Neutrino flavor mixing, outflow hydrodynamics, and νp-process nucleosynthesis in supernovae

Amol V. Patwardhan

SLAC National Accelerator Laboratory

State of the Universe seminar
Tata Institute of Fundamental Research

March 23, 2023

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

1. Core-collapse supernovae and neutrinos
2. Origin of proton-rich elements, and νp-process nucleosynthesis
3. Outflow hydrodynamics to the rescue
4. Neutrino flavor mixing and the νp-process

Key motivations and definitions

∗ Neutrinos

- Elementary particles
- No electric charge
- *Not* massless, but **really** small masses
- Don't interact much (only weak interactions)
- Byproduct of some types of nuclear reactions, e.g., decay of a neutron into a proton (but other ways to make them too)

Key motivations and definitions

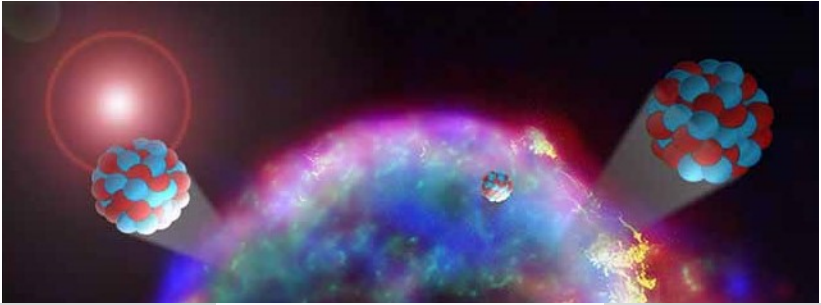
* Supernovae (core-collapse supernovae)

- Explosions of massive stars that are much heavier than our sun
- Final stage in the life cycle of massive stars after multiple stages of nuclear burning
- Triggered by gravitational collapse of stellar core, when it gets so heavy that gravity overcomes pressure support
- Neutrinos have a big part to play

Key motivations and definitions

∗ Nucleosynthesis

- The process of combining protons and neutrons into nuclei
- Takes place in the early universe and in stars
- Early universe (‘primordial’ or ‘big-bang’) nucleosynthesis makes Helium — and trace amounts of other light nuclei
- Heavier nuclei are made in stars through a variety of processes
- Neutrinos have a big part to play



Key motivations and definitions

∗ Neutrino flavor oscillations

- Neutrinos come in three ‘flavors’: electron, muon, and tau
- Neutrino is produced in *any one* flavor — as it propagates, it evolves into a quantum superposition of *all three flavors*, with oscillating strengths in each flavor
- Subsequent interactions depend on flavor composition — critically important for supernovae and nucleosynthesis

How do stars ~~explode~~ shine

- Nuclear fusion (hydrogen to helium) produces energy in the stellar core, which generates thermal pressure to balance the inward pull of gravitation . . .
- . . . until nuclear fuel gets spent, pressure support disappears, core contracts, temperature rises
- Two ways to stop the core contraction: (i) the electron gas gets compressed to the limit permitted by Pauli's exclusion principle from Quantum Mechanics; (ii) the core temperature rises high enough to trigger additional nuclear fusion
- Whether (i) or (ii) occur depend on the mass of the star — lighter stars experience (i), heavier ones experience (ii)

Massive Stars: Endgame

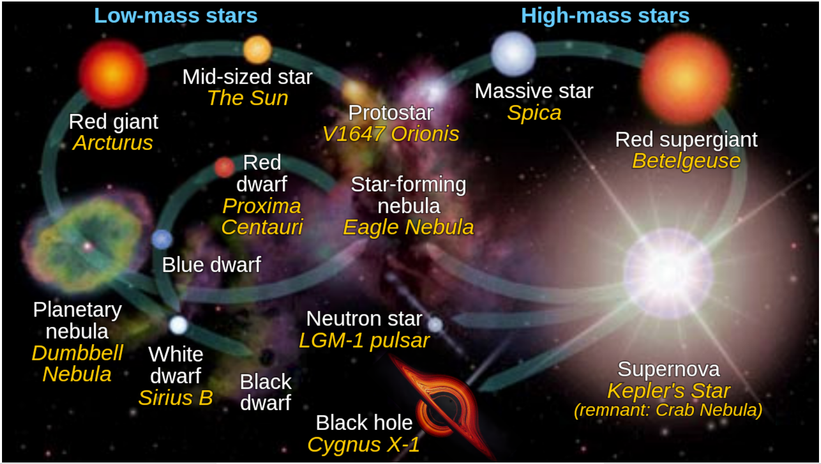
- In sufficiently massive stars, this process can repeat all the way to Iron (Fe):

  $$\mathrm{H} \to \mathrm{He} \to \mathrm{C} \to \mathrm{O/Ne/Mg} \to \mathrm{Si} \to \mathrm{Fe}$$

  This cycle terminates at Fe, the most stable nucleus. Fusion beyond Fe *costs* energy, rather than producing it
- Only way to support an Fe core against gravitational collapse is electron degeneracy pressure [scenario (i) from earlier]
- In *really* massive stars $(M_\star > 8\,M_\odot)$, even that is not enough, and the Fe core collapses once it becomes sufficiently heavy
- Core-collapse accompanied by prodigious neutrino production, as electrons combine with protons to form neutrons

Massive Stars: Endgame

Depending on the core mass, the collapse either terminates at nuclear density (for $M_{\text{core}} \lesssim 2\,M_{\odot}$), forming a neutron star, or proceeds all the way to a black hole (for $M_{\text{core}} \gtrsim 2\,M_{\odot}$)



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. ($t_{pb} < 0$ 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)

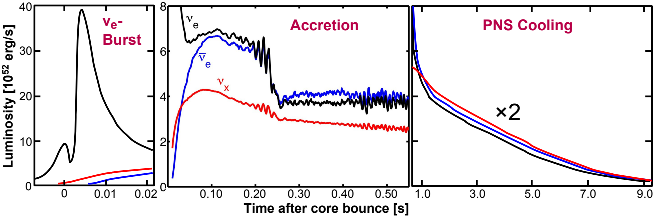
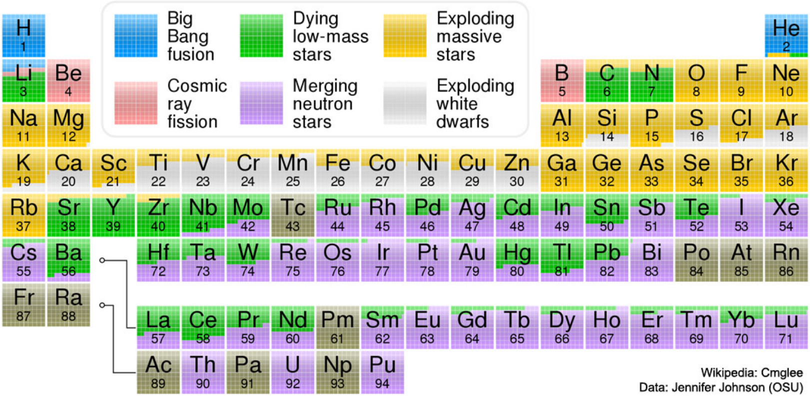


Figure: Taken from H.-T. Janka (1702.08713).

Outline

1. Core-collapse supernovae and neutrinos
2. Origin of proton-rich elements, and νp-process nucleosynthesis
3. Outflow hydrodynamics to the rescue
4. Neutrino flavor mixing and the νp-process

The origin of the elements



Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

Figure: Astronomy picture of the day (2020 August 9)

Chart of the nuclides

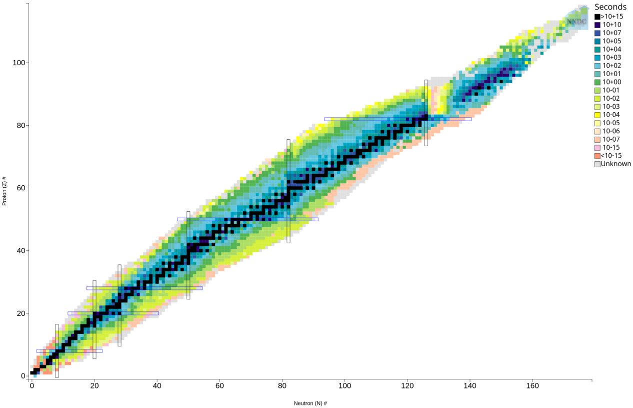


Figure: Chart of Nuclides - National Nuclear Data Center

Chart of the nuclides

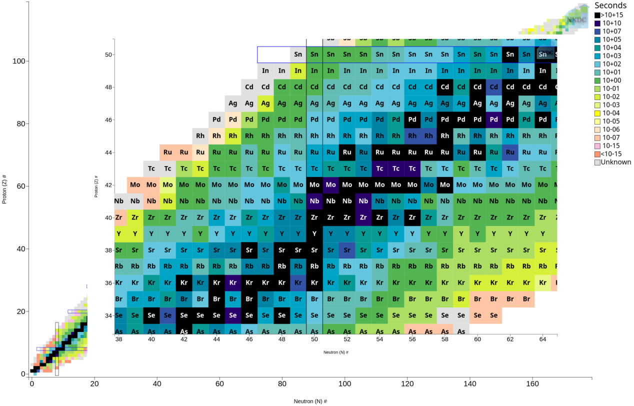


Figure: Chart of Nuclides - National Nuclear Data Center

The s-process, the r-process, and the p-process

- Nuclides along the valley of stability are made predominantly by ‘slow’ neutron capture (the s-process), occurring mainly in Asymptotic Giant Branch stars. Characterized by slow neutron capture rates, compared to the beta decay rates

- The nuclides on the more neutron-rich side of the valley aren’t accessible to the s-process, and must be synthesized via ‘rapid’ neutron capture (r-process) — i.e., with neutron capture rates that are much faster than the beta decay rates. Environments with *very high* neutron availability, e.g., neutron star mergers, and possibly core-collapse supernovae, are candidate sites

- The nuclides on the neutron-deficient side of the valley cannot be approached via either the s-process or the r-process tracks. Any processes able to synthesize these nuclei are given the generic name ‘p-process’

Proton-rich heavy elements in nature

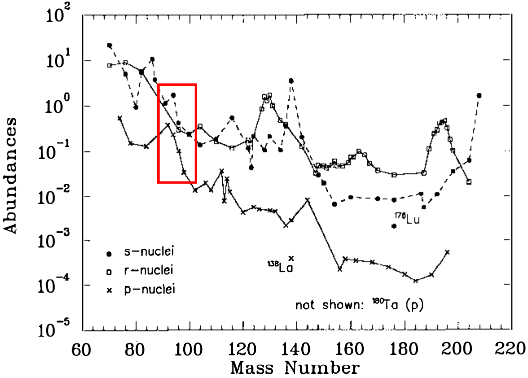


Figure: The solar system abundances of r-nuclei, s-nuclei, and p-nuclei (B. S. Meyer, Annu. Rev. Astron. Astrophys. 1994. 32: 153–190). Most p-nuclides have abundances 1–2 orders of magnitude lower than nearby s- and r-process (neutron-rich) nuclides. Except for ^{92,94}Mo and ^{96,98}Ru.

Synthesis of p-rich nuclides

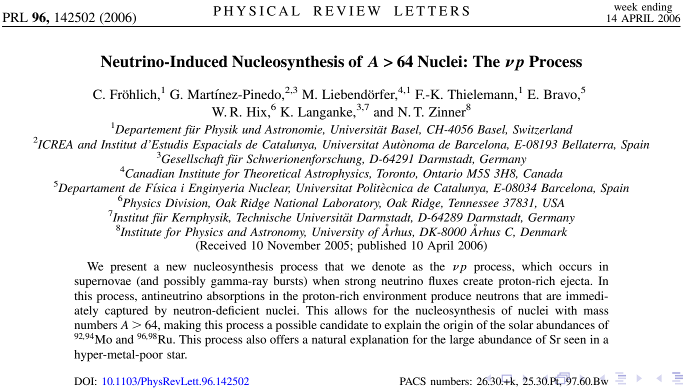
- Consistent ratio of p-rich/n-rich abundances suggests that transmutation of previously formed n-rich nuclides (e.g., via photodistintegration) could explain p-nuclide origin — apart from the anomalously high abundances near the ^{92}Mo peak
  - γ-process [Woosley & Howard (1978)]: photodisintegration 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 regions of high temperature/density (e.g., in core-collapse supernovae) could be suitable 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) 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

C. Fröhlich,[1] G. Martínez-Pinedo,[2,3] M. Liebendörfer,[4,1] F.-K. Thielemann,[1] E. Bravo,[5]
W. R. Hix,[6] K. Langanke,[3,7] and N. T. Zinner[8]
[1]*Departement für Physik und Astronomie, Universität Basel, CH-4056 Basel, Switzerland*
[2]*ICREA and Institut d'Estudis Espacials de Catalunya, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain*
[3]*Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany*
[4]*Canadian Institute for Theoretical Astrophysics, Toronto, Ontario M5S 3H8, Canada*
[5]*Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, E-08034 Barcelona, Spain*
[6]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[7]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
[8]*Institute for Physics and Astronomy, University of Århus, DK-8000 Århus C, Denmark*
(Received 10 November 2005; published 10 April 2006)

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 once the $3\alpha \rightleftharpoons {}^{12}$C reaction falls out of equilibrium, and these remain in quasi-equilibrium with $A > 56$ nuclei till 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 $T > 3$ 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 GK $> T > 1.5$ 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

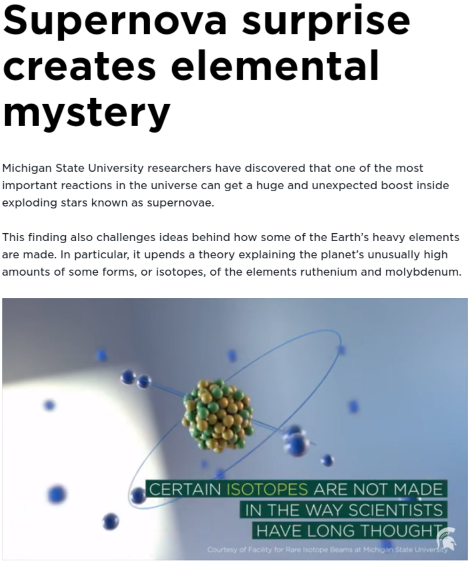
See also:
Pruet *et al.*, ApJ 644, 1028 (2006)
S. Wanajo, ApJ 647, 1323 (2006)

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.

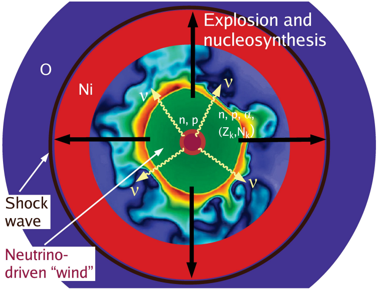
Courtesy of Facility for Rare Isotope Beams at Michigan State University

Outline

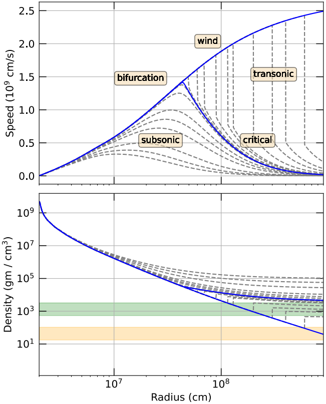
1. Core-collapse supernovae and neutrinos
2. Origin of proton-rich elements, and νp-process nucleosynthesis
3. Outflow hydrodynamics to the rescue
4. Neutrino flavor mixing and the νp-process

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]:

$$\begin{aligned} \dot{M} &= 4\pi r^2 \rho v, && (1) \\ v\frac{dv}{dr} &= -\frac{1}{\rho}\frac{dP}{dr} - \frac{GM}{r^2}, && (2) \\ \dot{q} &= v\left(\frac{d\epsilon}{dr} - \frac{P}{\rho^2}\frac{d\rho}{dr}\right), && (3) \end{aligned}$$

  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

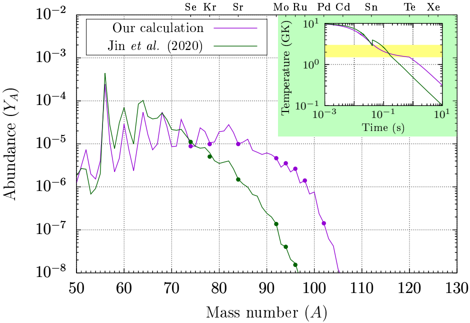


Figure: Nucleosynthesis yields in a νp-process simulation with a subsonic outflow profile (purple) obtained by solving the outflow equations [using a $13\,M_\odot$ progenitor model, with $M_{\rm PNS} = 1.8\,M_\odot$ and $R_{\rm PNS} = 19\,$km], and with a supersonic outflow profile (green) described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

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)

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

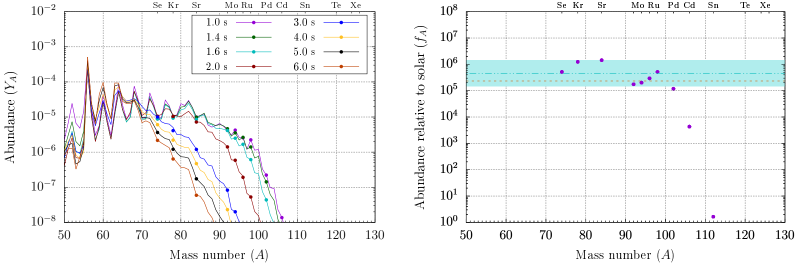


Figure: A sequence of nucleosynthesis yields computed using second-by-second outflow profile snapshots. **Left:** yields from $13\,M_\odot$ progenitor outflows at different post-bounce times, driven by an exponentially decreasing neutrino luminosity, $L_\nu \propto \exp(-t/\tau)$, with $\tau = 3\,\mathrm{s}$. **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!

Different progenitor masses

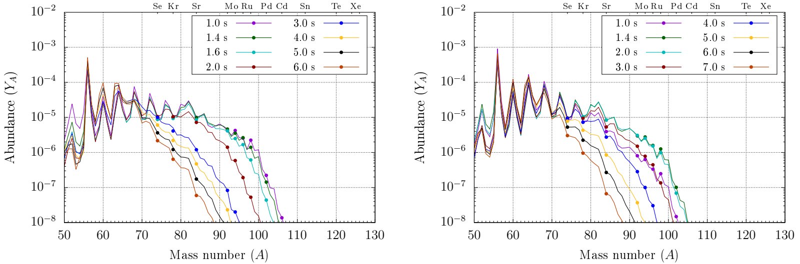


Figure: A sequence of nucleosynthesis yields computed using second-by-second outflow profile snapshots. **Left:** $13\,M_\odot$ progenitor outflow profiles. **Right:** $18\,M_\odot$ progenitor outflow profiles. In each of these cases, a PNS mass of $1.8\,M_\odot$ with a radius of $19\,\mathrm{km}$ was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

9.5 $M_\odot$ progenitor calculation

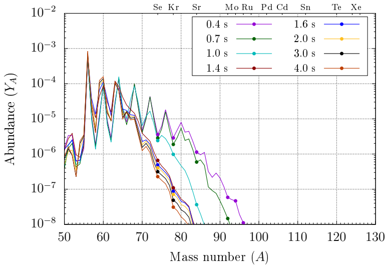


Figure: Nucleosyntheic yields for a 9.5 $M_\odot$ progenitor calculation with $M_{\text{PNS}} = 1.4\,M_\odot$ and $R_{\text{PNS}} = 19\,\text{km}$ (low entropy) and a self-consistently modelled supersonic outflow profile. **Left:** Yields across steady-state outflow snapshots. **Right:** Integrated yields.

Outline

1. Core-collapse supernovae and neutrinos
2. Origin of proton-rich elements, and νp-process nucleosynthesis
3. Outflow hydrodynamics to the rescue
4. Neutrino flavor mixing and the νp-process

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

$$H_{\nu\nu}(\mathbf{p}) \propto G_F \sum_{\mathbf{q}} \rho_\nu(\mathbf{q}) \; (1 - \cos\theta_{\mathbf{pq}})$$

Collective flavor oscillations: synchronized and bipolar

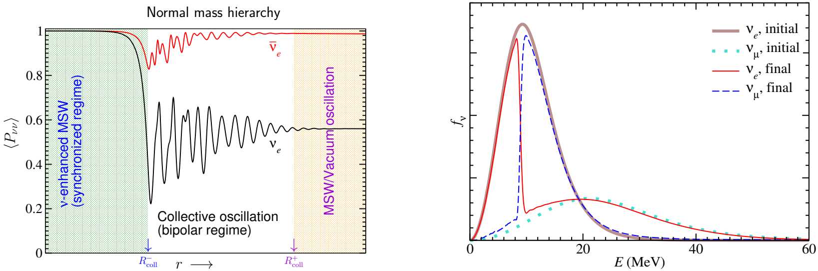
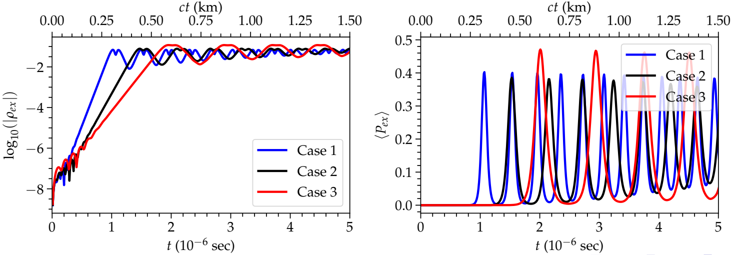


Figure: Taken from Duan et al. (1001.2799). **Left:** regimes for different types of neutrino oscillations in a CCSN environment. **Right:** a neutrino spectral split/swap resulting from collective flavor effects.

"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, Martin, Duan, et al.: 1905.13335, 2102.10188, 2102.12556, 2103.11497, 2111.00437, 2112.12686, 2203.02783, 2207.03189, 2301.07049 — some of these involve simulating collective neutrino oscillations on a quantum computer)

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 $\bar{\nu}_{\mu,\tau}$ $\implies$ flavor equilibration increases ν_e average energy much more than it does for $\bar{\nu}_e$.

Neutrino flavor equilibration and the νp-process

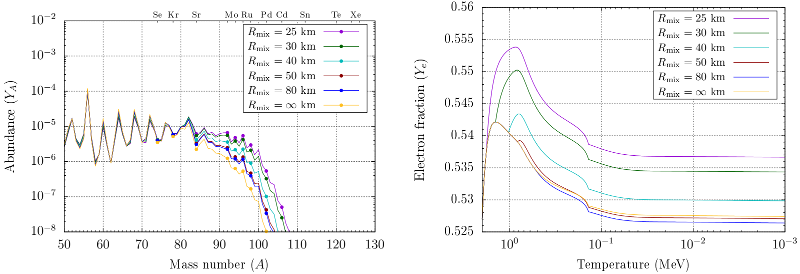


Figure: Nucleosynthesis calculations with different flavor equilibration radii R_{mix}. **Left:** Abundance vs Mass number. **Right:** Electron fraction vs Temperature.

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

Conclusions

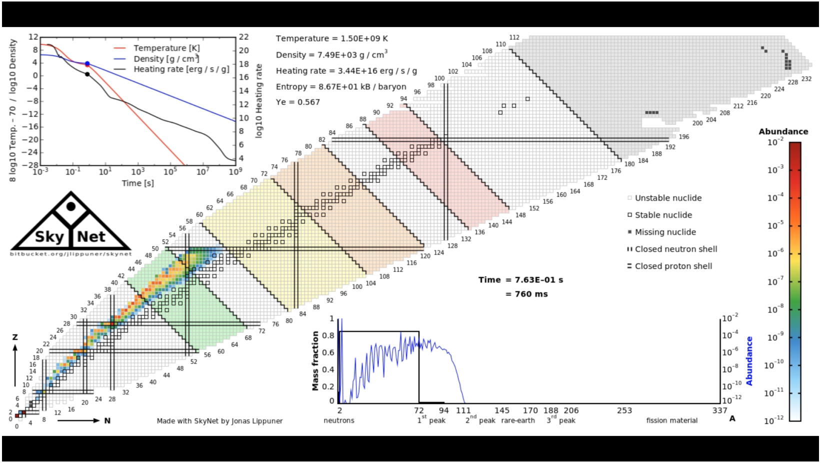
- νp-process appears to be alive and well! (for now at least)
- The hydrodynamics of the outflow are extremely crucial in determining νp-process outcomes
- Subsonic profiles with self-consistently modeled outflow physics can give robust νp-process yields, despite the enhanced triple-α reaction rate
- 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

A SkyNet calculation



Getting the integrated yields

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

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

- 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 $O_{A,Z} = f_{A,Z} \times (M_{\mathrm{out}}/M_{\mathrm{ejec}})$, where $M_{\mathrm{out}}/M_{\mathrm{ejec}} \sim 10^{-4}$. 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

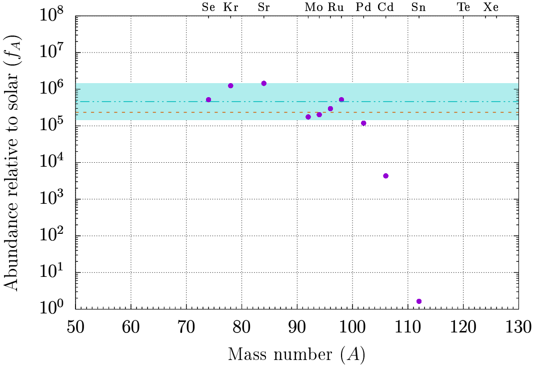


Figure: Integrated yields for the $13\,M_\odot$ progenitor calculation. The colored band represents a range of f_{max} to $f_{\text{max}}/10$, where f_{max} is the highest production factor among the p-nuclides. Red dashed line represents the minimum production factor needed to account for observed solar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

PNS mass dependence $\implies$ variability

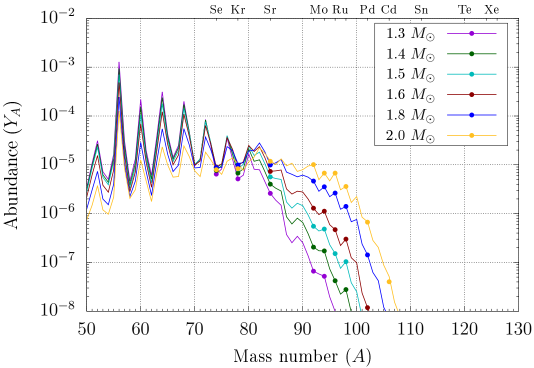


Figure: A comparison of nucleosynthesis yields for self-consistently modeled outflow profiles with different protoneutron star masses, each with radius $R_{\text{PNS}} = 19\,\text{km}$. Heavier PNS $\implies$ deeper gravitational potential $\implies$ higher entropy, which is more favourable for the νp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

PNS radius dependence $\implies$ EoS dependence

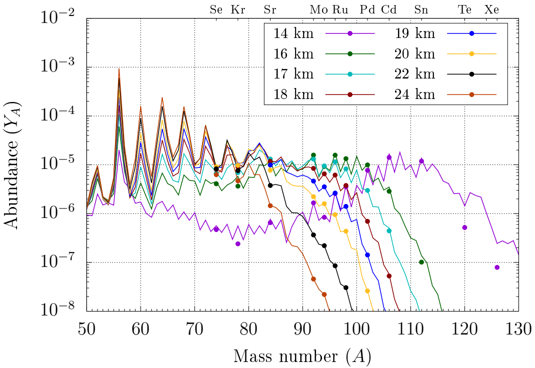


Figure: A comparison of nucleosynthesis yields for self-consistently modeled outflow profiles with different protoneutron star radii, each with mass $M_{\text{PNS}} = 1.8\,M_{\odot}$. More compact $\implies$ deeper gravitational potential $\implies$ higher entropy, which is more favourable for the νp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

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

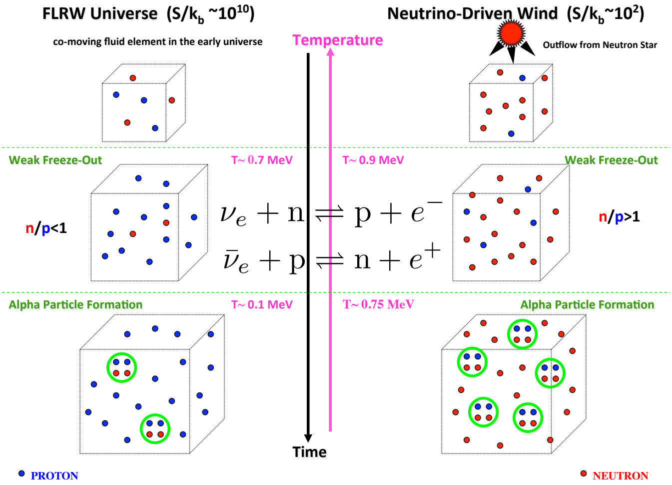
    - $T \sim 0.7\,$MeV: rate of above reactions falls below expansion rate of the universe $\implies$ weak freeze-out. After that, only free-neutron decay can change n/p ratio
    - $T \approx 0.1\,$MeV: $Y_p/Y_n \approx 7$. Rate of $n(p,\gamma)d$ (and subsequent reactions which make ^{3}He, ^{3}H, ^{4}He) 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 $T < 0.1\,$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

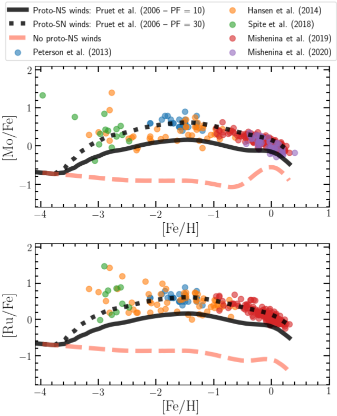


Figure: Observed abundances of [Mo/Fe] and [Ru/Fe] in metal poor stars, and predicted abundances for a p-rich proto-NS wind model from Pruet *et al.* (2006), as a function of metallicity [Fe/H] (F. Vincenzo *et al.*, MNRAS 508, 3499–3507 (2021)). Note the scatter at low metallicities.

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 $(\gamma, p)/(\gamma, \alpha)$ + β-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)

Outflow profiles for T vs t

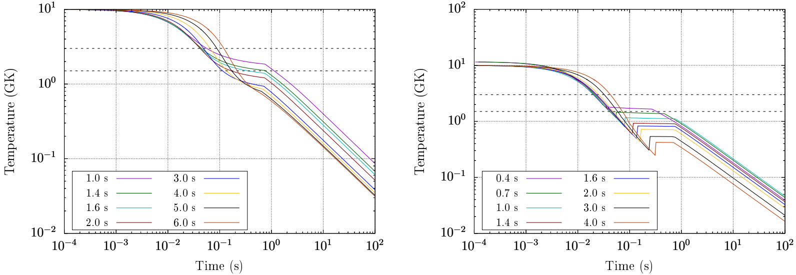


Figure: A comparison of Temperature vs time profiles for self-consistently modeled 13 $M_\odot$ (supersonic) and 9.5 $M_\odot$ (subsonic) progenitor outflows.

Variability of yields with initial Y_e

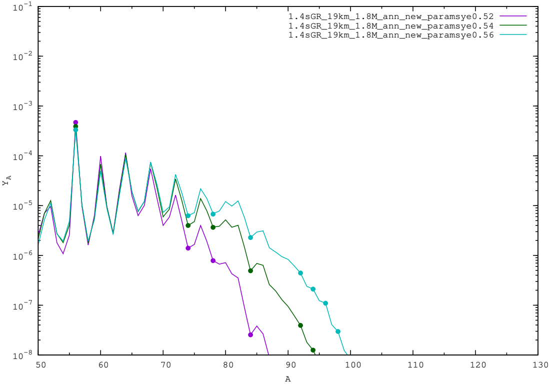


Figure: A comparison of nucleosynthesis yields for self-consistently modeled outflow profiles with different initial Y_e values.

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}Nb/^{92}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}Nb/^{92}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