# $\nu p$-process in Core-Collapse Supernovae: Imprints of General Relativistic Effects

**arXiv: 2508.02055**


Ian Padilla-Gay

*Postdoctoral Research Associate (SLAC)*

ianpaga@slac.stanford.edu


**In collaboration with:**


Alexander Friedland, Derek Li, Giuseppe Lucente & Amol V. Patwardhan


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Network for Neutrinos, Nuclear Astrophysics, and Symmetries
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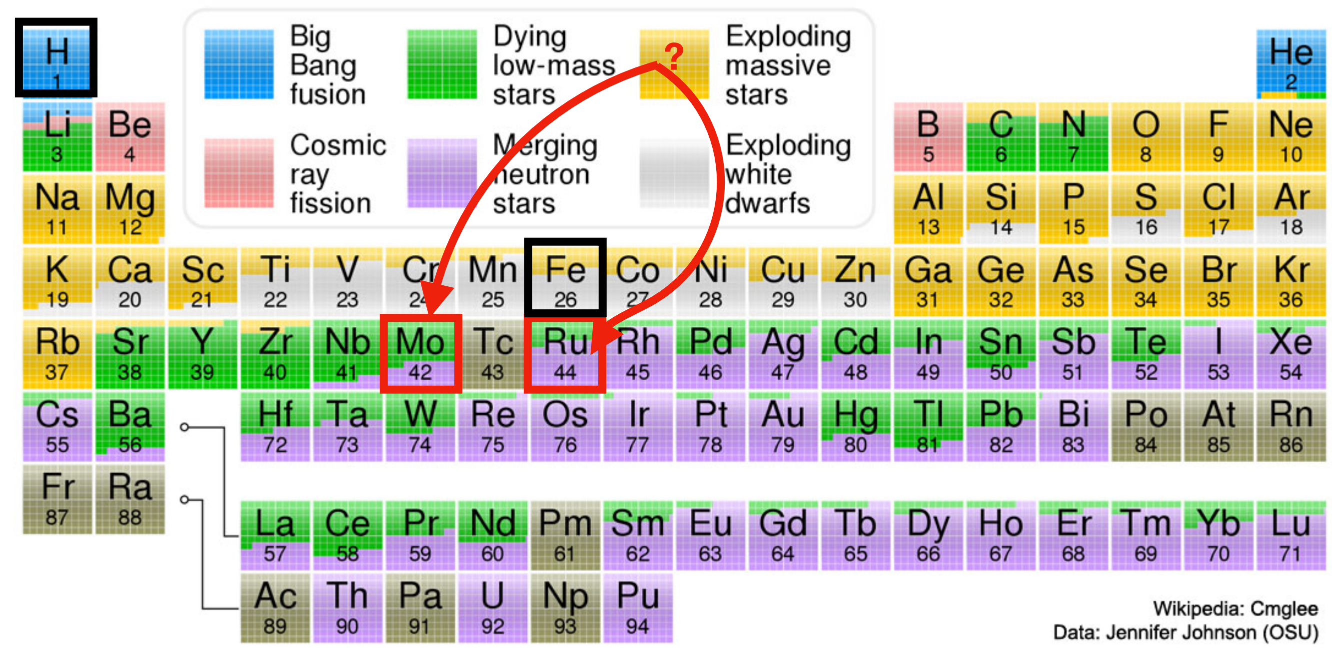
Most nuclides created via s- or r-process
(neutron-rich nuclides)



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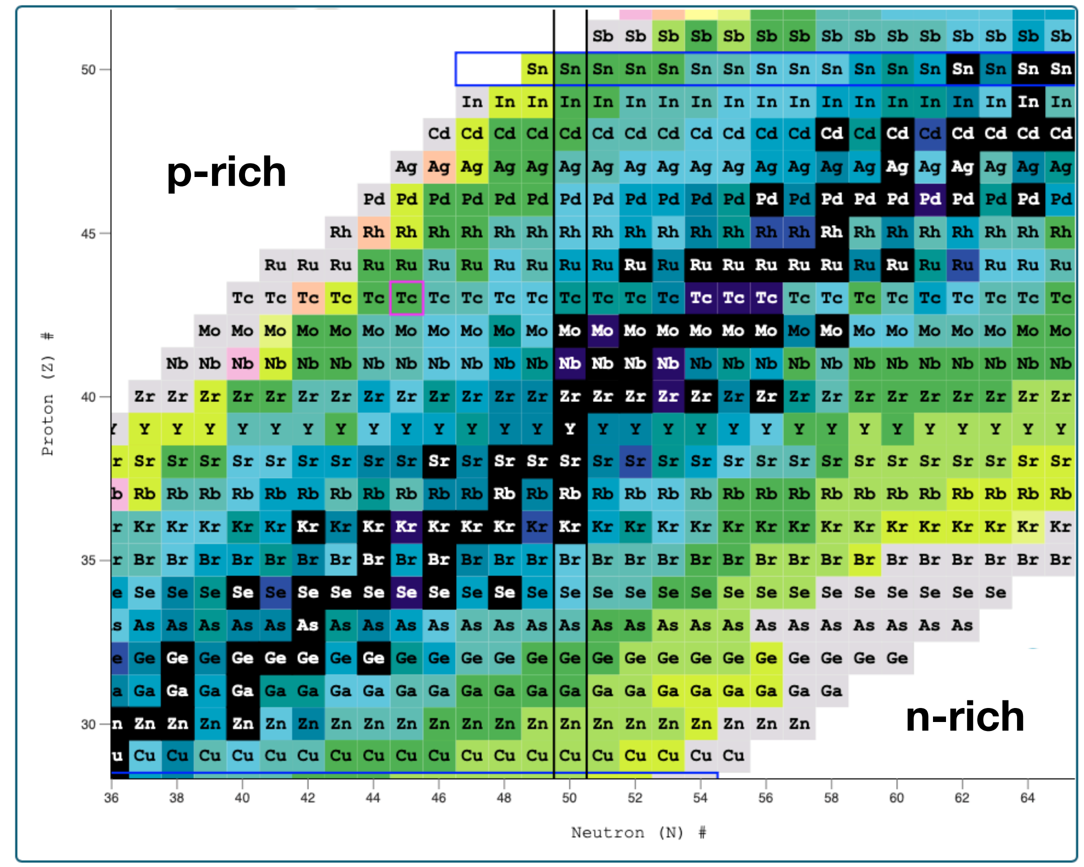

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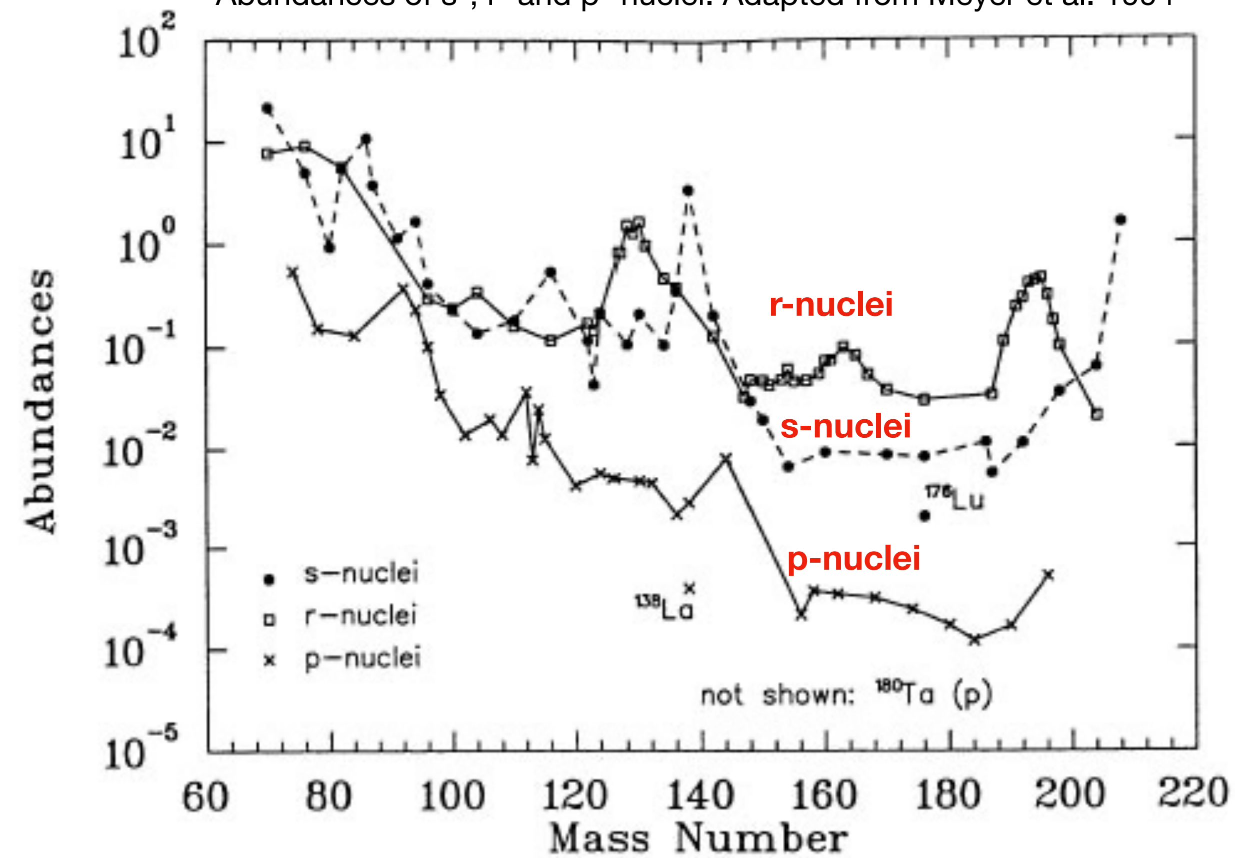

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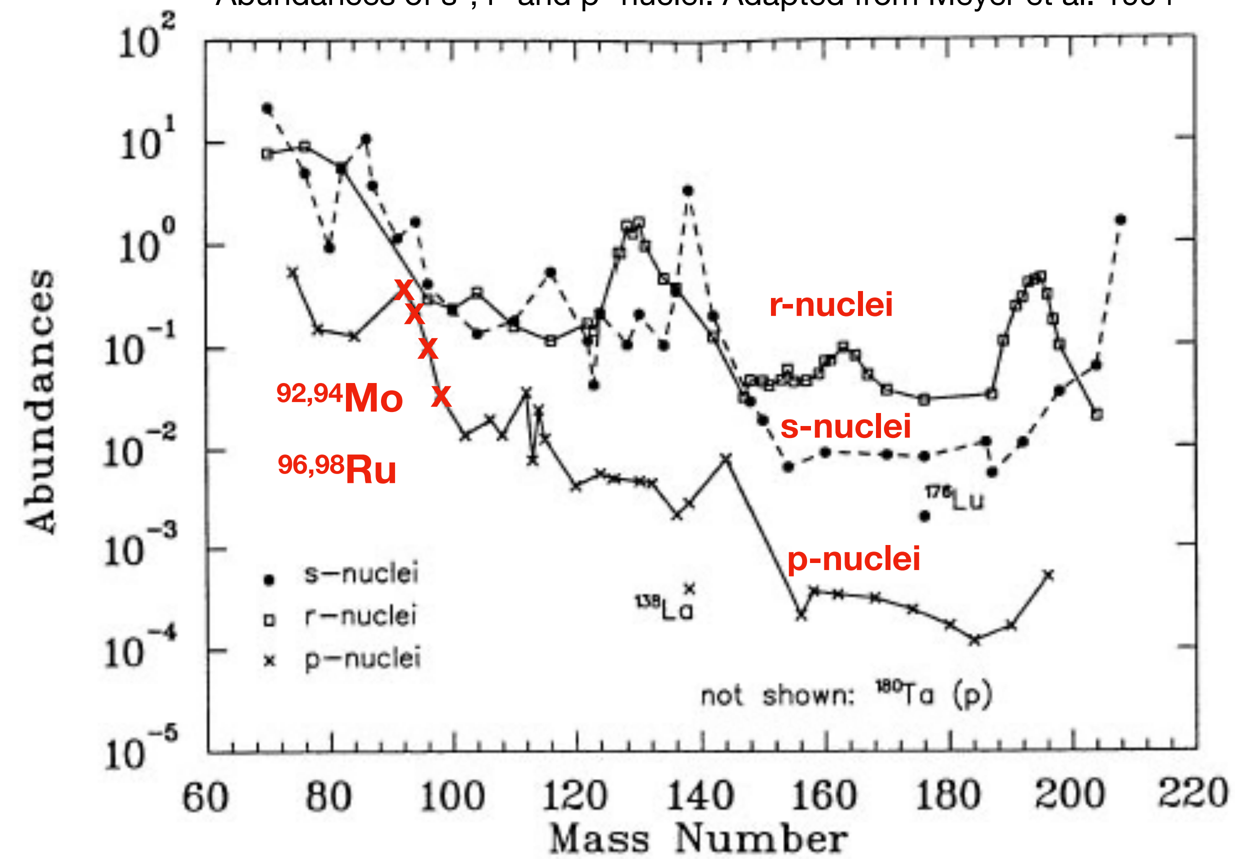


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Suggests the need of a primary process.

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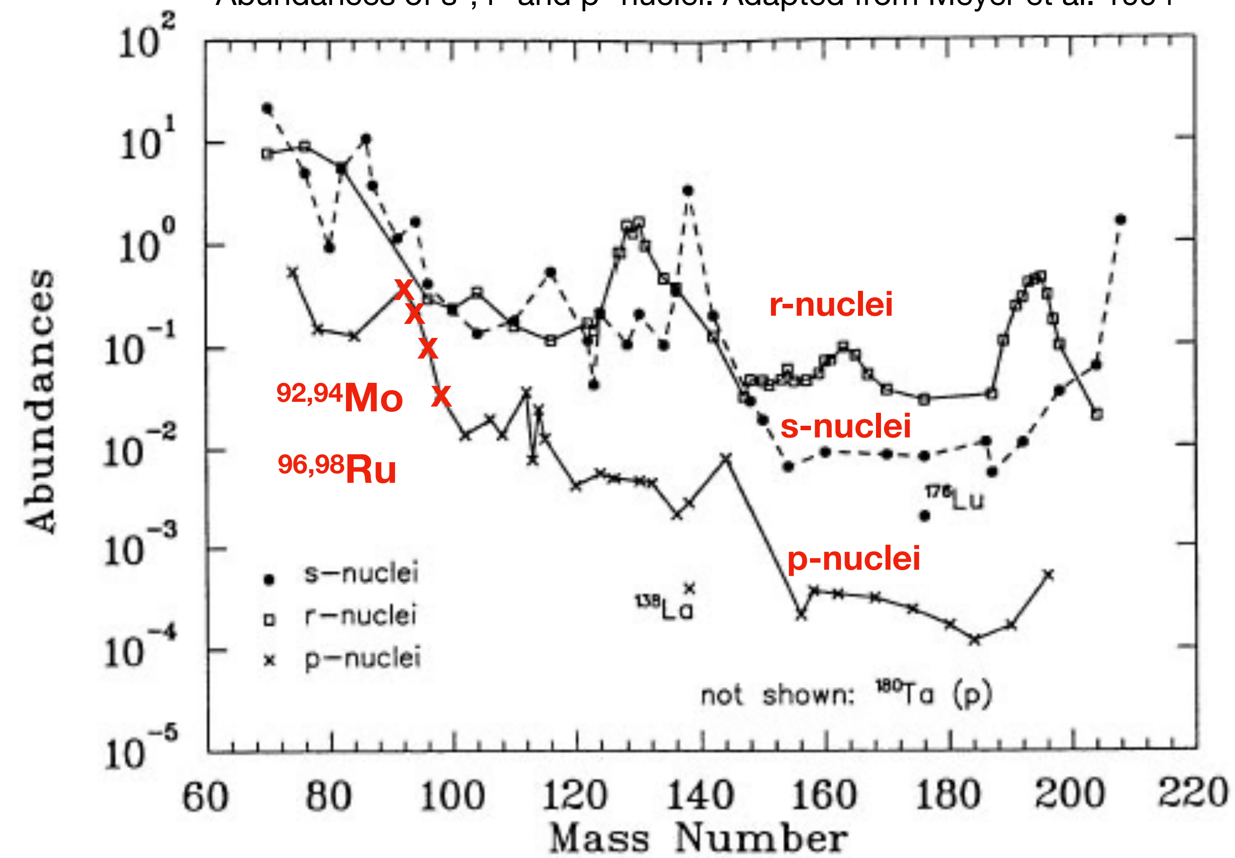


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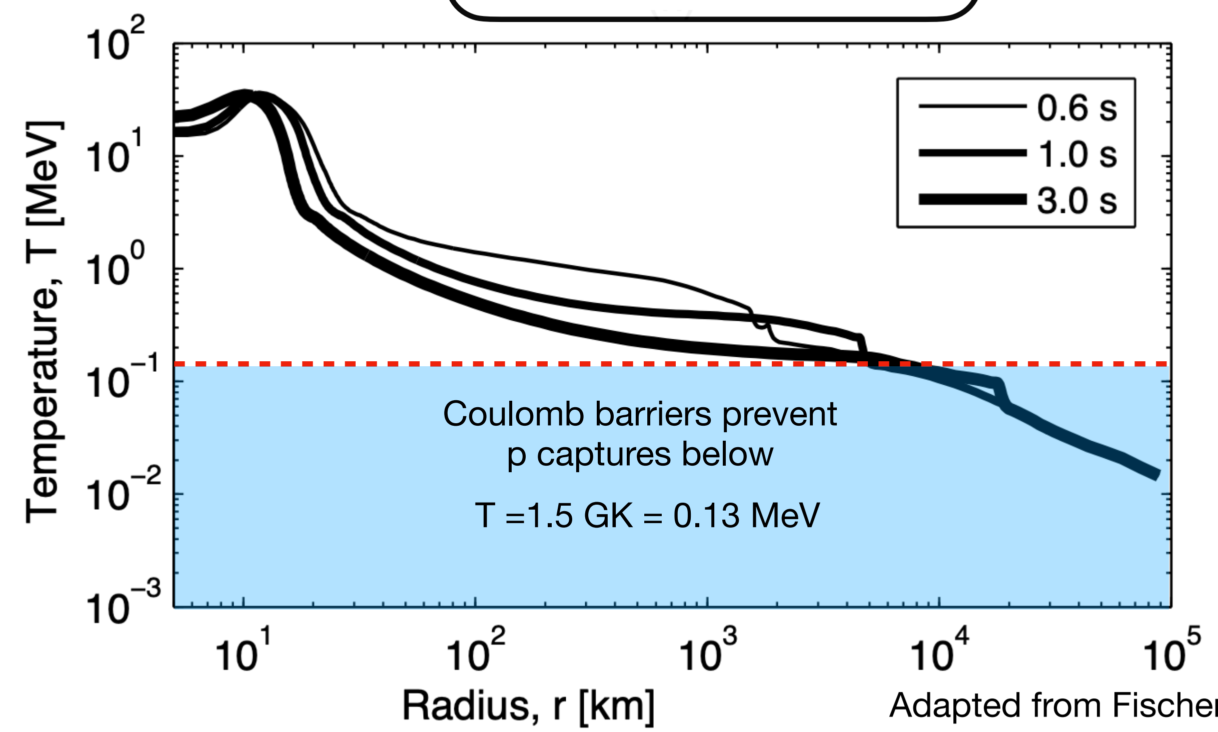
Rapid p capture? $rp$-process. But:
Long “Waiting points”
(e.g., Ge-64 takes 1 min to decay)

**We only have ~few seconds before Coulomb barriers.**

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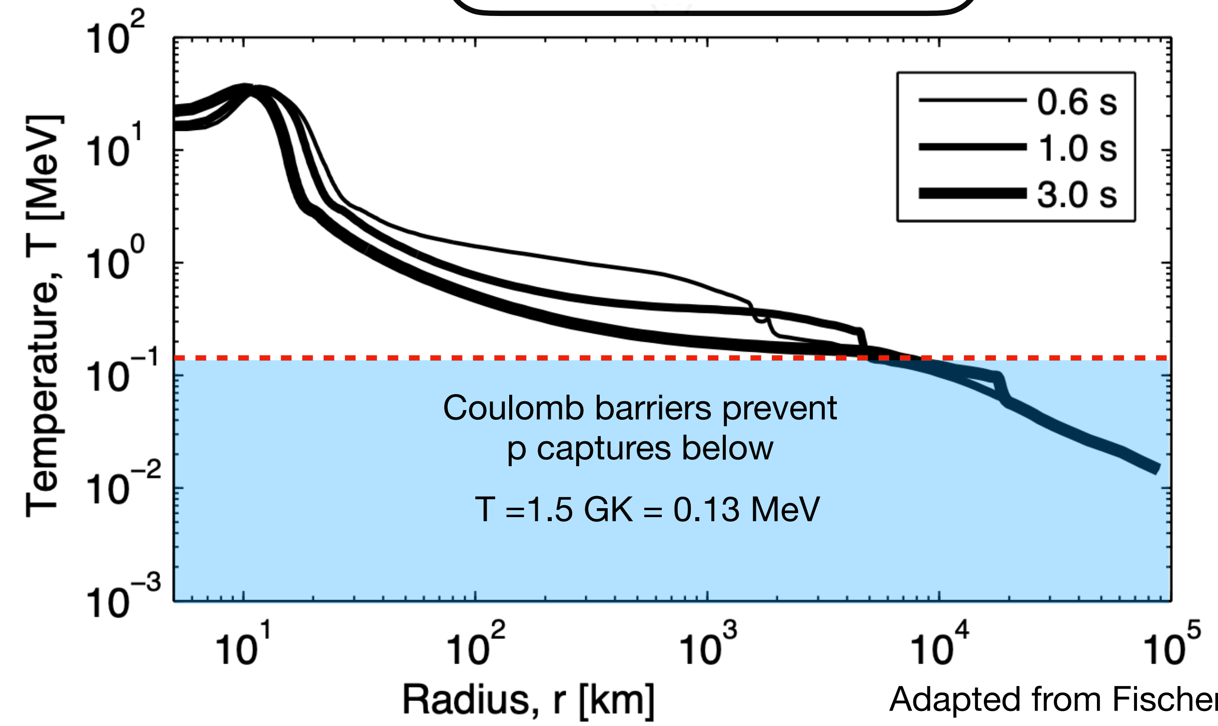


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Good news: Neutrinos can help bypass "waiting points".

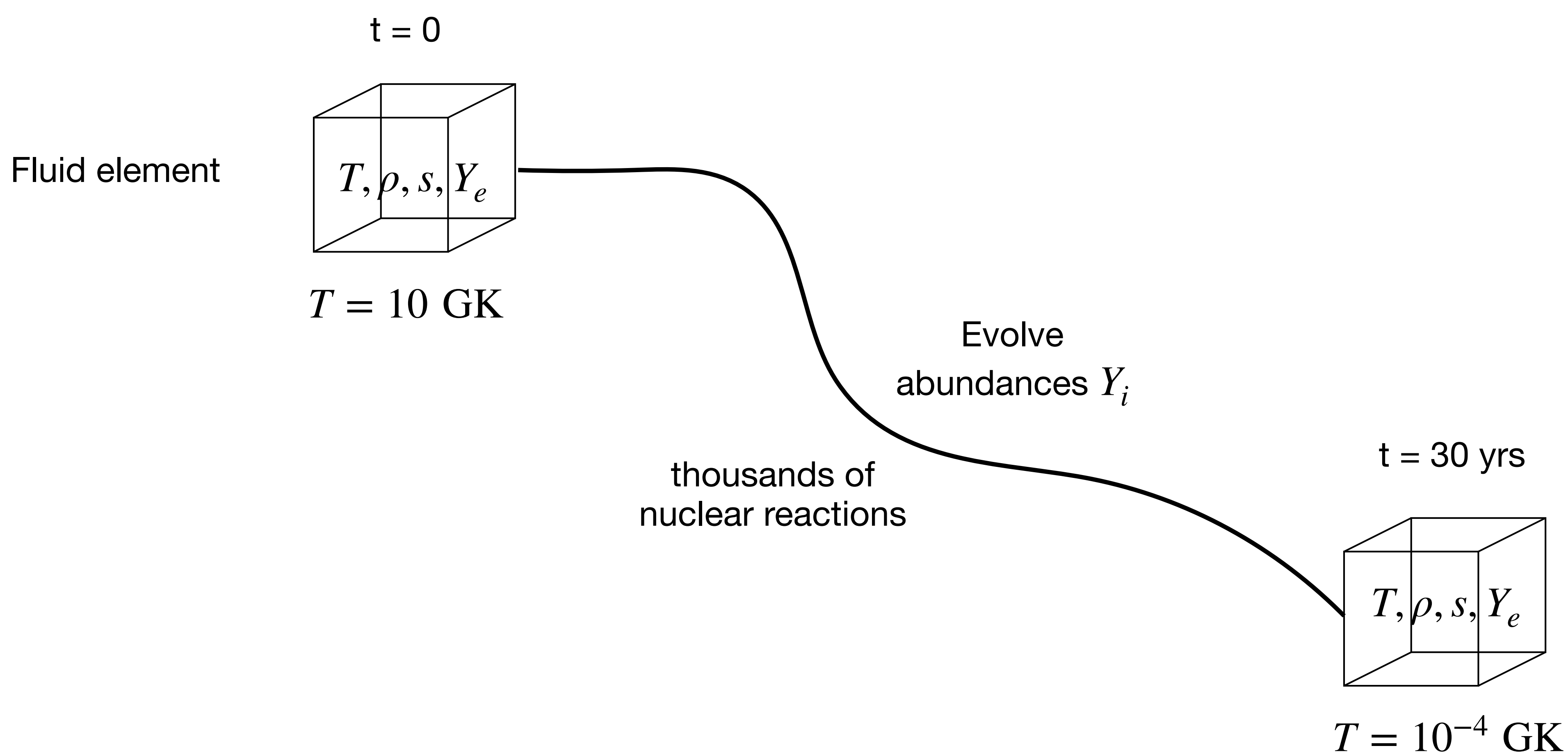
The $\nu p$-process Could be a solution.

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

**Neutrino-Induced Nucleosynthesis of $A > 64$ Nuclei: The $\nu p$ 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]

# Stages of the $\nu p$-process




**SkyNet**[1]: Nuclear reaction network that evolves the abundances of nuclear species



[1] SkyNet: A modular nuclear reaction network library, Jonas Lippuner, Luke F. Roberts, The Astrophysical Journal Supplement Series, Volume 233, Issue 2, article id. 18, 31 pp. (2017)

# The $\nu p$-process: Stage I

**$\nu p$-process[1]:**

1. NSE evolution mode for $T \gtrsim 10$ GK. Nuclei $\rightleftharpoons$ free n and p.
2. Around $T \sim 9$ GK, $\alpha$-particles ($^4$He) are formed.
3. For $T > 6$ GK, the reaction $3\alpha \rightleftharpoons {}^{12}\mathrm{C}$ is in equilibrium. Nothing happens.
4. But when $T < 6$ GK, the reaction $3\alpha \rightleftharpoons {}^{12}\mathrm{C}$ falls out of equilibrium, **seed nuclei ($A \geq 12$) up to $^{56}$Ni are formed**. Seeds remain in QSE with heavier nuclei as long as $6\ \mathrm{GK} > T > 3\ \mathrm{GK}$.

**T = 5 GK, t = 0.02 s**

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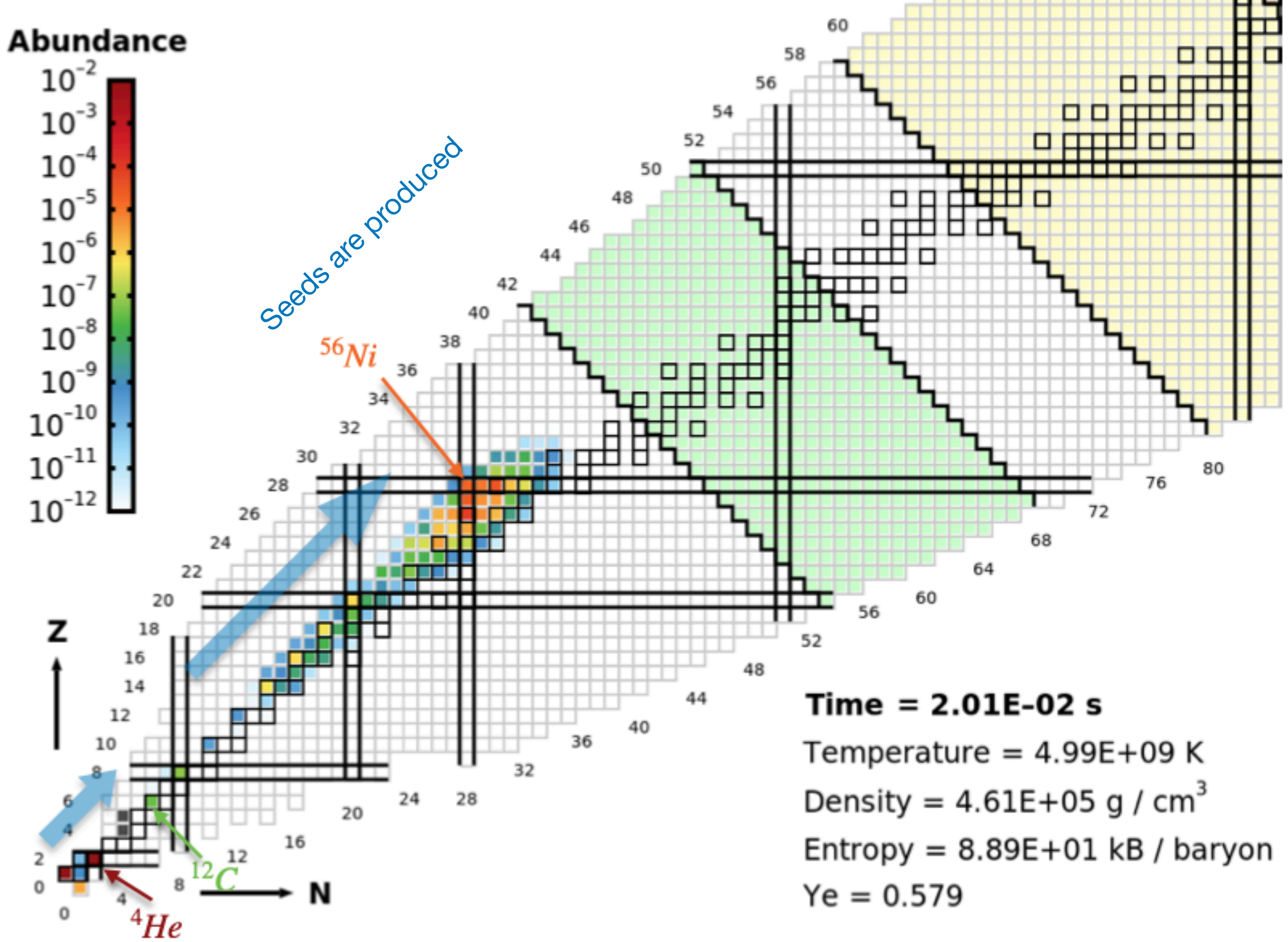


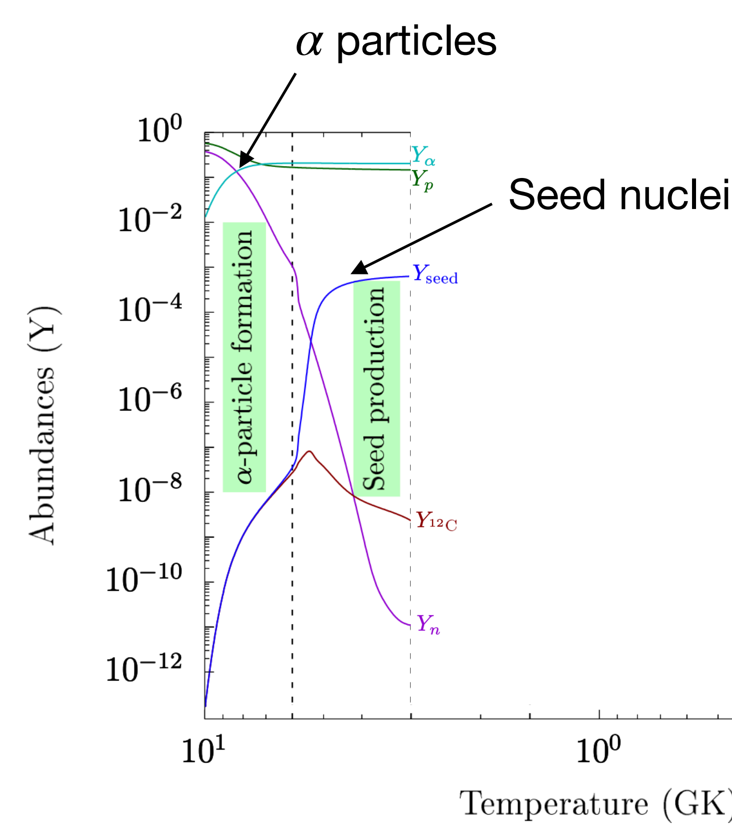


[1] Neutrino-Induced nucleosynthesis of A > 64 Nuclei: The $\nu p$-process, C. Frôhlich et al, PRL 96 142502 (2006)

[2] Uncertainties in the vp-process: Supernova Dynamics Versus Nuclear Physics, Wanajo, Janka & Kubono, The Astrophysical Journal, Volume 729, Issue 1, article id. 46, 18 pp. (2011).

# The $\nu p$-process: Stage II

$\nu p$-process[1]:

5. For $T < 3$ GK, the system freezes out of all equilibria and we can go **beyond $^{56}$Ni**.
6. In the window $3\ \text{GK} > T > 1.5\ \text{GK}$, $\bar{\nu}_e$ **capture on free protons** $p(\bar{\nu}_e, e^+)n$ creates a subdominant **neutron population**.
7. $(n,p)$ and $(n,\gamma)$ are triggered to **bypass the $\beta^+$ waiting points**. Combined with **proton captures** $(p,\gamma)$, the flow moves along the $rp$-process nucleosynthesis chain.

**T = 1.5 GK, t = 0.7 s**

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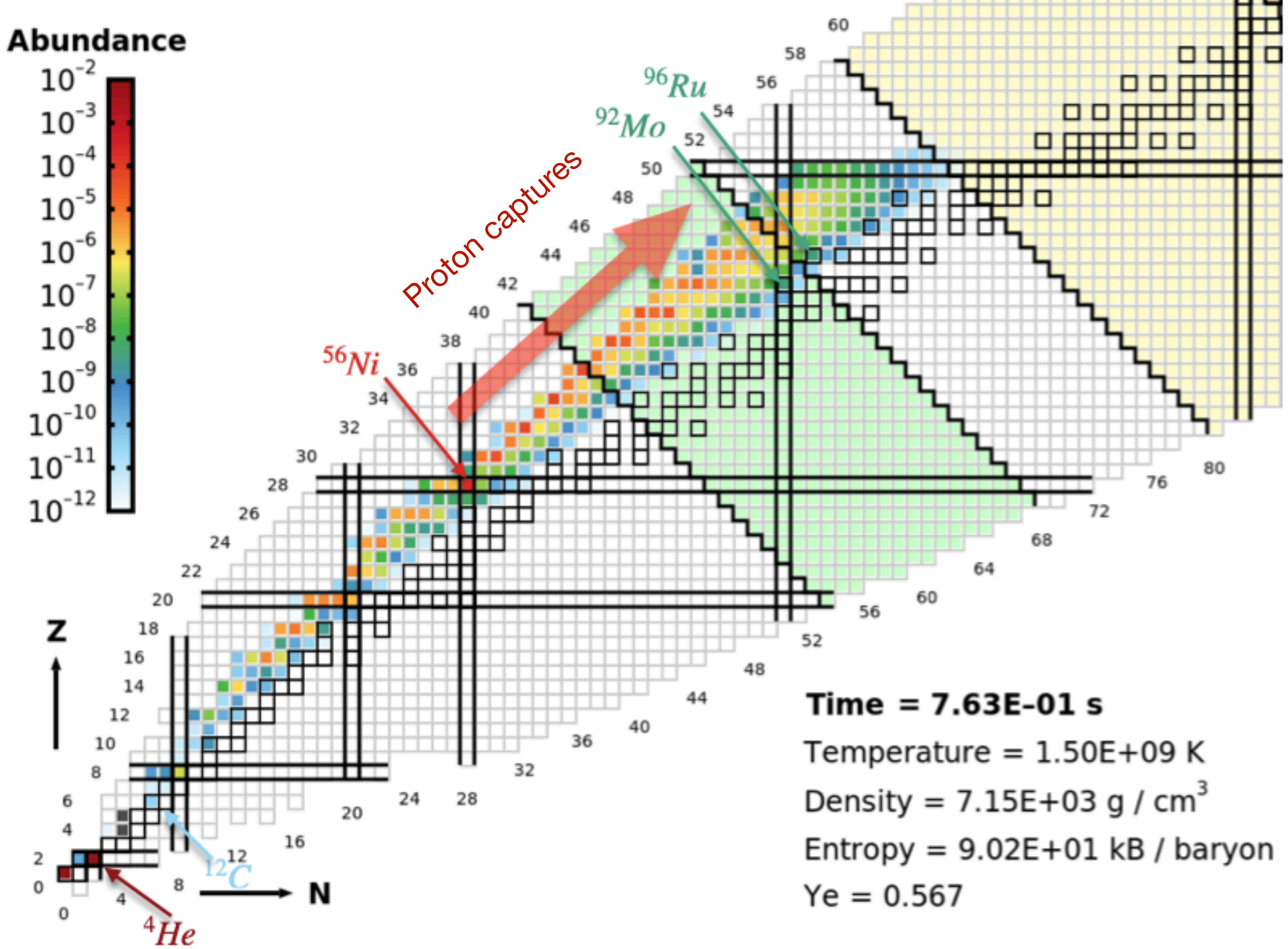


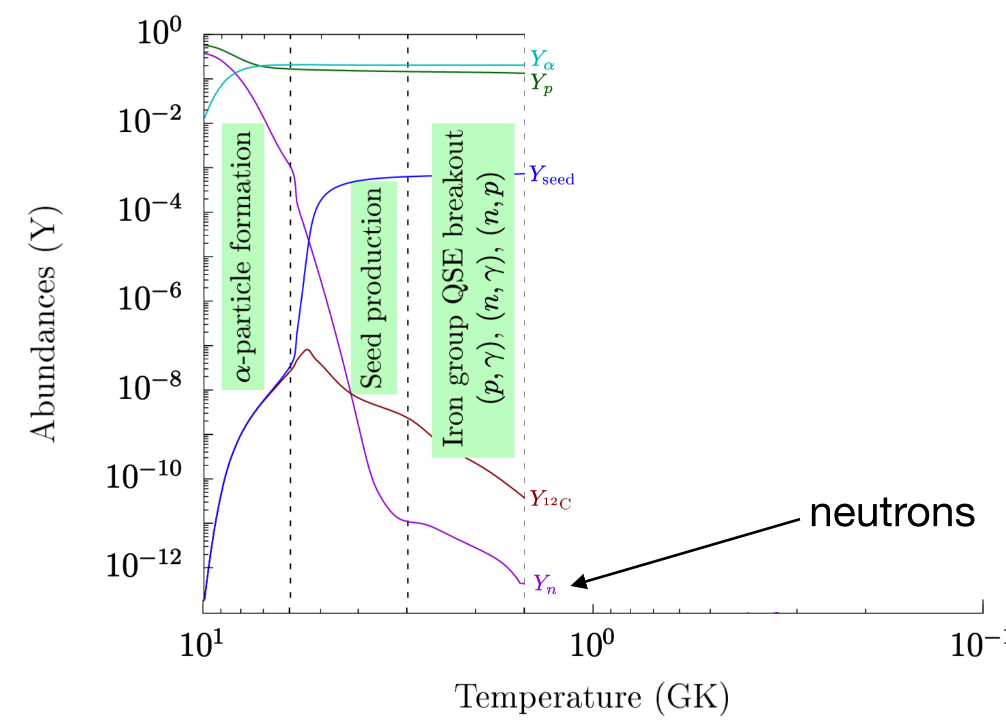


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# The $\nu p$-process: Stage III

**$\nu p$-process[1]:**

8. Outflow continues to cool down below $T < 1.5\ \mathrm{GK}$, Coulomb barriers **make it impossible** for protons to be captured $(p, \gamma)$.
9. $\bar{\nu}_e$ interactions on free protons $p(\bar{\nu}_e, e^+)n$, however, **continue neutron production**.
10. The resulting **late-time neutron captures**, $(n, \gamma)$ and $(n, p)$, push the composition **towards the valley of stability**.
11. Interestingly, the shielded **$^{92}$Nb can be produced**.

**T = 0.3 GK, t = 10 s**

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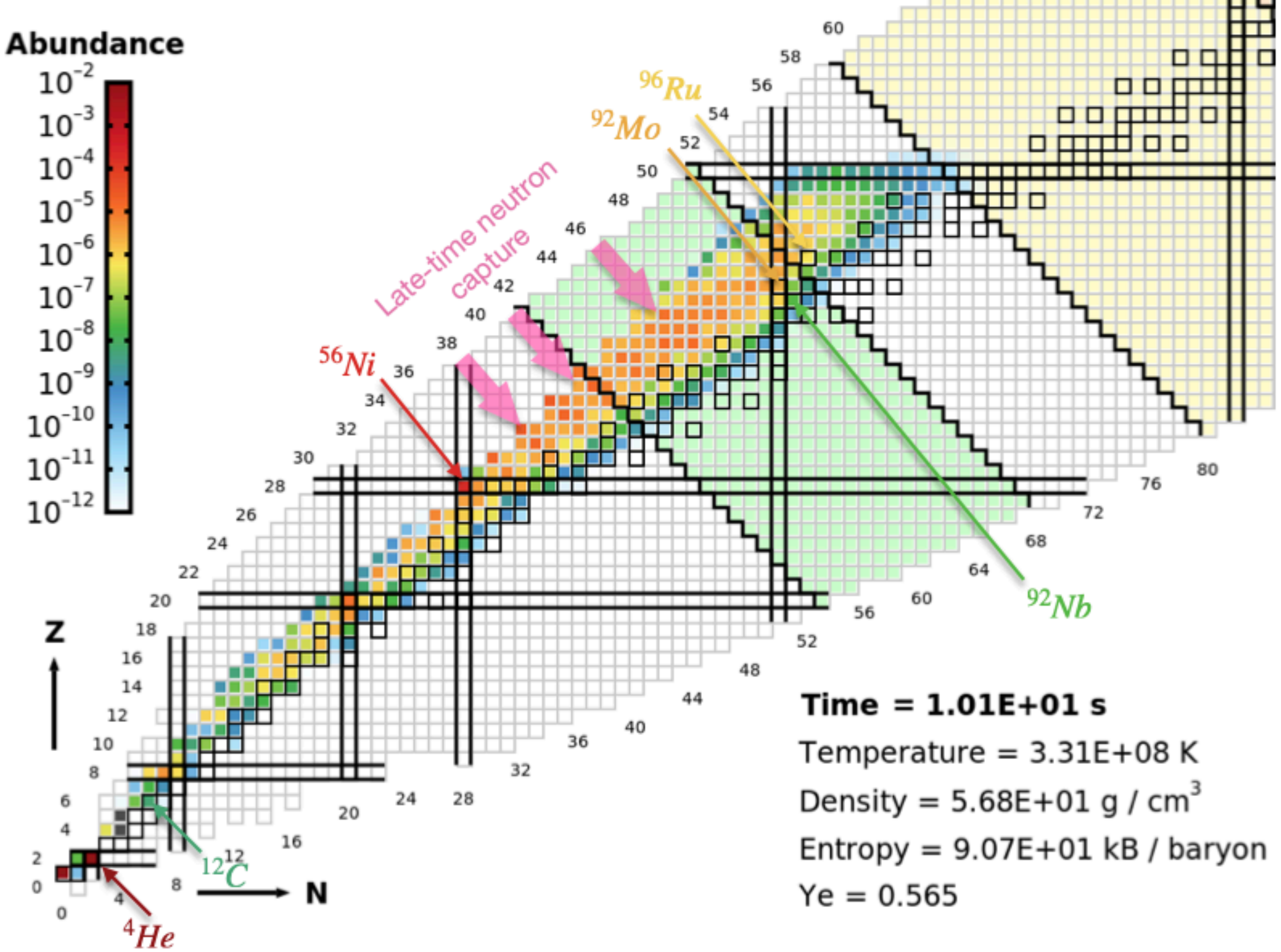


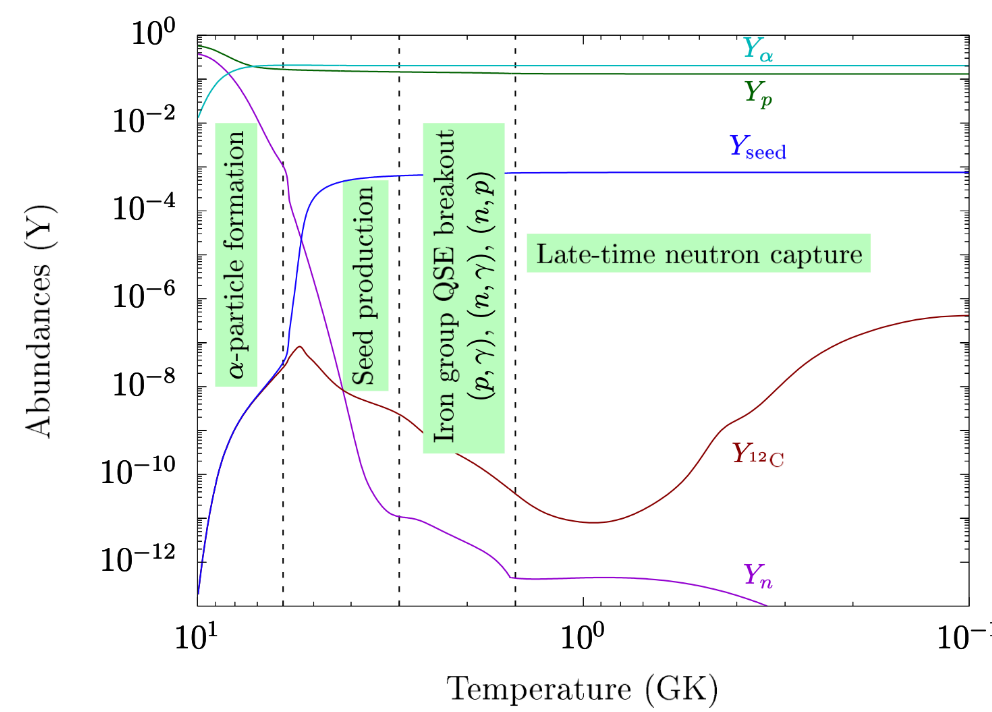


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# The $\nu p$-process: Stage IV

**$\nu p$-process[1]:**

12. Around $t \sim 10^9$ $s$ (31 years), late-time $\beta^+$ decays complete the formation of **stable isotopes**.

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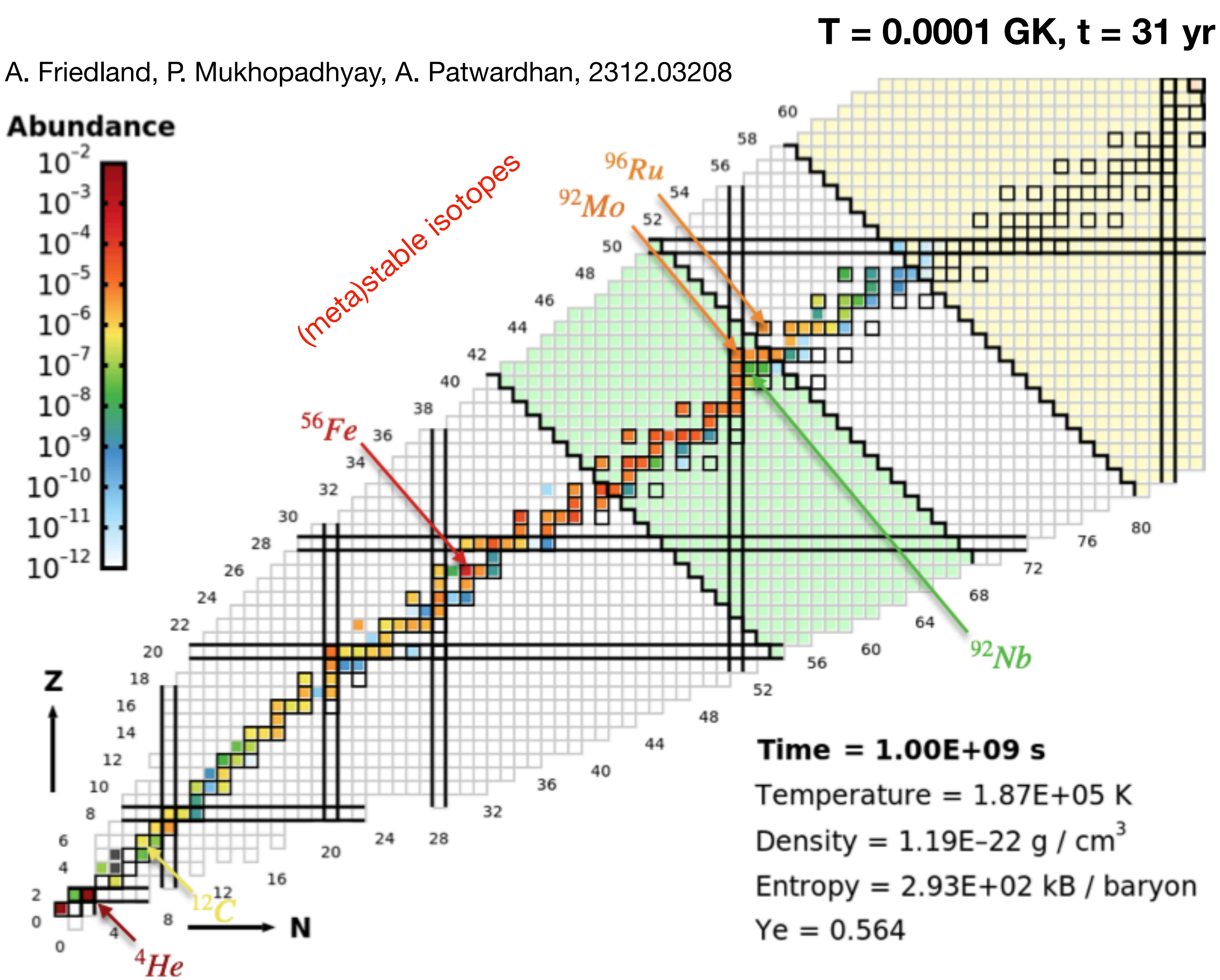


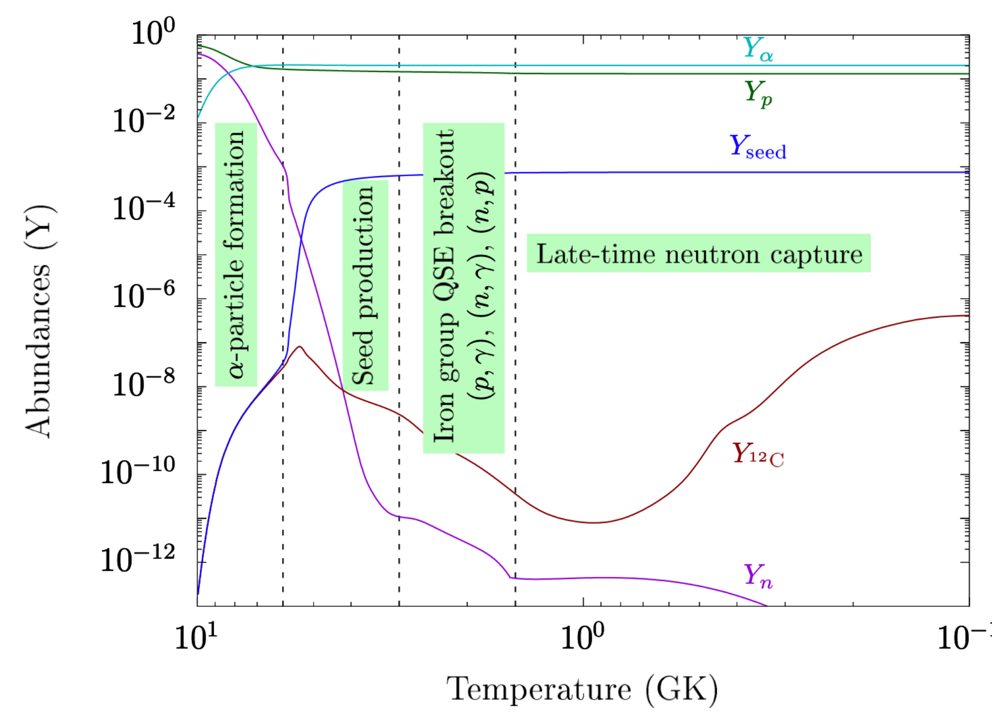


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# General-relativistic steady-state outflows

Model the neutrino-driven outflow:

- Baryon-number conservation (continuity equation, i.e. constant $\dot{M}$)

$$\frac{1}{\rho_b}\frac{d\rho_b}{dr} = -\frac{1}{u}\frac{du}{dr} - \frac{2}{r}$$

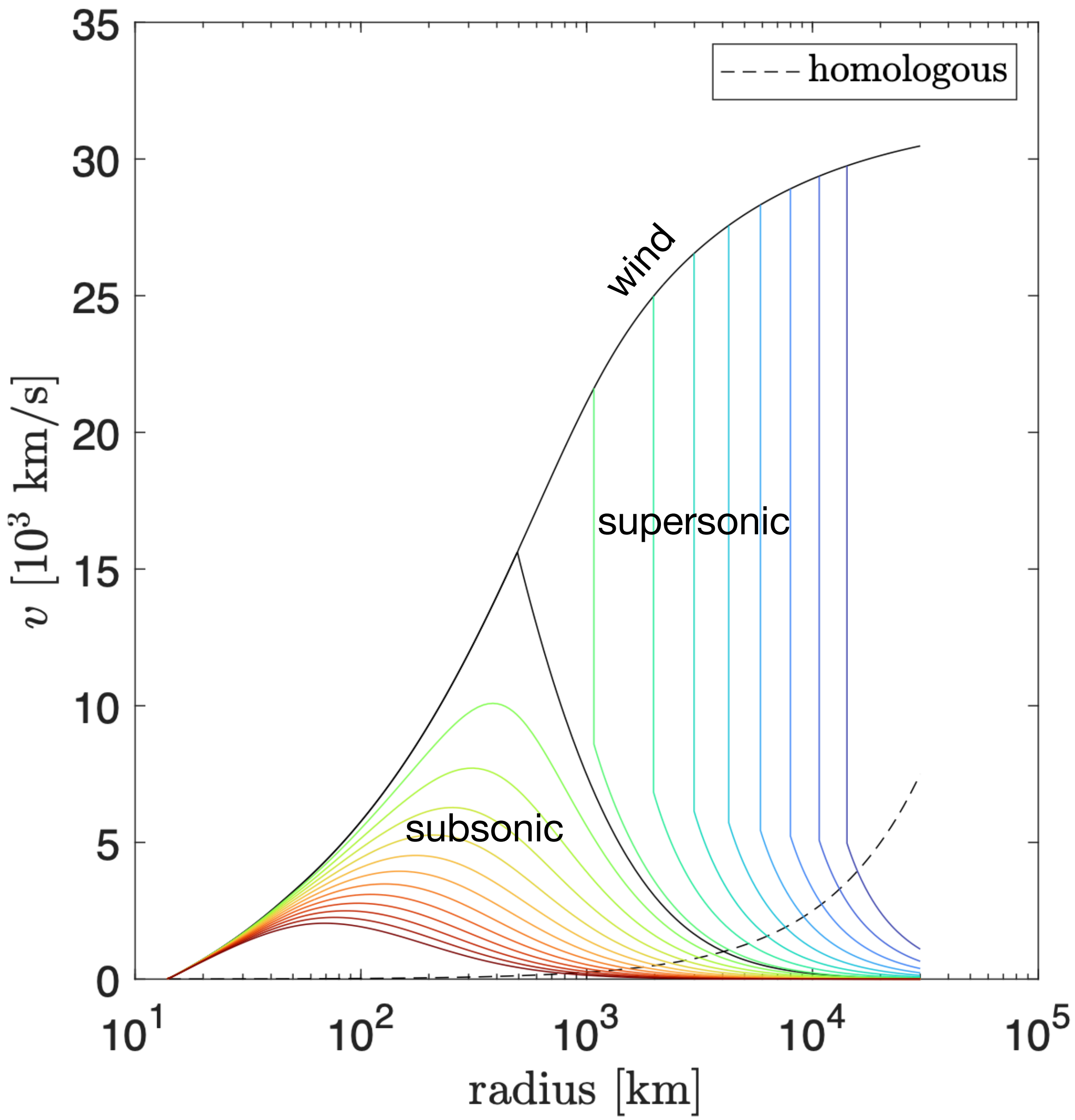
- Momentum conservation of the baryon-radiation plasma (Euler equation)

$$u\frac{du}{dr} = -\frac{GM}{r^2} - \frac{1}{\rho + P}\frac{dP}{dr}\left(1 + u^2 - \frac{2GM}{r}\right)$$

- The thermodynamic identity (first law)

$$u\frac{dS}{dr} = \frac{\dot{q}}{T}$$

Different kinds of solutions




(Each color corresponds to a different far-pressure)

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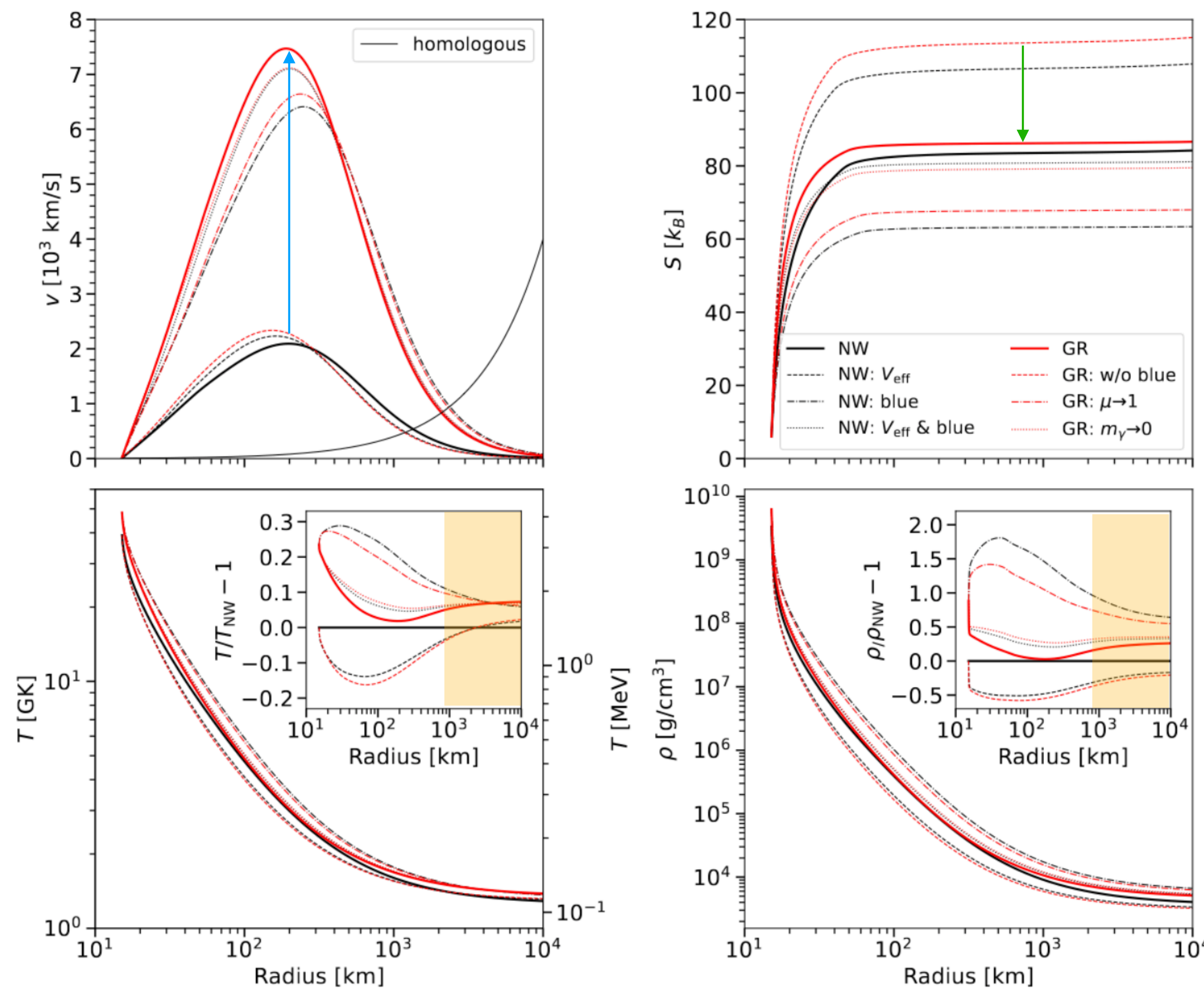
# Disentangle GR effects

Consider outflows from: Newtonian, full GR, and "partial GR" implementations.

From NW to GR:

- The peak subsonic velocity **increased** by ~3 due to **blueshift.**
- Similar entropies: $\Delta S \lesssim 5$. (What you **gain** from GR hydro, you **lose** from blueshift, approx.)
- $T$ and $\rho_b$ are modified close the PNS, yet these corrections **persist at large radii.**

**Trajectory for** $t_{\rm launch} = 2.5$ s



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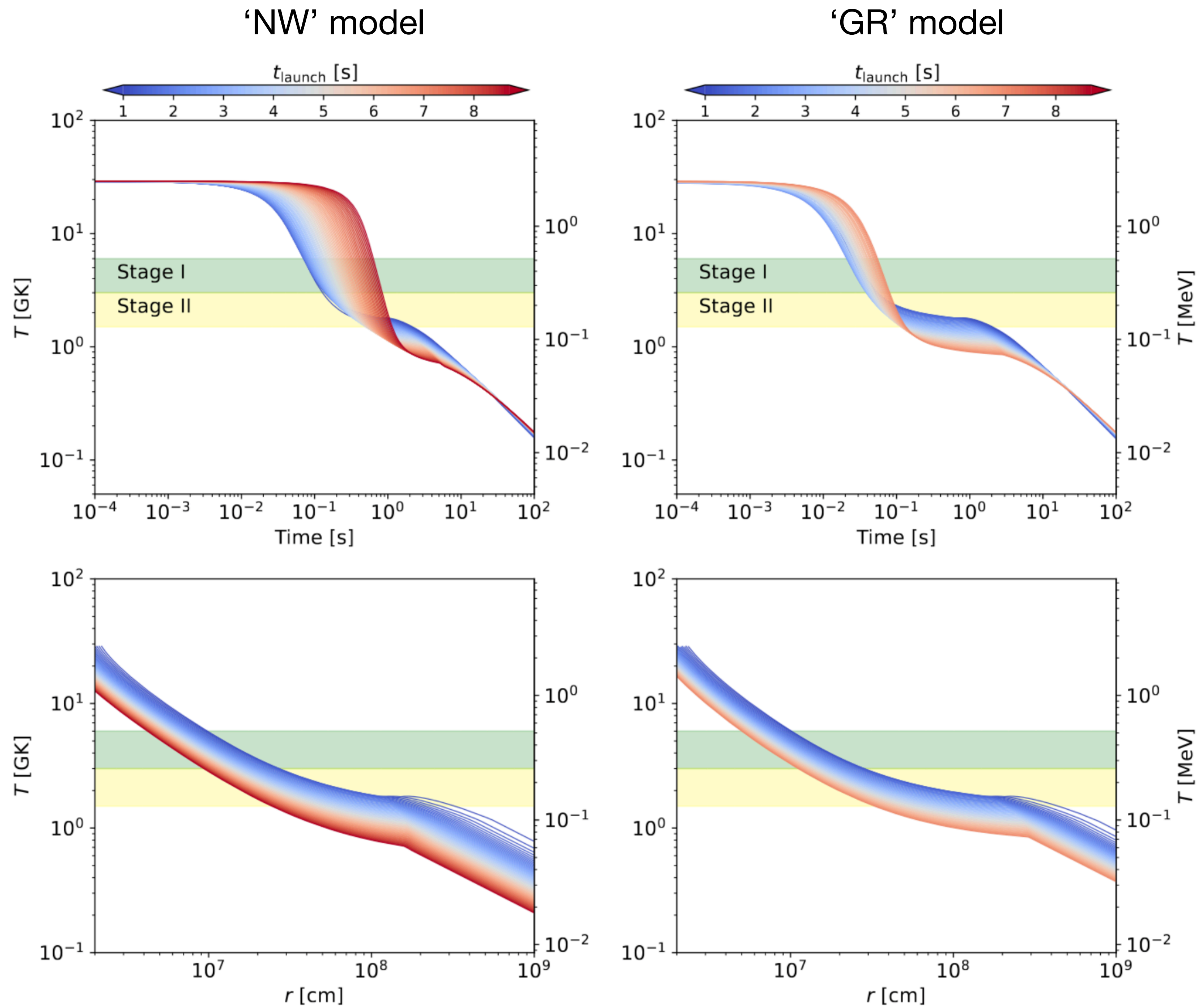
# Time evolution of the outflows

We input each trajectory into SkyNet to compute yields.

- Some indicators of the efficiency of the $\nu p$-process:
  - Duration of **Stage I** and **Stage II** (short, long).
  - Entropy per baryon. ($S \gtrsim 70$)
  - Distance to PNS. (Closer)

**Trajectories for** $t_{\rm launch} = 1 - 8$ s



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# Optimal window for Mo, Ru

- Most effective $\nu p$-production around $t_{\rm launch} = 2.5$ s where there's a peak in $\Delta_n$ (solid).
- These neutrons facilitate $(n,p)$, $(n,\gamma)$ and $(p,\gamma)$ exchanges, which enable the synthesis of heavy nuclei.

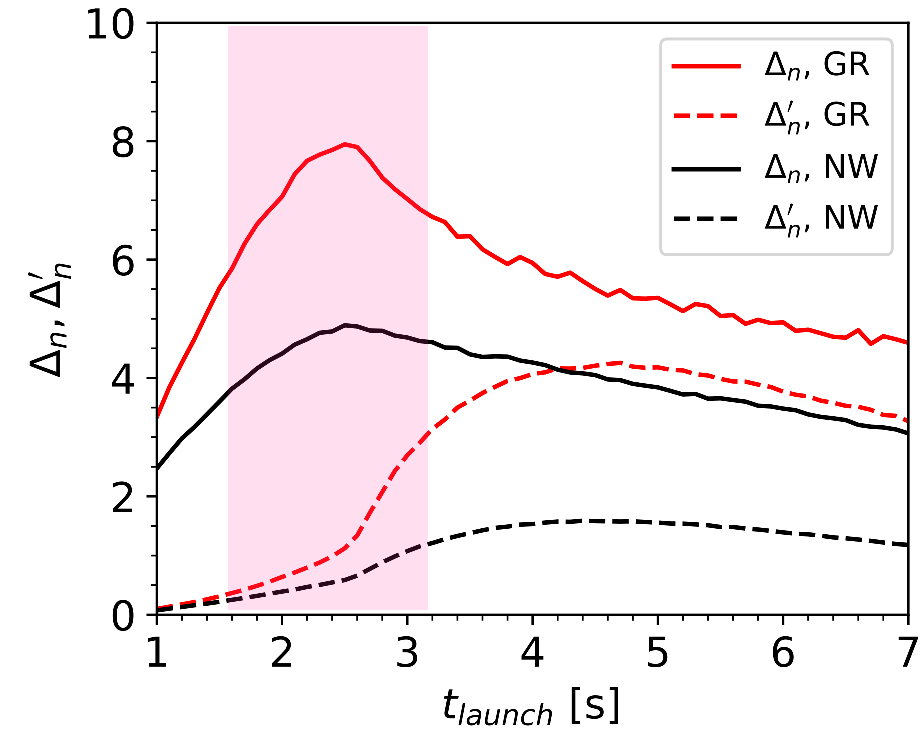
$$\Delta_n = \frac{Y_p\, n_{\bar{\nu}_e}}{Y_{A\geq 12}}$$

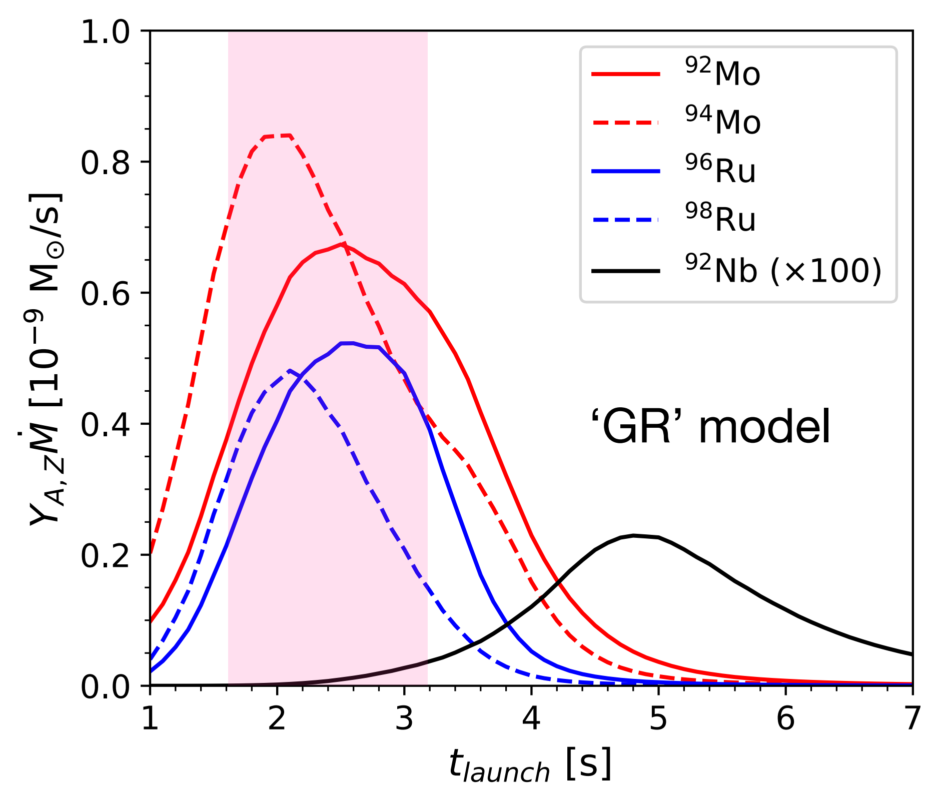
Neutrons per seed

$$n_{\bar{\nu}_e} = \int_{T=3\ \rm GK}^{T=1.5\ \rm GK} \lambda_{\bar{\nu}_e} dt$$

Number of $\bar{\nu}_e$ captured on free protons leading to neutron formation.

| Case | $t_{\rm launch}$ [s] | $Y_p/Y_{A\geq12}$ | $n_{\bar{\nu}_e}$ [$\times10^{-3}$] | $n'_{\bar{\nu}_e}$ [$\times10^{-3}$] | $\Delta_n$ | $\Delta'_n$ | $v_{\rm peak}$ [$10^3$ km/s] |
|---|---|---|---|---|---|---|---|
| NW | 2.5 | 112.4 | 43.4 | 6.6 | 4.8 | 0.5 | 2.09 |
| GR | 2.5 | 470.6 | 16.9 | 3.1 | 7.9 | 1.1 | 7.47 |
| NW | 5.0 | 137.5 | 28.0 | 12.9 | 3.8 | 1.5 | 1.33 |
| GR | 5.0 | 786.8 | 6.8 | 5.8 | 5.3 | 4.1 | 5.98 |



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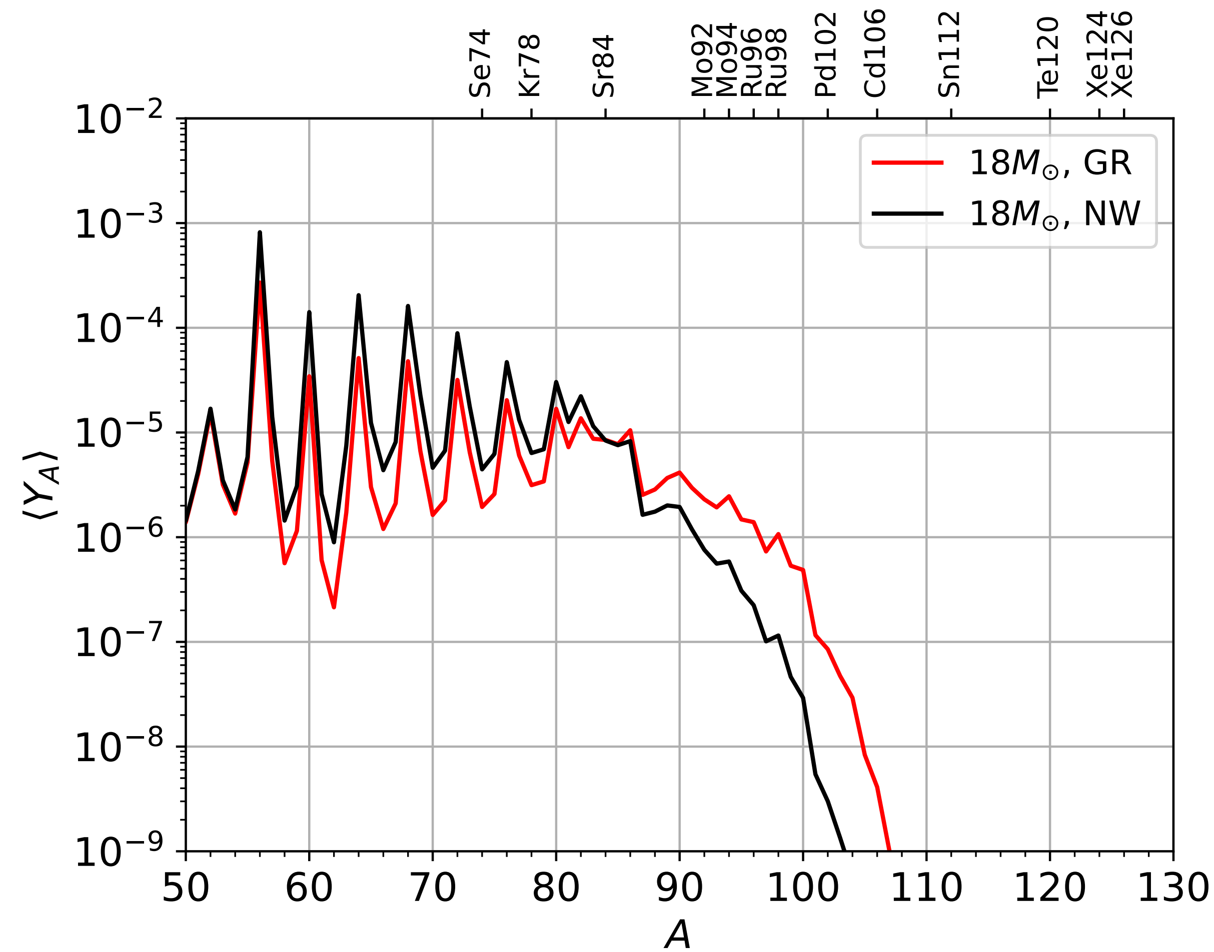
# Time-integrated yields

- Time-integrated yields $\langle Y_A \rangle$ for 'NW' and 'GR' in our benchmark $18\ M_\odot$ progenitor model.

$$\langle Y_{A,Z} \rangle = \frac{\int dt\, Y_{A,Z}(t)\dot{M}(t)}{\int dt\, \dot{M}(t)}$$

- GR effects such as blueshift and corrections to the hydrodynamics **enhance** the yields in the $95 \lesssim A \lesssim 105$ mass range.

- Final abundance of *Niobium-92* **boosted** by a factor of ~24.




| Element | NW | GR | GR/NW |
|---|---|---|---|
| $^{92}$Mo | $8.18 \times 10^{-7}$ | $2.42 \times 10^{-6}$ | 3.0 |
| $^{94}$Mo | $6.30 \times 10^{-7}$ | $2.59 \times 10^{-6}$ | 4.1 |
| $^{96}$Ru | $2.42 \times 10^{-7}$ | $1.47 \times 10^{-6}$ | 6.1 |
| $^{98}$Ru | $1.24 \times 10^{-7}$ | $1.13 \times 10^{-6}$ | 9.1 |
| $^{92}$Nb | $3.38 \times 10^{-10}$ | $8.14 \times 10^{-9}$ | 24.1 |



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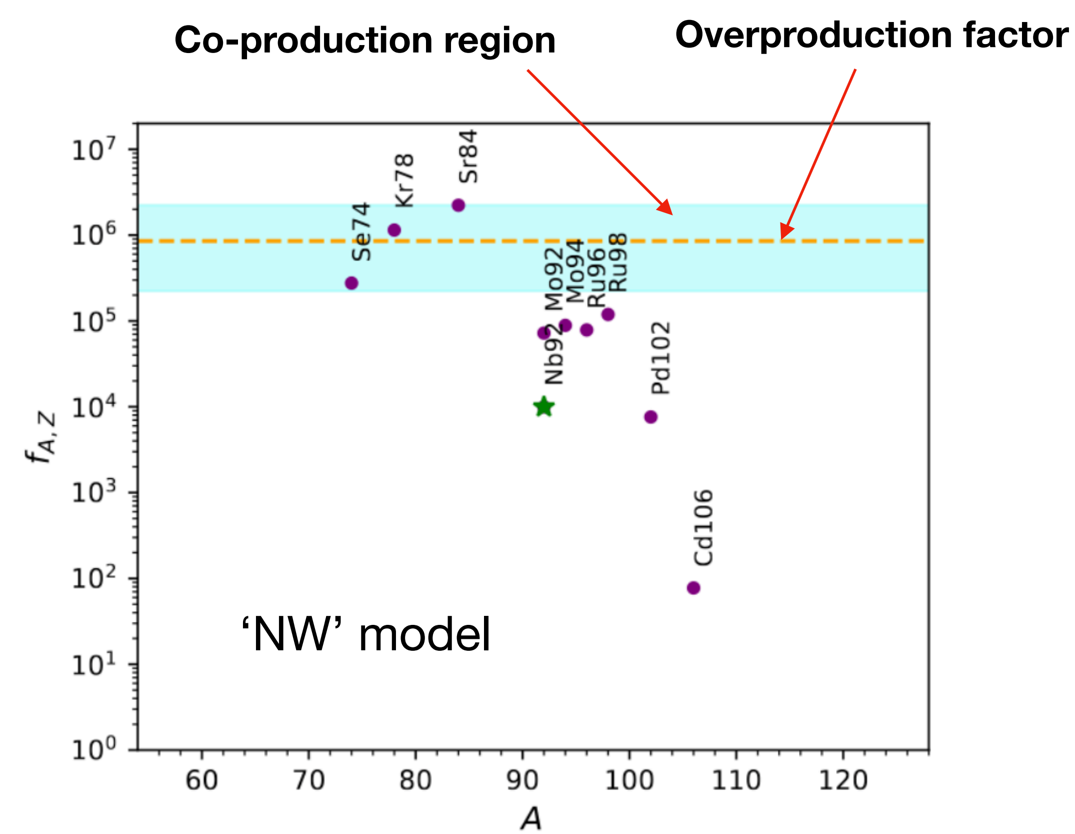
# Production factors

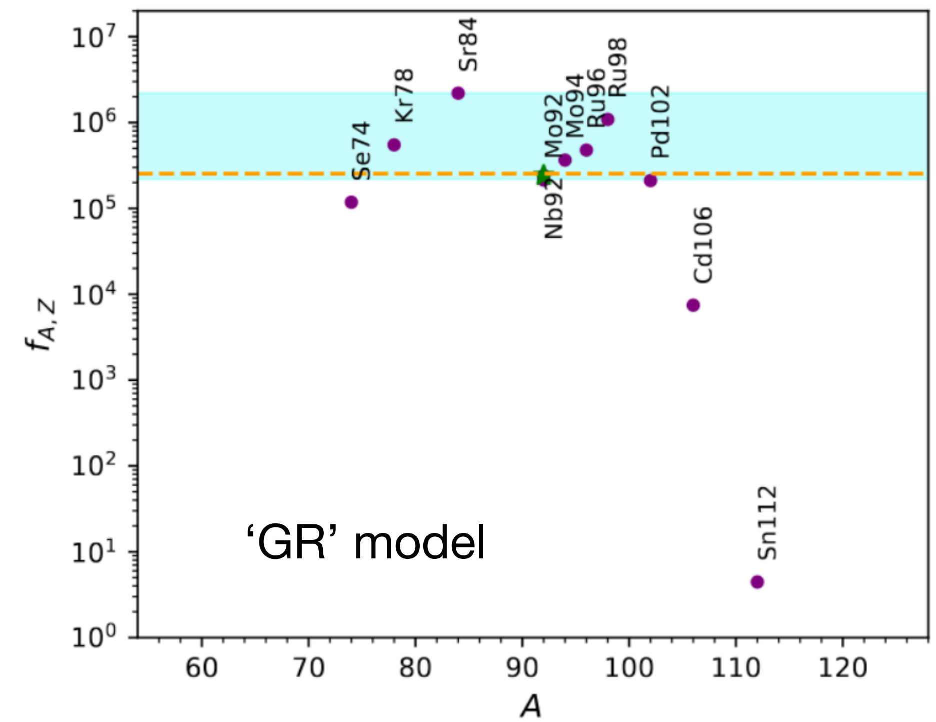
*Production factor:* fair comparison with solar abundances.

$$f_{A,Z} = \frac{\langle X_{A,Z} \rangle}{X^{\odot}_{A,Z}}$$

- **Sufficient in the relative sense?** If nuclides are inside the band ($f_{A,Z} > f_{\max}/10$) then they are considered to be ***co-produced*** in significant quantities.
- **Sufficient in the absolute sense?** An ***overproduction factor*** > 10 in a SN to explain the solar abundance of given nuclide.

- **NW case:** production of nuclides with $A \gtrsim 90$ not only suppressed *relative* to lighter ones but also *absolutely* insufficient.
- On the other hand, **GR case:** nuclides up to Palladium-102 efficiently produced.



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# Conclusions

**In this paper, we found that:**

- GR impacts the $\nu p$ yields by changing the conditions near the PNS. This changes the entire tracer trajectory.
- GR modifies neutrino heating, the expansion speed, mass outflow rate and entropy per baryon in the outflow.
- These changes suppress seed production: Faster expansion means fewer seeds which results in greater $\Delta_n$, improving the $\nu p$ yields.
- $^{92,94}$Mo, $^{96,98}$Ru and $^{92}$Nb are formed in sufficient amounts.
- We identify optimal $\nu p$-process conditions to inform supernova simulations.



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