Successful $\nu p-$process in neutrino-driven Core-collapse supernova outflows

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NTN workshop - June 21, 2022

The origin of elements

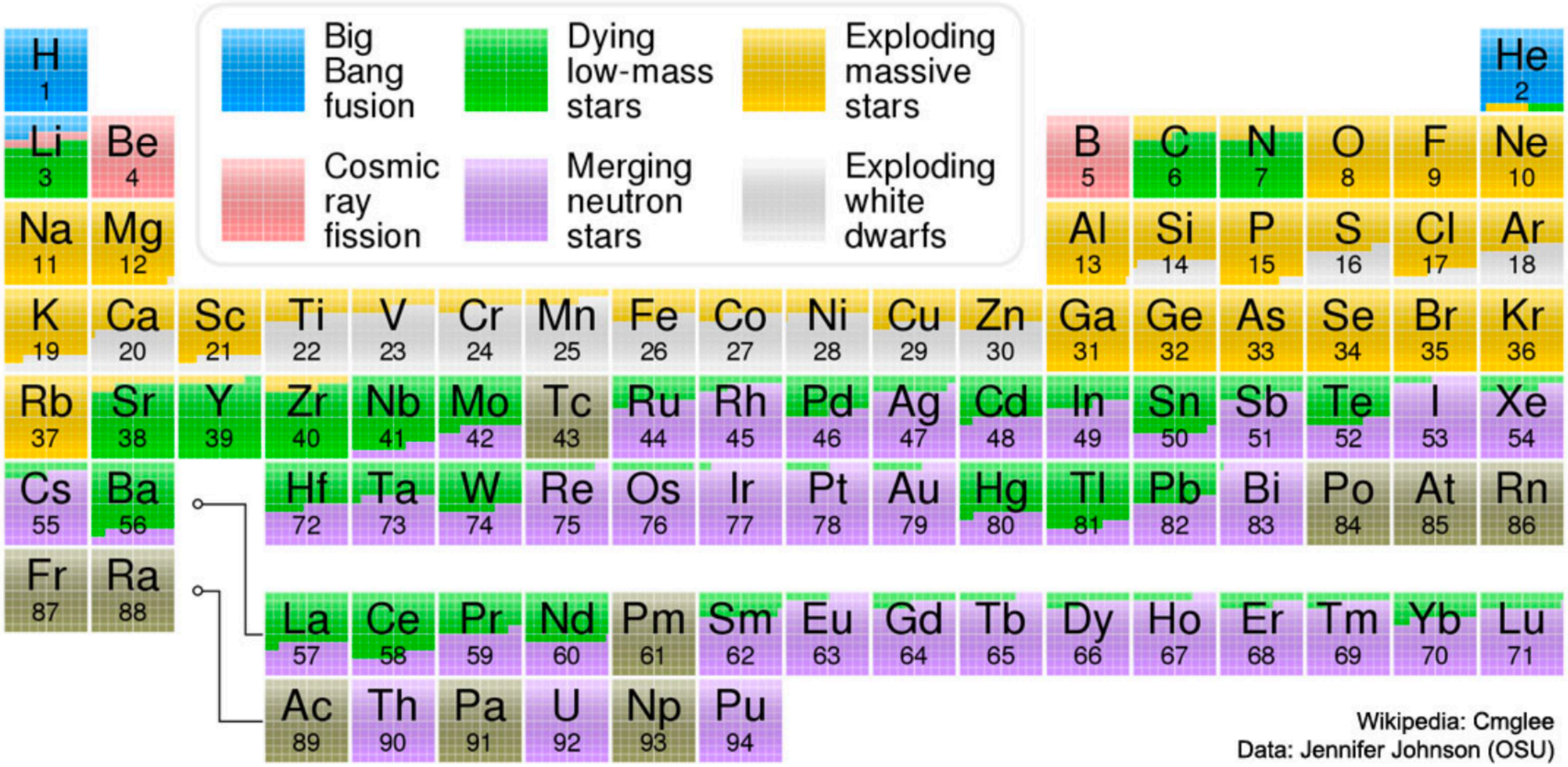


Figure: Astronomy picture of the day (2020 August 9)

The origin of elements

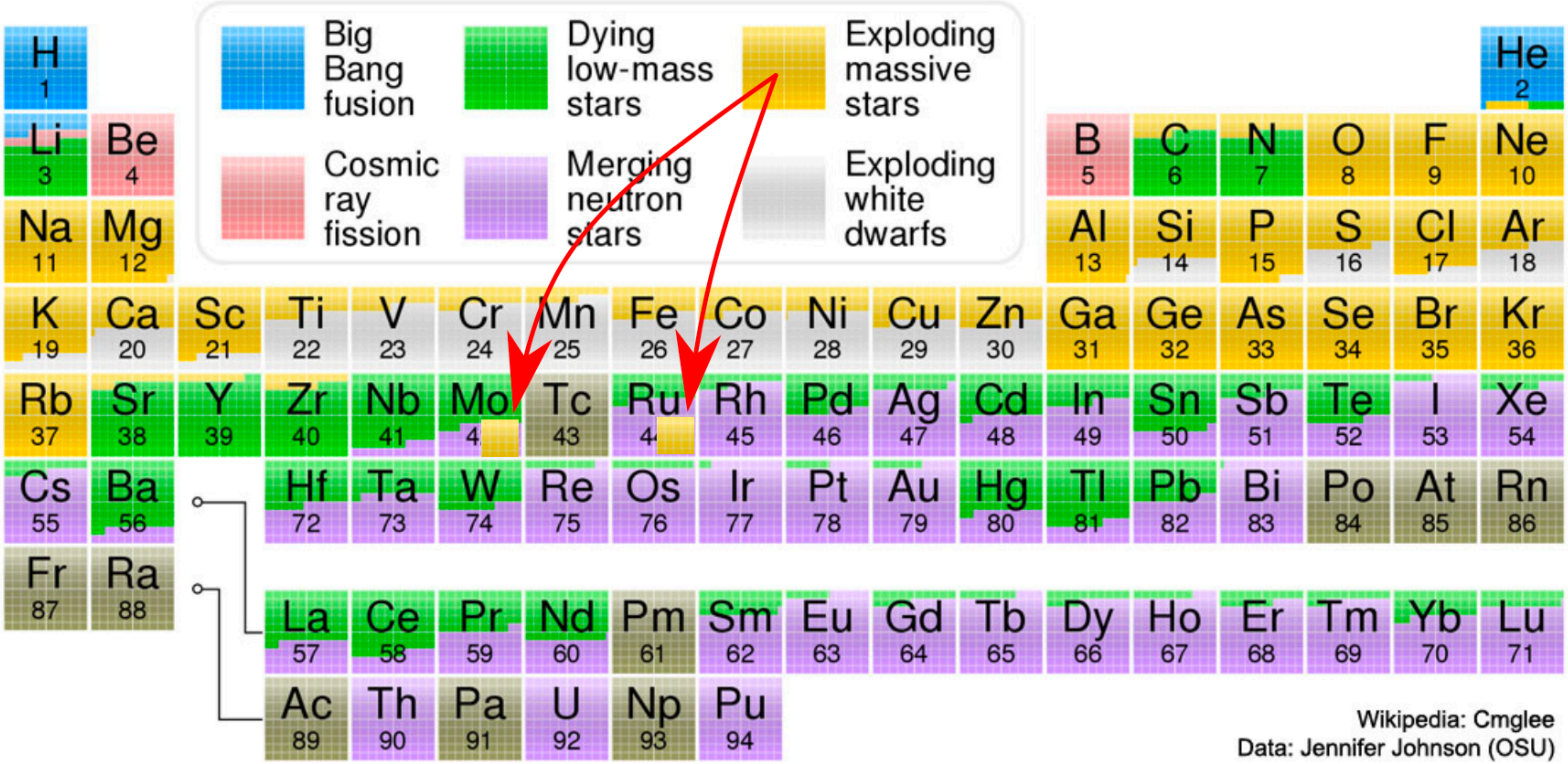
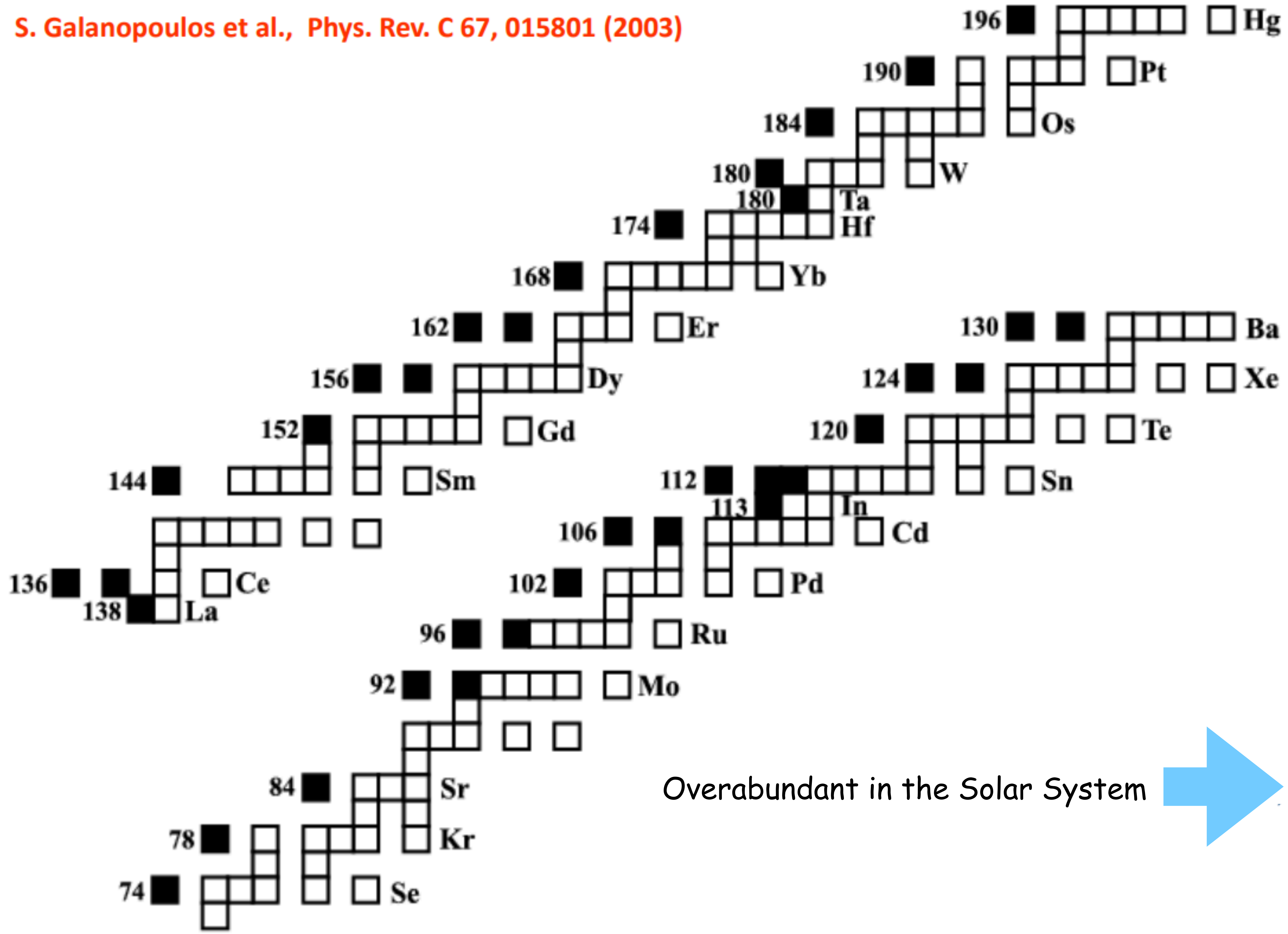


Figure: Astronomy picture of the day (2020 August 9)

Proton-rich ($p-$)nuclei

S. Galanopoulos et al., Phys. Rev. C 67, 015801 (2003)

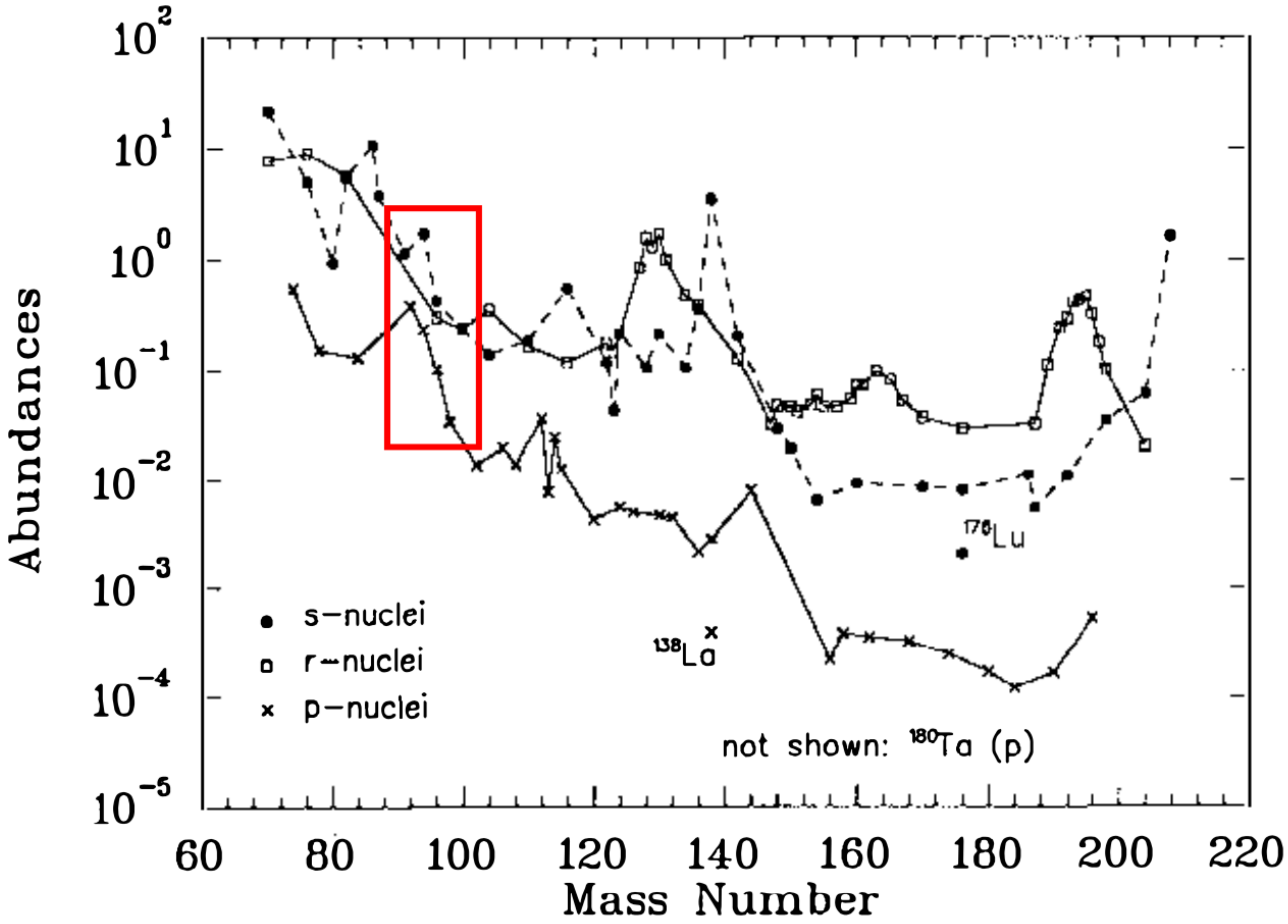


Overabundant in the Solar System

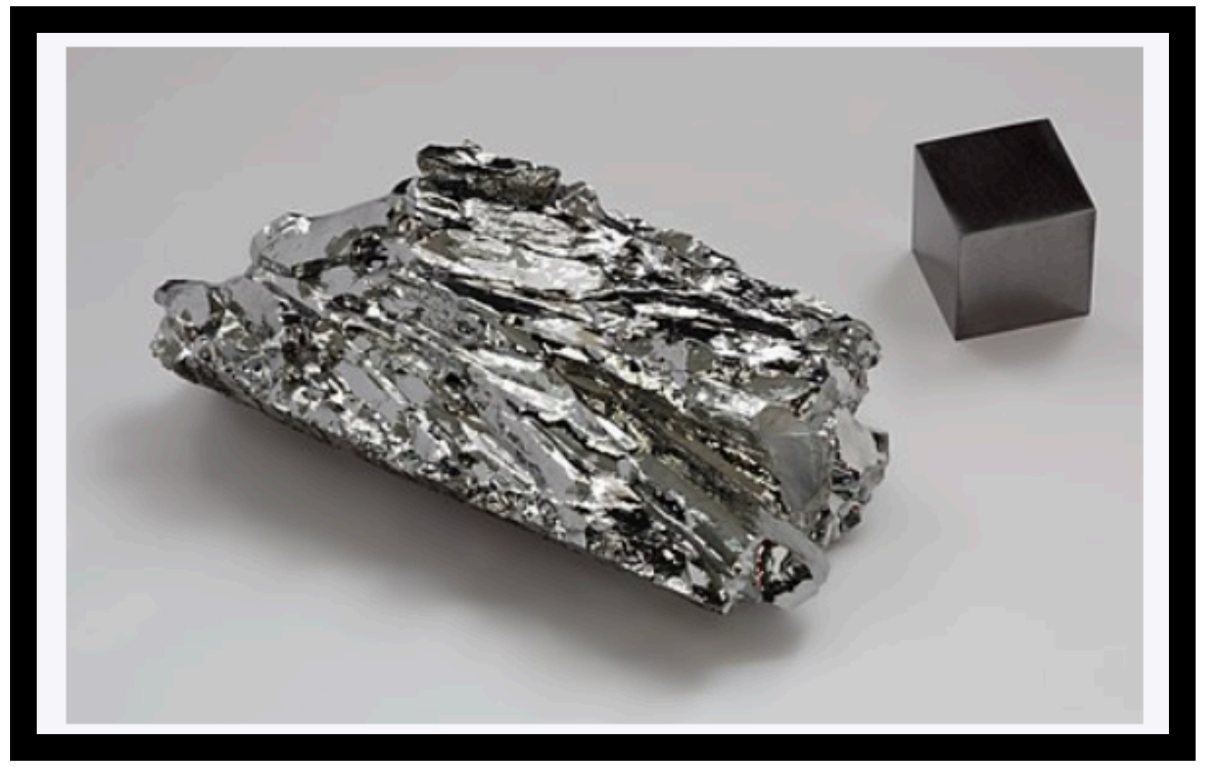
p-nuclei solar abundances

p nucleus	(%)	p nucleus	(%)	p nucleus	(%)
74_Se	0.89	114_Sn	0.65	156_Dy	0.06
78_Kr	0.35	115_Sn	0.34	158_Dy	0.10
84_Sr	0.56	120_Te	0.096	162_Er	0.14
92_Mo	14.84	124_Xe	0.10	164_Er	1.61
94_Mo	9.25	126_Xe	0.09	168_Yb	0.13
96_Ru	5.52	130_Ba	0.106	174_Hf	0.162
98_Ru	1.88	132_Ba	0.101	180_Ta	0.012
102_Pd	1.02	138_La	0.09	180_W	0.13
106_Pd	1.25	136_Ce	0.19	184_Os	0.02
108_Cd	0.89	138_Ce	0.25	190_Pt	0.01
113_In	4.3	144_Sm	3.1	196_Hg	0.15
112_Sn	0.97	152_Gd	0.20		

Overabundance of isotopes of Mo and Ru



Mo



Ru

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.

Challenging to make $Mo^{92,94}$ and $Ru^{96,98}$ – Outstanding problem since 1970's

P-process mechanisms:

- $\gamma-$process (Woosley and Howard, 1978, ApJS 36, 285)
    - Photodisintegration of neutron-rich isotopes.
    - Occurs in exploding white dwarfs or during O/Ne shell burning in massive stars.
    - Produces some Mo^{92} but underproduces others.
- $rp-$process (Schatz et al., Phys. Rept. 294, 167-263 (1998))
    - Proton captures followed by $\beta+$ decays.
    - Surface of accreting neutron stars.
    - Hindered by beta decay waiting points, such as of Ge^{64}, with over a minute of beta decay lifetime.

Challenging to make $Mo^{92,94}$ and $Ru^{96,98}$

P-process mechanisms:

- $\alpha-$process (Hoffman et al. ApJ, 460, 478 (1996))
  - Proceeds via chain of α, n, p captures in outflows with $Y_e \sim 0.48 - 0.49$.
  - Produces Mo^{92} but doesn't produce $Mo^{94}, Ru^{96,98}$ etc.
- $\nu-$process (Woosley et al., ApJ, 356, 272 (1990))
  - Neutrino captures on stable nuclei.
  - May occur in core-collapse supernovae with large neutrino fluxes.
  - Difficult to implement because outflow needs to be very close to the PNS.

None of these processes work for making sufficient $Mo^{92,94}$ and $Ru^{96,98}$

New mechanism proposed in 2005

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

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

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(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.

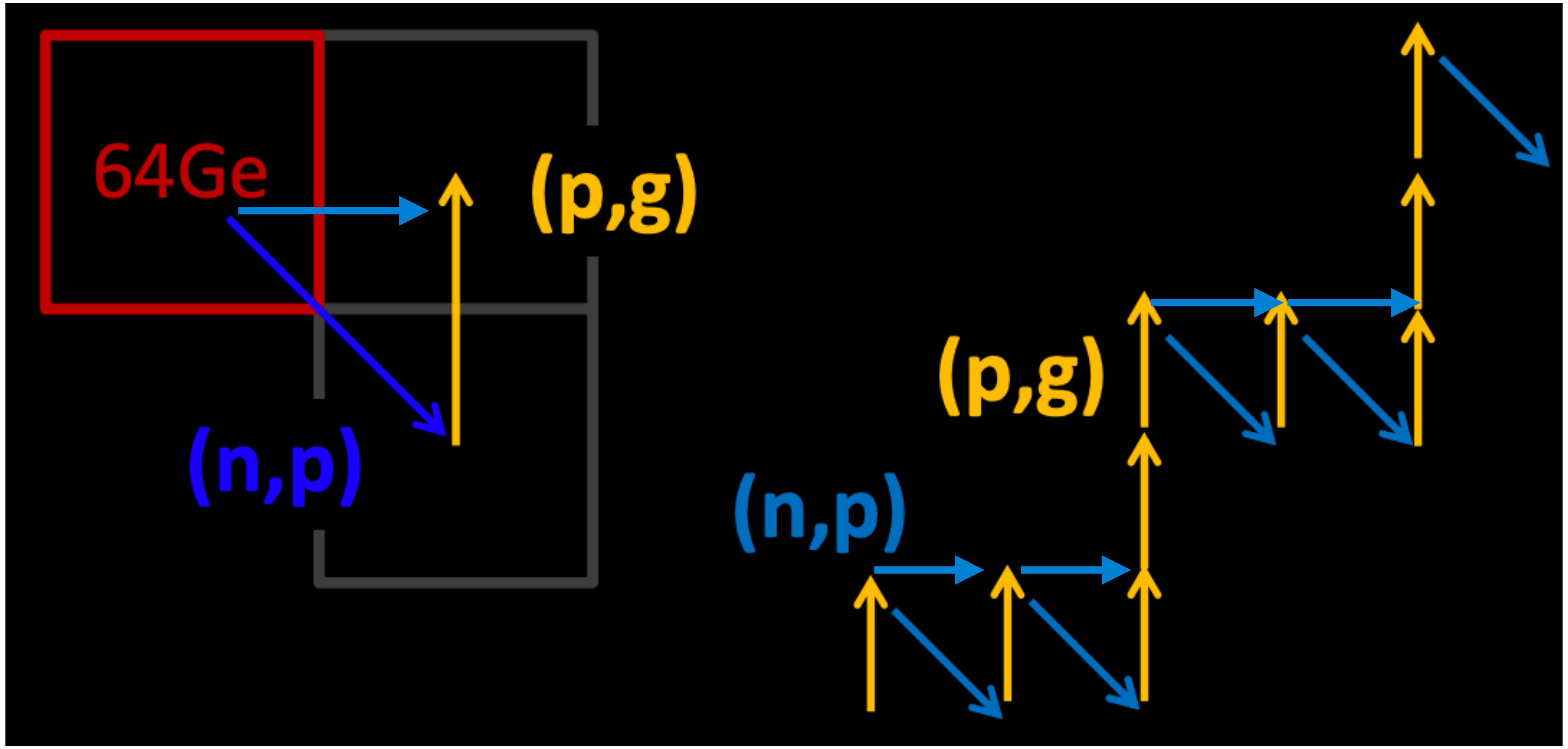
$\nu p-$process : attractive solution for $p-$nuclide origin puzzle

Step 1: Neutrino capture on protons gives a tiny fraction of neutrons, which can help bypass the β^+ decay waiting points in $rp-$ process.

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Step 2: (n,p) and (n,γ) reactions on ^{56}Ni.

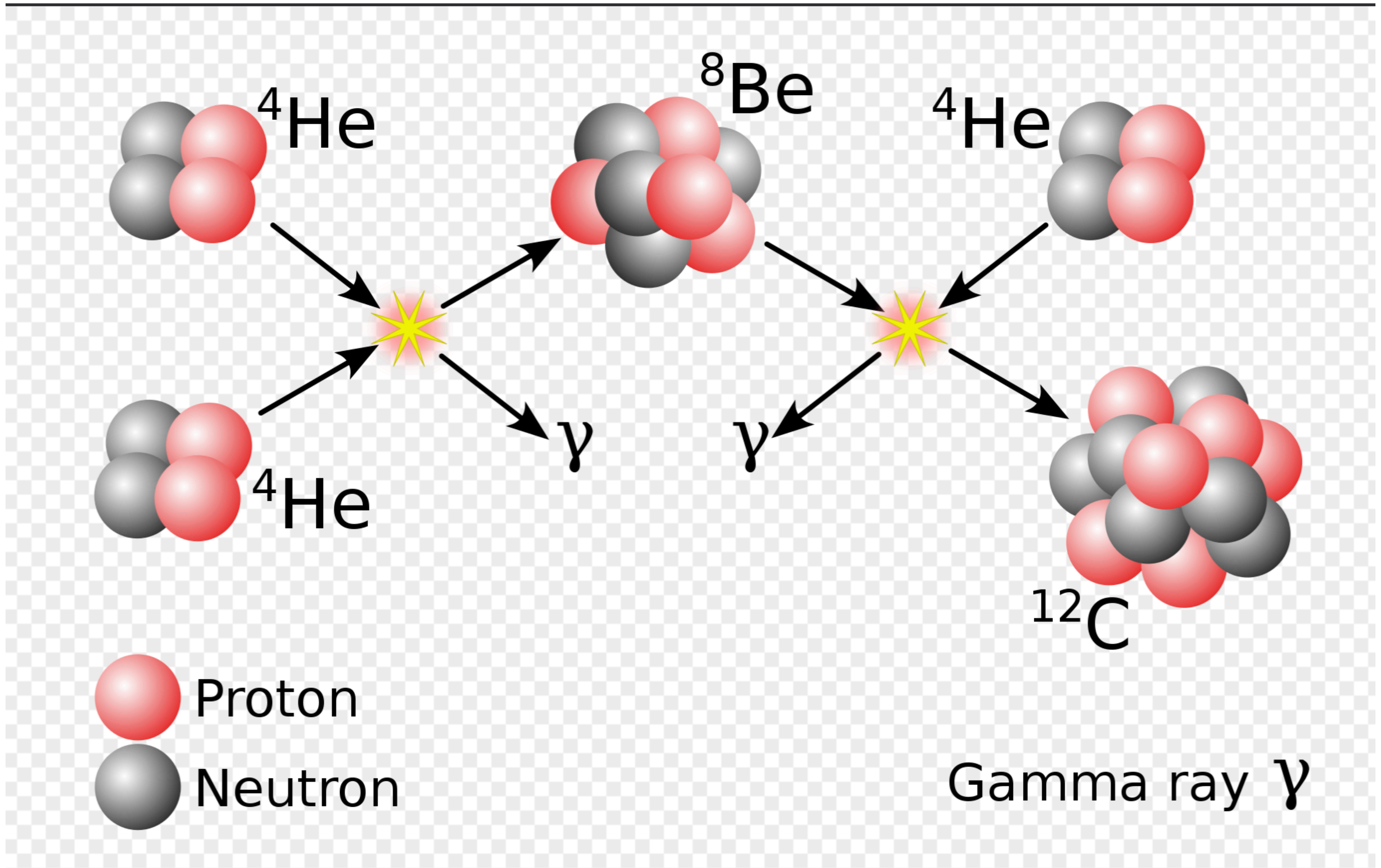
Step 3: Immediately followed by proton captures



Optimal conditions for the $\nu p-$process

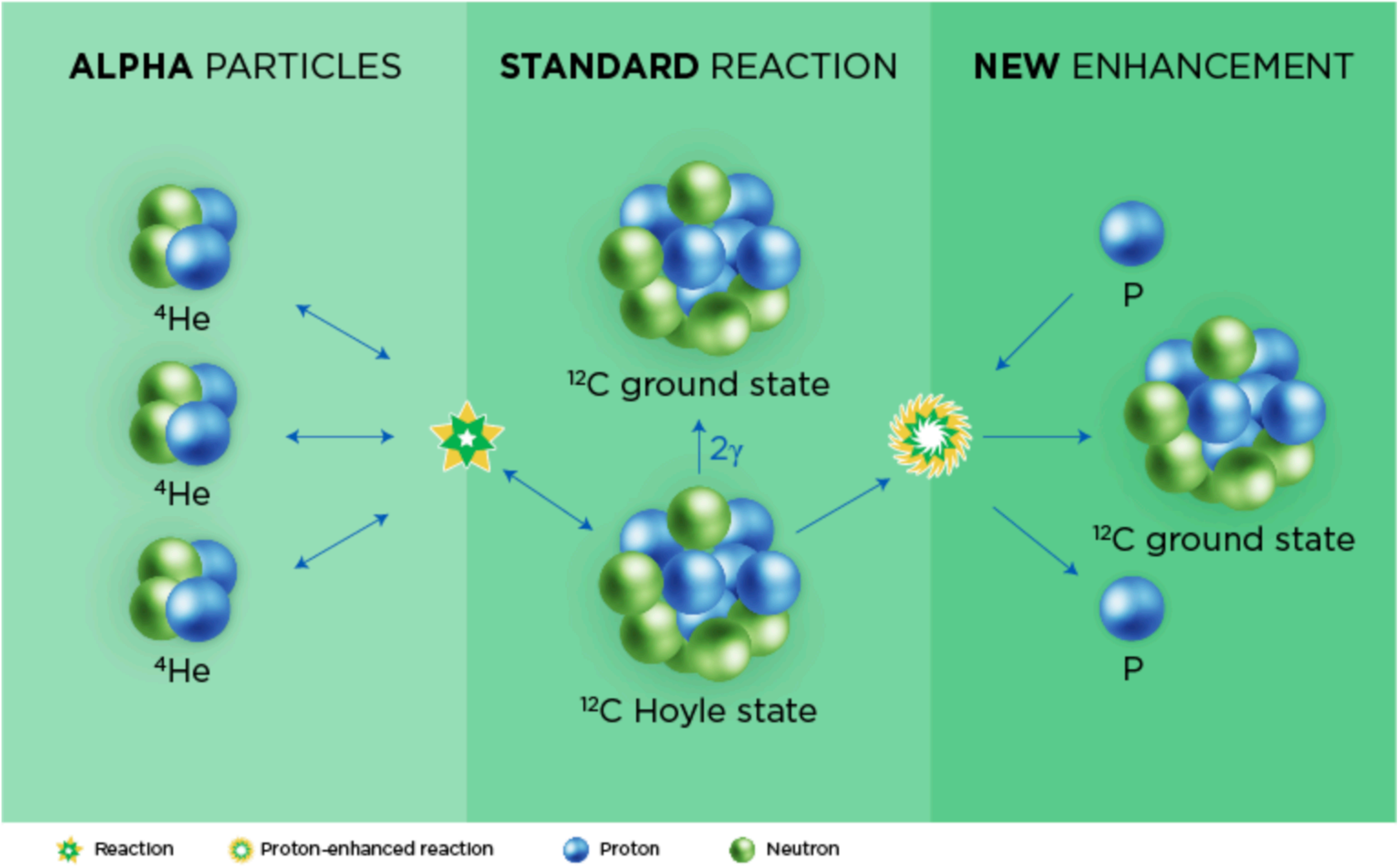
- Proton-rich environment.
- Presence of a large neutrino flux.
- $\nu p-$ process occurs for $3 \text{ GK} \lesssim T \lesssim 1.5 \text{ GK}$.
- Higher entropy generally favourable.
- Supernova outflows have a lot of neutrinos, relatively high entropies, can be proton rich — ideal candidates for the $\nu p-$process

Importance of triple-α reaction rates



Triple-α reaction bridges light (A < 12) and heavy (A >= 12) nuclei.
Larger reaction rates decreases proton to seed ratio at the onset of $\nu p-$process.
Enhanced triple-α rates decrease the rates of $\nu p-$ process.

Enhanced triple-α reaction rates



No way $\nu p-$can make these elements?

- Difficult to reproduce observed ratios of ^{92}Mo and ^{94}Mo [Fisker:2009,Bliss:2014,Bliss:2018] as well as ^{96}Ru and ^{98}Ru [Bliss:2018].
- Even worse, the absolute production rates seem to be too low to explain the Solar System abundances of these and other p-nuclides [Bliss:2018].
- Especially dire with the recent calculations [Jin et al, Nature (2020)] that took into account in-medium effects enhancing the rate of the triple-α reaction.

State-of-the-art results on the $\nu p-$ process

MSUTODAY

Dec. 2, 2020

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.

But accelerating the triple-alpha reaction also puts the brakes on the supernova's ability to make heavier elements on the periodic table, Roberts said. This is important because scientists have long believed that proton-rich supernovae created Earth's surprising abundance of certain ruthenium and molybdenum isotopes, which contain closer to 100 protons and neutrons.

"You don't make those isotopes in other places," Roberts said.

But based on the new study, you probably don't make them in proton-rich supernovae, either.

"What I find fascinating is that you now have to come up with another way to explain their existence. They should not be here with this abundance," Schatz said of the isotopes. "It's not easy to come up with alternatives."

Link for the press release: MSU Nature

These are actually good reasons for expecting that the process will not work

1) We need enough neutrons per seed for nu-p. Otherwise, the nucleosynthesis chain won't reach up to Mo and Ru.

2) Having too many neutrons is also a problem because then, neutron rich final products will be made.

3) One needs the right balance of seed production to neutron production in the outflow to have enough nu-p yields.

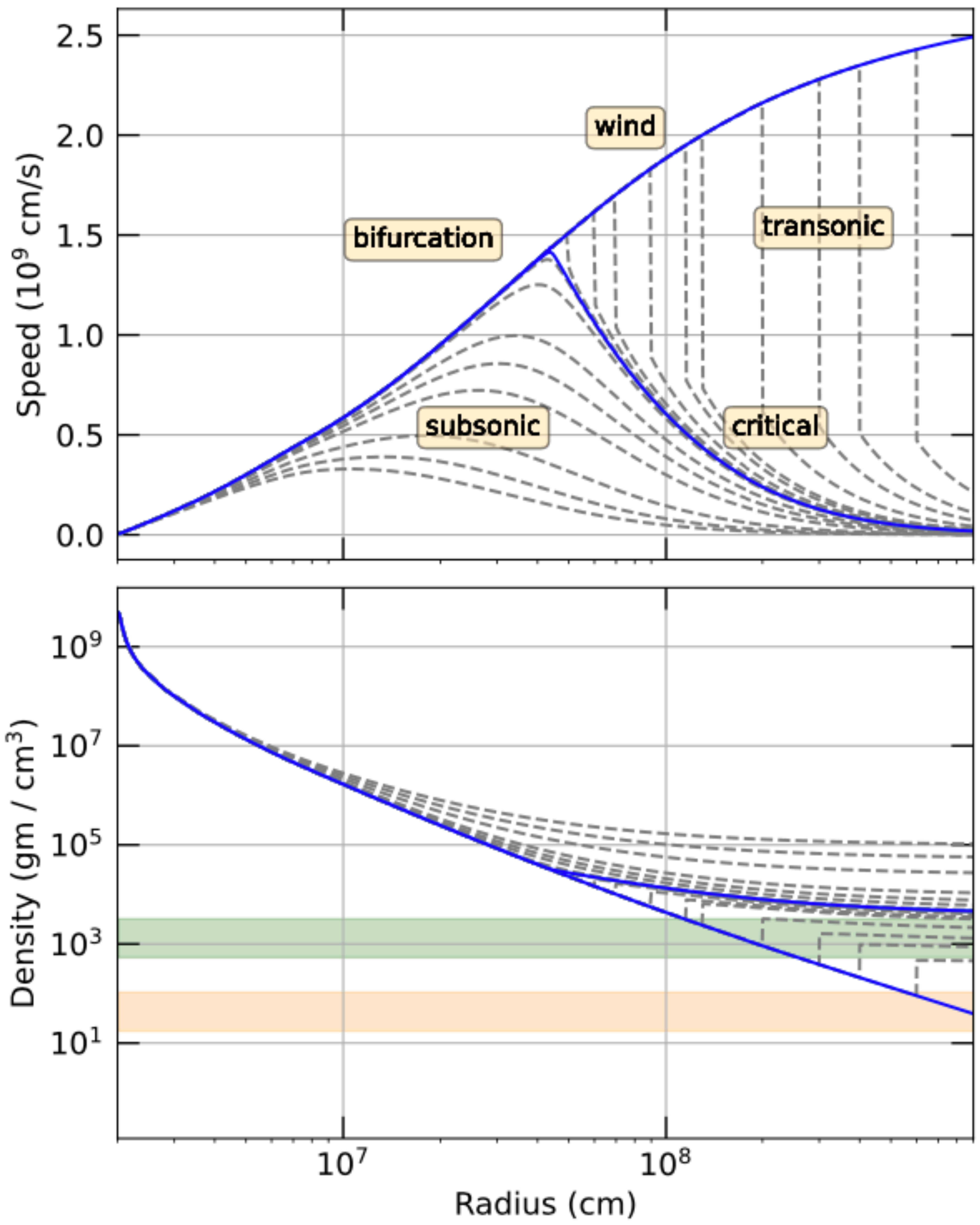
3) Seeds are made during triple-alpha reaction, (T~0.6MeV), and neutrons are made later due to large neutrino fluxes, neutron production stops after ~0.15 MeV.

4) It's not obvious apriori that a realistic neutrino-driven outflow would satisfy this condition.

5) On top of this, there is the issue of triple-alpha enhancement.

We show that self-consistent treatment of hydrodynamics is extremely important for making any conclusions about $\nu p-$ process nucleosynthesis in supernovae.

Hydrodynamics of neutrino-driven outflows



Neutrino-driven outflows can be either subsonic or supersonic.

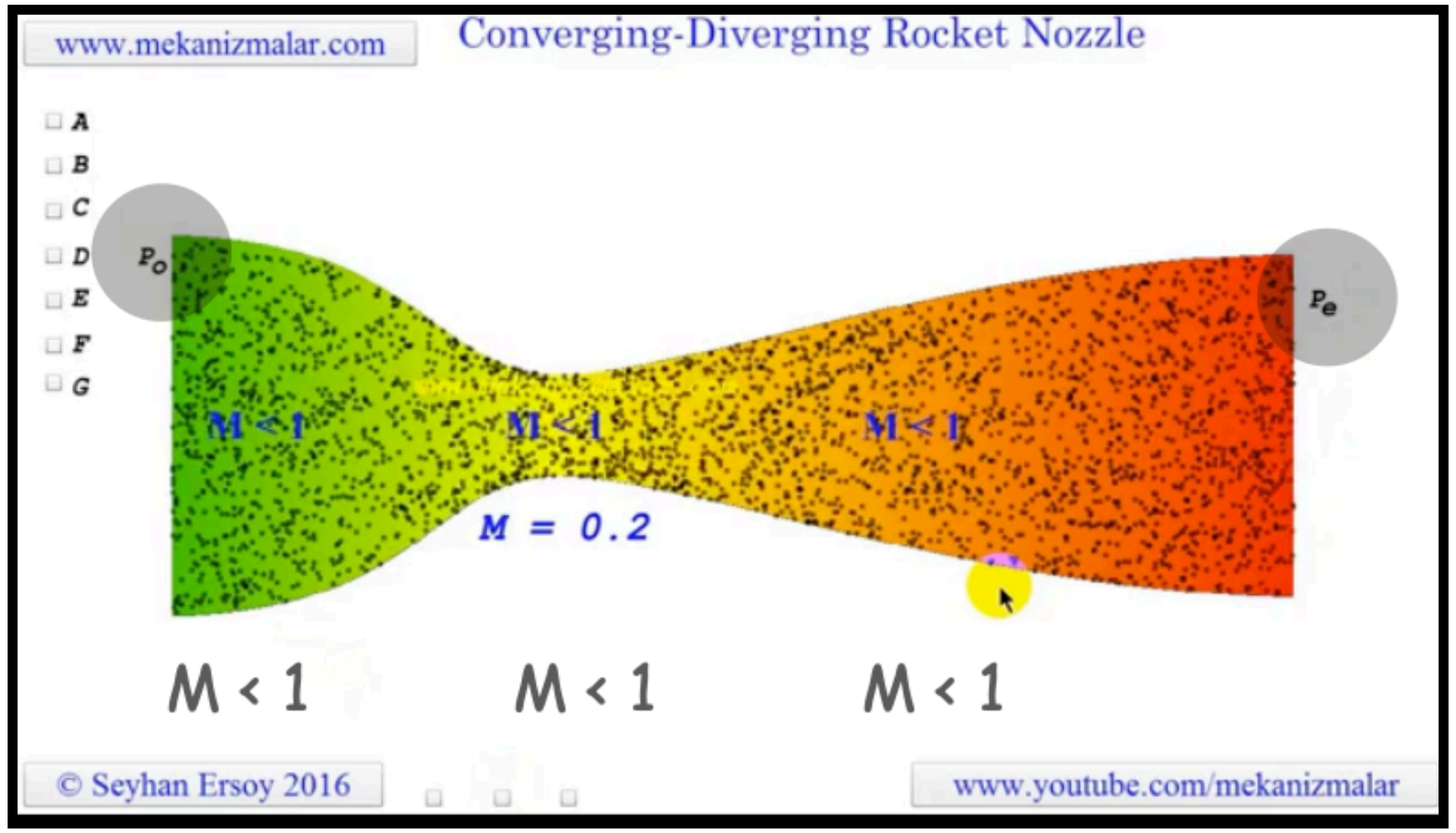
Our hydrodynamic calculations show that realistic supernovae are on the edge of being supersonic or subsonic.

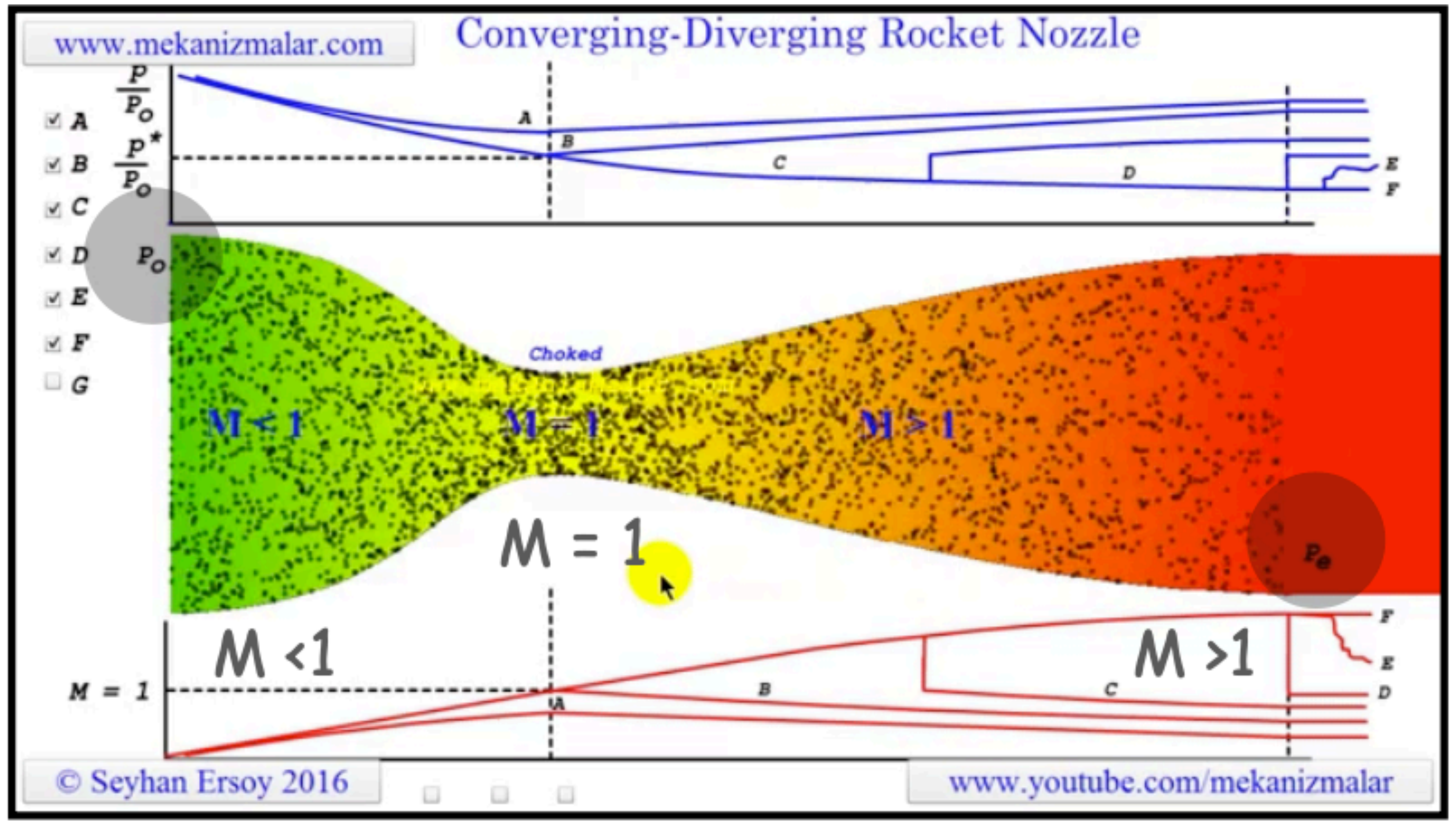
Typical core-collapse supernovae are near-critical.

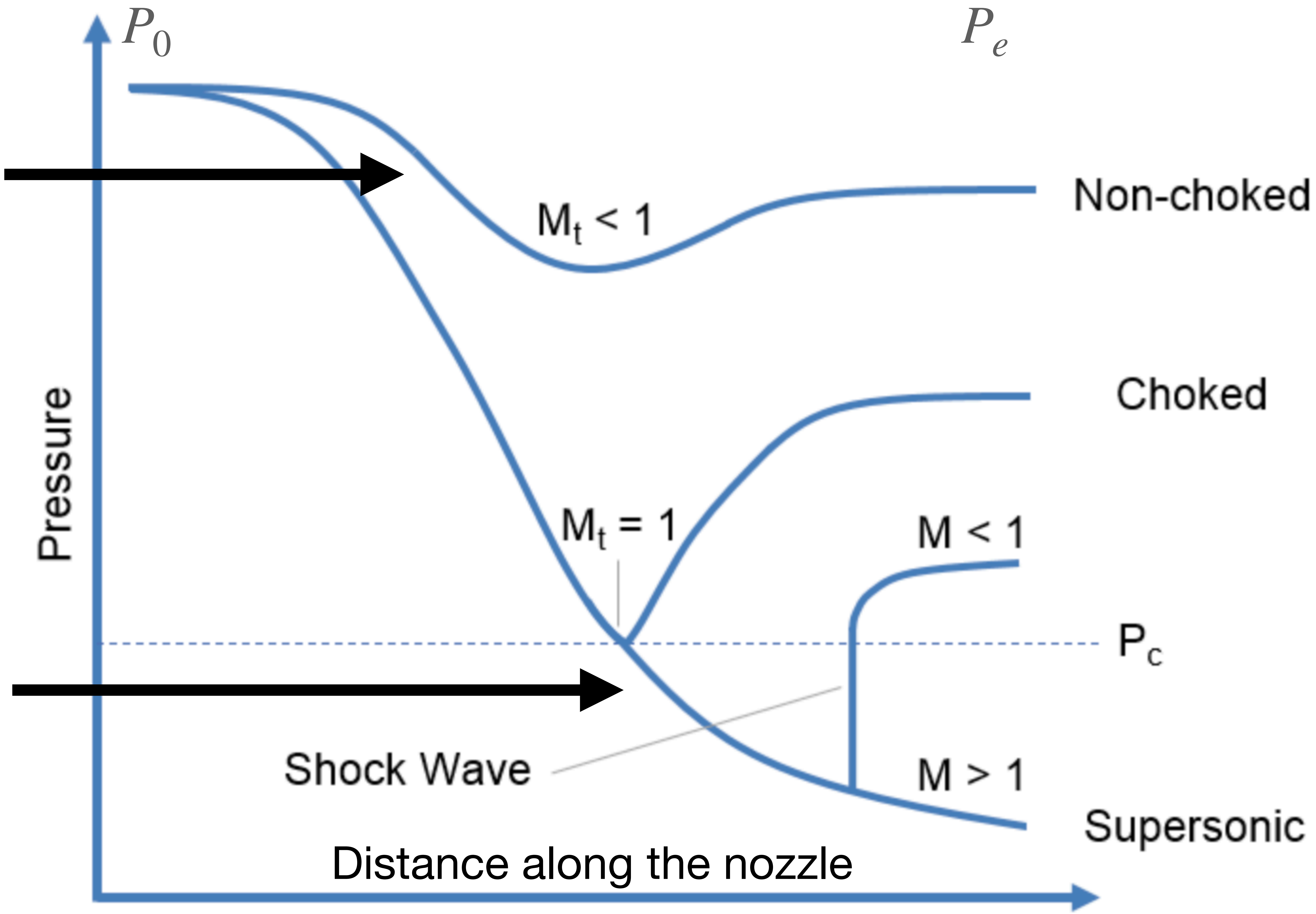
This behaviour is unusual and previously undescribed. However, can be crucial for nucleosynthesis.

A. Friedland and P. Mukhopadhyay, arxiv:2009.10059

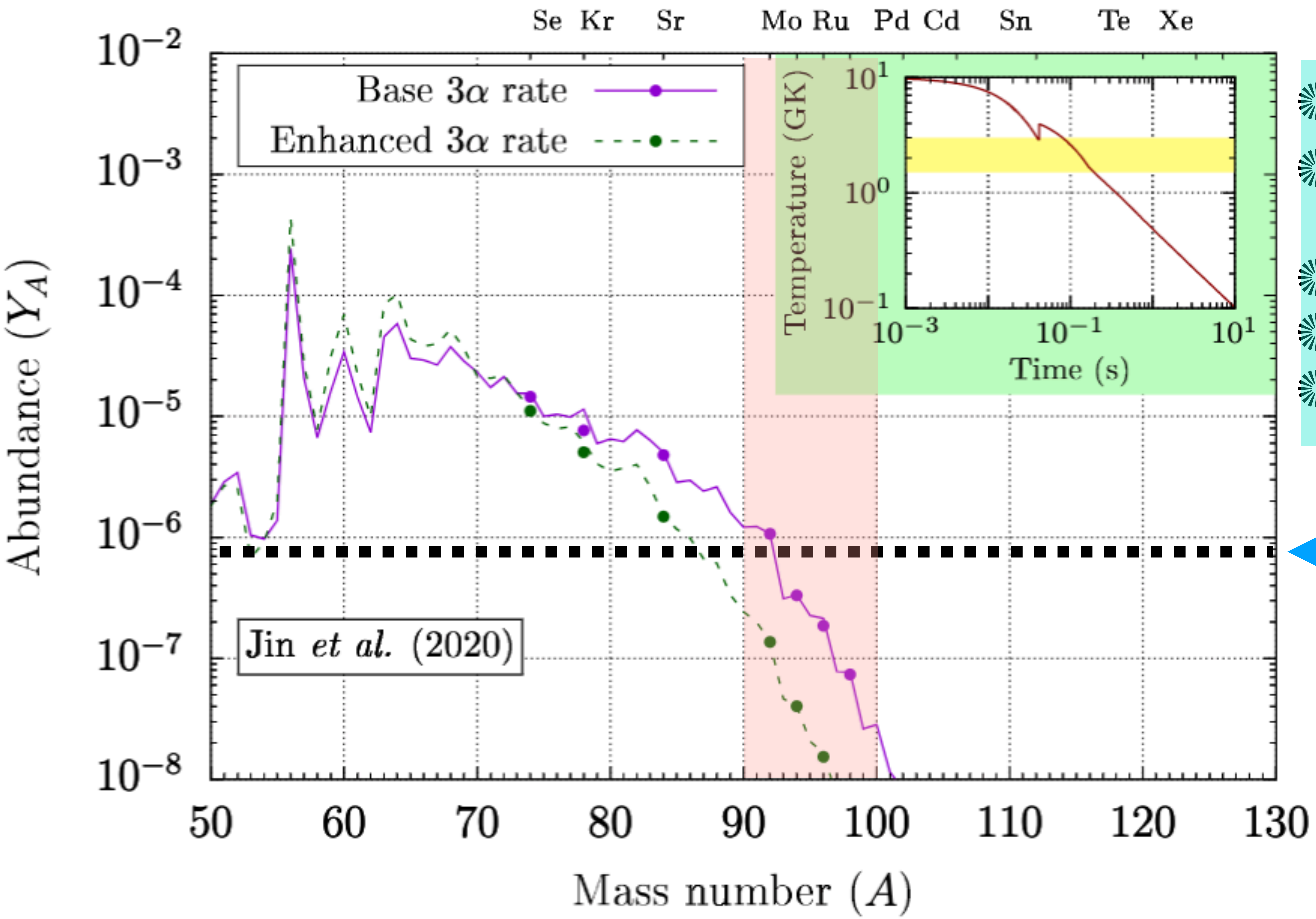
Analogy to rocket engine nozzles







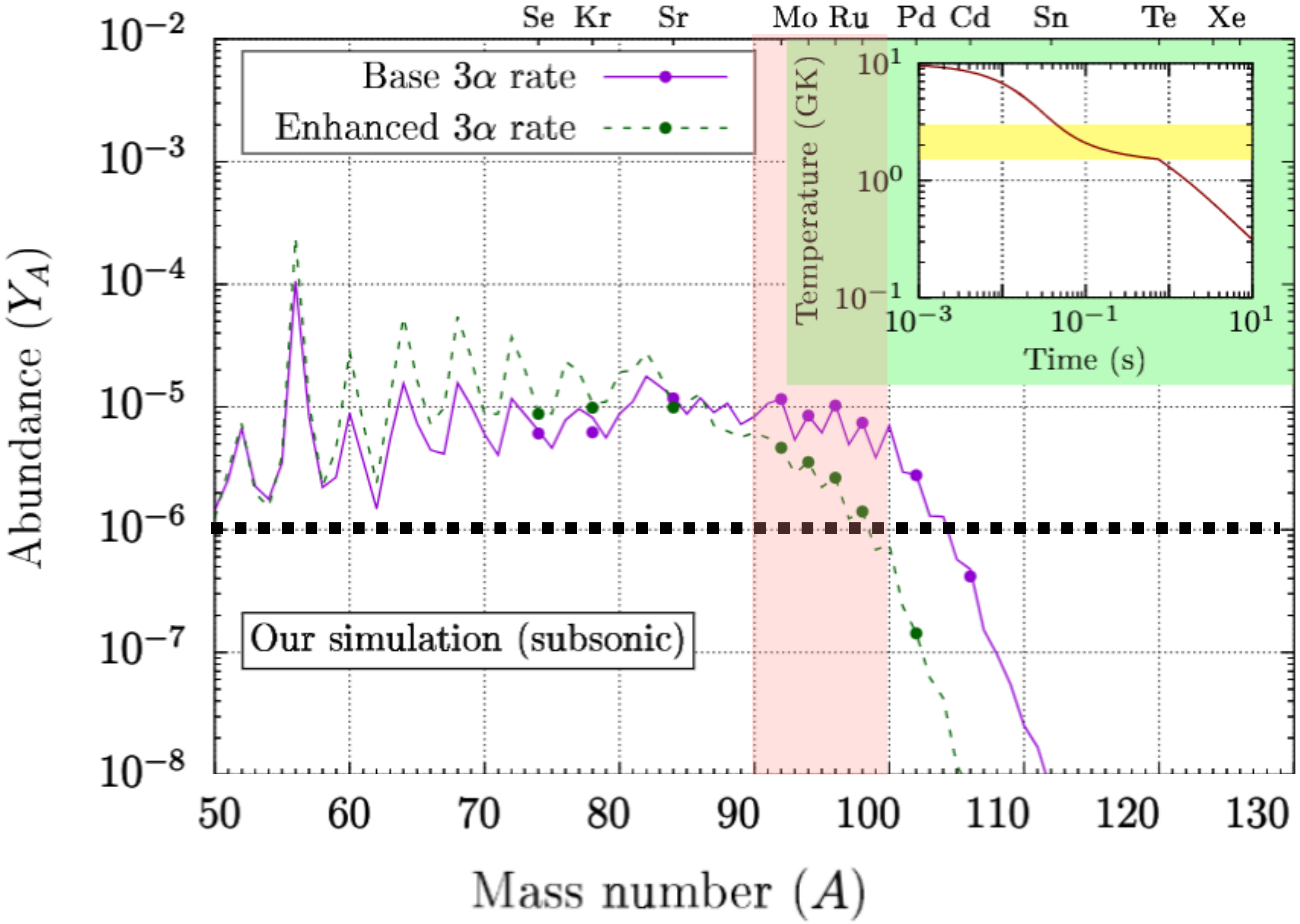
Supersonic outflows yield poor $\nu p-$process



- Enhanced triple-α rates kill νp.
- Standard treatments use only one supersonic/shocked outflow — shown in inset.
- Outflows are treated parametrically.
- Subsonic outflows are not considered.
- $\nu p-$ process is in crisis!

Abundance needed to explain Solar origin

But.. we have been studying different types of possible outflows. what yields do subsonic outflows have?

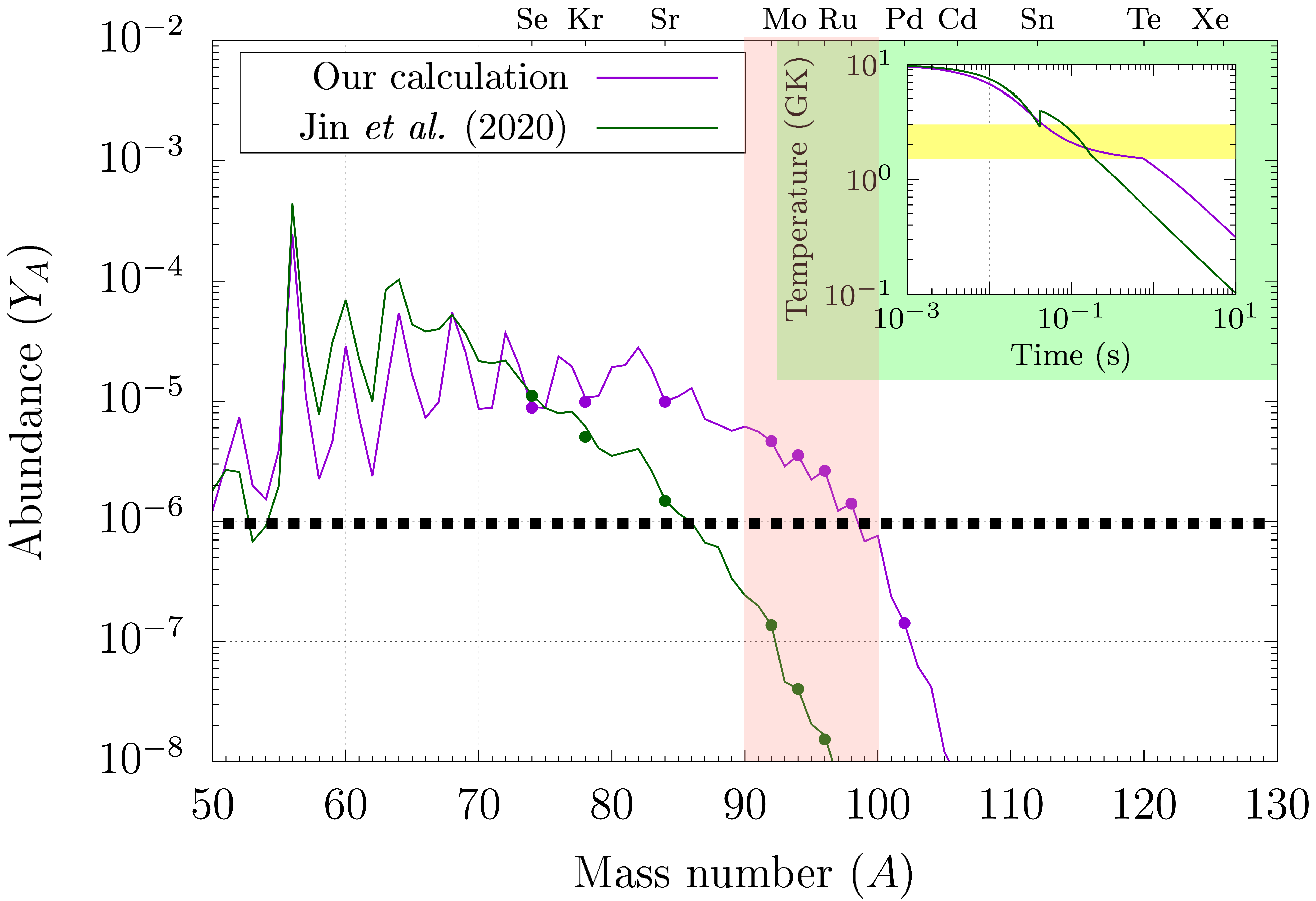


Our results

- Subsonic outflows greatly help !
- Yields can be large enough to explain solar abundances of Mo and Ru.
- Isotopic ratios can also be roughly reproduced.
- We checked for a range of progenitors.
- Yields vary with PNS mass and radius.
- Massive PNS of ~1.6–1.8 $M_\odot$ favored.
- Not a fine-tuned scenario.
- $\nu p-$ process not in crisis!

Friedland A, PM, Patwardhan A, (to appear)

Subsonic outflows greatly enhance yields

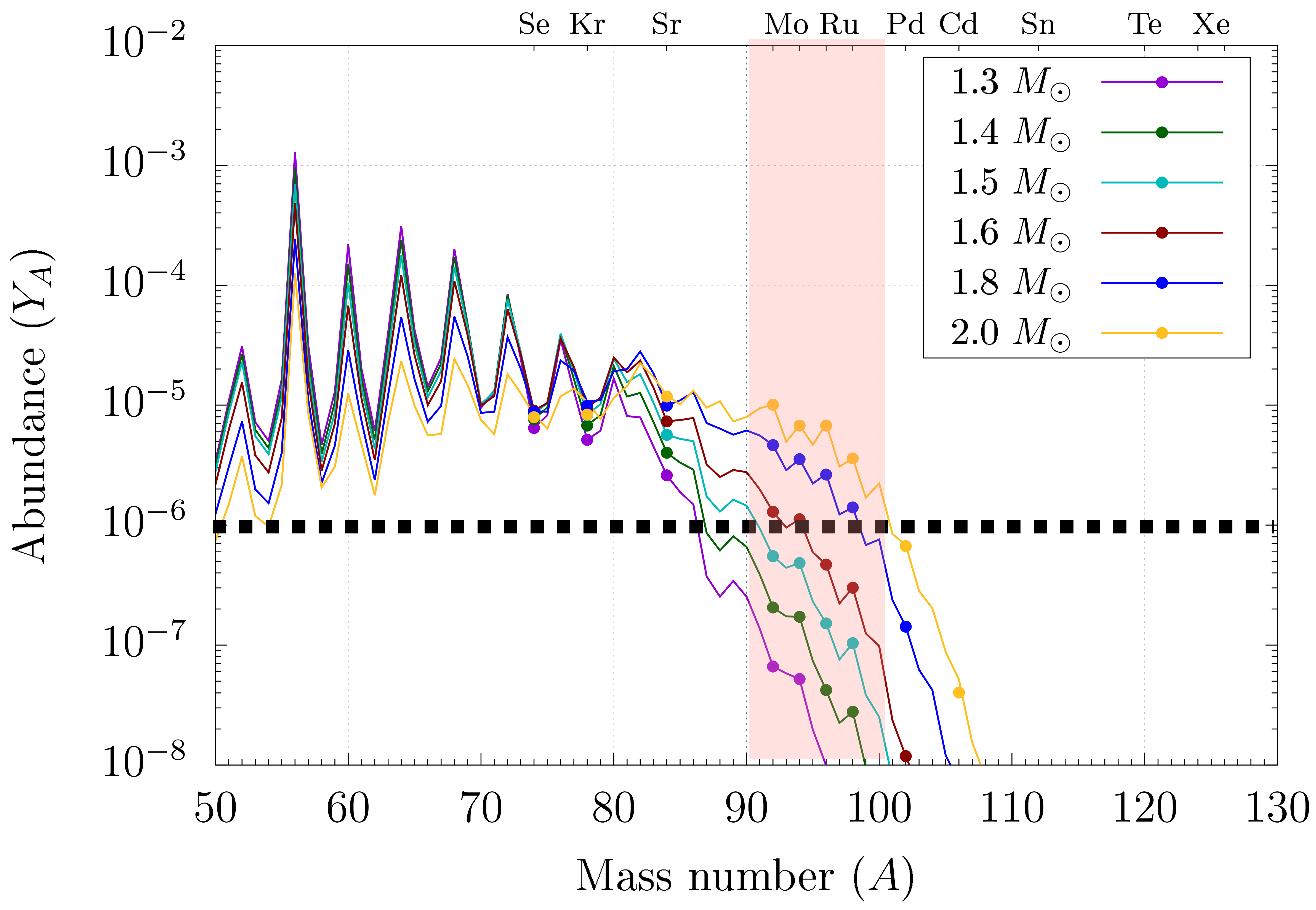


Subsonic outflows can enhance yields between A=90-100 by more than 2 orders of magnitude.

Friedland A, PM, Patwardhan A, (to appear)

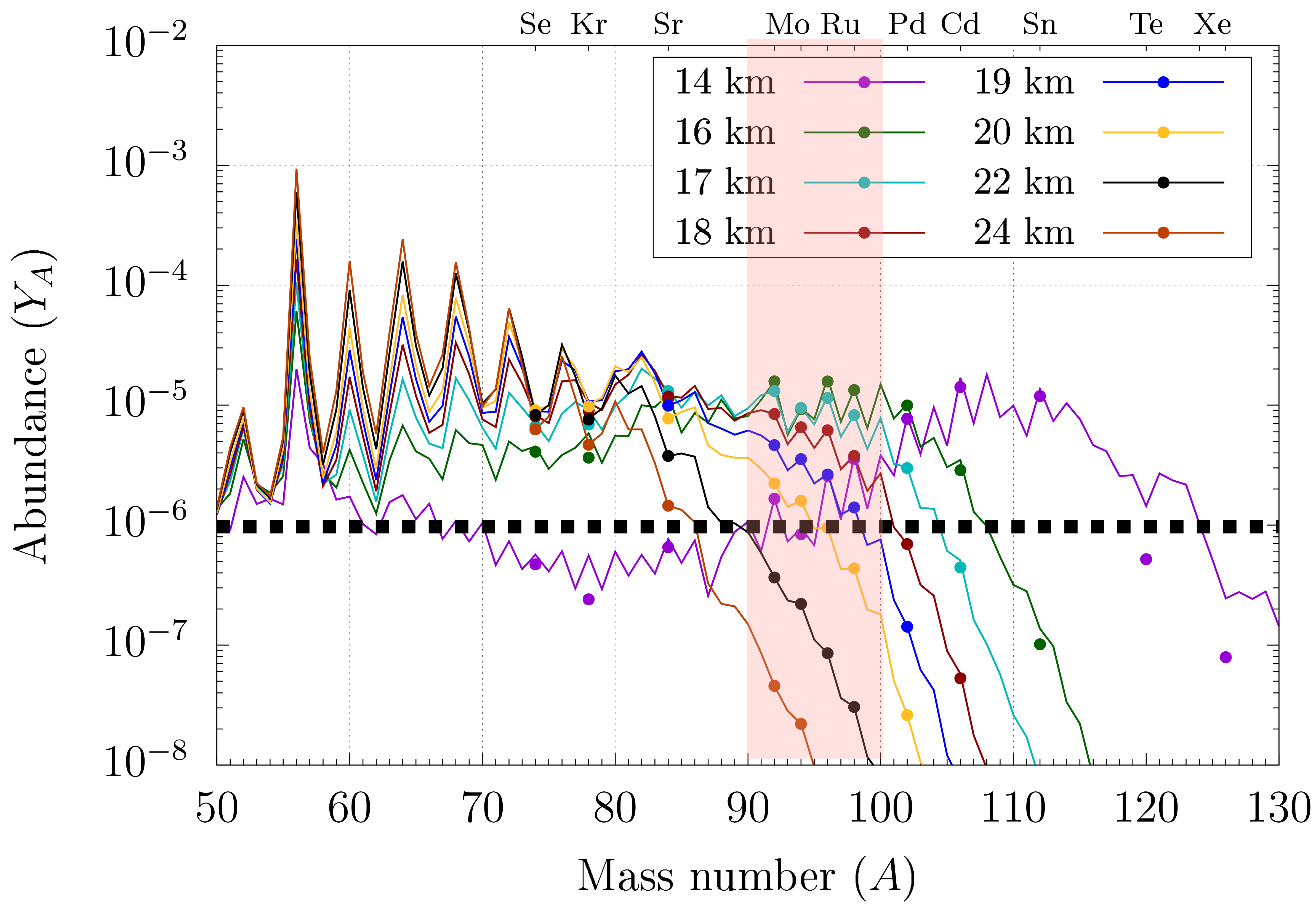
We find that yields vary with PNS properties like mass and radius

PNS Mass dependence



Heavier PNS gives higher yields

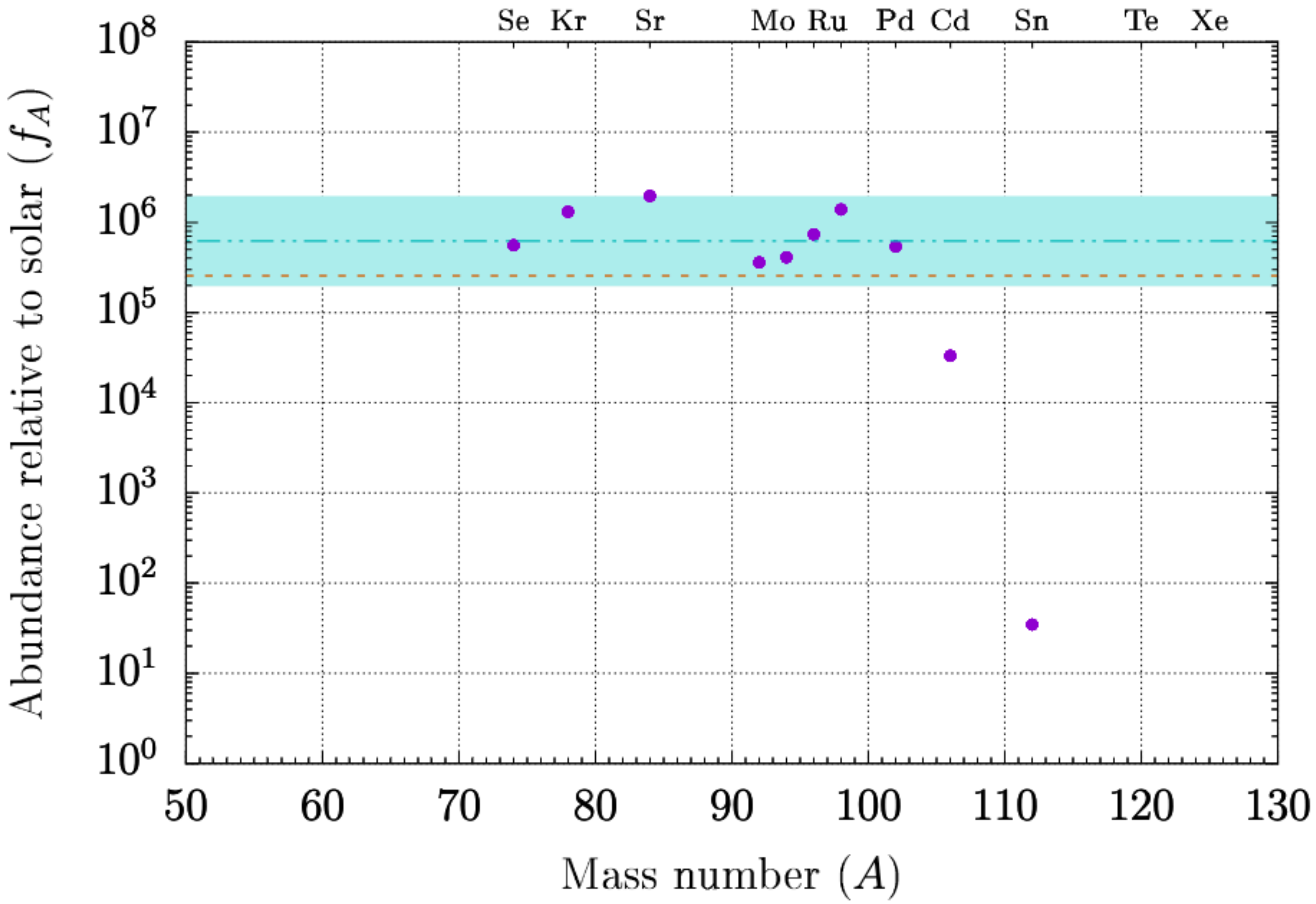
PNS radius dependence

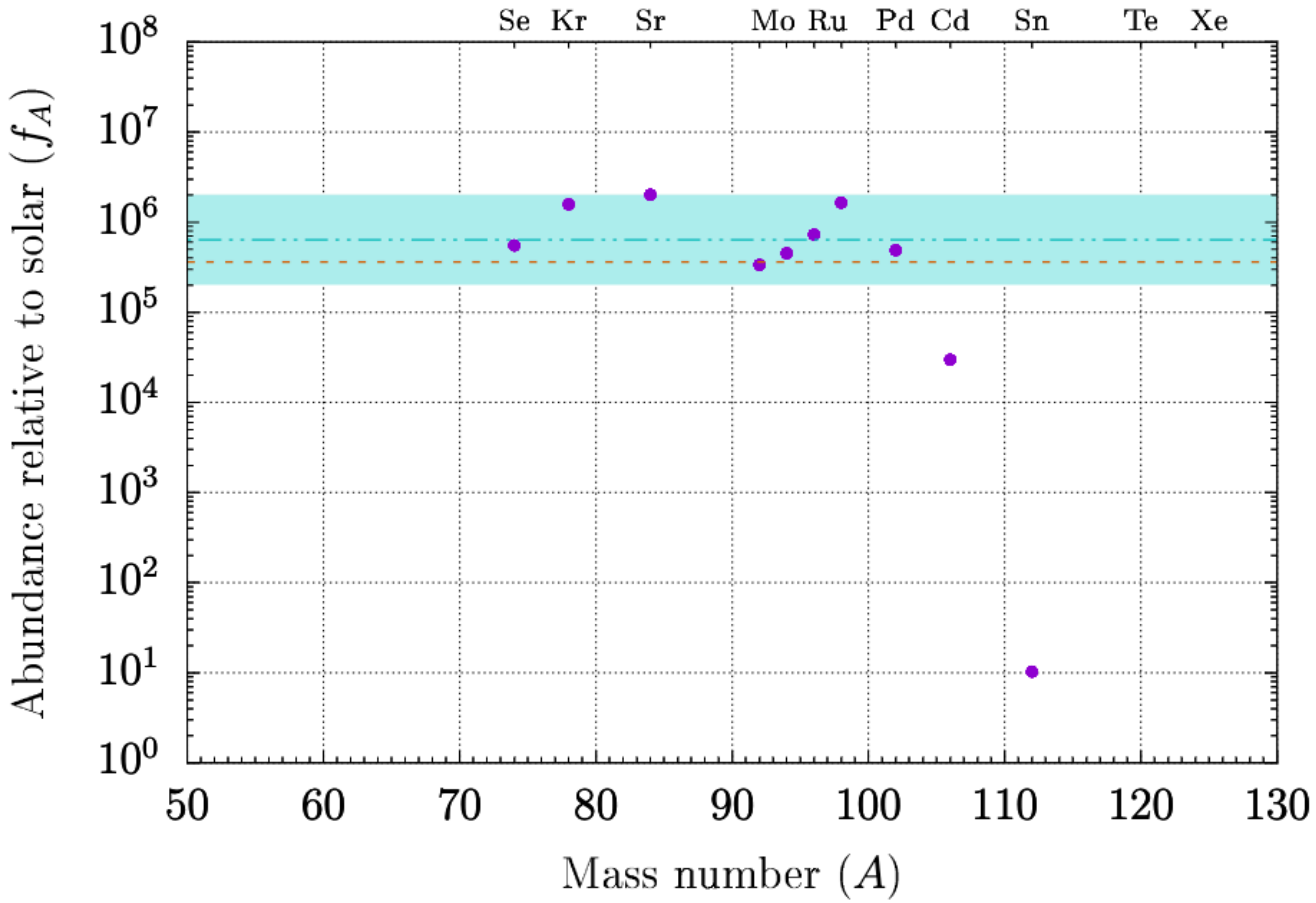


Compact PNS gives higher yields

Friedland, PM, Patwardhan, to appear

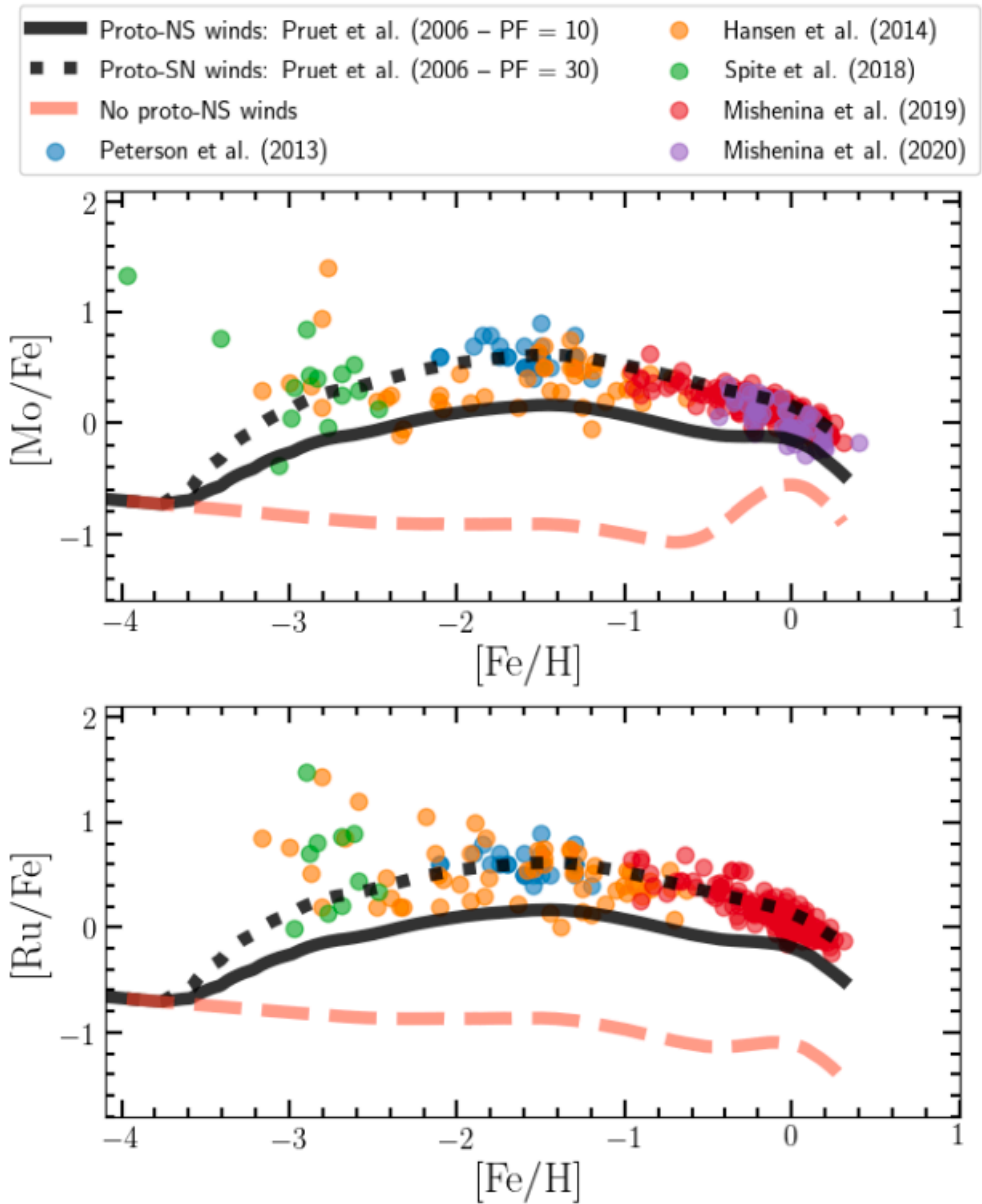
Production factors of different nuclides are also consistent





The blue band indicates the range of production factors allowed to be consistent with the observed abundances of isotopes

We find that yields vary with PNS properties like mass and radius



Observed abundances of [Mo/Fe] and [Ru/Fe] in metal poor stars. (F.Vincenzo et al. MNRAS 508, 2021).

There is a considerable scatter at low metallicities. We find variations in Mo and Ru yields for different supernovae.

Our picture consistent with the data here.

Summary

- Its remarkable that the solution with appropriate hydrodynamics works because apriori, it is unexpected.
- Carefully modelling hydrodynamics can highly impact $\nu p-$ process yields.
- Subsonic outflows help. Supersonic outflows give poor yields.
- Robust yields for a range of progenitor masses checked.
- Massive PNS $\sim 1.8\ M_\odot$ favoured for $\nu p-$ process.
- Results need to be followed by detailed numerical simulations.
- Galactic Chemical Evolution studies are needed for concrete distributions of such isotopes and the overall variability of yields.

Thank You!