

# $\nu p$ -process nucleosynthesis in core-collapse supernovae: impact of outflows and neutrino mixing

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(w/ Payel Mukhopadhyay, Alex Friedland, Shuo Xin)

N3AS seminar

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# Outline

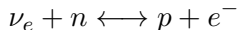
- 1 Core-collapse supernovae, neutrinos, and flavor oscillations
- 2 Origin of proton-rich elements, and  $\nu p$ -process nucleosynthesis
- 3 Hydrodynamics to the rescue ...
- 4 ... and perhaps a little help from neutrino mixing

# 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:  $\nu$ s are the main carriers of gravitational binding energy ( $\sim 99\%$ ) and lepton number radiated away from the star
  - B.E.  $\sim 10^{53}$  ergs  $\implies \sim 10^{58}$   $\nu$ s 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
- $\nu$ -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



- 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  $\nu_e$  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)

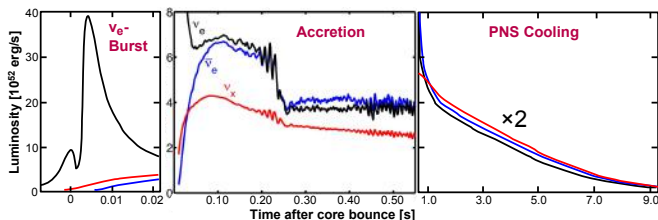


Figure: Taken from H.-T. Janka (1702.08713).

# 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

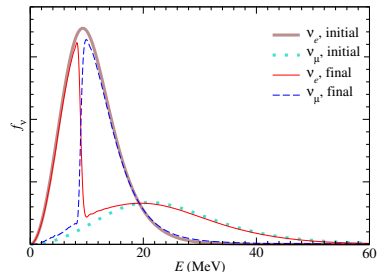
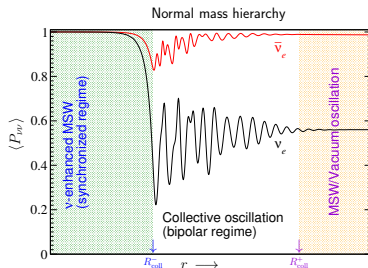
$$i\frac{\partial\rho}{\partial t} = [H, \rho],$$

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

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

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

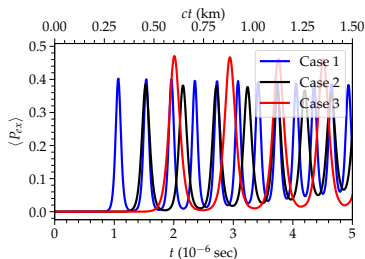
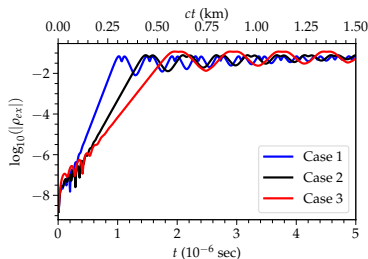
# Collective flavor oscillations: synchronized and bipolar



**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  $\nu_e$  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.: 1905.00082, 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)

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# Chart of the nuclides

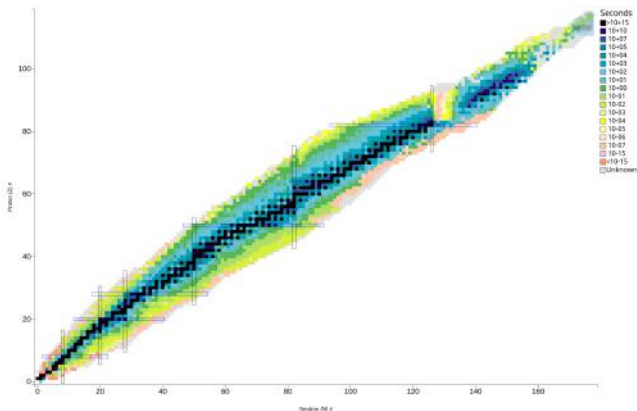


Figure: Chart of Nuclides - National Nuclear Data Center

## Chart of the nuclides

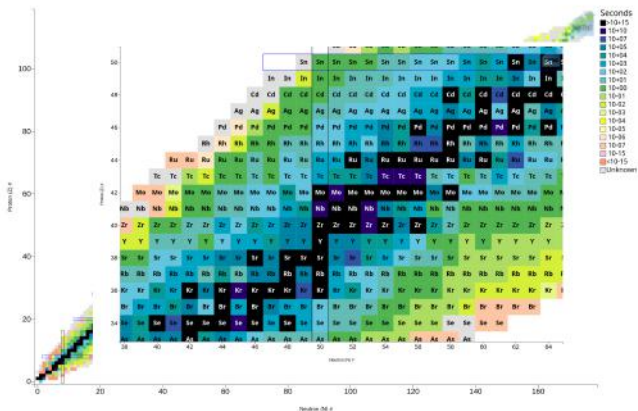
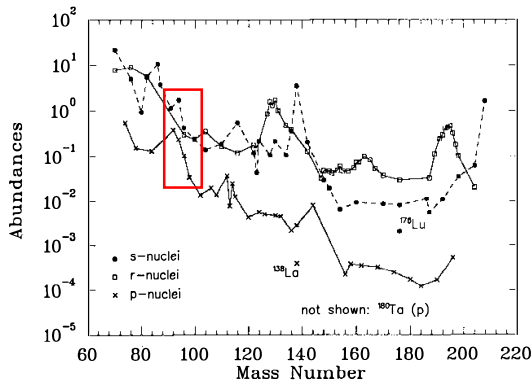


Figure: Chart of Nuclides - National Nuclear Data Center

# 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  $^{92,94}\text{Mo}$  and  $^{96,98}\text{Ru}$ .

# 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 photodisintegration) could explain  $p$ -nuclide origin — apart from the anomalously high abundances near the  $^{92}\text{Mo}$  peak
  - $\gamma$ -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  $^{92}\text{Mo}$  but not enough  $^{94}\text{Mo}$  and  $^{96,98}\text{Ru}$**
  - $\nu$ -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  $^{92,94}\text{Mo}$  and  $^{96,98}\text{Ru}$ , 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.,  $^{56}\text{Ni}$
  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  $\beta^+$  decays, is stalled by  $\beta^+$  decay “waiting point” nuclei (e.g.,  $^{64}\text{Ge}$ ) along the reaction flow, with lifetimes much longer than the outflow dynamical timescales [[Wallace & Woosley \(1981\)](#); [Schatz et al. \(1998\)](#)]

# What about $^{92,94}\text{Mo}$ and $^{96,98}\text{Ru}$ ?

- Transmutation of  $n$ -rich nuclides likely cannot explain the anomalously high abundances of  $^{92,94}\text{Mo}$  and  $^{96,98}\text{Ru}$
- New mechanism proposed in 2005: the  $\nu p$ -process

PRL **96**, 142502 (2006)

PHYSICAL REVIEW LETTERS

week ending  
14 APRIL 2006

## Neutrino-Induced Nucleosynthesis of $A > 64$ Nuclei: The $\nu p$ Process

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(Received 10 November 2005; published 10 April 2006)

We present a new nucleosynthesis process that we denote as the  $\nu p$  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  $^{92,94}\text{Mo}$  and  $^{96,98}\text{Ru}$ . This process also offers a natural explanation for the large abundance of Sr seen in a hyper-metal-poor star.



# The $\nu p$ -process

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

# Favourable conditions for $\nu p$ -process

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

1. Short time interval ( $\tau_1$ ) 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 ( $\tau_2$ ) 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  $\nu p$ -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  $\nu p$ -process efficacy
- Among these were reported difficulties in producing the correct isotopic ratios, as well as required absolute yields of  $^{92,94}\text{Mo}$  and  $^{96,98}\text{Ru}$  [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  $\nu p$ -process yields as a result of an in-medium enhancement of the triple- $\alpha$  reaction rate<sup>†</sup>.

### A nail in the coffin of the $\nu p$ -process?

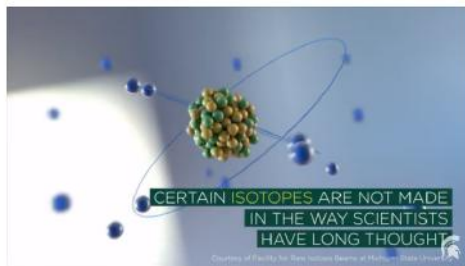
<sup>†</sup> **Note:** an enhancement in the  $3\alpha \rightarrow ^{12}\text{C}$  reaction rate leads to increased seed-nuclei formation and lowers the proton-to-seed ratio in the outflow, decreasing the  $\nu p$ -process potency

# 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.

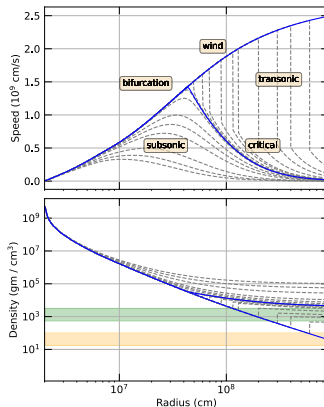
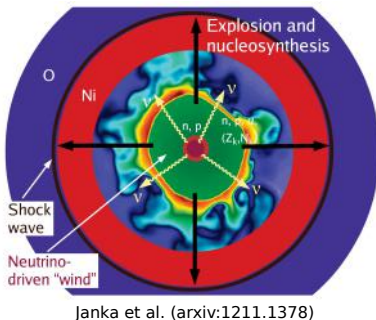


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# Hydrodynamics of neutrino driven outflows

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](https://arxiv.org/abs/2009.10059)).



# Semi-analytic outflow model

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

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

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

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

plus corrections due to GR effects, changing  $g_*$ , 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)

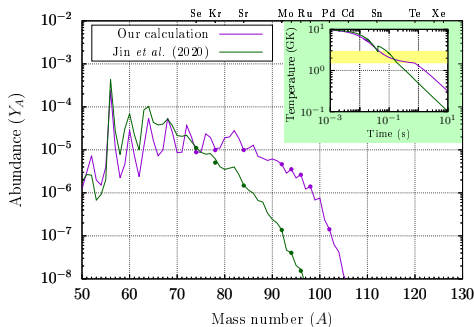
# Subsonic outflows (and high entropy) to the rescue

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

- Subsonic outflows are much more conducive to optimal  $\nu p$ -process yields
- Outflow spends more time in the  $3 \text{ GK} > T > 1.5 \text{ GK}$  band where the  $\nu p$ -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  $(n, \gamma)$  reactions
- Triple- $\alpha$  enhancement still hurts the  $\nu p$ -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

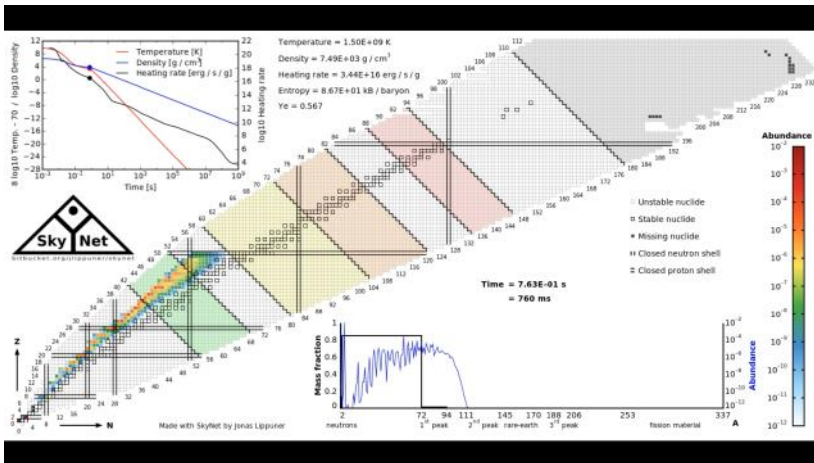


**Figure:** Nucleosynthesis yields in a  $\nu p$ -process simulation with a **subsonic outflow profile (purple)** obtained by solving the outflow equations [using a  $13 M_{\odot}$  progenitor model, with  $M_{\text{PNS}} = 1.8 M_{\odot}$  and  $R_{\text{PNS}} = 19 \text{ km}$ ], and with a **supersonic 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.**

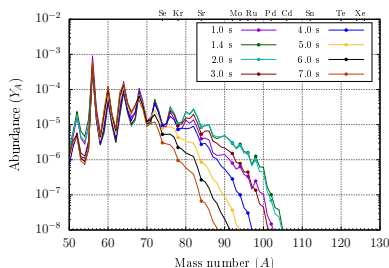
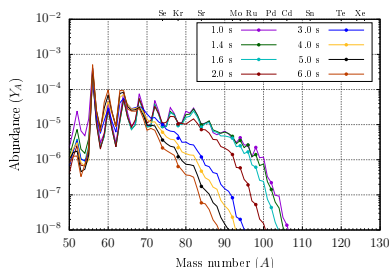
# Nucleosynthesis calculations and inputs

- Nucleosynthesis calculations performed using open source [SkyNet](#) code [[Lippuner and Roberts, ApJS 233, 18 \(2017\)](#)]
- Triple- $\alpha$  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  $\tau = 3$  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



# Heavy progenitors ( $M > 10 M_{\odot}$ ): subsonic outflows likely



**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 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!

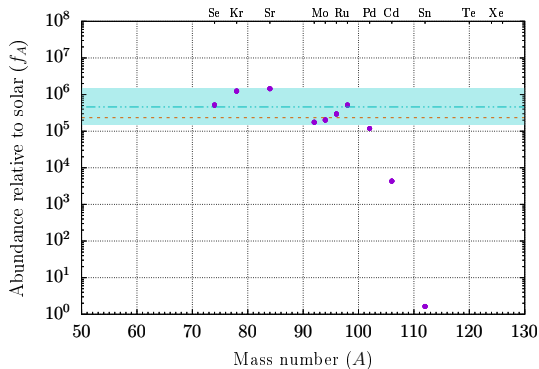
# Getting the integrated yields

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

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

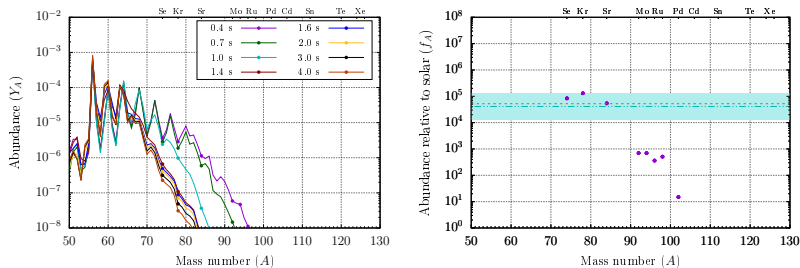
- The isotopic “production factor” is defined as  $f_{A,Z} = \langle Y_{A,Z} \rangle / Y_{A,Z}^{\odot}$ , where  $Y_{A,Z}^{\odot}$  is the observed mass fraction of that isotope in the solar system (normalized so that  $\sum A Y_{A,Z}^{\odot} = 1$  over all the nuclides)
- The “overproduction factor” is then given by  $O_{A,Z} = f_{A,Z} \times (M_{\text{out}}/M_{\text{ejec}})$ , where  $M_{\text{out}}/M_{\text{ejec}} \sim 10^{-4}$ . 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



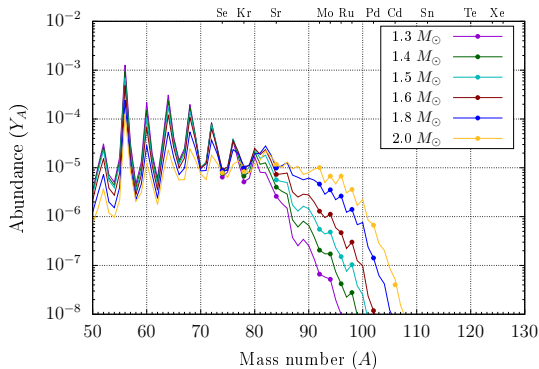
**Figure:** Integrated yields for the  $13 M_{\odot}$  progenitor calculation. The colored band represents a range of  $f_{\max}$  to  $f_{\max}/10$ , where  $f_{\max}$  is the highest production factor among the  $p$ -nuclides. Red dashed line represents the minimum production factor needed to account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

## $9.5 M_{\odot}$ progenitor calculation: supersonic outflow



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

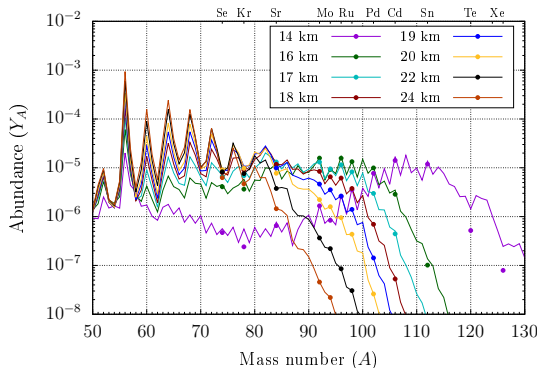
# PNS mass dependence $\Rightarrow$ variability



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



# PNS radius dependence $\Rightarrow$ 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  $\Rightarrow$  deeper gravitational potential  $\Rightarrow$  higher entropy, which is more favourable for the  $\nu p$  process.

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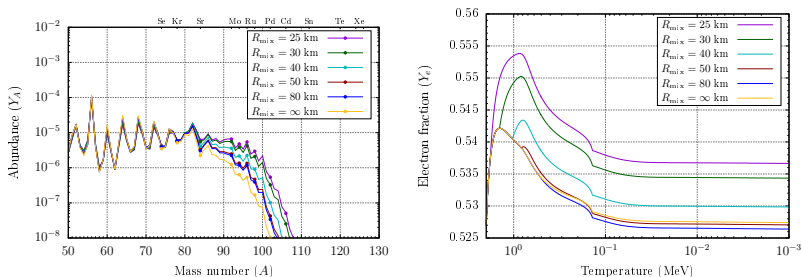
# Neutrino mixing and electron (proton) fraction

- The nuclear composition of a  $p$ -rich outflow at 3 GK consists of mainly protons,  $\alpha$ s, 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.  $\nu p$ -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  $\nu_e$  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  $\nu_e$  average energies, such as mixing between  $\nu_e$  and the more energetic  $\nu_{\mu,\tau}$  flavors, could make the outflow more proton-rich, improving the  $\nu p$ -process efficacy.**

# Neutrino flavor mixing implementation

- Flavor mixing implemented as complete and sharp flavor equilibration among  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$  (and among  $\bar{\nu}_e$ ,  $\bar{\nu}_\mu$ ,  $\bar{\nu}_\tau$ ) at radius  $R_{\text{mix}}$ , so that the energy distributions of each flavor at  $r > R_{\text{mix}}$  are given by  $(f_{\nu_e} + f_{\nu_\mu} + f_{\nu_\tau})/3$ , where  $f_{\nu_\alpha}$  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 ( $6 \text{ GK} \gtrsim T \gtrsim 3 \text{ GK}$ ),
  - (c) after QSE freeze-out ( $3 \text{ GK} \gtrsim T \gtrsim 1.5 \text{ GK}$ ).Increasing  $\nu_e$  and  $\bar{\nu}_e$  average energies by flavor mixing has varying effects across these regimes. Typical hierarchy between  $\nu_e$  and  $\nu_{\mu,\tau}$  average energies is more pronounced than that between  $\bar{\nu}_e$  and  $\bar{\nu}_{\mu,\tau} \implies$  **flavor equilibration increases  $\nu_e$  average energy much more than it does for  $\bar{\nu}_e$ .**

# Neutrino flavor equilibration and the $\nu p$ -process



**Figure:** Nucleosynthesis calculations with different flavor equilibration radii  $R_{\text{mix}}$ . **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  $R_{\text{mix}}$ . Flavor equilibration is found to universally improve the  $\nu p$ -process efficacy, more so if it occurs closer to PNS.

# Neutrino flavor equilibration and the $\nu p$ -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  $\nu p$ -process.
- In (b) and (c), the  $\nu_e(n, e^-)$  rates lose their importance because of neutron depletion during  $\alpha$ -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  $\nu p$ -process.

# Conclusions

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

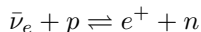
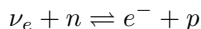


# Bonus slides

# $p$ -rich nucleosynthesis does not happen easily!

- Case in point — early universe ( $S/n_b \sim 10^{10}$ )

- $T \gtrsim \text{MeV}$ : weak equilibrium



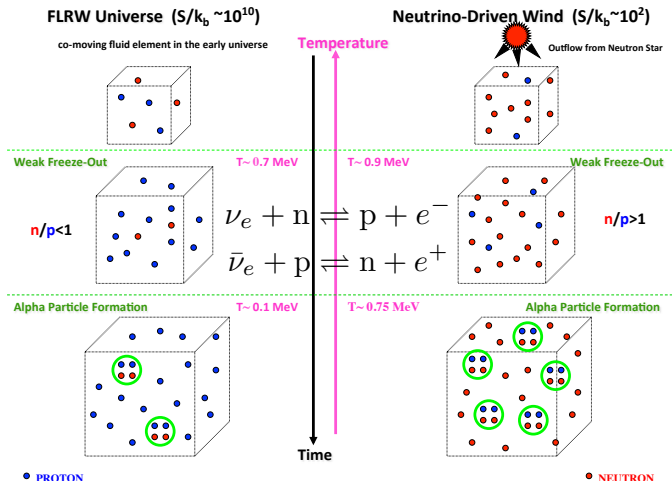
- $T \sim 0.7 \text{ MeV}$ : rate of above reactions falls below expansion rate of the universe  $\implies$  weak freeze-out. After that, only free-neutron decay can change  $n/p$  ratio
- $T \approx 0.1 \text{ MeV}$ :  $Y_p/Y_n \approx 7$ . Rate of  $n(p, \gamma)d$  (and subsequent reactions which make  ${}^3\text{He}$ ,  ${}^3\text{H}$ ,  ${}^4\text{He}$ ) falls below expansion rate. Freeze-out from nuclear statistical equilibrium (NSE) leads to  $\alpha$ -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  $\alpha$ -particles are made (and traces of  ${}^2\text{H}$ ,  ${}^3\text{He}$ ,  ${}^7\text{Li}$ )

# $p$ -rich nucleosynthesis does not happen easily!

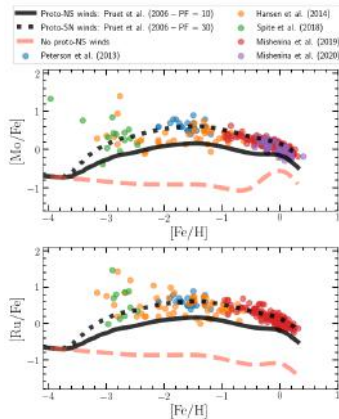
- In a hypothetical early universe with more neutrons than protons (e.g., if  $m_n$  were less than  $m_p$ ), BBN could probably make heavier elements through neutron captures
- $\mathcal{Q}$ . What would happen if the (proton-rich) early universe (or some sub-regions of it) had a much lower entropy ( $S/n_b \sim 100$ )?

# 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.**

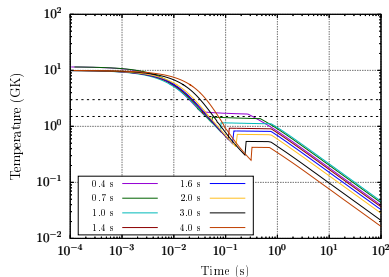
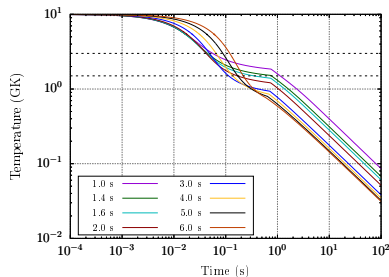
# $p$ -process mechanisms [Rauscher *et al.* (2013)]

- $\gamma$ -process (Woosley and Howard, 1978, ApJS 36, 285)
  - Photodisintegration of neutron rich isotopes either via  $(\gamma, n)$  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  $^{92}\text{Mo}$  but underproduces  $^{94}\text{Mo}$  and  $^{96,98}\text{Ru}$
- $\nu$ -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  $\nu$  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  $\beta^+$  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  $\beta^+$  decay “waiting points” along the nucleosynthesis chain
- $\alpha$ -process (Hoffman *et al.* ApJ, 460, 478 (1996))
  - Proceeds via chain of  $\alpha$ ,  $n$ , and  $p$  captures following  $\alpha$ -rich freezeout in neutrino-driven outflows with  $Y_e \sim 0.48$ –0.49
  - Can make  $^{92}\text{Mo}$  but not much  $^{94}\text{Mo}$  or  $^{96,98}\text{Ru}$
  - Makes appreciable amounts of  $^{92}\text{Nb}$  (comparable to  $^{92}\text{Mo}$ )

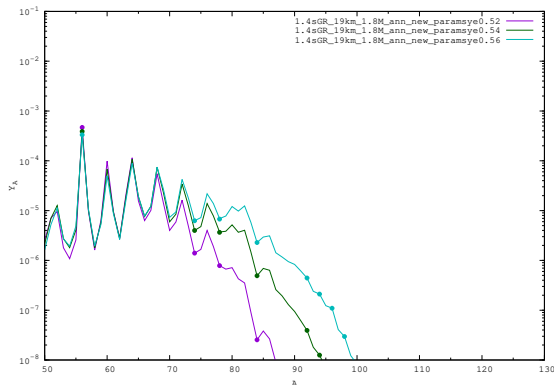
# Outflow profiles for $T$ vs $t$



**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,  $^{92}\text{Nb}$ , is also known to occur in nature, but cannot be made in the  $\nu p$ -process — shielded from  $p$ -rich nuclear flows by the neighboring stable  $^{92}\text{Mo}$
- Can be made in the  $\gamma$ -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  $^{92}\text{Mo}$  must also produce  $^{92}\text{Nb}$  concurrently, thereby putting the  $\nu p$  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  $^{92}\text{Nb}$  and  $^{92}\text{Mo}$  respectively

# The $\alpha$ -process ( $Y_e = 0.48$ ) — the Niobium solution

