SN core – nonlinear neutrino flavor physics – has been omitted. N3AS, by developing new methods to take into account effects like those of Figs. 4 and 5, can give DUNE experimentalists a far more reliable starting point for their simulations.

Neutrino flavor evolution in dense media: In the Sun the MSW mechanism associated with matter of changing density can progressively rotate the local mass eigenstates, producing a level crossing that greatly enhances the flavor oscillation probability for the appropriate mass hierarchy. Yet far more complex and interesting phenomena occur in the dense media within SNe and NS mergers, where neutrinos interact not only with matter particles (nucleons, nuclei, and electrons) but also among themselves, and where the dynamics frequently involves a transition from diffusion of neutrinos in local thermodynamic equilibrium with matter to free-streaming of those neutrinos. While solar neutrino oscillations can be well described by one-body evolution in a background potential governed by coherent forward scattering on matter particles, neutrino flavor evolution in SNe and NS mergers requires one to solve a quantum many-body problem involving nonlinear flavor-dependent forward scattering among neutrinos, inelastic interactions with matter particles destroying coherence, and in general seven degrees of freedom ($1+3+3$ for time, space, and momentum). Neutrinos in the early universe require a similar description. These problems require both a formalism treating all of the physics and the development of practical numerical techniques for solutions.

Consider the case of coherent flavor evolution outside the neutrino sphere in a SN, where neutrinos are free-streaming to good approximation. This problem is already complex due to forward scattering among neutrinos in the vicinity of the neutrino sphere, where flavor evolution of neutrinos with different energies and traveling in different directions becomes coupled, leading to a range of collective oscillations [9, 10]. Subsequent flavor evolution is governed by the regular MSW mechanism for the atmospheric and solar neutrino mass splittings, but is also complicated by sound waves, shock waves, and turbulence, which can induce non-adiabatic jumps in neutrino flavor survival probability [11] or flavor de-polarization [12–16]. The known implications for astrophysics are far-reaching: as neutrinos play an essential role in the SN explosion and nucleosynthesis, neither the explosion mechanism nor the nucleosynthetic output can be reliably predicted unless the neutrino flavor evolution problem is solved. Further, the same physics affects the interpretation of SN neutrino signals in terrestrial detectors.

If this problem is not addressed, then any attempt to interpret DUNE or Hyper-Kamiokande data obtained from the next galactic SN would be afflicted by model uncertainties difficult to quantify. With about 20 events recorded in the world's detectors for SN1987A, it was possible to argue that the basic energy output ($\sim 10^{53}$ ergs) and time constant (~ 3 sec) were consistent with theory, but no more. Standards today are radically different. A supernova in the galaxy will produce ~ 3000 ν_e events in DUNE and $\sim 10^5$ $\bar{\nu}_e$ events in Hyper-Kamiokande, observable for $\gtrsim 10$ sec and $\gtrsim 1$ min, respectively [6,7]. The extracted precise neutrino "light" curve and spectra will facilitate a powerful test of our understanding of SN neutrino emission and the connection to the explosion and nucleosynthesis, provided that we can determine the associated neutrino flavor evolution accurately. Other exciting physics might be revealed as well: e.g., the proto-neutron star created in the explosion might become a black hole, thereby terminating neutrino emission, due to a change in the nuclear EoS as the star radiates its energy and lepton number.

At the outset of N3AS we recognized that neutrino flavor evolution in dense media was a "grand challenge" problem that needed to be solved now, to guide experimentalists who are already thinking about data streams and analysis protocols of mega-detectors now entering the construction phase. N3AS faculty discovered collective neutrino oscillations in supernovae [9] and led the global efforts to treat these and related phenomena [10,17–34]. Beyond this coherent neutrino flavor evolution, inclusion of inelastic neutrino interactions in dense media is the next stage of the challenge. We are likely the only team prepared to take up the challenge: N3AS collaboration has been developing a versatile formalism [35–38], the quantum kinetic equations (QKE), to treat neutrino transport and flavor evolution simultaneously [39–41].

Guided by N3AS's faculty experts in this area — Fuller, Balantekin, Cirigliano, McLaughlin, Qian — a number of our N3AS-Hub Fellows have made important contributions to understanding neutrino flavor evolution in dense media. Patwardhan has examined simple isotropic systems in a many-body framework, finding the eigenvalues and eigenvectors that can be used to study evolving systems in the adiabatic limit [33]. Rrapaj has treated the full quantum mechanical problem with a small number of neutrinos [34]. Sen has explored the so-called "fast flavor oscillations" in supernovae due to certain spatial asymmetries of neutrino emission [42]. Richers has performed the very first supernova modeling in which the QKE treatment of neutrino transport and flavor evolution is implemented, albeit under the assumption of isotropy (see Fig. 5) [44]. He has also been extending the treatment to non-isotropic cases including NS mergers. Finally, Grohs has adapted the QKE formalism to the early universe, where neutrinos carry nearly half the energy density and play dynamic roles. They drop out of thermodynamic equilibrium with the background plasma and start free-streaming just when the primordial nucleosynthesis is under way. Grohs has been exploring for the first time the energy and flavor transport of neutrinos at this critical epoch.

The applications of QKEs to one of the hottest topics in flavor physics, fast flavor oscillations, is next on the N3AS agenda. It is known that very small fluctuations in the flavor field can be unstable to growth modes, but these modes have not been simulated successfully in realistic astrophysical conditions. The current state of the field is that it is known that these modes are unstable, but not to what extent they grow, e.g. do they saturate, or if they do not saturate, how they develop. As part of the effort on the QKEs, we will develop a framework in which to treat neutrinos coming from many different directions – a crucial piece of physics that is currently missing in efforts to solve the problem of fast flavor oscillations [45].

While much remains to be done, it is impressive how quickly this group of young researchers, residing at different institutions, has been able to assimilate the complex physics of collective oscillations and the QKE formalism, turning the latter into a practical numerical tool for SN and Big Bang simulations. The Network is responsible: it provided the resources and connectivity, including access to the expertise of multiple faculty, connections to each other, and the N3AS team concept that they ran with. Had these five Fellows been hired on group grants at five separate institutions, the chance of such convergence would have been zero.

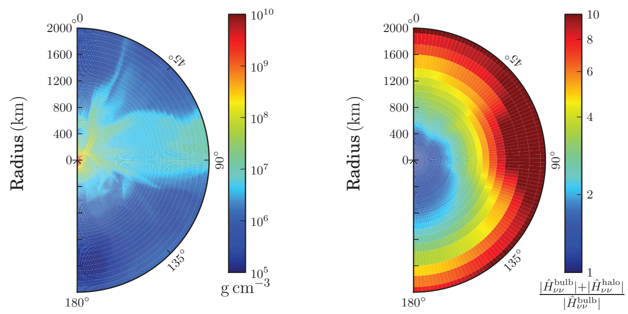

Figure 4: Left: Snapshot of the density distribution (contours with color coded scale) in a supernova model calculation [43], taken 500 ms after core bounce, a time when neutrinos are most important in re-energizing the stalled shock wave. The color scale indicates the density during the accretion epoch, a time when neutrino flavor transformation could be influential on our models for neutrino heating and composition. Right: Though only ~ 1 in 1000 neutrinos coming from the neutron star will suffer a direction changing scattering, those scattered neutrinos can have an outsized effect on the potential which governs neutrino flavor transformation: the relative change in the magnitude of that potential is shown. This scattering, one of several effects, thus modifies SN neutrino flavor distributions.

Supernova Neutrinos and Neutrino Responses: The feasibility of measuring neutrinos from a galactic supernova was established with the observation by the Kamiokanda and Irvine-Michigan-Brookhaven detectors of approximately 20 events from SN1987A. The scale and sophistication of neutrino detectors has progressed enormously over the past three decades, with Super-Kamiokande representing the state-of-the-art. But a further order-of-magnitude advance in the technology will soon arrive: Construction in the Sanford Laboratory of the cavity for the Liquid Ar detector DUNE with a fiducial mass of 40 kton [47] is underway, while construction of the 258 kton water detector Hyper-Kamiokande [48] will start this April. These detectors will record ~ 3000 ν_e events and up to $\sim 10^5$ $\bar{\nu}_e$ events, respectively, from the next galactic supernova, mapping out the neutrino light curve and spectra for $\gtrsim 10$ sec up to minutes, with virtually no background due to the depth of these detectors. A great deal of information can be extracted from these neutrino data:

1. During the observations the proto-neutron star will radiate most of its lepton number and most of its gravitational binding energy. Associated changes — collapse into a black hole, or transition of the nuclear matter to a new phase affecting the neutrino opacity — could produce a shut-off or a change of slope in the neutrino emission.
2. The success or failure of various neutrino-induced modes of nucleosynthesis typically depends on the neutrino flux, temperature, flavor, and their time evolution. To date we have relied on theory, despite the known complexity of neutrino transport inside the proto-neutron star.

Unlike the case of SN1987A, the quality of the data we will obtain from the next galactic SN will provide a rigorous test of SN neutrino emission.

3. Uncertainties about the neutrino mass hierarchy reflect the fact that, to date, we have not been able to use medium effects to probe the sign of the atmospheric neutrino mass splitting. At the simplest level, this quantity generates a level crossing for the MSW effect, typically in the carbon zone, well outside the neutrino sphere. This crossing will be imprinted on either ν_e or $\bar{\nu}_e$ spectrum, depending on the mass hierarchy. If the complicating effects of collective oscillations are properly address (see discussion around Fig. 3), the effects should still be interpretable with multiple observables during the early emission phase, given high quality data [49]. Alternatively, the hierarchy can be extracted from the $\bar{\nu}_e$ rise time, by exploiting the event rate obtainable with IceCube [50].
4. The GW signal from a galactic supernova is detectable, though the signal-to-noise ratio of 1.5–11.5 is not favorable [51]. Thus the strategy for successful detection is multi-messenger: simultaneous observation of the neutrinos [52]. This coordination can help localize the SN to within a few to 10 degrees, opening up the possibility of rapidly scanning a limited area to detect the delayed (typically by hours to days) UV and x-ray optical signals from shock breakout. As shock breakout provides information on progenitor properties such as the radius, its observation would help us connect the multi-messenger signals to a specific underlying stellar model [53].
5. As the QKE approach to SN neutrino transport and flavor evolution is developed and embedded in realistic 3D models, we will be able to determine the degree to which spectral swaps or splits due to collective oscillations are imprinted on the neutrino signals in terrestrial detectors. While existing results obtained without a full QKE calculation should be viewed with caution, it has been claimed that non-thermal features in the ν_e or $\bar{\nu}_e$ spectra will exist depending on the mass hierarchy [54].

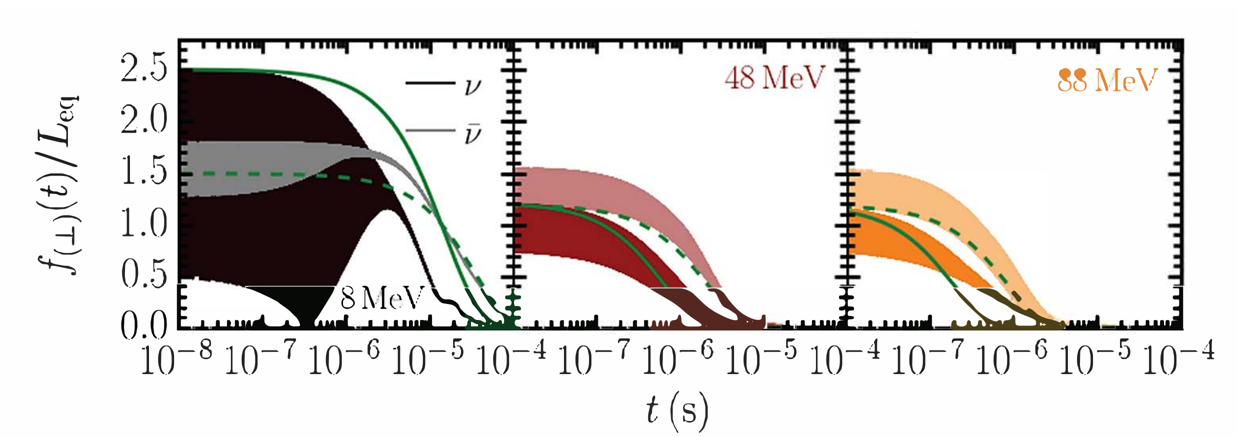

Figure 5: The first calculation [44] of quantum flavor decoherence for conditions matching the neutrino decoupling region of a core-collapse supernova. The amount of quantum flavor coherence is shown as a function of time for neutrinos (dark) and antineutrinos (light) at three different energies. Compared to the case without flavor oscillations shown by the green solid (neutrinos) and dashed (antineutrinos) curves, collisions together with flavor oscillations drive the neutrino distribution to have no flavor coherence at a significantly different rate. Work done by N3AS Fellow Richers.

All of these issues argue for the importance of the N3AS program to develop a quantitative formalism — solution of the QKEs — to treat SN neutrino transport and flavor evolution. While the urgency of this work depends on an unknown —namely, when the next wave of galactic SN neutrinos will reach earth — it will be very disappointing if that wave arrives while we remain unprepared to extract the physics from the data.

Detector counting rates determine the incident neutrino flux to the extent that the nuclear response is known. At the lower energies relevant to SN neutrinos, this problem is reasonably tractable. Members of N3AS have performed quantum Monte Carlo calculations of the neutral current inclusive response for neutrinos scattering off ^{12}C, from threshold through the quasi-elastic region [55]. Similar techniques could be applied to ^{16}O, which would yield cross sections important to Super- and Hyper-Kamiokande. Although more model dependent, shell-model responses can be evaluated for heavier targets like Ar, using highly parallelized codes we have developed [56]. Although the work is very much exploratory, inclusive nuclear responses are potentially interesting as an application for quantum computers [57].

Neutrino Mass in Cosmology and in the Lab: Massive neutrinos and DM are arguably the two outstanding demonstrations that the minimal standard model of particle physics is incomplete. In the case of neutrinos, no gauge-invariant renormalizable mass term can be constructed with the fields present in the standard model. Astrophysics and cosmology played a huge role in the discovery of massive neutrinos and DM and, in the next few years, could yield results that would dramatically alter the course of subatomic physics. N3AS and its partners could make major contributions to this progress.

When Super-Kamiokande announced its discovery that neutrino oscillations were responsible for the atmospheric neutrino anomaly, one of the most exciting possibilities came from equating m_ν^2 to the atmospheric neutrino mass splitting Δm_{32}^2 and the Dirac mass m_D to the top quark mass in the seesaw mass formula

$$m_\nu \sim m_D \left(\frac{m_D}{m_R}\right).$$

This yielded a right-handed neutrino mass $m_R \sim 10^{16}$ GeV, suggesting that by studying neutrino masses, one might be probing the physics of Grand Unification. Neutrino mass remains one of the most intense intersections between inner and outer space: on the one hand it drives flagship programs of the US nuclear and particle physics communities, including KATRIN, Project-8, ton-scale searches for neutrinoless double beta decay, and the long-baseline LBNF/DUNE program; on the other hand it motivates next-generation high-precision tests of cosmology, with significant near-term progress likely to follow from CMB polarization studies (e.g., Simons Array) in combination with galaxy surveys (e.g., DESI). Next-generation instruments that will further push precision are already in advanced planning stages (e.g., CMB-S4) [46]. N3AS and its partners will bring together exceptional expertise in neutrino mass: model building, theory input to direct neutrino mass measurements and neutrinoless double beta decay [58–60], cosmological tests of large-scale structure, and astrophysical consequences of flavor oscillations of massive neutrinos (see above).

Powerful constraints on neutrino mass are emerging from cosmology. As described below, the "fingerprints" of neutrino mass and hierarchy appear in multiple guises on the CMB power spectrum and other probes of large-scale structure. All of the astrophysical and cosmological environments in which neutrino mass plays a role are complex, and thus measurements must be combined in ways that reduce parameter degeneracies (see [61] for an excellent review). For example, recognized parameter degeneracies are motivating planned CMB measurements of the polarization induced by photons scattering off the additional electrons liberated by re-ionization [62]. The future challenges to the field are very much data-science driven: the extraction of critical information from a variety of independent astrophysical, cosmological, and laboratory data sets, all of which have multiple parameter dependences and associated measurement systematics.

We will benefit greatly from a partner with complementary expertise in the extraction of physics from cosmological data sets. In MA6 we describe the proposed N3AS joint institute structure and partnership with the Centre Pierre Binétruy. The Centre, created in memory of one of France's most distinguished theoretical cosmologists, builds on long-standing partnerships between CNRS and Berkeley in extracting physics from CMB and Type Ia supernova data sets. There are connections to the Berkeley Center for Data Science, which in part grew out of Saul Perlmutter's interests in the analysis of cosmological data sets. In part because of these efforts, N3AS-PFC will start a modest graduate student program on the data science/astrophysics intersection.

Just as we were fortunate in solar neutrino physics that the mass splitting Δm^2_{21} and the solar density conspired to give a level crossing in the middle of the solar neutrino spectrum, producing a tell-tale distortion of that spectrum, we are fortunate in cosmology. In the early universe the energy density of relativistic neutrinos ρ_ν is comparable to that of photons ρ_γ,

$$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8} N_{\text{eff}} \left(\frac{4}{11}\right)^{4/3},$$

where if neutrinos are assumed to be fully decoupled from the thermal plasma when electrons and positrons annihilate, the effective number of relativistic species is $N_{\text{eff}} = 3$. (One motivation for the N3AS development of QKEs is to precisely determine the small deviation of N_{eff} from 3.) Relativistic neutrinos free-stream out of overdense regions, erasing structures on small scales. As the temperature of the background neutrinos today, $T_\nu \sim 1.7 \times 10^{-4}$ eV, exceeds both $|\Delta m^2_{32}|^{1/2}$ and $|\Delta m^2_{21}|^{1/2}$, at least two neutrino species are now nonrelativistic. Consequently, neutrinos transitioned from being relativistic to nonrelativistic as our universe evolved to its present state, which produced a characteristic neutrino-mass imprint on structures that is scale and redshift dependent. These effects are disproportionate to the relatively small contributions neutrinos make to the critical density of the present universe.

Standard analyses done in the framework of a ΛCDM cosmology contain on the order of a dozen parameters including the baryon and cold dark matter energy densities, but also N_{eff} and the sum of neutrino masses $\sum m_\nu$, the latter representing the contributions of neutrinos to the matter density at late times. The parameters are then fit to cosmological data (see, e.g., [63].) Important data sets include the CMB temperature and polarization anisotropies from Planck 2015 [64], extractions of the local Hubble constant from studies of Cepheid variables [65,66], a variety of results on Baryonic Acoustic Oscillations [67–69], the Joint Light-curve Analysis Type Ia luminosity distances [70], Planck measurements of the CMB lensing potential power spectrum [71], and weak lensing data from the CFHTLenS survey [72, 73]. A recent analysis [75] established an upper bound of 0.112 (0.146) eV (95% CL) on $\sum m_\nu$ for the normal (inverted) hierarchy, to be compared to the expected minimum value of 0.060 (0.100) eV. An upper bound below 0.100 eV would indicate a normal hierarchy. For another comparison, the latest direct measurement by Katrin gave an upper bound of 1.1 eV (90% CL) for the mass eigenstate mostly associated with ν_e [76].

While the power of cosmology to constrain both the absolute scale of neutrino mass and the hierarchy is apparent, the credibility of results will depend on the degree of concordance among the various determinations. The fits producing the cosmological bounds above also find that the local

Hubble constants obtained from Cepheid variables and from the CMB disagree at $\sim 4\sigma$ [75]. The origin of the discrepancy has not been identified: either systematics or new physics could be responsible. The environment that N3AS will establish — connecting theorists interested in laboratory, astrophysical, and cosmological probes of neutrino mass and providing them with opportunities to interact with the experimentalists and observers who are producing the data — will encourage the kinds of careful cross checks that are needed to extract fundamental physics from complex data sets.

MA2 - Nucleosynthesis: [Haxton, Kasen, Lattimer, McLaughlin, Qian, Quataert, Surman]

Overview of the Science: Modern cosmology began with nucleosynthesis: the production of the light elements in the Big Bang provided the first example of a precise result on a fundamental cosmological parameter — the baryon-to-photon ratio η — deduced from astrophysical observables, namely the primordial abundances of He and other light elements. The precision was achieved by combining a quantitative model of the early universe that describes the competition between two clocks, one cosmological (the Hubble expansion) and one from microphysics (weak interaction rates), with careful laboratory measurements of the cross sections mediating the light-element nucleosynthesis.

Almost without exception, there are important connections between nucleosynthesis and neutrinos. A byproduct of the Big Bang is the cosmological neutrino background. Though indirect, the evidence for these neutrinos is based on a concordant cosmology that succeeds in explaining the primordial abundances of the light elements and the observed CMB power spectrum. This success places stringent constraints on new physics that would alter the effective number of relativistic species $N_{\rm eff}$ in the early universe, e.g., sterile neutrinos, axions, or other dark radiation. As noted above, cosmology, in the next decade, may prove our most powerful test of both the sum of neutrino masses and the hierarchy, complementing laboratory neutrino experiments that probe the masses, mass splittings, and CP properties.

The coupling of nucleosynthesis and neutrinos also extends to many of the nuclear processes that drive the evolution and explosion of stars and create the heavier elements for the chemical evolution within galaxies. The weak interaction regulates hydrostatic stellar burning in the Sun: $p + p \rightarrow d + e^+ + \nu_e$ governs the rates of both neutrino and energy production, via the creation of neutrons in the guise of deuterium. The resulting connection between the Sun's photon and neutrino luminosities led to the discovery of oscillations of massive neutrinos. In explosive environments such as SNe or NS mergers, neutrinos, through their charge-changing weak interactions, control the neutron-to-proton ratio (isospin) of the ejected material. Neutrino "winds" can also drive material ejection in such sites. Coupled with flavor oscillations, neutrino interactions set the conditions for producing a wide range of heavy elements in these environments. With major facilities like LIGO and Super-Kamiokande already in operation and more to come, an increasingly important aspect of multi-messenger astrophysics is the use of both neutrinos and nucleosynthesis to constrain the underlying microphysics of the observed transient cataclysmic events. To make use of such multi-messenger data, sophisticated teams like those of N3AS are needed – collaborations that can produce high-fidelity astrophysical models of the explosions while incorporating the coupled microphysics of neutrinos and nucleosynthesis, with all their flavor and nuclear physics complexity.

N3AS has unmatched experience in the nexus of MA1 and MA2 – understanding nucleosynthesis in explosive environments where neutrinos are controlling the isospin and thermodynamics [77,78]. The neutrino QKE technology developed under MA1 will have immediate impacts on our understanding of nucleosynthesis. This includes in SNe the impact on the neutrino process and the

νp-process. In NS-NS and NS-BH mergers, improved neutrino wind descriptions will help us determine whether the nucleosynthesis from this wind contributes to the blue or red components of the kilonova. There are also implications for modeling rare types of SNe that form accretion disks, a possible source of r-process elements in metal-poor stars.

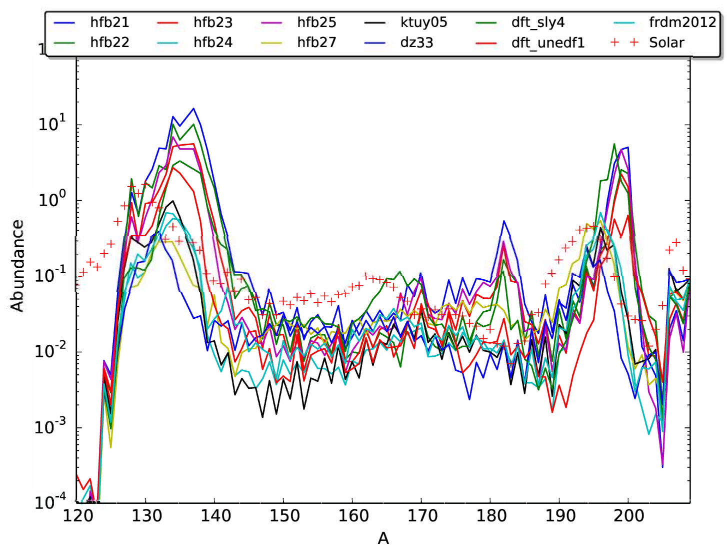

Figure 6: The abundance patterns predicted by eleven different sets of nuclear inputs using the same astrophysical conditions. Conditions are similar to those that would be predicted in an accretion disk wind. Within the next five years the spread in this figure should shrink, as FRIB near-dripline data becomes available. Figure credit: FIRE collaboration (unpublished).

The r-process and GW170817: The site of the r-process – the astrophysical environment that creates and maintains the billion-degree temperatures and enormous neutron fluxes needed to synthesize about half of the heavy elements – has been debated for 60 years. This question was one of eleven that "From Quarks to the Cosmos" challenged the community to solve in the 21st century. At least a partial answer may soon be in hand due to the kilonova accompanying the NS merger GW170817. Simultaneously, due to FRIB, nuclear physics uncertainties (see Fig. 6) affecting the r-process may soon come under control. Consequently we may be able to use nucleosynthesis as a probe of SNe and NS mergers, almost as successfully as we used He synthesis to define the state of our universe three minutes after the Big Bang.

One of the key motivations for forming N3AS in 2016 was the anticipation of events like that of August 17, 2017 — GW170817 [112]. Our group has an especially deep connection to the nucleosynthesis that accompanies a NS merger. The original suggestion that double NS and NS-BH (black hole) mergers might be the site of nucleosynthesis via rapid neutron capture, the r-process, came from Lattimer [79]. The critical multi-messenger connection was first suggested by Li and Paczyński, who first outlined how a merger would be followed by an optical display powered by decay of newly synthesized neutron-rich radioactive nuclei [80]. The early foundation for quantitatively interpreting the electromagnetic emission from GW170817 was established by Quataert in his explorations of the properties of the accretion disks created in NS mergers, including a key 2008 paper with Brian Metzger and Tony Piro [81]. Perhaps the most significant paper in the field was the 2010 paper by Metzger, Quataert, Kasen, and collaborators [82], presenting the first calculations of the optical transients following mergers that self-consistently determined the radioactive heating from r-process nuclei using a nuclear reaction network. From this heating they were able to characterize the light curve — its rise on a timescale of one day, its subsequent decline, and the luminosity. They introduced the term "kilonova" to describe the peak brightness. The paper observed "Because the emission produced by NS merger ejecta is powered by the formation of rare r-process elements, current optical transient surveys can directly constrain the unknown origin of the heaviest elements in the Universe." In 2013 Kasen, Badnell, and Barnes [83, 84] pointed out that the "opacity of the expanding r-process material ... is dominated by line transitions from those ions with the most complex valence electron structure, namely the lanthanides." These results allowed them to connect significant synthesis of heavy r-process elements with a longer-lived, redder component of the light curve, while synthesis of ^{56}Ni and light r-process elements with much lower opacity would yield a shorter-lived, bluer transient [85].

This work was an important reason we formed N3AS in 2016: the prediction of a quantitative optical diagnostic for the r-process in combination with an anticipated LIGO/Virgo/KAGRA discovery of NS mergers sometime in the next decade. While we recognized the urgency of preparing an analysis framework adequate to interpret the multi-messenger signals from future merger observations, neither we nor most others in the community anticipated that the first event would not be a decade away, but instead seen early in LIGO Observing Run 2 (O2). A second event GW190425 was observed in April 2019, very shortly after the start of LIGO O3, but without a detected optical counterpart [86]. This second event also included a physics surprise, a combined binary mass of 3.3–3.7$M_\odot$, considerably in excess (by 5σ) of the binary NS systems in our own galaxy and possibly suggesting a different dynamical origin for GW190425. The increased sensitivity of O3 now allows detection of NS mergers out to $\sim$ 100–140 Mpc.

The theory challenge presented by LIGO/Virgo/KAGRA is both daunting and exciting. The underlying physics has much in common with core-collapse SNe: neutrino transport of energy and lepton number subject to the effects of flavor oscillations, dynamics sensitive to the nuclear equation of state, complex hydrodynamics, and diverse nucleosynthesis in rapidly expanding ejecta. NS mergers are arguably more complicated geometrically, and that geometry is intertwined with strong-field gravity. With SNe, however, we have struggled for three decades with a data set from one event, SN1987A, that includes $\sim$20 neutrino interactions, barely enough to constrain gross features of the explosion. LIGO has opened up a radically different era. GW measurements can constrain the masses, orbital parameters, spins, and dynamics of individual mergers, and as they are extended to higher frequencies with coming detectors, they will increasingly probe aspects of the nuclear equation of state governing the mergers. The associated electromagnetic observations will help us characterize the accretion disks that form in the mergers. The spectrum and its evolution with time directly probe the opacity of the newly-synthesized elements and the radioactivities powering the emission. Perhaps best of all, we will obtain a lot of data on individual events while simultaneously developing an understanding of the cosmology of mergers: already the range of detection is approaching a billion light years. This combination of plentiful data and multiple probes creates the kinds of exciting interactions between experiments/observations and theory that drive scientific progress.

Even with the single kilonova in hand, interesting questions arise about the nature of the r-process that occurred. The slow decline of the light curve is attributed to a source of high opacity, the lanthanide elements. The lanthanides are produced by the r-process, but this observation only indicates a partial r-process; a full r-process would extend out to the actinides. N3AS members have been instrumental identifying the expected signature of actinide production in the light curve, stemming from the radioactive decay of ^{254}Cf [87]. We are likely to find other distinctive radionuclei and predict their observational signatures. This work would have to be integrated into MA5 modeling efforts on the merger outflows, and with MA1 efforts to describe weak processes in the outflow. Thus N3AS will continue to play a lead role in interpreting future kilonova observations.

Cosmology, chemistry, and the r-process: The origin of the r-process elements, which comprise about half of the solar abundances for the species heavier than iron, is a longstanding puzzle. A key result from GW170817 is that its light curve appears to require significant quantities of newly-synthesized lanthanides, thus indicating that an r-process occurred in the ejecta and proceeded beyond the peak at mass number $A \sim 130$ characteristic of an r-process pattern.

The importance of such a result derives from a broader goal to use the chemical enrichment of galaxies as a probe of the evolution of cosmological structure. It is fortuitous that the era of GW astronomy is opening up at the same time when the entire history of star formation is about to be revealed: the James Webb Space Telescope (JWST) is expected to be launched next year and begin its program to map the infra-red universe. It is already clear that connections will be found among formation of the first galaxies within their dark-matter potentials, cosmology of transient events like kilonovae and gamma-ray bursts, and chemical enrichments that trace the birth and death of stars within galaxies.

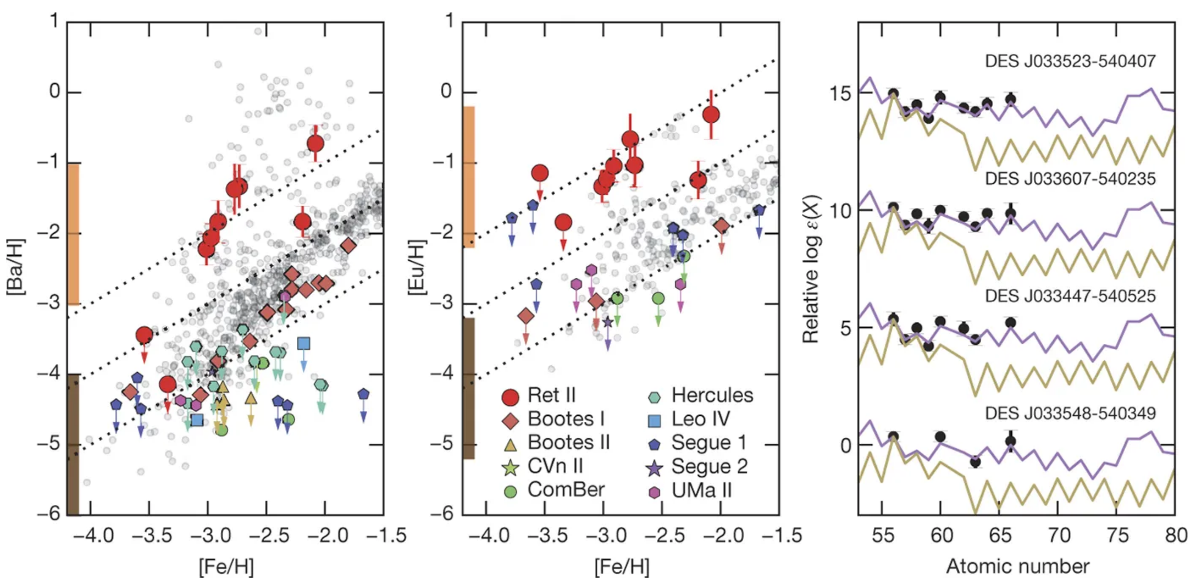

Figure 7: The intriguing problem posed by Ret II and other UFDs that illustrates the cross-cutting nature of the problems that arise in astrophysics – in this case potentially linking nucleosynthesis, neutron star, and DM interests within N3AS. Left panel: The abundance ratios [Ba/H] and [Fe/H] in stars from Ret II (red points), in halo stars (grey points), and in other UFDs (colored points). The orange and brown vertical bars indicate the abundance ranges that would be expected following a neutron star merger and in a core-collapse supernova, respectively. The dotted black lines show constant [Ba/Fe] abundances. Arrows denote upper limits. Middle panel: As in the left panel, but for [Eu/H] abundances. Right panel: Abundance patterns beyond barium for the four brightest europium-enhanced stars in Ret II (black dots), compared with the solar r-process and s-process patterns (purple and yellow lines, respectively). Solar patterns are scaled to stellar barium abundance. Stars are offset from each other by multiples of five. From [89].

The Sun provides us with an r-process pattern that defines the integrated contributions of sources through the history of our galaxy. We also have a vast amount of data from low-metallicity halo stars that are enriched in r-process material, presumably reflecting the enrichment of star-forming gas by r-process sources in the early galaxy. Remarkably, the pattern of the heavy elements beyond Ba matches very closely that of the Sun, suggesting an underlying mechanism that produces similar r-process yields in every event. Finally, puzzling data have been obtained of ultra-faint dwarf (UFD) galaxies. One of these UFDs — Reticulum II (Ret II) — contains a number of individual stars with large and relatively uniform r-process enrichments consistent with yields from a single binary NS merger. No other UFDs, however, show such enrichments (see Fig. 7). There is a significant amount of observational data available on NS binaries including those that can merge within $\sim$ 10 Gyr, and thus are relevant to GW detection. Models that attempt to account for binary NS data are sensitive to a number of input parameters, including the kick velocities of newly created NS. The UFD results are interesting because they allow us to test such models, and hence the cosmology that will be needed to interpret future GW data, at an extreme, namely galaxies with very shallow gravitational potentials from which kicked neutron stars may easily escape. UFDs are thought to be the oldest, most DM-dominated, and most metal-poor galaxies: to the extent that the nucleosynthesis (or lack thereof) is probing the gravitational physics of these early galaxies, one can learn about the early behavior of DM at small scales. Thus the issues that RetII data present tie MA2, MA3, and MA4 together, while also involving the modeling in MA5.

Within this decade we should learn a great deal about the rate of NS mergers and thus the role of mergers as potentially the dominant source of r-process material within our galaxy and others. However, there are strong indications that NS mergers are not the only r-process source: we have abundant evidence from metal-poor halo stars that an r-process operated at early times, e.g., when the Fe to H ratio was $\sim 10^{-3}$–10^{-2} times the solar value, [Fe/H] ~ -3 to -2. Because NS mergers were much rarer than SNe that were responsible for Fe enrichments at such early times, it would be difficult to account for the approximately linear trend of the r-process tracer element Eu with Fe had NS mergers been the sole r-process source [88]. Thus there may be need for at least one other r-process mechanism, to explain the data at low metallicity. On the other hand, the role of NS mergers in r-process enrichment will be better quantified with progress in population synthesis models that aim to understand the rates of GW events. These models are also connected with short gamma-ray bursts (GRBs), which though poorly understood, have long been thought to originate from NS mergers. This association gained great credibility with the Fermi telescope observation of a short GRB 1.7 sec after the arrival of the GW from GW170817.

These connections — LIGO/Virgo/KAGRA and the GW detectors to follow, electromagnetic observations of kilonovae, short GRB models and observations, population synthesis models, chemical evolution studies within our galaxy and UFDs, and the near-term prospect that JWST will provide a detailed characterization of the first stars and galaxies — beautifully illustrate why we need to form teams of experts working to piece together the clues from multi-messenger astrophysics. We also need young researchers who can navigate this new world, trained not as specialists under the tutorage of a PI, but integrated into a team where the ability to "see the big picture" becomes essential in an age of rapidly evolving multi-messenger astrophysics.

Origin of heavy elements in the early universe: Much of our detailed knowledge about the r-process comes from observations of metal-poor halo stars with [Fe/H] ~ -3 to -2. The arguments given above suggest that while NS mergers may prove to be the dominant r-process source over galactic history, it is less likely that they account for the heavy elements at very early times, barring exceptional conditions, such as a population of primordial NS binaries in globular clusters [90], or alternatively some mechanism that produces very short ($\sim 10^6$ yr) merger times. There are nucleosynthetic objections to such scenarios, specifically the scatter of [Eu/Fe] observed at low metallicity. An excellent review of the arguments and counterarguments is given in [91].

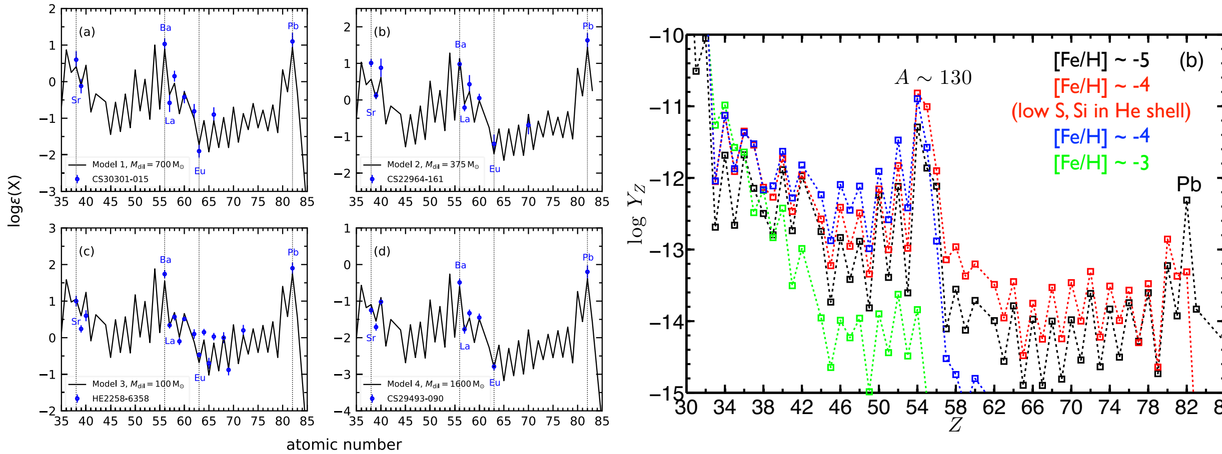

Figure 8: An illustration of two mechanisms that could explain neutron-capture abundances seen in low-metallicity galactic halo stars, when NS mergers should be rare. Left: Calculations of the neutron-capture nucleosynthesis induced by mixing of protons into He shells of early massive stars are compared to observations of metal-poor stars. The abundances match those seen very well [109]. Right: Abundance patterns for neutrino-induced nucleosynthesis in He shells of early supernovae with different initial metallicities indicated by [Fe/H]. Note that this r-process "turns off" at metallicity $Z \sim -3$, as the neutron source is too weak to drive a full r-process at that point [107, 108]. Much of this work has involved a collaboration between the Berkeley and Minnesota N3AS teams.

Our knowledge of the high-redshift universe will expand enormously with the launch of JWST, expected early in 2021, when this PFC will be starting up. The early universe is an intrinsically interesting time for nucleosynthesis, characterized by the rapid evolution of massive stars and frequent ejection of nuclear material into the interstellar medium. With that material initially low in metals, both the evolution and explosion of massive stars born out of it are special, generating features such as mixing, winds, jets, large neutrino fluences, and accretion disks, all of which are important to various modes of heavy element nucleosynthesis (e.g., see Fig. 8). Another great challenge for N3AS will be to better understand what processes governed the early chemical evolution of galaxies by rapidly integrating the new information soon to be obtained on early star formation.

N3AS has a great deal of expertise in nucleosynthesis: we can envision helping to catalyze discussions between observers and those in nuclear astrophysics who model explosions and the associated nucleosynthesis. N3AS members played major roles in exploring the "hot bubble" SN r-process, in which high-temperature and somewhat neutron-rich atmosphere above the proto-NS is ejected via neutrino-driven winds, adding $\sim 10^{-3} M_\odot$ of material per supernova into the interstellar medium [92, 93]. They developed much of the microphysics [94] that, in the end, showed that much of the ejecta would not be neutron-rich. They helped convince the community that, despite its seeming plausibility, this site cannot account for heavy r-process abundances: one cannot make use of the neutrino-driven wind to eject material from the proto-NS atmosphere without destroying the delicate proton-neutron balance necessary for a successful r-process.

N3AS members continue to be deeply involved in modeling winds and the associated nucleosynthesis [78, 95–98] and in exploring yield sensitivities to uncertain dense matter and neutrino physics [77, 94, 99–104]. They also developed much of the theory of neutrino-driven nucleosynthesis that occurs in the mantles of core-collapse supernovae, including the ν-process, νp process, and ν-driven r-processes [103, 105–108].

As noted previously, the r-process abundances seen in metal-poor halo stars may require more than one r-process mechanism, for which some of the suggestions are summarized in [91]. N3AS members explored a neutrino-driven r-process in the He zones of low-mass, low-metallicity supernovae (see right panel of Fig. 8) [107, 108]. This process proceeds through a path not too close to the neutron-drip line, where we have a better understanding of the nuclear physics. As the source of neutrons is the charge-changing neutrino breakup of ^{4}He, this process is acutely sensitive to the neutrino mass hierarchy: successful if the hierarchy is inverted, but not if it is normal. By requiring low metallicity, the above r-process could account for the abundances seen in the early Galaxy, while naturally "turning off" at higher metallicity. Therefore, it combines early-universe stellar conditions, namely the more favorable neutron-to-seed ratios that are possible at low metallicity, with novel nuclear and neutrino physics, illustrating how varied the possibilities are.

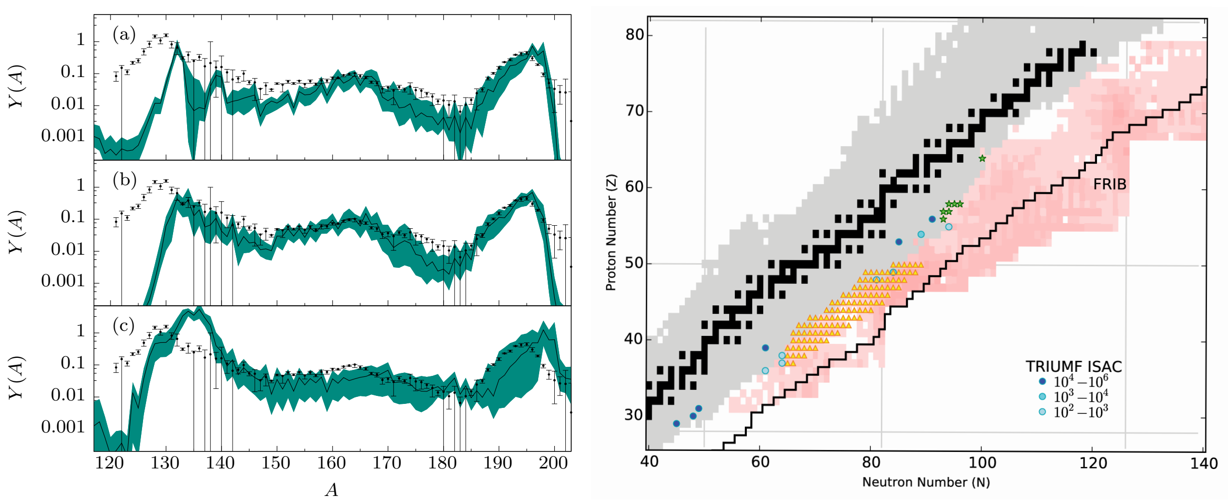

Figure 9: Left panel: Abundance patterns Y(A) versus mass number A for fifty r-process simulations with astrophysical conditions corresponding to high-entropy (top panel, (a)), low-entropy (middle panel, (b)), and fission-recycling (bottom panel, (c)) outflows, as described in [110]. The shaded region shows the full range of abundance patterns produced, and the black line shows their mean. All patterns are scaled to solar abundances. Right panel: The estimated capabilities at the future FRIB to map masses near neutron drip, with the new region to be explored indicated in pink (black line: 10^{-4} particles per second) [111].

Nuclear physics of the r-process: The connections between nucleosynthesis and cosmology can only be made to the extent that the nuclear microphysics controlling nucleosynthetic pathways is understood. We are very fortunate that the progress in astrophysics is being matched by progress in the laboratory, especially the near-term prospect that FRIB will substantially improve our knowledge of the properties of the neutron-rich parents of r-process nuclei. Our limited knowledge of nuclear masses and decay rates along the r-process path is currently one of the limiting uncertainties in nucleosynthesis networks. Figure 6 depicts uncertainties induced by mass models, as evaluated by the FIRE collaboration. In Fig. 9, the left panel shows the error bands from a single model, the UNEDF1 density functional, arising from propagating the uncertainties in the input data to determine their impact on r-process uncertainties. This shows that a great deal of the uncertainty comes from the limited experimental data. Thus the importance of the right panel, showing the impact FRIB will have in extending our knowledge of masses much further toward the drip line.

N3AS has significant expertise in this technical but still important issue that impacts what we can learn from the r-process. The issues go beyond mass data and error propagation, as illustrated by the following examples. The relationship between the stable r-process abundances that we measure and the neutron-rich isotopes synthesized in transient, billion-degree astrophysical explosions can be altered as the parent isotopes decay, once the explosion subsides. In addition to neutron emission accompanying beta decay, neutrons can be spalled off the parents if the explosion occurs in an intense flux of neutrinos. Such processes tend to smooth out even-odd abundance differences associated with nuclear structure effects such as pairing. If the neutron flux is sufficient, the r-process can fission cycle. Indeed, if fission cycling is generic to Nature's r-process, this mechanism could explain the stability of the r-process pattern beyond barium.

MA3 - Dense Matter for Fundamental Astrophysics: [Carlson, Gandolfi, Lattimer, Phillips, Prakash, Reddy]

Overview of the Science: The detection of GWs and electromagnetic (EM) waves from the first observed binary neutron star merger, GW170817, ushered in a new era of multi-messenger astrophysics in which NSs are poised to play a leading role [112, 113]. The fortuitous proximity of this event provided detailed observations that led to fundamental new insights about NSs and dense matter [114], and provided indirect evidence for the synthesis of heavy elements [115]. Observations confirmed, in broad-brush, theoretical predictions for NS merger dynamics supporting the idea that these extreme multi-physics phenomena can be modeled with advanced simulations to interpret the multi-messenger data [114–117]. Remarkably, it also revealed that two of the forefront questions in nuclear astrophysics: "What are the states of matter at the extreme densities inside neutron stars?" and "Where and how are the heavy-elements synthesized in the universe?" are intimately connected. The overarching goal of MA3 research is to advance calculations of thermodynamic and transport properties of dense matter needed to interpret diverse multi-messenger observations of NSs and address both of these questions.

Equation of state of cold dense matter and neutron star structure: The relationship between the pressure and the energy density, or the equation of state (EOS), of cold dense matter uniquely determines the structure of NSs. Thus observations of NSs that provide measurements of their masses, radii, tidal deformabilities and moments of inertia constrain the dense matter EOS and offer insights into NS internal properties and composition. The composition and phase structure of NSs, especially in the inner core where non-nucleonic degrees of freedom are likely to emerge, is poorly known. Fig. 10 illustrates our current expectations for NS interiors, and the poor constraints on the EOS, and the corresponding NS mass-radius relation. The black and red lines are included in this figure to show schematically how more stringent constraints on the EOS will lead to tighter restrictions on the radii of typical NSs with mass $\simeq 1.4 M_\odot$ and vice-versa. Below we describe research needed to tighten constraints on the EOS and the NS mass-radius relationship and elucidate its implications for astrophysics and for the discovery of new states of matter at high density.

Radio observations of pulsars have precisely determined several NS masses, and the recent discovery of several pulsars with masses greatly in excess $1.4 M_\odot$ has led to new insights [118, 119]. The largest measured masses with accuracies better than 10% are 2.01 ± 0.04 for PSR J0348+0432 [120], $2.14^{+0.10}_{-0.09} M_\odot$ for PSR J0740+6620 [121], and $2.27^{+0.17}_{-0.15} M_\odot$ for PSR 2215-5135 [122]. In general relativity, there is a maximum central density and a maximum mass $M_{\max}$ that can be supported before gravitational collapse to a black hole occurs. This limit depends primarily on the high-density EOS in the NS inner core, and these observations strongly suggest that $M_{\max} \gtrsim 2 M_\odot$ and also establishes a lower limit to neutron star radii of $\simeq 8.2$ km from causality [118].

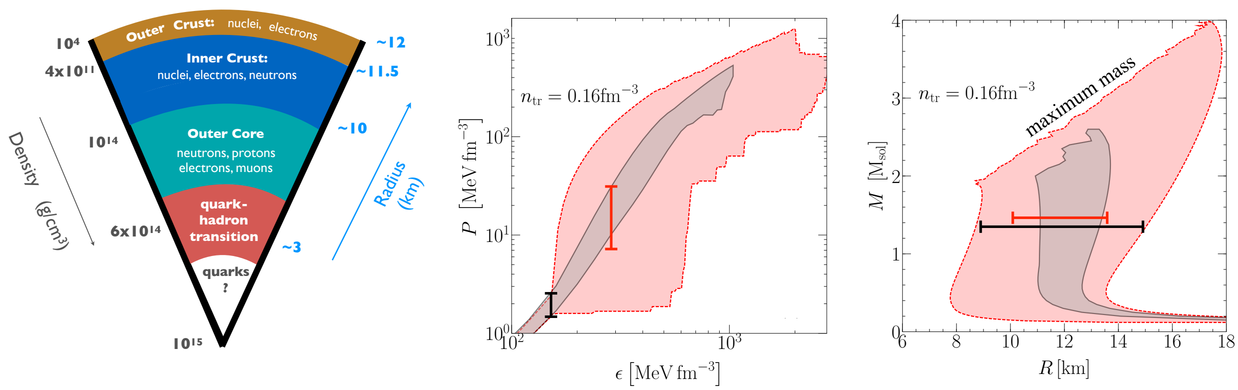

Figure 10: Left panel: Theoretical expectations for the NS composition. The EOS (middle panel) uniquely determines the structure of neutron stars (right panel). The range of possible behavior of the EOS and the mass-radius relationship is obtained by incorporating theoretical predictions for baryon density $n_B < n_{tr} = n_{\rm sat}$ where $n_{\rm sat} = 0.16$ fm^{-3}, and observations of massive NSs [123].

Measurements of NS radii from x-ray observations of quiescent sources [124, 125] indicate a range 10 km $< R_{1.4} <$ 13 km but their accuracy is limited by systematic effects of order a few kms. In addition, NASA's Neutron Star Interior Composition ExploreR X-ray telescope, attached to the space station, is returning valuable information concerning NS masses and radii. The pulse-profile modeling of periodic thermal x-ray emissions from PSR J0030+045 indicate a NS radius of about 13 ± 1.2 km to 68% confidence, but systematic uncertainties gauged by the results from different models [126, 127] are of order 0.5 km. While these radius ranges are consistent with expectations from dense matter theory, the associated errors are still too large to distinguish among different dense matter models and scenarios for phase transitions. However, dramatic progress in multi-messenger observations of NSs is presently occurring and is expected to accelerate during the next few years, as underscored by GW170817 [112]. Modeling of the observed GW strain accurately reveals information about NS masses and the binary tidal deformability, which is a particular combination of the stars' individual tidal deformabilities weighted by the stars' masses. Several other types of observations that include quasi-periodic oscillations observed in magnetar giant flares can be studied using NS seismology [128], pulsar timing of extremely compact relativistic binaries leading to measurements of moments of inertia [129], and continued progress in pulsar mass measurements [118, 119] can provide independent constraints for the NS mass and radius.

Theory shows that the binary tidal deformability is a good proxy for the NS radius in the vicinity of $1.4M_{\odot}$. Detailed analysis of data from GW170817 indicate that the stellar radii of the components was about 11 ± 1 km [130, 132, 133], a significant improvement over previous astrophysical and nuclear estimates. Nevertheless, there are systematic effects in the modeling of binary NS mergers that introduce additional uncertainties of about 0.5 km (for example, the results depend on the assumed priors for the tidal deformabilities), and further theoretical work is necessary to reduce these systematics. The GW17817 result is consistent with that of NICER, and further analyses of additional sources by NICER and LIGO/Virgo/KAGRA will likely provide improved constraints. Among the new NICER sources will be systems with known masses, and anticipated additional gravitational wave events may be sufficiently similar to GW170817 that their data will be additive.

GW170817 was a multi-messenger event. The kilonova's visible and infrared light curve is consistent with the ejection of neutron-rich matter containing newly synthesize, radioactive r-process elements [115]. Had the coalesced remnant of GW170817 dynamically collapsed into a black hole on millisecond timescales, which would have occurred if its total mass had exceeded that for gravitational stability, it is unlikely sufficient ejection would have occurred to explain the observations. In addition, if the remnant was too long-lived, longer than a few tenths of a second, neutrino emission might have poisoned the ejecta by converting neutrons to protons which would short-circuit the r-process, and thermal heating of the ejecta would have made the kilonova much brighter than observed. Importantly, recent work suggests that EM observations of GW170817 and future gravitational wave sources can provide useful information about the the compactness (M/R) of NSs [134] and the NS maximum mass [117], directly constraining NS properties and the EOS of cold dense matter [133, 135, 136].

To improve the constraints on NS structure and provide insight about dense matter properties, it is now clear that joint analyses will be needed [126, 127, 133]. Input on the EoS of neutron-rich matter at moderate density – $n_B < (1-3)n_{\rm sat}$, where $n_{\rm sat} = 0.16$ fm^{-3} is the saturation density – will have to be combined with detailed analyses of future GW and x-ray observations, informed by an understanding of the underlying astrophysics. NS radii and the pressure of matter at $(1-3)$ $n_{\rm sat}$ in the outer core of the NS are tightly correlated [137] and recent advances in dense matter theory now provides the tools to calculate the EOS of dense neutron-rich matter with reliable error estimates [138–146].

During the past decade chiral effective field theory (ChiEFT) has become the standard approach for deriving microscopic nuclear interactions. It provides a systematic expansion for nuclear forces in powers of momentum, p, over a breakdown scale, Λ_χ. These modern interactions are now being incorporated into Quantum Monte Carlo (QMC) calculations [144, 147], and into an efficient new framework to use Monte Carlo integration to evaluate many-body perturbation theory (MBPT) diagrams to high order in the perturbation expansion [148]. Together they enable a rigorous quantification of the theoretical uncertainties for the EOS induced by finite-order truncation of the ChiEFT expansion. Many-body forces appear naturally in ChiEFT, with the first non-vanishing contribution from three-nucleon forces entering at $O(p/\Lambda_\chi)^3$. The three-nucleon forces at the next higher order, $O((p/\Lambda_\chi)^4)$ have a rich operator structure. This sophisticated description of three-nucleon forces has only recently been incorporated in state-of-the-art ab initio calculations of finite nuclei and nuclear matter. Drischler et al. studied neutron and symmetric matter using ChiEFT nuclear forces, including three- and four-nucleon forces up to $O((p/\Lambda_\chi)^4)$ using MBPT to fourth order, and found that the estimated error of the higher order diagrams is much smaller than the uncertainty induced by truncation of the ChiEFT expansion [148]. Drischler, Phillips and collaborators have used these calculations and a new model of correlated EFT truncation errors to infer the Fermi momentum at which the EFT expansion breaks down. This is the first statistically rigorous assessment of the density range over which ChiEFT calculations of strongly interacting matter are valid. They find a breakdown scale, $\Lambda_\chi \approx 500$ MeV for neutron matter, corresponding to baryon density $n_B \simeq 3n_{\rm sat}$. In related work, Tews et. al used a local coordinate space version of the ChiEFT potentials in QMC to address the evolution of EFT truncation errors with density in calculations of the neutron matter EoS [146]. This EoS with the associated error estimates up to $n_{\rm sat}$ and $2n_{\rm sat}$, and a general parameterization of the EoS at higher density was used to provide informed priors for the GW data analysis of the gravitational wave data from GW170817 [133]. By using a theoretical EoS over the range of densities where errors remain under control, one can gain more leverage from the data on the EoS at higher density, where little is known.

In the NS inner core the inter-particle separation is comparable to the size of a nucleon, and quark degrees of freedom must become relevent. The large observed NS maximum mass $M_{\rm max} \gtrsim 2M_\odot$ [120, 121, 149] disfavors strong first-order phase transitions at high density and has provided valuable guidance for the construction of models of high density matter that includes non-nucleonic degrees of freedom such as hyperons [150], meson condensates, and deconfined quark matter [151–153]. N3AS will bed able to advance these models of phase transitions by including the effects of many-body interactions and quantum corrections beyond mean field theory to explore the range of possible behavior at high density and its impact on NS structure. We will develop and classify [154] models of EoSs at high baryon density to identify signatures of phase transitions from the joint analyses of the existing and anticipated GW, x-ray, optical, neutrino and radio data. These high-density models will be consistently melded with the more rigorous and reliable calculations of the EoS of neutron-rich matter at moderate density describe above. A collaborative effort involving dense matter physicists and astrophysicists is needed to correlate and interpret diverse observations of NSs to obtain masses, radii, tidal deformabilities and moments of inertia. The expertise assembled in this PFC is well suited to accomplish this. The insight gained on properties of nuclear matter at very high density will impact nuclear physics, but also allow one to model a variety of high-density astrophysical environments more accurately.

Equation of state of hot dense matter for binary NS merger simulations: Simulations of binary NS and NS-BH systems require as input the EoS of dense matter over wide ranges of density ($10^{-8} \lesssim n/n_{\rm sat} \lesssim 10$) and temperature ($0 < T(\text{MeV}) \lesssim 100$) (see Fig.1). This is due to the large compression and mass of the remnant achieved during the binary NS merger. Conditions in the post-merger remnant also depends on the composition, temperature, neutrino trapping, magnetic fields and rotation, and in concert, they produce either stable massive NSs, long-lived supermassive neutron stars (SMNSs), short-lived hypermassive NS (HMNS), or stellar mass BHs. In each case the associated GW and EM emission is detectable and is expected to be distinct, and presents opportunities for fundamental discoveries.

Recent simulations of binary NS and NS-BH mergers have clearly demonstrated that all aspects of post-merger dynamics are strongly influenced by the EoS of hot dense matter [116, 156–158]. Although significant advances have been made in calculating the EoS of dense matter at zero temperature in recent years, there is an urgent need to improve calculations of the EoS at finite temperature to interpret multi-messenger observations of binary NS and BH-NS mergers. While it was adequate to combine ChiEFT calculations neutron matter at moderate density and use simple parameterizations at higher density to analyze observations of the structure of cold NSs, the extension of the

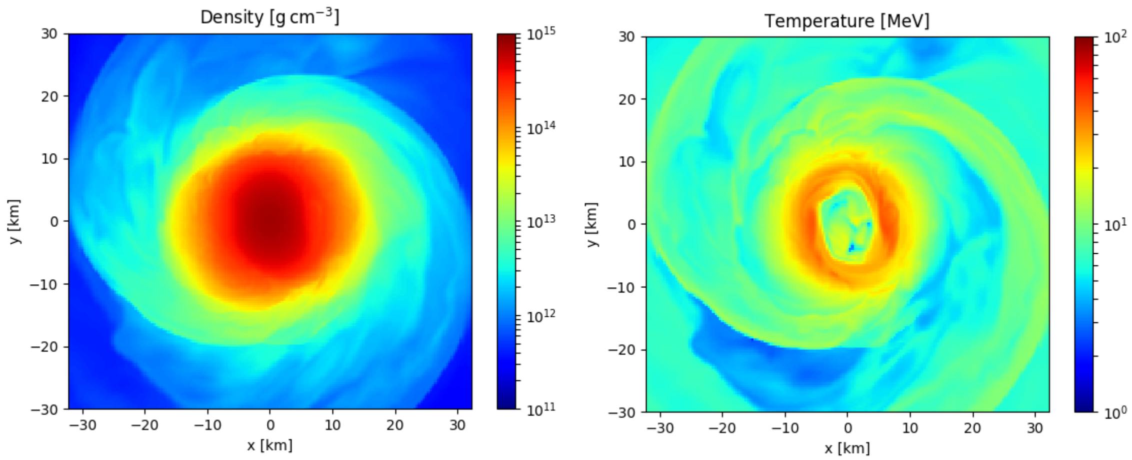

Figure 11: The extreme densities and temperatures encountered in NS mergers extracted from numerical relativity simulations. Figure courtesy of David Radice from Ref. [155]

EoS to finite temperatures for use in NS simulations need to be based on thermodynamically consistent physical models across the full-range of ambient conditions encountered. In addition to the relationship between pressure and energy density, knowledge of the compositional dependence of the EoS, and its thermal and transport properties will be critical in merger simulations. Although several models have been developed to provide the microphysical input needed in simulations (for a recent review see Ref. [159]), there is an urgent need include the uncertainties associated with the poorly constrained interactions between nucleons at short-distances, three- and four-body forces, and to move beyond the mean field approximation in these calculations. This is a major challenge for dense matter theory. In what follows we outline the relevant dense matter research, and the need for a coordinated and collaborative approach to address this challenge.

The first step is to advance finite temperature calculations of the EoS by employing ChiEFT based on modern two- and three-nucleon potentials in MBPT and quantify the evolution of truncation errors (due to the perturbative expansion and the EFT operator expansion). MBPT, combined with Renormalization Group methods, is a computationally efficient framework for estimating the many-body uncertainties through order-by-order comparisons. We will employ a novel Monte Carlo MBPT framework developed by Drischler et al. that uses automatic code generation for diagrams associated with MBPT. A recently developed GPU acceleration of high-dimensional momentum integrals, developed by McElvain, will enable the proper inclusion of three-nucleon forces, finite temperature effects and finite proton fractions in EoS calculations. These calculations together with existing astrophysical constraints (on the NS maximum masses, radii, and tidal deformability) will then be used to guide the development of a new class of phenomenological models for the EoSs that will go beyond mean field theory to extend consistently the finite temperature EoS to densities and temperatures beyond those that can be accessed by the ChiEFT approach. This approach will include the reasonable range of behavior for nuclear EoS that is consistent with EFT error analysis at moderate density and will incorporate phase transitions to new states of matter at high density in a thermodynamically consistent approach. We will develop EoS models for phase transitions to matter containing quarks that would be suitable for use in merger simulations and work closely with the computational astrophysicists to identify robust observable signatures.

Of particular interest in the short term is to use the improved models of the EoSs to determine the effect of dense matter physics and phase transitions on the lifetime of remnants formed after merger and on the ejected mass and its composition. The latter is expected to directly impact r-process nucleosynthesis and associated EM post-merger (kilonova) emission. This PFC brings together all the expertise needed to perform a suite of binary NS and NS-BH merger simulations with a well-informed set of EoSs and to employ advanced neutrino transport schemes (discussed in MA1) to predict the ejected mass and composition, and to perform the photon transport and nuclear reactions in the ejecta needed to predict observed EM emission. This comprehensive effort is needed to reliably use to EM observations to constrain the EoS and to assess the robustness of proposed correlations between the NS compactness, maximum mass, and the lifetime of the remnant [116, 134, 135]. In addition, we will employ the finite temperature EoS discussed above and the associated neutrino physics (discussed below and in MA1) in astrophysical simulations (MA5) of core-collapse supernovae and proto-neutron star cooling to predict their neutrino and GW signatures.

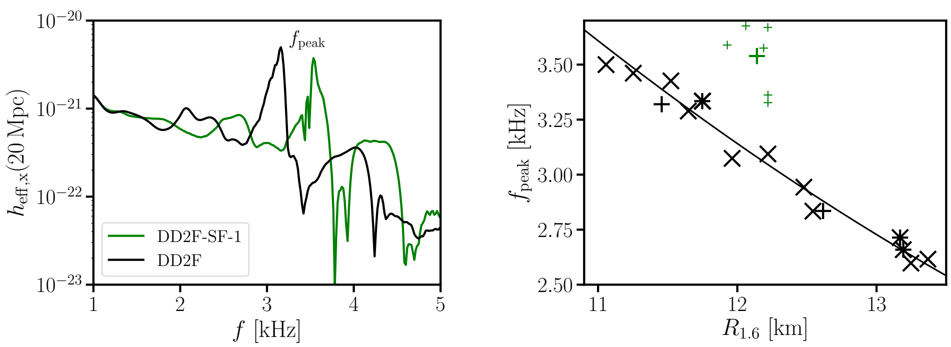

Figure 12: Predicted post-merger GW signals from Ref. [160]. Black curves correspond EoSs with only nucleons, and exhibit a strong correlation between the peak of quasi-normal mode frequencies and the radius of a cold NS with mass $M = 1.6\ M_{\odot}$, In contrast models which allow for a phase transition to quark matter (in green) results in a more compact hypermassive NS and are characterized by a higher peak oscillation frequency.

Although no evidence of a post-merger GW signal from GW170817 or GW190425 was found at frequencies up to 4 kHz, the prospects for future detections of post-merger GW signals in third generation GW detectors are excellent [161]. In the near term, a close by event may provide a detectable post-merger GW signal in aLIGO [162]. The advanced EoS models of hot dense matter that we shall develop and invorporate into binary NS merger simulations, working with the MA5 team, will be critically important to understanding the correlation between the pre-merger GW signal, and the post-merger GW and EM signatures. In particular, this will help identify signatures of the phase transitions that would occur in hypermassive neutron stars where the highest matter densities and temperatures are achieved. We will explore in systematic detail a recent suggestion in Ref. [160] that the frequency of the observable GW emission from the hypermassive neutron star is strongly correlated with the radius of a cold NS with mass $M = 1.6\ M_{\odot}$, and that this correlation is altered in the presence of first-order phase transition as shown in Fig. 12.

Neutrino processes in dense matter: Neutrino transport of energy, momentum, and lepton number plays an important role in SNe, NS merger dynamics, and in the thermal evolution of young and old NSs. In core-collapse SNe, the flavor dependent neutrino opacities of dense matter determine the spectral and temporal characteristics of neutrino emission [163], which is critical for the explosion mechanism [164], the synthesis of heavy-elements [165] and for neutrino detection on Earth [166]. In NS mergers, weak interactions and neutrinos deplete neutrons in the neutron-rich ejecta and directly influence the r-process synthesis of heavy-elements [167], the kilonova power source [115]. At high matter density when the typical neutrino wavelength is large compared to the inter-particle separation, several nucleons and leptons are involved in the scattering process, and the strong and electromagnetic correlations between them can greatly alter the neutrino-matter interaction rates [168]. Although model calculations of the neutrino emissivities and opacities of hot dense matter have provided many useful insights [169], a framework to obtain these rates consistently with the underlying nuclear EoS and with error estimates is lacking. In addition, calculations of neutrino interaction rates in dense matter containing quarks, hyperons, and or meson condensates are either often ignored altogether, or included without properly accounting for correlations. A major focus of the dense matter research relating to neutrino interactions will be to address these issues. Collaborative research in this PFC will develop methods to calculate the linear response functions of hot dense matter over the wide range of ambient conditions of interest to neutron star mergers and for cold matter encountered in old neutron stars where superfluidity and superconductivity greatly modify the low energy response properties [170, 171].

As with the EoS studies, one focus of our efforts will be develop methods to use ChiEFT Hamiltonians to calculate the linear response functions needed for a description of the neutrino scattering, absorption, and emission rates in dense nuclear matter. We will combine the analytic methods (diagrammatic re-summation) and computational methods such as QMC [172] and molecular dynamics [173] to calculate the relevant response functions and properly account for many-body effects such as screening [168] and multi-pair excitations [174]. Similar methods will then be used to calculate the neutrino rates in models of dense matter which allow for phase transitions to matter containing non-nucleonic degrees of freedom such as pions [175], quarks [176–178], hyperons [179]. This will provide a comprehensive coverage of neutrino rates for the full range of ambient conditions encountered in SNe and NS mergers.

Recent x-ray observations of cooling of accreting NSs [180] has provided new opportunities to study the thermal and transport properties, and neutrino cooling of old and cold NSs which are reheated by nuclear reactions deep in the NS crust [181]. Models that combine nuclear reaction physics, low temperature properties of the solid and superfluid NS inner crust, and neutrino cooling in the core have been employed quite successfully to interpret x-ray light curves in quiescence for several sources to deduce constraints on the thermal conductivity [182], specific heat [183] and neutrino cooling rates [184]. These studies provide strong evidence for rapid neutrino cooling in the NS MXB 1659-29, and motivate detailed calculations of the neutrino emissivity of different possible phases of cold dense matter to discover signatures of phase transitions in the core. This PFC brings together the expertise in dense matter theory and strong interactions to revisit calculations of the neutrino emissivity of neutron stars, incorporate them in NS cooling models [185], and perform the model-data comparisons using Bayesian inference methods [186] to assess the role of phase transitions in NS cooling.

In addition, the methods described above to advance calculations of the linear response functions of dense matter needed for neutrino reactions can be easily adapted to calculate the rate of production and propagation of exotic particles such axions [187], dark photons [188], gauge bosons associated with hidden sectors [189], and other dark matter particles. Through collaborations between the MA3, MA4 and MA5 efforts this PFC will advance our understanding of the potential role of dark matter in core collapse SNe, NS mergers, and cooling NSs.

Integration to confront multi-messenger observations: The existing and expected multi-messenger data from accreting NSs, binary NS mergers, and future galactic SNe contain valuable information about extreme environments and processes. Our ability to unambiguously extract fundamental insights about NSs and dense matter (MA3), neutrino physics (MA1), nucleosynthesis (MA2), and dark matter (MA4) will depend critically on a coordinated collaborative effort between all the MAs in this PFC. The modeling effort (MA5) which relies on input from all the MAs is the conduit for these collaborations to confront observations. Propagating errors presents unique challenges in model-data comparison. For example, theoretical uncertainties in the input dense matter physics yields not only the size of the errors, but also their correlation structure, and its implementation in simulations requires close collaborations between MA3 and MA5. The combination of expertise in this PFC uniquely positions us to carefully assess how different sources of uncertainty in the models need to be accounted for and propagated by designing suitable suites of simulations to interpret different observations.

MA4 - Dark Matter in Nuclear Physics: [Cirigliano, Fuller, Gardner, Haxton, Lin, Mack, Quataert, Reddy]

N3AS Objectives: One of the grand challenge problems for physics is identifying the source and particle properties of dark matter (DM) – if indeed DM is shown to be a particle. N3AS has an important though focused role in this grand-challenge – the calibration of terrestrial, astrophysical, and cosmological laboratories for dark matter. The work includes

1. the application of effective field theory to determine what can and cannot be learned from terrestrial direct-detection experiments;
2. the accurate characterization of the "conventional physics" of astrophysical laboratories for DM, so that possible DM signals from such sites can be identified with new physics; and
3. the use of nucleosynthesis as an additional probe of DM galactic dynamics.

Overview: The dark matter/dark sector problem has defied resolution for decades. In fact, as direct detection experiment have reached and penetrated beyond the weak scale, the DM mystery has only deepened. Accommodating DM will almost certainly require beyond-standard-model (BSM) physics: the only standard-model particles contributing to dark matter, the light neutrinos, contribute less than 1% of the closure density, according to recent cosmological analyses [75]. (Though less constraining, KATRIN now restricts the contribution to $\lesssim$ 3.5%.) Consequently, DM appears to be a doorway to new physics: the resolution of the DM problem will change our fundamental descriptions of particle physics.

Astrophysical observations establish that roughly a quarter of the closure fraction of the universe stems from components with non-relativistic kinematics, with baryon rest mass contributing only some 20% of this. The rest, the DM, must reside in a non-baryonic component or, conceivably, multiple components. These non-baryonic components must be long-lived or stable, each with a small enough collisionless damping scale to be consistent with structure observations, gravitationally active, but without appreciable interactions with ordinary matter or with themselves, and essentially collision-less, at least on large scales [190–192]. DM candidates include WIMPs, axions, sterile neutrinos with keV-MeV masses, primordial BHs, low-mass hidden-sector particles, and composite dark sectors with dark analogs of pions or nucleons. Particle DM could range in mass from 10^{-22} eV – bosonic DM with a high particle number and enormous deBroigle wave lengths that would require coherent or wave-based detection methods – to heavy scales, include the weak, GUT, and Planck scales. Every scenario takes physics beyond the standard model – likely even the production of primordial BHs in the very early universe.

All evidence for DM is cosmological and gravitational. But there is enormous interest in three other possible manifestations of DM. First, DM might be detected through its scattering off ordinary matter or its interactions with electromagnetic fields. Massive G2 (generation-two) direct detection experiments are being mounted to detect weak scale DM – WIMPS (Weakly Interacting Massive Particles) – through the energy they can transfer to nuclei during elastic scattering. Similarly, light axions can be detected through their conversion to microwave photons, as they pass through a spatially varying magnetic field. Second, DM might be produced in high-energy collisions. At the LHC the debris of p-p collisions is examined for visible SM particles accompanied by missing transverse momentum – indicating that an invisible particle escaped the detector without interacting. Dark analogs of photons have similarly become a popular target for searches at electron machines and in table-top atomic experiments. Third, DM might be produced in a variety of astrophysical explosions, or contribute to the cooling of various astrophysical objects. This connects DM to a principal concern of this proposal, the quantitative description of astrophysical explosions and the validation of those descriptions through multi-messenger observations.

Direct detection and fixed-target experiments: The cosmological abundance of DM is generally attributed to its production in the early universe: at sufficiently high temperature dark matter and ordinary matter are kept in equilibrium through their mutual interactions. As the universe cools, reactions begin to slow relative to the Hubble expansion, allowing the DM to freeze out. The resulting abundance is governed by the velocity-weighted cross section for production and self-annihilation, $\langle\sigma v\rangle$. The observed matter abundance is well-reproduced for $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ cm^3/c, which is a value characteristic of a 100 GeV particle that interacts via weak interactions. This "WIMP (weakly interacting massive particle) miracle" has had an important impact on experiment, motivating ton-scale direct-detection experiments such as LUX/LZ [193], Xenon1T [194], PandaX-II [195], and SuperCDMS [196] that seek to detect the elastic scattering of WIMPs off nuclei via nuclear recoil. The lightest supersymmetric particle in supersymmetric extensions of the standard model is a natural WIMP candidate.

The kinematics of direct detection (DD) are unusually. WIMPs are cold, traveling at a velocity $v \sim 10^{-3}$, and thus they can transfer only 10s of keV to targets, below typical (but not all) thresholds for nuclear excitation. In contrast their momentum transfers are significant, ranging up to ~ 200 MeV/c, a value large compared to the inverse size of nuclei. This means that the scattering is sensitive to the internal structure of the nucleus: the WIMPs can "see" current and charge distributions, magnetic and anapole moments, etc. A description of the scattering that treats the nucleus as a point particle, characterized only by charge and spin, should not be adequate.

The most common framework for the analysis of direct detection, though, dates to the early focus on stable supersymmetric WIMPS. A nonelativistic reduction of simple vector and axial-vector operators formulated at the light quark level (u, d, s) leads to leading Fermi (spin-independent or SI) and Gamow-Teller (spin-dependent or SD) couplings. Most comparisons between different

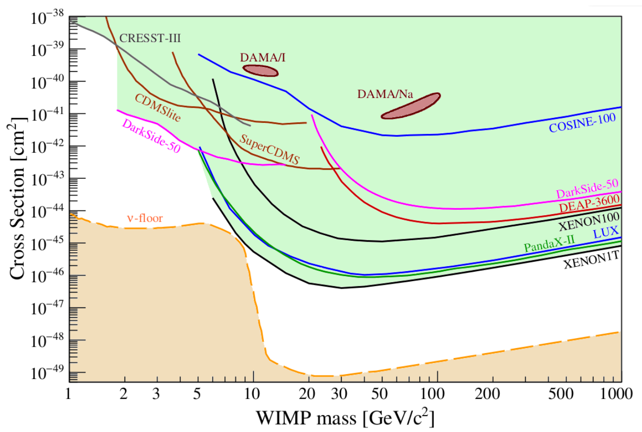

Figure 13: A compilation of direct-detection limits on the simple spin-independent cross section for dark matter scattering off nuclei, as a function of the WIMP mass. The neutrino floor indicates the background from solar neutrino scattering off the same target nuclei. Not all experimental results are shown, for clarity. Figure from [197].

experiments – experiments employing nuclear targets that differ in their spins, isospins, and electroweak moments – have been made using this simple framework. A recent partial compilation of experimental cross section limits from SI coupling is shown in Fig. 13.

Many classes of BSM theories can accommodate DM, with one or more new particles that may interact weakly with ordinary matter, each with different consequences for low-energy physics in general and DD experiments in particular. Interest in a variety of alternatives has increased, with evidence for supersymmetry so far absent at the LHC. This presents a challenge: one could start with a favorite UV theory, reducing it to a nucleon-level interaction that can be embedded in nuclear physics calculations of DD. But there are many such UVs theories. The challenge, then, is to find a procedure for mapping the full range of ultraviolet theories into a simpler but complete low-energy effective theory, thereby defining the full range of DD responses in different targets. In addition to efficiency, this effective field theory (EFT) approach has another advantage: it defines what can and what cannot be learned from DD, thereby determining a complete set of independent experiments. Once the coefficients (the low-energy constants) of the EFT are determined (or, lacking detection, bounded), these constraints can be "ported" up to any other energy scale, including to the UV to constrain candidate fundamental theories.

Members of this PFC proposal, notably those at Berkeley and Los Alamos, have played prominent roles in developing EFT treatments of DD [198–203]. This work has demonstrated that much more can be learned from DD experiments than is apparent in standard SI/SD analyses: there are six, not two, independent nuclear response functions. In particular, the analysis shows that derivative-coupled theories, which one might naively expect to lead to DD rates suppressed by a factor $v^2 \sim 10^{-6}$, are in fact much more visible in DD, because of the large internal velocities of nucleons bound in nuclei. The Berkeley work coupled the EFT formulation with state-of-the-art shell-model calculations of the nuclear responses, producing an analysis script that has been used by most of the major collaborations to generalize their experimental analyses [204–206]. The experimentalists have modified their cuts to optimize the signal-to-noise ratio for specific operators. Figure 14 illustrates the large variations in the nuclear response to DM as the operator choice and isospin are varied – good news in that DD detection can probe more physics than generally assumed (including theories with velocity-dependent interactions), though it also implies that when DM is discovered, we will need multiple experiments using targets with complementary properties. Such analyses can also be done in the light-quark EFT basis: the N3AS Los Alamos group made this choice, with chiral EFT then used to derive equivalent nucleon-level operators.

This work – focused on GeV-TeV WIMP masses – should be extended to include inelastic scattering: certain operators, like the axial charge, cannot contribute to elastic scattering due to the combined constraints of CP and parity, but can induce transitions to low-energy states of certain Ge and Xe isotopes. But the real opportunity for N3AS is the opportunity to make connections between DD and astrophysical tests of DM. Both SN cores and NS mergers are characterized by temperatures well within the range of validity of a nucleon-level EFT. The possibility that DM in cosmology is in fact a (slightly) collisional fluid, with interactions in the fluid DM-baryon suppressing small-scale structure, is of interest [207]. EFT is a framework that would allow one to correlate DM constraints from DD with many of those from astrophysics and cosmology.

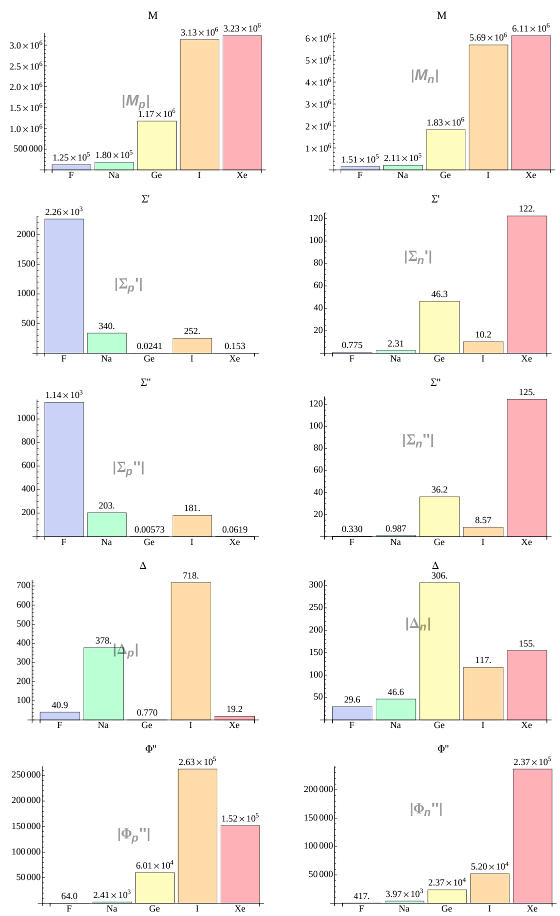

Figure 14: The magnitude of the nuclear responses for representative operators that arise in a Galilean-invariant effective field theory treatment of DD [198, 200]. Each of the responses has, at threshold, a connection to a familiar standard-model responses, e.g., from top to bottom, generalized charge, longitudinal spin, transverse spin, orbital angular momentum, and spin-orbit interactions. The latter two operators govern the sensitivity of DD to derivative-coupled theories – previously it was thought that velocity-dependent interactions would be greatly suppressed in DD. The two isospin choices shown are couplings to protons only (left) and to neutrons only (right). Operator sensitivity from target to target varies greatly. N3AS has worked with several of the experimental collaborations – most recently Pandax-II – to generalize experimental analyses to account for the range of responses Nature allows.

The generalization of EFT methods for a much wider range of DM candidates is of great interest: a lot of experimental effort is being invested in detectors sensitive to sub-GeV mass dark matter candidate particles and dark forces [208]. These candidate particles are being targeted in certain DD experiments. As the momentum transfer scale is lowered, new aspects of many-body physics can play a role.

Fixed-target experiments [209–211] can probe low-mass DM candidates. The large accelerator beam luminosity augments interaction rates, compared to particle-particle collision rates. However, nuclear physics issues arise in characterizing the signal and estimating background rates. Members of this PFC collaboration (Lin, Gardner) are currently computing the dark-bremsstrahlung production cross section and parity-violating asymmetry for different dark gauge boson models, both with proton and electron beams. This is another case where laboratory limits can be related to ones obtained from astrophysics and cosmology, including DM influence on the weak decoupling/BBN epoch in the early universe (Fuller, Lin, Grohs, DeGouvea, Sen), on stellar evolution and core collapse (Qian, Rrapaj, Fuller), and on compact object mergers (Reddy, Fuller, Quataert, Kasen, McLaughlin).

Measurements of particle decays provide another handle to constrain the low-mass dark sector. In particular, the first row of the CKM matrix, which is extremely well known, provides an important unitarity test. Recently, tensions with the Standard Model have emerged, both in tests of CKM unitarity and of Cabibbo universality [212]. Interestingly, axion models that support axion-pion mixing, such as in Ref. [213], could act to redress these tensions. Of course, such effects interplay with ongoing work in the assessment of Standard Model isospin-breaking effects and radiative corrections, in which members (Gardner, Haxton, Balantekin) of our PFC collaboration have expertise. Our aim will be to exploit this expertise to leverage progress in related dark matter/dark sector physics.

Dense astrophysical environments as dark matter laboratories: N3AS work to better characterize high-matter-density and high-energy-density environments – combining state-of-the-art standard-model microphysics with sophisticated simulations – will reduce the uncertainties inherent in the use of astrophysical "laboratories" for new physics. Such systems can be modified by dark forces and dark decay channels, including sterile neutrinos – new neutrinos with sub-weak interaction strengths. Sterile neutrinos can alter early universe physics, compact object thermodynamics, and nucleosynthesis. In the case of the Big Bang, it has been shown that solution of the full QKEs, as described in MA1, is generally necessary to properly treat the thermalization of sterile neutrinos at the time of BBN, unless the initial lepton asymmetry is small [214, 215]. Improved data will continue to raise standards: anticipated advances include future 30m-class telescope determinations of the primordial deuterium abundance and Stage-4 CMB determinations of the primordial helium abundance and N_{eff} [216].

Compact objects can be sources and sinks for DM. Light dark matter can be produced thermally in SNe, altering their cooling and producing a galactic source of hotter dark matter that can be more easily seen in DD experiments [217]. Due to the large neutron chemical potential, light DM particles carrying baryon number and having a mass $\lesssim 2$ GeV will be produced in large numbers in the cores of NSs, if the DM can reach chemical equilibrium. This will soften the EoS and dramatically lower the maximum mass achievable [218]. Some variants of WIMPs can accumulate in NSs, eventually leading to their implosion. Likewise, small primordial BHs, for example with masses $\sim 10^{-10}\,\mathrm{M}_\odot$, can similarly induce implosion.

Moreover, dark sector physics may impact the compact object merger events in observable ways [219,220]. For example, accumulating or captured dark sector particles could lead to "halos" of such particles around compact objects. These halos can alter the gravitational wave signatures of merger events [219]. In some dark sector models, condensed structures, compact dark objects (CDOs), can form and these can be gravitationally captured and lead to novel in-spiral GW signatures [220]. Additionally, the existence of new dark sector particles could allow for additional luminosity channels in the evolution of the massive star progenitors of NSs and BHs, perhaps altering the populations of these remnants in ways that can be constrained. The possibilities with GW and electromagnetic transient astronomy are promising.

The abundance of exotic dark matter scenarios altering the physics of compact objects is reminiscent of the early days of the solar neutrino puzzle [221], when four dozen plausible solutions to the puzzle were available in the literature. All but one were eliminated by ever more precise standard solar models in combination with detailed multi-messenger constraints from photoabsorption lines, helioseismology, and solar neutrinos. We see N3AS playing a similar role, advancing the state-of-the-art in the modeling of compact objects and mergers, as described in MA3 and MA5. This improvement will be driven by better algorithms and faster computing platforms, but also by the increasingly precise data coming from multi-messenger observations. Consequently, compact objects and mergers will become more quantitative laboratories for new physics. In this way we can ensure that bounds on DM derived from compact objects will stand up; and that claims for discovery of new physics will need to meet a high bar.

From stellar and galactic astrophysics to dark matter dynamics: The standard cosmology based on cold dark matter (CDM) and dark energy explains a wide range of observational data, including structures on or above the scale of galaxy clusters. However, difficulties arise at the galactic scale, including the core-cusp and the "too big to fail" problems. These problems may reflect an incomplete treatment of the coupling between DM and the baryons, and the influence of this coupling on gas dynamics (i.e., *baryonic feedback*) in CDM simulations: This issue was raised in MA2, in connection with RetII and other UFDs (see Fig. 7). That is, these issues are closely connected to the nucleosynthesis and chemical evolution studies at the heart of this proposal. Baryonic processes are expected to alter the CDM distribution through various feedback mechanisms, especially the redistribution of gas by SN explosions, altering the CDM spatial distribution via gravitational interactions. Our collaboration's extensive expertise in the nuclear processes that drive chemical evolution and power outflows, and the resulting nucleosynthesis, can provide key physics input into front-line large scale structure calculations.

Studies of Milky Way stars from Sloan Digital Sky Survey observations, as well as from the Gaia space telescope, have shown that the galactic disk is not in a steady state [222,223]; this runs counter to the assumptions under which the dark matter density and velocity distribution, both critical quantities in dark matter laboratory searches, are estimated [224]. Observational probes of the fundamental symmetries of the Milky Way disk can help reveal the ongoing mechanisms that shape the galaxy [225], and their impact explored through self-consistent solutions of the Vlasov and Poisson equations for the dark-matter distribution function.

In the early universe, the interaction of DM and baryons is a crucial ingredient of predictions for the impact of DM models on early stars and galaxies [226, 227] and on potential signals of DM particle interactions in indirect detection searches [228]. Interactions within a composite dark sector could also have a profound impact on early structure formation. Combining our expertise on DM and dark sector models, nuclear and nucleosynthesis physics, and galaxy evolution will allow us to make robust predictions for the impact of DM particle physics on astrophysical signals and early baryonic structures.

MA5 - Astrophysical Simulations: [Foucart, Kasen, Quataert, Radice]

Overview: Numerical simulations of core-collapse SNe, NS mergers, and neutrino-cooled accretion disks are critical tools in our effort to connect fundamental microscale physics (e.g. the neutrino physics from MA1, and dense matter physics of MA3) to macroscopic astrophysical events and their observable GW, electromagnetic (EM), and neutrino emission signals, as well as their contribution to r-process nucleosynthesis (MA2). With continued improvements in the sensitivity of GW detectors and the rise of wide-field surveys for discovering for EM transients, the next decade should see a wealth of interesting signals. Meanwhile, experimental nuclear facilities, like FRIB, will acquire data on rare nuclei of importance in these astrophysical environments. Maximizing the scientific return of these programs requires reliable theoretical models that incorporate nuclear inputs while interpretting astronomical signals.

Due to the complexity and nonlinearity of SNe and NS mergers, first principles modeling relies on multi-physics simulations in which general relativity, small-scale turbulence, magnetohydrodynamics, and neutrino and photon transport all play an important role. These simulations remain a work in progress: high-fidelity high-resolution simulations in 3D have are only now becoming possible due to increased computational resources and better numerical algorithms. As exascale computational facilities come online we anticipate a new era of predictive numerical science, where simulations allow theoretical ideas to be critically tested against experimental data.

Simulations of mergers and SNe naturally complement many of the research activities of the N3AS network. These simulations take as inputs the EoS of dense matter (MA3) and neutrino microphysics (MA1). Conversely, the output of simulations provides information about the detectability of any theoretically motivated change to the EoS and/or to the properties of neutrinos. Finally, the study of r-process nucleosynthesis requires a good understanding of the outflows produced by astrophysical events, of nuclear physics, of radiative processes (MA3), and of existing uncertainties at each of these modeling steps. Work on merger and SN simulations emphasizes the essential value of a N3AS network that naturally connects the diverse scientists and topics involved.

Supernova Simulations. How did the elements come into existence? What makes stars explode as SNe, novae, or x-ray bursts? What is the nature of NSs? What can neutrinos tell us about stars? These are the four fundamental open questions in nuclear astrophysics highlighted in the 2012 decadal survey in nuclear physics published by the National Academy of Sciences. Core-collapse SNe (CCSNe) are at the heart of all of these questions. They are the explosive deaths of massive stars; the furnaces in which many of the elements making up Earth and our bodies are synthesized, and the birth place of compact objects: NSs and BHs. CCSNe are the primary astrophysical target of multi-kiloton-scale neutrino detectors such as SuperK in Japan and DUNE in South Dakota.

Despite the overwhelming observational evidence that at least some massive stars do explode as CCSNe, *e.g.*, [229], and despite the intense theoretical work in the past 60 years, the mechanism powering CCSNe is still not fully understood [230]. Among many proposed explosion mechanisms, the most promising is the so-called delayed neutrino mechanism [231], which posits that neutrinos radiated by the protoneutron star reinvigorate the stalled shock generated at core bounce. Thanks to advances in simulation technology and increased computing power, 3D simulations with sophisticated neutrino transport have recently become possible and are starting to show successful explosions powered by the delayed neutrino mechanism for a variety of progenitors [232–234].

However, even when successful, current simulated CCSN explosions are marginal, meaning that small changes in the input physics or the initial model can turn an explosion into a dud [235], and the predicted explosion energies fall short of the canonical 10^{51} erg expected for a typical CCSN [236]. What is missing? Is this discrepancy arising because of finite resolution and limited time integration in the simulations, or is there a more fundamental problem with our understanding of the physics of the explosion? Connected to the central issue of the explosion mechanism are a number of important open questions. Which stars produce NSs and which stars produce BHs? Which elements are synthesized in the explosions and how did CCSNe affect the chemical evolution of our galaxy? How do the nuclear physics uncertainties translate into the spread of the simulation results? What is the impact of neutrino oscillations?

Historically, our understanding of CCSNe has progressed hand in hand with the availability of computing power and with our knowledge of neutrinos and weak interactions [241]. The N3AS collaboration includes experts in the physics of neutrinos (MA1), in their transport properties inside dense matter (MA3), and in the simulation of SNe. On the simulation side, at UC Berkeley the group of Kasen performs detailed photon-radiation transport calculations to interpret light curves and spectra of explosive transients [237]. The UC Berkeley group is also developing a new neutrino-radiation hydrodynamics code for CCSNe and post-merger simulations that will combine technology from FLASH [238] and Castro [239] with the new block-structured adaptive-mesh-refinement (AMR) infrastructure AMREx [240] as part of an effort funded by DoE through the ECP and SciDAC programs. At Penn State, Radice is an expert in the study of turbulence [242] and GW generation in CCSNe. For example, Radice has recently completed one of the first studies characterizing the GW signal from many full-3D simulations with sophisticated neutrino transport [243]. Radice is developing the capabilities of his open source code WhiskyTHC [244] to study the GW and neutrino signals from CCSN in 3D full-GR by coupling it with the multi-group M1 neutrino transport code ZelmaniM1 [245].

CCSN simulations are, however, only as good as their input physics, so efforts to exploit new computing resources are only meaningful if they are accompanied by corresponding improvements in the input physics that will be delivered by MA3. This is a key driver of N3AS. In addition, N3AS brings together under the same umbrella experts in the study of neutrino oscillations and SN simulators. Calculations run by MA5 simulators will generate a detailed map of the physical conditions attained in CCSNe, which will then be used by MA1 neutrino theorists to study the nature of oscillations occurring in such environments. In turn, once the anticipated effects of flavor oscillations have been clarified, they can be integrated back into the SN simulations (presumably through an approximate sub-grid procedure) to determine their influence on the SN explosion dynamics, nucleosynthesis, and neutrino signals. Clearly the field is ripe for joint collaborative efforts between these two otherwise weakly interacting communities.

The CCSN simulations will provide context to determine how the dense matter calculations discussed (MA3) and the general matter and neutrino coupling (MA3) affects the CCSN physics. By combining uncertainty-quantified simulations of the explosion engine, of the longer term shock propagation and breakout, and of the radiative transfer in the ejecta, we will be able to make detailed predictions for all the multimessenger signals expected from the next galactic CCSN: neutrinos, GWs, and light. Our simulations will also make quantitative predictions of the nucleosynthesis yield of SNe, as well as the mass, spin, and kick distribution of compact objects. These predictions will then be confronted with chemical abundance measurements of elements in stars from spectroscopic surveys, radio and x-ray observations of compact objects in our galaxy, and LIGO observations of compact binaries.

Merger Simulations: The first detection of GWs powered by a NS merger [112], GW170817, was a huge step forward for the study of compact objects and for nuclear astrophysics generally. The GW

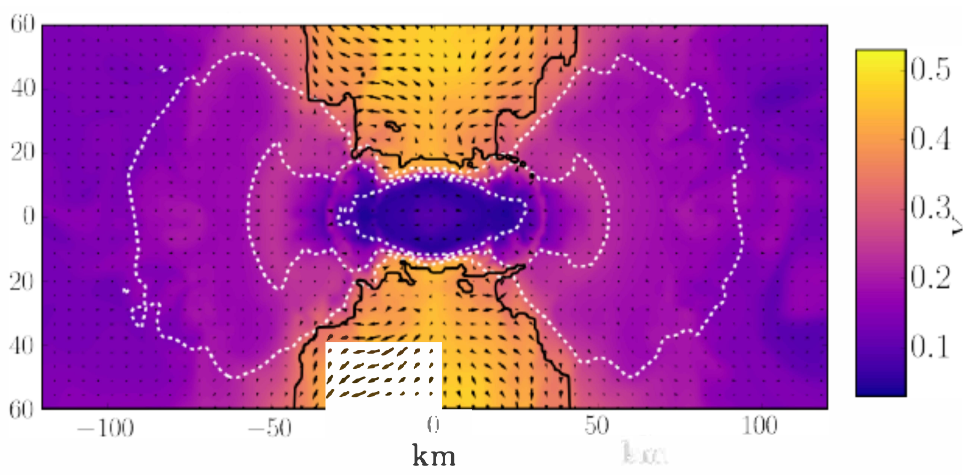

Figure 15: Electron fraction Y_e ($\sim$ fraction of protons in the matter) in the post-merger remnant of a NS-NS binary. We show a vertical slice through the remnant and surrounding torus. Dashed white lines show density contours with the neutron-rich remnant at the center. The black contour is the boundary between bound and unbound material. Outflows in the polar regions are unbound, and have been protonized by emission and absorption of neutrinos. Adapted from [256]

signal provided a new set of independent constraints on the EoS of dense neutron-rich matter [130] which were later complemented by bounds derived from the existence and magnitude of the EM signals [131, 135, 158]. Multi-band EM observations also broadly confirmed theoretical predictions for the existence of optical/infrared transients powered by the radioactive decay of r-process matter ejected during and after merger.

However, GW170817 also demonstrated that significant uncertainties in the modeling of EM signals powered by NS mergers remain important limiting factors in our ability to extract information from these events. Indeed, inferences made from EM signals remain model dependent, and model uncertainties are poorly constrained. These uncertainties can only be understood and reduced through studies combining nuclear physics, merger simulations, and radiation transport. Merger simulations, in particular, need to improve the accuracy and reliability of their predictions for the mass, velocity, composition, and geometry of matter outflows. While the outflows produced during BH-NS mergers are reasonably well understood ($\sim 10\%$ uncertainties in mass and velocity, known composition) [246], the mass ejected during double NS mergers is only known to $\sim 50\%$ [247] with even larger uncertainties in the outflows from post-merger accretion disks (mass known within a factor of $2-3$, with very uncertain composition) [249].

Merger simulations share a number of requirements with the CCSN simulations discussed in the previous section. Relativistic hydrodynamics is required to evolve merging NSs, while high-resolution simulations and/or subgrid models are needed to capture the crucial role played by magnetic fields and turbulence [250]. While neutrino transport is not as crucial to the dynamics as in SNe, it is still necessary to understand the cooling of the post-merger remnant and the composition of matter outflows (see Fig. 15). The latter is important for nuclear astrophysics, as it largely sets the outcome of the r-process and impacts the properties of kilonovae [84]; without information about the composition of the outflows, it is difficult to extract information about the

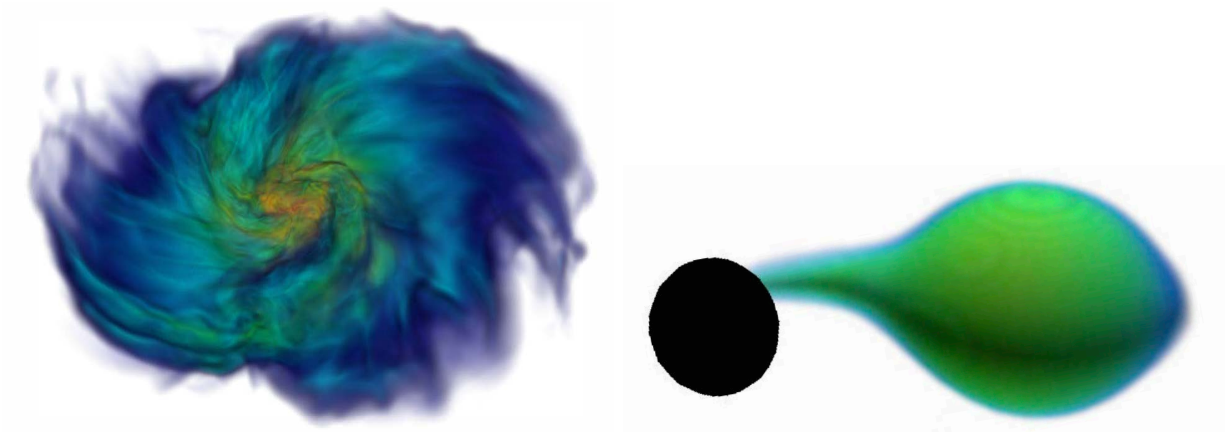

Figure 16: Simulations of a NS-NS merger with the WhiskyTHC code (left, showing the post-merger remnant surrounded by ejected material), and of a BH-NS binary with SPEC (right, showing the onset of mass accretion).

properties of merging binaries from kilonova observations. The EoS of dense matter also plays an important role in merger simulations: it affects the GW signal, the mass and properties of matter outflows, as well as the interaction rates of neutrinos with the NS and with merger outflows. Finally, simulations need to evolve Einstein's equations of general relativity to properly estimate the mass ejected and predict GW signals.

Within the proposed N3AS network, two numerical relativity groups use state of the art codes to simulate mergers (see Fig. 16). At UNH, Foucart is one of the lead developer of the MHD, neutrino, and nuclear physics modules in SPEC, a general relativistic radiation MHD code that evolves Einstein's equations using spectral methods, and solves the relativistic MHD equations using high-order shock-capturing finite volume methods. Approximate neutrino transport is included using a gray moment scheme. Planned developments to SPEC include the implementation of Monte-Carlo neutrino transport and of improved neutrino physics (e.g. pair annihilations), and explorations of out-of-NSE evolution of the ejecta, exotic equations of state, and non-ideal MHD. A next-generation code, Spectre, aims to use task-based parallelism and Discontinuous Galerkin methods to allow for improved scalability. At Penn State, Radice models mergers using WhiskyTHC, an open source state-of-the-art GR HD code that makes use of the Einstein Toolkit. The code implements several high-order high-resolution shock-capturing schemes and supports finite-temperature-tabulated nuclear EoS, with a simplified treatment of weak reactions and neutrinos. WhiskyTHC includes small-scale angular momentum transport due to magneto-turbulence in combination with sub-grid models calibrated with very high-resolution GRMHD simulations. Planned developments include coupling WhiskyTHC to the neutrino-radiation code ZelmaniM1 to improve the fidelity of the neutrino transport, and to add a resistive-MHD solver.

In addition, we will study the equally important evolution of post-merger remnants. Indeed, merger simulations only provide us with partial information about the properties of matter outflows in NS mergers. The post-merger evolution of the remnant may dominate the mass ejection through the outflow of $\sim (15-50)\%$ of the mass of the remnant accretion disk [248,249]. Simulations of the post-merger remnant are typically carried out with codes that do not evolve Einstein's equations, but can follow the evolution of the system for longer timescales ($\sim$ 10 seconds). Foucart, Kasen

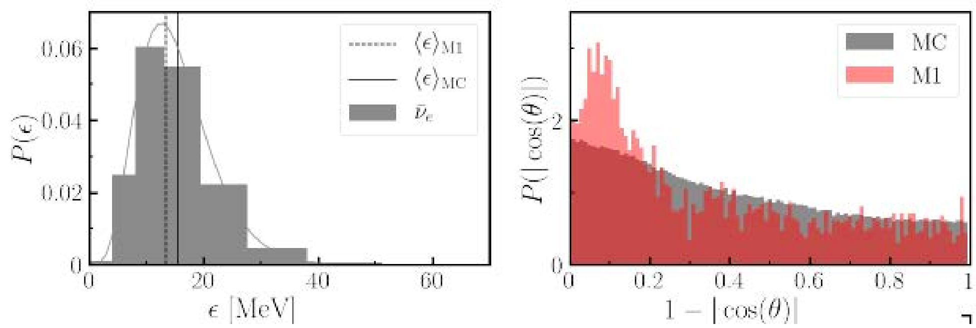

Figure 17: Comparison between an approximate neutrino transport scheme (two-moment formalism) and a Monte-Carlo solution to the radiation transport equation, from [255]. *Left*: Energy distribution of electron antineutrinos in the Monte-Carlo evolution, and average energy in the two-moment schemes (dashed line) and Monte-Carlo evolution (solid line). *Right*: Angular distribution of the neutrinos in the moment scheme (M1, red) and in the Monte-Carlo scheme (MC, grey). θ is the angle with the rotation axis of the system. While the average energy is reasonably accurate in the two-moment scheme, the angular distribution of the neutrinos is significantly biased. Similar results are found for other neutrino species.

and Quataert are involved in studies of the post-merger remnant, through collaborations with the developers of such codes (Tchekhovskoy, Fernandez). For example, we recently demonstrated the large impact of different post-merger magnetic field structures on the amount of matter ejected after merger, and on the properties of relativistic jets powered by merger remnants [249]. Foucart is also contributing to the implementation of radiation transport methods in the post-merger code H-AMR. Planned improvements in our post-merger studies include the use of improved initial conditions imported from merger simulations, and of radiation transport in post-merger simulations. So far, only a short simulation of a post-merger remnant has been completed with advanced neutrino transport methods [253], while longer simulations rely on leakage schemes that capture neutrino cooling but not the impact of neutrinos on the composition of the outflows [248, 249].

One of our main objectives is to reduce errors in the modeling of merger outflows. Given the computational expense of fully capturing turbulence and magnetic field amplification, using subgrid models for angular momemtum transport as pioneered by Radice [251] (see also [252] for an alternative model) and also implemented in SPEC represents our best hope to reduce modeling errors in the outflow properties. Improved neutrino transport (e.g. as developed by Foucart [254]) and neutrino microphysics are also crucial to quantify the accuracy of approximate transport methods in predicting the outflow composition and the contribution of neutrino pair annihilation to powering relativistic jets. Indeed, a major drawback of most current neutrino transport methods is that they do not converge to a solution of the true Boltzmann equation, and thus have errors that can only be quantified by detailed comparisons with a full transport calculation (e.g. [255], Fig. 17).

The N3AS network can greatly enhance the ability of the UNH and Penn State groups to generate results of use to the nuclear astrophysics community. First, we will perform simulations of identical binary systems with two completely different numerical codes, implementing different microphysics. This will allow us to more rigorously estimate systematic errors in simulations, and increase confidence in our results. Second, many of the planned improvements will benefit from collaborations with scientists specializing in neutrino physics (MA1), nucleosynthesis (MA2), and in the study of dense matter (MA3). In particular, neutrino studies performed in MA1 inform us on important neutrino process whose implementation should be prioritized in simulations, while nucleosynthesis studies performed in MA2 inform us on the source of errors that most affect the outcome of the r-process and kilonovae. Simulations of NS mergers are rapidly becoming more complex and multidisciplinary, and the ability to rely on a network of scientists with the necessary expertise in each of these topics allows for more focused and efficient choices in our research. Finally, simulations performed at UNH and Penn State are already used to calibrate waveform models including finite-size effects [257, 258], that can then serve to extract EoS information from GW observations. The ability to interface with the program of MA3, and in particular to streamline implementation of new/particularly interesting EoS's in simulations and to test their impact on observables, will make it easier to asses the importance and detectability of any proposed modification to the EoS of dense matter.

Connecting Simulations to Observations: The matter ejected in mergers and SNe gives rise to thermal EM emission over the days and weeks that follow. For mergers, the quasi-isotropic optical/infrared transient (or kilonova) is powered by the radioactive decay of newly synthesized r-process isotopes. By modeling the light curves and spectra of these transients we can constrain the total mass, kinetic energy, composition and geometrical distribution of ejected matter, providing valuable insight into the physics of the event and its contribution to cosmic nucleosynthesis.

Radiative transfer calculations provide the link between multi-physics simulations and astronomical data. N3AS members will model SN and merger light curves and spectra using modern multi-dimensional time-dependent Monte Carlo transport calculations that couple radiation to detailed atomic microphysics [237]. The N3AS network will establish a simulation pipeline whereby the output of dynamical explosion simulations (MA5) (which incorporate the microphysics of MA1 and MA3) are fed into extensive nuclear reaction network codes (MA2) to determine detailed yields. These results will then be post-processed by radiative transport codes to synthesize predicted light curves and spectra and compare to astronomical data. These end-to-end simulations provide the means to validate/falsify theoretical ideas, physically interpret multi-messenger data, and make predictions that guide the planning of future experimental programs.

Members of N3AS network are involved in and will interact closely with observational programs aimed at acquiring data on SNe and mergers. UC Berkeley has been a historical center in time domain astronomy; Co-PI Kasen is currently PI of an ongoing Keck telescope program joint between three UC campuses that has been allocated multiple target of opportunity to observe potential EM counterparts to LIGO/Virgo sources. Kasen is also a collaborator on multiple observational programs for multi-messenger astrophysics using the Las Cumbres Observatory, the Swope/Lick telescopes, and the Gemini telescope, and is also a member of the proposed Nimble mission, a future space-based facility that would provide multi-wavelength coverage for transients. The close coupling between theory, simulation and observation will ensure that N3AS plays a major role in enabling the future of multi-messenger nuclear astrophysics.

MA6: International Partnerships and the Joint Institutes: [Haxton, Kasen, Quataert, Seljak; Collaborators Hatsuda, Nagataki, Perlmutter, Stompor]

Overview: Experimental astrophysics and cosmology has set high standards for international collaboration: the global character of the field has been shaped by the size of its facilities, the openness of the community and funding agencies to partnerships, the need for sharing data sets often obtained from a variety of instruments, and the importance of exploiting unique geographies for ground-based observatories and detectors in ice, water, or deep underground. The Auger Observatory, ALMA, the Dark Energy Survey, and DUNE are examples of projects conceived as international efforts. The Supernova Neutrino Early Warning System and the joint observations agreement between LIGO, Virgo, and KAGRA are examples of international networks that, through rapid data sharing, enhance overall detection capabilities. Drivers for the globalization of astrophysics and cosmology include both the glowing complexity and scale of the detectors and the complexity of the massive data sets these detectors yield, requiring analysis teams and meticulous crosschecks to guard against unrecognized systematics: this impacts all aspects of the field, including theory and modeling. This international connectivity not only characterizes the field's science, but has become important aspect in the training and mentoring of young people: early exposure to international science can help young researchers build networks that will persist throughout their careers.

N3AS has formed partnerships with three strong international partners that will enhance and extend our science, significantly increase the international visibility of N3AS, leverage the N3AS NSF investment, advance N3AS diversity efforts, and open up new funding possibilities. The partners are

1. *The Centre Pierre Binétruy*, a visitor center established January 1, 2020, at Berkeley by IN2P3 of CNRS (Centre National de la Recherche Scientifique) as a Unité Mixte Internationale. The science focus is dark energy, dark matter, neutrinos, and the analysis of GW observations.
2. *The RIKEN-Berkeley Center (Astrophysics)*, which extends an exciting partnership with RIKEN-Berkeley to areas of astrophysics overlapping N3AS, with particular emphasis on the numerical modeling of SNe, mergers, and associated explosive astrophysics. The RIKEN-Berkeley Center (Astrophysics) is a joint effort of RIKEN's iTHEMS (Interdisciplinary Theoretical and Mathematical Sciences Program) and ABBL (Astrophysical Big Bang Laboratory).
3. Innovative Training Network (ITN) *Elusives* and the Research and Innovation Staff Exchange (RISE) program *InvisiblesPlus*, coordinated Horizon2020 programs of the EU. These programs share the research and broader-impact goals of N3AS, and have the potential, through partnerships, to advance N3AS recruitment and diversity goals.

Center Pierre Binétruy: Pierre Binétruy was an eminent French cosmologist who did his PhD training under Mary K. Gaillard, just prior to her move from CERN to Berkeley. Binétruy later spent time at Berkeley as a postdoc and as a Miller Visiting Professor. His collaborations with Berkeley on topics in cosmology, gravity, and data analysis in astrophysics continued throughout his career. In 2005 Binétruy founded IN2P3's Astroparticle and Cosmology (APC) Laboratory, serving as its Director for the first eight years. Through his advocacy APC developed partnerships with a global network of equivalent centers of excellence, including KIPAC at SLAC, the University of Chicago, the Perimeter Institute, and KIT/Helmholtz at Karlsruhe. He advocated for CNRS (The French Center for Scientific Research) involvement in GW research, leading to CNRS involvement in LISA Pathfinder and LISA, and with Berkeley's George Smoot, cofounded the Paris Center for Cosmological Physics. In 2017 Binétruy and other French astrophysicists had initiated discussions with Berkeley about the possibility of creating a Unité Mixte Internationale (UMI) – an international joint research laboratory – that would host French astrophysicists at Berkeley, strengthening collaborations with US partners, jointly sponsoring workshops, and conducting student exchanges.

After Binétruy's untimely death that year, these discussions continued among Pierre's Paris colleagues and members of the Berkeley Center for Cosmological Physics (BCCP), N3AS-Hub, and the Berkeley Physics Department, focused on the creation of the Centre Pierre Benétruy. An MOU between Berkeley and CNRS was completed in 2019, and the UMI started January 1, 2020, with the arrival of the first two students. International interest in the UMI is significant: on January 14 Philippe Etienne, the Ambassador of France to the U.S., accompanied by a delegation of CNRS and embassy officials, came to Berkeley to participate in an afternoon scientific symposium to celebrate the opening of the UMI.

The science focus of the UMI aligns well with N3AS:

1. Clarifying the nature and cosmological roles of dark energy, DM, and neutrinos and other relativistic particles;
2. Understanding the origin of primordial fluctuations and the role they played in the evolution of the universe's present large-scale structure;
3. Exploiting GWs to improve our understanding of astrophysical environments, fundamental physics, and high-field gravity; and
4. Developing the applications of data science to multi-messenger astrophysics.

Centre activities will focus on organizing meetings and workshops oriented toward international activities in astrophysics; providing support and guidance for visiting researchers from France; and conducting fundraising activities in France, Europe, and the US. An important goal is to encourage collaborations between France, the U.S., and other countries that will advance next-generation scientific challenges in cosmology and astrophysics. The co-directors of the Centre are Saul Perlmutter, Berkeley, and Radek Stompor, CNRS.

The possibility of a mutually beneficial partnership with N3AS-PFC led to the Joint Institutes proposal below, and also influenced the proposed science focus of the Centre, especially in the area of GWs and their implications for merger models, nucleosynthesis, and the EoS. Work in this area will build on the data analysis expertise of the IN2P3 laboratories developed in the context of the operating VIRGO project, and in preparations and design of the future, Europe-led satellite mission LISA. Like N3AS-PFC, the UMI sees an important role in interpreting GW signals as part of a more general multi-messenger effort. E. Chassande-Mottin and E. Porter of APC play key roles in the analysis of the Virgo and combined LIGO/Virgo data sets, while S. Babak and A. Petiteau are on the forefront of preparations for the LISA data analysis pipeline. N3AS could support these efforts by relating GW signals to the dynamics of mergers and their ejecta, making the connections to nucleosynthesis. There are potentially interesting synergies with other topics from the science portfolio of the UMI, in particular with neutrino studies in the context of understanding the NS collapses, and with CMB data analysis and data science. In parallel with these theory and data science connections to N3AS, the UMI will be engaged with BCCP experimentalists on CMB and other detector developments, collaborating on selected hardware problems. A significant benefit to N3AS stemming from these multiple UMI connections will be in fostering closer connections between theory and experiment/observation, including international opportunities.

The RIKEN-Berkeley Center (Astrophysics): RIKEN, Japan's largest comprehensive research institute, has long led Japanese efforts to promote global research engagement, having established to date more than 300 research MOUs with international partners, investing a significant fraction of its annual budget of nearly $0.8B overseas. Recently RIKEN has made new commitments to strengthen its ties to the west coast of the US and to Europe, establishing US West Coast Collaboration Office at Lawrence Berkeley Laboratory and a Europe Office in Brussels. The former is based on an MOU between LBL, the Berkeley Physics Department, and RIKEN Executive Director Motoko Kotani, completed in late 2017, and on a RIKEN Collaborative Research Agreement between Berkeley Physics and RIKEN's international research program iTHEMS – the Interdisciplinary Theoretical and Mathematical Sciences Program – and its Director, Tetsuo Hatsuda.

RIKEN-Berkeley fellows engaged in areas like lattice QCD are already resident at Berkeley under this agreement, and the 2019 RIKEN-Berkeley workshop on Quantum Information Science (which RIKEN Executive Director Kotani attended) was a significant international success [259]. With the creation of N3AS, discussions began with iTHEMS about astrophysics becoming the next focus of the RIKEN-Berkeley collaboration. Chief Scientist of RIKEN's Astrophysical Big Bang Laboratory and Deputy iTHEMS Program Director Shigehiro Nagataki, with several of his colleagues and a contingent of Japanese students, visited Berkeley last August, to see the campus and discuss collaborative possibilities. ABBL is a theory group focused on modeling explosive events like SNe and associated transients, such as gamma-ray bursts.

This was the origin of the proposal to create RIKEN-Berkeley Center (Astrophysics) as a joint effort of iTHEMS and ABBL, focused on problems such as:

1. state-of-the-art multi-dimensional modeling of core-collapse and thermonuclear SNe;
2. transient events, including the mechanisms responsible for short and long gamma ray bursts;
3. explosive nucleosynthesis and the r-process;
4. NS structure and cooling; and
5. neutrino propagation and transport at high density.

The alignment with N3AS interests is excellent. In addition, N3AS leadership of the Exascale ExaStar Project [260] parallels RIKEN's development of and preparation for Fugaku, the near-exascale successor to the K-computer that is expected to be completed in 2021. One of 9 priority applications of Fugaku is fundamental physics and the evolution of the universe. We anticipate opportunities for sharing code-development tasks and for cross-validation.

Discussions are in progress for ABBL and iTHEMS to exchange an MOU with Institute for Cosmic Ray Research (ICRR) to provide theory support for laboratory projects like Super- and Hyper-Kamiokande and KAGRA. Through the Joint Institute proposal described below, this relationship will help strengthen connections between N3AS and highly relevant experimental efforts in Japan.

N3AS-PFC and the Joint Institutes: One of the limiting aspects of N3AS-Hub was the lack of a true "center" that could serve as a focal point for both the collaboration and the broader community N3AS wants to engage. As described in the introduction to the MAs, the confluence of the PFC call, the Center Pierre Binétruy, and the RIKEN-Berkeley Center presents an opportunity to create something rather special – Joint Institutes cooperatively work on topics linking the large-scale structure of the universe to the fundamental physics of the micro-world, advancing the theory and computational tools that will allow us to interpret the multi-messenger signals from current and next-generation instruments. The coupling of the three institutions will create a center with a significant international presence and connections to some of the world's most significant experimental facilities.

The RIKEN-Berkeley Center supports the salaries of researchers at the senior postdoc level and their research expenses, including funding for activities like joint workshops. IN2P3 supports the salaries of its visitors, and will utilize grant opportunities to generate research and workshop funding (see below). N3AS would be the host institute, staffed with a full-time administrator and a media/outreach officer. Approval of this proposal will trigger a university remodeling of a 1600 sf area for the joint institutes, immediately adjacent two conference rooms, a seminar room, and an open interaction area – Cosmology Commons (see Sec. f). These conference and interaction areas include state-of-the-art video conferencing tools. Elsewhere we describe the importance of this physical space to the collaborative activities of N3AS-PFC, opening up opportunities that were not available to N3AS-Hub, in regard to both collaboration activities and community outreach. Here we focus its role in supporting the joint institutes. In the case of the UMI, N3AS would host UMI theory visitors, while experimentalists would be hosted by BCCP and associated experimental groups. RIKEN visitors will be theorists. The physical space described in Sec f will accommodate up to four long-term UMI or RIKEN visitors, up to four N3AS postdocs, while providing space for 10-12 shorter-term visitors. Together with the local N3AS members, this will create a critical mass of researchers. N3AS's administrator will support UMI and RIKEN visitors, include travel, grant management, purchasing, and orientation of new visitors (appointments, ID cards, computing access, etc.).

While UMI and RIKEN visitors will come at no salary cost, N3AS-PFC will provide modest local expenses. Berkeley is an expensive area, and visiting postdocs and other non-faculty personnel have minimum salary requirements imposed by a union agreement. N3AS per diem support provides a mechanism to cover differentials that may exist between the home salaries of young researchers and Berkeley postdoctoral scales. Postdocs-paid-by-others are included in the Berkeley benefit pool, and thus have this coverage in addition to any provided through their home institutions.

This proximity of the joint institute members will stimulate interactions, generate opportunities for shared seminars and jointly organized workshops, while also creating an astrophysics theory center within Berkeley Physics Department with significant international visibility. The N3AS area is adjacent to the Physics Department's dark matter and neutrino experiments, and is connected by a skybridge to BCCP and to theory activities in New Campbell Hall, Berkeley's astronomy building.

The N3AS-Hub was successful in seeking outside funding, through the Heising-Simons Foundation, to supplement NSF funding of the Hub. The Foundation provides 20% of Hub funding, which proved essential to the support of the full N3AS program originally envisioned. Berkeley Development has identified a second foundation that has a history of supporting international endeavors similar to the Joint Institutes. There will be an opportunity to apply for such support in summer 2020.

Partnership possibilities with Elusives and InvisiblesPlus: Elusives and *InvisiblesPlus* were established as coordinated European Union Horizon2020 programs, in the same year that N3AS-Hub was approved by the NSF. The three efforts have similar motivations, improving the coordination among fragmented theory efforts in multi-messenger astrophysics, while growing the field through student and postdoctoral recruitment and mentoring. Research interests include neutrinos, DM, and particle-antiparticle symmetry. The INT project *Elusives* and the RISE project *InvisiblesPlus* are taking advantage of an important European asset, a strong contingent of senior women working in the field. Over 50% of the scientists leading the project are women, and one of the recruitment goals is gender balance. The projects have existing connections to CNRS (a beneficiary node) and to Berkeley/LBL and the University of Washington (partners).

N3AS would like to encourage interactions between Network postdocs and associated students, and their counterparts in *Elusives* and *InvisiblesPlus*, in part to encourage networking. As the ITN focus is on young researchers – advanced graduate students and beginning postdoctoral researchers – N3AS contacts with *Elusives* and *InvisiblesPlus* researchers could help N3AS postdoctoral recruiting and advance our diversity goals. With the encouragement of senior leaders of these programs, we intend to invite several of their young researchers to participate in the N3AS-Hub summer school that will be held in August. *Elusives* was recently approved for a five-year extension, becoming *HIDDeN*. We anticipate the connections we establish in our first summer school will lead to continuing exchanges, if N3AS-PFC is approved.

MA7: Community Building

An important goal of N3AS is to strengthen nuclear physics at its interface with astrophysics and particle physics: as described in MA1 - MA5, many issues critical to multi-messenger astrophysics involve complex many-body systems – neutrino Fermi seas, nuclear matter at extreme densities and isospins, etc. – or require state-of-the-art simulation. Much of the expertise needed for attacking these problems resides in nuclear astrophysics. Our group organized N3AS because we were concerned that the nuclear astrophysics community is too small – funding tends to focus on the major facilities – and dispersed over many small groups and individuals. This is especially true in neutrinos, DM, and other "fundamental physics" sectors of nuclear astrophysics. The small-group, dispersed nature of nuclear astrophysics creates obstacles for young researchers, who have difficulty acquiring the scientific breathe needed to be successful in the multi-messenger era. The N3AS organizers also felt the field needed a focal point – a center that can help attract really strong young people into nuclear astrophysics, from the field's boundaries with astrophysics and particle physics. Berkeley has been very effective in this role during N3AS-Hub, helping our institutions attract excellent postdocs. Such a center can address other needs, providing a venue for workshops and frequent collaboration meetings that will building bridges to astrophysics and particle physics, to experimentalists and observers, and to other nuclear physicists wanting to take part in N3AS activities. MA6 described how we will created a physical center – the Joint Institutes – with a critical mass of long-term senior participants and postdocs, and with the needed breadth. This MA describes the community aspects of of N3AS-PFC and the center, including the postdoctoral and student programs, the N3AS summer school, and the plans for workshops, collaboration meetings.

N3AS-PFC Postdoctoral Training and Mentoring: We have been gratified by the speed with which the N3AS-Hub Fellows have engaged with the physics described in MAs 1-5, helping to drive much our science in areas like neutrino propagation, the extraction of EoS constraints from kilonova properties, and core-collapse SNe. We also feel that we have demonstrated the soundness of the N3AS's unconventional plan for "growing" the nuclear astrophysics/fundamental symmetries community: Fellows hired by the Network, hosted by a site, with the freedom and travel resources to collaborate across the Hub, gaining broad exposure to the multi-messenger astrophysics field. They have network with each other, collaborating on a variety of topics, and made good use of the access N3AS provides to a variety of senior leaders. Things have also work well administratively. The three searches N3AS conducted yielded large postdoctoral candidate pools, with N3AS competing well for the very best of these. The hiring through Berkeley has simplified the administration, guaranteed uniform treatment, and lowered costs.

The timing of the PFC call is ideal for continuing, allowing a smooth transition from the Hub to PFC: Approval of N3AS-PFC by mid-2020 would permit us to search for Fellows in fall 2020, with appointment beginning in fall 2021. The PFC plan assumes that four Fellows would be hired each year, a rate we demonstrated to work well under N3AS-Hub. The Hub → PFC transition plan is shown in Fig. 18. The Fellow level rebuilds for a low of five in 2021/22. If the PFC were then renewed after five years, the pattern of four hires per year and a steady effort of 12 postdocs could be continued. This effort, over time, would create a significant presence for nuclear physics in multi-messenger astrophysics, benefitting the entire field. To put this plan in context, the N3AS Fellows program would then be about 15% that of the NASA Fellows program (Hubble/Einstein/Sagan).

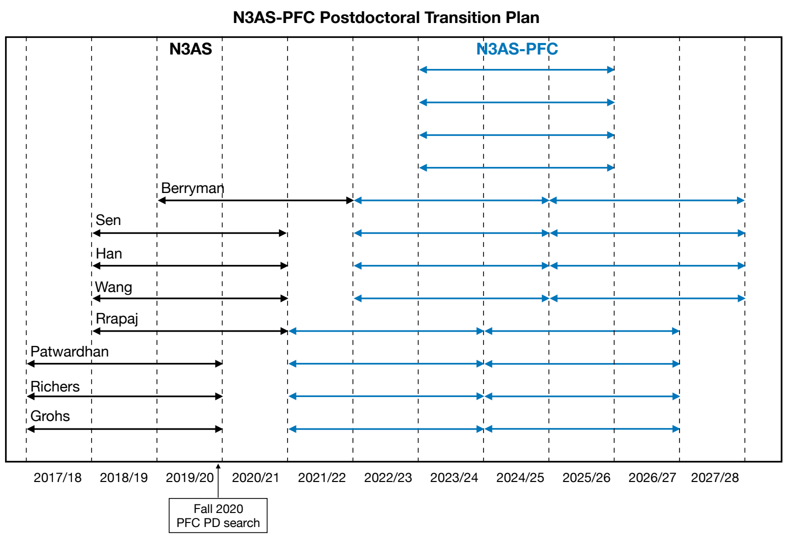

Figure 18: The plan for the Fellows program in the transition from N3AS-Hub to N3AS-PFC. The plan is based on a steady state of four Fellows appointed each year. The timing of the PFC would allow N3AS to be rebuilt from a minimum of five Fellows in 2021/22. The pattern could be continued in steady state, were the PFC renewed after five years.

The model we adopted in N3AS-Hub of three centers and eight sites – postdocs are hosted by a site for two years then move to one of three centers (Berkeley, San Diego, Seattle) for a third year – worked well in most respects. As we assist with moving costs and as appointments are continuous through Berkeley, the postdocs did not find the extra move a burden. The Fellows have benefitted from the additional networking this plan allows, and from the freedom to choose the third-year site, which for second-term Fellows can be helpful in identifying the optimal "launching pad" for a faculty career. The one flaw we identified in the plan was that our assumption that the Fellows would naturally distribute themselves among the three centers, due to physics preferences, was not correct. Most have wanted to come to Berkeley.

The N3AS-PFC Fellows plan is built around a single center (Berkeley) and 12 sites, and gives the Fellows the freedom to choose any site or Center for the third year. This plan is now workable because of Berkeley's commitment to build a physical center for N3AS and the Joint Institutes (see Sec f): there will be space and a critical mass of senior mentors to accommodate any fraction of the Fellows at Berkeley. This new plan also gives the Fellows the freedom to choose their third-year location without constraints, which we think is appropriate.

Graduate Students: A Data Science Team: The support of graduate students working with individual N3AS-Hub faculty is provided through individual PI grants. This policy will be continued under N3AS-PFC for students working closely with individuals. However, we will experiment with one graduate student team effort – two students selected from our group – on data science aspects of multi-messenger astrophysics, with an initial emphasis on GWs from NS mergers. These students would develop analysis tools for connecting new observations to N3AS modeling, working closely with selected faculty expert in NSs and data science, such as Lattimer and Seljak.

GW observations of NS mergers encode the effects of finite-size and possible mass ejection, which impact r-process nucleosynthesis and properties of the kilonova. NS deformation associated with finite size leads to additional energy loss and enhancement of the GW signal. The mass-averaged (or binary) deformability of the NSs, which varies as the sixth power of the NS radii, can be extracted from GW signals. In the case of a BH-NS merger, as only one object is deformable, the binary deformability is determined by the lone NS.

In the two cases for which LIGO/Virgo data has been released, GW170817 and GW190425, the signals were interpreted as binary NS mergers. The initial GW170817 analysis assumed the deformabilities of the NSs were uncorrelated – though there are physical arguments for relaxing this assumption. In the case of GW190425, the signal could also be plausibly interpreted as a BH-NS merger. A student team that develops its own analysis tools would be able to explore these and other alternatives, while also making connections to relevant N3AS work, such as the EoS or the mass ejection important to nucleosynthesis. These tools would allow N3AS to make multi-messenger connections between LIGO/Virgo/KAGRA data and, for example, known NS properties, to draw more quantitative conclusions about the underlying EoS.

More specifically, in the case of GW170817, constraints derived on the EoS from the duration and other properties of the kilonova imply a neutron star maximum mass of about 2.2-2.3 $M_\odot$ [131], similar to the bound of $\sim 2M_\odot$ established from pulsar timing measurements. Effects not yet adequately considered in the kilonova analysis include the effects of rotation and finite temperature. As future GW measurements probe higher frequencies and thus shorter separations, the data can be mined for addition physics, e.g., the point of tidal disruption and the gravitational oscillation modes of the coalescing remnant.

N3AS-PFC will give the students an opportunity to interact with the CNRS data analysis team for Virgo, through ABBL with KAGRA physicists, and hopefully also with LIGO. Analyses could be performed with priors and EoS assumptions motivated by other N3AS studies, including N3AS simulations of the merger and subsequent kilonova. The effects of fast rotation could be explored.

Workshops, Collaboration Meetings, and Community Participation: As described in Sec c, we have been successful in working with KITP and INT on certain types of workshops – ones that can be planned at least six months to a year in advance, where the interests align with those of the host. Under N3AS-PFC we will continue to utilize the venues the community has created for such meetings. But we have, in general, been held back by the lack of opportunities for more spontaneous and more focused collaboration meetings involving subsets of N3AS membership (and others). (The one exception to this came from the accidental grouping of N3AS members interested in neutrinos in the Midwest: they found it feasible to meet regularly at Fermilab, traveling by car. These members found that these working-group opportunities were extremely valuable.)

We would have the resources under N3AS-PFC to do better.

1. N3AS-PFC would provide opportunities for working-group meetings several times per year in each of the areas covered by MA1 - MA5. We envision meetings lasting two or at most three days, as many of the senior N3AS members have teaching duties. N3AS-PFC would have an administrative assistant who could help with local travel arrangements and space to accommodate such gatherings (if no other venue is preferable), lowering the organization barriers that have inhibited such gatherings under N3AS-Hub.
2. N3AS-PFC will conduct workshops in partnership with the Center Pierre Binétruy and the

RIKEN Berkeley Center (Astrophysics). These workshops would be an opportunity to engage experimentalists and observers, given that our partners have connections to Virgo, LISA, and Kamiokande. We would also continue to sponsor occasional community-focused workshops like those N3AS-Hub has organized.

3. Each fall, after the new contingent of N3AS Fellows has arrived, we will conduct a short symposium to introduce the Fellows to each other and to their mutual physics interests. This will generate early interactions among the Fellows and reinforce the network aspects of N3AS.

N3AS activities are always open: we will continue to welcome others who want to participate. The workshops we have held under N3AS-Hub were advertised and nonN3AS members and N3AS members were supported, up to limits imposed by workshop budgets. In each of the N3AS-meetings, we have invited other young researchers to participate, supporting their travel. In the working-group meeting described above, nonN3AS members involved in research collaborations would be invited and treated as N3AS members. The facilities we create at Berkeley will be available to others, if there is space available.

N3AS-sponsored Annual Summer School: In Sec. c.6 we described the important role N3AS members played in creating summer schools to help educate and motivate young researchers, while also providing opportunities for networking with others sharing common research interests.

For some time several members of N3AS have been interested in establishing an annual workshop in multi-messenger astrophysics, that would attract theorists, experimentalists, and observers from relevant areas of nuclear, particle, and astrophysics. The need is clear: the field is rapidly growing and multidisciplinary, yet (in contrast to Europe) the US lacks a regularly held school. A prototype of the type of school we propose – focused on advanced graduate students and beginning postdoctoral researchers and emphasizing multi-messenger connections – is that two of us (Haxton, Fuller) organized in Asilomar, prior to the TAUP2013 meeting. The webpage describing the program and including the archived lecture series is available here.

As noted earlier, N3AS-Hub, with some additional support from the NSF, will host a one-time summer school on the campus of UC Santa Cruz, Aug. 16-23. We intend to involve N3AS faculty as lecturers and N3AS postdocs as discussion leaders and assistants. In addition to the contribution the school will make in student training, broadening student perspectives on the field, and creating a sense of community among young researchers, the school will help us advertise N3AS to our target community, young people who might later apply to join N3AS as Fellows. We mentioned, in connection with *Elusives* and *InvisiblesPlus*, the role the school could play in connecting young researchers from the US and Europe, and the potential benefits.

If the N3AS-PFC proposal is approved, we will continue this school annually, rotating among locations distributed over the US, and sharing the responsibility for the organization among N3AS members. The N3AS-PFC outreach officer would help us with the web site preparation, administrative support, etc. This proposal requests participant and lecturer costs for five such schools. If N3AS-PFC were then discontinued at some point in the future, we would work to set up a framework for continuing the school, following the model of the National Nuclear Physics Summer School.

3e. Education, HR, Diversity, and Outreach[N3AS; Collaborator Colette Patt]

Many of the broader impacts of N3AS-PFC are discussed in MA6 and MA7, including community building; strengthening the international connections of nuclear astrophysics; creating a novel Fellows program to mentor and enrich the training of young researchers; creation of an annual summer school in multi-messenger astrophysics to serve advanced graduate students and beginning postdoctoral researchers; and training graduate students in the use of data science in astrophysics. Here we describe a significant additional outreach effort that N3AS will undertake because of its relevance to the public research universities within N3AS.

The Challenge: In 2016 a series of reports was issued by the Lincoln Project of the American Academy of Arts and Sciences [261]. The project was named in recognition of the Morrill act of 1862, which laid the groundwork for US land-grant colleges. The report pointed out that the 2009 recession and associated cuts to public research education were unusual – unlike previous recessions, as the country recovered economically, university funding was not restored. The Lincoln Project's first recommendation addressed the need to identify new cost efficiencies and identify new revenue streams to help sustain the public research universities.

These changes have created new barriers to higher education in the form of tuition increases and reduced financial aid, undercutting education as one of the most effective tools for advancing social and economic mobility – an issue that arguably lies at the heart of increasing U.S. economic stratification and associated political polarization. Universities have looked for solutions that would allow them to keep faith with their public missions, despite changing economics.

While all of the public research universities in N3AS are facing the same challenges, the UC campuses, Berkeley and San Diego, may be moving the most rapidly to find solutions. UC has consistently tried to fulfill its public mission: in the annual College Access Index [262] compiled by the New York Times, six of the top ten places in 2019 are held by UC campuses. With rising tuition threatening its access goals, UC turned to community college (CC) partnerships. UC's Transfer Pathways [263] program, established in 2015, helps highly motivated and highly performing students from California's CC system enter UC as rising juniors. That system – 2.1 million students attending 115 colleges – is the largest coordinated program in US higher education. Transfer Pathways was motivated by studies showing that students who transfer to selective, four-year colleges and universities are more likely to graduate than students who enroll directly from high school. A report by the Jack Kent Cooke Foundation [264] attributes the success rate to both the intrinsic talent of these students and their greater determination to finish, given their life experiences. The Transfer Pathways program was designed to streamline the transfer process via attention to articulation and UC breadth requirements, so that bright and motivated community college students can perform at UC on a par with four-year students, completing their bachelor's degrees after two years of additional training.

This program could also improve the diversity of Physics and other STEM disciplines: Many of the students are nontraditional, often older and financially self-supporting, and more likely to come from low-income families and underrepresented communities: 56% of Native American undergraduates and 52% of Hispanic undergraduates are enrolled in community college, according to the National Center of Education Statistics [265]. Many of these students are keenly interest in STEM, which can be a doorway to economic well-being for the students and their families. It is likely that a first-generation student who achieves a STEM degree will, before age 30, be the highest wage earner in his/her extended family. This is one reason that Physics and other STEM majors are popular with CC transfer students. STEM fields comprise over half of the majors in the program [263]. At Berkeley one-third of entering Physics students (~ 40 annually) are transfers, compared to 21% system-wide; 94% of the transfer students come from CCs.

STEM transfer student are looking to the public research universities to continue their education. Although 41% of undergraduates begin in CC, they represent only 5% of the students enrolled in the nation's top 100 most selective institutions – a list dominated by privates. Princeton University first admitted transfer students in 2018 – a class of 13. In 2019 Harvard accepted 15 transfers (CC or otherwise) from approximately 1600 applications, a yield below 1%.

If one takes the long view, the transfer of a CC student could be the first step in a 6-8 year process creating a more diverse postdoctoral candidate pool for astrophysics in general, and for N3AS postdoctoral hiring, in particular: increasing diversity at the postdoctoral level – the stepping stone to a faculty appointment – is viewed as a difficult challenge [266].

The same economics that is driving the growth of the transfer-student population presents challenges for programs like UC Transfer Pathways: adequate support programs for the transfers are generally lacking. Physics is particularly challenging for transfers because student knowledge is built on coordinated courses, beginning with year one. New transfers can find that the courses they took in CC do not in fact meet articulation requirements. Compounding the academic challenges, transfer students lack the support structures that four-year students have already established: they join a class that has been together for two years, where members are familiar with the campus, department procedures, and each other. Study groups are already established. A transfer student may be the only new student from his CC. Transfer students also face special challenges in finding undergraduate research opportunities, without which the step to graduate school becomes higher: they compete with four-year students who also want positions, and who know the faculty and may have friends already in the research labs they hope to join.

UC has found that Physics transfer student match or exceed four-year students in getting to the B.A., but only about one third of them persist in their initially preferred Physics major. They move to a less challenging field. An important talent pipeline that in principle could help the field become more inclusive, is in fact broken.

N3AS Role: Individual STEM departments are scrambling to help the transfer students, providing transfer student orientation courses, peer and faculty mentoring, and online tutorials in areas of common weakness, such as mathematical physics – to the extent that support can be found [267]. In discussions with university professionals expert in outreach and diversity programs, transfer student issues were identified as an opportunity for N3AS:

1. Astrophysics can be communicated to undergraduates – the problems are physical and have a "wow" factor.
2. The public-university character of N3AS give the transfer student challenge relevance.
3. There is a substantial literature on efforts to improve performance and persistence outcomes for STEM undergraduates, pointing to the importance of addressing both the academic and social-psychological needs of students [268].
4. Our professional experience as researchers and mentors is well matched to the needs of transfer students: this is not an outreach activity that we would need to outsource to an outreach officer. The program we envision would in fact build on our experience in creating a supportive network for postdocs, even utilizing the Network's young researchers.
5. We want to take on a challenge that could improve the diversity of physics.
6. We can envision building a program pragmatically, extending it to multiple sites in steps, improving the program as we gain experience.

7. Because we are addressing an issue important to our universities, the program would have a good chance to survive after the PFC sunsets, if we prove its value.
8. Metrics such as graduation rates in the major can be used in evaluating our efforts.
9. Because N3AS involves multiple institutions and both graduate students and postdocs, there is the possibility that transfer student involvement in N3AS can continue post B.A., providing continuing motivation.

The program proposed below was developed with the help of collaborator Dr. Colette Patt, Director of the Mathematical and Physical Sciences (MPS) Graduate Diversity Office, Berkeley.

1. Our goal over the first five-year term of the PFC is to establish transfer student support programs successively in UC Berkeley, UC San Diego, and Kentucky, each of which [263, 269, 270] has a transfer student program focused on recruitment from CCs. Additional programs would be added at a similar pace, if the PFC is continued for a second term.
2. At each site the N3AS program would be integrated into relevant campus programs for transfer students. For example, at the first site (Berkeley), our partners will be the MPS Diversity Office [271], the University's Transfer Student Center [272], and the Transfer Alliance Project (TAP) [273].
3. Selected undergraduate transfer students with interests in astrophysics would be welcomed into N3AS. A site like Berkeley could accommodate up to 12 undergraduates per year – about 30% of the transfer students. N3AS faculty, Fellows, and graduate students could serve as mentors. For Fellows and grad students, an interview process where the mentees are selected could create a sense of investment. N3AS-PFC would support this program through modest annual stipends for the transfer students ($3K/academic year), while treating the students as N3AS undergraduate researchers. This would provide both tangible and social incentives to stick with physics, despite its difficulty.
4. As the program progresses, it would create peer mentors that could play a role in recruiting, e.g., by returning to a CC in the company of TAP recruiters to publicize transfer opportunities including our N3AS program.
5. Involvement in research is an effective way to encourage students to remain in STEM [274]. Our goal would be to transition our transfer mentees into research, as they become ready, starting with biweekly group meetings to discuss astrophysics and build a social network. Such interactions are helpful in enhancing achievement and improving retention in STEM [275]. The students could progress to directed reading, and then to beginning research. Experimental opportunities could be provided through our Joint Institute partnerships and through the Department.
6. Metrics for the program would include the percentage of students who persist to the B.A., the quality of the research the students perform, and the percentage deciding to continue into graduate school – inspired by the research experiences they enjoyed as undergraduates. Students interested in applying to graduate school at N3AS institutions would be encouraged to do so. We intend to continue student tracking after the B.A., regardless of career choice.
7. The N3AS-PFC administrator assisting in the development of this program would travel to other sites to supervise initial organization of those programs.

f. Shared Facilities

In this section we describe

1. the plans for creating a physical center at Berkeley to accommodate N3AS, its visitors, and its international partners;
2. administrative staffing of N3AS-PFC and the Center;
3. the integration of the 12 sites; and
4. involvement of outside US and international physicists,

The N3AS Center: Most of particle, nuclear, and astrophysics at Berkeley is housed primarily in Old LeConte, one of three building that comprise the Physics Department. If this PFC proposal is funded, the university has agreed to remodel a 1600+ sf area on the third floor of Old LeConte as an N3AS Center (see Fig. 19). The remodeling would begin as soon as a decision on the proposal has been made. The location – the northwest corner of LeConte – is ideal for a Center with an astrophysics focus and an active visitor center. The area connects directly by skybridge to the 3rd floor of New Campbell, opening on to an interaction area (Cosmology Commons), a conference room, and an open office area occupied by young researchers with the Berkeley Center for Cosmological Physics. On the physics side the planned N3AS area has adjoining conference and seminar rooms. Both conference rooms and the Commons are equipped with LCD screens for video-conferencing. Nearby offices are occupied by experimentalists working on dark matter and neutrinos.

The remodeling would provide three offices for N3AS postdocs and for longer-term RIKEN and UMI visitors: this space will accommodate up to 8 researchers. There is space for two administrative staff and up to 11 additional visitors. The plans call for using DIRTT glass walls [276] throughout, to create a feeling of openness to encourage interactions.

The four Berkeley members of N3AS have offices near this area. They, 3-4 N3AS Fellows spending their third years in Berkeley, and approximately four long-term RIKEN and CNRS members from the core of the Joint Institutes. Others using this area routinely will include local graduate students collaborating with N3AS members, visitors (including faculty on sabbatical), and NASA Fellows who decide to associate with N3AS. The center would be heavily used during the collaboration meetings and workshops described in MA7.

Administrative Staffing: The Joint Institutes arrangement brings senior personnel to Berkeley who will add to and strengthen PFC science, at no salary cost to N3AS. In return, N3AS will extend its administrative "umbrella" to include its two Joint Institute partners. The proposal requests support for two N3AS administrative staff. The PFC's lead administrator would be responsible for day-to-day management of the PFC's cooperative agreement, monitoring and reconciling expenditures, and working with the N3AS Director on budget planning and reporting. This administrator would take care of the Network's postdocs, including initial appointments, visa issues, moving expenses, laptop and other purchases, travel, etc., and help CNRS and RIKEN visitors with relocation, setting up their Visiting Faculty or Visiting Scientists appointments. The lead administrator would help individual Joint Institute members with daily administrative needs, and maintain general infrastructure such as a supply cabinet, printing, and copying. The administrator would also manage any other grants held by the Joint Institutes, e.g., the RIKEN grant that was established to cover local research and travel costs of RIKEN visitors (which the N3AS director currently

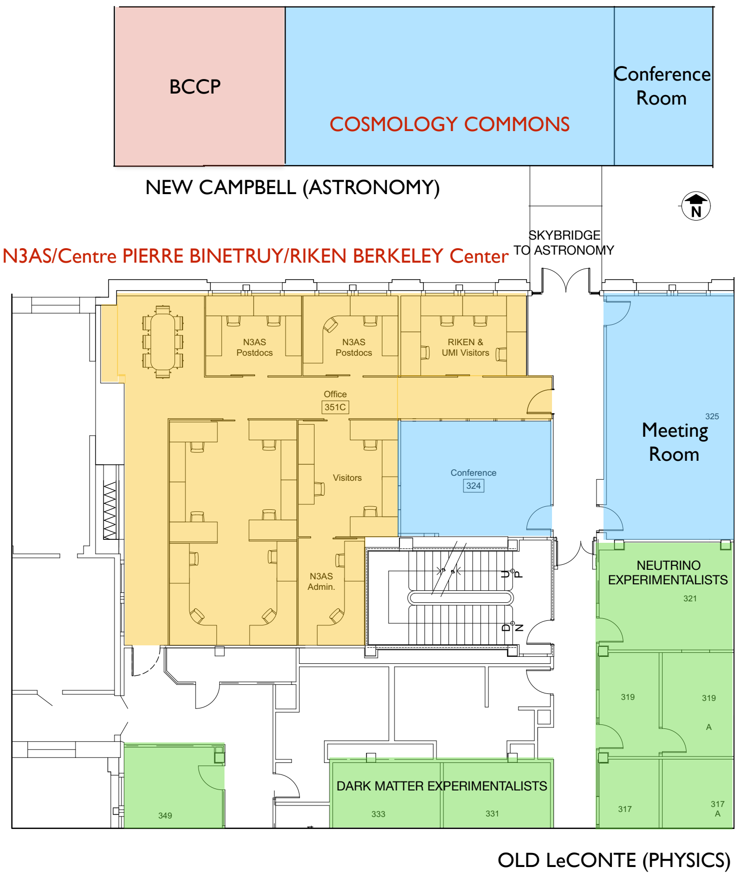

Figure 19: The 1600 sf area that would be remodeled for N3AS and its RIKEN and CNRS partners is shown in tan. Nearby conference, seminar, and interaction areas are shown in blue. Neighbors include dark matter and neutrino experimentalists, and an open office area for young researchers belonging to the Berkeley Center for Cosmological Physics (BCCP). This space would be available by the end of 2020.

manages on behalf of RIKEN). This would include foundation support for the Joint Institutes, if future proposals succeed.

The second administrator will focus on outreach – events, media, and our transfer student undergraduate program. This person would maintain the N3AS web site, including archives of seminars presented under N3AS auspices. The outreach administrator would manage the annual summer school, the N3AS annual meeting, frequent small collaboration meetings, workshops, and any other organized activities of this: this includes arranging for housing and travel, as needed. These activities may be hosted by the Center, by one of the sites, or in another location (e.g., the 2020 summer school at UCSC). N3AS will have a mailing list and an electronic newsletter that the outreach administrator will help create. A key responsibility will be to design and execute our undergraduate transfer student program, working with N3AS faculty and university outreach and diversity officials, including Dr. Patt. The person selected for this position would need to be willing to travel, to work with counterparts at UCSD or Kentucky, as our transfer student program progresses to new sites.

The centralization through Berkeley simplifies day-to-day administration: N3AS faculty and postdocs use a single set of online tools. Most transactions will be entered by researchers, e.g., requests for travel reimbursements. All N3AS members can be given access to these tools. The two administrators will be able to help, if any member encounters difficulties.

Integration of the 12 Sites: As intended when we first conceived of N3AS, the purpose of the Hub/PFC is to help a nationally representive group of researchers work coherently to increase the footprint of nuclear and neutrino astrophysics within nuclear physics, while growing the field's boundaries in the important area of multi-messenger astrophysics. N3AS procedures were designed to keep the focus on the Network: Fellows are selected by vote of the group and are regarded as N3AS, not site, postdocs. Almost all activities are carried out by multi-institution volunteers. A typical example is the 2020 summer school, where Balantekin (Wisconsin), Prakash (Ohio U), and Surman (Notre Dame) volunteered to lead the effort. Our Fellows really "get it:" they almost immediately adopted the mindset of being colleagues in a distributed effort, rather than postdocs connected to a site, and they have been exceptionally active in organizing regular video-conference meetings and similar activities. N3AS is fully integrated by design.

Involvement of Outside US and International Physicists: We have described elsewhere in this proposal our formal connections with CNRS and RIKEN through the Joint Institutes: these relationship are based on MOUs that were vetted through CNRS, RIKEN, and campus management. The formal connections reflect the fact that CNRS and RIKEN are making substantial and continuing financial contributions to the Joint Institutes, and these efforts are political visible, e.g., of interest to the respective San Francisco consulate offices. The N3AS-PFC connections of *Elusives* and *InvisiblesPlus* are informal, and might be termed pragmatically reciprocal. The parties are excited about the opportunities for working together through exchanges and participation in schools, but will let these interactions grows organically. The science and broader impact aspects of these relationships have been previously described. N3AS-PFC would be open to further connections of either type, provided the activity advances our science and broader impact goals and does not erode N3AS's focus.

The workshops and annual meetings conducted under N3AS-Hub have been open to the US and international communities, and we have supported the participation of both senior and junior nonN3AS scientists. The two largest N3AS-driven workshops (those on parity violation) were widely advertised and dominated by non-N3AS participants. In the case of the annual meetings, we have been active in soliciting the participation of and supporting younger researchers, as we think their interactions with N3AS Fellows is of mutual value.

With the creation of N3AS-PFC, the Network will have a physical space at Berkeley that could accommodate small workshops and collaboration meetings proposed by non-N3AS members. N3AS would be open to hosting such groups if the subject of the meeting fits into the N3AS scientific scope.

g. Collaboration with Other Sectors

Most of our interactions and collaborations have been described under the MAs or in Sec. e. Here we list our senior participating investigators and collaborators, referencing as needed other parts of our proposal.

Senior Participating Investigators; Our senior participating investigators are Carlson, Cirigliano, and Gandolfi from the Nuclear and Particle Physics, Astrophysics, and Cosmology theory group (T2) of Los Alamos National Laboratory. T2 is an N3AS site. The Los Alamos group is a major player in nuclear and neutrino astrophysics and in fundamental symmetries, including effective-field-theory-based approaches to lepton-number and time-reversal violation at low energies. The group has helped developed the QKE approach to neutrino propagation at high density, and its work on quantum Monte Carlo techniques, impacting problems from neutrino-nuclear responses to the high-density nuclear EoS, leads the field.

Collaborators: Collaborators under N3AS-PFC include

1. Tetsuo Hastsuda, Director of iTHEMS, and Shigehiro Nagataki, Chief Scientist of the Astrophysical Big Bang Laboratory, RIKEN. The N3AS partnership with the Berkeley RIKEN Center (Astrophysics) is covered under MA6. In particular, this partnership links us to an internationally prominent group in the simulation of supernovae, mergers, and associated transient events, with interests very strongly aligned with the science of MA5, and having access in the near future to exascale computing. This group has a close relationship with Kamioka groups involved with Super- and Hyper-Kamiokande and with KAGRA.
2. Saul Perlmutter, Berkeley, and Radek Stompor, CNRS, are the co-directors Centre Pierre Binétruy, described in MA6. The Centre will bring great strength in areas such as the Cosmic Microwave Background tests of neutrino mass, and connections to the CNRS data analysis team of Virgo. The Centre includes both experimentalists/observers and theorists, and the later will be housed in the Joint Institutes area. Through the co-director Perlmutter, there is also a valuable connection to BIDS (Berkeley Institute for Data Science), which includes among its major interests the analysis of large astrophysical data sets. Perlmutter is the Faculty Director of BIDS.
3. Silvia Pascoli, Professor, University of Durham, is the Coordinator for the new European Union Horizons2020 ITN *HIDDeN*, and was Deputy Coordinator for its predecessor, *Elusives*. She has been designated as the contact person for these programs and *InvisiblesPlus* with N3AS.
4. Colette Patt, Director of Diversity Programs, Division of Mathematical and Physical Sciences, and Science Diversity Director, Berkeley, is the N3AS contact with a variety of Berkeley, regional, and national programs focused on student and postdoc diversity in STEM fields. She currently directs Berkeley's NSF-AGEP (Alliance for Graduate Education and the Professoriate) and EDGE programs. Her research focuses on retention and advance of science students coming from diverse background. She will act in N3AS as the conduit between the N3AS Transfer Student program and university offices responsible for UC Transfer Pathways.

We have other national laboratory connections arising from N3AS faculty joint memberships in relevant collaborations:

1. The Lawrence Berkeley and Lawrence Livermore National Laboratories have a connection both to N3AS and to RIKEN through the lattice QCD collaboration CalLat. CalLat members have participated in several of our activities due to their interest in the parity-violating NN force, double beta decay, and sub-1% calculations of $g_A(q^2)$ over the momentum range relevant to LBNE (eliminating a significant uncertainty).

2. Oak Ridge National Laboratory leads the SciDAC project TEAMS and is a member of the Exascale Computing Project ExaStar (led by LBNL), collaborations involving N3AS members and important in developing collapse and mergers codes for coming exascale platforms.

h. International Collaboration

Our international collaborations are described under MA6. The scientific benefits to NA3S from the partnership with the Centre Pierre Binétruy include connections to the CMB community involved in cosmological data analyses that could, for example, yield new constraints on the absolute neutrino mass and hierarchy; and interactions with key CNRS members of the analysis team for Virgo and LISA Pathfinder. The broader impacts will include the young French theoretical researchers – graduate students and postdocs – who will visit the Centre and interact with their N3AS counterparts, as well as the experimentalists and observers who will visit the Centre and enrich the theory/experiment interface. The N3AS partnership with the Centre and with RIKEN should help us compete for private funding to leverage the funding we may receive from NSF.

The scientific benefits of the partnership with the RIKEN Berkeley Center (Astrophysics) include leveraging N3AS strengths in modeling core collapse, mergers, and associated transitions. Important opportunities in code development could arise from efforts in Japan and the US to prepare for the exascale platforms that will exist in both countries by the end of 2021. In his last visit to N3AS, RIKEN ABBL chief scientist Nagataki and two of his colleagues were accompanied by a dozen graduate students, who they introduced to Berkeley and LBNL. While no formal plans have been made, interesting student visiting and exchange opportunities exist.

N3AS-Hub, *Elusives*, and *InvisblesPlus* were established in the same year. These three efforts share common broader-impact goals of motivating and inspiring young researchers. The European efforts focus on younger researchers – advanced graduate students and beginning postdoctoral researchers – and have rather brilliantly coordinated efforts toward gender equality in astrophysics, by creating networks of senior women who are prominent in particle astrophysics. N3AS hopes to benefit by bring *Elusives*, and *InvisblesPlus* veterans to the U.S. as N3AS Fellows, where we can them take the next step into tenure-track faculty positions.

i. Seed Funding and Emerging Areas

The theme of this proposal – multi-messenger astrophysics – is consider by most of physics to be an emerging area. The field has grown out of four extraordinary discoveries – neutrino mass and mixing (solar and atmospheric neutrinos), DM (galaxy velocity curves, CMB, large-scale structure of the universe), dark energy (Ia SNe, large-scale structure, flatness), and GWs (BH and NS mergers)– made in the past two decades.

Although N3AS does not sequester seed funding for junior investigators, a balance of ages among the senior investigators is important to us, as we are trying to grow the field, and “second generation” physicists now in junior faculty positions play crucial roles in the recruiting and mentoring of the third generation. This was a consideration in the original formation of N3AS-Hub. While the choice of new members added to N3AS-PFC reflect scientific priorities – specifically the recommendation of the NSF midterm review panel to strengthen the N3AS DM component, and LIGO/Virgo discoveries that have made the modeling of NS mergers and associated transients an urgent priority – four of the six new N3AS members are junior faculty:

1. Francois Foucart, Asst. Professor (2017-), Univ. New Hampshire: merger and SN modeling
2. Tongyan Lin, Asst. Professor (2017-), UC San Diego: DM phenomenology
3. Katherine Mack, Asst. Professor (2018-), North Carolina State: DM in astrophysics (also, media-based outreach)
4. David Radice, Asst. Professor (2019-), Penn State: mergers and SN modeling

N3AS should be a significant source of support for these junior faculty as they begin their careers.

j. N3AS Management

In this section we collect together various proposal elements relevant to project management.

Governance: The structure NSF created in the cooperative agreement for N3AS-Hub would be continued: a director (PI) supported by an executive committee of four (the coPIs). In N3AS-Hub the PI and co-PIs interact frequently – most often by email, and as needed by Zoom or in person. While the PI has overall responsibility for executing the cooperative agreement, in practice the PI and coPIs work in consensus. The Executive Committee consists of the PI and Baha Balantekin, George Fuller, Gail McLaughlin, and Sanjay Reddy.

Scientific Organization: Responsibility for scientific organization of N3AS-PFC would be distributed over the executive committee and Senior Investigators, with the following representative of N3AS-Hub activities:

MA1	Neutrino Properties and Astrophysics	Joe Carlson, Andre DeGouvea, Yong-Zhong Qian
MA2	Nucleosynthesis	Dan Kasen, Rebecca Surman
MA3	Dense Matter in Astrophysics	Daniel Phillips, Stefano Gandolfi
MA4	Dark Matter	V. Cirigliano, Tongyan Lin, Katherine Mack
MA5	Astrophysical Simulations	Francois Foucart, David Radice
MA6	International Partnerships	Executive Committee
MA7	Community Building, Workshops	Executive Committee
	Transfer Student Outreach	Executive Committee
	Postdoctoral Committee	V. Cirigliano, S. Gardner, M. Prakash
	Data Science Undergraduates	Jim Lattimer, Uros Seljak
	Summer School	B. Balantekin, M. Prakash, R. Surman
	UC Berkeley Interactions	Wick Haxton, Eliot Quataert

For MA1 through MA5, the designated coordinators would be responsible for organizing N3AS faculty and Fellows to execute the science program outlined in this proposal, through regular Zoom meetings and face-to-face collaboration meetings.

The Executive Committee will take responsible for community interactions and international partnerships including joint workshops or other shared activities with the Joint Institutes: this is MA6, MA7, and the material covered in Sec. e.

The Postdoctoral Committee is responsible for organizing the annual Fellow search and for monitoring issue affecting Fellow welfare. If any issues arise that require action – for example, difficulties between a Fellow and his/her site host – this committee is expected to propose remedies and to ask the PI to take any necessary actions. The Summer School committee listed is the one organizing the N3AS-Hub school is 2020; that responsibility would rotate from year to year, with at least one hold-over appointment to ensure continuity.

Haxton and Quataert are the current chairs of Physics and Astronomy, respectively, at Berkeley, and thus can be helpful if any campus issues arise, other than those the PI would normally address.

Administrative functions: Budget planning and monitoring, appointments, reimbursements, and similar administrative functions will be done through Berkeley. The advantages of this approach (instead of 12 subcontracts) include efficiency and simplicity, reduced costs, continuity of fellow salaries and benefits, the ability to monitor and manage costs centrally month-by-month, and reinforcement of the concept of a centralized network, where decisions made are focused on the project, not individual site preferences or needs. The two administrators helping N3AS will be able to quickly establish relationships with their counterparts in Campus Shared Services at Berkeley (campus's centralized administration) who will act on N3AS requests for new appointment, visa assistance, reimbursements, etc.

Travel reimbursements, purchases, and similar requests can be easily initiated by N3AS faculty or Fellows using online forms. Under N3AS-Hub such requests are routed to the PI for high-level approval, then forwarded by him to the relevant CSS staff member, who verifies accuracy and compliance with NSF and UC rules before initiating payment. The volume of such requests has had an impact on the PI. Under N3AS-PFC the N3AS lead administrator would take on much of this burden.

Advisory Committee Under N3AS-Hub we wanted the advisory committee to attend and take part in the annual meeting – but the task of finding a date that would be workable for N3AS faculty and Fellows proved very challenging, even before advisory committee constraints were considered. Based on this experience, we will adopt a new model for our N3AS-PFC advisory committee, where membership is year-by-year, with members chosen once the annual meeting date is selected, allowing us to verify availability. The following year, we would hope to attract some of the same members back for continuity, but those not available could be replaced by others with similar backgrounds. By capping appointments at three years, while maintaining a pool of past advisors who not yet served three years and thus can be reused, we should be able to guarantee adequate committee participation at each meeting.

Annual meetings will provide a great overview of PFC progress, as (following the model established by the Hub) they include summaries of progress of the MAs, posters or oral presentations by all of the fellows, descriptions of community interactions, etc. We would ask the Advisory Committee to stay over for an extra day, meeting with the N3AS Executive Committee to discuss what they heard and other issues the Executive Committee would raise.

The primary function of Advisory Committees like those that serve the INT and KITP is to select future workshops and programs, which are scheduled one to two years in advance. The N3AS advisory committee would not have a similar role, as the primary focus of N3AS is on the science of MA1-MA5 and on career advancement of N3AS Fellows and students. Most of our workshop-like activities would be science-driven collaboration meetings scheduled with quick turn-around times, or collaborative activities with the Joint Institutes. The Advisory Committee could comment on past activities, though, if they decide N3AS choices can be improved.

k. Institutional and Other Sector Support

The following summarize the institutional commitments to N3AS-PFC:

1. UC Berkeley will undertake an extensive remodeling of an area on the 3rd floor of Old LeConte of approximately 1600 sf, to provide a center for N3AS to accommodate Fellows, N3AS administrative functions, N3AS visitors, and associated RIKEN and CNRS scientists. This work will begin shortly after proposal approval. It will also make available a nearby conference room, as needed. See Fig. 19.

2. The 12 N3AS sites commit to hosting their associated N3AS Fellows, providing space and other amenities typically provided to postdocs. Faculty at sites agree to serve as mentors to postdocs they host.

3. RIKEN has agreed to support the Joint Institutes concept, providing salaries, research support, and occasional support for joint workshops, establishing the RIKEN Berkeley Center (Astrophysics). An MOU is in place, and commitment letters from the RIKEN iTHEMS Director and from the ABBL Chief Scientist are included as supplementary documents. Significant funding for first-year research operations (the year beginning Fall, 2020) has been provided.

4. CNRS with send theoretical visitors to participate in the newly established UMI Centre Pierre Binètruy, as part of the Joint Institutes concept, supporting visitor salaries. The MOU between CNRS and Berkeley establishing the Centre is in place, and first-year research funding for the Centre has been pledged by CNRS. Commitment letters from the CNRS UMI co-Directors are included in the supplementary documents.

5. The Diversity Officer for Berkeley's Mathematical and Physical Sciences Division will help N3AS develop the transfer student support program described in Sec. e. A commitment letter is included.

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Postdoctoral Researcher Mentoring Plan

Mentoring is a principal responsibilities of the senior investigators: Our obligations to the N3AS Fellows and graduate students includes not only providing a good science environment, but also helping them to develop the professional skills they need to take the next step in their careers.

1. The project's plan for hiring postdoctoral researchers is based on creating the largest possible candidate pool, then evaluating candidates in a manner that emphasizes quality, rather than a candidate's "fit" to a specific project. All senior members participate in candidate selection, de-emphasizing site influences, "attended" electronically candidate interviews and participating in followup discussions. We offer leading candidates an opportunity to visit their top-choice site, before deciding.
2. Fellows select their sites based on their own assessment of opportunities and fit: Fellows as professionals and equals, not as "project scientists" supporting a pre-existing research plan. The two-year site choice is subject only to the constraint that the positions are equitably distributed among the sites. In year three Fellows are free to join the Berkeley Center or any new site. Each candidate, in consultation with the senior investigators, will choose a mentor at his/her site as well as one in a second site, based on scientific overlap – a dual-mentor scheme.
3. N3AS-PFC will have a two-person Fellows committee providing oversight. The committee is responsible for making Fellows aware of career development opportunities. For example, at Berkeley these include forums on science-by-inquiry methods, opportunities to discuss science with students from less advantaged school districts in the Bay Area, instruction in supervising undergraduate research projects, outreach opportunities at institutions like the California Academy of Sciences, etc. Other sites have similar resources. The committee will review the annual mentoring reports, and may make suggestions, or in case of serious issues, can bring problems to the PI with suggestions for corrections. The mentoring committee members play the role of ombudsman, available to the Fellows for any issues they would like to raise in confidence. If a situation arises that has no solution, N3AS-PFC has unusual flexibility to make changes. Our group of senior investigators has a outstanding record of past mentorship - several of the senior investigators are themselves former mentees.
4. N3AS-PFC Fellows will have frequent speaking opportunities due to travel among the sites, involvement in the annual meeting, and connections to the many community workshops and programs (INT, KITP, etc.) that the N3AS faculty help to organize. The mentors will nominate Fellows for talks and otherwise work to gain them exposure. We will encourage the Fellows to take leading roles in drafting papers. The Fellows will play active roles in our annual summer school as discussion leaders and poster session organizers.
5. In their third years the Fellows have an opportunity to move to any site of their choosing; several of our sites have especially active visitor programs that connect fundamental nuclear physics/astrophysics to sister subfields, giving the Fellows an opportunity to experience and take advantage of interactions with other sectors. Local N3AS senior investigators can help with this networking. Because Fellows remain Berkeley postdocs throughout, in some sense the third year is similar to a sabbatical year for a faculty member – and opportunity to immerse oneself in a new scientific environment, building new collaborations and new interests. The ability to interact with others outside one's immediate specialty can be a decisive factor in building a career. The third year is the time N3AS-PFC Fellows will seek their next positions. The senior investigators at sites with third-year Fellows will be active in encouraging applications to the various fellowship and faculty openings. When interview opportunities arise, practice "job talks" will be scheduled, and constructive suggestions made.

Data Management Plan

N3AS-PFC data activities will meet all requirements of, and in most cases exceed, the NSF policy on the dissemination and sharing of research data. Our collaboration supports the principles of the corresponding Office of Science Statement on Digital Data Management: "To the greatest extent and with the fewest constraints possible, and consistent with the requirements and other principles of this Statement, data sharing should make digital research data available to and useful for the scientific community, industry, and the public."

Addressing the points in the NSF Grants Guide:

1. The data produced through N3AS-PFC research and collaborative activities will include research papers, electronic versions of seminars that N3AS members present, and the digital output generated by N3AS codes, particularly those described in MA5.

2. The standards for data, in the case of research papers, are those defined by the arXiv and by the journals in which N3AS members publish. Our electronic talks are typically prepared in Powerpoint or Keynote. Our digital data are generated in various forms. Output from our large-scale shell model calculations, for example, are digital wave function files typically stored on local disks for a period. We usually derive from that data a much more compact representation of the amplitudes required to calculate operator transitions – the so-called one- and two-body density matrices. The output from many of our astrophysics codes is often visual: code output is captured in pixelated figures that are included in publications. We follow best practices in graphically presented data, retaining the digital input from which the graphs are made.

3. Standards for sharing data: In the case of research papers, our members post all papers on the arXiv at the time they are submitted for publication, unless there are restrictions from journal embargo policies. We believe all of the major journals in which N3AS members regularly publish belong to CHORUS, and thus adhere to the policy of open public access to publications within one year of publication. In the case of electronic talks, the N3AS-PFC web site will have a page where members can upload talks they have presented. We will encourage but not require N3AS members to do so. Typically we will make digital data freely available. For example, the density matrices from N3AS dark matter direct detection studies are stored on an open web site along with a Mathematica script that users can employ to calculate cross sections and rates. Requiring others to replicate calculations we have done would waste computer resources and slow science progress. Several key codes – e.g., WhiskyTHC and the latest versions of the shell-model code Bigstick – are open source and/or available on GitHub.

4. Policies and provisions for re-use: In the case of journal publications, the only restrictions on reuse are those imposed by the publisher. In most cases they allow reuse with the consent of the authors, which we would always provide. N3AS researchers will allow others access to digital data and, as illustrated in the case of the density matrices described above, will endeavor to put digital data in forms that are readily usable by others.

5. Policies on archiving: Publications and research papers are, of course, archived indefinitely by both the preprint arXiv and the publisher. Raw digital data are stored on local disks to the extent possible: there are physical limitations when dealing with large data sets.

   In cases where long-term storage of data is physically impossible, we typically extract from that data quantities like the density matrix. This compact information is much more useful to others. This information is always retained, and frequently made public. Some contemplated N3AS work could result in public data files that would be attached to codes like Kepler and Mesa, supplementing or replacing current tables.