Neutrinos in supernovae: flavor mixing and νp-process nucleosynthesis

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PHYSICS FRONTIER CENTER
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Outline

1. Core-collapse supernovae and neutrinos
2. Neutrino flavor oscillations in core-collapse supernova environments
3. Origin of proton-rich elements, and νp-process nucleosynthesis
4. Outflow hydrodynamics to the rescue... with a little help from neutrino mixing

Core-collapse supernovae and neutrinos

- Stars with $M_\star \gtrsim 8\,M_\odot$ undergo core collapse when core mass exceeds $\sim 1.4\,M_\odot$, i.e., when gravity overcomes electron degeneracy pressure support
- Core bounce at nuclear density sends shockwave through infalling material $\rightarrow$ shock eventually loses energy and stalls before it can blow up the star
- Details of the explosion mechanism unknown, but neutrinos expected to play a major role
- CCSNe are neutrino factories: νs are the main carriers of gravitational binding energy ($\sim 99\%$) and lepton number radiated away from the star
  - B.E. $\sim 10^{53}$ ergs $\implies \sim 10^{58}$ νs with $\langle E_\nu \rangle \sim 10$ MeV

Core-collapse supernovae and neutrinos

- Neutrinos depositing $\sim 1\%$ of their energy behind the stalled shock front could revive the shock and explode the star
- ν-induced heating in the aftermath of explosion drives baryonic matter outflows from the surface of the nascent neutron star
- Charged-current weak processes govern the energy deposition and n/p ratio, a crucial input for nucleosynthesis

$$\nu_e + n \longleftrightarrow p + e^-$$
$$\bar{\nu}_e + p \longleftrightarrow n + e^+$$

- Flavor asymmetric processes: thorough understanding of neutrino flavor evolution therefore required

Stages of neutrino emission from CCSN

- Late stages of nuclear burning (C/O onwards), via e-pair annihilation, plasmon decay, bremsstrahlung, etc. ($t_{pb} \ll 0\,$s)
- Early stages of core-collapse (via neutronization), before onset of neutrino trapping ($t_{pb} \sim 0$ s)
- During shock-breakout (neutronization "burst") — peak neutrino luminosity, albeit mostly in ν_e flavor ($t_{pb} \sim 10$ ms)
- Pre-explosion accretion phase ($t_{pb} \sim 100$–$500\,$ms)
- Late-time PNS cooling phase ($t_{pb} \sim 1$–$10\,$s)

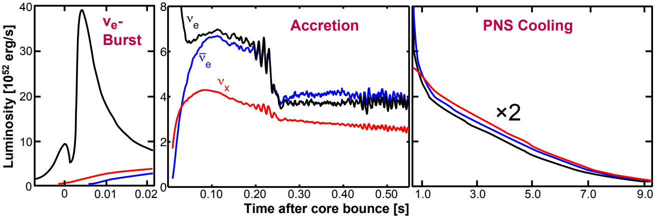

Figure: Taken from H.-T. Janka (1702.08713).

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Neutrino oscillations in supernovae

- Role of neutrinos in transporting energy and lepton number during various stages of SN is obscured by flavor oscillations, which can exhibit collective phenomena in environments with large neutrino densities

$$i\frac{\partial \rho}{\partial t} = [H, \rho],$$

where $H = H_{\text{vac}} + H_{\text{mat}} + H_{\nu\nu}$

- In the free-streaming region, these collective effects are driven by coherent ν-ν forward scattering: this brings in nonlinearity and a geometric complexity to the problem

$$H_{\nu\nu} = \sqrt{2} G_F \sum_{\alpha} \Big[\int_{\nu} dn_{\nu,\alpha}\, \rho_{\nu,\alpha}(\boldsymbol{p}')(1 - \hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{p}}') - \int_{\bar{\nu}} dn_{\bar{\nu},\alpha}\, \rho_{\bar{\nu},\alpha}(\boldsymbol{p}')(1 - \hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{p}}') \Big]$$

Collective flavor oscillations: synchronized and bipolar

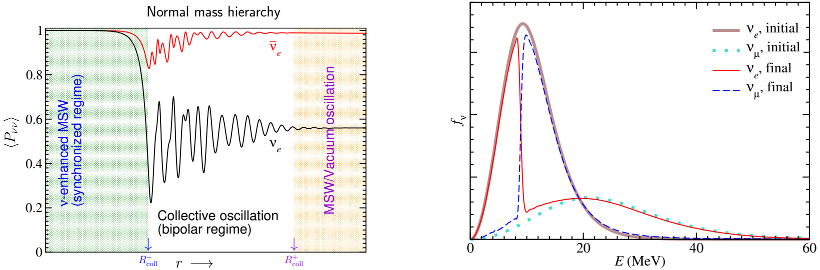
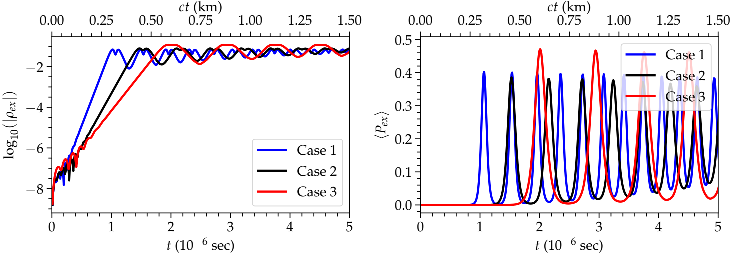


Figure: Taken from Duan et al. (1001.2799). **Left:** regimes for different types of neutrino oscillations in a CCSN environment. **Right:** a neutrino spectral split/swap resulting from collective flavor effects.

"Fast" collective flavor transformations

- In addition, "fast" collective flavor oscillations — driven by electron-lepton number crossings in the angular distributions of ν_e and $\bar{\nu}_e$, could lead to significant flavor conversion on timescales much shorter than bipolar oscillations, i.e., within $\mathcal{O}(1\text{–}10\text{s})$ of km from the PNS, making them more relevant for shock reheating and nucleosynthesis
- Recent reviews by Tamborra and Shalgar (2011.01948) and Richers and Sen (2207.03561)



Other cool problems in supernova neutrino oscillations

- Collisionally triggered collective flavor instabilities (Lucas Johns et al.: 2104.11369, 2206.09225, 2208.11059)
- 'Halo' effect from backscattered neutrinos (J. F. Cherry et al.: 1203.1607, 1302.1159, 1908.10594, 1912.11489; V. Cirigliano et al.: 1807.07070)
- Quantum entanglement and many-body collective effects (Patwardhan, Cervia, Balantekin, Siwach, Coppersmith, Johnson, Lacroix et al.: 1905.04386, 1908.03511, 2109.08995, 2202.01865, 2205.09384; Rrapaj, Roggero, Xiong, et al.: 1905.13335, 2102.10188, 2102.12556, 2103.11497, 2111.00437, 2112.12686, 2203.02783, 2207.03189 — some of these involve simulating collective neutrino oscillations on a quantum computer)

Outline

Chart of the nuclides

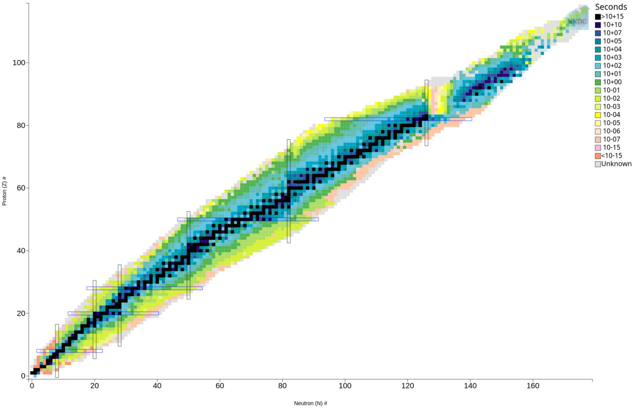


Figure: Chart of Nuclides - National Nuclear Data Center

Chart of the nuclides

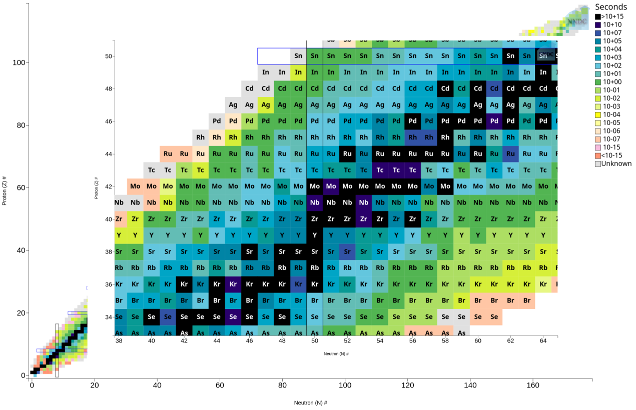


Figure: Chart of Nuclides - National Nuclear Data Center

Proton-rich heavy elements in nature

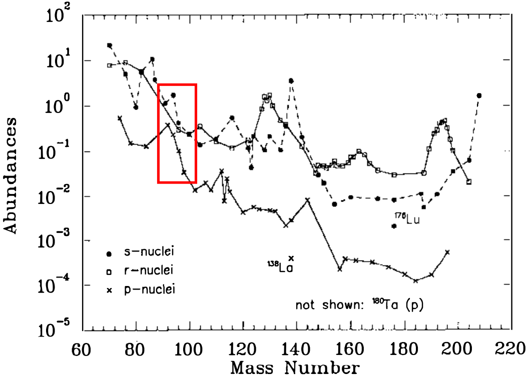


Figure: The solar system abundances of r-nuclei, s-nuclei, and p-nuclei (B. S. Meyer, Annu. Rev. Astron. Astrophys. 1994. 32: 153–190). Most p-nuclides have abundances 1–2 orders of magnitude lower than nearby s- and r-process (neutron-rich) nuclides. Except for ^{92,94}Mo and ^{96,98}Ru.

Synthesis of p-rich nuclides

- Consistent ratio of p-rich/n-rich abundances suggests that transmutation of previously formed n-rich nuclides (e.g., via photodistintegration) could explain p-nuclide origin — apart from the anomalously high abundances near the ^{92}Mo peak
  - γ-process [Woosley & Howard (1978)]: photodisintegration of neutron rich isotopes. Occurs during explosive O/Ne shell burning in massive stars, or in exploding white dwarfs (type-Ia supernovae). Could account for most p-nuclides and some ^{92}Mo but not enough ^{94}Mo and ^{96,98}Ru
  - ν-process [Woosley *et al.* (1990); Fuller & Meyer (1995)]: transmutation of stable nuclei via neutrino captures in core-collapse supernovae. Outflowing material must remain close to NS for long time to ensure high neutrino fluence
- If transmutation of n-rich nuclides isn't enough to account for ^{92,94}Mo and ^{96,98}Ru, then could proton capture be the answer?

Proton capture nucleosynthesis

- Heavy-element nucleosynthesis via proton capture requires specific conditions:
  1. Prevalence of free protons to capture on seed nuclei, e.g., ^{56}Ni
  2. Temperatures high enough to overcome Coulomb barriers, but low enough to be out of nuclear quasi-equilibrium: $1.5\,\text{GK} < T < 3\,\text{GK}$
- Suggests that matter outflows from, e.g., core-collapse supernovae, could be candidate sites
- The classic rp-process: rapid proton captures interspersed by β^+ decays, is stalled by β^+ decay "waiting point" nuclei (e.g., ^{64}Ge) along the reaction flow, with lifetimes much longer than the outflow dynamical timescales [Wallace & Woosley (1981); Schatz *et al.* (1998)]

What about ^{92,94}Mo and ^{96,98}Ru?

- Transmutation of n-rich nuclides likely cannot explain the anomalously high abundances of ^{92,94}Mo and ^{96,98}Ru

- New mechanism proposed in 2005: the νp-process

PRL **96,** 142502 (2006) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2006

Neutrino-Induced Nucleosynthesis of $A > 64$ Nuclei: The νp Process

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We present a new nucleosynthesis process that we denote as the νp process, which occurs in supernovae (and possibly gamma-ray bursts) when strong neutrino fluxes create proton-rich ejecta. In this process, antineutrino absorptions in the proton-rich environment produce neutrons that are immediately captured by neutron-deficient nuclei. This allows for the nucleosynthesis of nuclei with mass numbers $A > 64$, making this process a possible candidate to explain the origin of the solar abundances of ^{92,94}Mo and ^{96,98}Ru. This process also offers a natural explanation for the large abundance of Sr seen in a hyper-metal-poor star.

DOI: 10.1103/PhysRevLett.96.142502 PACS numbers: 26.30.+k, 25.30.Pt, 97.60.Bw

The νp-process

- Matter outflows in core-collapse supernovae are accompanied by prodigious ν_e and $\bar{\nu}_e$ fluxes, and these outflows can be proton-rich in certain situations
- Seed nuclei up to ^{56}Ni are formed via freeze-out from nuclear quasi-equilibrium as the outflow cools to $T \sim 3\,$GK
- $\bar{\nu}_e$ capture on free protons (in a p-rich wind) converts a small fraction ($\sim$ few %) of protons into neutrons, triggering (n,p) and (n,γ) reactions to bypass the β^+ decay waiting points. These, combined with (p,γ), keep the flow moving along the rp chain for $3\,\text{GK} > T > 1.5\,\text{GK}$
- At $T \lesssim 1.5\,$GK, Coulomb barriers inhibit further (p,γ) reactions, and the νp-process ends

Favourable conditions for νp-process

Wanajo *et al.*, ApJ 729, 46 (2011)

1. Short time interval (τ_1) for $T > 3\,\mathrm{GK}$
2. High entropy-per-baryon ($S \gtrsim 70$) in the outflow
3. High electron (or proton) fraction ($Y_e > 0.55$)
4. Long time interval (τ_2) in the $3\,\mathrm{GK} > T > 1.5\,\mathrm{GK}$ band

(1)–(3) facilitate a high proton-to-seed ratio at the onset of the νp-process, and (4) leads to a larger integrated $\bar{\nu}_e$ fluence, furnishing more neutrons to drive the reaction flow towards higher mass numbers

See also:
Pruet *et al.*, ApJ 644, 1028 (2006)
S. Wanajo, ApJ 647, 1323 (2006)

However . . .

- Several questions raised in the intervening years regarding the νp-process efficacy

- Among these were reported difficulties in producing the correct isotopic ratios, as well as required absolute yields of ^{92,94}Mo and ^{96,98}Ru [e.g., Fisker *et al.* (2009), Bliss *et al.* (2018)]

- These issues became particularly dire with recent calculations [Jin et al., Nature vol. 588, pg. 57–60 (2020)] reporting heavy suppression of νp-process yields as a result of an in-medium enhancement of the triple-α reaction rate†.
  A nail in the coffin of the νp-process?

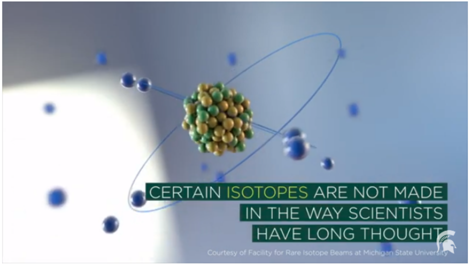
† **Note:** an enhancement in the $3\alpha \rightarrow ^{12}$C reaction rate leads to increased seed-nuclei formation and lowers the proton-to-seed ratio in the outflow, decreasing the νp-process potency

Elemental mystery

Supernova surprise creates elemental mystery

Michigan State University researchers have discovered that one of the most important reactions in the universe can get a huge and unexpected boost inside exploding stars known as supernovae.

This finding also challenges ideas behind how some of the Earth's heavy elements are made. In particular, it upends a theory explaining the planet's unusually high amounts of some forms, or isotopes, of the elements ruthenium and molybdenum.



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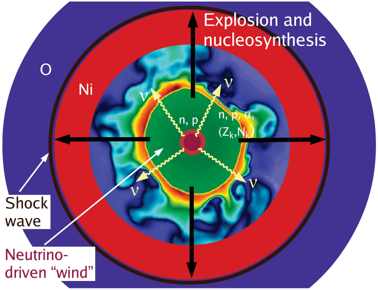
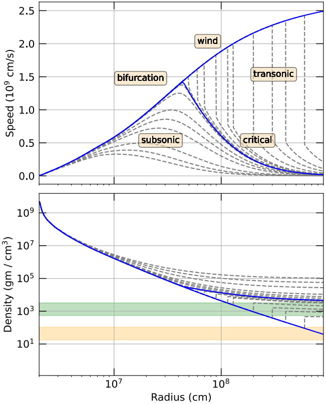
Hydrodynamics of neutrino driven outflows

Neutrino driven outflows can expand supersonically or subsonically. In fact, in typical core-collapse supernova environments, they are often near-critical and therefore sensitive to the precise boundary conditions. (A. Friedland and P. Mukhopadhyay, arxiv:2009.10059).



Janka et al. (arxiv:1211.1378)



Semi-analytic outflow model

- Spherically symmetric, steady-state outflow equations [Qian and Woosley, ApJ 471 (1996) 331-351]:

$$\dot{M} = 4\pi r^2 \rho v, \tag{1}$$

$$v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{GM}{r^2}, \tag{2}$$

$$\dot{q} = v\left(\frac{d\epsilon}{dr} - \frac{P}{\rho^2}\frac{d\rho}{dr}\right), \tag{3}$$

  plus corrections due to GR effects, changing $g_\star$, etc.

- For radiation-dominated ejecta, these can be converted into coupled ODEs for T, S, and v

- Integrate using boundary conditions of T and S at the PNS surface, and far pressure at the outer boundary (large radii)

Subsonic outflows (and high entropy) to the rescue

[A. Friedland, P. Mukhopadhyay, AVP, *in preparation*]

- Subsonic outflows are much more conducive to optimal νp-process yields
- Outflow spends more time in the $3\,\text{GK} > T > 1.5\,\text{GK}$ band where the νp-process operates optimally
- Also, the material remains closer to NS compared to supersonic outflows, allowing for greater exposure to $\bar{\nu}_e$ fluxes which make neutrons needed for (n, p) and (n, γ) reactions
- Triple-α enhancement still hurts the νp-process, but may not kill it completely!
- In addition, a high entropy $S \gtrsim 80$ is required to obtain good yields — corresponds to $M_{\text{PNS}} \sim 1.8\,M_\odot$ for $R_{\text{PNS}} = 19\,\text{km}$

A comparison: subsonic vs supersonic outflows

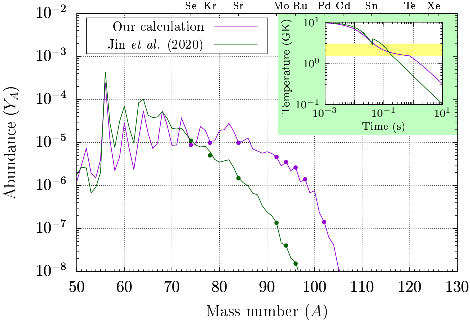


Figure: Nucleosynthesis yields in a νp-process simulation with a subsonic outflow profile (purple) obtained by solving the outflow equations [using a $13\,M_\odot$ progenitor model, with $M_{\text{PNS}} = 1.8\,M_\odot$ and $R_{\text{PNS}} = 19\,\text{km}$], and with a supersonic outflow profile (green) described in a parametric form with entropy $S = 80$ by Jin *et al.* (2020). The subsonic outflow shows $\sim$ 2 orders of magnitude higher yields of Mo and Ru.

Integrated yields for a $13\,M_\odot$ progenitor model

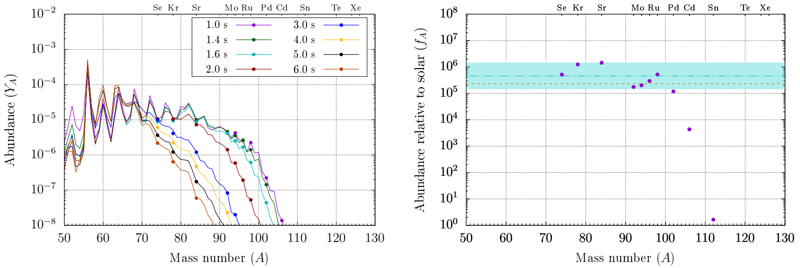


Figure: A sequence of nucleosynthesis yields computed using second-by-second outflow profile snapshots. **Left:** yields from $13\,M_\odot$ progenitor outflows at different post-bounce times, driven by an exponentially decreasing neutrino luminosity, $L_\nu \propto \exp(-t/\tau)$, with $\tau = 3$ s. **Right:** Integrated yields for the same calculation. $f_A \gtrsim 10^5$ are required to explain solar abundances.

Optimal yields reached at different times for different progenitor masses, but generally within 1–2 s when the mass outflows are still appreciable. No progenitor fine-tuning needed!

Neutrino mixing and electron (proton) fraction

- The nuclear composition of a p-rich outflow at 3 GK consists of mainly protons, αs, and seed nuclei, with their abundances depending on the proton fraction prior to freeze-out from nuclear statistical equilibrium (NSE) at $T \simeq 6$ GK. νp-process efficacy depends on proton-to-seed ratio at 3 GK

- The electron (or proton) fraction (Y_e) prior to NSE freeze-out set by ν_e and $\bar{\nu}_e$ capture rate competition. Since $\bar{\nu}_e$ have higher average energies, a luminosity hierarchy $L_{\nu_e} > L_{\bar{\nu}_e}$ is required for p-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.

Neutrino flavor mixing implementation

- Flavor mixing implemented as complete and sharp flavor equilibration among ν_e, ν_μ, and ν_τ (and among $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$) at 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_{ν_α} are the initial distributions (see also: Xiong *et al.*, arXiv:2006.11414)

- Effect of neutrino mixing examined over three regimes:
  (a) before NSE freeze-out ($T \gtrsim 6$ GK),
  (b) between NSE and QSE freeze-out (6 GK $\gtrsim T \gtrsim$ 3 GK),
  (c) after QSE freeze-out (3 GK $\gtrsim T \gtrsim$ 1.5 GK).
  Increasing ν_e and $\bar{\nu}_e$ average energies by flavor mixing has varying effects across these regimes. Typical hierarchy between ν_e and $\nu_{\mu,\tau}$ average energies is more pronounced than that between $\bar{\nu}_e$ and $\bar{\nu}_{\mu,\tau}$ $\Longrightarrow$ flavor equilibration increases ν_e average energy much more than it does for $\bar{\nu}_e$.

Neutrino flavor equilibration and the νp-process

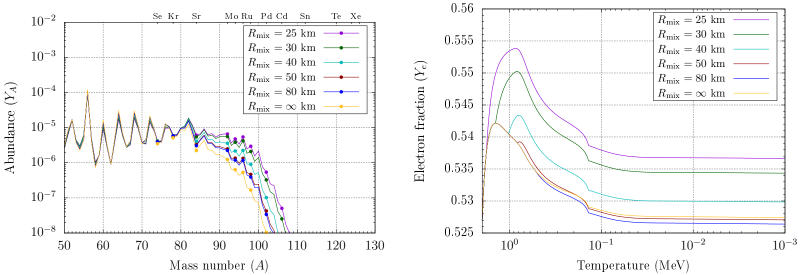


Figure: Nucleosynthesis calculations with different flavor equilibration radii $R_{\rm mix}$. **Left:** Abundance vs Mass number. **Right:** Electron fraction vs Temperature.

[AVP, A. Friedland, P. Mukhopadhyay, and S. Xin, *in preparation*]
In our model, we study these different regimes by varying the radius $R_{\rm mix}$. Flavor equilibration is found to universally improve the νp-process efficacy, more so if it occurs closer to PNS.

Conclusions

- νp-process appears to be alive and well! (for now at least)
- The hydrodynamics of the outflow are extremely crucial in determining νp-process outcomes
- Subsonic profiles with self-consistently modeled outflow physics can give robust νp-process yields, despite the enhanced triple-α reaction rate
- Neutrino flavor mixing close to the surface of the protoneutron star can also improve p-nuclide yields considerably, primarily through an enhancement in the early proton-to-seed ratio

Future work

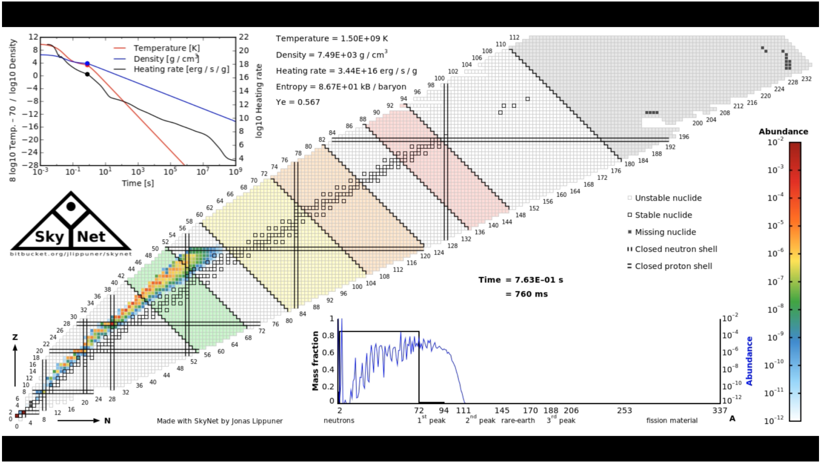
- The variability of yields observed for simulations with different PNS masses offers a bridge to Galactic chemical evolution
- Dependence on PNS radius suggests possible means to get another handle on the nuclear EoS
- The effect of neutrino mixing demonstrated using the simple flavor equilibration model motivates future studies which couple fast-flavor transformations of neutrinos to a nucleosynthesis network.
- Ultimately, all of this must be tested using nucleosynthesis calculations with 3D simulations. This framework provides guidance for such simulations.

Bonus slides

Nucleosynthesis calculations and inputs

- Nucleosynthesis calculations performed using open source SkyNet code [Lippuner and Roberts, ApJS 233, 18 (2017)]
- Triple-α enhancement was implemented using a code made available publicly by the authors of Jin *et al.* (2020)
- Neutrino luminosity taken to vary with time (exponential decay with $\tau = 3\,\mathrm{s}$) and nucleosynthesis trajectories represented by a sequence of steady-state outflow snapshots for different post-bounce times. Initial Y_e taken to be 0.6
- Self-consistent modelling of outflows using the semi-analytic framework. Post-shock densities for the far boundary condition adopted from simulations described in Sukhbold *et al.*, ApJ 821 38 (2016)

A SkyNet calculation



Different progenitor masses

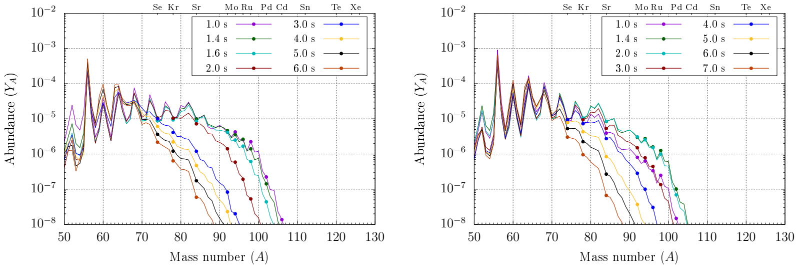


Figure: A sequence of nucleosynthesis yields computed using second-by-second outflow profile snapshots. **Left:** $13\,M_\odot$ progenitor outflow profiles. **Right:** $18\,M_\odot$ progenitor outflow profiles. In each of these cases, a PNS mass of $1.8\,M_\odot$ with a radius of $19\,\mathrm{km}$ was used in the semi-analytic outflow model.

Optimal yields reached at different times for different progenitor masses, but generally within 1–2 s when the mass outflows are still appreciable. No progenitor fine-tuning needed!

Getting the integrated yields

- For a nuclide (A, Z), we define the time-averaged abundance:

$$\langle Y_{A,Z} \rangle = \frac{\int Y_{A,Z}(t_{\rm pb})\, \dot{M}(t_{\rm pb})\, dt_{\rm pb}}{\int \dot{M}(t_{\rm pb})\, dt_{\rm pb}}, \qquad (4)$$

- The isotopic "production factor" is defined as $f_{A,Z} = \langle Y_{A,Z} \rangle / Y^{\odot}_{A,Z}$, where $Y^{\odot}_{A,Z}$ is the observed mass fraction of that isotope in the solar system (normalized so that $\sum A\, Y^{\odot}_{A,Z} = 1$ over all the nuclides)

- The "overproduction factor" is then given by $O_{A,Z} = f_{A,Z} \times (M_{\rm out}/M_{\rm ejec})$, where $M_{\rm out}/M_{\rm ejec} \sim 10^{-4}$. To explain the solar system abundance of a nuclide, one must have $O_{A,Z} \gtrsim 10$, and therefore $f_{A,Z} \gtrsim 10^5$

Integrated yields for the $13\,M_\odot$ progenitor calculation

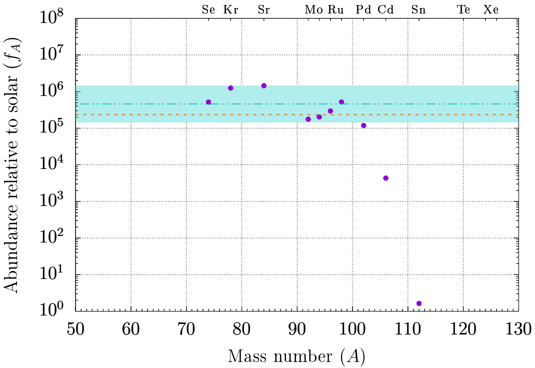


Figure: Integrated yields for the $13\,M_\odot$ progenitor calculation. The colored band represents a range of $f_{\max}$ to $f_{\max}/10$, where $f_{\max}$ is the highest production factor among the p-nuclides. Red dashed line represents the minimum production factor needed to account for observed solar abundances.

PNS mass dependence $\implies$ variability

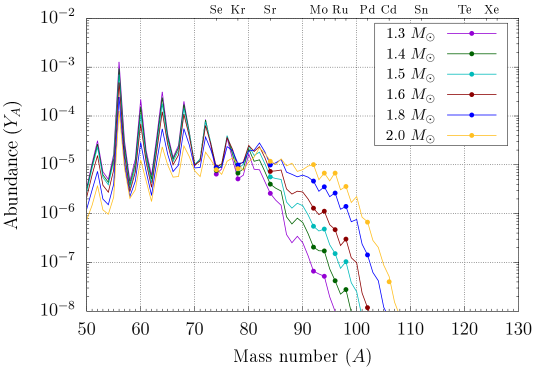


Figure: A comparison of nucleosynthesis yields for self-consistently modeled outflow profiles with different protoneutron star masses, each with radius $R_{\text{PNS}} = 19\,\text{km}$. Heavier PNS $\implies$ deeper gravitational potential $\implies$ higher entropy, which is more favourable for the νp process.

PNS radius dependence $\Longrightarrow$ EoS dependence

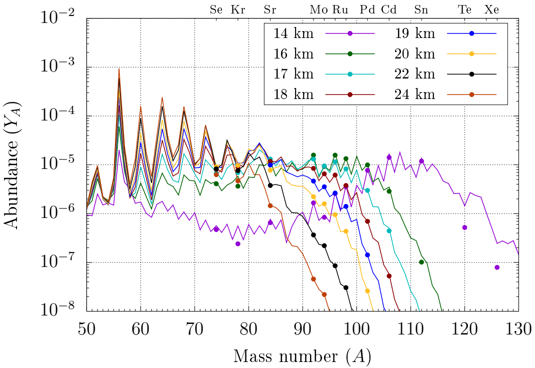


Figure: A comparison of nucleosynthesis yields for self-consistently modeled outflow profiles with different protoneutron star radii, each with mass $M_{\text{PNS}} = 1.8\, M_\odot$. More compact $\Longrightarrow$ deeper gravitational potential $\Longrightarrow$ higher entropy, which is more favourable for the νp process.

Neutrino flavor equilibration and the νp-process

- 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 3 GK, 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.

p-rich nucleosynthesis does not happen easily!

- Case in point — early universe ($S/n_b \sim 10^{10}$)
  - $T \gtrsim$ MeV: weak equilibrium

$$\nu_e + n \rightleftharpoons e^- + p$$
$$\bar{\nu}_e + p \rightleftharpoons e^+ + n$$

  - $T \sim 0.7\,\text{MeV}$: rate of above reactions falls below expansion rate of the universe $\implies$ weak freeze-out. After that, only free-neutron decay can change n/p ratio
  - $T \approx 0.1\,\text{MeV}$: $Y_p/Y_n \approx 7$. Rate of $n(p,\gamma)d$ (and subsequent reactions which make ^{3}He, ^{3}H, ^{4}He) falls below expansion rate. Freeze-out from nuclear statistical equilibrium (NSE) leads to α-particle formation + a sea of protons
  - Coulomb barriers inhibit proton capture at $T < 0.1\,\text{MeV}$ $\implies$ in our boring p-rich universe, only α-particles are made (and traces of ^{2}H, ^{3}He, ^{7}Li)

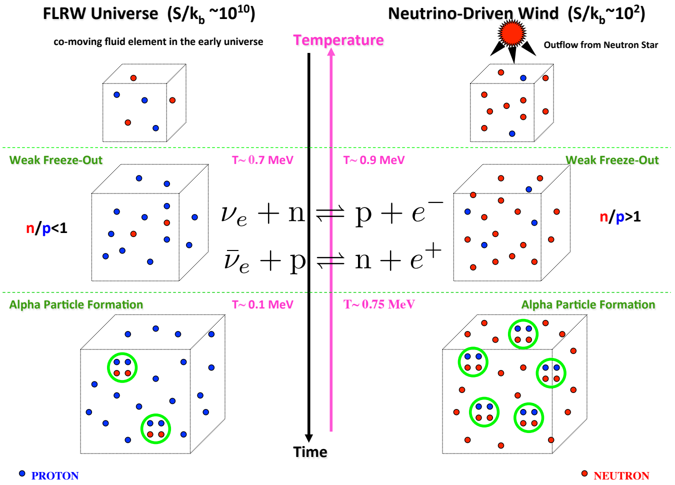
p-rich nucleosynthesis does not happen easily!

- In a hypothetical early universe with more neutrons than protons (e.g., if m_n were less than m_p), BBN could probably make heavier elements through neutron captures

- $\mathcal{Q}$. What would happen if the (proton-rich) early universe (or some sub-regions of it) had a much lower entropy ($S/n_b \sim 100$)?

Neutrino-driven outflows in core-collapse supernovae

Slide from George Fuller



Mo and Ru in metal poor stars

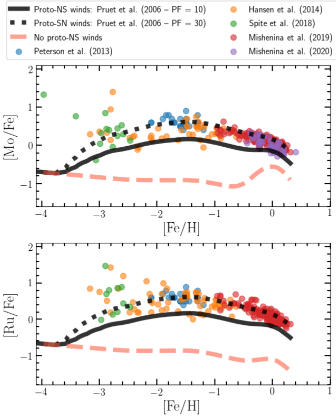


Figure: Observed abundances of [Mo/Fe] and [Ru/Fe] in metal poor stars, and predicted abundances for a p-rich proto-NS wind model from Pruet *et al.* (2006), as a function of metallicity [Fe/H] (F. Vincenzo *et al.*, MNRAS 508, 3499–3507 (2021)). Note the scatter at low metallicities.

p-process mechanisms [Rauscher *et al.* (2013)]

- γ-process (Woosley and Howard, 1978, ApJS 36, 285)
  - Photodisintegration of neutron rich isotopes either via (γ, n) or via $(\gamma, p)/(\gamma, \alpha) + \beta$-decays
  - Occurs during explosive O/Ne shell burning in massive stars, or in exploding white dwarfs (type-1a supernovae)
  - Can make some ^{92}Mo but underproduces ^{94}Mo and ^{96,98}Ru
- ν-process (Woosley *et al.*, ApJ, 356, 272 (1990); Fuller and Meyer, ApJ 453, 792 (1995))
  - Neutrino captures on stable nuclei
  - May occur in core-collapse supernova environments where ν fluxes large enough to offset small cross-sections
  - Outflowing material must remain in close proximity to NS for significant length of time — difficult to implement

p-process mechanisms

- rp-process (Schatz *et al.*, Phys. Rept. 294, 167–263 (1998); L. Bildsten, astro-ph/9709094)
  - Rapid proton capture followed by β^+ decays
  - Occurs on the surface of accreting neutron stars where thermonuclear H/He burning drives up temperatures enough for a short amount of time to overcome Coulomb repulsion
  - Hindered by β^+ decay "waiting points" along the nucleosynthesis chain
- α-process (Hoffman *et al.* ApJ, 460, 478 (1996))
  - Proceeds via chain of α, n, and p captures following α-rich freezeout in neutrino-driven outflows with $Y_e \sim 0.48$–0.49
  - Can make ^{92}Mo but not much ^{94}Mo or ^{96,98}Ru
  - Makes appreciable amounts of ^{92}Nb (comparable to ^{92}Mo)

9.5 $M_\odot$ progenitor calculation

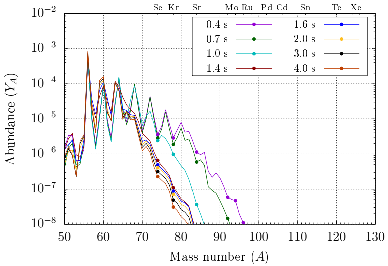


Figure: Nucleosyntheic yields for a 9.5 $M_\odot$ progenitor calculation with $M_{\rm PNS} = 1.4\,M_\odot$ and $R_{\rm PNS} = 19\,$km (low entropy) and a self-consistently modelled supersonic outflow profile. **Left:** Yields across steady-state outflow snapshots. **Right:** Integrated yields.

Outflow profiles for T vs t

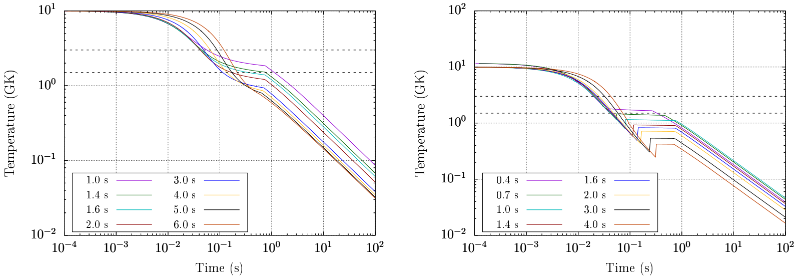


Figure: A comparison of Temperature vs time profiles for self-consistently modeled 13 $M_\odot$ (supersonic) and 9.5 $M_\odot$ (subsonic) progenitor outflows.

Variability of yields with initial Y_e

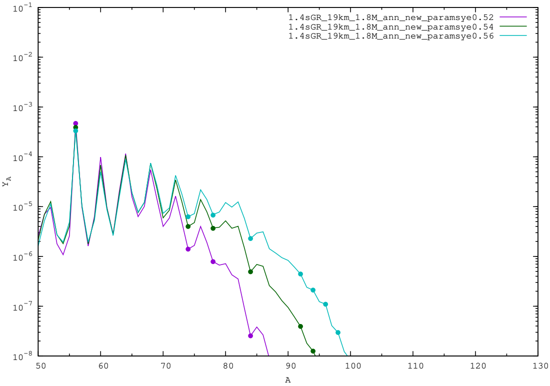


Figure: A comparison of nucleosynthesis yields for self-consistently modeled outflow profiles with different initial Y_e values.

The Niobium puzzle

- Another p-rich nucleus, ^{92}Nb, is also known to occur in nature, but cannot be made in the νp-process — shielded from p-rich nuclear flows by the neighboring stable ^{92}Mo
- Can be made in the γ-process — production ratio of $^{92}\text{Nb}/^{92}\text{Mo}$, convolved with suitable models for galactic chemical evolution (GCE) and ISM mixing, is roughly consistent with the inferred ratio in the early solar system
- This is used as an argument that any process that produces the bulk of ^{92}Mo must also produce ^{92}Nb concurrently, thereby putting the νp process in doubt [Rauscher *et al.* (2013)]
- However: (i) considerable uncertainties in both the production and the inferred early solar system ratios of $^{92}\text{Nb}/^{92}\text{Mo}$, and (ii) consistency between ratios doesn't preclude two separate processes from being dominant sources of ^{92}Nb and ^{92}Mo respectively

The α-process ($Y_e = 0.48$) — the Niobium solution