r-Process Nucleosynthesis in Black Hole–Neutron Star Mergers with Neutrinos

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1. Introduction

Black hole–neutron star (BHNS) mergers produce gravitational waves [1] and are a possible site for r-process nucleosynthesis [2–4], ejecting $\sim 0 - 0.2\, M_\odot$ depending on the black hole mass and spin [5–7]. Neutrinos emitted from the hot accretion disk can impact the nucleosynthesis [8]. We investigate r-process nucleosynthesis in BHNS merger ejecta with different levels of neutrino irradiation.

2. BHNS merger and ejecta simulation

The BHNS merger simulation was carried out with the fully relativistic code *SpEC* [9] using a neutrino leakage scheme [6, 10] and the LS220 equation of state (EOS) [11]. Fig. 1 shows the disrupted neutron star at $\sim$5 ms after merger. We continue to evolve the ejecta with the Newtonian smoothed particle hydrodynamics (SPH) code *StarSmasher* [12, 13]. Fig. 2 shows a snapshot of the SPH evolution.

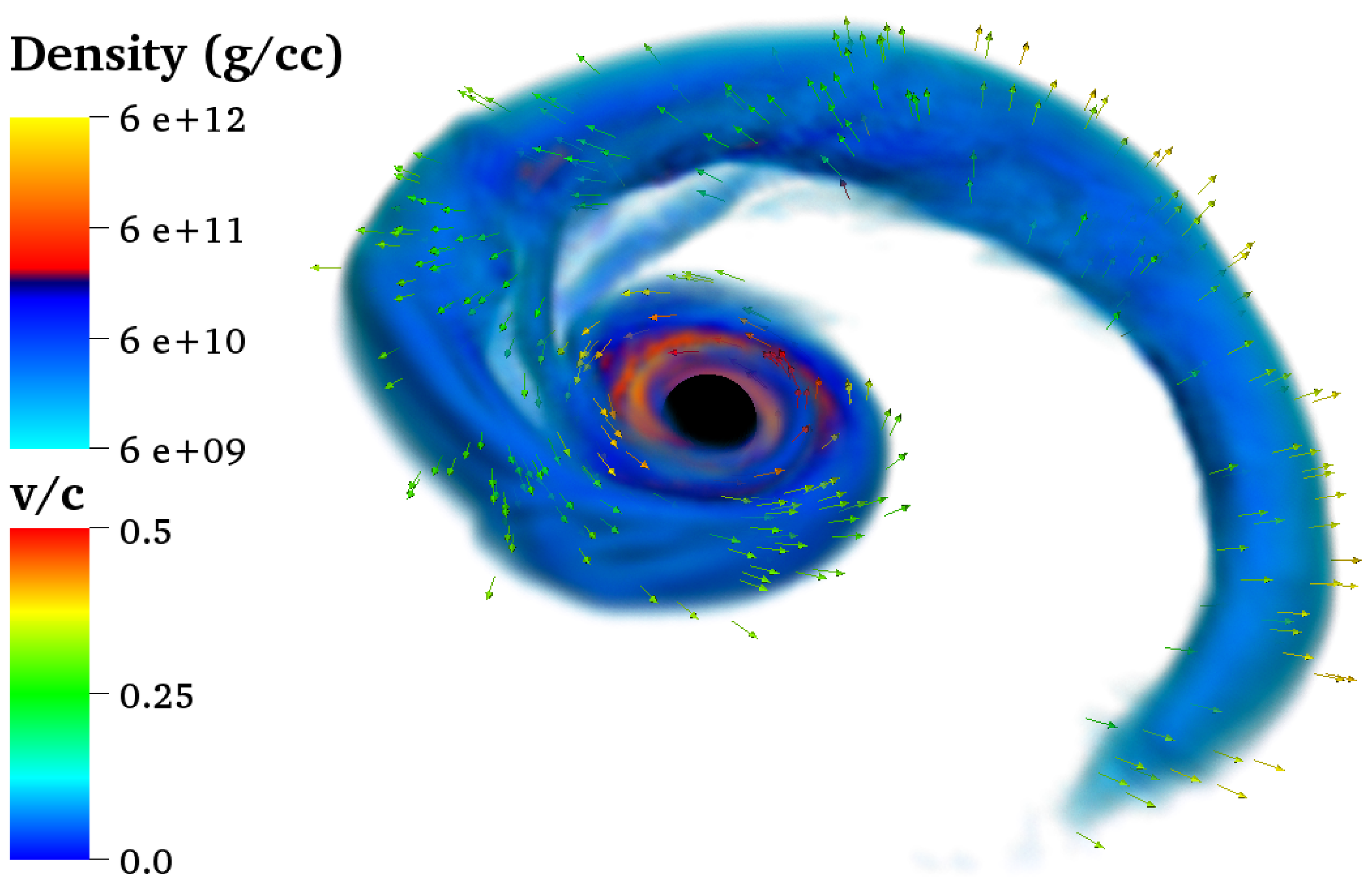

Figure 1: Volume rendering of the BHNS merger. From [6].

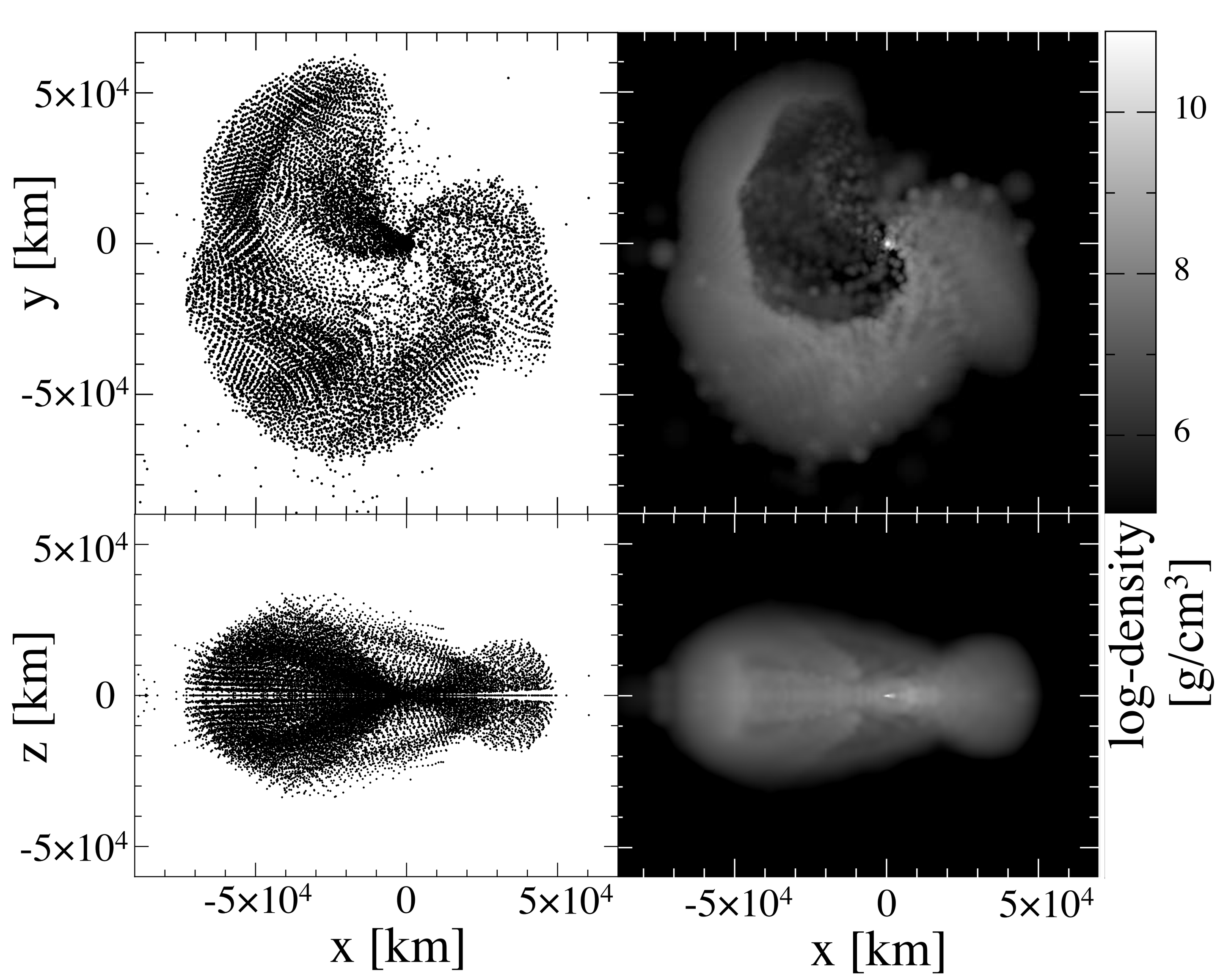

Figure 2: Snapshot of the SPH evolution of the ejecta. From [14].

3. Nucleosynthesis

For the nucleosynthesis calculation, we use *SkyNet* [15] to post-process each unbound SPH trajectory starting from nuclear statistical equilibrium (NSE). Assuming homologous expansion, we extend the density histories as $\rho \propto t^{-3}$. We use different constant neutrino luminosities L_{ν_e} and $L_{\bar{\nu}_e} = 1.5\, L_{\nu_e}$ with $\langle E_{\nu_e} \rangle, \langle E_{\bar{\nu}_e} \rangle = 12, 15\,\mathrm{MeV}$. We evolve 7843 nuclear species and 110,000 reactions with *SkyNet*, using rates from REACLIB [16], symmetric fission rates from [17, 18], weak rates from [19–21], and neutrino capture rates from [22]. *SkyNet* includes a multi-species, non-degenerate ideal gas EOS [15, 23]. Fig. 3 shows a snapshot of an example *SkyNet* evolution.

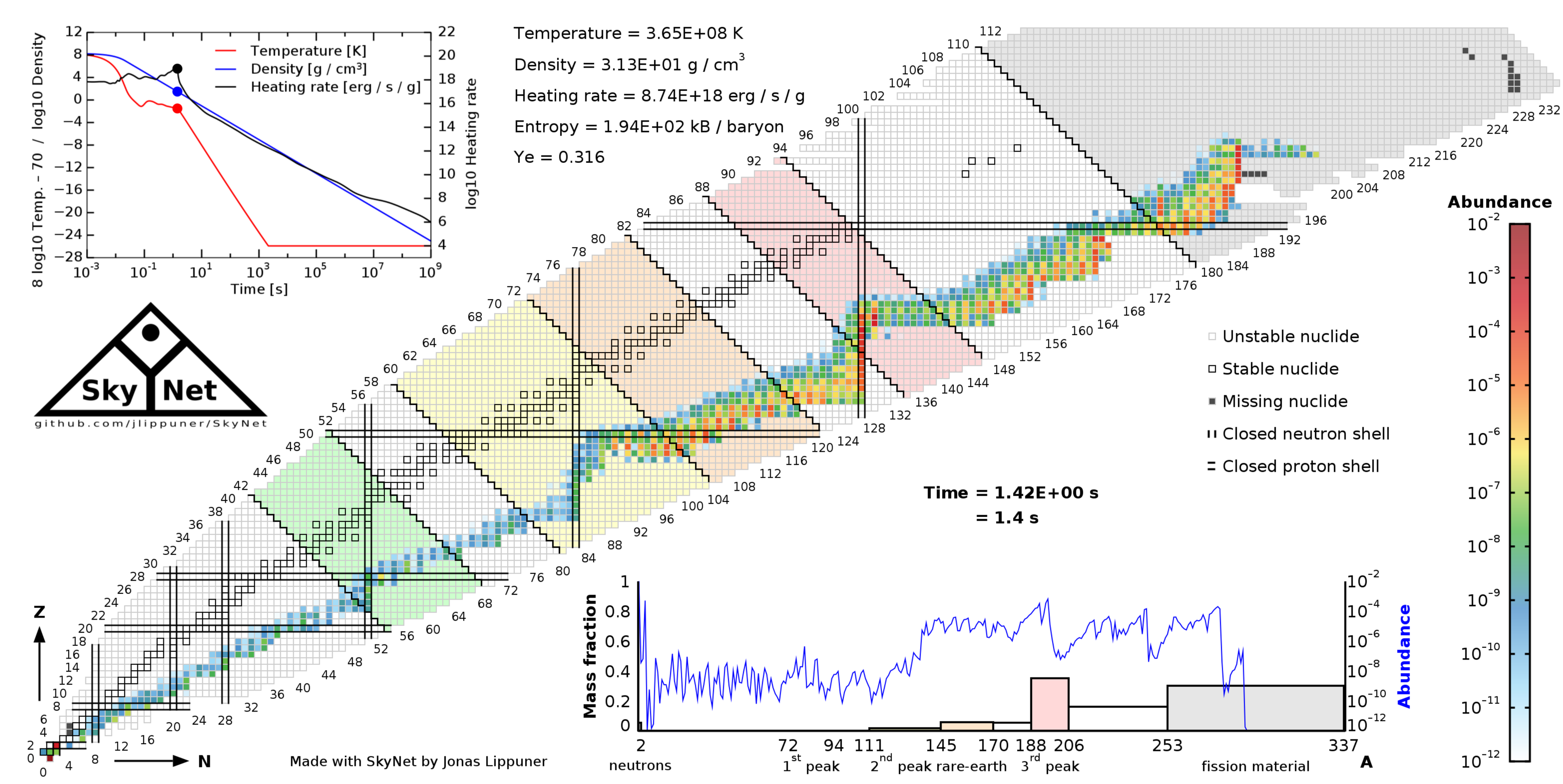

Figure 3: Snapshot of nucleosynthesis evolution with *SkyNet*. From [15].

4. Results

All trajectories robustly produce the full r-process (2nd and 3rd peaks) and match the observed solar r-process abundances [24] fairly well. The final abundances are identical for different neutron star masses, black hole masses, and black hole spins. Neutrinos have no effect on abundances above $A \sim 90$, but an increased neutrino luminosity significantly enhances the first peak ($A \sim 80$). Fig. 4 shows the final abundances for different neutrino luminosities.

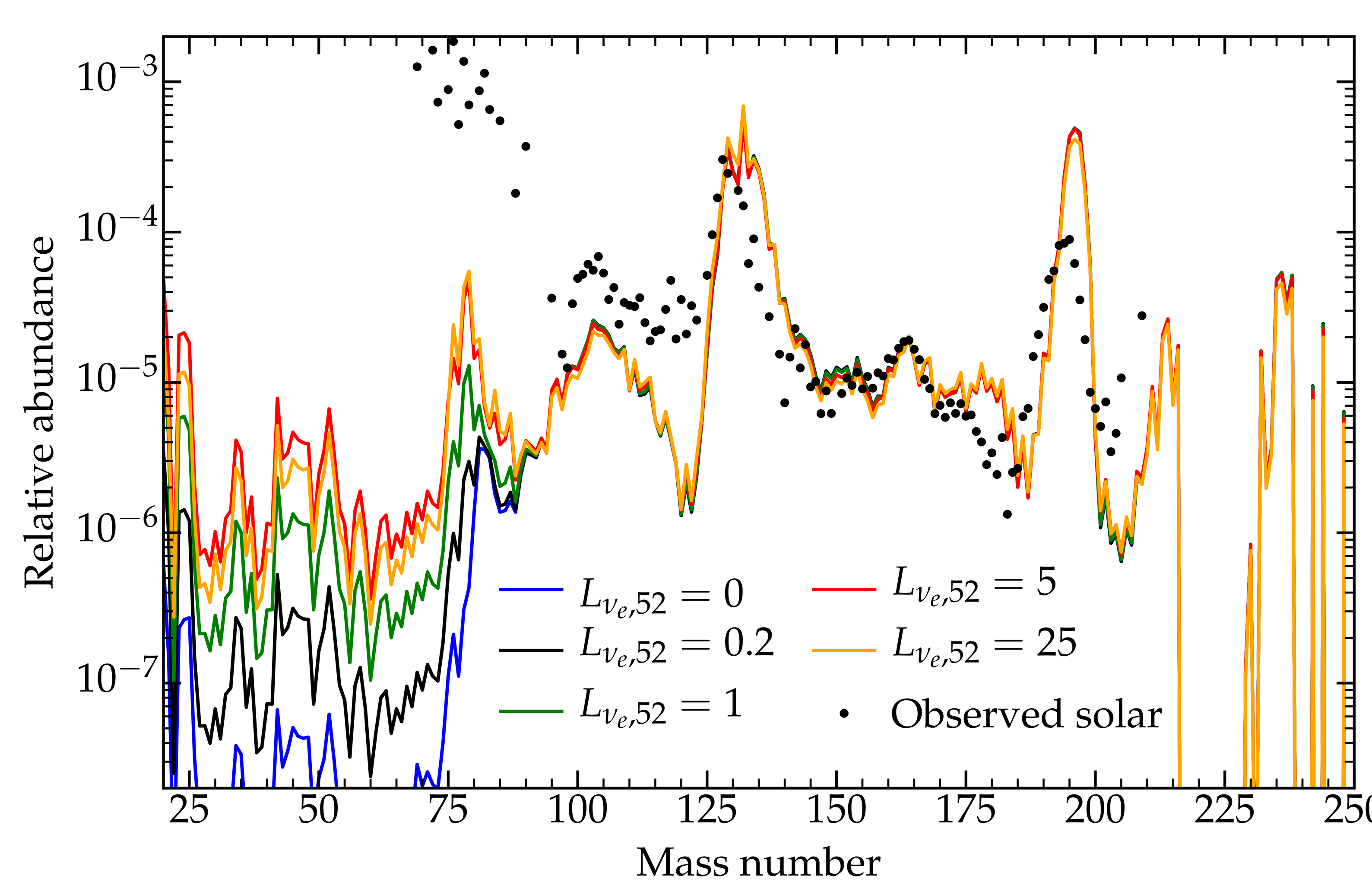

Figure 4: Final abundances for different neutrino luminosities. From [14].

5. Novel first peak production mechanism

In binary neutron star mergers, neutrinos push the Y_e distribution above 0.25, which introduces an incomplete r-process that enhances the first peak and reduces the 2nd and 3rd [e.g. 25–27]. But the BHNS ejecta expands so quickly that even $L_{\nu_e} = 2.5 \times 10^{53}\,\mathrm{erg\,s^{-1}}$ does not push Y_e past 0.25 (c.f. Fig. 5) and we still obtain the full r-process. Instead, neutrinos convert some neutrons to protons, which quickly form alpha particles and then ^{12}C. Neutrons capture on these additional low-mass seed nuclei to enhance the first peak (seed nuclei from NSE have $A \gtrsim 80$). Neutrons are exhausted before the low-mass seed nuclei can be processed past the first peak.

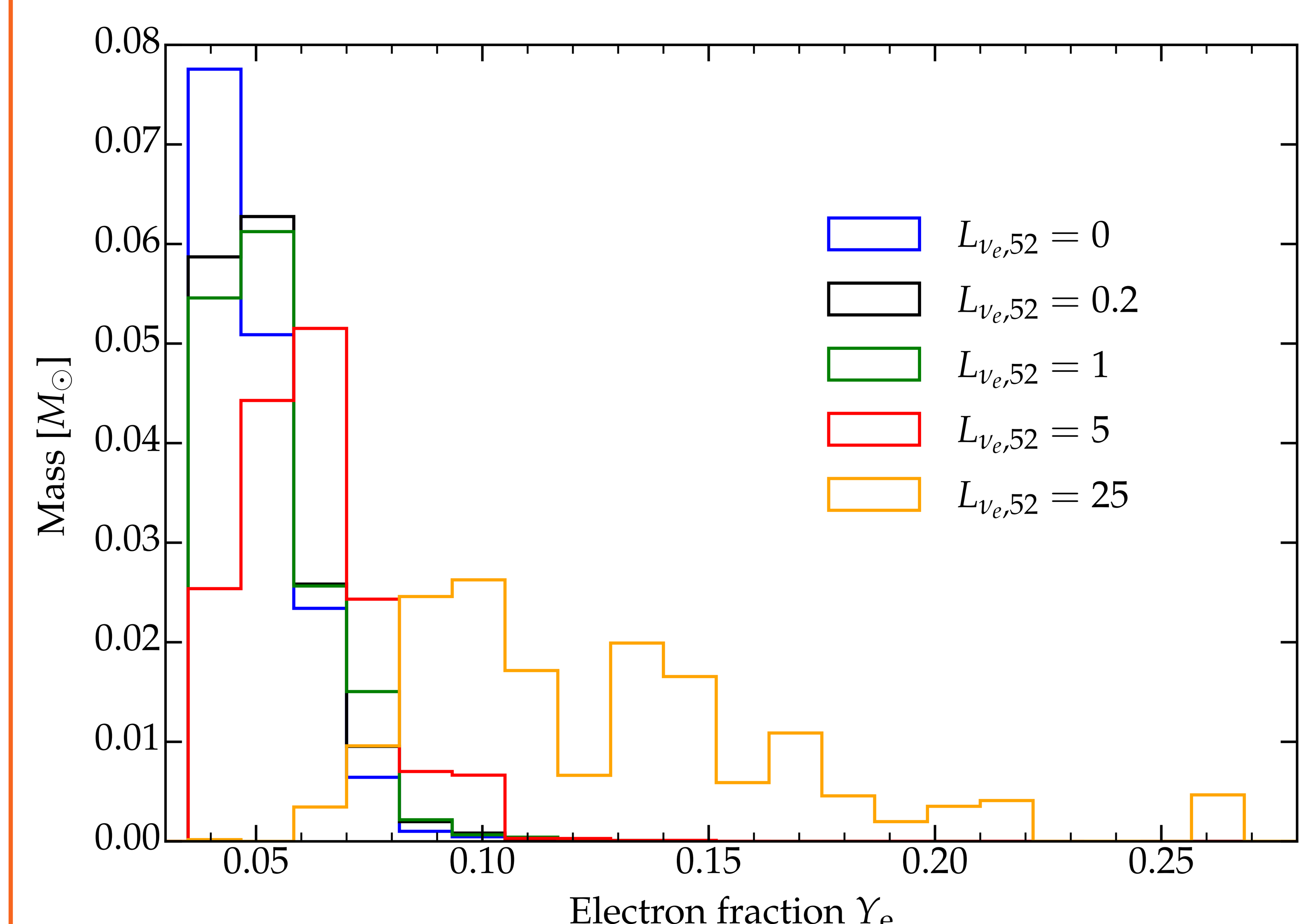

Figure 5: Y_e distribution for different neutrino luminosities. From [14].

6. Conclusion

We have mapped the ejecta from a fully relativistic BHNS merger simulation into a Newtonian SPH code and run nucleosynthesis with *SkyNet* in the resulting trajectories with different neutrino luminosities. We find that the full r-process is produced in all cases and unaffected by neutrinos. But the first peak is significantly enhanced with increasing neutrino irradiation due to a new first peak production mechanism in which neutrinos produce additional low-mass seed nuclei but do not affect the abundances above $A \sim 90$.

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