NP3M

NP3M seminar

Successful νp-process in a core-collapse supernova

Alexander Friedland

SLAC NATIONAL ACCELERATOR LABORATORY

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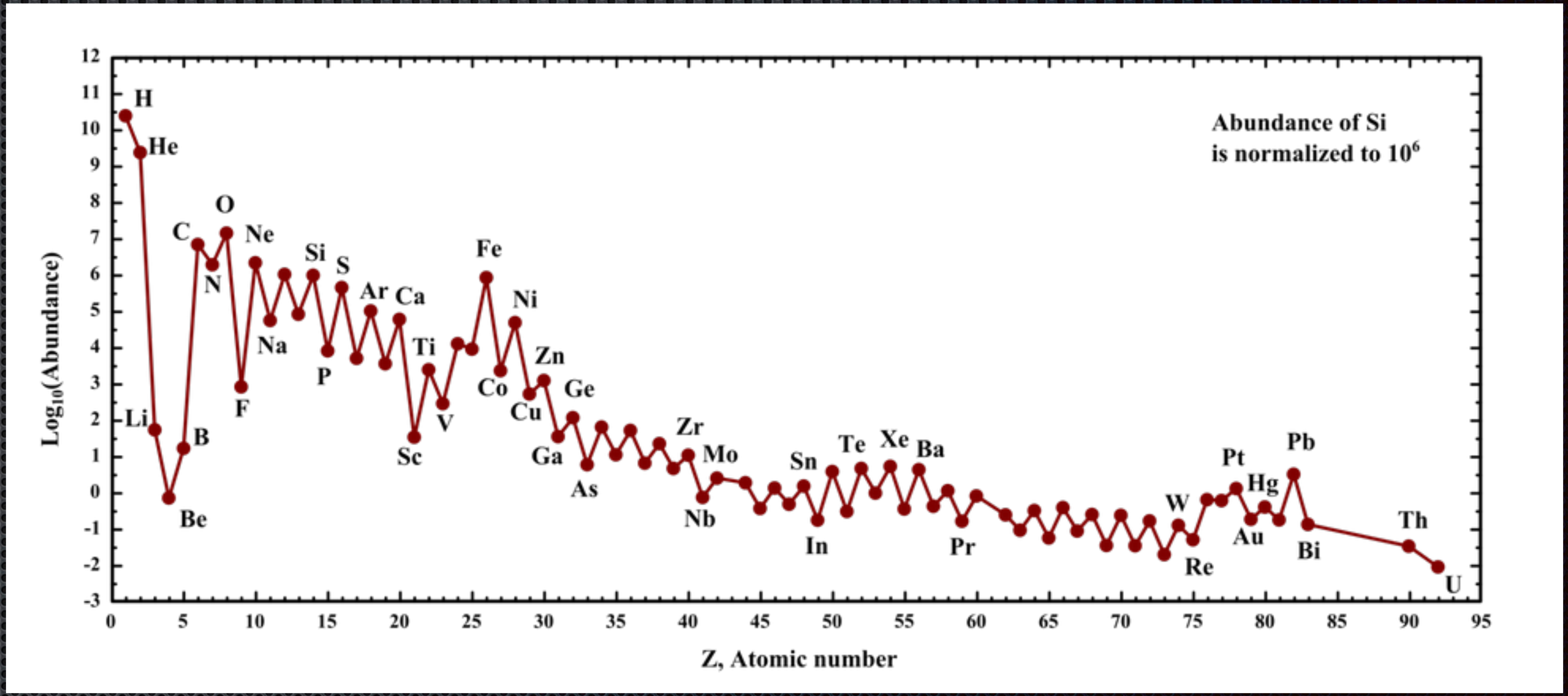
Meet the team

Amol Patwardhan
SLAC Postdoc -> U. Minnesota

Payel Mukhopadhyay
Stanford grad student -> NTN Fellow, Berkeley

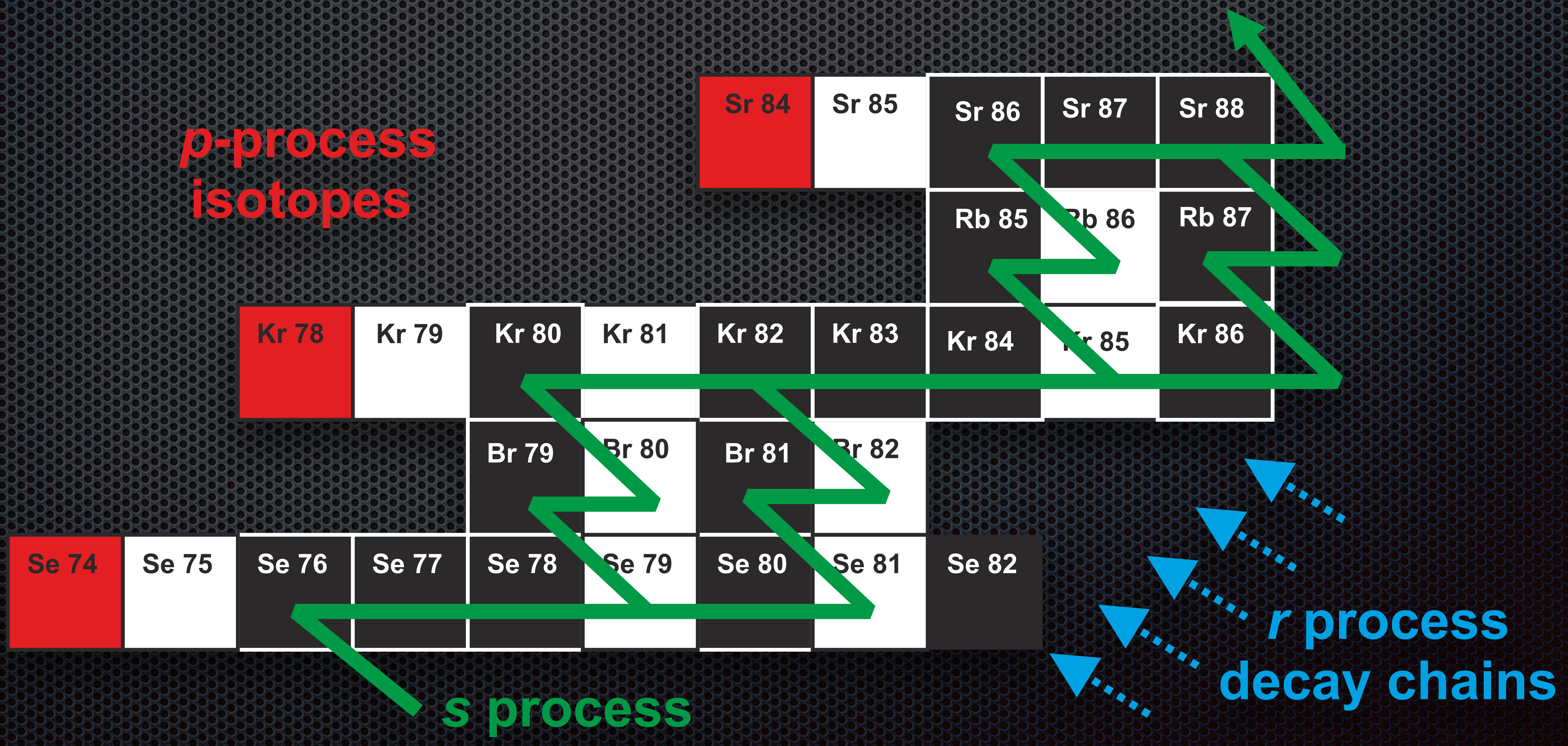
Heavy elements

- Relative abundances of the iron group elements can be well predicted by statistical equilibrium arguments (Hoyle, 1946)
- Abundances above the iron peak have to be produced in dynamical processes
- Main mechanism is neutron capture, not suppressed by the Coulomb barrier (Burbidge, Burbidge, Fowler and Hoyle 1957; Cameron 1957)
- Most of the elements heavier than iron are indeed synthesized in this way, by the s- and r- processes



P-rich nuclides: an enduring mystery

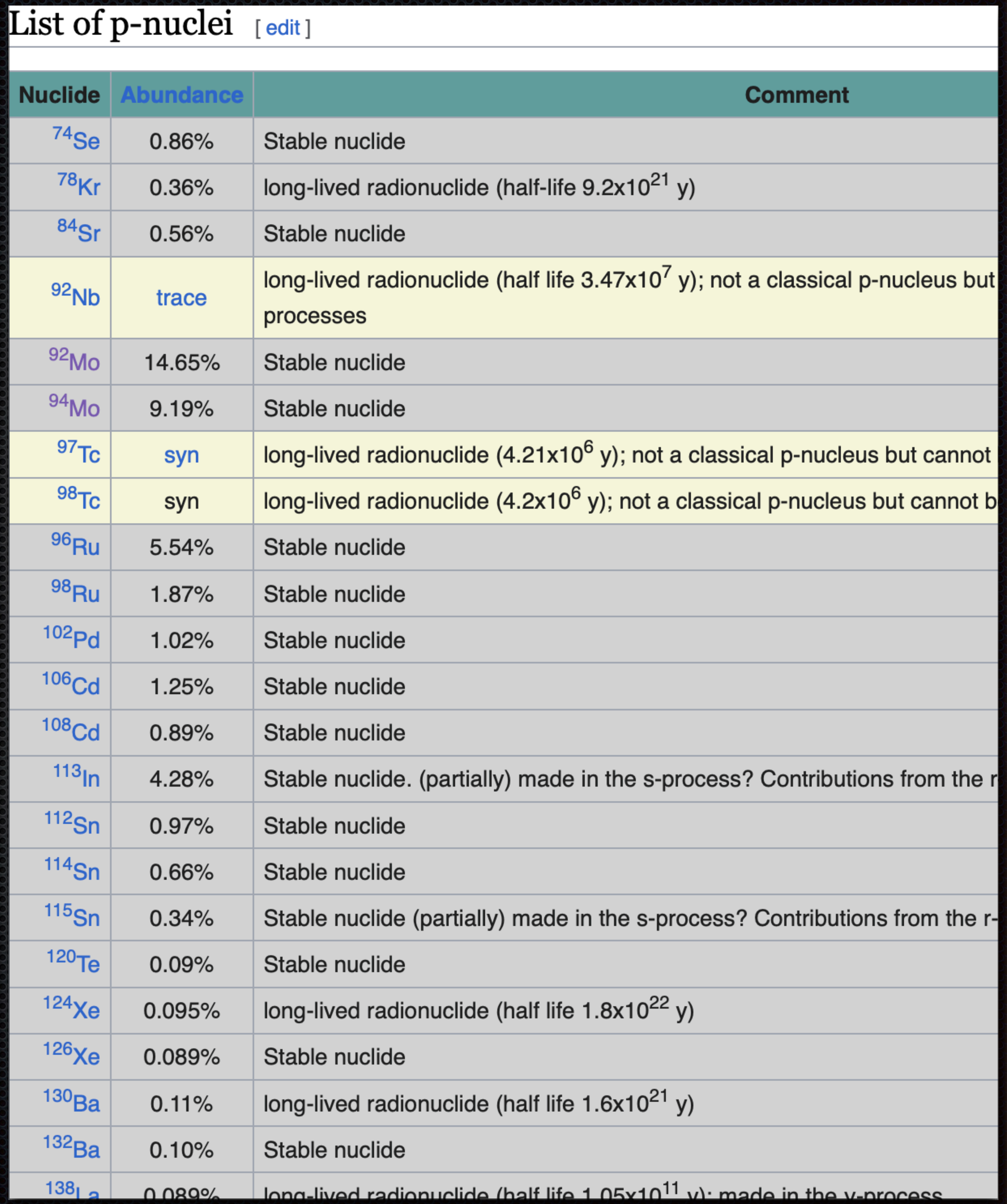
- A number of naturally occurring, proton-rich isotopes are bypassed by s- and r-processes, must be produced by different mechanisms [already noted in B2FH (1957); review, in, e.g. Rauscher et al (2013)]



P-nuclei abundances

Most p-nuclei are at a percent level or less of the corresponding s- and r-nuclei

But not all: about a quarter of molybdenum comes in the form of two p-isotopes, ^{92}Mo and ^{94}Mo

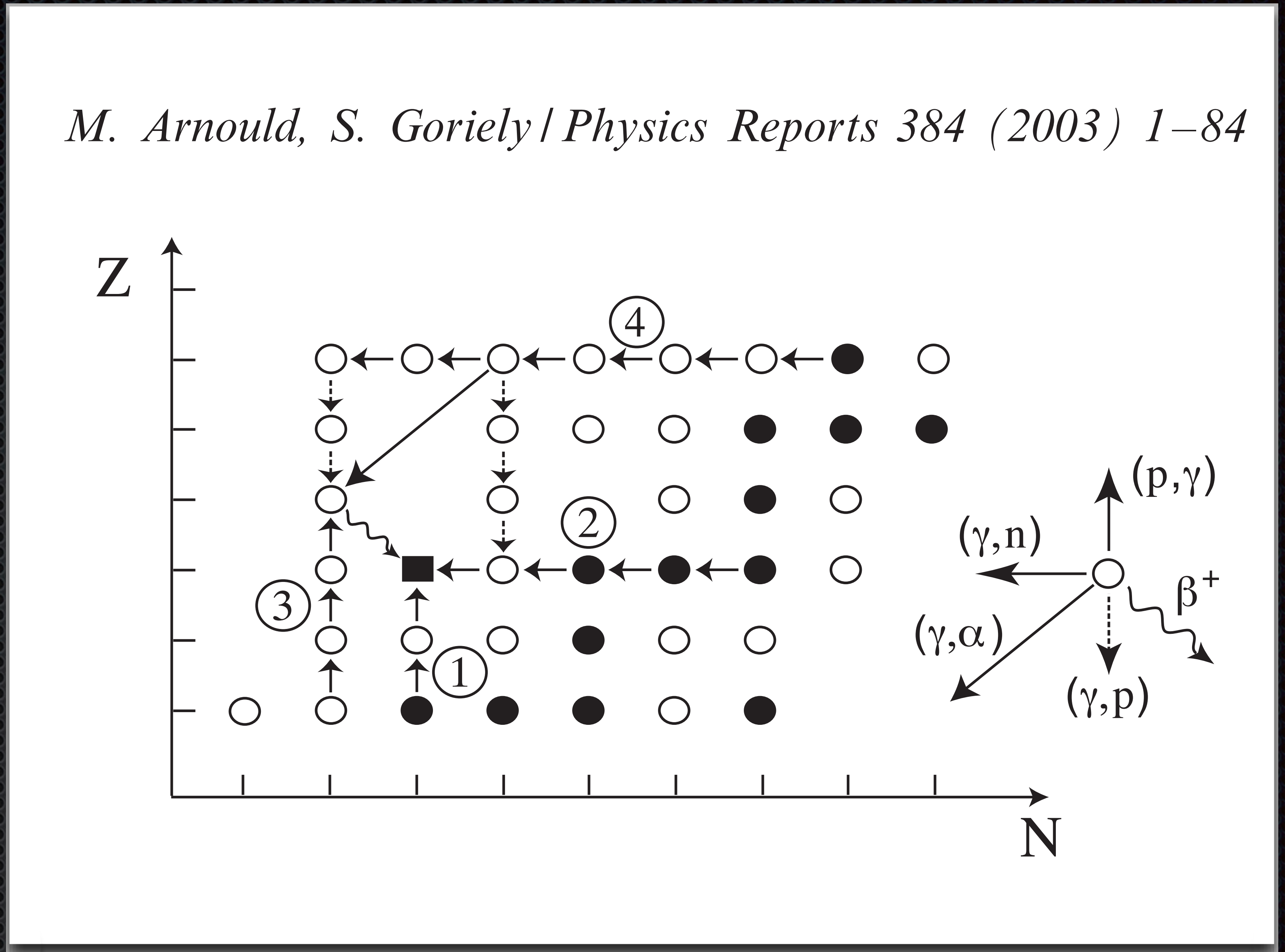


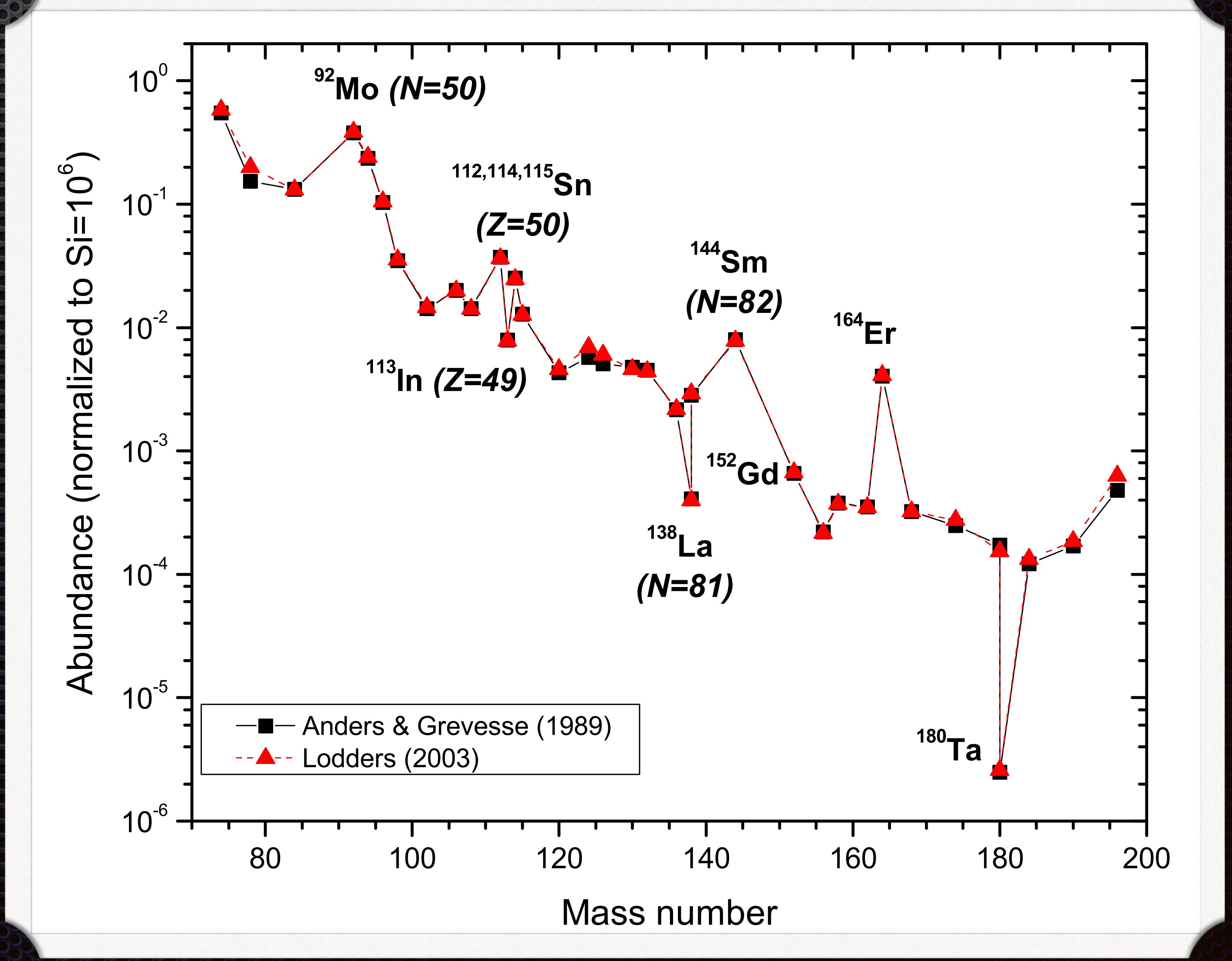
List of p-nuclei [edit]

Nuclide	Abundance	Comment
^{74}Se	0.86%	Stable nuclide
^{78}Kr	0.36%	long-lived radionuclide (half-life 9.2x10^{21} y)
^{84}Sr	0.56%	Stable nuclide
^{92}Nb	trace	long-lived radionuclide (half life 3.47x10^{7} y); not a classical p-nucleus but processes
^{92}Mo	14.65%	Stable nuclide
^{94}Mo	9.19%	Stable nuclide
^{97}Tc	syn	long-lived radionuclide (4.21x10^{6} y); not a classical p-nucleus but cannot
^{98}Tc	syn	long-lived radionuclide (4.2x10^{6} y); not a classical p-nucleus but cannot b
^{96}Ru	5.54%	Stable nuclide
^{98}Ru	1.87%	Stable nuclide
^{102}Pd	1.02%	Stable nuclide
^{106}Cd	1.25%	Stable nuclide
^{108}Cd	0.89%	Stable nuclide
^{113}In	4.28%	Stable nuclide. (partially) made in the s-process? Contributions from the r
^{112}Sn	0.97%	Stable nuclide
^{114}Sn	0.66%	Stable nuclide
^{115}Sn	0.34%	Stable nuclide (partially) made in the s-process? Contributions from the r-
^{120}Te	0.09%	Stable nuclide
^{124}Xe	0.095%	long-lived radionuclide (half life 1.8x10^{22} y)
^{126}Xe	0.089%	Stable nuclide
^{130}Ba	0.11%	long-lived radionuclide (half life 1.6x10^{21} y)
^{132}Ba	0.10%	Stable nuclide
^{138}La	0.089%	long-lived radionuclide (half life 1.05x10^{11} y); made in the ν-process

Gamma process

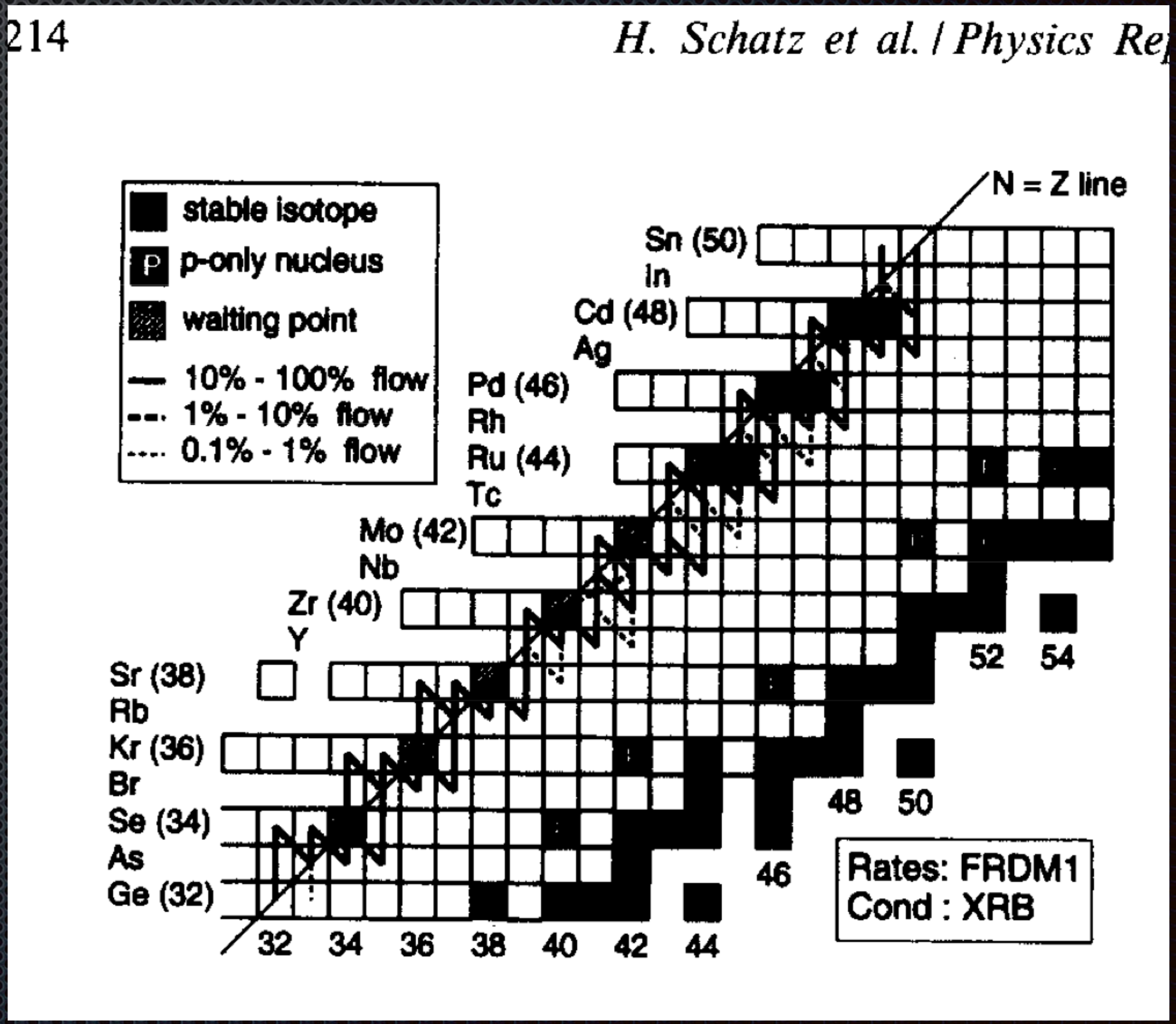
- Some of the p-nuclides can be made in secondary processing of s- and r- isotopes
- However, solar s-process abundances of heavier elements are not enough to explain ^{92,94}Mo and ^{96,98}Ru
- We are thus led to consider proton capture


M. Arnould, S. Goriely / Physics Reports 384 (2003) 1–84

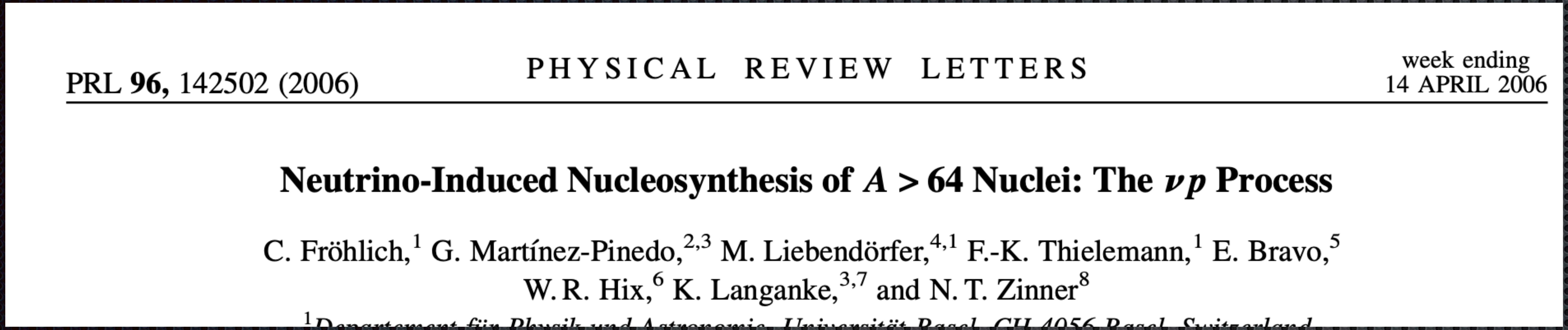


Proton capture conditions

- Synthesis by proton capture requires a specific temperature window
    - 1.5 GK < T < 3 GK
    - High enough to overcome the Coulomb barrier, but low enough so that gammas don’t dissociate the nuclei (QSE with the iron group)
- This suggests an environment in which the material expands and cools, passing through the desired temperature band
- But typical timescales are $\lesssim 1$ sec, while the chain based on proton captures and beta decays has a number of waiting points (slow beta decays)



$\nu p-$process: an elegant proposal

- 

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]

- νp-process is an attractive proposal [Frohlich et al (2005), Pruet et al (2005), Wanajo (2006)]. Site: in a neutrino-driven outflow from the surface of PNS
  - The outflow is proton-rich and expands in the presence of a large flux of neutrinos
  - Key observations: neutrinos will convert some of the protons into neutrons. These neutrons are immediately captured on proton-rich seeds, helping bypass the waiting points

Decade of careful studies identified a number of problems

- 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]
- Neutrons can drive the composition to the neutron-rich side [Arcones et al 2012]
- The absolute production rates seem to be too low to explain the Solar System abundances [Bliss:2018].
- Relative production rates of different p-isotopes seem to be incompatible with observations [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.

Field in crisis?

Article

Enhanced triple-α reaction reduces proton-rich nucleosynthesis in supernovae

https://doi.org/10.1038/s41586-020-2948-7

Shilun Jin[1,2,3], Luke F. Roberts[1,2]✉, Sam M. Austin[1,2] & Hendrik Schatz[1,2]

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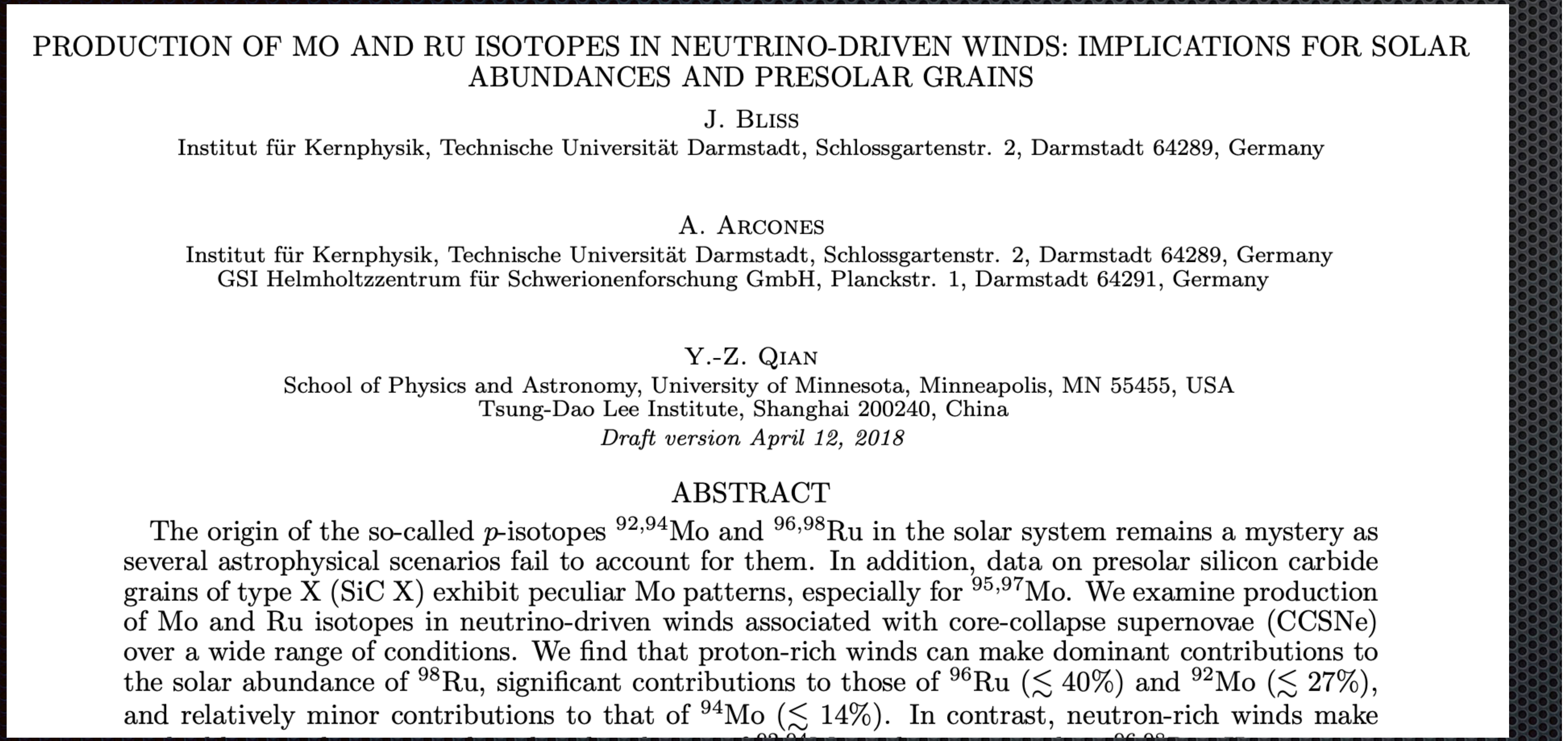

PRODUCTION OF MO AND RU ISOTOPES IN NEUTRINO-DRIVEN WINDS: IMPLICATIONS FOR SOLAR ABUNDANCES AND PRESOLAR GRAINS

J. Bliss
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr. 2, Darmstadt 64289, Germany

A. Arcones
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr. 2, Darmstadt 64289, Germany
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, Darmstadt 64291, Germany

Y.-Z. Qian
School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
Tsung-Dao Lee Institute, Shanghai 200240, China

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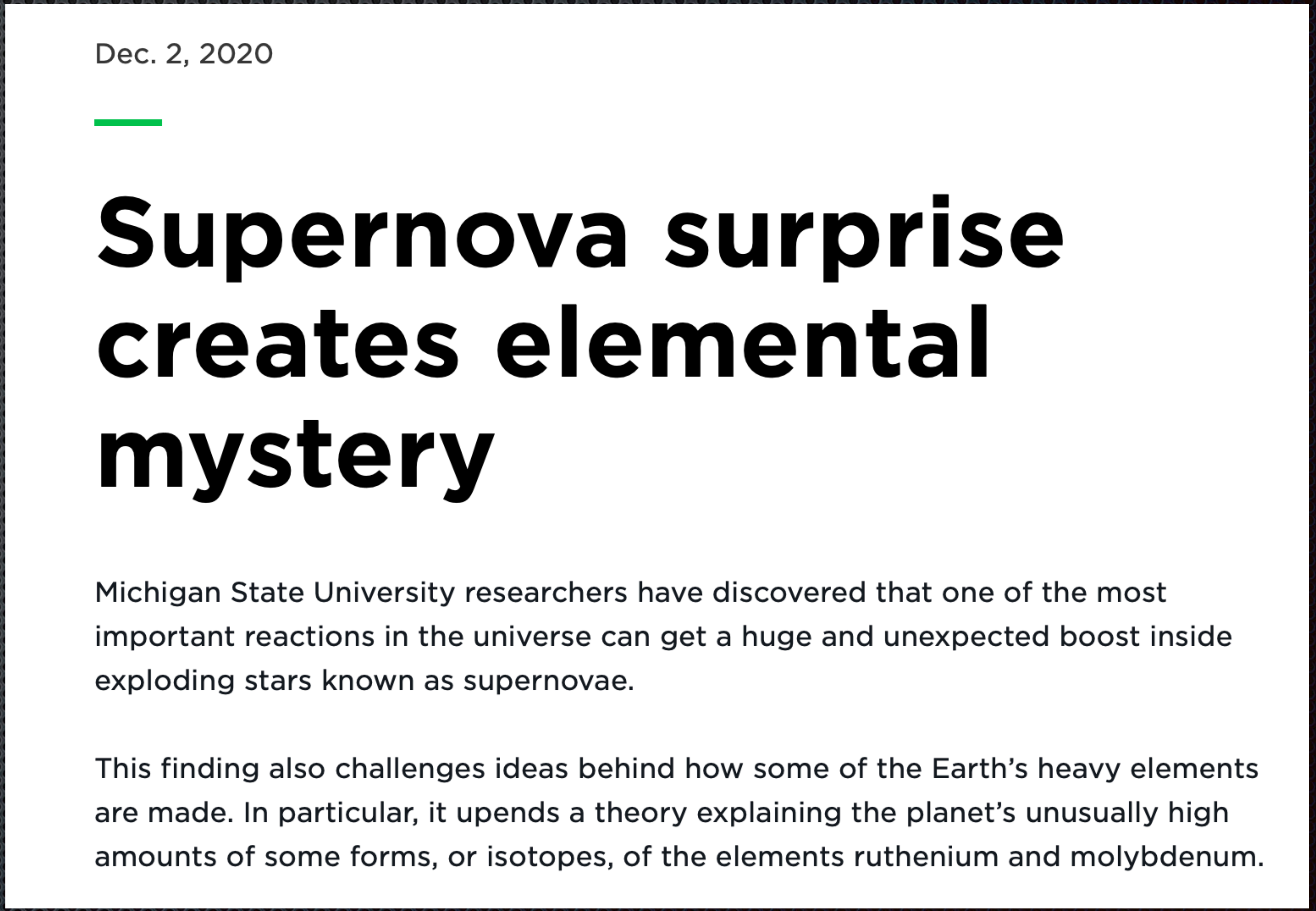
ABSTRACT

The origin of the so-called *p*-isotopes ^{92,94}Mo and ^{96,98}Ru in the solar system remains a mystery as several astrophysical scenarios fail to account for them. In addition, data on presolar silicon carbide grains of type X (SiC X) exhibit peculiar Mo patterns, especially for ^{95,97}Mo. We examine production of Mo and Ru isotopes in neutrino-driven winds associated with core-collapse supernovae (CCSNe) over a wide range of conditions. We find that proton-rich winds can make dominant contributions to the solar abundance of ^{98}Ru, significant contributions to those of ^{96}Ru ($\lesssim 40\%$) and ^{92}Mo ($\lesssim 27\%$), and relatively minor contributions to that of ^{94}Mo ($\lesssim 14\%$). In contrast, neutron-rich winds make



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.

^{92}Nb: a no-go theorem for νp-process?

- ^{92}Nb is shielded from beta-decays from the proton-rich side by stable ^{92}Mo
- Its presence in meteorites is an argument against rp- and nu p-processes [Dauphas et al 2003, Rauscher et al 2013]

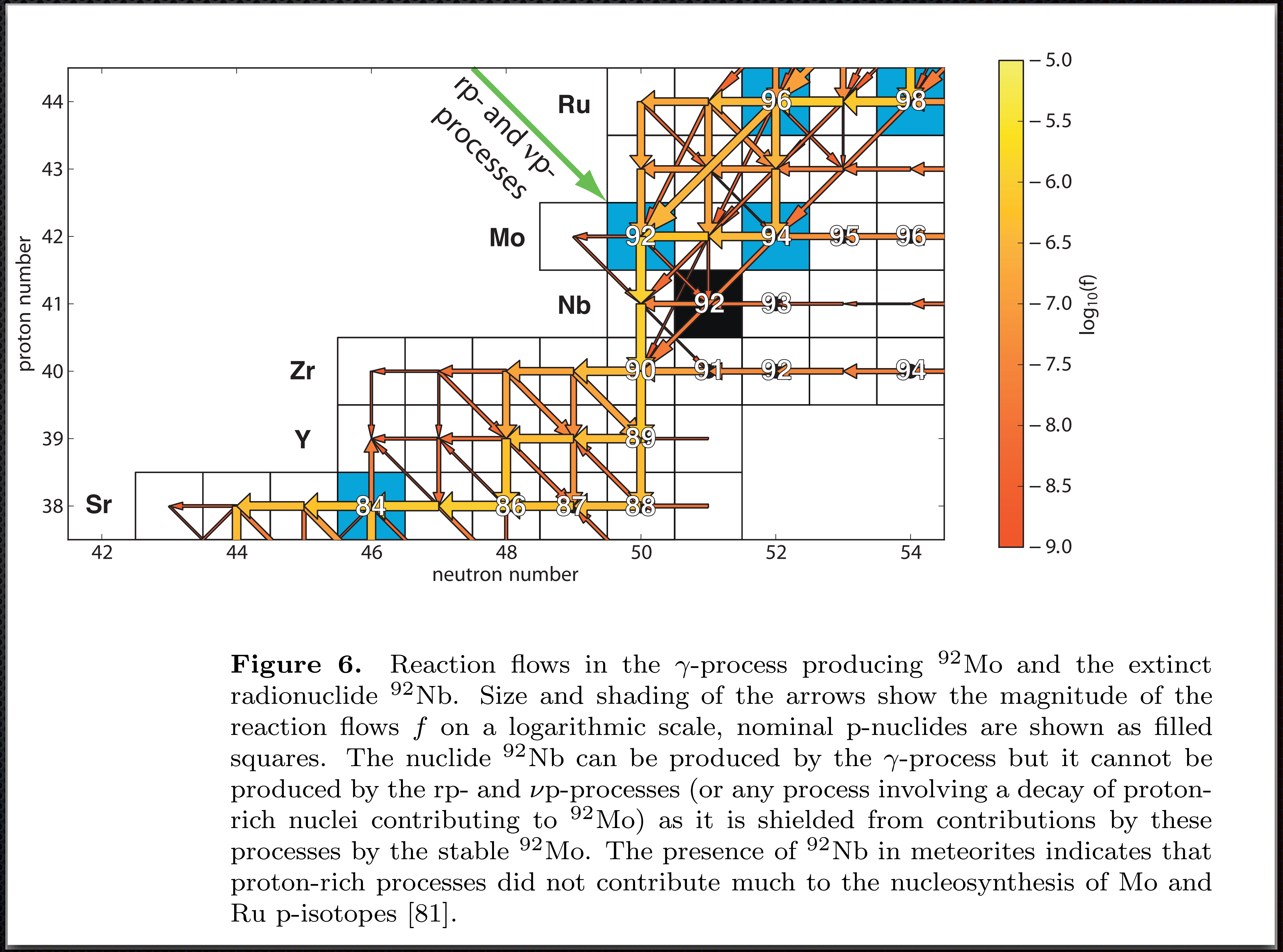
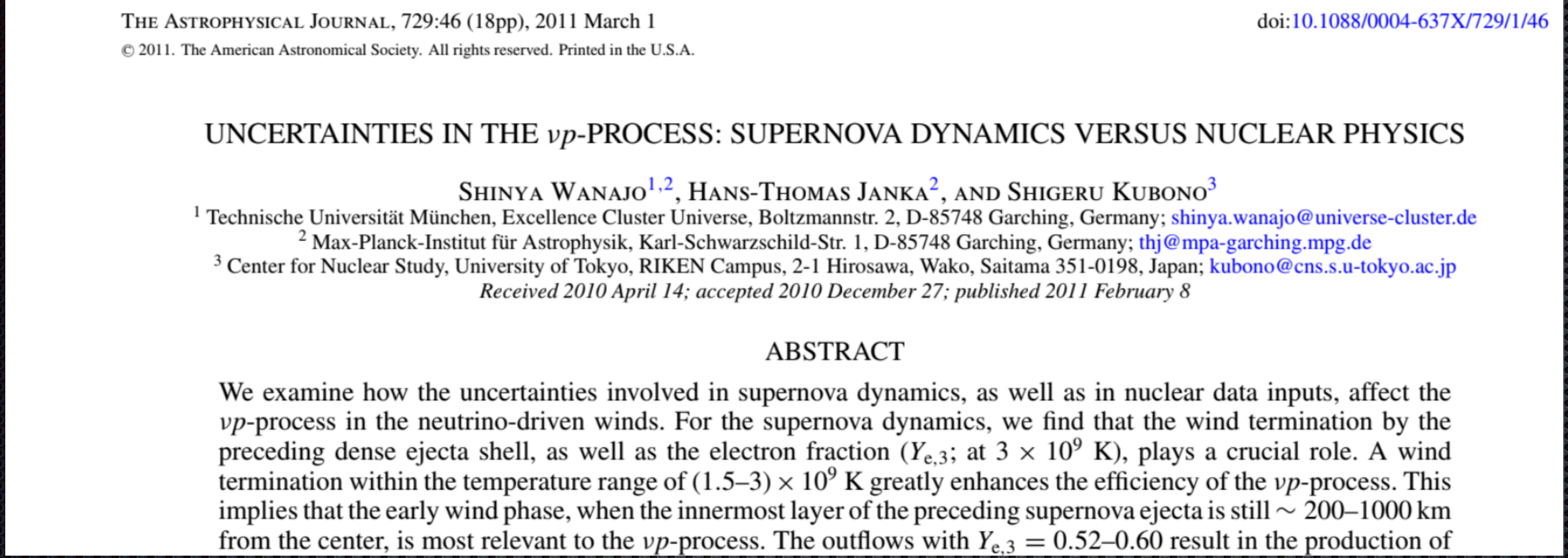


Figure 6. Reaction flows in the γ-process producing ^{92}Mo and the extinct radionuclide ^{92}Nb. Size and shading of the arrows show the magnitude of the reaction flows f on a logarithmic scale, nominal p-nuclides are shown as filled squares. The nuclide ^{92}Nb can be produced by the γ-process but it cannot be produced by the rp- and νp-processes (or any process involving a decay of proton-rich nuclei contributing to ^{92}Mo) as it is shielded from contributions by these processes by the stable ^{92}Mo. The presence of ^{92}Nb in meteorites indicates that proton-rich processes did not contribute much to the nucleosynthesis of Mo and Ru p-isotopes [81].

Outflow dynamics



THE ASTROPHYSICAL JOURNAL, 729:46 (18pp), 2011 March 1 doi:10.1088/0004-637X/729/1/46

UNCERTAINTIES IN THE νp-PROCESS: SUPERNOVA DYNAMICS VERSUS NUCLEAR PHYSICS

SHINYA WANAJO[1,2], HANS-THOMAS JANKA[2], AND SHIGERU KUBONO[3]
[1] Technische Universität München, Excellence Cluster Universe, Boltzmannstr. 2, D-85748 Garching, Germany; shinya.wanajo@universe-cluster.de
[2] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany; thj@mpa-garching.mpg.de
[3] Center for Nuclear Study, University of Tokyo, RIKEN Campus, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan; kubono@cns.s.u-tokyo.ac.jp

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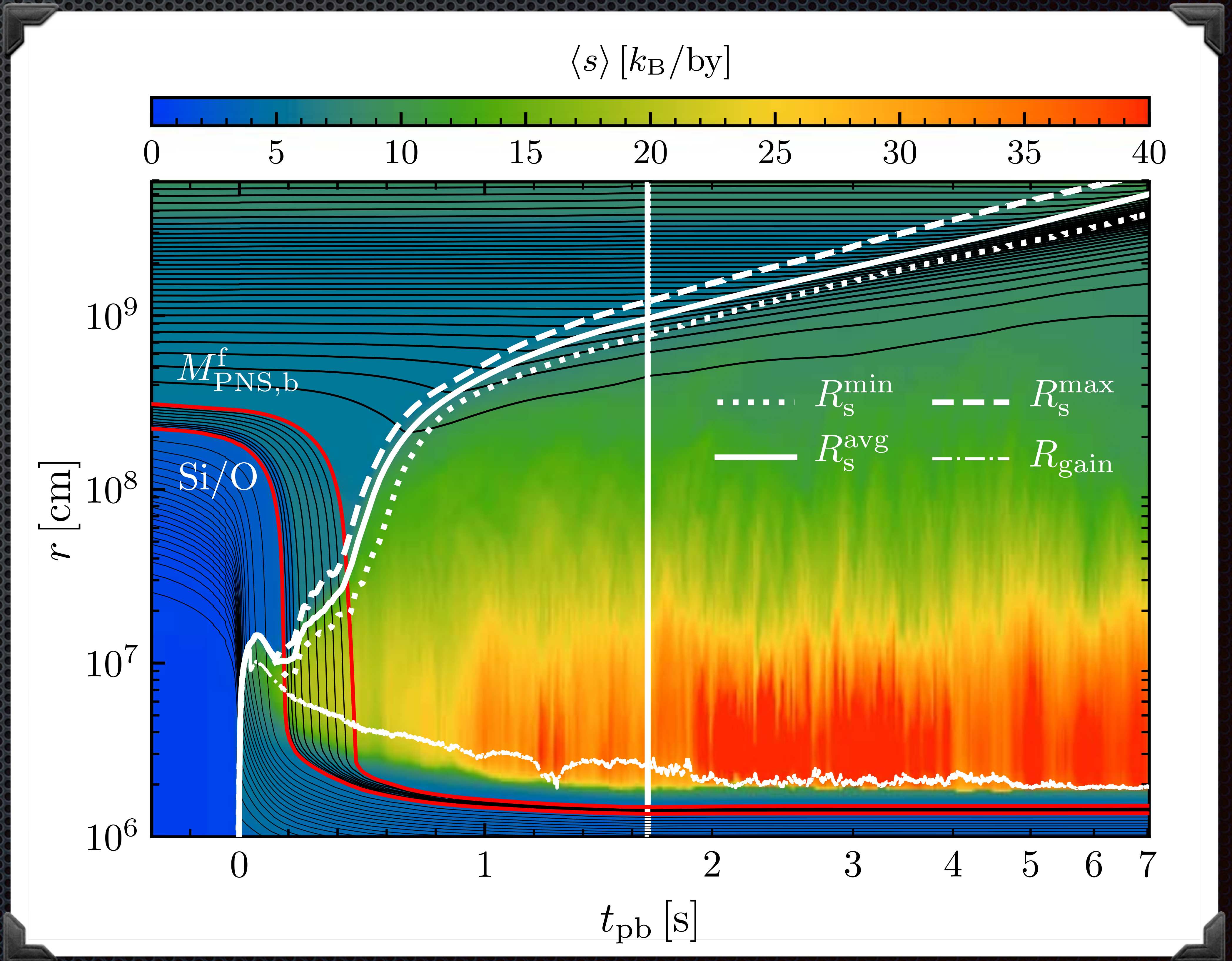
ABSTRACT

We examine how the uncertainties involved in supernova dynamics, as well as in nuclear data inputs, affect the νp-process in the neutrino-driven winds. For the supernova dynamics, we find that the wind termination by the preceding dense ejecta shell, as well as the electron fraction ($Y_{e,3}$; at 3×10^9 K), plays a crucial role. A wind termination within the temperature range of $(1.5–3) \times 10^9$ K greatly enhances the efficiency of the νp-process. This implies that the early wind phase, when the innermost layer of the preceding supernova ejecta is still ~ 200–1000 km from the center, is most relevant to the νp-process. The outflows with $Y_{e,3} = 0.52–0.60$ result in the production of

- The νp-process involves several stages, nontrivial matching required
- Hydrodynamics of the outflow is known to be important
- Existing studies start with a wind profile with a termination shock, vary parameters, such as entropy S and Ye.

Physics of the neutrino-driven outflow

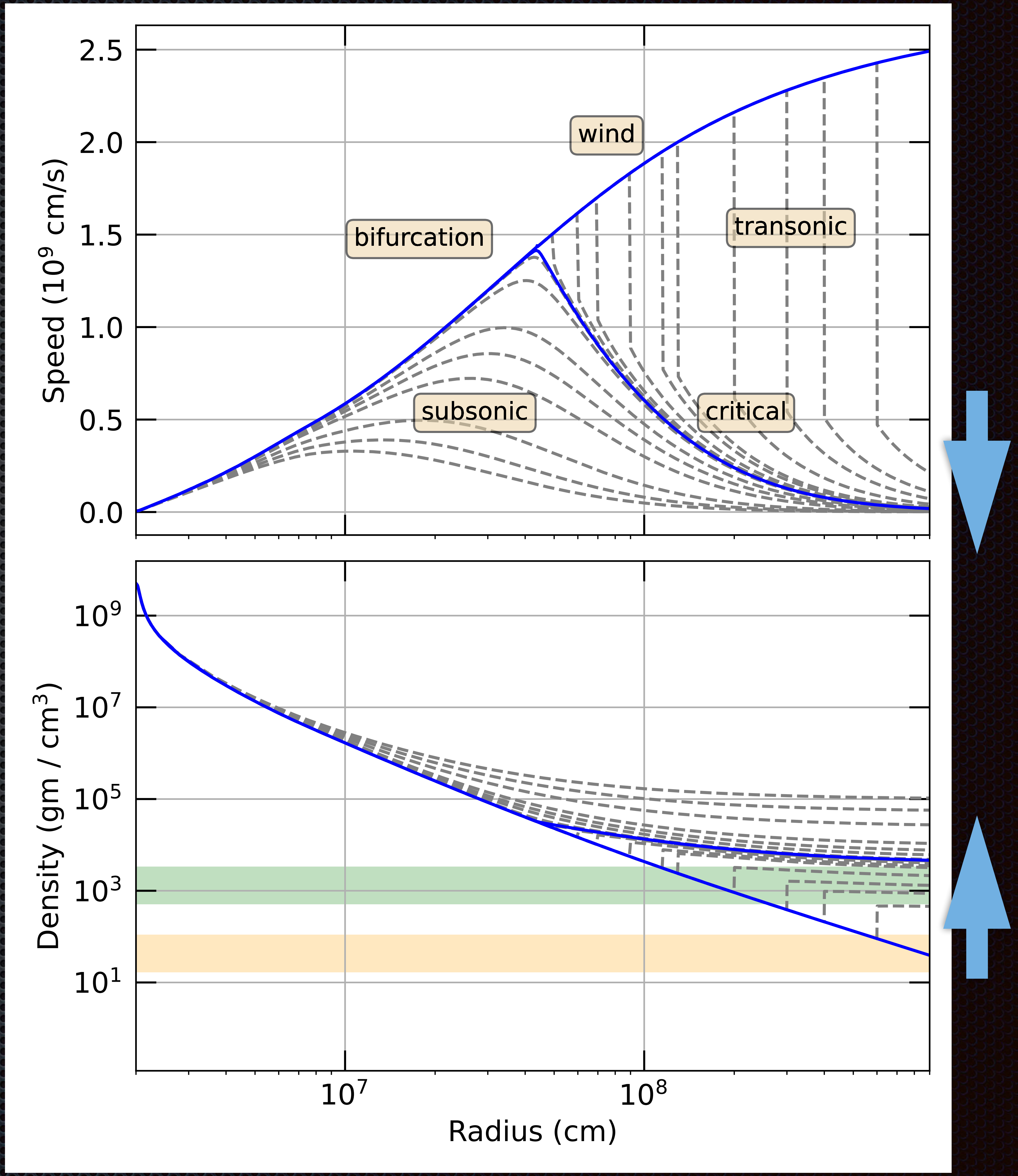
- Neutrino heating in the outer layers, $\sim G_F^2 T_\nu^6$, is not balanced by reemission, $\sim G_F^2 T^6$.
  - *Gain radius, essential for understanding the explosion mechanism*
- Energy deposited is removed by matter outflow
- To unbind a nucleon, $G_N m_N M_{PNS}/R_{PNS} \sim T^4/n_N$
- entropy per baryon, $S \sim T^3/n_N$
- $S \sim (m_N/T)(G_N M_{PNS}/R_{PNS}) \gtrsim 50$
  - Seconds after the explosion is launched



Bollig et al 2021 (3D)

Neutrino-driven outflows in a SN are special!

- We had previously studied the outflow profiles for modeling neutrino signals in DUNE (matter profile matters for oscillations!)
- Fixing the neutrino heating and the PNS gravity, one can look for solutions as a function of the surrounding pressure P
- At high P, a family of smooth subsonic curves.
- As P approaches a critical value, the velocity curve develop a kink
- As P is further reduced, the kink turns into a step: a termination shock develops.
- A remarkable fact about supernova conditions is that the outflows are *near-critical*, both subsonic and supersonic regimes are possible, depending on the progenitor mass. More plowed mass -> higher surrounding pressure P.



A.F., Mukhopadhyay, PLB (2022)

Nozzle flows

- A similar phenomenon occurs in an entirely different physical system: a flow of a compressible gas through a nozzle
    - Different geometry, no gravity
- By regulating ambient pressure in the lab, can go from subsonic to transonic flows
- Of course, in the lab, conditions can be fine-tuned to be near-critical

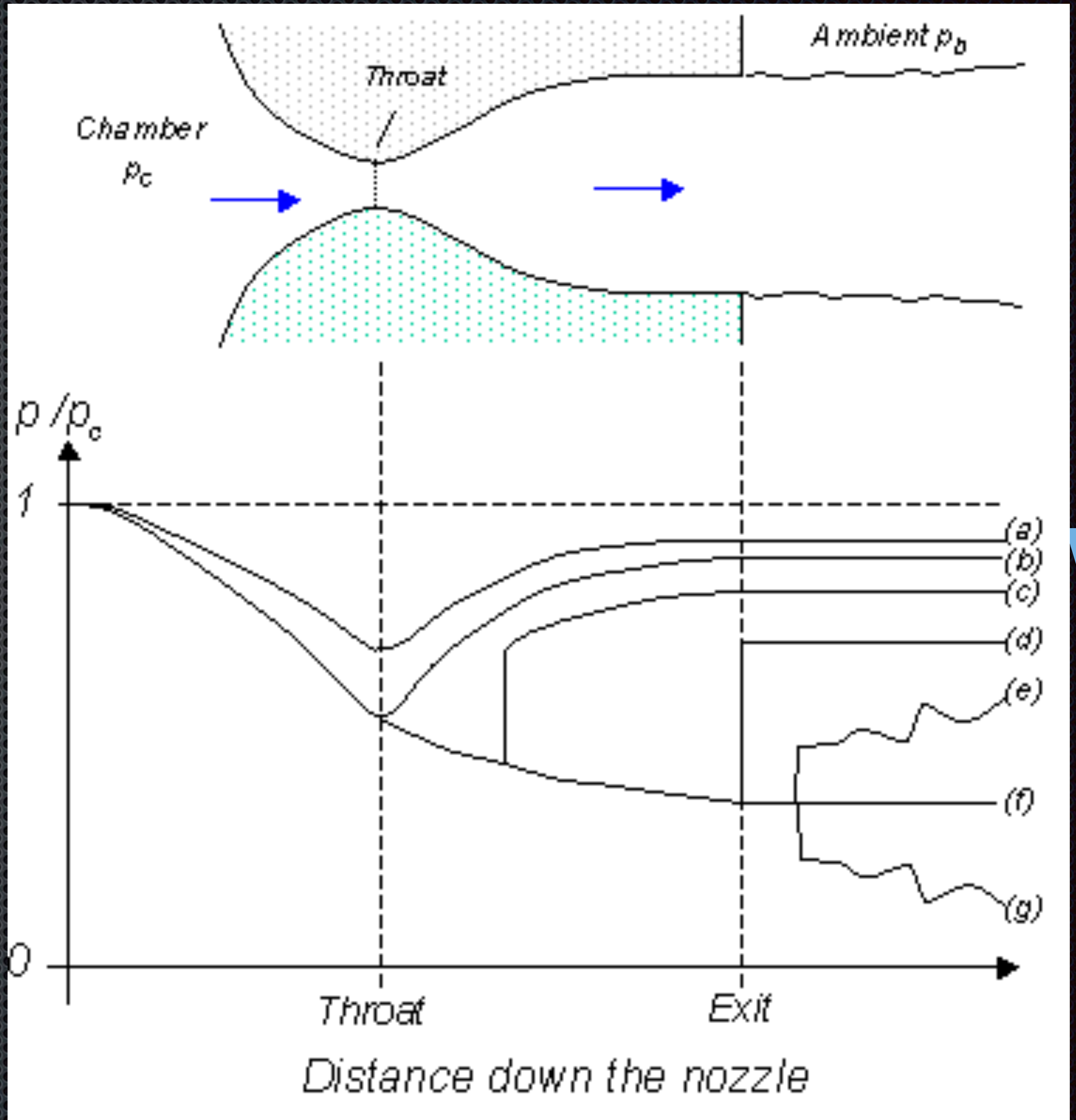
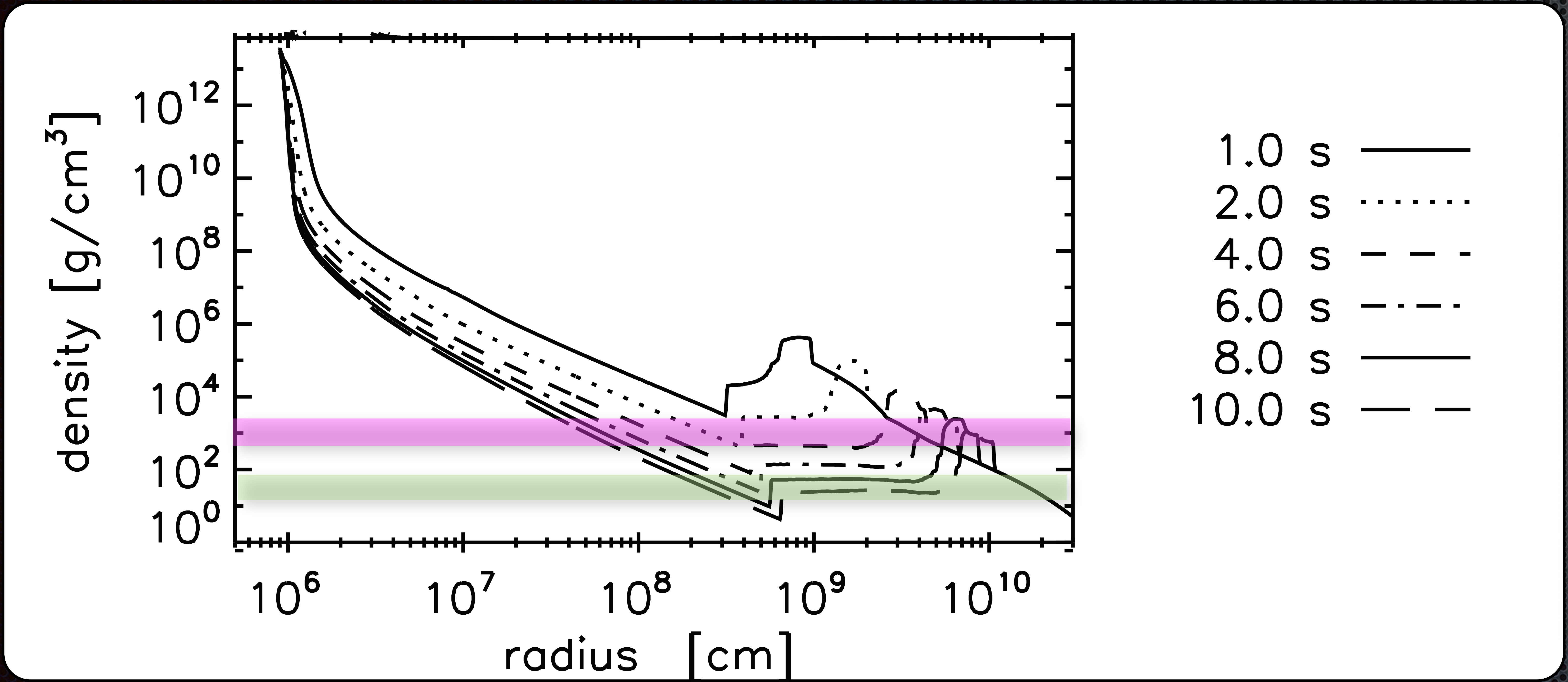
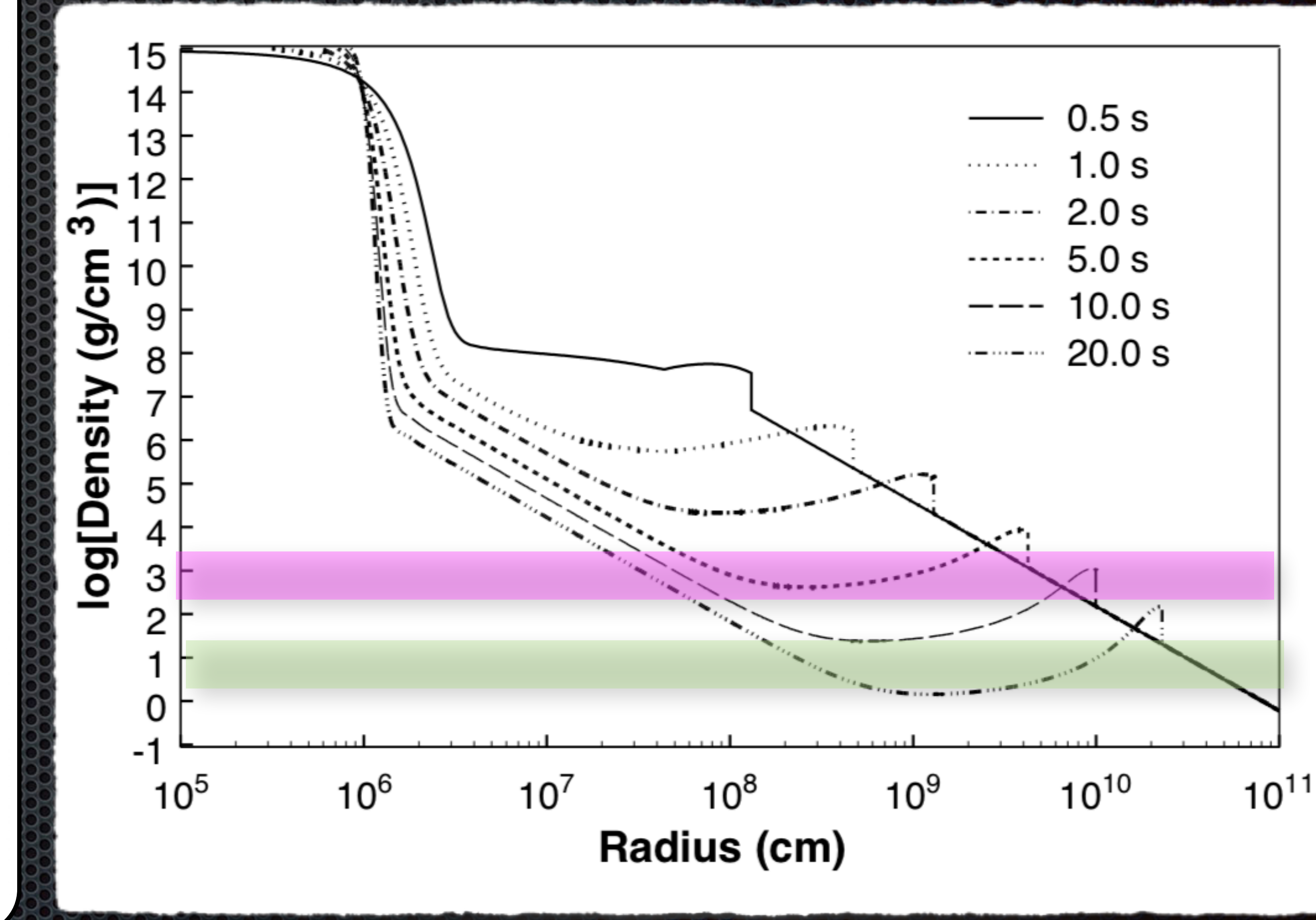


Figure 4 Pressure distribution along the nozzle. Labels refer to flow regimes in figure 3.

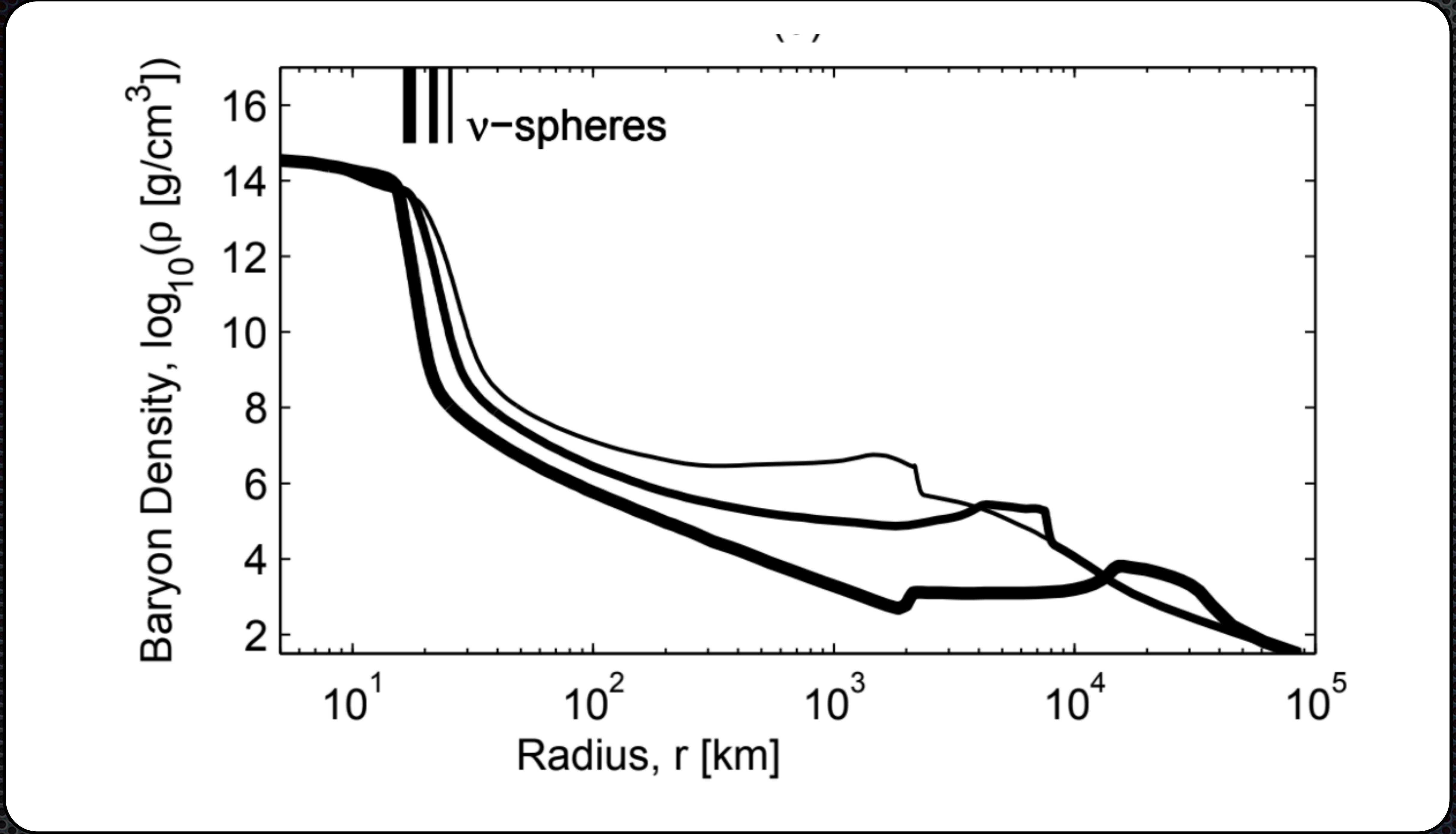
Densities features in the hot bubble





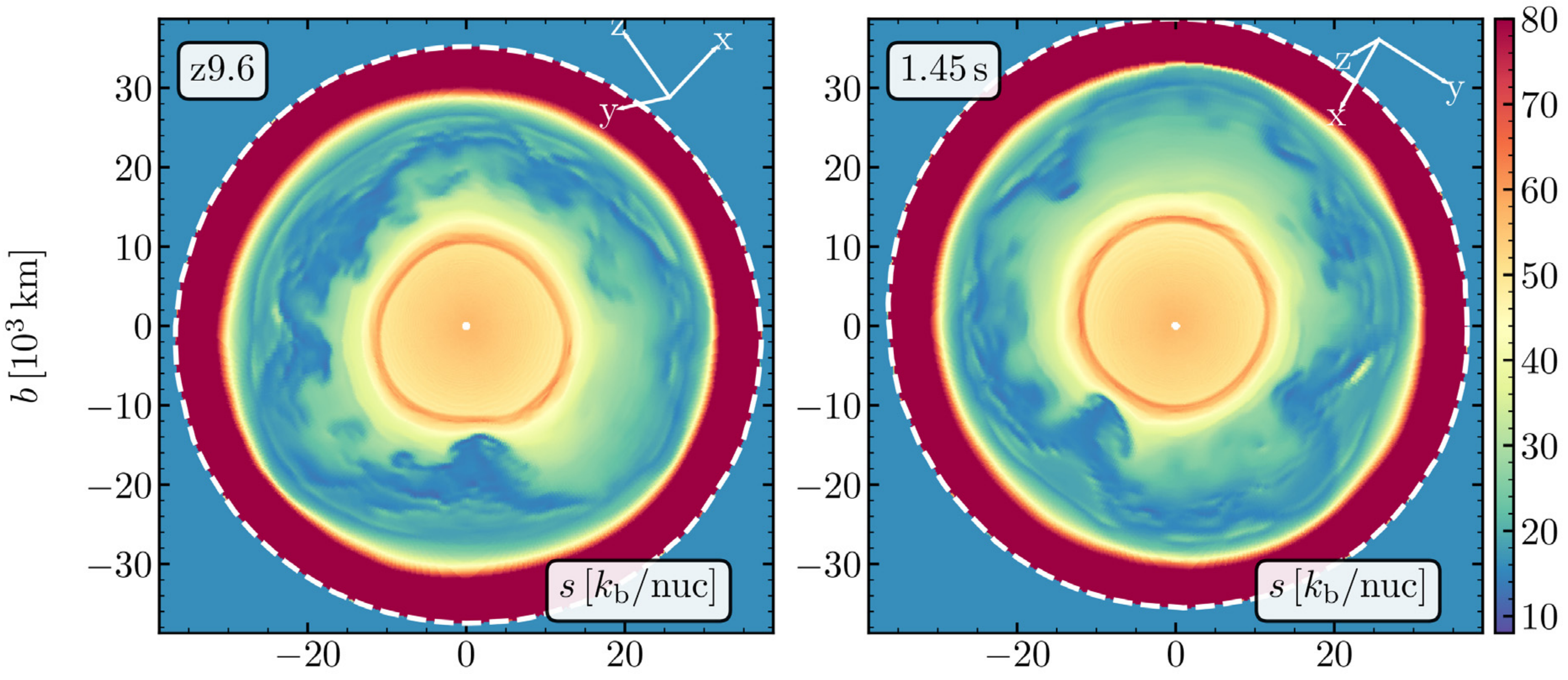
- The profiles of Wilson et al are pretty smooth in the hot bubble
- In contrast, in the simulation by Arcones et al, 2006, wind termination shocks

Near-criticality in numerical simulations



- $10.8 M_\odot$ progenitor from Fischer et al (2009)
- Subsonic outflow at 1 sec. Termination shock appears at 3 sec!

Wind termination shock in 3D



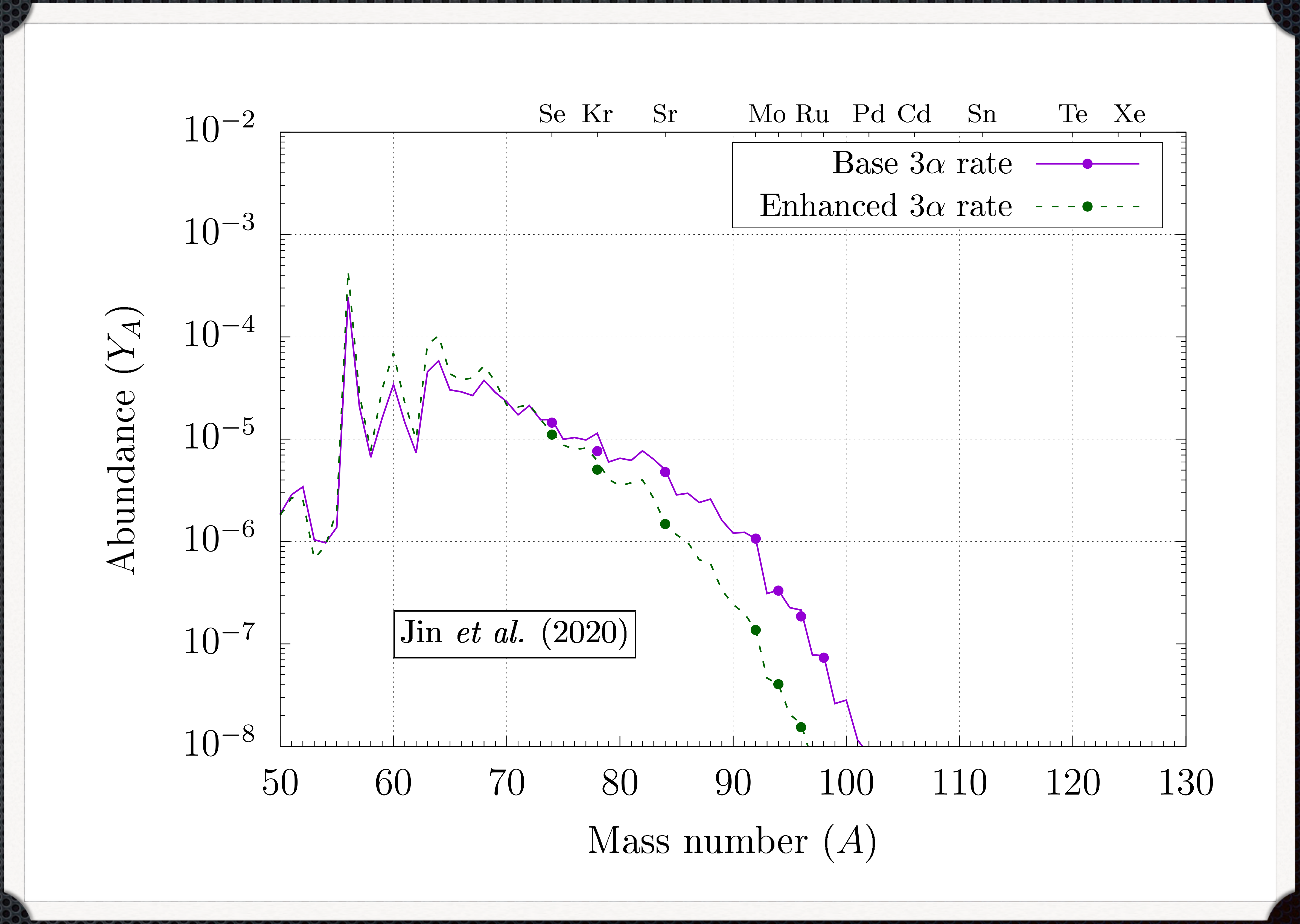
- 3D simulation from Stockinger et al (2020)

Need to explore all possible outflow regimes

- Strategy:
- Do not start with detailed multi-d simulations
  - First survey possible regimes to identify optimal conditions [see Bliss, Arcones, Qian (2018) for similar approach]
- Do not constrain the outflow type by an ansatz (remember near-criticality!)
- Do not vary parameters ad hoc
  - Vary physical properties of the system: PNS mass and radius, progenitor mass, neutrino spectra, etc. Solve for the outflow self-consistently.

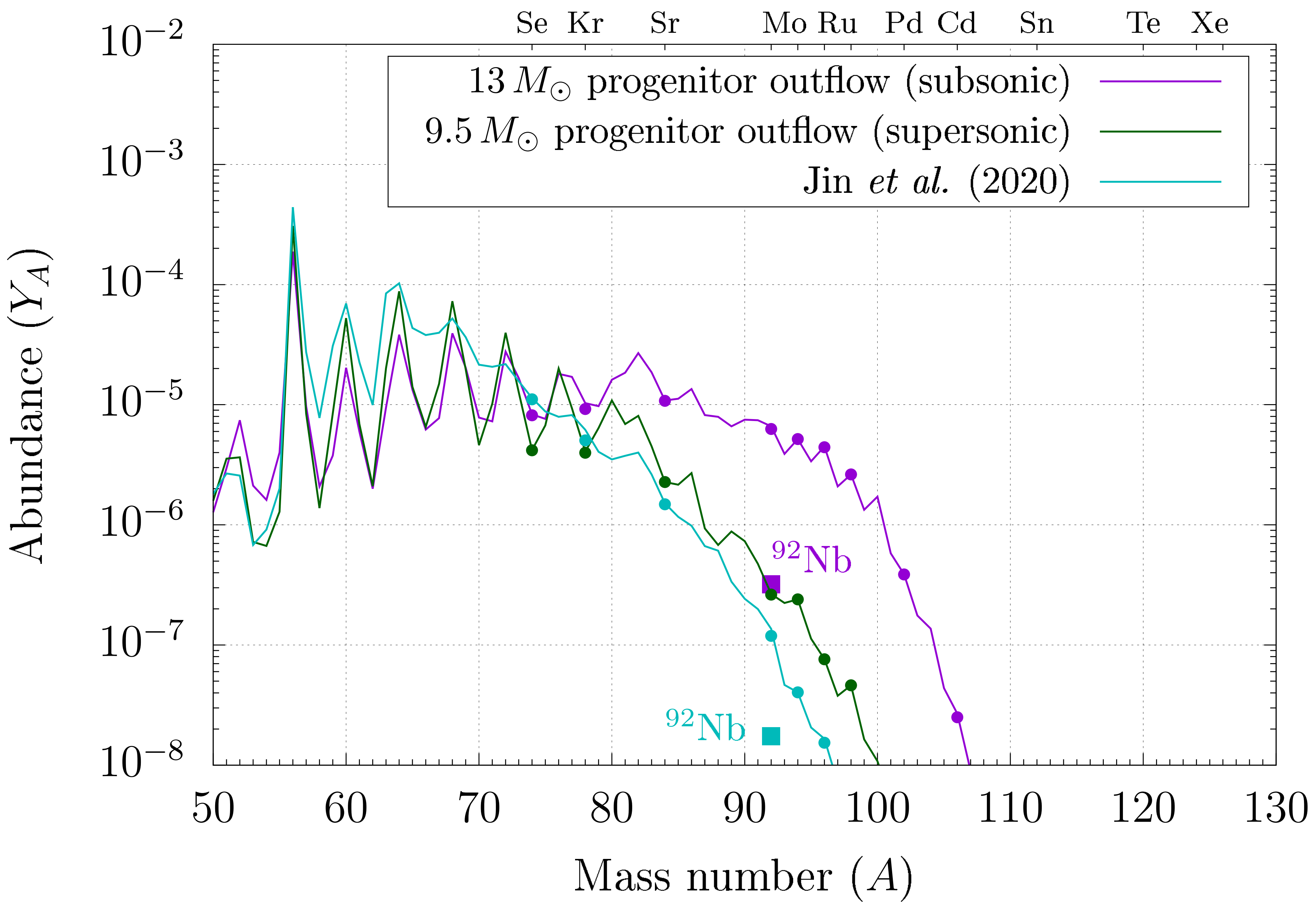
Here are results of Jin et al (2020)

- Yields obtained for parametrized outflow profile with entropy ($S = 80$) that has been used in Jin et al (2020)
  - Reproduced by us using **SkyNet** for comparison.
  - Huge thanks goes to Jonas Lippuner and the authors of of the Nature paper for making the codes public



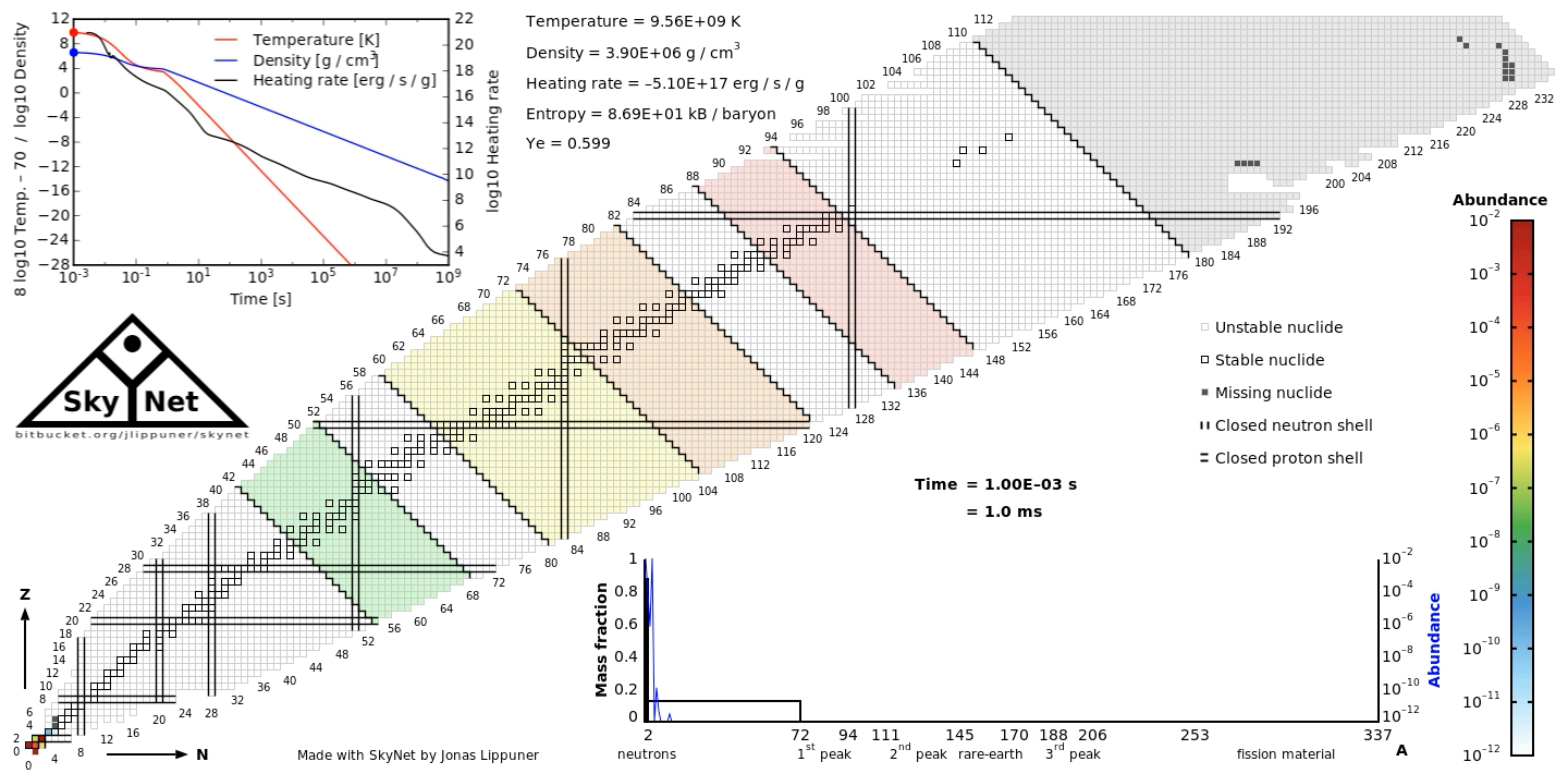
Instantaneous yields in subsonic and supersonic outflows (computed self-consistently)

- The yields of Mo and Ru in a subsonic case are more than an order of magnitude higher
- With the triple-αenhancement, we obtain the ratio $^{92}Mo/^{94}Mo \sim 1.5$, consistent with the measured ~ 1.57.
- The ratio $^{96}Ru/^{98}Ru \sim 2.45$ is also consistent with measured solar ratio of ~ 2.91
- ^{92}Nb? How come?



$13M_\odot$ model has $M_{PNS} = 1.8M_\odot$ (later)

Simulation



Temperature = 9.56E+09 K

Density = 3.90E+06 g / cm^3

Heating rate = –5.10E+17 erg / s / g

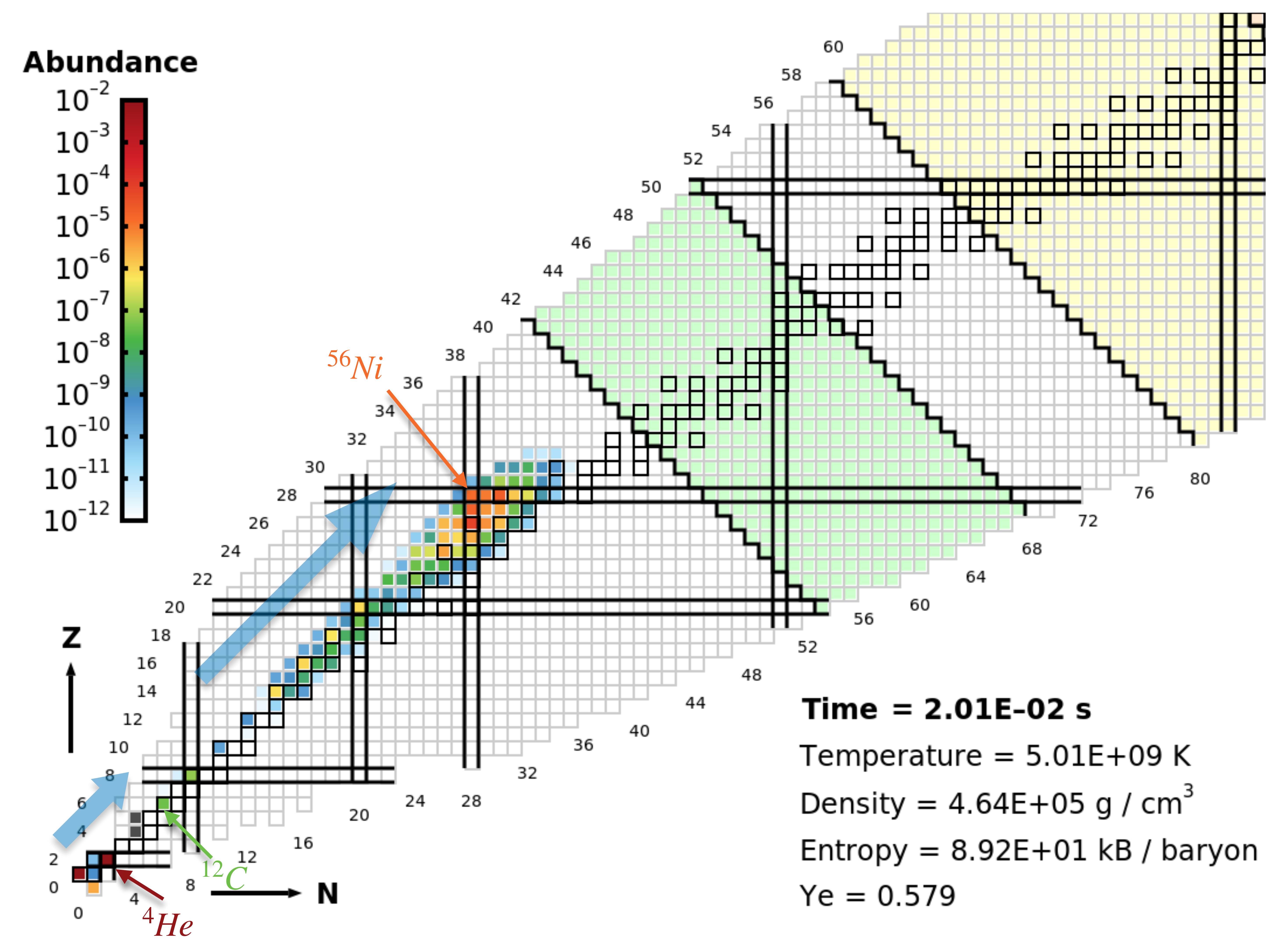
Entropy = 8.69E+01 kB / baryon

Ye = 0.599

Time = 1.00E–03 s
= 1.0 ms

Made with SkyNet by Jonas Lippuner

Stage I: seed formation



Time = 2.01E-02 s

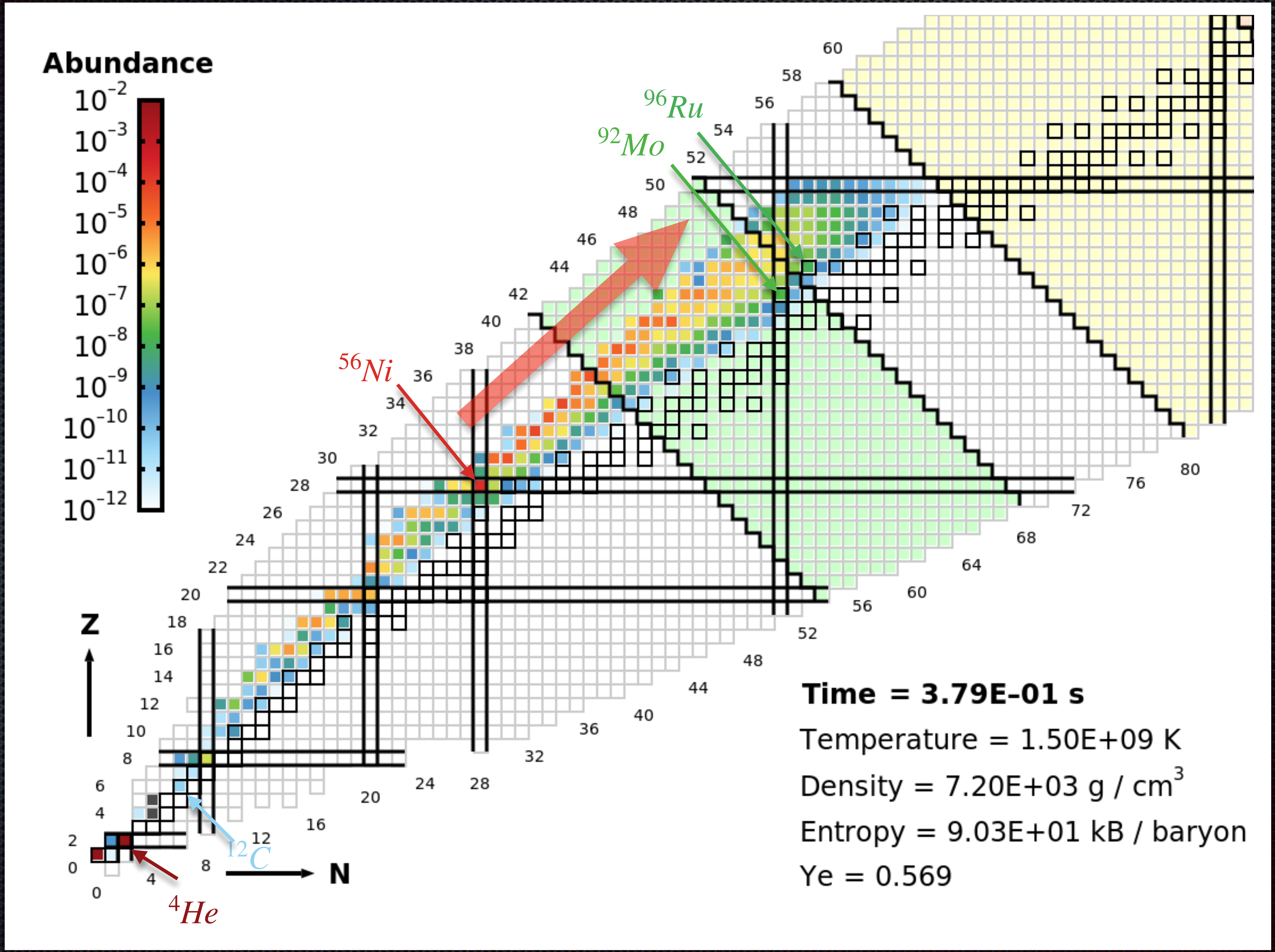
Temperature = 5.01E+09 K

Density = 4.64E+05 g / cm^3

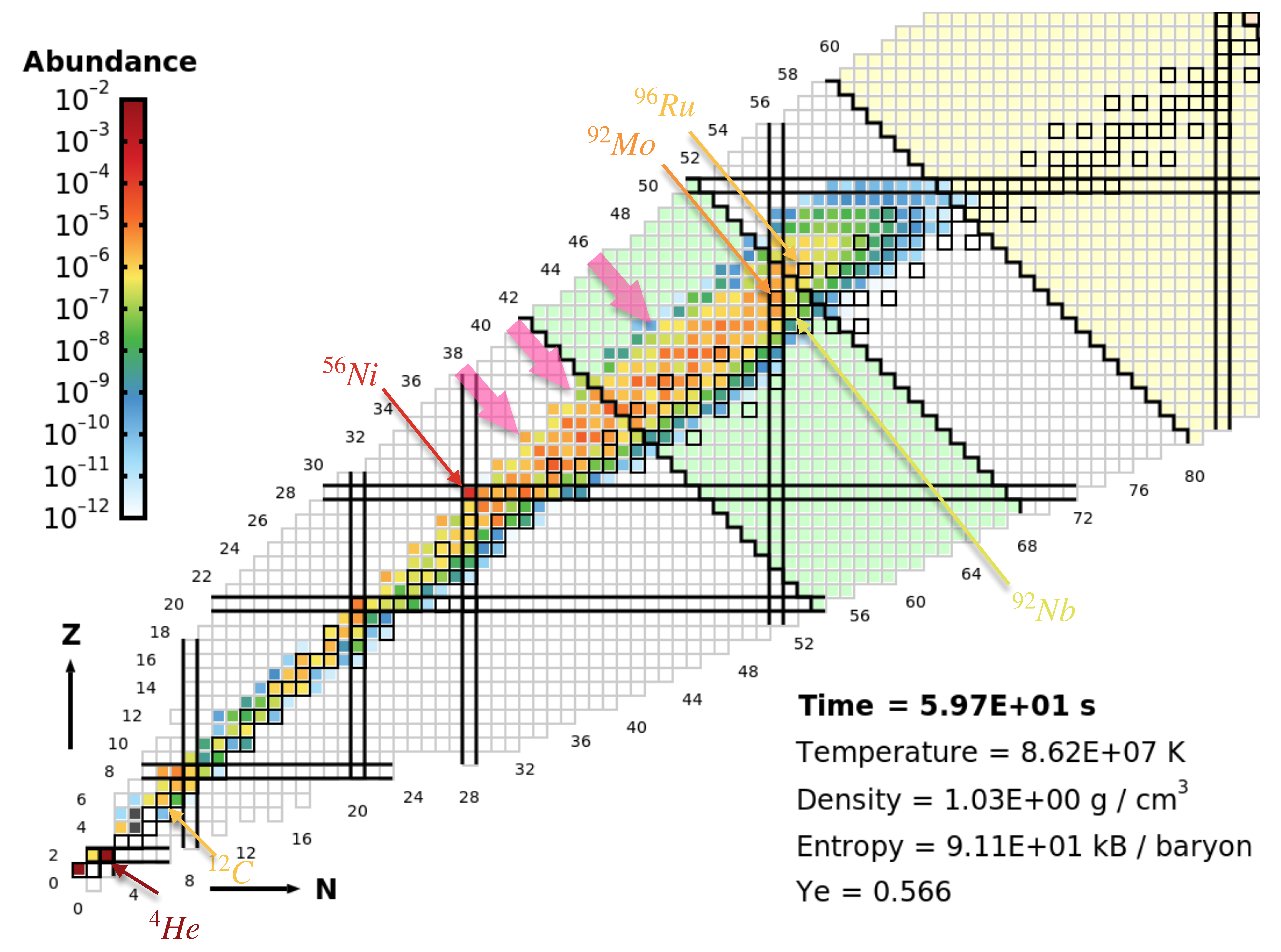
Entropy = 8.92E+01 kB / baryon

Ye = 0.579

Stage II: proton and neutron capture



Stage III: late-time neutron capture



Time = 5.97E+01 s

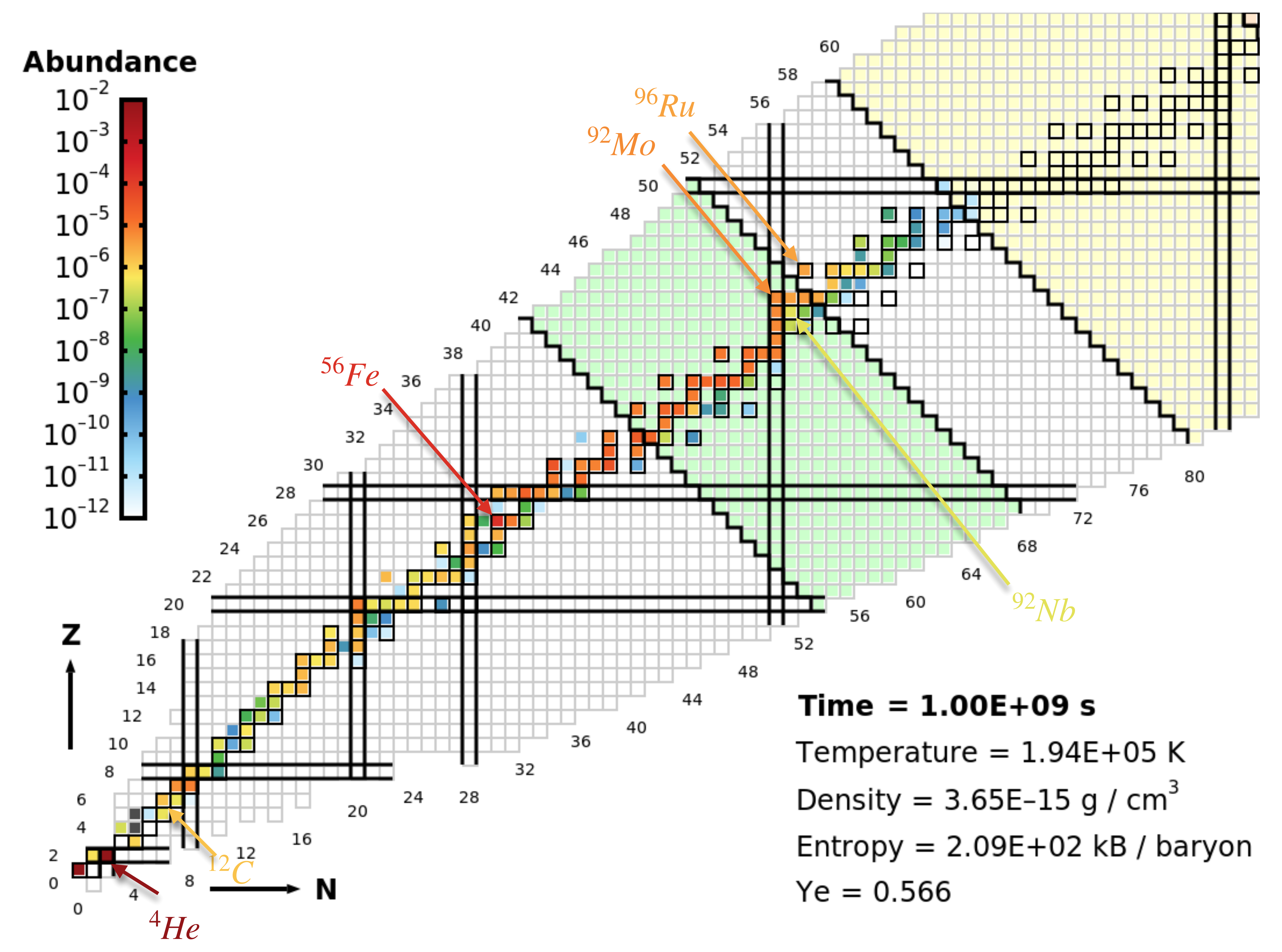
Temperature = 8.62E+07 K

Density = 1.03E+00 g / cm^3

Entropy = 9.11E+01 kB / baryon

Ye = 0.566

Stage IV: final beta decays



Time = 1.00E+09 s

Temperature = 1.94E+05 K

Density = 3.65E–15 g / cm^3

Entropy = 2.09E+02 kB / baryon

Ye = 0.566

Why does it work?

- For successful nu p process to make Mo and Ru, need about to make about 10 neutrons per seed nucleus
    - In-medium effects create more carbon by de-exciting the Hoyle state
    - Do we have enough neutrons at stage II?
- In a subsonic outflow, the material remains significantly closer to the protoneutron star. The result is up to 3 times more neutrons produced compared to the supersonic case
- What about neutrons made after T<1.5 GK? The process regulated by falling neutrino luminosities + material receding with the expanding front shock
    - 3-5 neutrons per seed during stage III. Not enough to make the composition neutron rich
    - But enough to drive it closer to the valley of stability and make some ^{92}Nb. Not by beta decays, but by late neutron capture!

Why does it work?

- What parameters do we adjust for this?
- ν_e and $\bar{\nu}_e$ fluxes to get $Y_e \sim 0.6$ (pinched-thermal spectra, see, e.g, Keil et al, Hudepohl et al)
- Progenitor mass $M_{prog} \gtrsim 12 M_\odot$, to obtain subsonic outflows
- $M_{PNS} \sim 1.8 M_\odot$, to control entropy per baryon
  - Sets carbon production (density at T ~ 0.3-0.5 MeV)

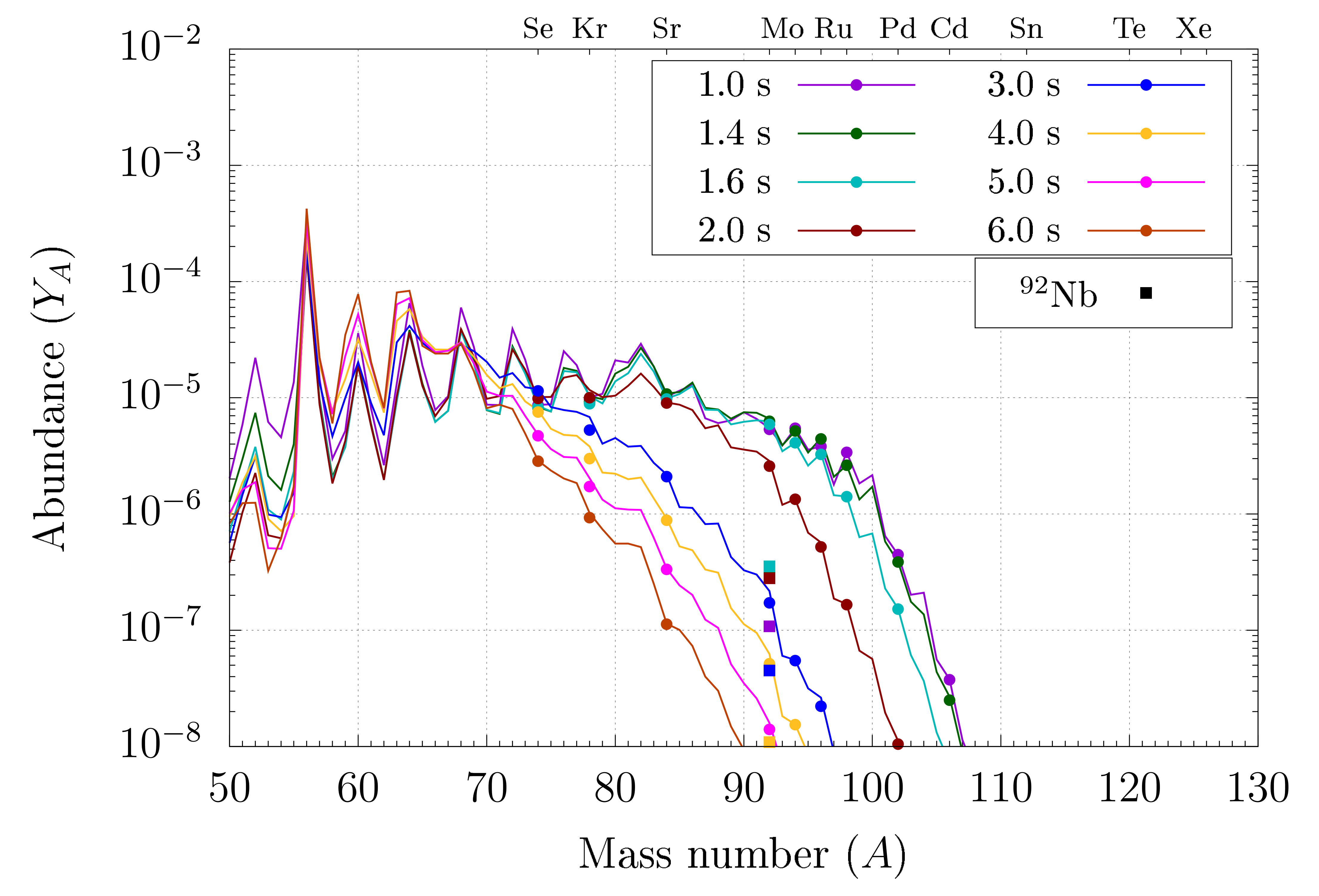
$$S \sim (m_N / T)(G_N M_{PNS} / R_{PNS}) \sim 85 - 90$$

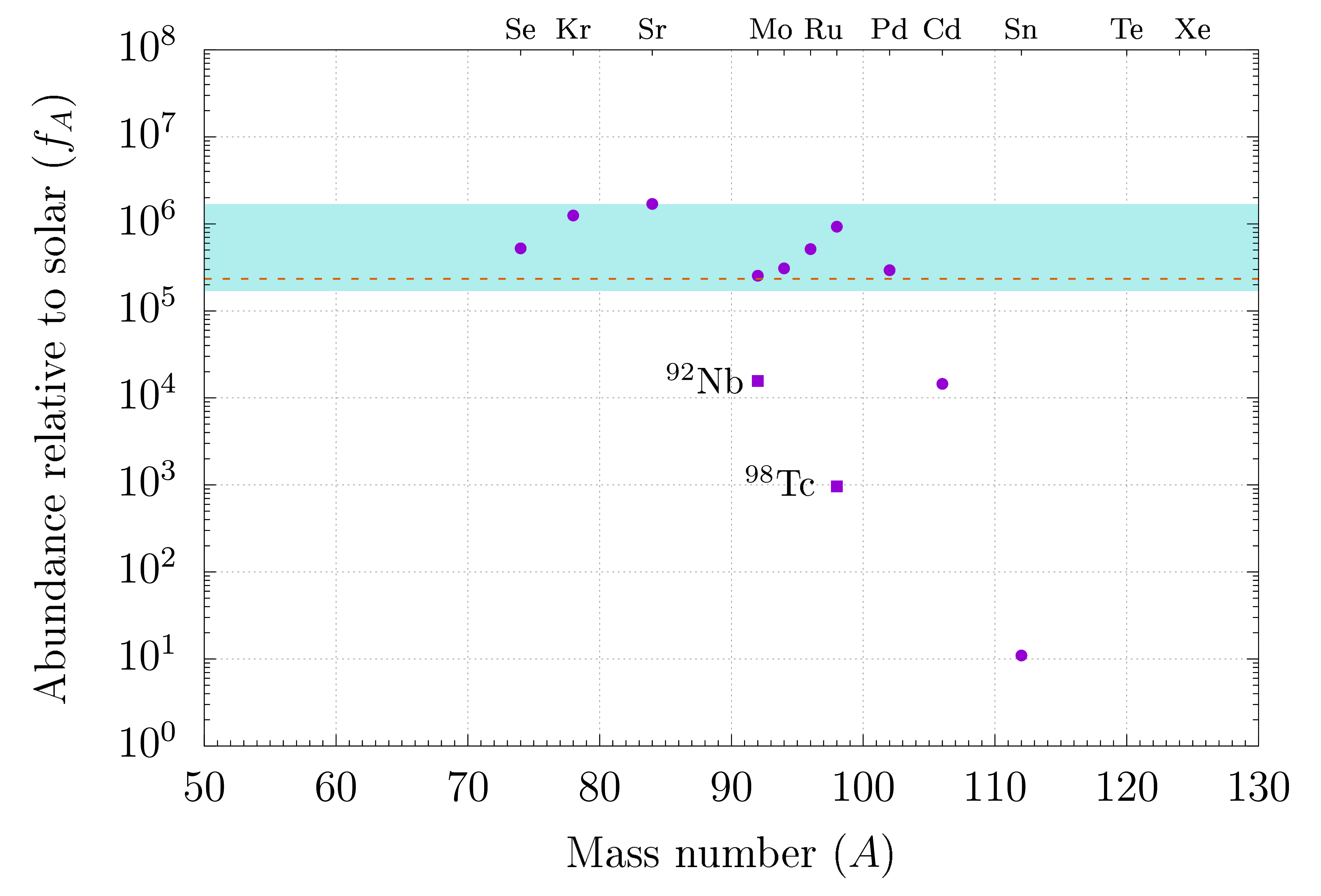
- No additional parameters left to adjust for stage III. ^{92}Nb just works.

Footnote

- Skynet out of the box does not produce ^{92}Nb.
- Turns out, any ^{92}Nb made decays to ^{92}Mo on the timescale of 10^2 seconds, contradicting data. The actual half-time of ^{92}Nb is about 37 Myr, making it a famous cosmochronometer.
- The issue was traced to a mistake in reactlib. This mistake is crucial in our analysis, as it reenforces the prejudice that ^{92}Nb is shielded by ^{92}Mo.

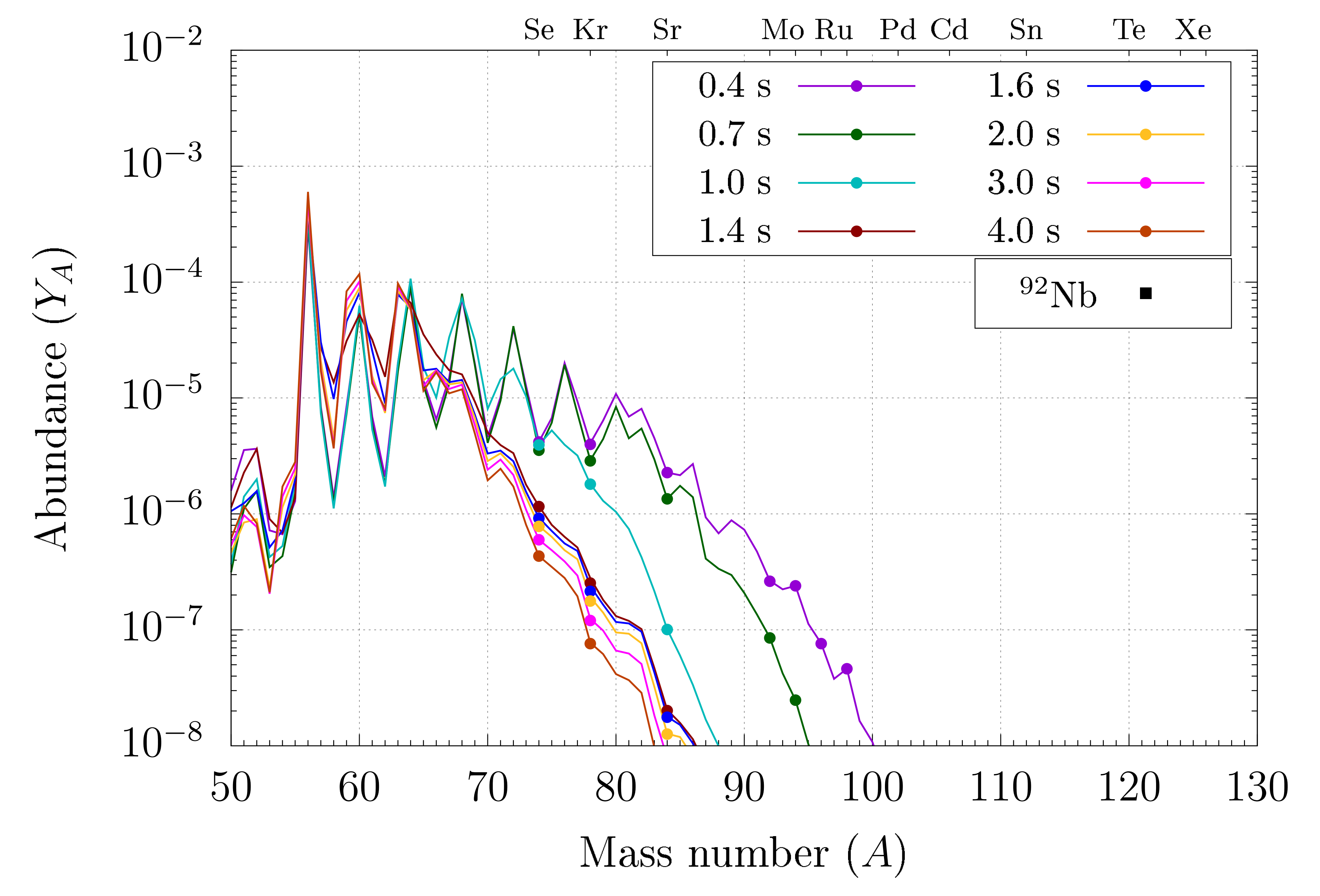
Time integrated yields, 13Msun progenitor (subsonic)

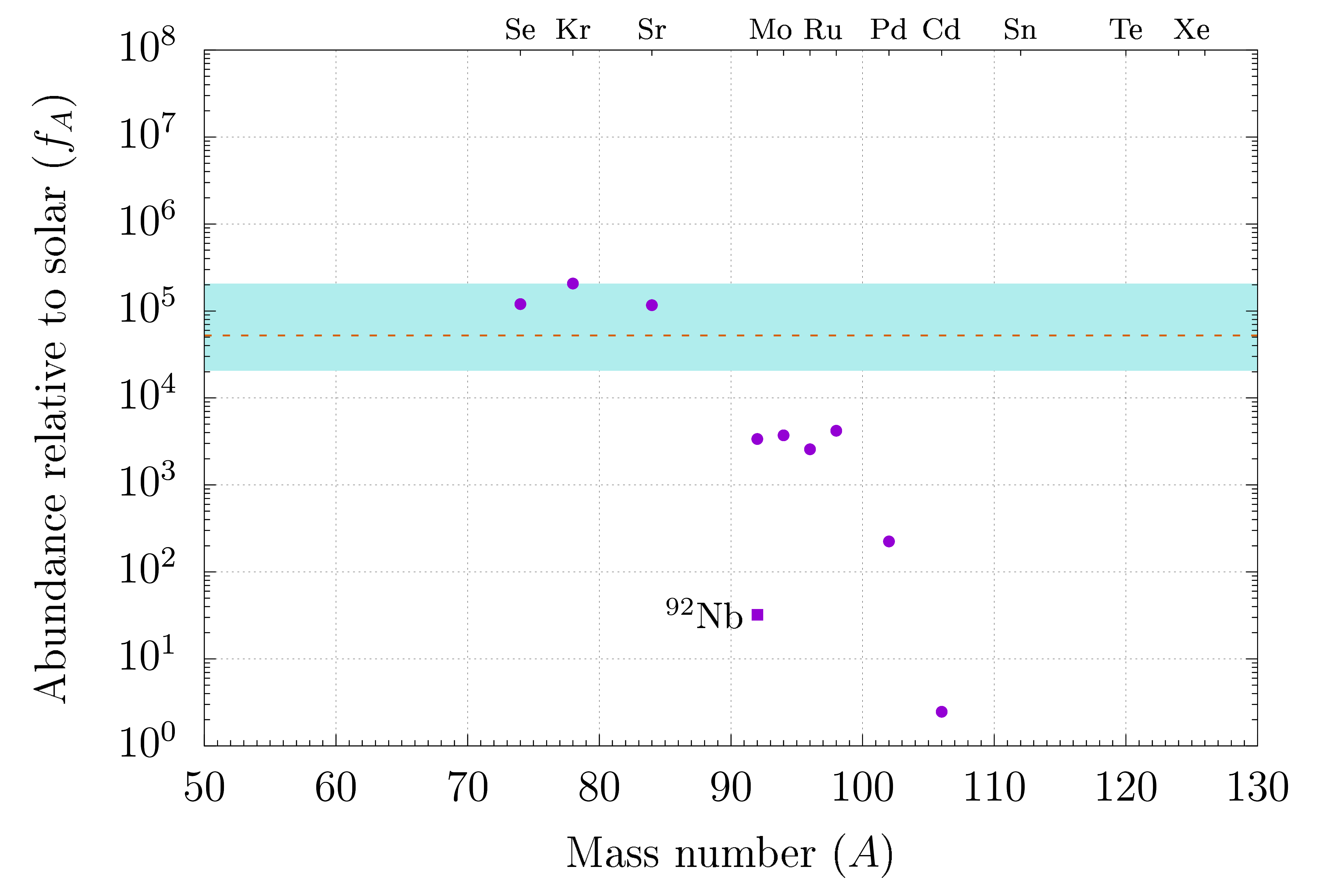




Most of the yields are produced before 2 sec after shock revival

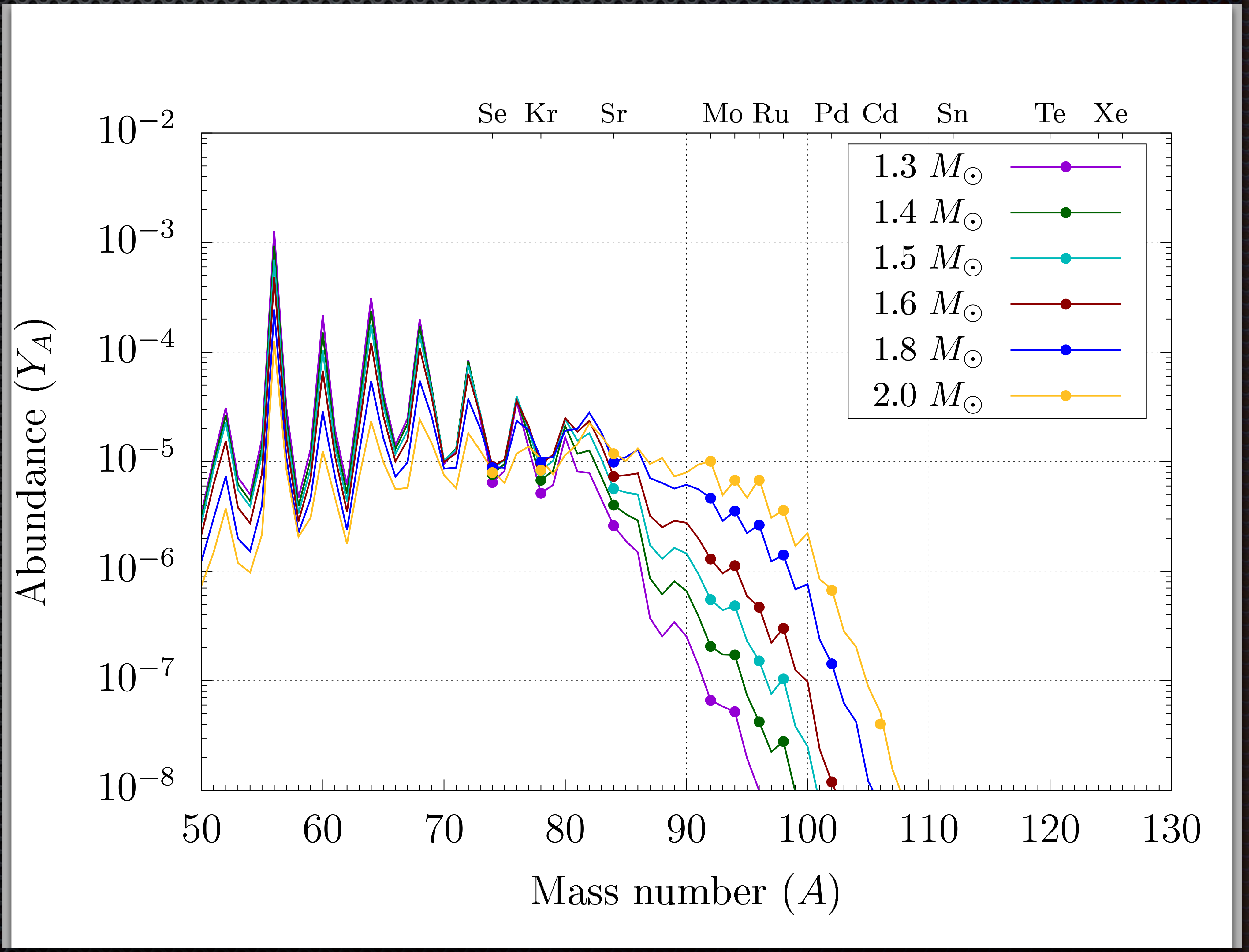
Time integrated yields, 9.5Msun progenitor (supersonic)





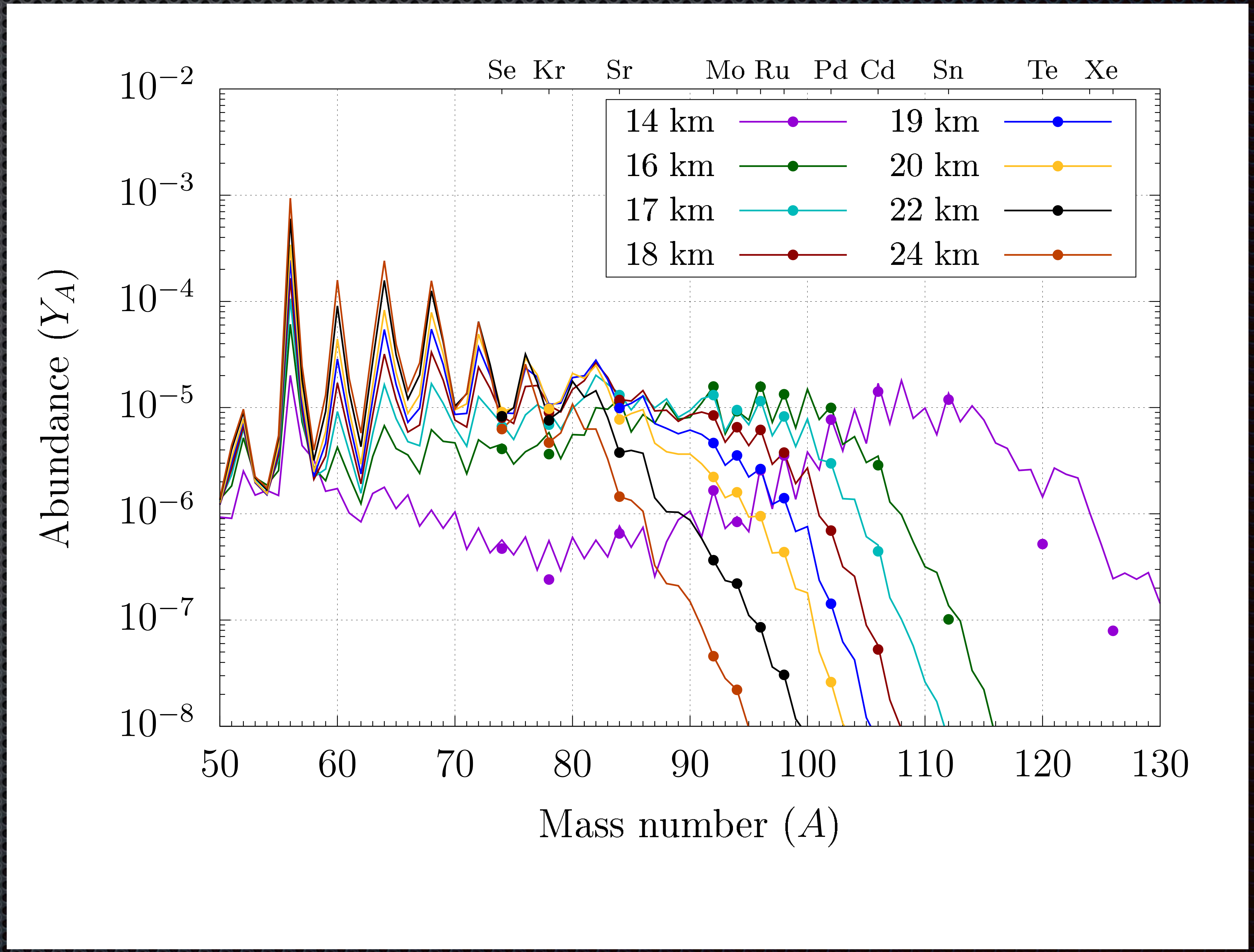
Protoneutron star mass

- Calculations favor PNS heavier than the Chandrasekhar value of $1.4M_\odot$
- This is understood analytically as a requirement of sufficiently high entropy per baryon (S ~ 80)
- Modern simulations for progenitors of $\gtrsim 13M_\odot$ indeed predict this, because of an extended accretion stage
- These progenitors are predicted to have subsonic outflows by our criterion, necessary for successful $\nu p-$process
- Nontrivial consistency!



Protoneutron star radius

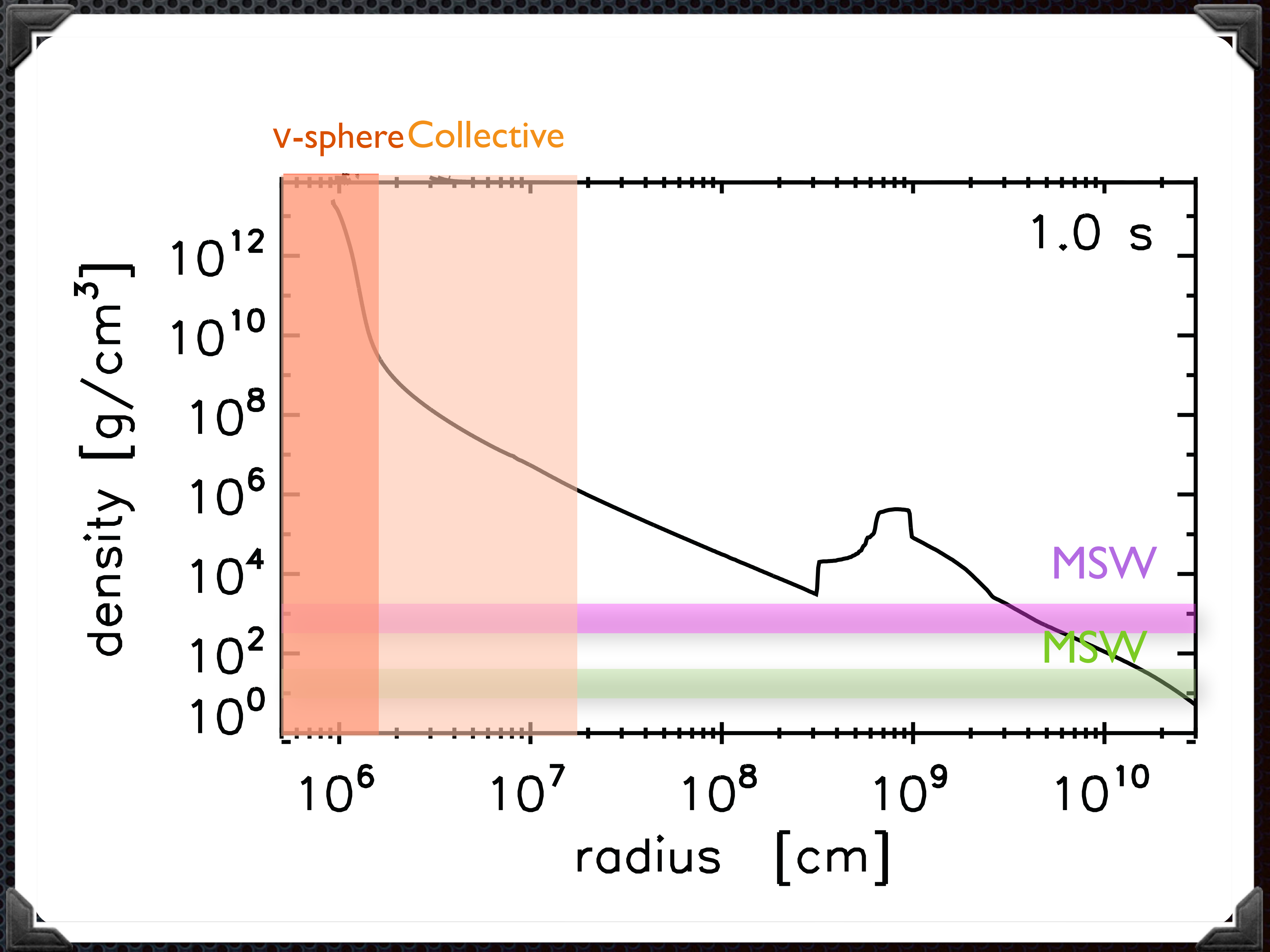
- Optimal yields during the first 1-2 seconds after shock revival (2-3 seconds post bounce).
- PNS simulations favor radius in the range $\sim 18 - 20$ km
- Notice that we are not interested in the final radius
- Sensitivity on nuclear EOS, cooling dynamics need to be systematically explored



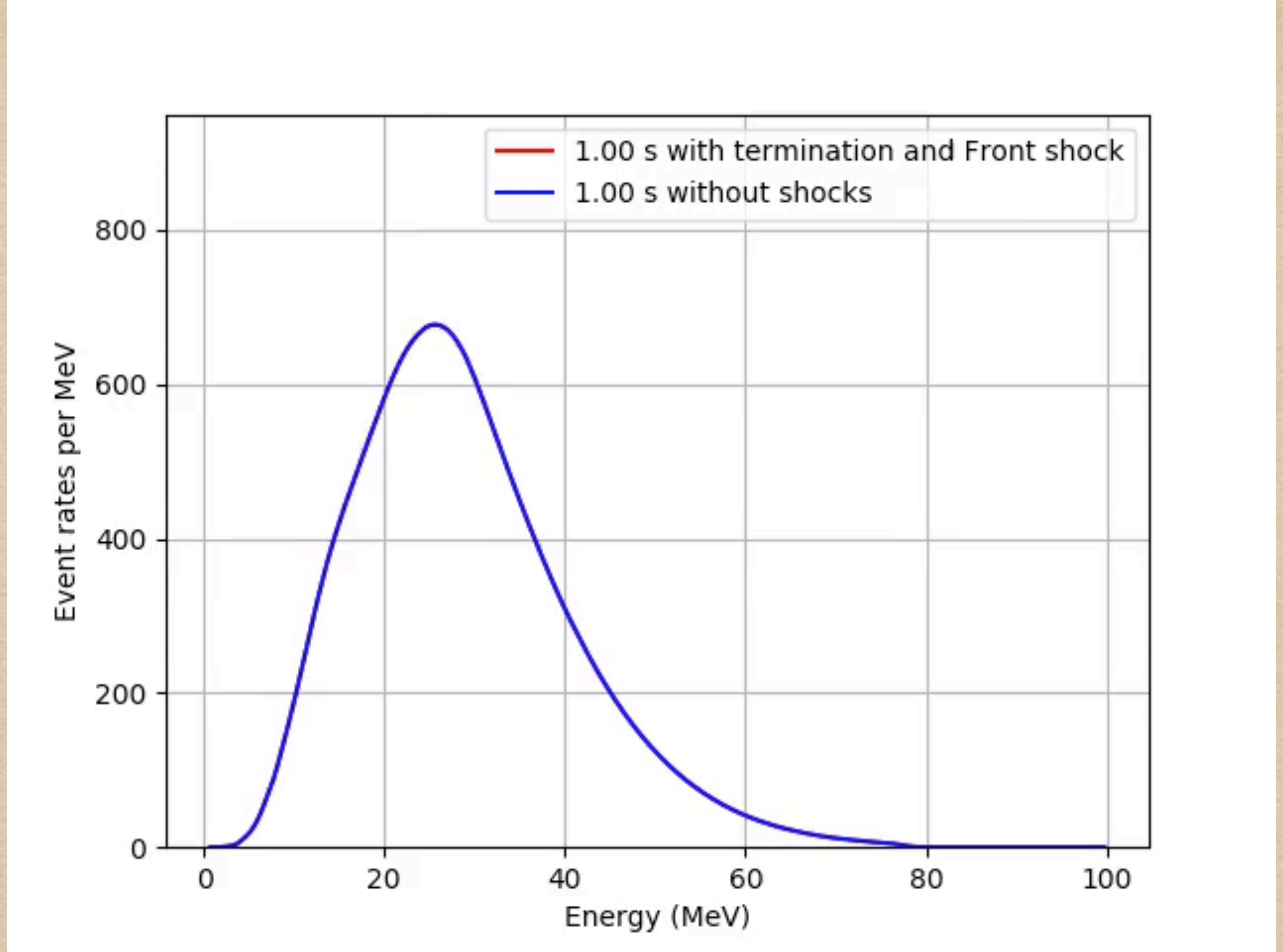
What can we see in neutrinos from the next galactic supernova?

Neutrino oscillations

- Neutrino oscillations are sensitive to the matter profile
- Evolving matter profile imprints time-dependent features on the nu_e signal that can be detected at DUNE
- These features are different for subsonic and supersonic profiles (termination shock is a non adiabatic feature)
- We combine the MSW and collective effect computed in a multiangle, spherically symmetric framework.



Signal as a function of time



Signals can appear as early as 1.3 sec !

And continues throughout the burst duration !

Spectacular non thermal features

Conclusions

- A quarter of molybdenum in the solar system comes in the form of two neutron-poor isotopes, 92Mo and 94Mo. This fact is very hard to explain.
- Nu p process strongly depends on the hydrodynamics of the outflow
- Neutrino-driven outflows in a supernova possess a special property of near-criticality. We must consider both subsonic and supersonic regimes self-consistently
- Sufficiently massive progenitors have subsonic outflows, heavier PNS. Both of these properties nontrivially combine to produce the right amount of p-nuclei up to ^{102}Pd, both in absolute and relative amounts
- ^{92}Nb is also produced in the right amount, thanks to late-time neutron capture (no free parameters)
- PNS properties at 2-3 seconds post-bounce are crucial. Interesting to understand the nuclear physics uncertainty
- Neutrino detection at DUNE can provide a nontrivial check that the conditions are right