Solar-system abundances of p-nuclides probe collective neutrino oscillations in supernovae

Ian Padilla-Gay

N3AS Postdoctoral Fellow (UC San Diego & UC Berkeley)

ianpaga@berkeley.edu

Talk based on:

arXiv:2508.02055 (Aug 2025)

arXiv:2607.15392 (Jul 2026)

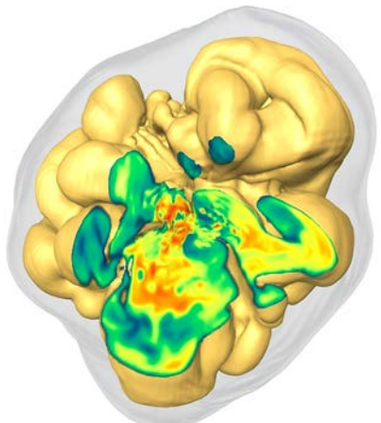
N3AS annual meeting, 17-19 August 2026, UC Berkeley

Supernova neutrinos, fundamental particles, are crucial for producing stable isotopes in the solar system

Optical/X-ray Composite Image of Supernova Remnant 0509-67.5 - NASA Science

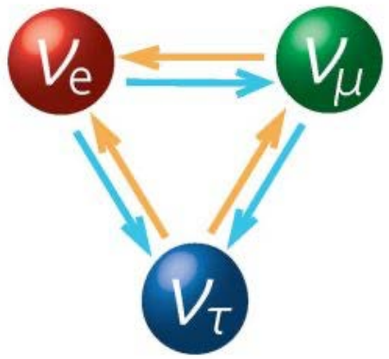
Main ingredients

Supernova dynamics
(relativistic hydrodynamics)



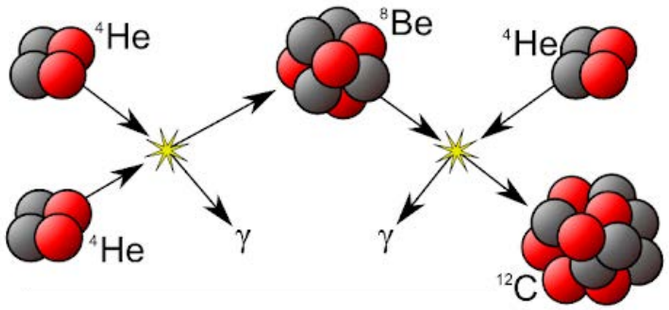
“What are the temperature, density, and entropy of the outflow?”

Neutrino collective oscillations
(quantum mechanics)



“What is the neutrino flavor content after some time?

Heavy-element nucleosynthesis
(nuclear astrophysics)

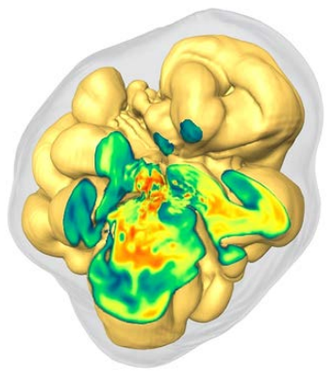


“How do we form heavier elements from lighter ones?”

Current challenges

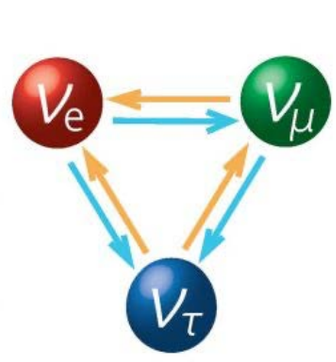
Supernova dynamics

- Major uncertainty: neutrino oscillations near the core[1]
- Simulations are expensive



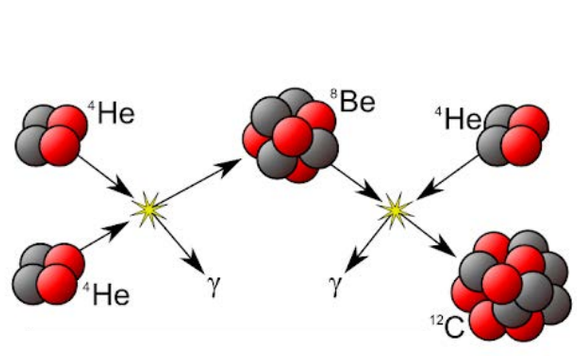
Neutrino collective oscillations

- Quantum many-body problem
- Mean-field: 7D problem $(\vec{x}, \vec{p}, t)$
- Very short time scales: μs-ns[2]



Heavy-element nucleosynthesis

- Models underproduce *Mo, Ru, Nb* relative to the solar system[3]
- Clear production mechanism?



[1] Long-Term Multidimensional Models of Core-Collapse Supernovae: Progress and Challenges, Annual Reviews, Hans-Thomas Janka, 2502.14836

[2]New Developments in Flavor Evolution of a Dense Neutrino Gas, Tamborra et al, Ann. Rev. Nucl. Part. Sci. 71 (2021) 165-188

[3]The p-process in supernovae, Woosley & Howard , Astrophysical Journal Supplement Series, vol. 36, Feb. 1978, p. 285-304.

Outline

1. Why the νp-process?

2. Role of neutrino flavor conversion

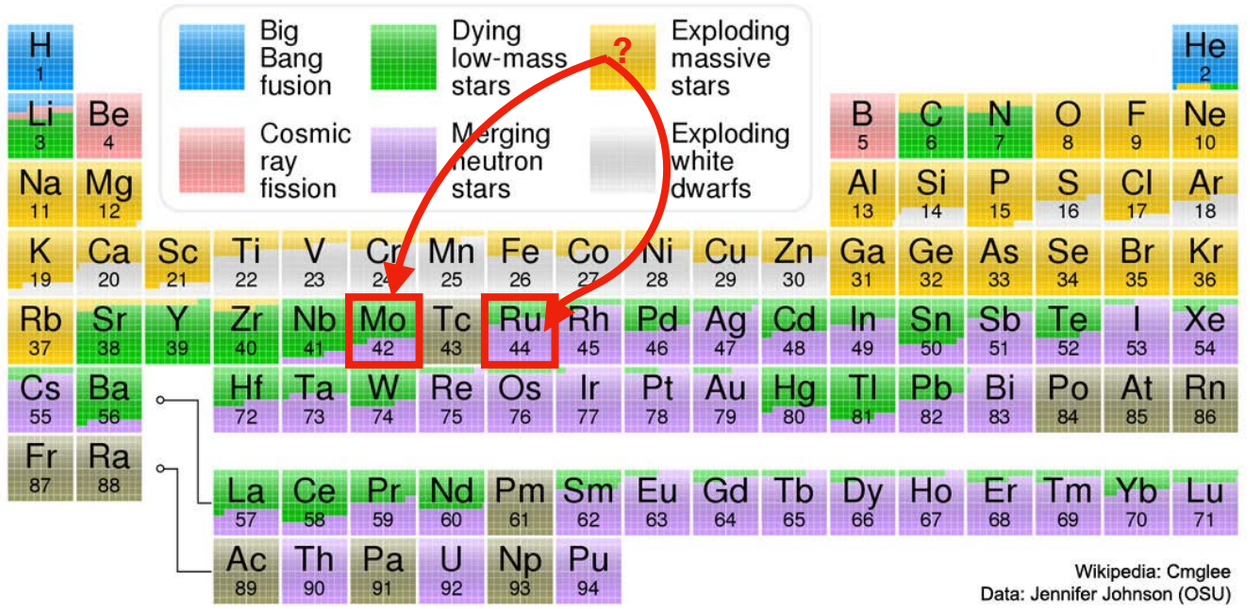
3. What did we learn?

Optical/X-ray Composite Image of Supernova Remnant 0509-67.5 - NASA Science

νp-process?

How are elements created?

Most nuclides created via s- or r-process (neutron-rich nuclides)



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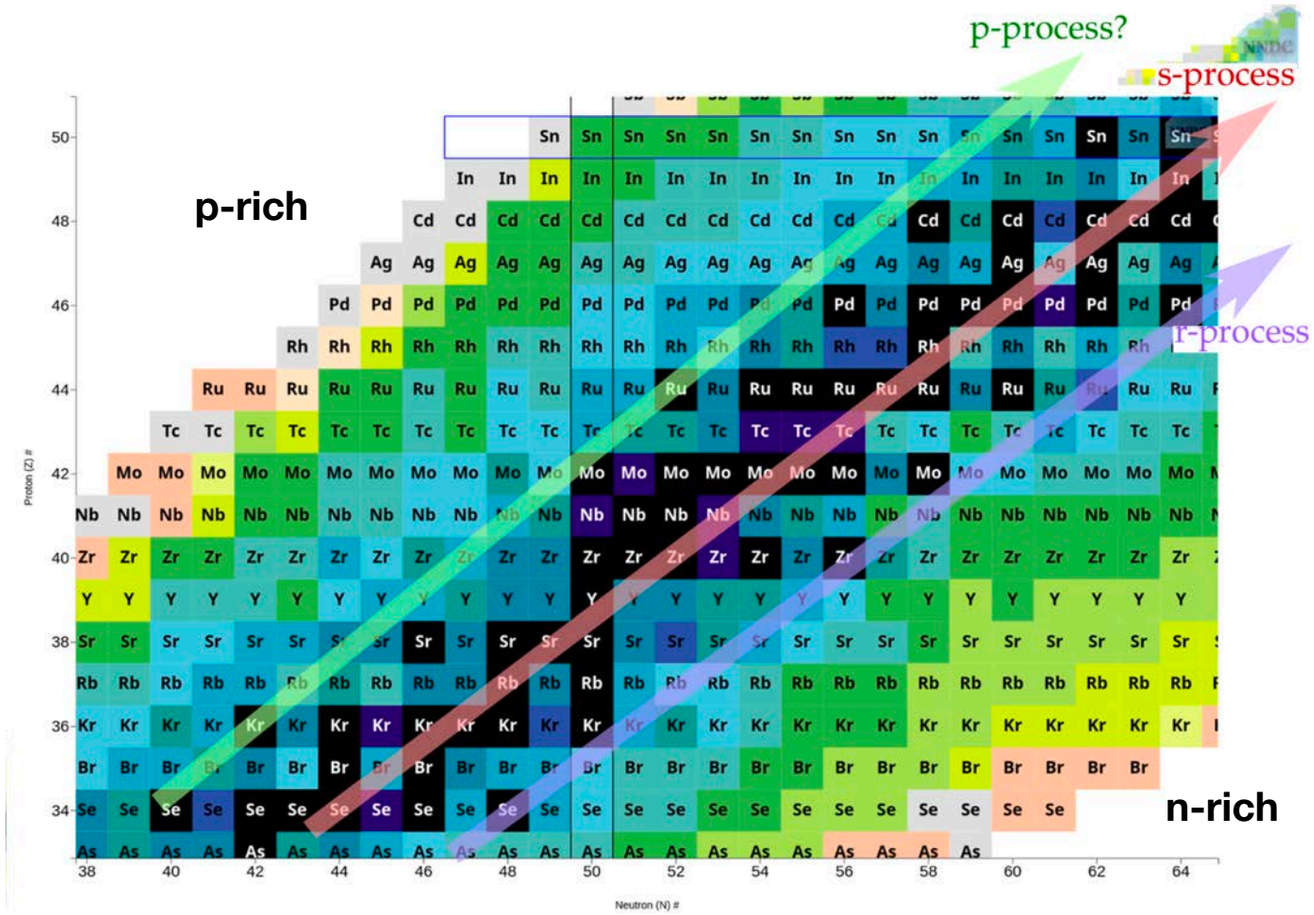
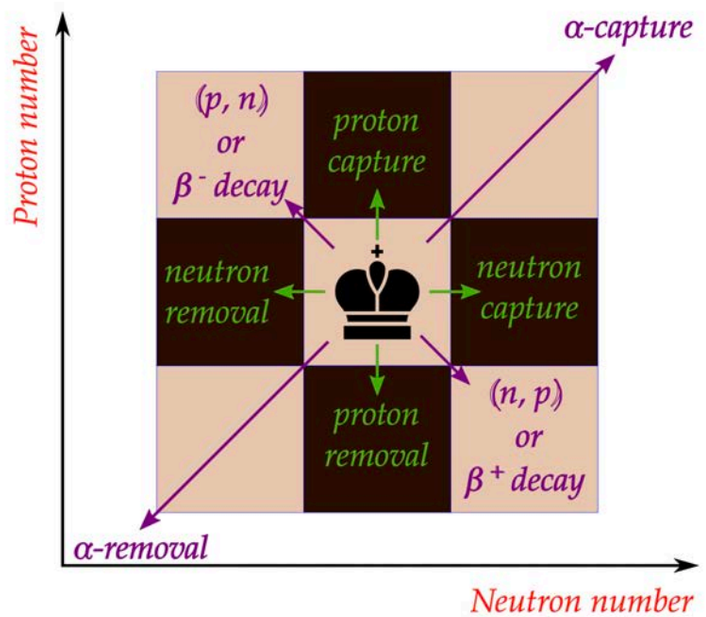


elementary
nuclear processes



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1-2 orders
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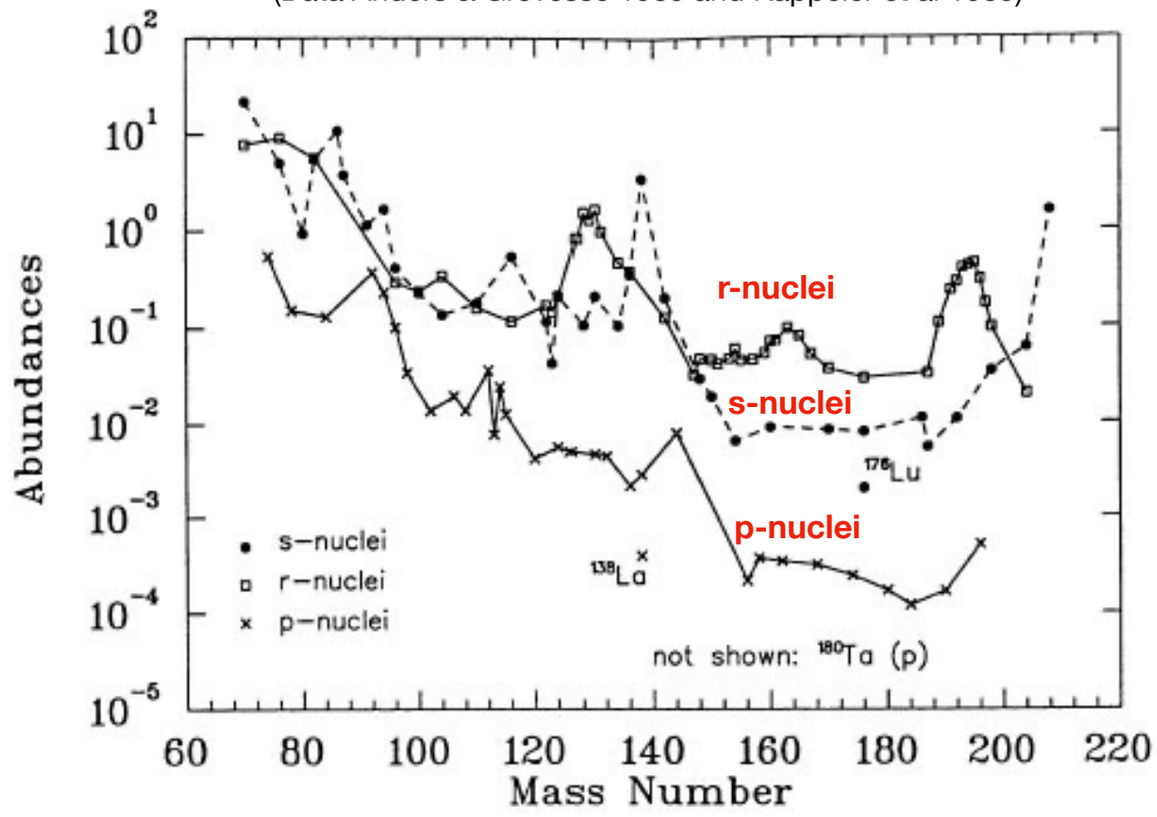

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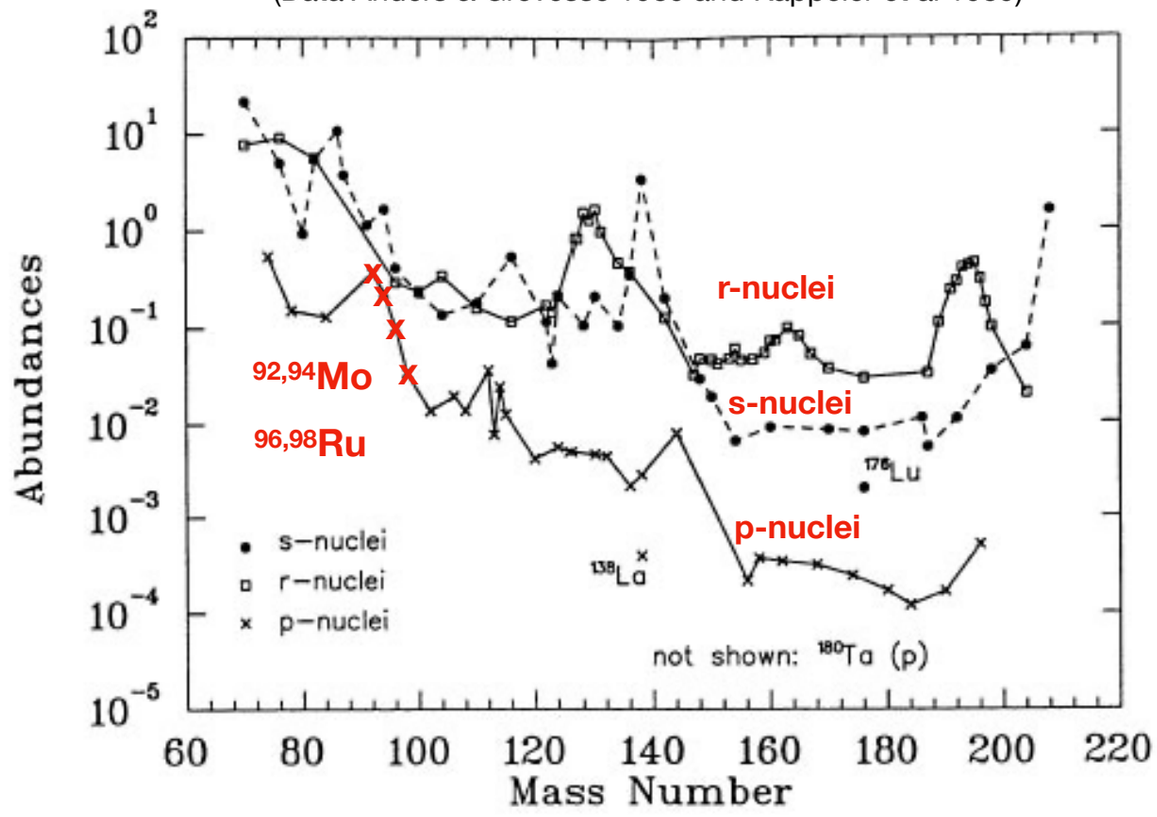

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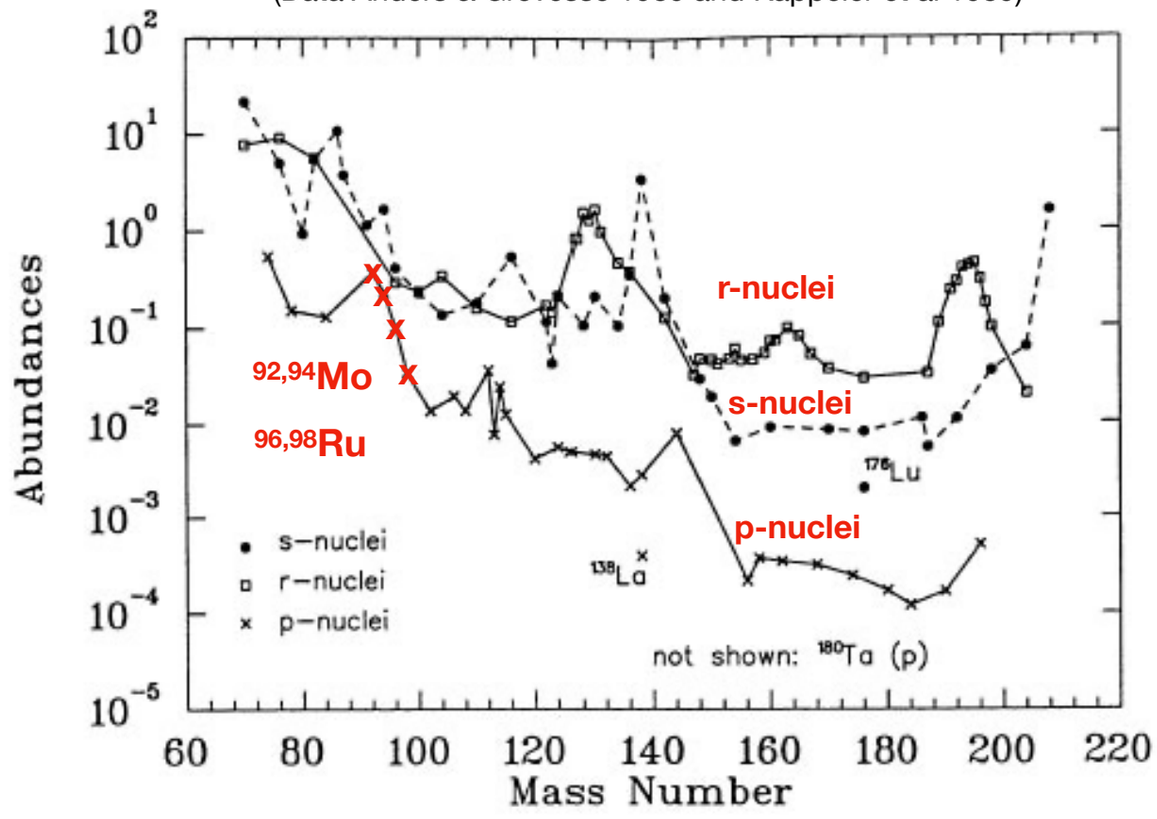

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= Long-standing issue in nuclear astrophysics.

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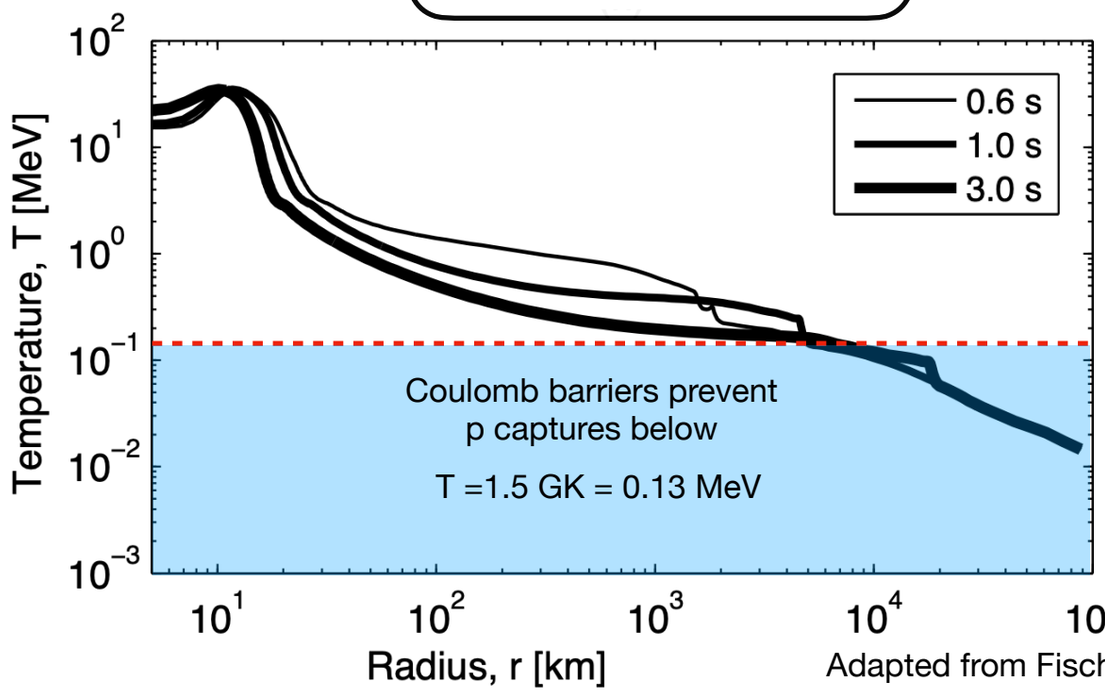
An “r-process” with protons?

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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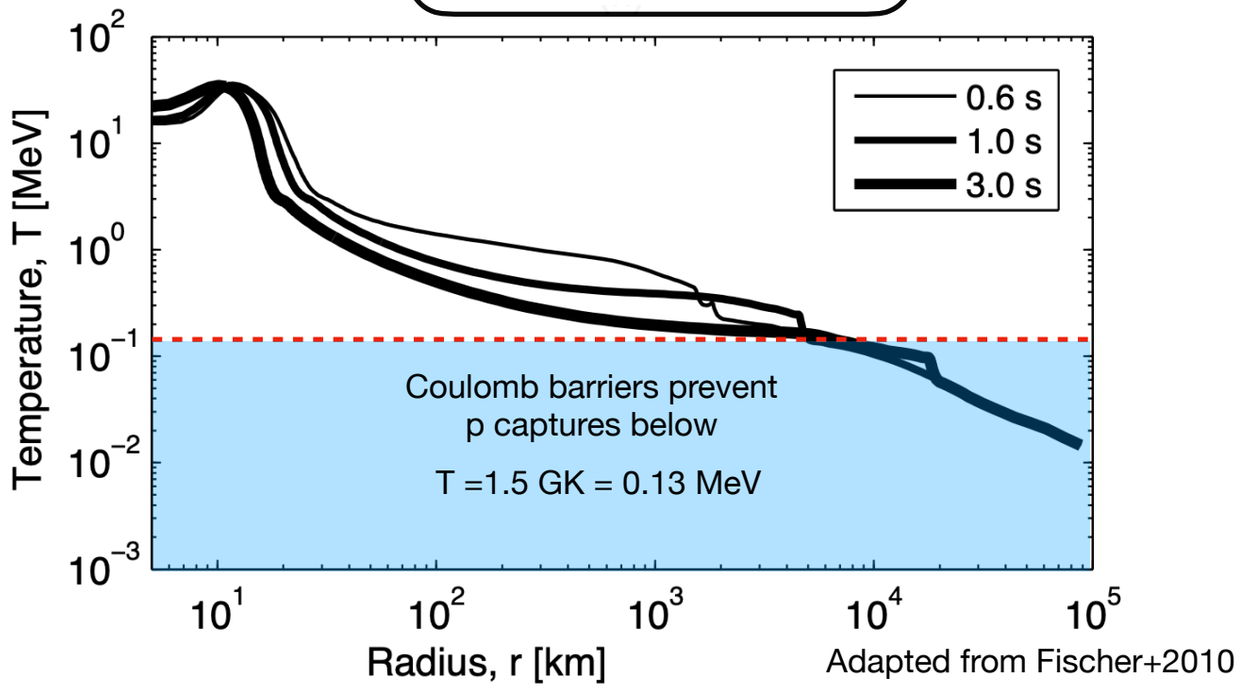

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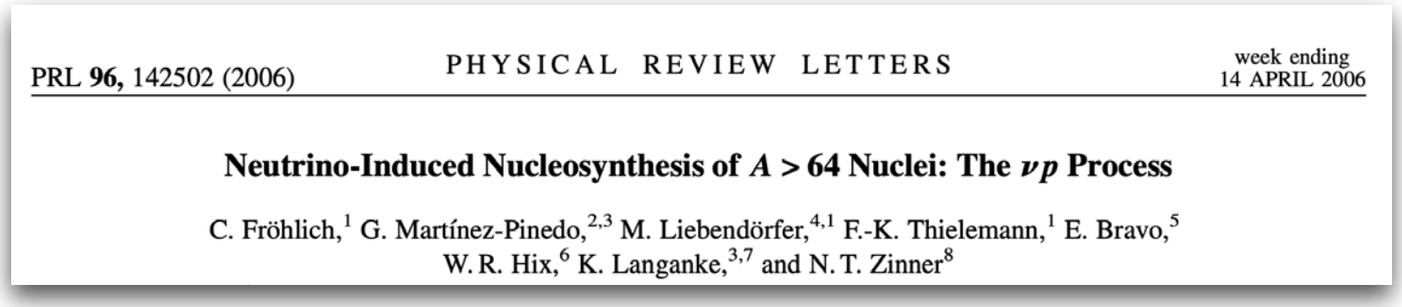
The νp-process could be a solution.



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

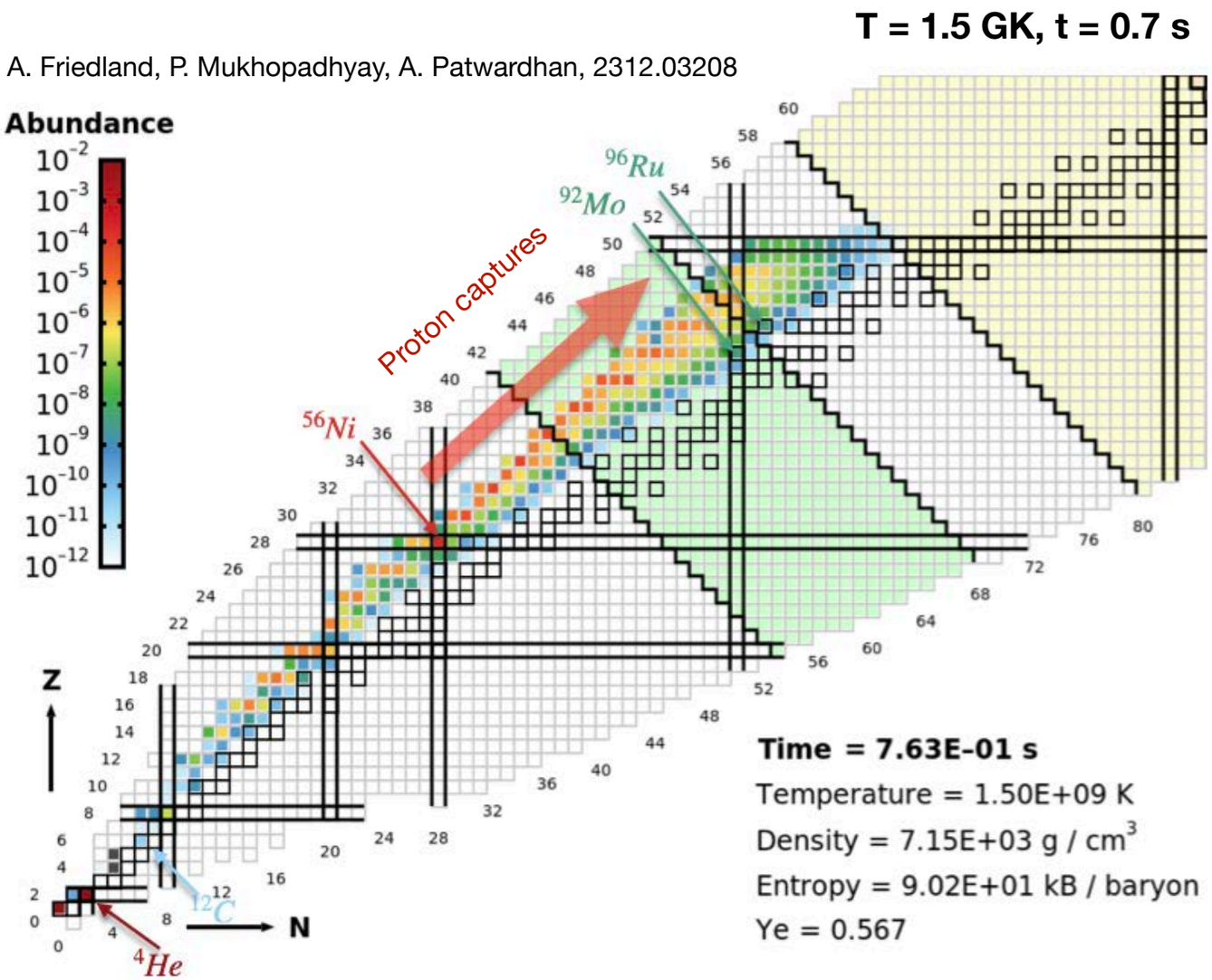
Neutrino-Induced Nucleosynthesis of $A > 64$ Nuclei: The νp Process

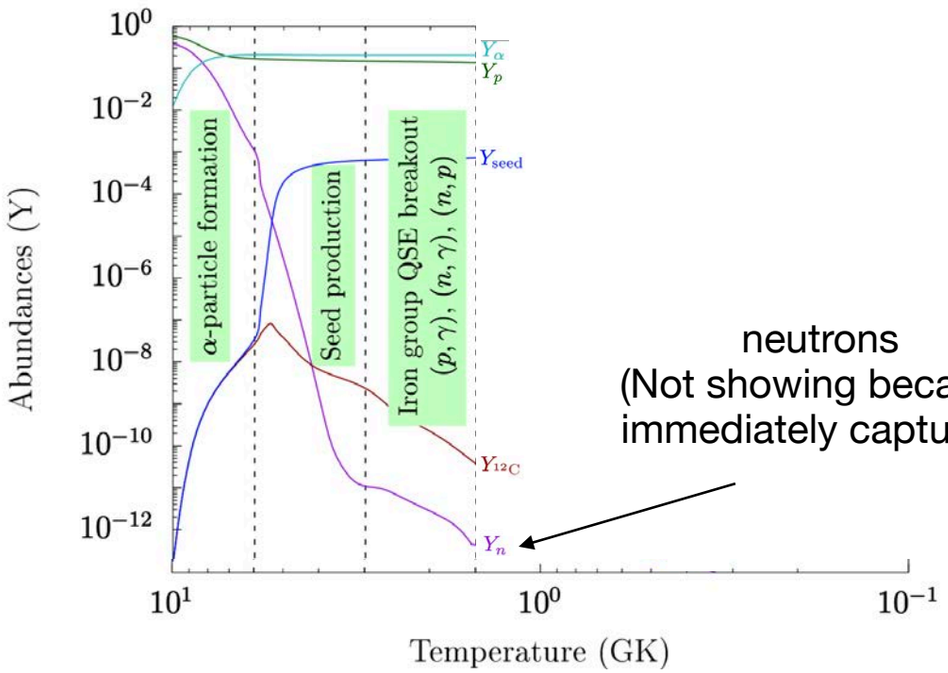
C. Fröhlich,[1] G. Martínez-Pinedo,[2,3] M. Liebendörfer,[4,1] F.-K. Thielemann,[1] E. Bravo,[5]
W. R. Hix,[6] K. Langanke,[3,7] and N. T. Zinner[8]

The νp-process in a nutshell

- When $T < 3$ GK, the system freezes out of all equilibria and we can go **beyond ^{56}Ni**.
- Not too hot, not too cold: $3\ \mathrm{GK} > T > 1.5\ \mathrm{GK}$, $\bar{\nu}_e$ **capture on free protons** $p(\bar{\nu}_e, e^+)n$ creates a subdominant **neutron population**.
- (n,p) and (n,γ) are triggered to **bypass the β^+ waiting points**. Combined with **proton captures** (p,γ), the flow moves along the rp-process nucleosynthesis chain.

A. Friedland, P. Mukhopadhyay, A. Patwardhan, 2312.03208





neutrons
(Not showing because immediately captured)

[1] Neutrino-Induced nucleosynthesis of A > 64 Nuclei: The νp-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).

General-relativistic steady-state outflows

Model the neutrino-driven outflow
IPG+, JCAP 02 (2026) 067

- Eq. 1—Baryon-number conservation (continuity equation, i.e. constant $\dot{M}$)

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

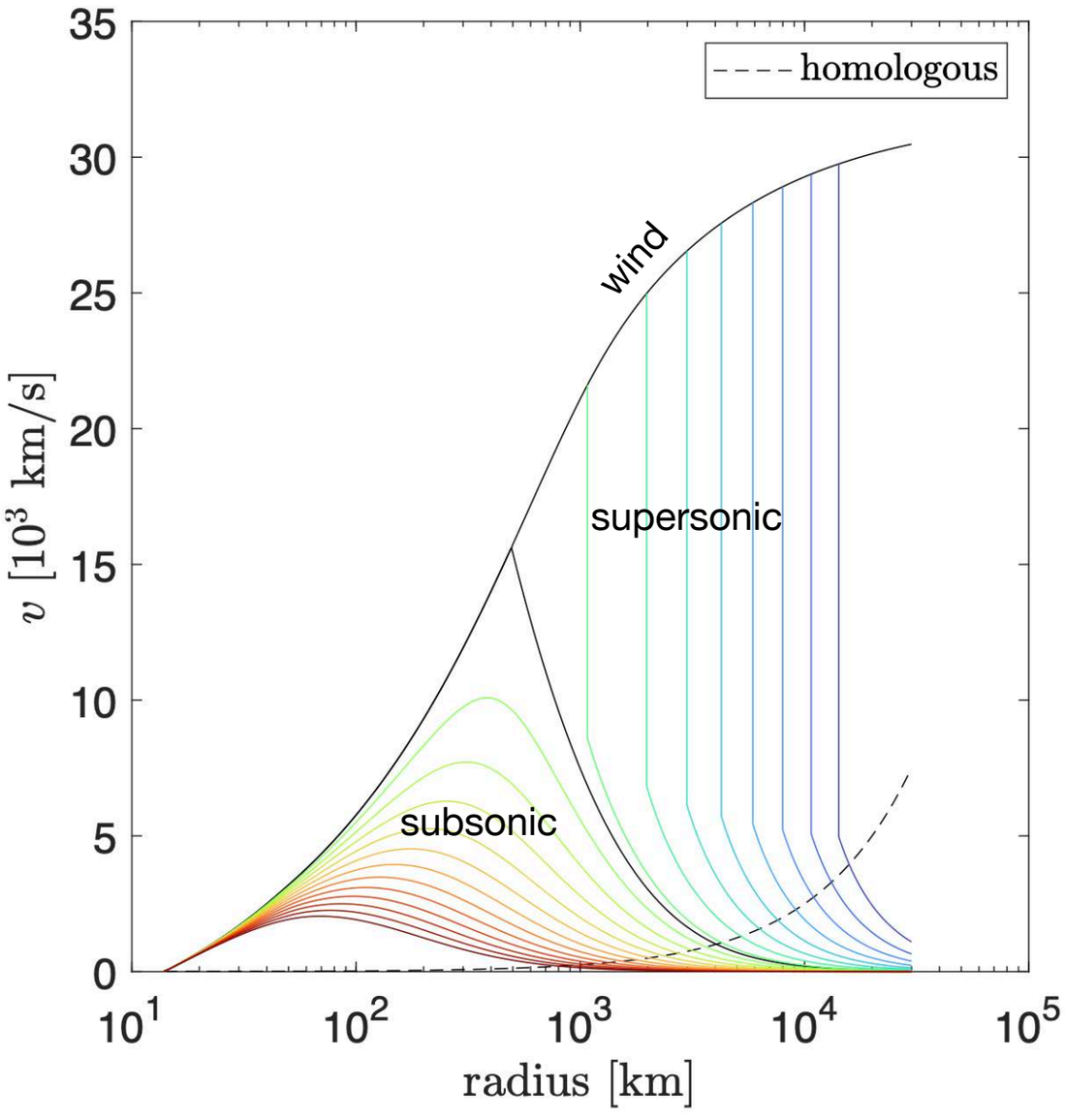
- Eq. 2—Momentum conservation of the baryon-radiation plasma (Euler equation)

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

- Eq. 3—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)

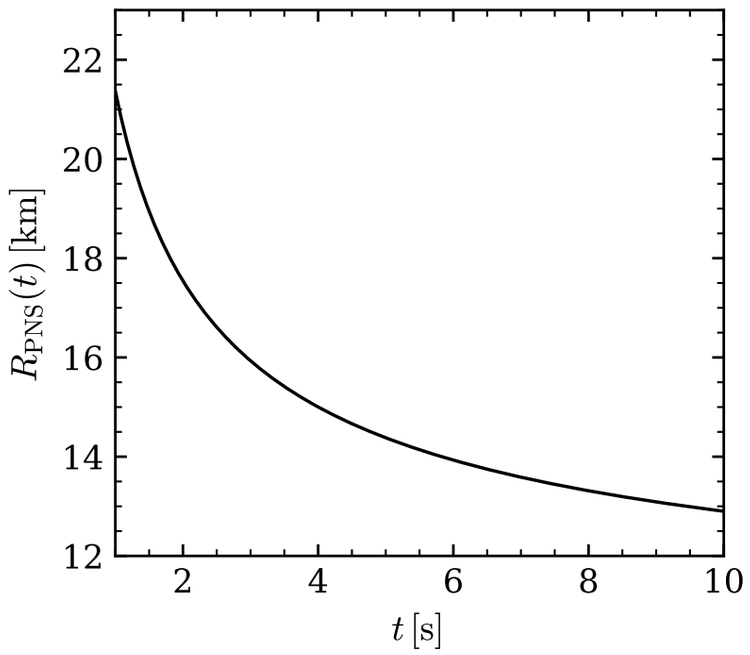
Supernova model

1D supernova from the Garching group. Model “out of the box”, not tailored for the νp-process

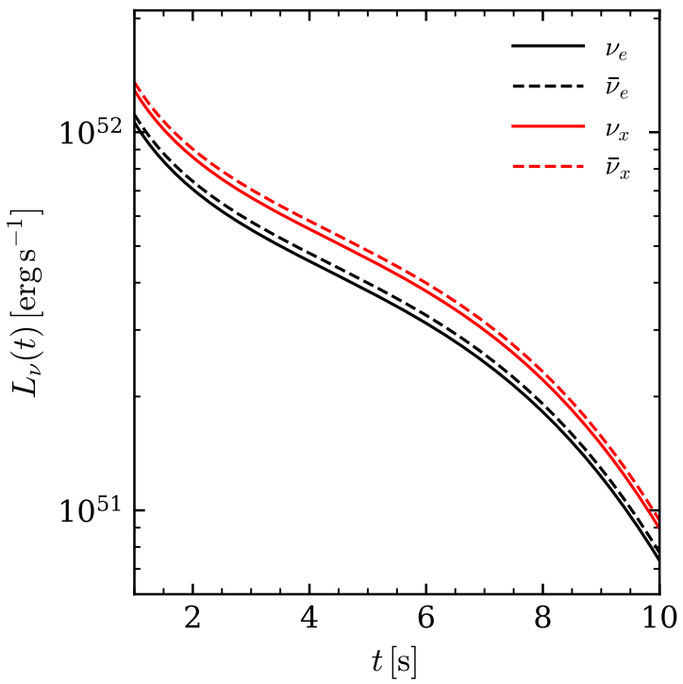
What we take from this model:

1. PNS mass, $M = 1.93\,M_\odot$ (sets potential GR/r in Eq. 2}
2. PNS radius, $R(t)$ (sets neutrino sphere, gain radius, compactness $2GM/R$)
3. $L_{\nu_e,\bar{\nu}_e,\nu_x,\bar{\nu}_x}$, pinched FD spectra (set neutrino heating in Eq. 3, weak rates$\rightarrow Y_e$)
4. $20\,M_\odot$ progenitor profile (sets far boundary pressure → sub/supersonic outflow)

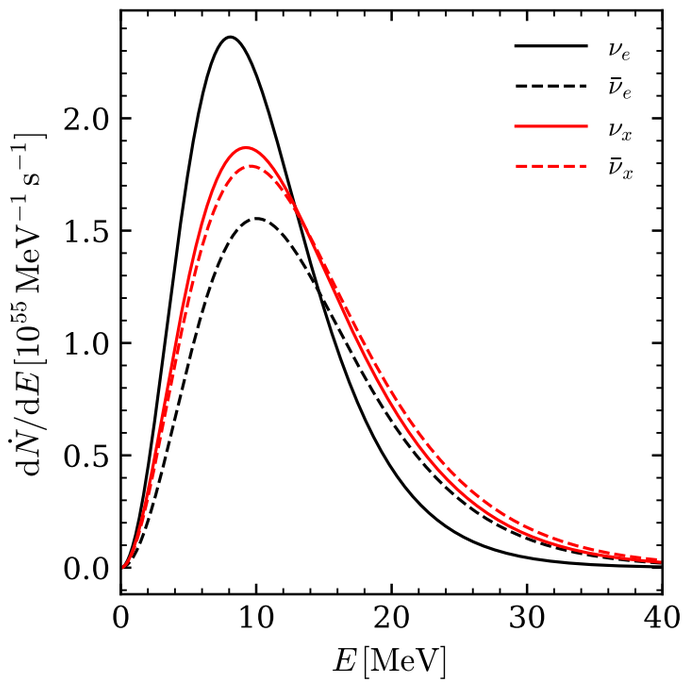
PNS evolution



Luminosities



Initial neutrino spectra



IPG+, arXiv:2607.15392

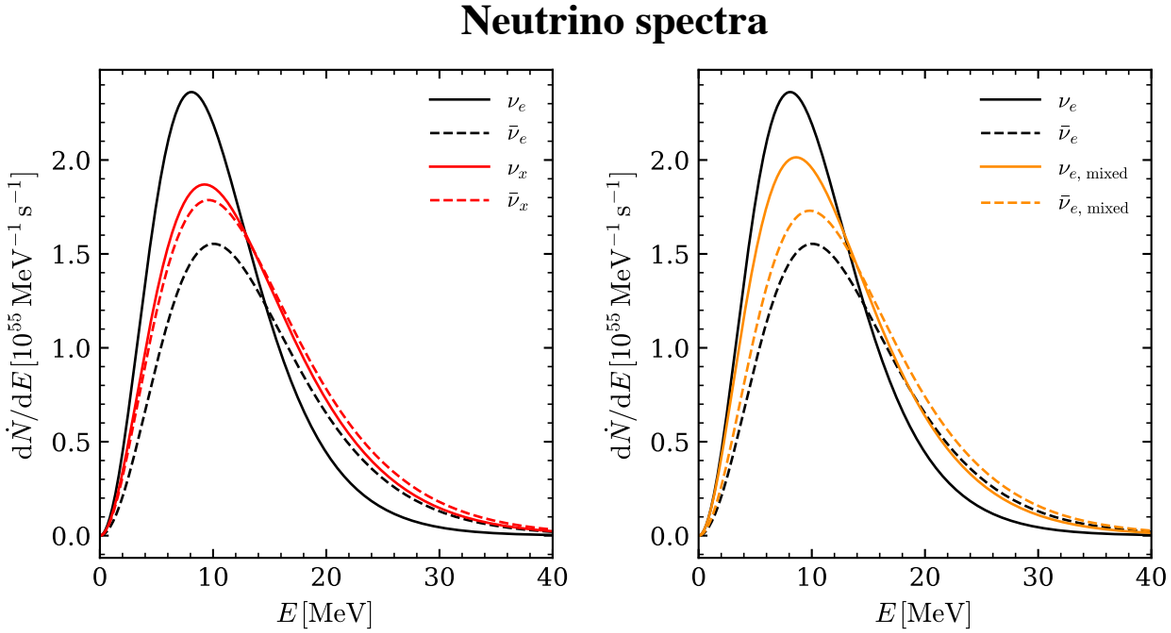
Oscillation-driven effects

Equilibrate ν_e ($\bar{\nu}_e$) with ν_x ($\bar{\nu}_x$) at given radius, and re-solve GR outflow after mixing

approximate limiting case*

$$f'_{\nu_e(\bar{\nu}_e)} = (f_{\nu_e(\bar{\nu}_e)} + 2f_{\nu_x(\bar{\nu}_x)})/3$$

Three coupled effects:



*flavor equilibration is constrained by individual $n_{\nu_\ell} - n_{\bar{\nu}_\ell}$ (and total) lepton-number conservation, i.e. fast flavor conversion does not convert any net flavor

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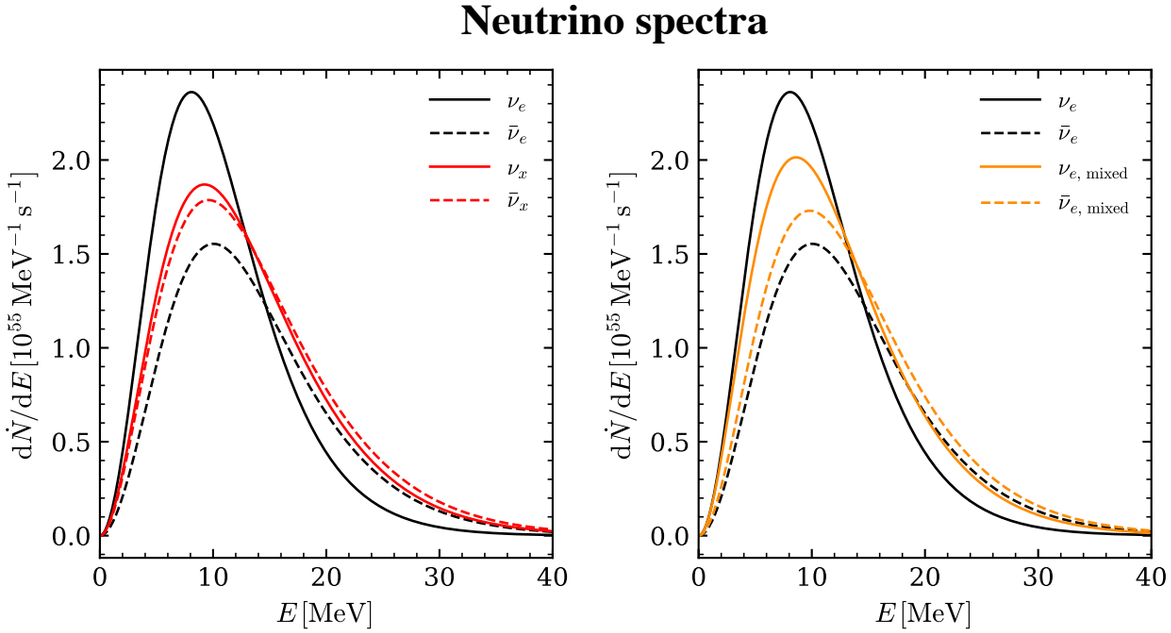
- Far conversions ($\Delta r_{\rm mix} \gtrsim 40$ km):
  - Don't change Y_e and $\dot{Q}$
  - Enhance $\bar{\nu}_e(p,n)e$ rate by 20%



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Three coupled effects:

- Far conversions ($\Delta r_{\rm mix} \gtrsim 40$ km):
  - Don't change Y_e and $\dot{Q}$
  - Enhance $\bar{\nu}_e(p,n)e$ rate by 20%
- Near conversions ($\Delta r_{\rm mix} \approx 1$-$40$ km):
  - Again, enhance $\bar{\nu}_e(p,n)e$ rate by 20%
  - Additionally, increase $\dot{Q}$ and $\dot{M}$ by 30%
  - And increase Y_e (next slide)

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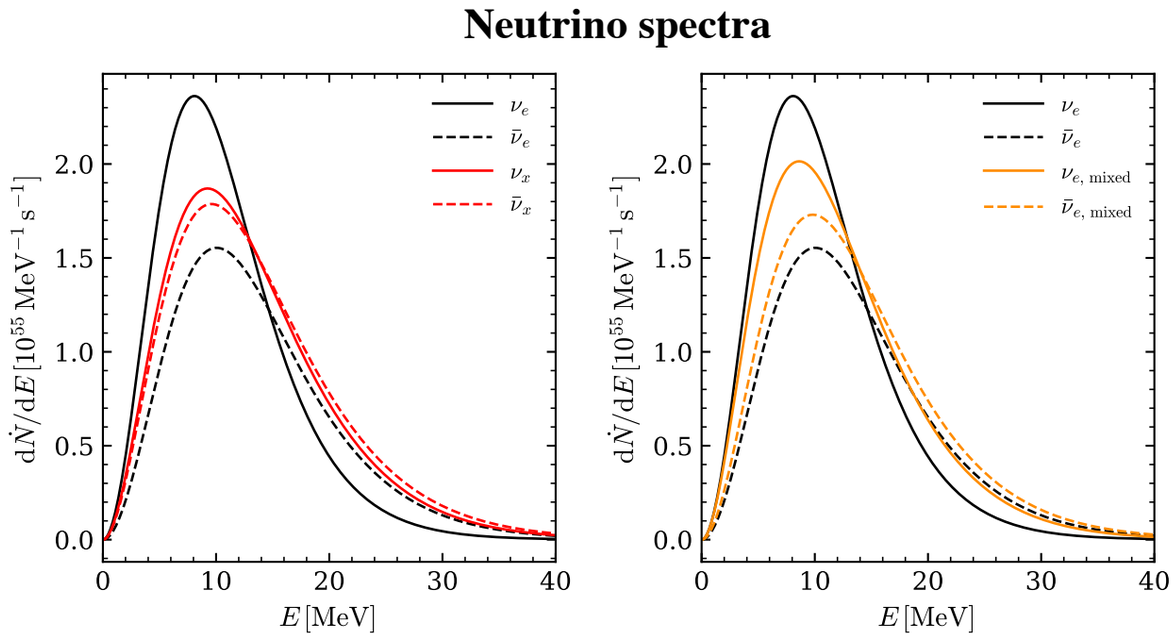
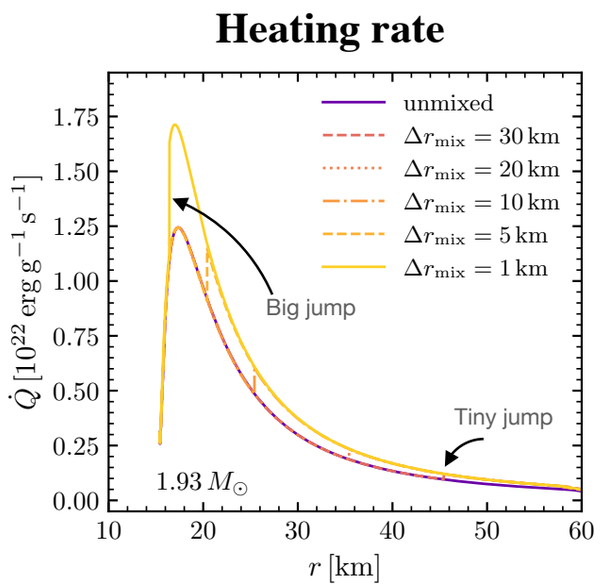
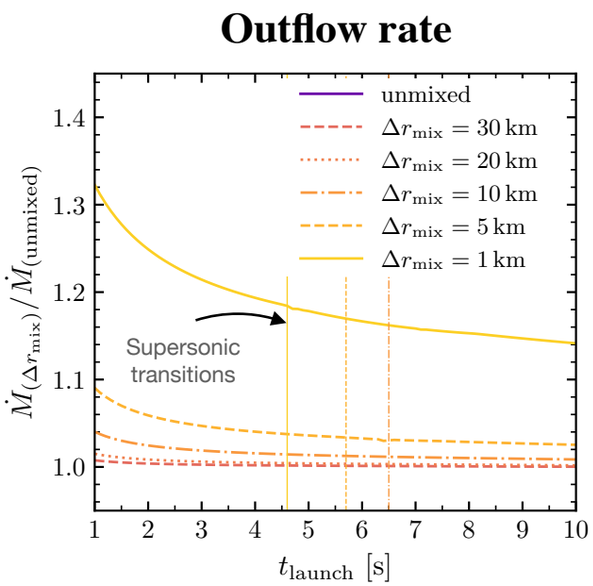




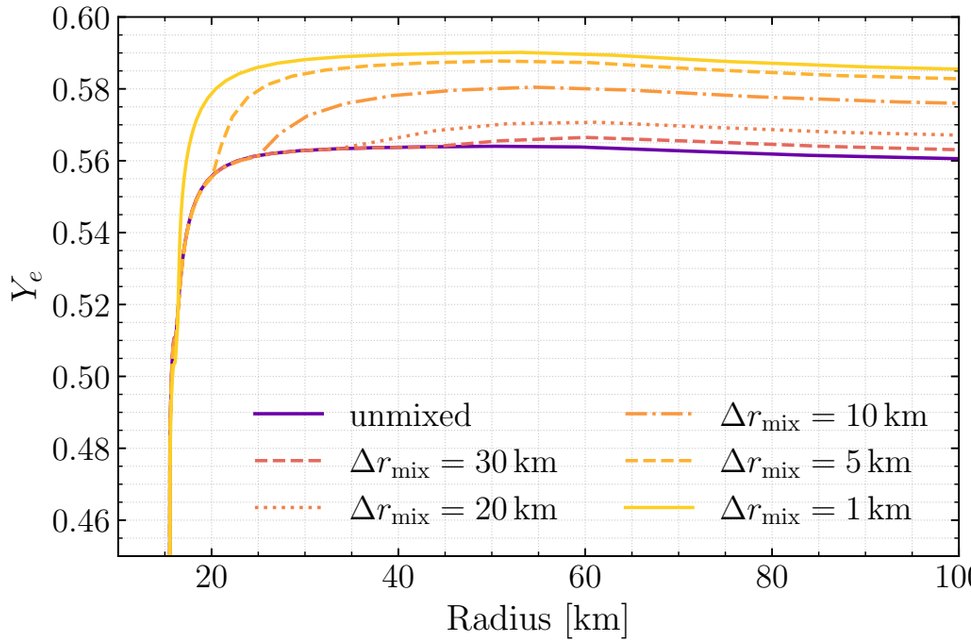


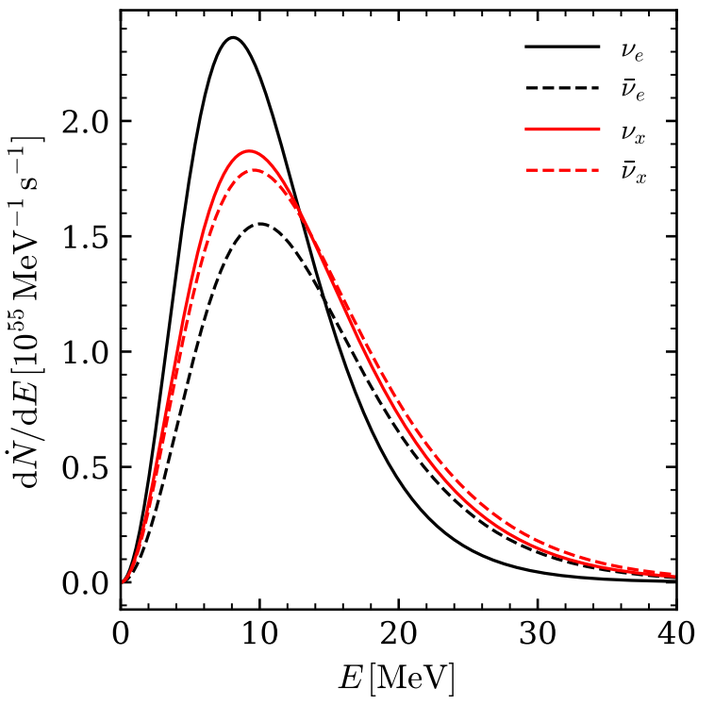
IPG+, arXiv:2607.15392

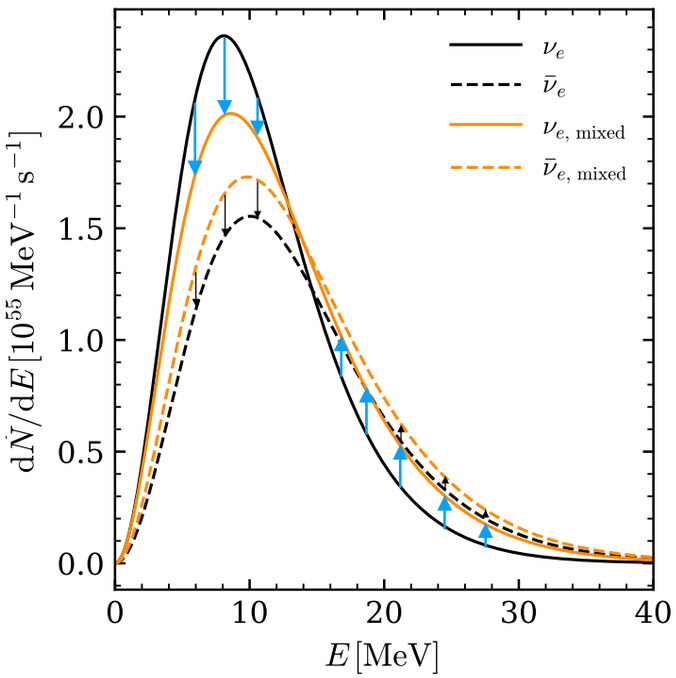
Mixing within 10 km makes Y_e optimal

- Unmixed: $Y_e \approx 0.56$
- Near conversions: $Y_e \approx 0.59$

$$Y_e = \frac{n_e}{n_b} = \frac{n_p}{n_p + n_n} \approx \left(1 + \frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}\right)^{-1}$$







The *increase* in Y_e follows from the hierarchy of the neutrino spectra:

- $f_{\nu_e,\rm mixed}$ more energetic on average
- $f_{\bar{\nu}_e,\rm mixed}$ ~unchanged (similar $\bar{\nu}_e$, ν_x)
- Larger increase in $\lambda_{\nu_e n}$ relative to $\lambda_{\bar{\nu}_e p}$ → boost in Y_e

IPG+, arXiv:2607.15392

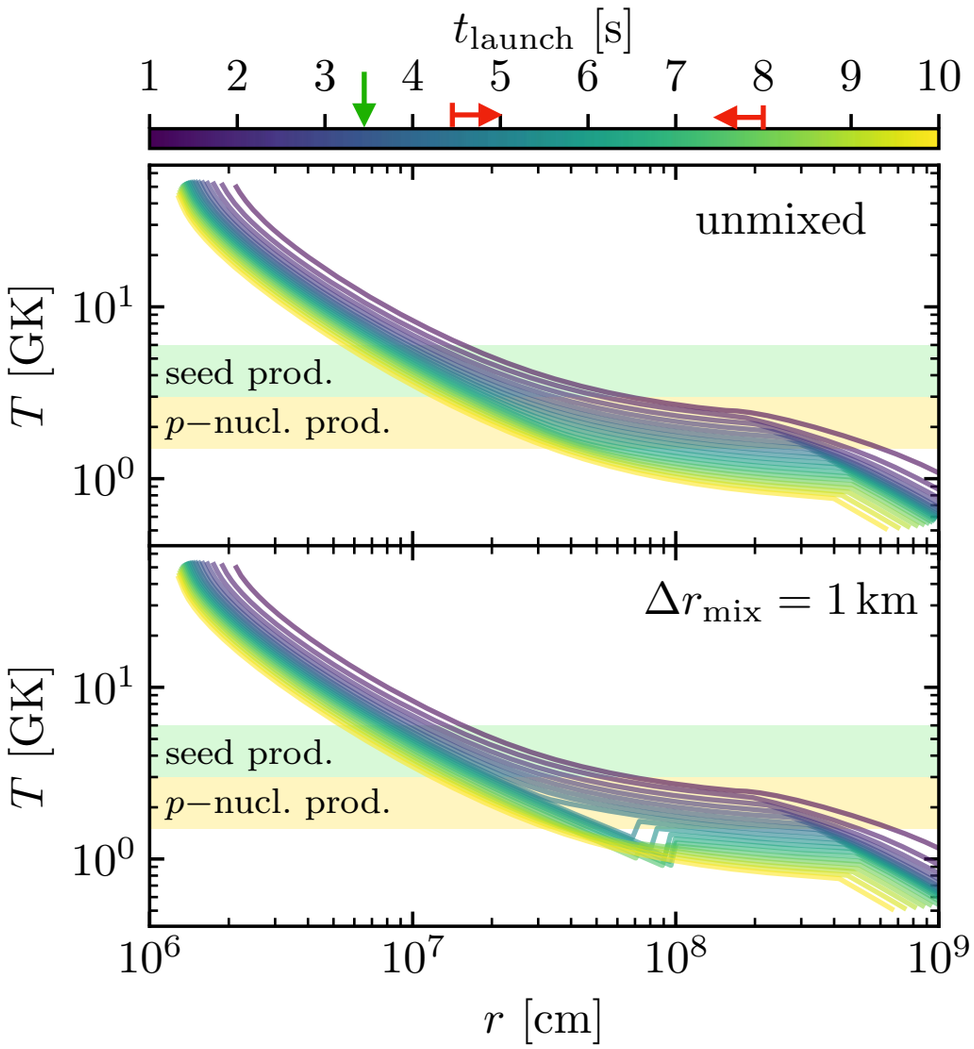
Extra heating changes the outflow

Histories of tracers launched at 1-10 s

Unmixed: subsonic throughout

Mixed at 1 km:

- Supersonic transition at 4.5 s
- Termination shock persists to 8 s

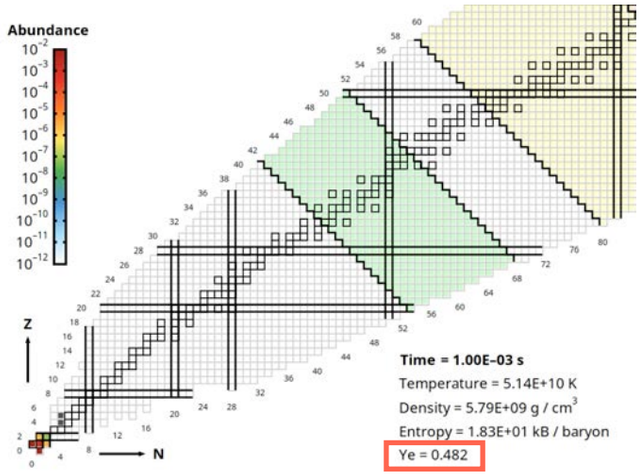


Unmixed: not terrible but suboptimal yields

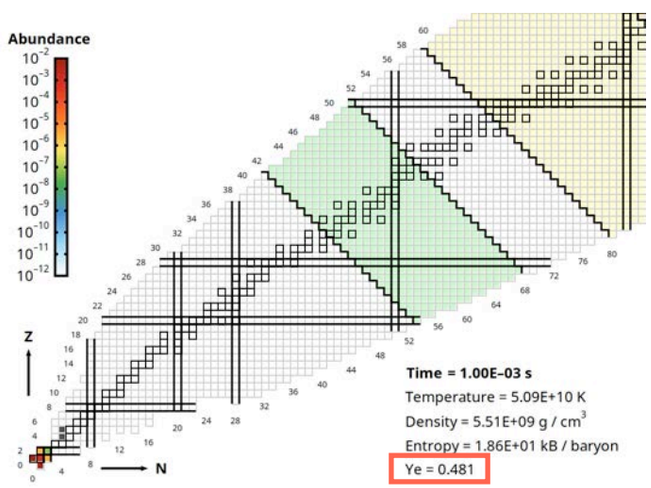
Mixed at 1 km:

- Outflows with mixing lead to better yields (higher Y_e)

Nucleosynthesis of trajectory launched at 3.5 s



unmixed



$\Delta r_{\rm mix} = 1\,{\rm km}$

IPG+, arXiv:2607.15392

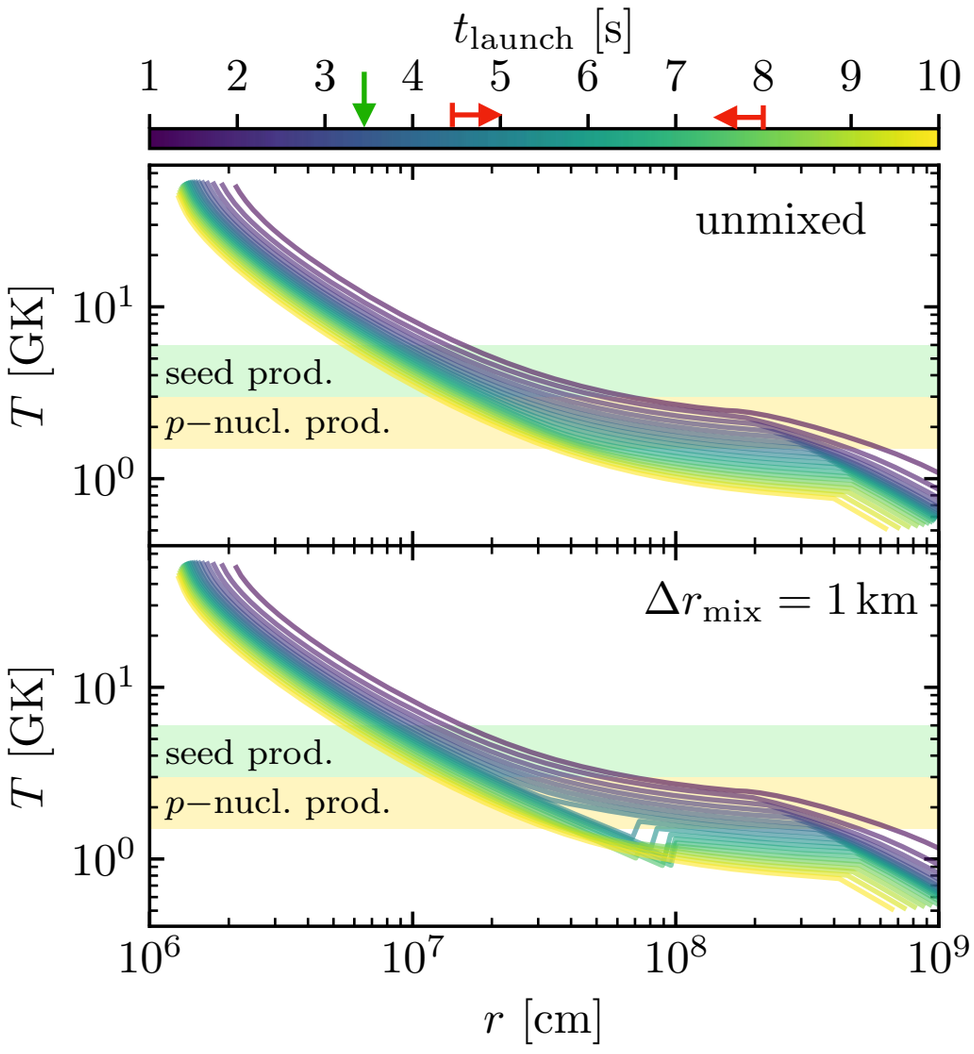
Extra heating changes the outflow

Histories of tracers launched at 1-10 s

Unmixed: subsonic throughout

Mixed at 1 km:

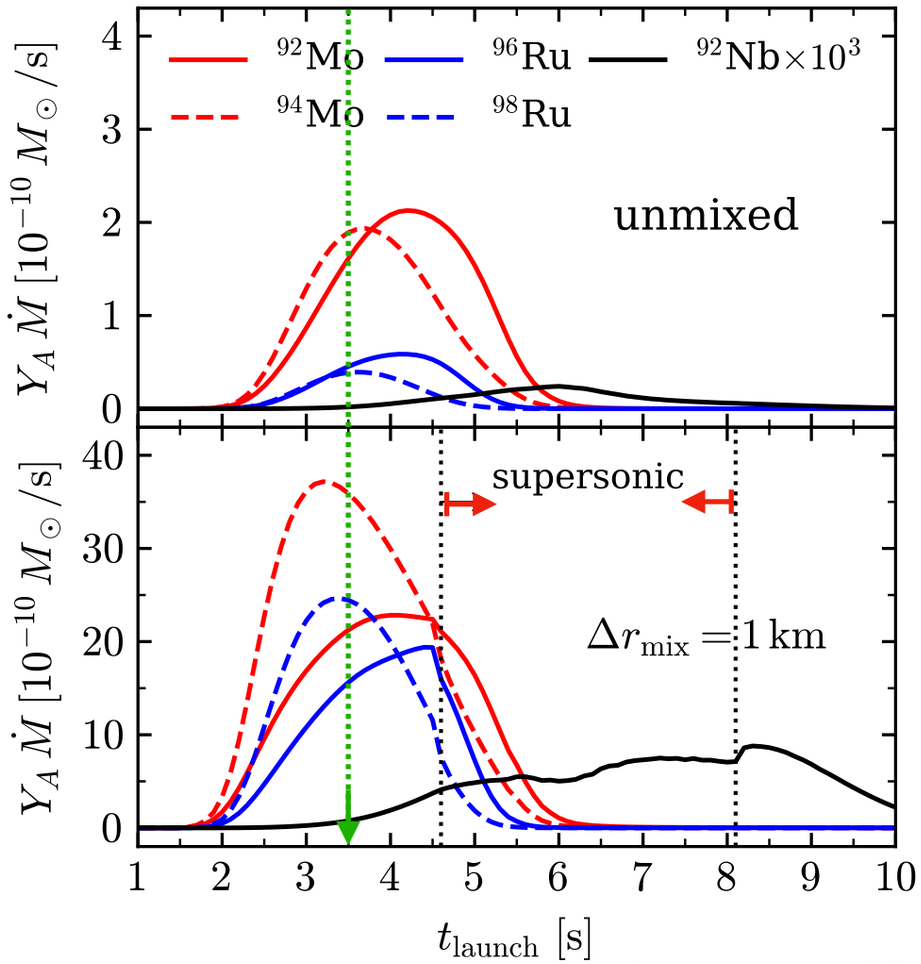
- Supersonic transition at 4.5 s
- Termination shock persists to 8 s



Unmixed: not terrible but suboptimal yields

Mixed at 1 km:

- Outflows with mixing lead to better yields (higher Y_e)
- Supersonic transition starts only after the peak



IPG+, arXiv:2607.15392

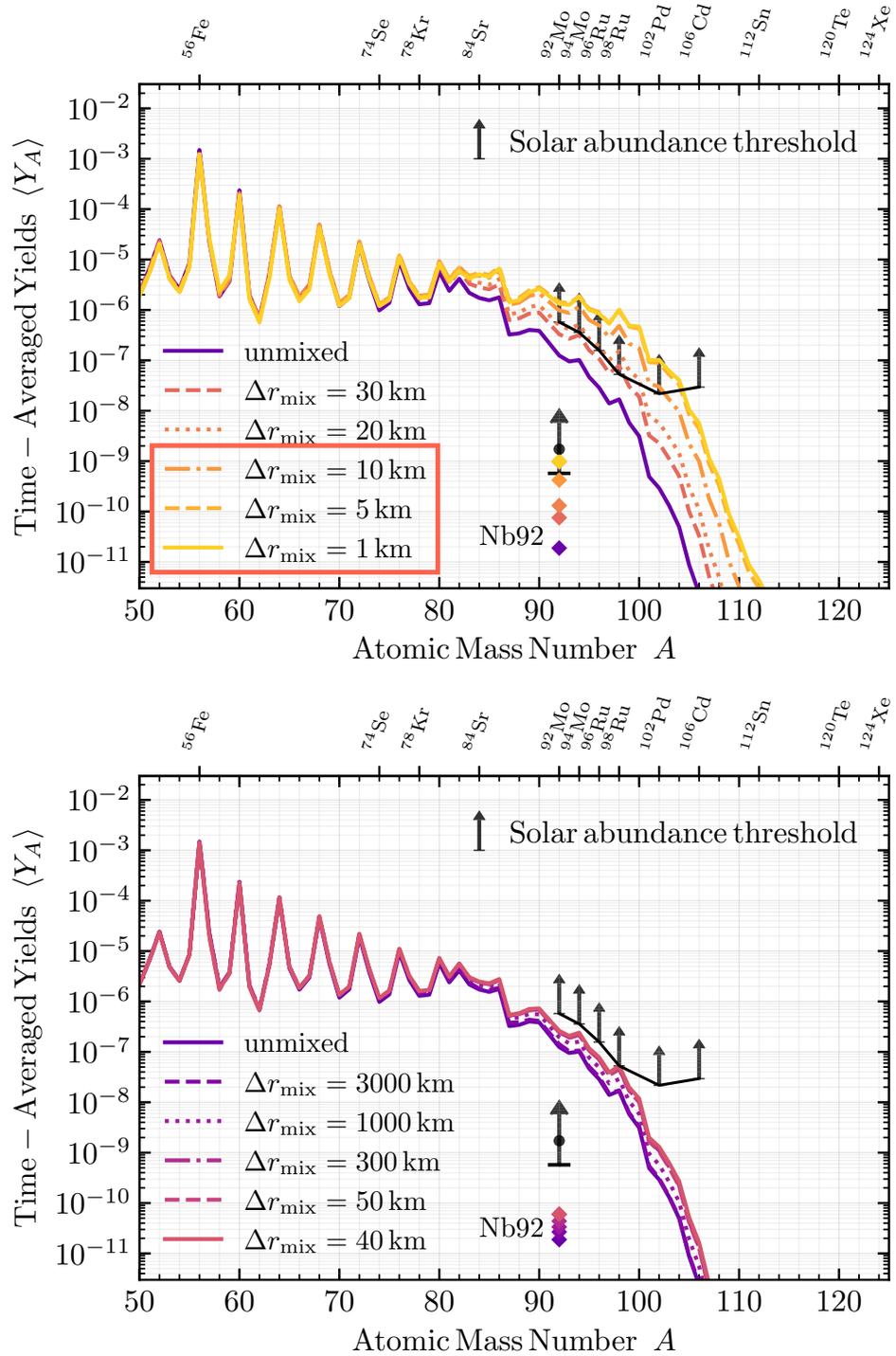
Only near conversion can explain the p-nuclide pattern

Near conversions:

- Time-averaged yields above threshold if mixing as close as 10 km from PNS

Far conversions:

- At 40-300 km, Y_e and heating are unchanged
- Only late neutron production affected



IPG+, arXiv:2607.15392

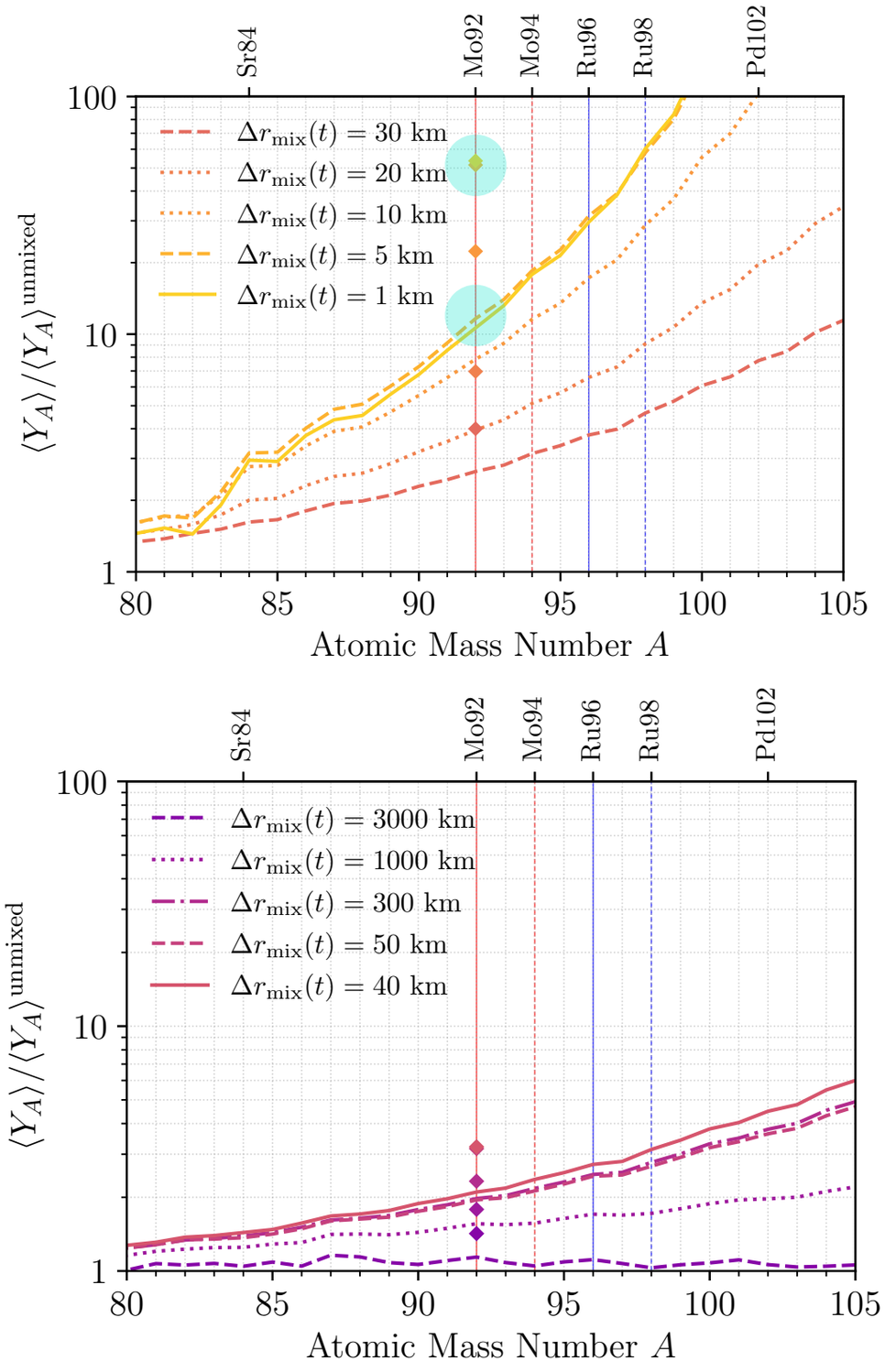
Only near conversion can explain the p-nuclide pattern

Near conversions:

- Time-averaged yields above threshold if mixing as close as 10 km from PNS
- ^{92}Nb enhanced by factor of ~50
- ^{92}Mo enhanced by factor of ~10

Far conversions:

- At 40-300 km, Y_e and heating are unchanged
- Only late neutron production affected
- Yields rise by factor of ~3, and remain below the solar threshold



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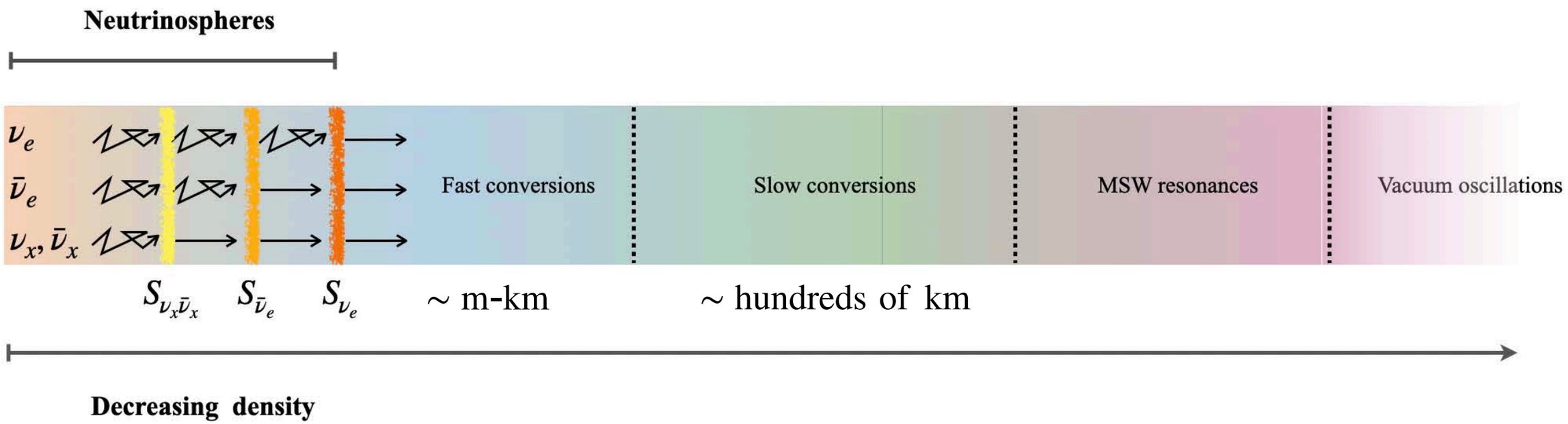
Abundance pattern suggests fast conversion

- Different regimes of flavor conversion as a function of matter and neutrino density



- $\Delta r_{\rm mix} \gtrsim 40$ km: far conversions (slow) have negligible impact on yields.
- $\Delta r_{\rm mix} \lesssim 40$ km: near effects, consistent with fast collective oscillations.
- The best yields are found when oscillations occur within 10 km from the PNS, indicating **fast collective oscillations.**

IPG+, arXiv:2607.15392

Takeaways from this talk

- **Near conversion solves the deficit—**yields with $A = 90$-100 boosted by factors of 20-60, bringing abundances into agreement with observations

- **Mixing radius matters—**Near conversions change Y_e, heating, hydrodynamics, and neutron supply; mixing beyond ~40 km doesn't do much

- **Solar abundances probe collective oscillations—**The preferred radius suggests a fast collective nature of neutrino mixing; physics that otherwise remain unaccessible to us