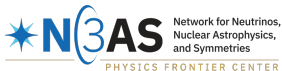# Neutrino-driven outflows and proton-rich nucleosynthesis in core-collapse supernovae

Amol V. Patwardhan

SLAC National Accelerator Laboratory

3rd New Physics Opportunities at Neutrino Facilities (NPN) workshop

July 11, 2023

Collaborators: Alexander Friedland, Payel Mukhopadhyay

Outline

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
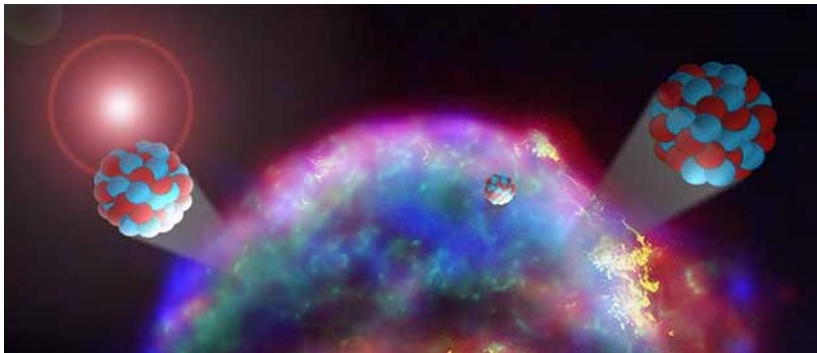
Core-collapse supernovae and neutrinos

- Stars with $M_\star \gtrsim 8\,M_\odot$ undergo core collapse & neutronization when core mass exceeds $\sim 1.4\,M_\odot$, i.e., when its gravity surpasses the limit of 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

$$\nu_e + n \longleftrightarrow p + e^-$$
$$\bar{\nu}_e + p \longleftrightarrow n + e^+$$
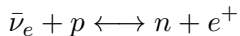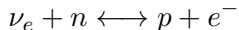
- Flavor asymmetric processes: thorough understanding of neutrino flavor evolution therefore required

Neutrino flavor evolution: matter effects

Matter backgrounds (electrons, nucleons, etc.) modify neutrino flavor evolution: "effective mass" through neutrino forward scattering. Mass level crossing $H_{\nu_e \nu_e} = H_{\nu_x \nu_x} \implies$ MSW resonance
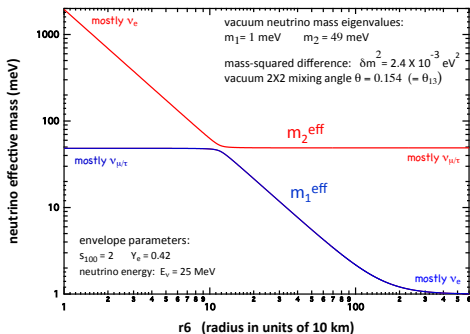

Figure: MSW resonance (figure by George Fuller)

Wolfenstein (1978, '79)
Mikheyev & Smirnov (1985)
Bethe (1986)
Haxton (1986)
Parke (1986)
and so on ...

Neutrino-matter Hamiltonian:

$$H_{\mathrm{mat}} = \lambda \, \vec{L} \cdot \vec{J}_{\mathbf{p}}$$

where $\lambda = \sqrt{2}\, G_F n_e$ and
$\vec{L} = (\sin 2\theta, 0, \cos 2\theta)_{\mathrm{mass}}$

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 $H = H_{\mathsf{vac}} + H_{\mathsf{mat}} + H_{\nu\nu}$

- 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

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

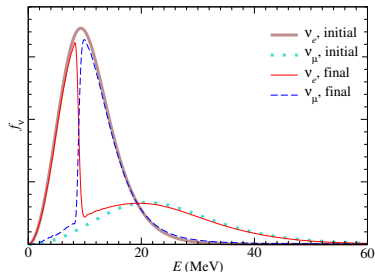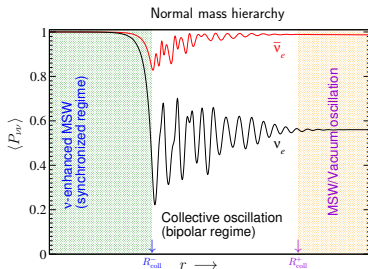# Collective flavor oscillations: synchronized and bipolar

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.

Other cool problems in supernova neutrino oscillations

- Fast collective flavor oscillations
  (e.g., Tamborra & Shalgar: 2011.01948, Richers & Sen: 2207.03561, and references therein)

- Matter-neutrino resonances
  (e.g., 1403.5797, 1507.00946, 1509.08975, 1510.00751, 1607.04671, 1801.07813)

- Collisionally triggered collective flavor instabilities
  (e.g., 2104.11369, 2206.09225, 2208.11059, 2210.09218, 2212.03750)

- 'Halo' effect from backscattered neutrinos
  (e.g., 1203.1607, 1302.1159, 1908.10594, 1912.11489, 1807.07070)

- Decoherence by wave-packet separation
  (e.g., 1512.09068, 1702.08338)

- Quantum correlations in collective neutrino flavor oscillations
  (e.g., hep-ph/0304082, hep-ph/0304055, hep-ph/0307140, hep-ph/0602016, . . . , 2305.01150 and references therein)

Outline

1 Core-collapse supernovae and neutrinos

2 Neutrino-driven outflows in core-collapse supernovae

3 Origin of proton-rich elements, and νp-process nucleosynthesis

4 Outflow hydrodynamics to the rescue

Neutrino oscillation signatures sensitive to matter effects

- Neutrino oscillations are impacted by the matter profile around supernovae, which in turn depends on the neutrino-driven outflow

- Shocks and turbulence in the SN hot bubble impact oscillations with potentially significant detection signatures: e.g., Schirato & Fuller (astro-ph/0205390), Friedland & Gruzinov (astro-ph/0607244), Boriello *et al.* (1310.7488), Friedland & Mukhopadhyay (2009.10059), Ekinci, Pehlivan & Patwardhan (2101.01797)

- Detectors like DUNE could help uncover non-trivial features of neutrino oscillation signals, outflow hydrodynamics, and help answer some outstanding nucleosynthesis questions

Neutrino-driven outflows

A few seconds into the explosion, neutrino heating of baryonic matter close to the proto-neutron star (PNS) causes an outflow of matter forming neutrino-driven outflows/winds
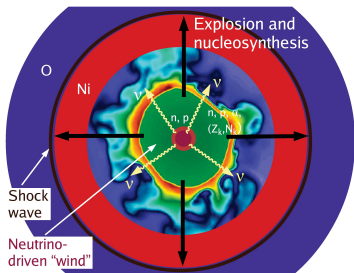
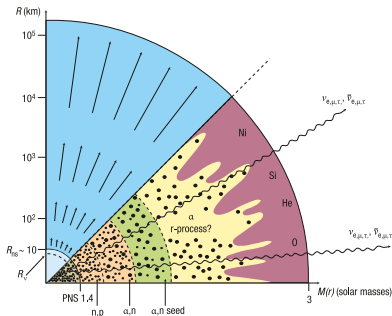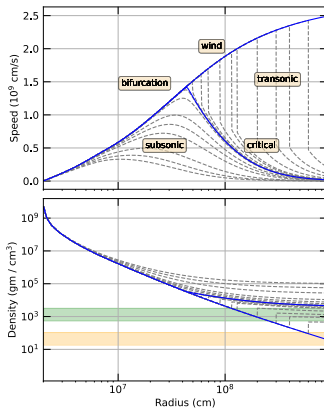

Janka et al. (arxiv:1211.1378)

Figure: **Left:** arxiv:1211.1378. **Right:** astro-ph/0601261.

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)

- Top panel: phase space of physical outflow velocity solutions

- Bifurcation point separating subsonic and shocked solutions

- Bottom panel: subsonic and shocked outflows for changing far density/pressure

- Existence of a 'critical' density below which shocks appear

CCSN and neutrinos
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ν-driven outflows
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Origin of p-rich elements, & νp-process
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Effect of hydrodynamics
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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)

Shock interaction with MSW resonances

As the shockwave advances through the supernova envelope, it passes through regions of densities corresponding to the MSW resonances (matter-enhanced neutrino flavor transformations). This leaves an imprint on the neutrino signal.
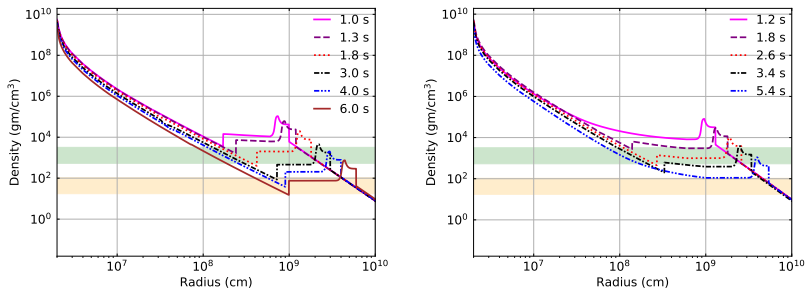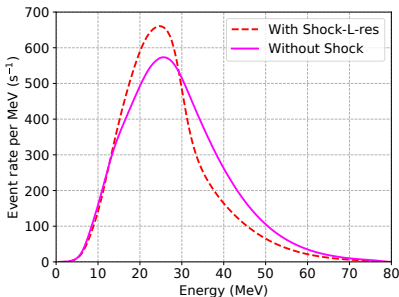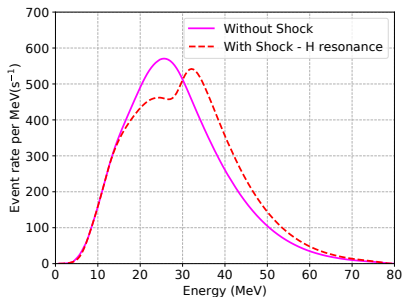

Figure: **Left:** A supernova model with a strong, persistent termination shock. **Right:** SN model with a weak, transient shock. [Friedland and Mukhopadhyay, *in preparation*]

Neutrino signal from shock-MSW interactions

Effect of shock passage through MSW resonance bands on the expected neutrino signal in DUNE for a supernova at $3\,\mathrm{kpc}$ (**Left:** 'high' resonance; **Right:** 'low' resonance)

[Friedland and Mukhopadhyay, *in preparation*]

Shock identification with time-energy binning

With a detailed time & energy binning analysis, signatures of neutrino-driven outflow shocks could be identified at a 5σ level (or better) for any SN in the galaxy using the expected neutrino signal in DUNE (would require good energy resolution)
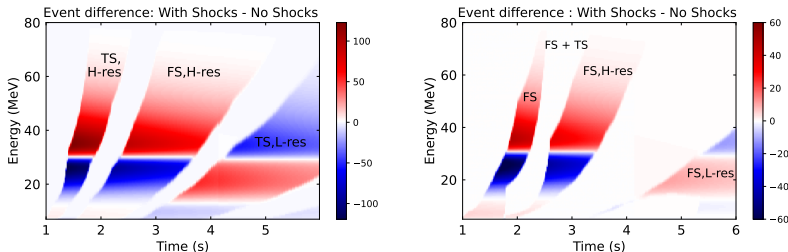

Figure: **Left:** A supernova model with a strong, persistent termination shock. **Right:** SN model with a weak, transient shock.
[Friedland and Mukhopadhyay, *in preparation*]

CCSN and neutrinos
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ν-driven outflows
ⵔⵔⵔⵔⵔⵔⵔⵔ●

Origin of p-rich elements, & νp-process
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Effect of hydrodynamics
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Conclusions, Summary and Outlook (Part I)

- The next supernova is expected to produce thousands of events in detectors like DUNE and HyperK. DUNE in particular is uniquely placed to detect a high-statistics ν_e signal (as opposed to $\bar{\nu}_e$)

- Neutrino signal thus detected can serve as a diagnostic of the developing explosion

- Impact of shock passage on the time evolution of detailed spectral features like pinching could be robustly identified for SN throughout the galaxy with a good energy resolution

Outline

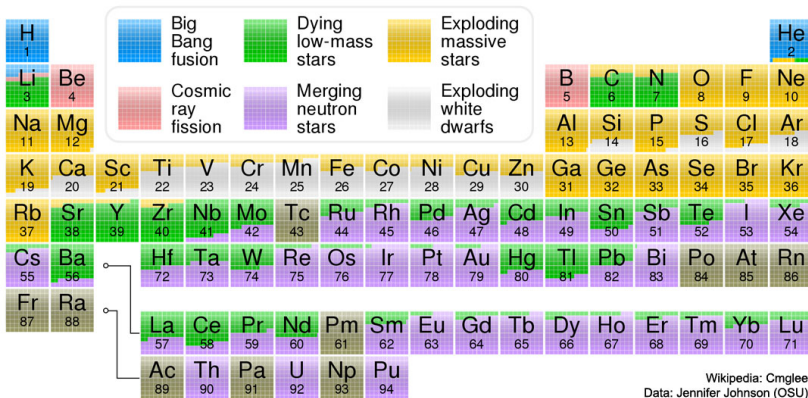# The origin of the elements

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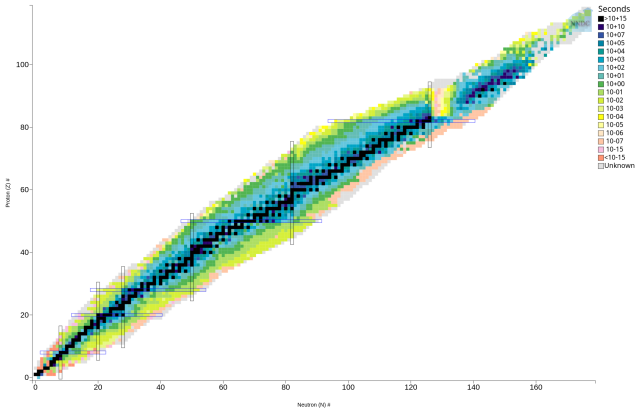
Chart of the nuclides

Figure: Chart of Nuclides - National Nuclear Data Center
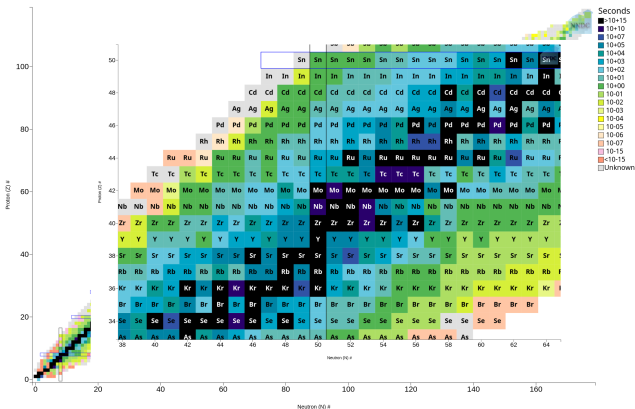
Chart of the nuclides

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

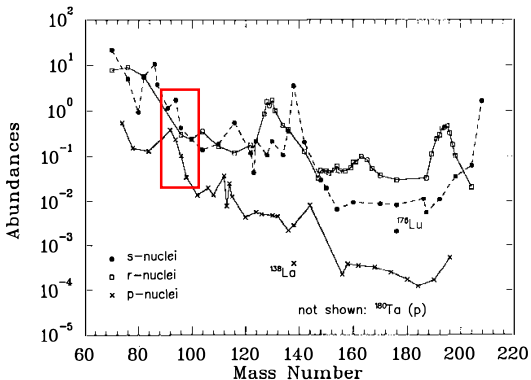

Figure: The solar system abundances of r-nuclei, s-nuclei, and p-nuclei (B. S. Meyer, Annu. Rev. Astron. Astrophys. 1994. 32: 153–190). Most p-nuclides have abundances 1–2 orders of magnitude lower than nearby s- and r-process (neutron-rich) nuclides. Except for ^{92,94}Mo and ^{96,98}Ru.

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:
     $1.5\,\mathrm{GK} < T < 3\,\mathrm{GK}$

- The classic rp-process [Wallace & Woosley (1981); Schatz *et al.* (1998)]: rapid proton captures interspersed by β^+ decays. Can occur on surfaces of neutron stars accreting material from a companion (associated with X-ray bursts). Bottlenecked by β^+ decay "waiting point" nuclei (e.g., ^{64}Ge), plus enriched material cannot get ejected in significant amounts

- (1) and (2) suggest that matter outflows from high temperature and density regions (e.g., in core-collapse supernovae) could be suitable candidate sites

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

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]

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[3]Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany
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[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.

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 $T \sim 3\,\mathrm{GK}$

- $\bar{\nu}_e$ 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 p-rich side for $3\,\mathrm{GK} > T > 1.5\,\mathrm{GK}$

- At $T \lesssim 1.5\,\mathrm{GK}$, Coulomb barriers inhibit further (p, γ) reactions, and subsequent (n, p) and (n, γ) reactions drive the nuclear flow back towards stability

The νp-process
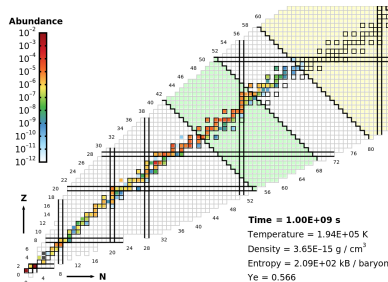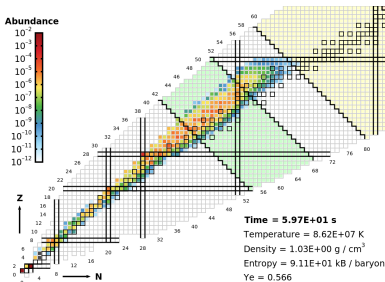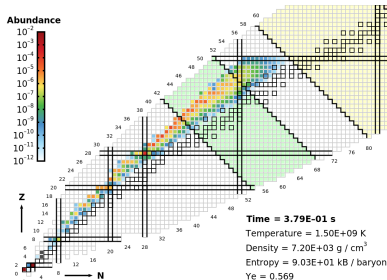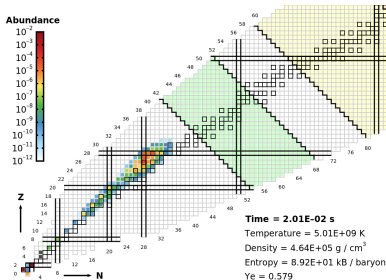
Favourable conditions for νp-process

Wanajo, Janka, & Kubono, ApJ 729, 46 (2011)

1. Short time interval (τ_1) for $T > 3\,\text{GK}$

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 $3\,\text{GK} > T > 1.5\,\text{GK}$ 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 doubts raised in the intervening years regarding the νp-process efficacy

a. Rauscher et. al (2013) have argued that νp cannot account for the bulk of the ^{92}Mo in the solar system due to its supposed inability to co-produce ^{92}Nb

b. Difficulties have been reported 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)]

c. Recent calculations [Jin et al., Nature vol. 588, pg. 57–60 (2020)] reported 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?
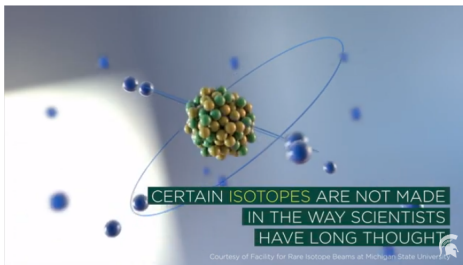
[†] **Note:** an enhancement in the $3\alpha \rightarrow {}^{12}$C rate leads to increased seed-nuclei formation and lowers the proton-to-seed ratio, decreasing νp-process potency

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.

CERTAIN ISOTOPES ARE NOT MADE
IN THE WAY SCIENTISTS
HAVE LONG THOUGHT

Courtesy of Facility for Rare Isotope Beams at Michigan State University

Outline

1. Core-collapse supernovae and neutrinos

2. Neutrino-driven outflows in core-collapse supernovae

3. Origin of proton-rich elements, and νp-process nucleosynthesis

4. Outflow hydrodynamics to the rescue

Subsonic outflows (and high entropy) to the rescue

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

- We discovered that 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 $R_{\text{PNS}} = 19\,\text{km}$

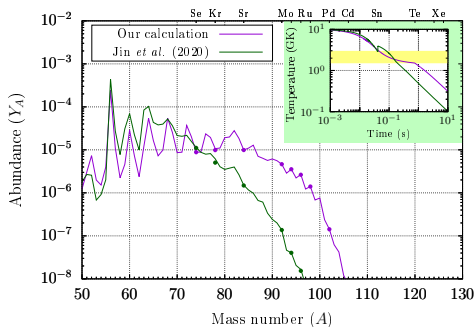# A comparison: subsonic vs supersonic outflows

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 $M_{\mathsf{PNS}} = 1.8\,M_\odot$ and $R_{\mathsf{PNS}} = 19\,\mathrm{km}$], 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)

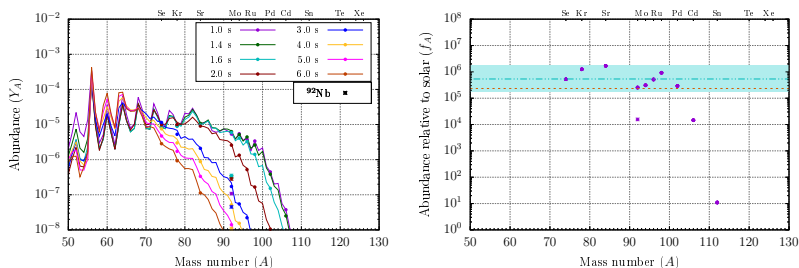# Integrated yields for a $13\,M_\odot$ progenitor model

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 $\tau = 3\,$s. **Right:** Integrated yields for the same calculation. $f_A \gtrsim 10^5$ are required to explain solar abundances.

Integrated yields demonstrate that sufficient quantities of ^{92,94}Mo and ^{96,98}Ru can be synthesized, both in an absolute sense, and in relation to the lighter p-nuclides. ^{92}Nb also co-produced!
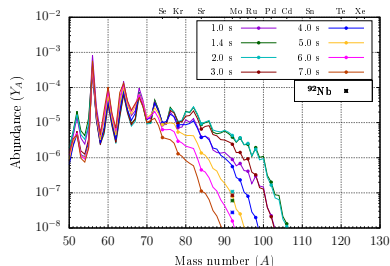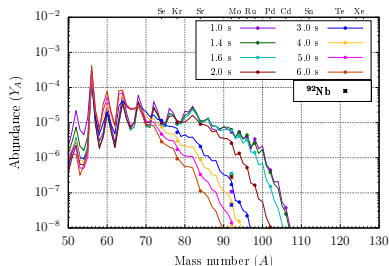
Different progenitor masses

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 $19\,\text{km}$ was used in the semi-analytic outflow model.

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

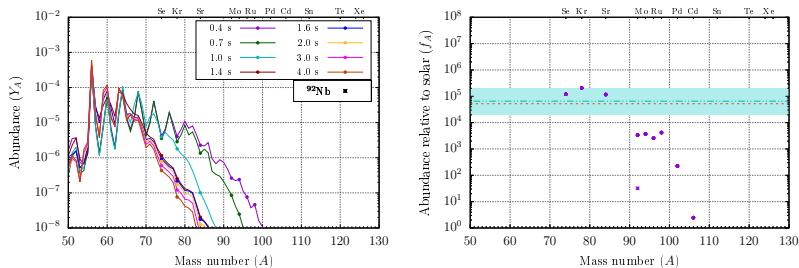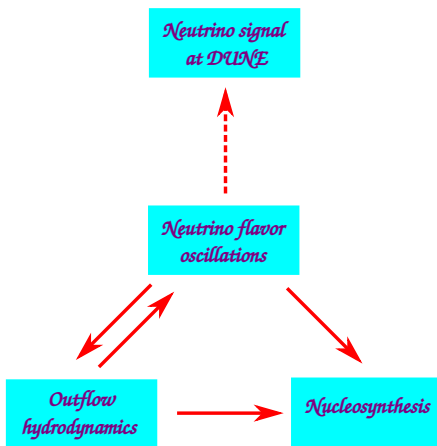# 9.5 $M_\odot$ progenitor calculation with supersonic outflow

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

Conclusions, Summary and Outlook (Part II)

- 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 (even with an enhanced triple-α reaction rate) by increasing the neutrino exposure of the outflow

- The nature of the supernova outflow (subsonic vs supersonic) has direct implications for the nucleosynthesis outcome, as well as for the expected neutrino signal in terrestrial detectors (e.g., DUNE). One may thus use the neutrino signal as a probe of hydrodynamics AND nucleosynthesis!

Conclusions, Summary and Outlook (Part II)

CCSN and neutrinos
○○○○○○○○

ν-driven outflows
○○○○○○○○○

Origin of p-rich elements, & νp-process
○○○○○○○○○○○○○

Effect of hydrodynamics
○○○○○○○○○

Bonus slides

Getting the integrated yields

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

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

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

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

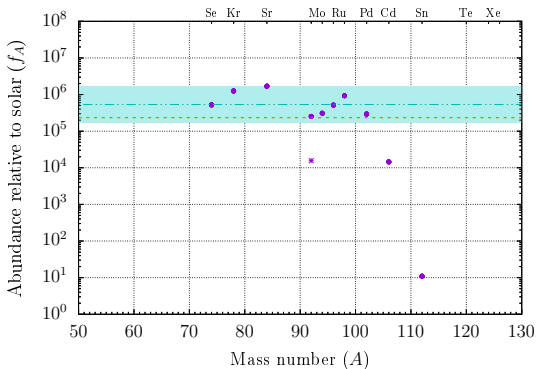# Integrated yields for the $13\,M_\odot$ progenitor calculation

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.
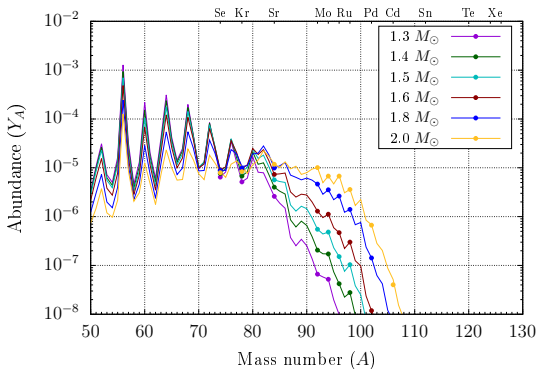
PNS mass dependence $\implies$ variability

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

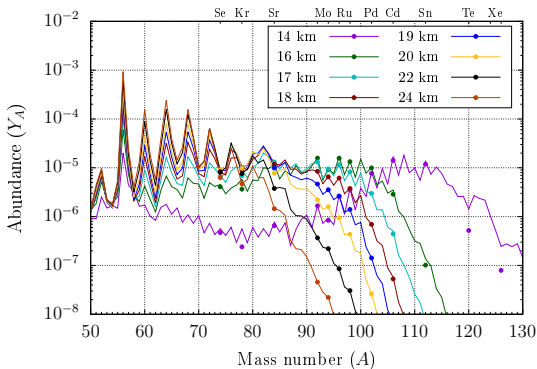# PNS radius dependence $\implies$ EoS dependence

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

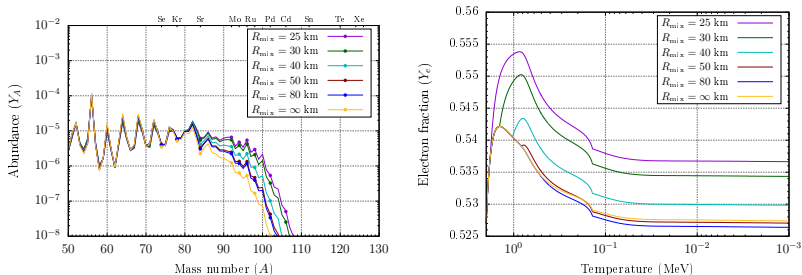# Neutrino flavor mixing and the νp-process

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*]
Flavor equilibration is found to universally improve the νp-process efficacy, more so if it occurs closer to PNS.

Neutrino-driven outflows in core-collapse supernovae

Slide from George Fuller
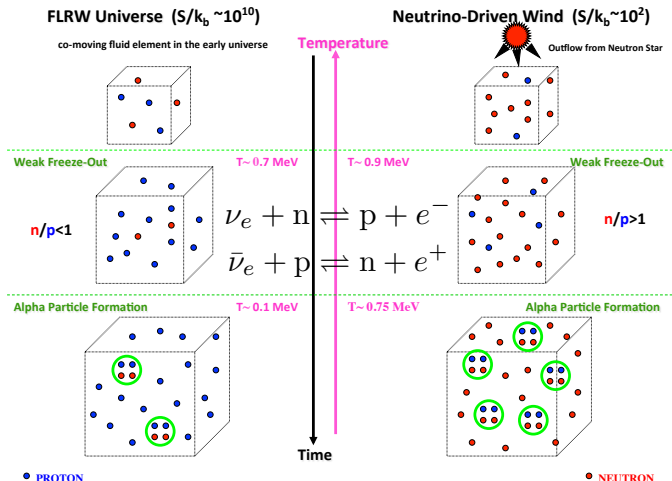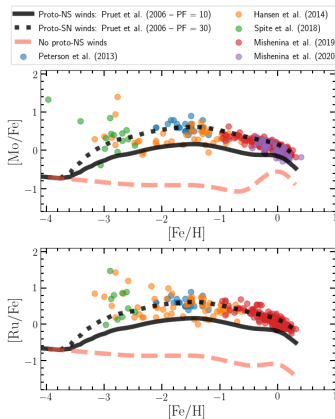
Mo and Ru in metal poor stars

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

CCSN and neutrinos
○○○○○○○○

ν-driven outflows
○○○○○○○○○

Origin of p-rich elements, & νp-process
○○○○○○○○○○○○○○

Effect of hydrodynamics
○○○○○○○○○

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)
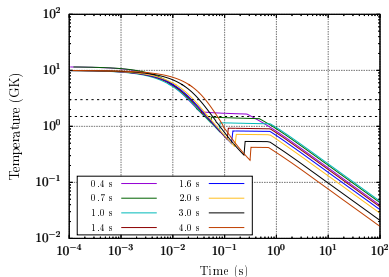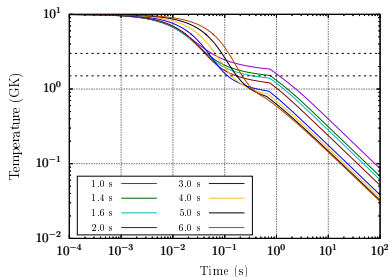
Outflow profiles for T vs t

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