ASTROPHYSICS

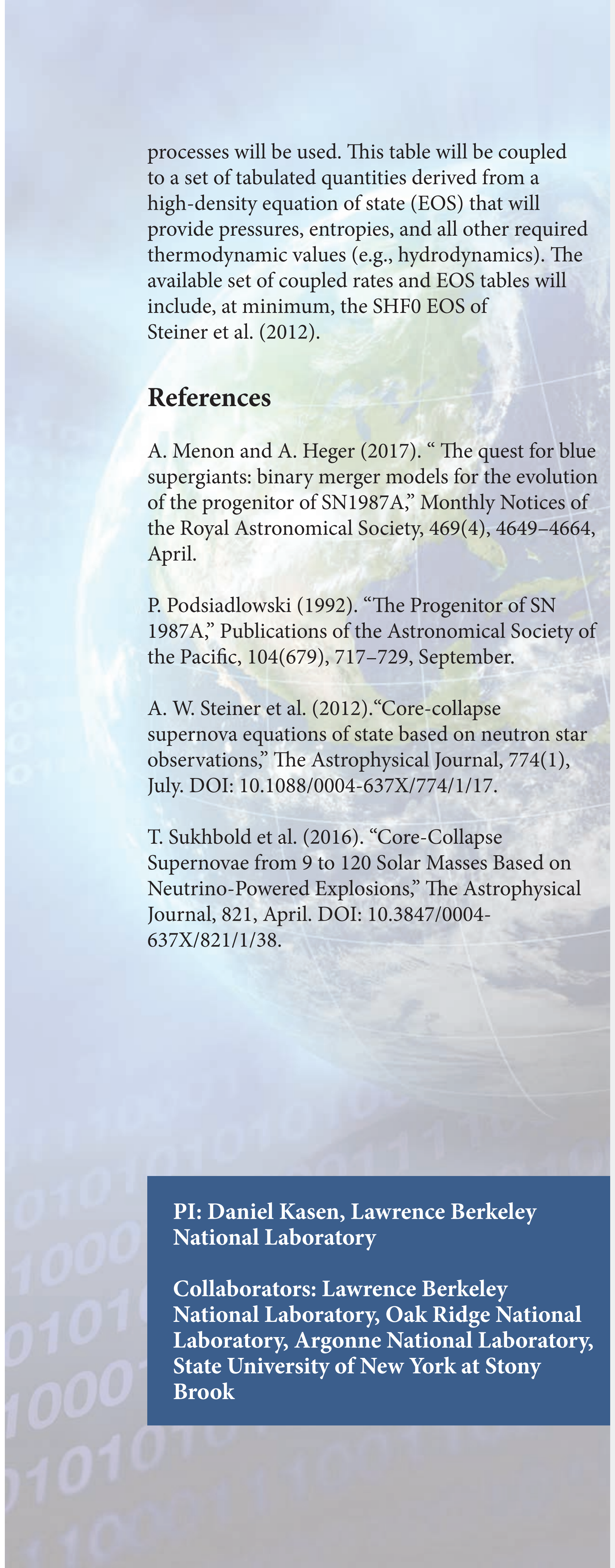
Exastar: Exascale Models of Stellar Explosions: Quintessential Multiphysics Simulations

Astronomical observations have confirmed that the production of heavy elements occurred early in galactic history. Yet many details remain outside the purview of direct observation. Exascale computing, through the Exastar Clash code, can be used to address fundamental questions in astrophysics including understanding the origin of elements. The Exastar project is using exascale computing to gain a fuller understanding of where heavy elements are born.

Exastar focuses on developing a new code suite, Clash, which will be a component-based multiphysics adaptive mesh refinement (AMR)–based toolkit that can accurately simulate coupled hydrodynamics, radiation transport, thermonuclear kinetics, and nuclear microphysics for stellar explosion simulations. Clash will reach exascale efficiency by building upon current multicore and many-core efficient local physics packages integrated into a task-based asynchronous execution framework based on current AMR technology. The fundamental goal in the development of Clash is to understand the production of the chemical elements found in these explosions, particularly those heavier than iron. While astronomical observations reveal that the production of the heaviest nuclei began early in galactic history, it is not known how and where these elements were formed. To address this topic via laboratory measurements, a series of nuclear science long-range plans have supported construction of radioactive ion beam facilities, culminating in the Facility for Rare Isotope Beams (FRIB). While FRIB is designed to acquire extensive data on the nuclei relevant for astrophysical nucleosynthesis, its end science goal cannot be met unless those experimental data are integrated into high-fidelity simulations of stellar explosions, such as supernovae and neutron star mergers, that define the conditions under which such heavy element production most likely takes place. Through a better understanding of the sites where the heaviest elements are made, Clash can help focus experimental efforts at FRIB on those reactions of greatest influence.

The Exastar challenge problem is a 3D simulation of the first 2 seconds of evolution after iron-core bounce of core-collapse supernovae (CCSNe). The progenitor star model will be chosen at run time from the best available models. The most likely progenitor models include (1) the solar metallicity 12 solar mass progenitor of Sukhbold et al. (2016), chosen because it represents, in some sense, the "center" of the distribution of massive stars that produce CCSNe, or (2) the binary merger model of Menon and Heger (2017), chosen because it is believed to closely mimic the progenitor system of Podsiadlowski (1992), the only CCSNe from which we have multimessenger signals to date.

The physical domain will extend from the center of the star out to fully enclose the helium shell of the evolved star. The precise location of this radius is progenitor dependent, but it is always more than 10,000 km. The maximum spatial resolution (enabled with AMR) will be at least 1 km at the surface of the proto-neutron star (i.e., in the inner 100 km or so of the event). At least 20 energy groups will be used to resolve the spectra of neutrinos of all flavors (i.e., electron, mu, tau, and their antiparticles) from 0 to 300MeV. An approximation to general relativistic gravity utilizing at least 12 moments in a multipole approach will be used, with the option to have a more realistic treatment if possible (e.g., conformally flat approximation). A set of tabulated neutrino–matter interaction rates that include emission, absorption, scattering, and pair production from various nuclear and nucleonic processes will be used. This table will be coupled to a set of tabulated quantities derived from a high-density equation of state (EOS) that will provide pressures, entropies, and all other required thermodynamic values (e.g., hydrodynamics). The available set of coupled rates and EOS tables will include, at minimum, the SHF0 EOS of Steiner et al. (2012).



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PI: Daniel Kasen, Lawrence Berkeley National Laboratory

Collaborators: Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory, State University of New York at Stony Brook

Progress to date

- Verified a new neutrino transport module in Clash.
- Completed a GPU implementation of nuclear kinetics and nonpolytropic equation of state.
- Integrated adaptive meshing from AMReX into Clash and performed baseline calculations on Titan.

Using exascale computing to model the physics of stellar explosions, Clash will inform planned and future astronomical experimental observations to answer questions about the origin of heavy nuclides in the universe.