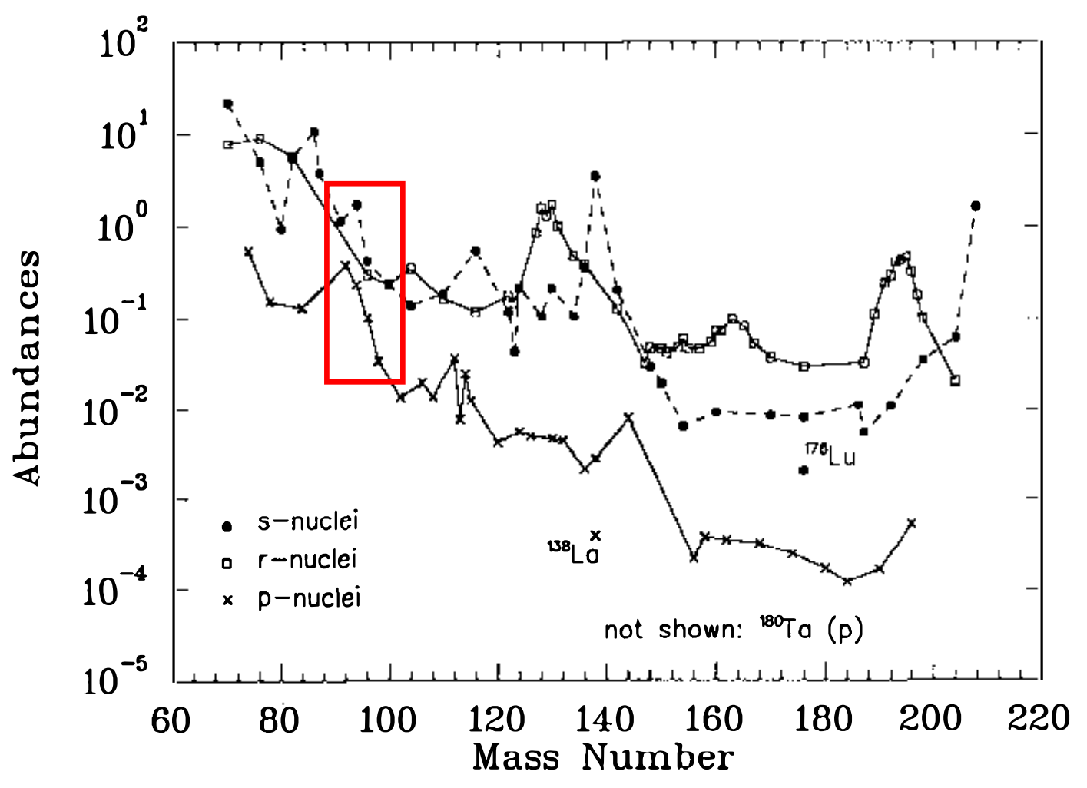

Neutrino flavor equilibration and νp-process nucleosynthesis in core-collapse supernovae

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1. Abstract

An enduring mystery in nuclear astrophysics pertains to the relatively high observed abundances of the proton-rich isotopes ^{92,94}Mo and ^{96,98}Ru. **An attractive proposal to solve this problem is called the νp-process** [1]. This process could operate in a core-collapse supernova (CCSN) hot bubble, formed by a neutrino-driven matter outflow from the surface of the protoneutron star (PNS) after the shock is launched. The precise outcome of this process depends on the physical conditions in the outflow and on the characteristics of the neutrino emission. **Here, we examine the effects of neutrino flavor equilibration near a PNS on νp-process yields.** This may arise, e.g., due to "fast" neutrino flavor conversions near a supernova core [2, 3].

2. The νp-process and the origin of proton-rich nuclides

The observed abundances of most of the naturally occurring proton-rich isotopes are likely to be accounted for by photodisintegration of pre-existing neutron-rich nuclides, but **^{92,94}Mo and ^{96,98}Ru have anomalously high abundances** to fit that pattern.

This motivates pathways involving proton captures on seed nuclei (e.g., ^{56}Ni), and the required physical conditions point to neutrino-driven outflows from core-collapse supernovae as natural candidate sites. The νp-process hypothesis is based on the observation that the CCSN outflows are accompanied by large ν_e and $\bar{\nu}_e$ fluxes. In some situations, **the outflows can be proton-rich, and $\bar{\nu}_e$ capture on protons creates a small but significant neutron population, enabling (n,γ) and (n,p) reactions which bypass the β-decay 'waiting points' (e.g., ^{64}Ge) of the classic rp-process and make p-rich nuclides well beyond the iron peak.**

3. Variability in yields

The νp-process viability in explaining the ^{92,94}Mo and ^{96,98}Ru solar-system abundances has been questioned, citing failures of numerical treatments to reproduce the observed isotopic ratios, as well as the required absolute yields [4], particularly in light of in-medium enhancements of the triple-α reaction rate [5].

A possible resolution lies in the dependence of the νp-process yields on the physical properties of the neutrino-driven outflow, such as the expansion timescale, entropy, electron fraction, and on the neutrino luminosities and energy spectra [6]. In a self-consistent model, these parameters depend on one another through a set of coupled hydrodynamical equations. In particular, **subsonically expanding neutrino-driven outflows show considerably better νp-process prospects compared to supersonic outflows**, potentially overcoming the aforementioned difficulties [7].

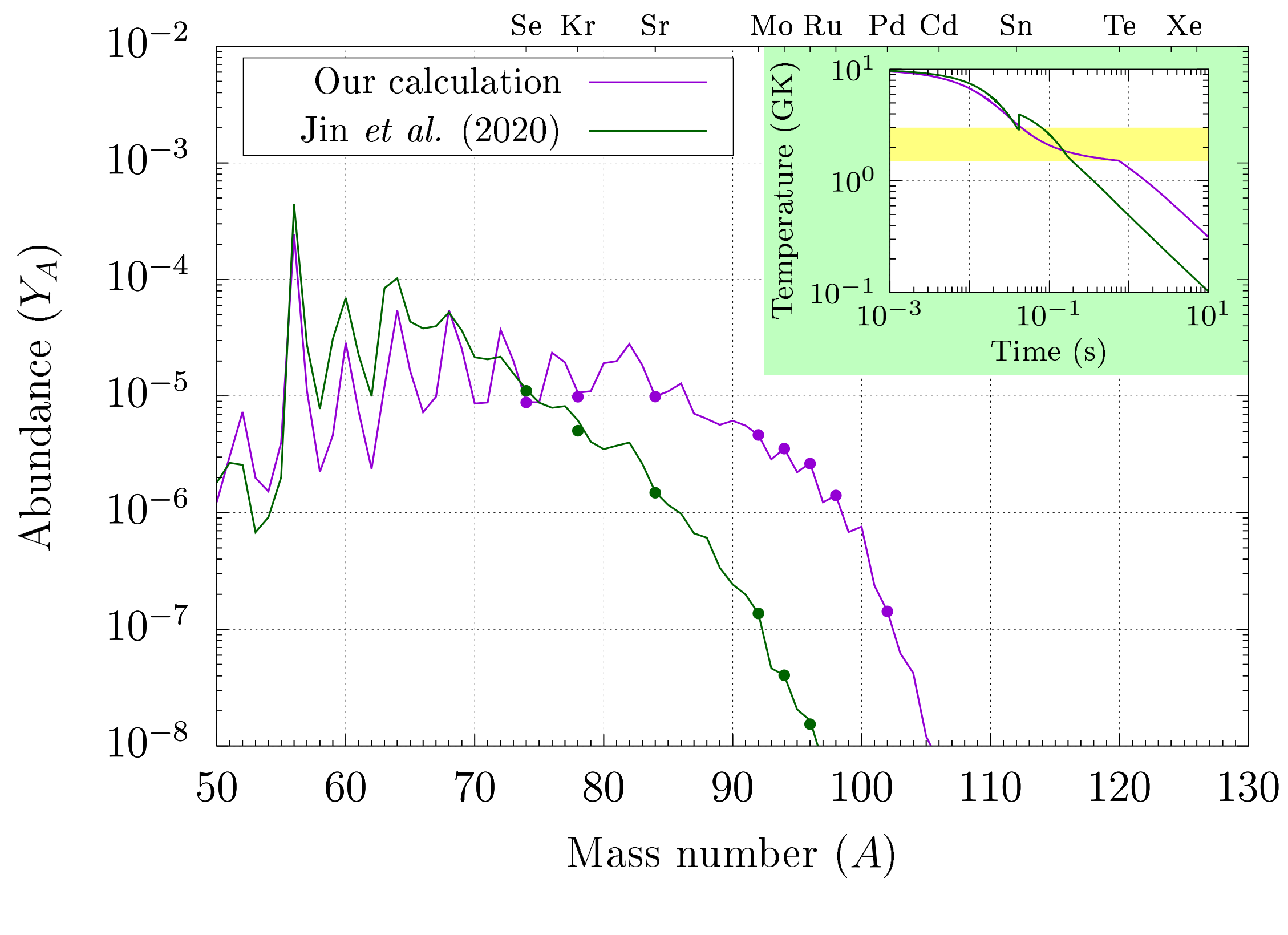

Figure 1: νp-process calculations with subsonic (purple) and supersonic (green) outflow profiles.

4. Electron fraction ramifications

The νp-process efficacy depends on: (i) the proton-to-seed ratio at $T \simeq 0.3$ MeV during freeze-out from nuclear quasi-equilibrium (QSE), and (ii) the integrated $\bar{\nu}_e$ fluence during the interval when $0.3\,\text{MeV} \gtrsim T \gtrsim 0.1$ MeV. The nuclear composition of a p-rich outflow at 0.3 MeV consists of mainly protons, α particles, and seed nuclei, and one of the factors setting their relative abundances is the proton fraction prior to freeze-out from nuclear statistical equilibrium (NSE), at $T \simeq 0.6$ MeV.

The electron (or proton) fraction (Y_e) prior to NSE freeze-out is set by a competition between ν_e and $\bar{\nu}_e$ capture rates. Since $\bar{\nu}_e$ have higher average energies than ν_e, a luminosity hierarchy $L_{\nu_e} > L_{\bar{\nu}_e}$ is required for proton-richness ($Y_e > 0.5$). Moreover, **any mechanism that enhances the ν_e average energies, such as mixing between ν_e and the more energetic $\nu_{\mu,\tau}$ flavors, could make the outflow more proton-rich, improving the νp-process efficacy.**

5. Outflow and neutrino mixing model

We use a subsonic outflow profile derived self-consistently from the hydrodynamical equations, with choices of boundary conditions and neutrino emission characteristics guided by state-of-the-art numerical CCSN simulations. Neutrino mixing is implemented through a simple scheme where complete flavor equilibration among ν_e, ν_μ, and ν_τ (and among $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$) occurs sharply at a radius R_{mix}, so that the energy distributions of each flavor at $r > R_{\text{mix}}$ are given by $(f_{\nu_e} + f_{\nu_\mu} + f_{\nu_\tau})/3$, where $f_{\nu_\alpha}(E)$ are the initial distributions.

6. Neutrino flavor equilibration and the νp-process

We examine the effect of neutrino mixing over three regimes: (a) before NSE freeze-out ($T \gtrsim 0.6$ MeV), (b) between NSE freeze-out and QSE freeze-out ($0.6\,\text{MeV} \gtrsim T \gtrsim 0.3$ MeV), and (c) after QSE freeze-out ($0.3\,\text{MeV} \gtrsim T \gtrsim 0.1$ MeV). Increasing the ν_e and $\bar{\nu}_e$ average energies (by flavor mixing) can lead to different effects across these regimes. Typically, the hierarchy between the average ν_e and $\nu_{\mu,\tau}$ energies is a lot more pronounced than that between $\bar{\nu}_e$ and $\bar{\nu}_{\mu,\tau}$. As a result, flavor equilibration increases the ν_e average energy much more than it does for $\bar{\nu}_e$.

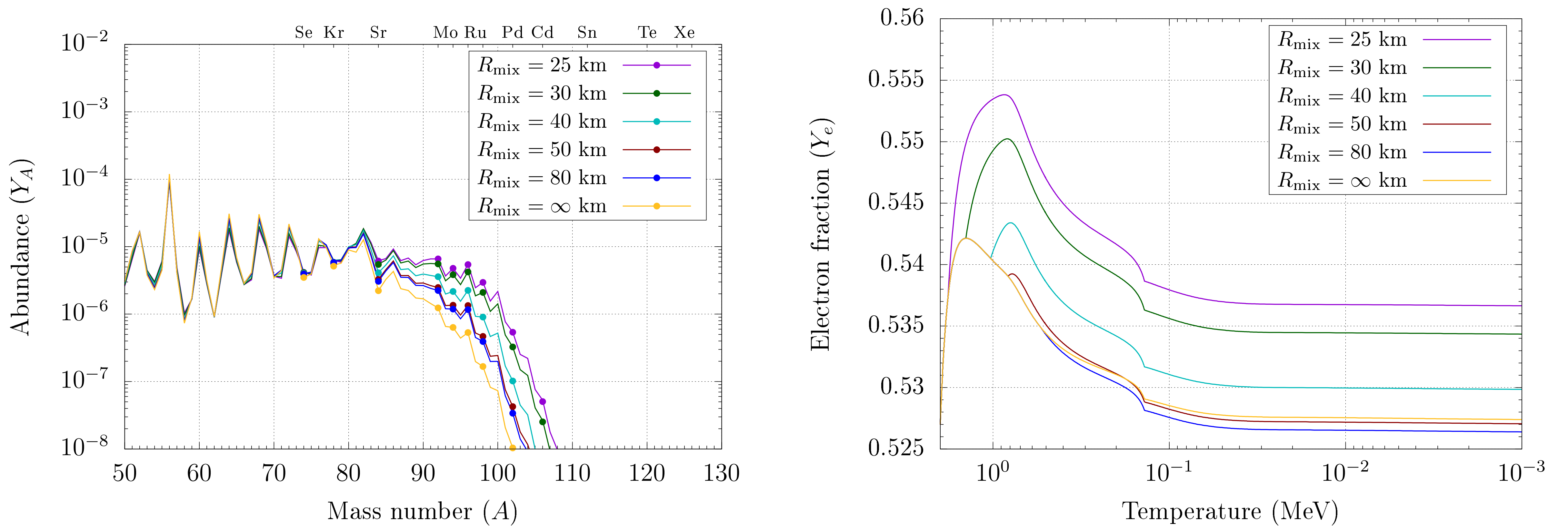

Figure 2: Nucleosynthesis calculations with different flavor equilibration radii R_{mix}. **Left:** Abundance vs Mass number. **Right:** Electron fraction vs Temperature.

In regime (a), flavor mixing increases the $\nu_e(n,e^-)$ capture rate, and drives Y_e higher, increasing the number of protons left behind after NSE freeze-out. This leads to a higher proton-to-seed ratio at $T \simeq 0.3$ MeV, and therefore a more robust νp process. In (b) and (c), the $\nu_e(n,e^-)$ rates lose their importance because of neutron depletion during α-particle formation, and therefore the effect of mixing is felt via the slight enhancement of the $\bar{\nu}_e(p,e^+)$ rate. In regime (b), mixing causes a slight depletion of protons relative to seeds; however, increased neutron production during (c) results in a net positive effect on the νp-process. In our model, we study these different effects by varying the radius R_{mix} of flavor equilibration. **Flavor equilibration is found to universally improve the νp-process efficacy, more so if it occurs closer to the PNS surface.** This motivates future studies coupling fast-flavor transformations of neutrinos to a nucleosynthesis network.

References/Acknowledgements

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