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Understanding the Origin of r-Process in the Era of Gravitational-Wave Astronomy

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Abstract

Although nuclear astrophysicists have known for over 60 years that many of the heaviest elements in the universe are produced through rapid neutron capture (r-process), the site or sites of r-process production has remained a matter of contention. A range of proposed sites exist associated with the energetic explosions in the universe: supernovae and gamma-ray bursts. Here we review the different sites, the details of r-process calculations, and the new understanding gained from the first gravitational wave detection of a short-duration gamma-ray burst produced by the merger of two neutron stars. This observation helps to cement some of the ideas behind r-process production but also brings a host of new questions. With prospects of further detections, it is likely that our understanding of r-process nucleosynthesis will rapidly increase over the next 5-10 years.

1 Proposed Sites of the r-Process

Nuclear astrophysicists have long known that the heaviest elements in the universe were likely produced through the capture of neutrons onto ions [1, 2]. Scientists identified two extremes in neutron capture: slow or "s-"process and rapid or "r-"process where the neutron capture rate is much longer (s-process) or much shorter (r-process) than the beta decay rate [1]. These two processes study extreme conditions and it is not surprising that it is also possible that heavy element production can occur in conditions where the capture rate is on par with the beta decay rate. This intermediate or "i-" process has been studied in more detail over the past few years [3, 6, 4].

With both the fast and slow neutron capture processes identified as the source of heavy elements, astronomers began to identify and study sites where such processes could occur. Because of the longer timescales, the s-process was assumed to be produced in stellar burning shells [1] and it is now believed that the bulk of the s-process is produced in asymptotic giant branch stars with a leading site being the thermal-pulse phase of these stars (for a recent review, see [5]). The i-process can occur both in stellar burning shels and stellar collapse and much more work is required to determine its relative importance. The obvious site for the r-process is in the formation of a neutron star during the collapse of a massive star where neutron rich conditions are possible and the timescales are short [1]. Determining how this r-process site will work has been an active area of research for 6 decades.

Rapid neutron capture requires a large source of neutrons and the first well-studied site focused on the newly formed neutron star in core-collapse supernovae [7]. The proto-neutron star is formed in the collapse of a massive star's iron core. The collapse occurs when electron capture reduces the electron degeneracy pressure that supports the core. As the core contracts, the electron capture rate increases, increasing the rate at which the electron degeneracy pressure is removed, ultimately producing a runaway collapse (infalling at free-fall velocities). The collapse continues until the core reaches nuclear densities where neutron degeneracy pressure and nuclear forces halt the collapse and form the proto-neutron star. The core becomes increasingly neutron rich until the neutrinos become trapped in the dense core. At the edge of the core, neutrinos continue to escape and this "neutrino-sphere" region can become quite neutron rich. The neutrino-driven winds blown off this neutrinosphere could potentially provide the conditions for the r-process.

At the neutrinosphere, electron capture ($e^- + p \rightarrow n + \nu_e$) increases the neutron fraction. But above this region, electron and anti-electron neutrinos streaming out of the core reset the electron fraction[1] ($\nu_e + n \rightarrow e^- + p, \bar{\nu}_e + n \rightarrow p + e^-$, reducing the free neutron fraction, making it more difficult to produce the r-process elements. Because the ejecta is driven by momentum deposition from neutrinos, it is difficult to avoid resetting the electron fraction. But the exact value of the electron fraction will depend upon the spectra of the outflowing neutrinos. A number of modifications have been proposed to fix this particular r-process site: neutrino physics and neutrino oscillations [8, 9, 10] as well as a series of alternate driving mechanisms that alter the flow of the ejecta. For example, magnetic fields can delay drive the ejection of matter in either an excretion disk [11] or a jet [12]. More explosive matter ejections, like those seen in supernova fallback mass ejecta [3], can also alter the flow, making it easier to produce r-process elements. These alternate models would work only in a subset of all supernovae.

A number of opportunities for r-process production exist also in the engines behind gamma-ray bursts. Long-duration gamma-ray bursts are believed to be produced in the collapse of a massive, spinning star [16, 17]. The angular momentum in the star is sufficient to prevent the material from immediately accreting onto the collapsed core (either a black hole or proto-neutron star). Instead, it forms a disk around the compact remnant and the accretion of this disk provides the engine behind gamma-ray bursts [16, 17]. Winds from the disk [13, 14, 15] and relativistic jets driven by magnetic fields [12] have also been proposed as r-process sites.

Short duration bursts are not believed to be produced in the collapse of a massive star, but through the merger of two compact objects. The merger produces a central compact object surrounded by an accretion disk, again producing a gamma-ray burst engine [16, 17]. Scientists predicted that supernova kicks would cause these binary systems to travel well beyond their formation site and, in some cases, beyond their host galaxy, prior to merger [16, 18]. This prediction was finally confirmed by observations [19], cementing neutron star mergers as the leading model for short-duration gamma-ray bursts. These

[1]The electron fraction, or Y_e is the average number of protons in the matter divided by the average number of neutrons plus protons

compact objects are already neutronized, and the material flung out during the merger is extremely neutron-rich, providing ideal conditions to produce r-process. The only concern with this particular r-process source was its unknown rate that was believed to be low. The detection of GW170817 coupled with its corresponding electromagnetic radiation demonstrated that the merger rate and ejecta might indeed be sufficiently high to explain most of the r-process elements [20].

In this review, we discuss many of the assumptions in r-process yield calculations (Section 2). Despite these assumptions, it is useful to understand basic trends in the r-process production. To build this intuition, we mine the simulation results from Lippuner & Roberts [21] to discuss trends in r-process production (Section 3). We conclude with a discussion of the implications from the first advanced LIGO detection of a neutron star merger.

2 Basics Behind r-Process Studies

Although all of these sites have been studied independently, the assumptions in these studies have often been very similar. By understanding these assumptions, we can better compare the different results in the literature as well as the limitations of these assumptions. The early systematic study by Qian and Woosley [7] of r-process from neutron star winds outlined a simple evolution that has been used, with modifications, by nearly every group studying r-process from a wide variety of sources from neutron star winds to neutron star mergers and collapsar jets.

r-Process nucleosynthesis depends sensitively on the conditions, and evolution of the conditions, of matter. Nuclear burning occurs when the temperatures are high and atoms are moving sufficiently high to overcome the energy barrier of electrostatic forces. The number of collisions is proportional to the density of neutrons and ions. If we consider ion and neutron fractions, the reaction rates depend on the density squared. How long the matter stays at a given temperature dictates exactly what is produced in these reactions. Because of this, scientists have focused on the temperature and density evolution, or trajectories, of the ejected matter. The trajectories used in these r-process studies typically use an exponential evolution [22]:

$$T(t) = T_0 e^{-t/\tau} \tag{1}$$

where $T(t)$ is the temperature at time t, T_0 is the peak temperature of the material and τ is the decay time. The entropy of a radiation dominated gas is:

$$S = S_0 T^3/\rho \tag{2}$$

where $S_0 = 1.4 \times 10^{-11} \mathrm{k_B}$ nucleon^{-1} and ρ is the density. If we assume entropy is conserved, the density evolution is simply:

$$\rho(t) = \rho_0 e^{-t/3\tau} \tag{3}$$

where ρ_0 is the density at peak temperature. Although this may be appropriate for some mass ejection scenarios, for many explosions, a power law profile is more appropriate (see [23] for a review). For example:

$$T(t) = T_0/(2t+1). \tag{4}$$

If we again assume entropy conservation, the corresponding density evolution for this power-law profile is:

$$\rho(t) = \rho_0/(2t+1)^3. \tag{5}$$

For this paper, we use the results from Lippuner & Roberts [21] who employed a two-componet approach:

$$\begin{aligned} \rho(t) &= \rho_0 e^{-t/\tau} \text{ if t} < 3\tau \\ &= \rho_0 (3\tau/et)^3 \text{ if t} > 3\tau \end{aligned} \tag{6}$$

where e is Euler's number. This study also allowed the entropy to increase through nuclear decay. The temperature is then set by this time dependent entropy:

$$T(t) = (S(t)/\rho(t))^{1/3}. \tag{7}$$

Figure 1 shows the entropy versus time for 6 models in Lippuner & Roberts [21] varying both the electron fraction and the evolutionary timescale. The entropy can change dramatically over time. Figure 2 shows the resultant change in temperature with this heating. This entropy variation will change the temperature, but the largest modifications occur after the material has cooled below a few billion Kelvin and expanded to low densities where the neutron capture rate is relatively low. Even so, the entropy evolution can affect the nuclear yields, especially for lower electron fractions. The study did not follow the heating in a full hydrodynamic calculation and it is possible that it will accelerate the ejecta, altering the timescale and minimizing the raise in temperature. Effects such as heating ultimately must be studied in hydrodynamic calculations.

The timescale (τ) for the evolution determines the time available for neutron capture, altering the yields. But the ejecta evolution does not follow either a power-law or exponential evolution profile and it may be that, ultimately, detailed yields require detailed calculations of the ejecta evolution. For jet models [12] and fallback ejecta [3] both found that the ejecta can have a complex ejecta path where the material can expand and compress multiple times before ejecting, an evolutionary path that is not well approximated by power-law or exponential solutions.

Finally, nuclear and neutrino physics uncertainties can dramatically alter the yields. One effect is that the neutrino capture can alter the electron fraction. For neutrino-driven outflows, the neutrinos strongly alter the electron fraction of the ejecta, and hence the r-process yields. Especially in these scenarios, neutrino physics (including neutrino oscillations) can play an important role in modifying the yields [26, 27, 24, 25, 28]. Even in accretion disk scenarios (e.g. the disk formed in neutron star mergers), neutrinos often dictate the electron fraction [13, 14, 15]. In addition, nuclear physics uncertainties, including fission rates, can dramatically change the yields (for a review, see [29]).

3 Rapid Neutron Capture and Heavy Element Production

Despite these uncertainties, we can gain considerable intuition from models with a fixed set of nuclear physics and a specific trajectory assumptions. For this study, we use the models from Lippuner & Roberts [21]. These models use the density evolution set by equation 6 and include direct nuclear heating to evolve the temperature (as in Figure 2). Lippuner & Roberts varied the electron fraction, entropy, and expansion timescale. Figure 3 shows the production of heavy r-process elements ($119 < A < 250$). It has been argued that the success of making the r-process is determined by the value of the product of the entropy cubed divided by the electron fraction cubed and the expansion timescale: $S^3/(Y_e^3\tau)$ [11]. This formula was based on the results of Hoffman et al [30]. Although this might be true for entropies above $100\mathrm{k_B}$ per nucleon, for lower entropies, it appears that the electron fraction is the dominant factor in determining the amount of r-process element production. For these models, electron fractions below about ~ 0.3 produce large fractions of r-process elements. Note, however, that there are some interesting features in the production rate: e.g., very neutron rich material at high entropy does not effectively produce the heavy r-process.

To produce the very heavy r-process elements ($A > 249$), the electron fraction must be even lower, $Y_e < 0.25$ (Figure 4). But the exact conditions needed to produce these very heavy elements does not have a linear dependence on the entropy or the evolution timescale. For long evolution timescales, high entropies are required to produce very heavy isotopes. But at faster evolution timescales, low entropies produce more very heavy isotopes than high entropies. The production rate of these isotopes is also sensitive to the nuclear physics and a number of results recently have found wide variation in the yields of the heaviest r-process elements with respect to uncertainties in the nuclear physics [31].

Figure 5 shows the Lanthanide production our range of explosion conditions. Lanthanides can dominante the important opacities shaping the light-curves from neutron star mergers known as kilonova. If heavy (isotopes at the 2nd peak and beyond) r-process elements are produced, we expect a sizable fraction of Lanthanides. Because the Lanthanide opacities are strong in the optical and near-infrared, the r-process-rich kilonova ejecta is believed to peak, for the most part, in the infra-red. The production of Lanthanides is similar to the total r-process production but with some similarities to the heavy r-process production. For long timescales, the production is reduced at low entropies. At short timescales, the production is slightly decreased for the lowest electron fractions and highest entropies.

4 The Gravitational Wave Era

A number of potential kilonova observations existed in the late-time emission of short-duration gamma-ray bursts (for a review, see [32]). But it wasn't until the joint gravitational-/electromagnetic-wave detection of a neutron star merger (GW170817) that we had a definitive detection of the emission from the r-process ejecta from neutron star mergers [20]. This detection fit well the existing models for these events assuming a sizable amount ($\sim 0.01\, M_\odot$) of r-process element [33, 34]. The bright infra-red spectrum at late times in

GW170817 is suggestive of heavy r-process production with strong Lanthanide lines. Unfortunately, the forest of lines of Lanthanide elements [35] blend in the ejecta and it is difficult to prove (e.g. by detecting a line of a heavy r-process element) that the heavy r-process was produced in this explosion. Indeed, scientists were able to fit the data with a range of ejecta compositions [36] and we can not prove without any doubt that heavy r-process elements were produced in GW170817.

However, standard models do predict roughly $0.01\,M_{\odot}$ of r-process ejecta and, if we take the standard-model yields (e.g. [37, 38]) and the rates inferred from the gravitational-wave detection, we find that neutron star mergers can dominate the r-process production in the universe [39, 40, 36]. This has led some scientists to claim that the problem of the r-process site is solved. This oversimplifies the problem. We are still understanding the exact conditions that make the r-process. Detailed models and an understanding of the nuclear physics uncertainties is critical. In addition, there is already a set of data that using neutron star mergers as the sole source for r-process does not seem to be able to explain (Cote et al., in preparation). As advanced LIGO helps us increase the number of neutron star merger detections, we will be able to better understand the role of neutron star mergers and, ultimately, the sources of the heavy r-process elements.

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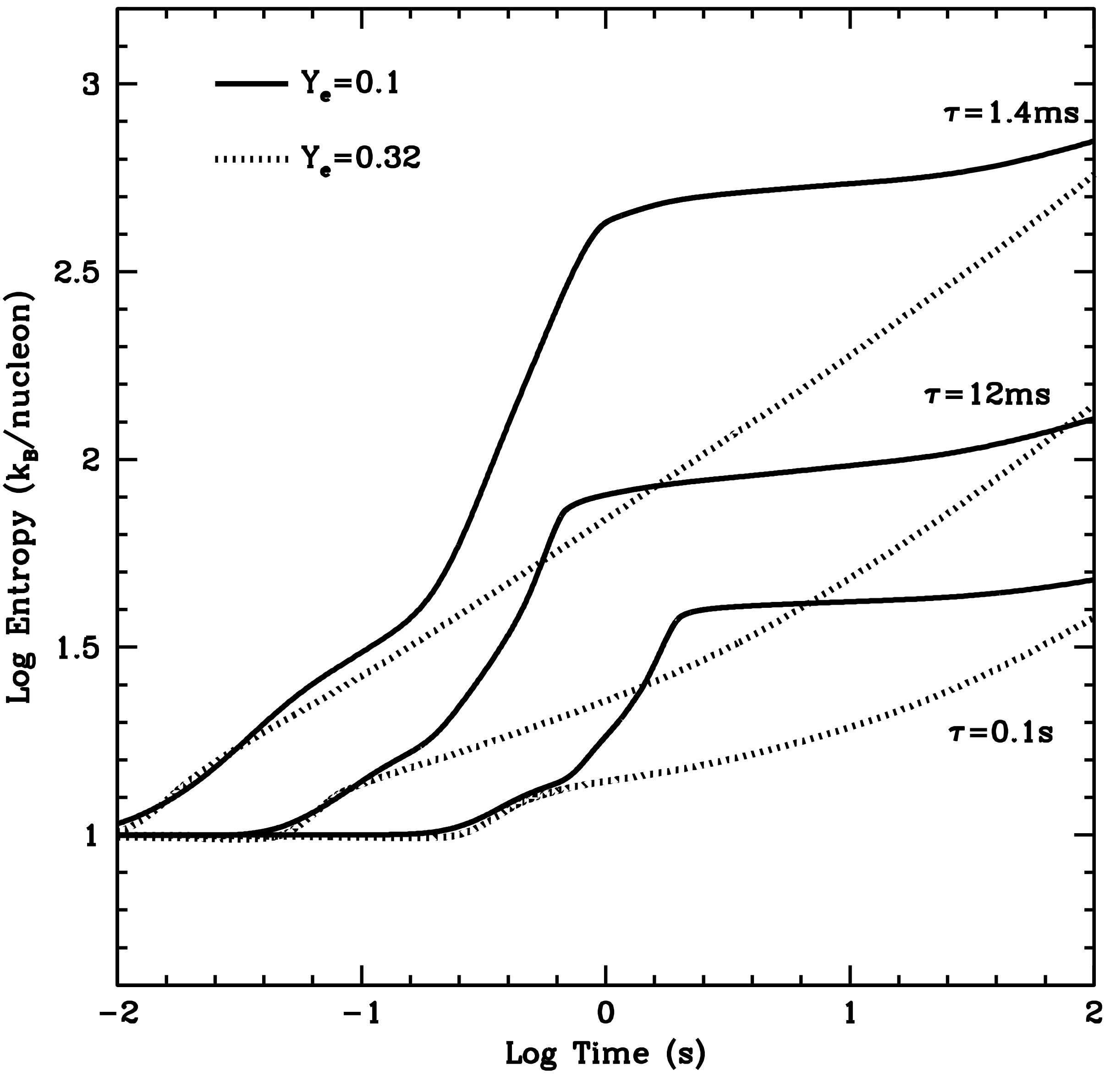

Figure 1: *Entropy versus time for 6 ejecta trajectories assuming two different electron fractions ($Y_e = 0.1, 0.325$) and 3 different expansion timescales ($\tau = 1.4, 12.0, 100.0\,s$). The evolution of the entropy and its total increase is lower for slower trajectories (with higher values of τ).*

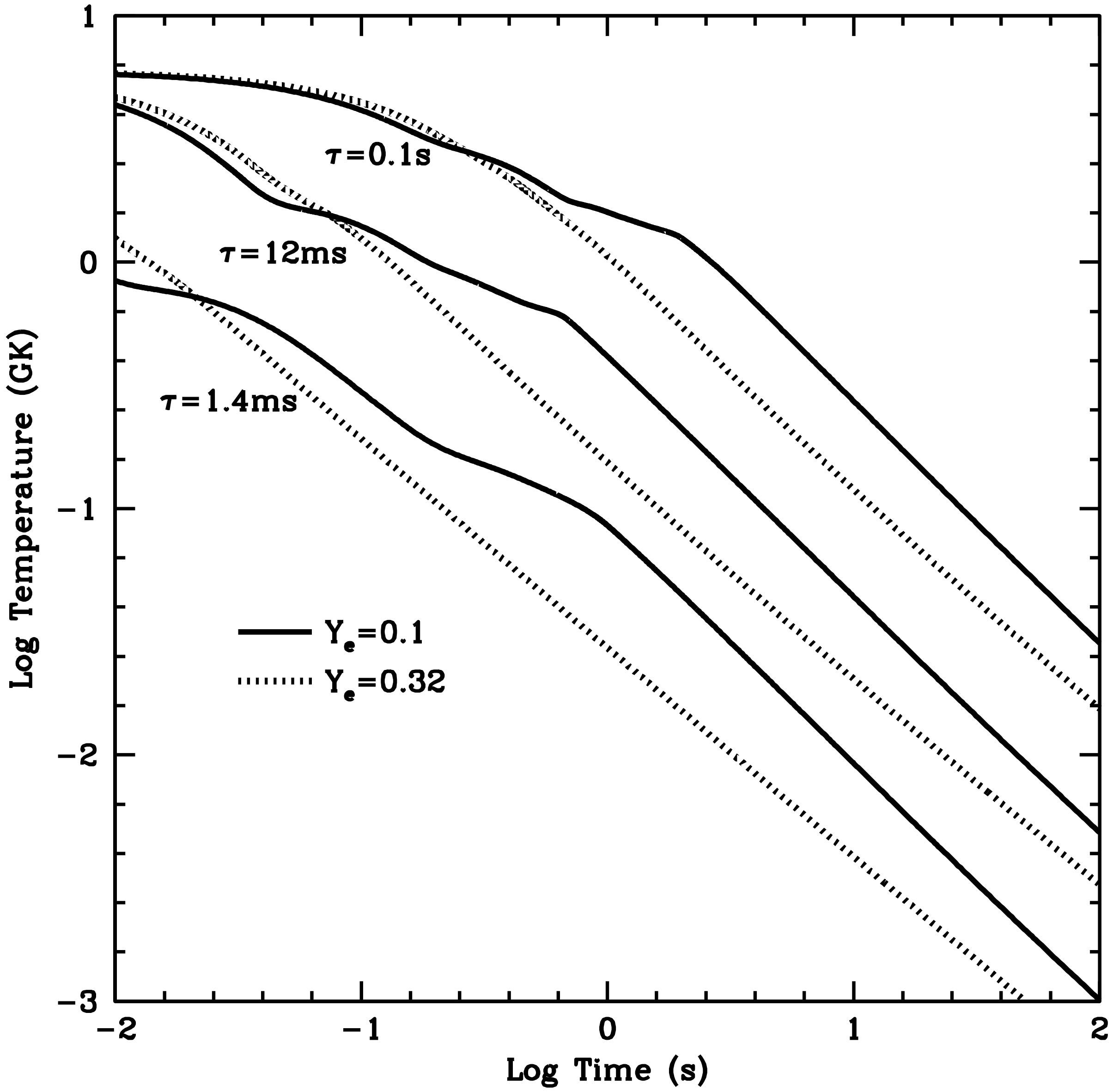

Figure 2: *Temperature versus time for 6 ejecta trajectories assuming two different electron fractions ($Y_e = 0.1, 0.325$) and 3 different expansion timescales ($\tau = 1.4, 12.0, 100.0\,s$). The evolution of the entropy and its total increase is lower for slower trajectories (with higher values of τ).* 62

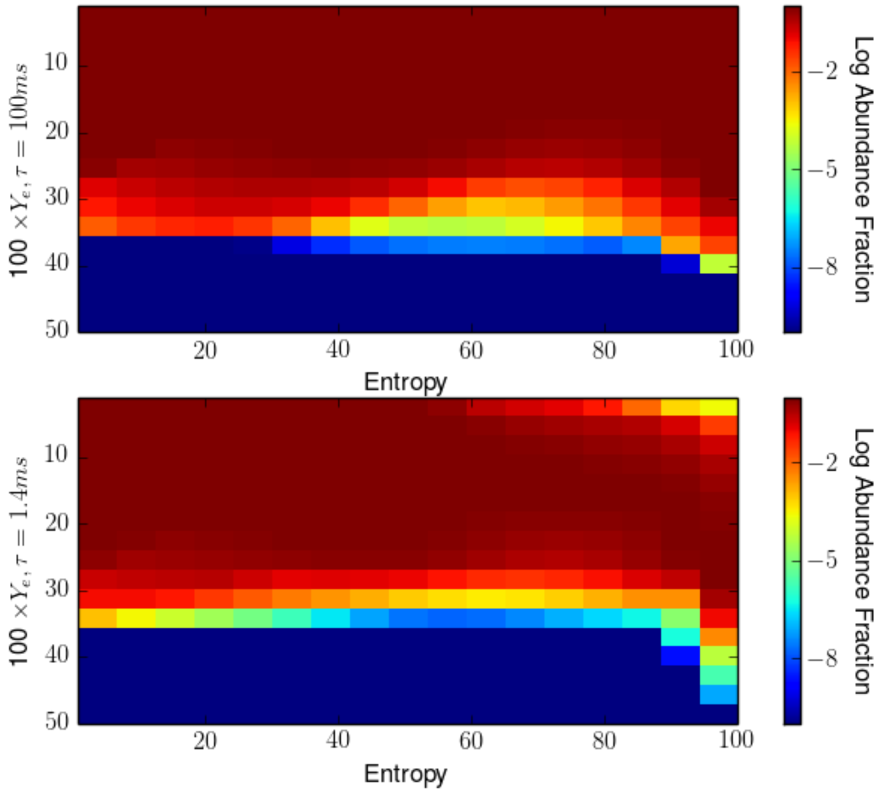

Figure 3: *Production of isotopes with average masses lying between 120 and 249 atomic mass units as a function of entropy (x-axis) and electron fraction (y-axis) for 2 different evolution timescales. For electron fractions below* ~ 0.3*, the production of these heavy r-process elements is high. It is possible to produce heavy r-process at higher electron fractions at high entropies.*

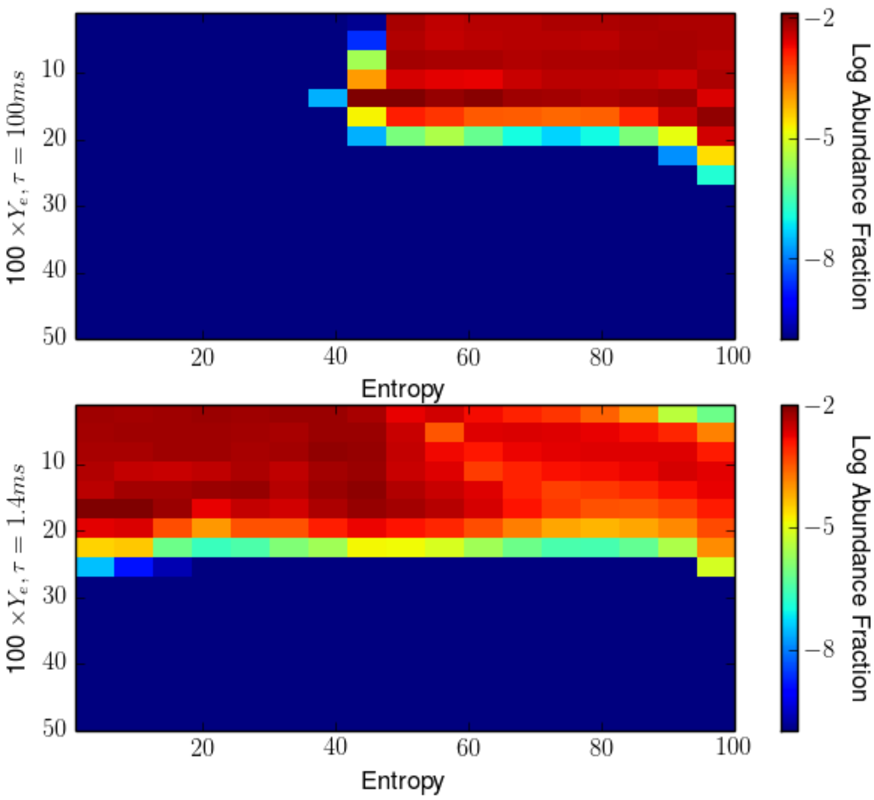

Figure 4: *Production of very heavy elements (*$A > 249$*) as a function of electron fraction, entropy, and evolution time (same parameters as in Figure 3). Lower electron fractions are needed to make these super-heavy r-process elements:* $Y_e < 0.25$*. In addition, the production of these heavy elements depends on both the entropy and the timescale. Note that there is not a generic trend in this production: for long evolution timescales, high entropies are needed, for short evolution timescales, lower entropies produce more super-heavy r-process elements.*

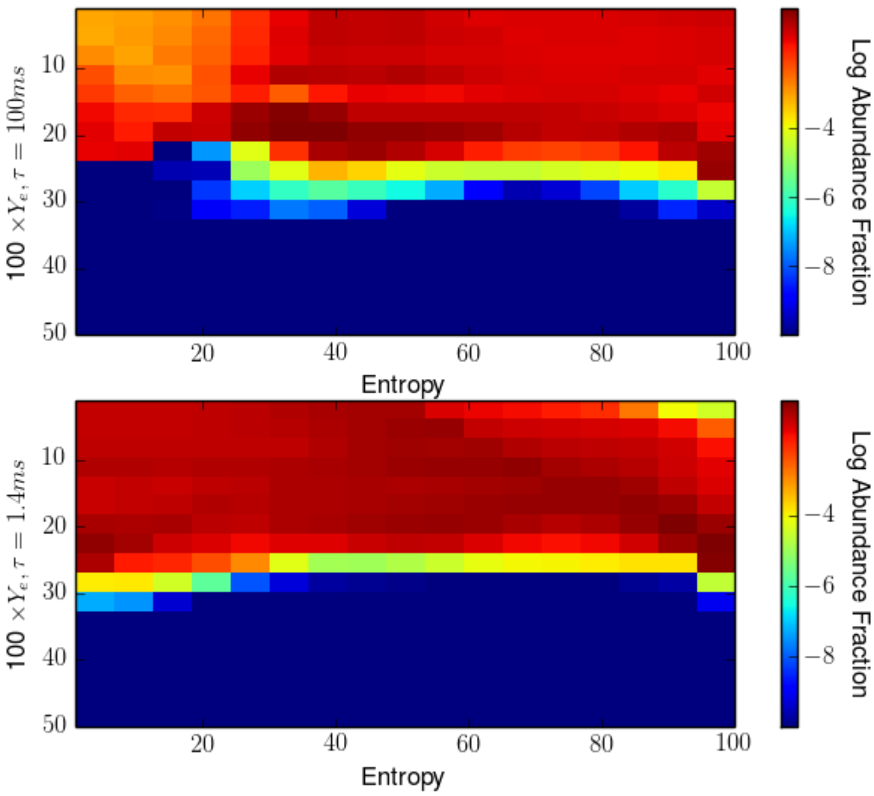

Figure 5: *Production of Lanthanides* ($57 < Z < 72$)*as a function of electron fraction, entropy, and evolution time (same parameters as in Figure 3). Lanthanide production lies somewhere in between very heavy r-process and the total r-process production requiring slightly lower electron fractions than the total r-process production. In addition, the production has additional variation based on both the entropy and the timescale.*