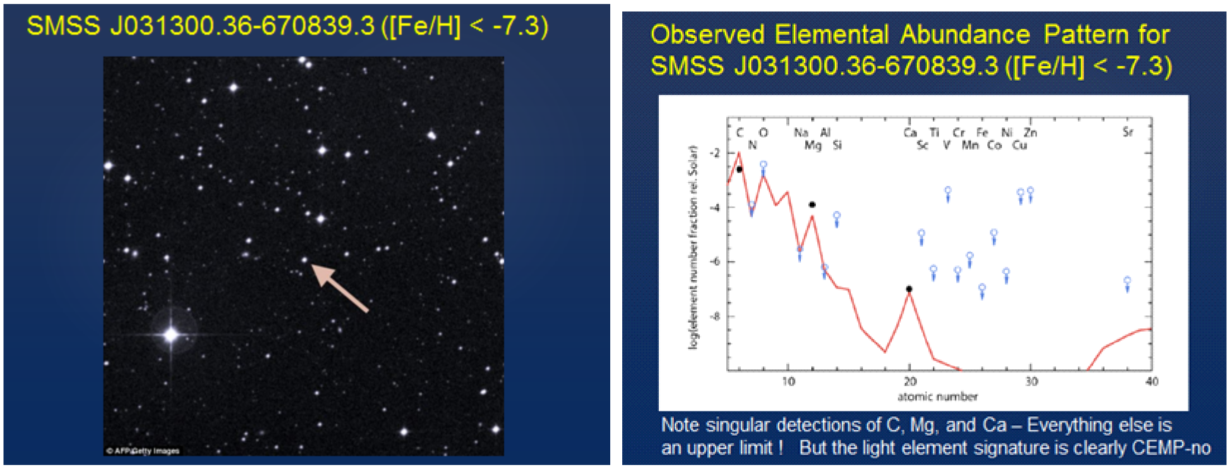
Sidebar S.IV.A: The carbon-to-oxygen ratio in our universe

A fundamental question is for nuclear astrophysics is the ratio of ^{12}C to ^{16}O that emerges in the very first generations of stars. This ratio is not only important for the development of the chemical building blocks of life, but also for the entire scheme and sequence of nucleosynthesis events as we imagine them now. The carbon-to-oxygen ratio determines the sequence of late stellar evolution phases for the massive stars that give rise to core collapse supernovae. It determines the ignition and burning conditions in Type Ia (thermonuclear supernovae) and it dictates conditions for the ignition of so-called superbursts observed in accreting neutron stars. Carbon induced reactions are therefore of extreme importance for our entire understanding or interpretation of nucleosynthesis patterns and the identification of nucleosynthesis sites.



Note singular detections of C, Mg, and Ca – Everything else is an upper limit ! But the light element signature is clearly CEMP-no

Figure S.IV.A.1**:** The oldest known star (arrow in left picture), with an age of about 13.6 billion years, is located in our Milky Way at a distance of 6000 light years from the sun. Its abundance pattern (right picture) proves early stellar nucleosynthesis of light elements like carbon and oxygen. Image Credit: Timothy Beers

Present extrapolation of the reaction rates associated with the $^{12}C/^{16}O$ ratio from the presently existing data depends very much on the reliability of nuclear structure and reaction models, which introduce orders of magnitude uncertainty into the predictions. This problem has been well known for decades and its solution requires new experimental efforts in a cosmic background free – or underground environment to provide the necessary experimental conditions for putting the question associated with low energy carbon capture and fusion reactions to rest.

Sidebar S.IV.B: The origin of heavy elements

A fundamental question for nuclear astrophysics is the origin of the neutron-rich elements heavier than iron. These heavy elements are produced either by a slow neutron capture process (the s-process) that takes place during helium and carbon burning phases of stellar evolution, or by a rapid neutron capture process (the r-process) that requires a much higher temperature and density environment. The latter can only be associated with violent events generating high neutron excess. The masses (binding energies) and the lifetimes of nuclei along the r-process path are the most important microscopic parameters for theoretical simulations. These inputs are currently taken from extrapolations based on theoretical models. Experiments at existing facilities on isotopes near the r-process path show us that these extrapolations are highly uncertain and may lead to faulty conclusions about the r-process conditions.

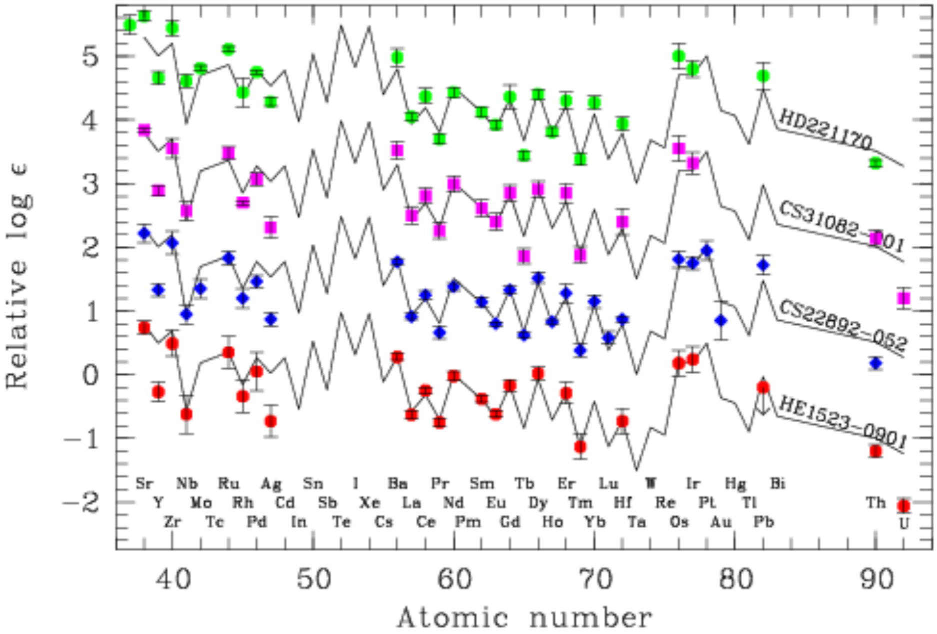


Figure S.IV.B.1: Abundance pattern of heavy elements in old, metal poor stars compared to the relative solar r-process distribution (solid lines). The absolute scales have been chosen arbitrarily for better presentation. Image Credit: Anna Frebel

New constraints are coming from large aperture observatories such as the Hubble Telescope, the VLT, Keck, Subaru, and Magellan observatories. Observations of early-generation stars indicate a heavy-element abundance distribution that matches the patterns in the higher mass range, albeit not the absolute abundances, of the r-process element abundance distribution in our Sun. This suggests that there may be a unique site for the r-process. The nature of the actual astrophysical site of the r-process has been a matter of fierce scientific debate for many decades. Both the neutrino-wind driven ejecta from a core collapse supernova and the violent collision of merging neutron stars could conceivably provide conditions for an r-process to occur – depending on many uncertain issues in nuclear and neutrino physics. Improved nuclear physics data from FRIB are crucial for making detailed predictions and to determine potential features for identifying the actual site. The r-process site is a critical issue in which observational, modeling, and experimental data are essential to reach a solution to an important and long-standing astronomical problem. The nuclear physics studies, in combination with signals from Advanced LIGO, will determine whether neutron star mergers can be a significant source of r-process elements.

Sidebar S.IV.C Advanced LIGO and Nuclear Physics

The detection of gravitational radiation from the violent merging of neutron stars in binary systems could have profound implications for nuclear astrophysics. We expect such mergers to be rare events in a galaxy like ours, perhaps happening once per ten thousand to million years. Fortuitously, the Advanced Laser Interferometer Gravitational-Wave Observatory (*Advanced LIGO*) will very soon be able to detect gravitational waves from these events, out to a distance of 200 mega-parsecs, a volume encompassing some millions of galaxies. In fact, the first observable from this observatory will be the *rate* of neutron star mergers, a key parameter in differentiating between sites proposed for the origin of the very heaviest nuclei, like uranium. We have known for more than 50 years that roughly half the nuclei with mass numbers greater than 100 originate in the r-process. It is a vexing problem that we know the r-process happens, but we do not know *where* it happens. Proposed production sites have centered on astrophysical environments either having abundant free neutrons or where neutrino or nuclear reactions can *mine* neutrons from lighter nuclei. Core collapse supernovae, which happen about once per century, and the much less frequent neutron star mergers are the leading candidate sites. Whatever site or sites contribute, ten thousand solar masses of r-process nuclei must be synthesized in our galaxy in 10 billion years. That datum, combined with an Advanced LIGO-inferred observed merger rate, could tell us whether mergers are a significant r-process source. If the r-process nuclei originate in neutron star mergers, the observed local rate of these events, combined with abundance observations at high redshift from the next generation of ground-based telescopes, may suggest a higher rate of compact object mergers in the past.

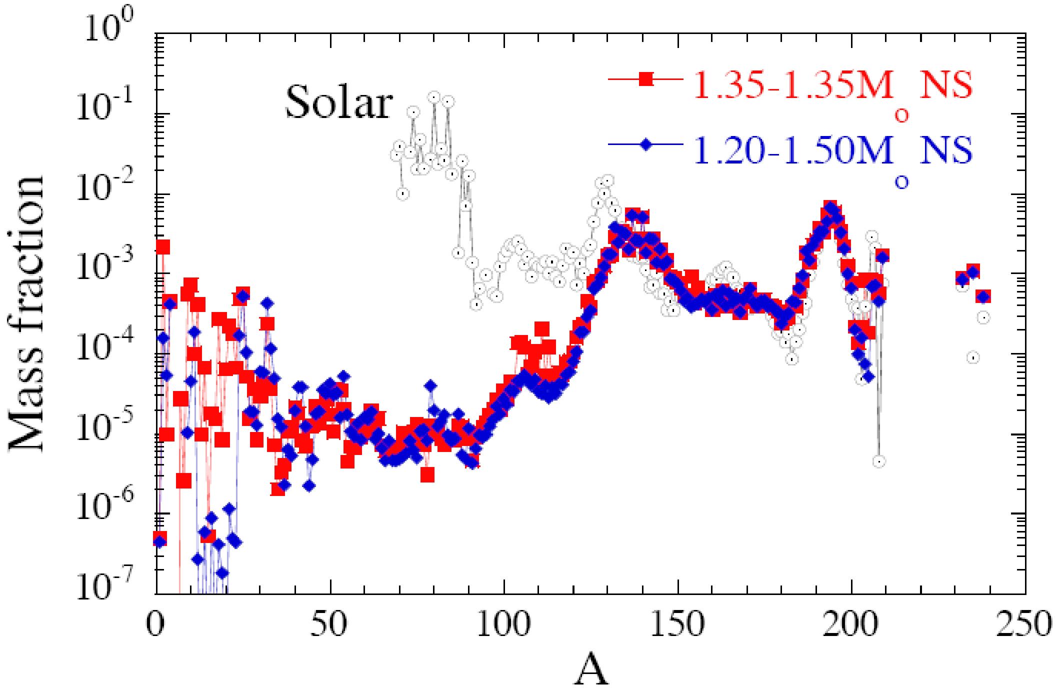


Figure S.IV.C.1: Nuclear abundance distributions as a function of atomic mass of the ejecta for two different combinations of neutron star mergers. The distributions are normalized to the solar r-process abundance distribution. Image Credit: Stephane Goriely

The gravitational waves that Advanced LIGO will observe come from violent motions of matter at nuclear density. As a result, the details of the observed neutron star in-spiral gravitational wave signal may give insights into the nature and behavior of ultra-dense neutron matter and the general conditions in the merger environment. In both mergers and core collapse supernovae, weak interactions, neutrino flavor physics, and neutrino-nucleus processes are key ingredients in understanding r-process nucleosynthesis. Knowing more about the merger environment can help guide this research.