Neutrino-Driven Outflows and the Origin of Light Heavy Elements

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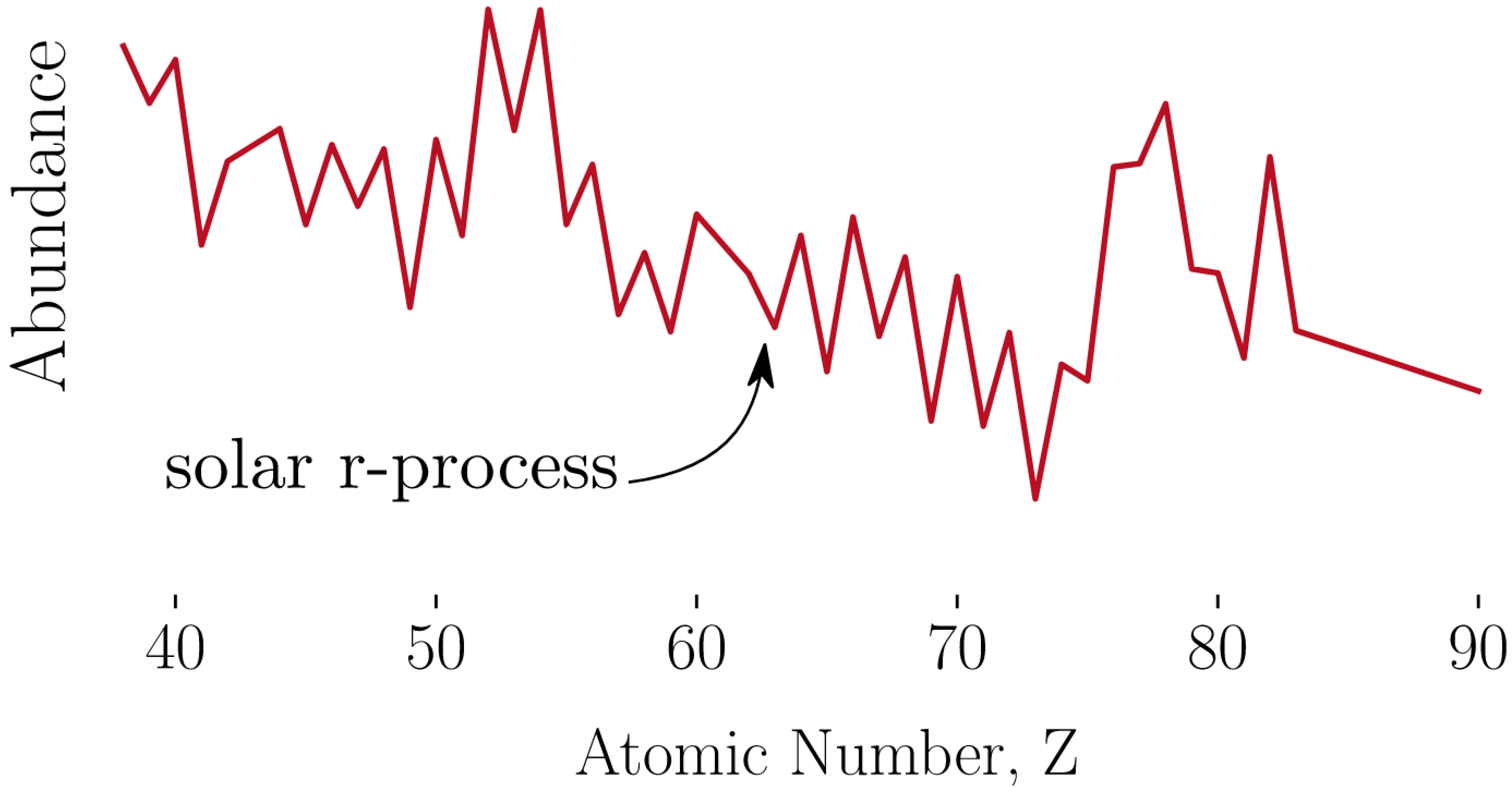
September 22, 2023

Nuclei in the Cosmos (NIC-XVII)

Image Credit: NASA/CXC/SAO

HD 122563 (DSS2/ Aladin Sky Atlas)

What do the ancient stars show us?



See also: C. Sneden, J. J. Cowan and R. Gallino, Annu. Rev. Astron. Astrophys. **46**, 241 (2008)

See talks by G. Martínez-Pinedo, G. McLaughlin and S. Honda • ‼️ *r-process = total solar - s-process - γ-process*

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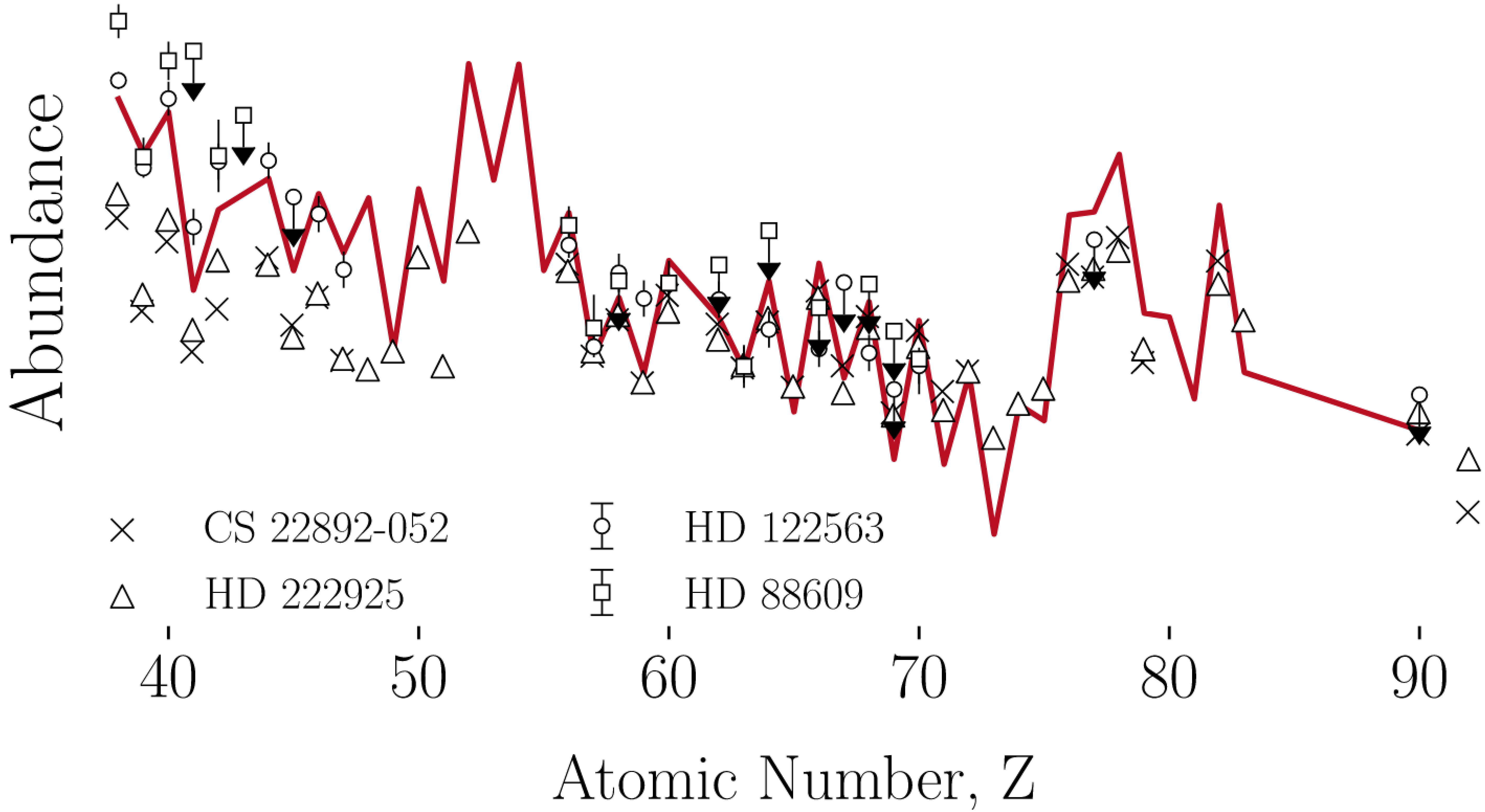

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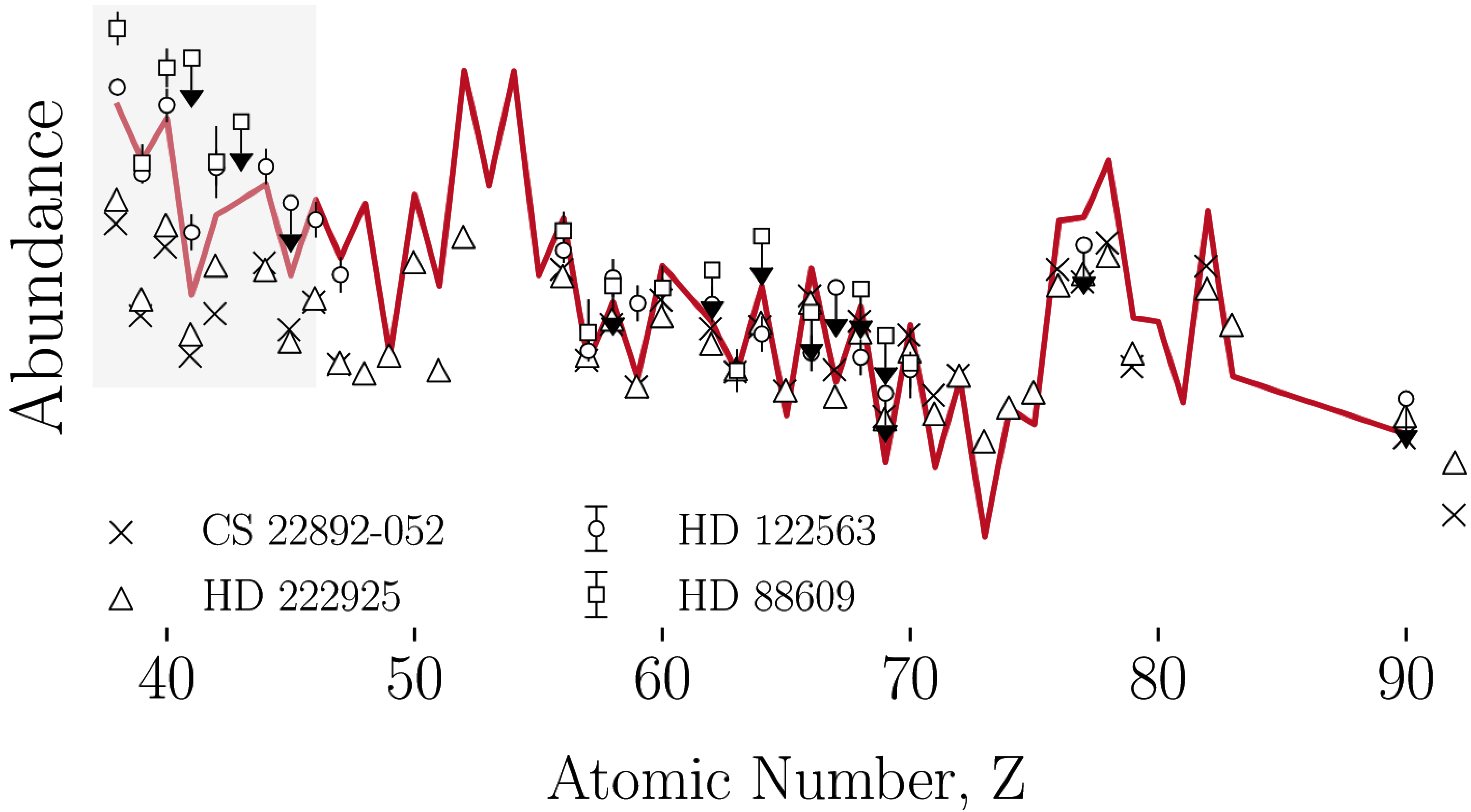

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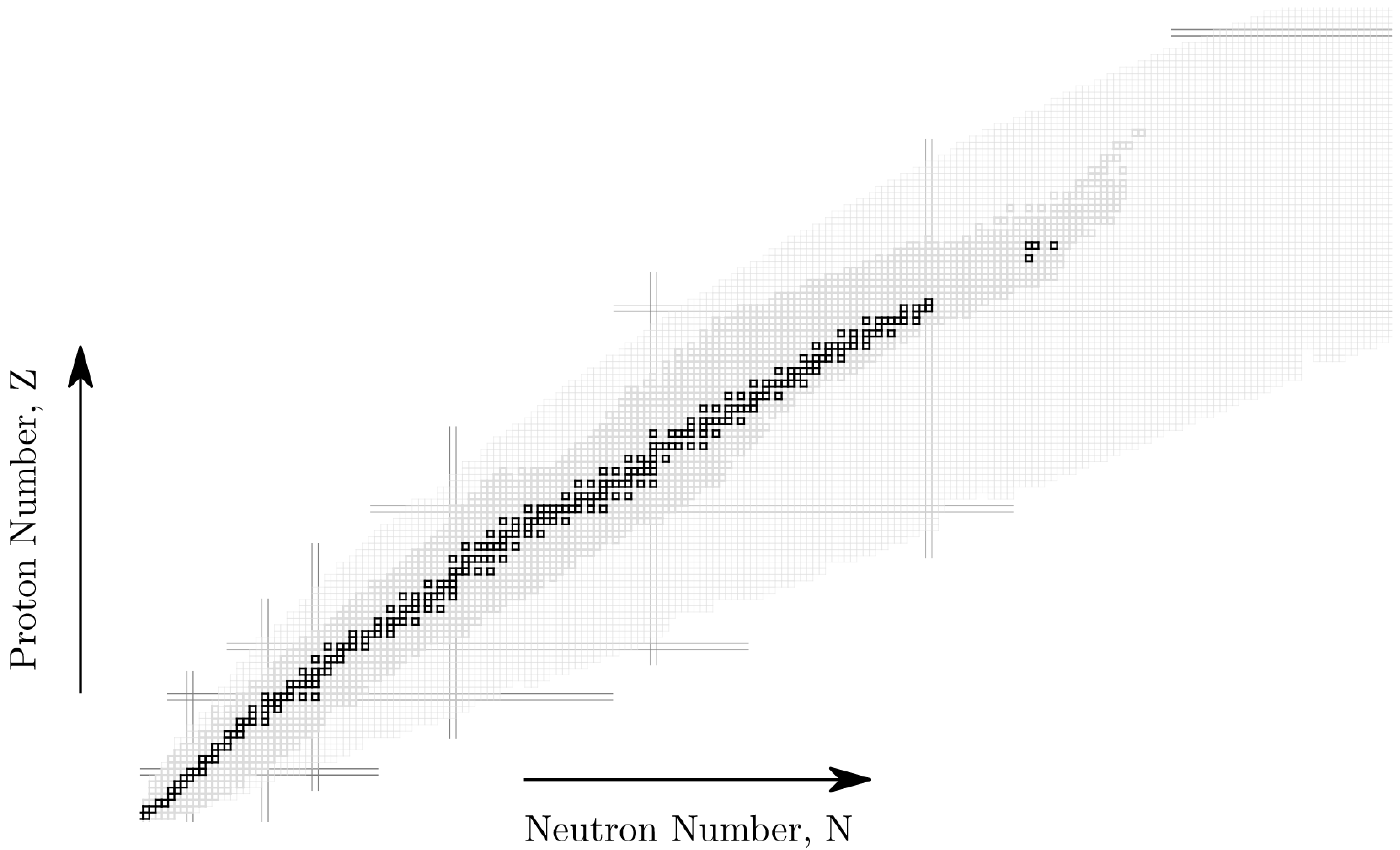
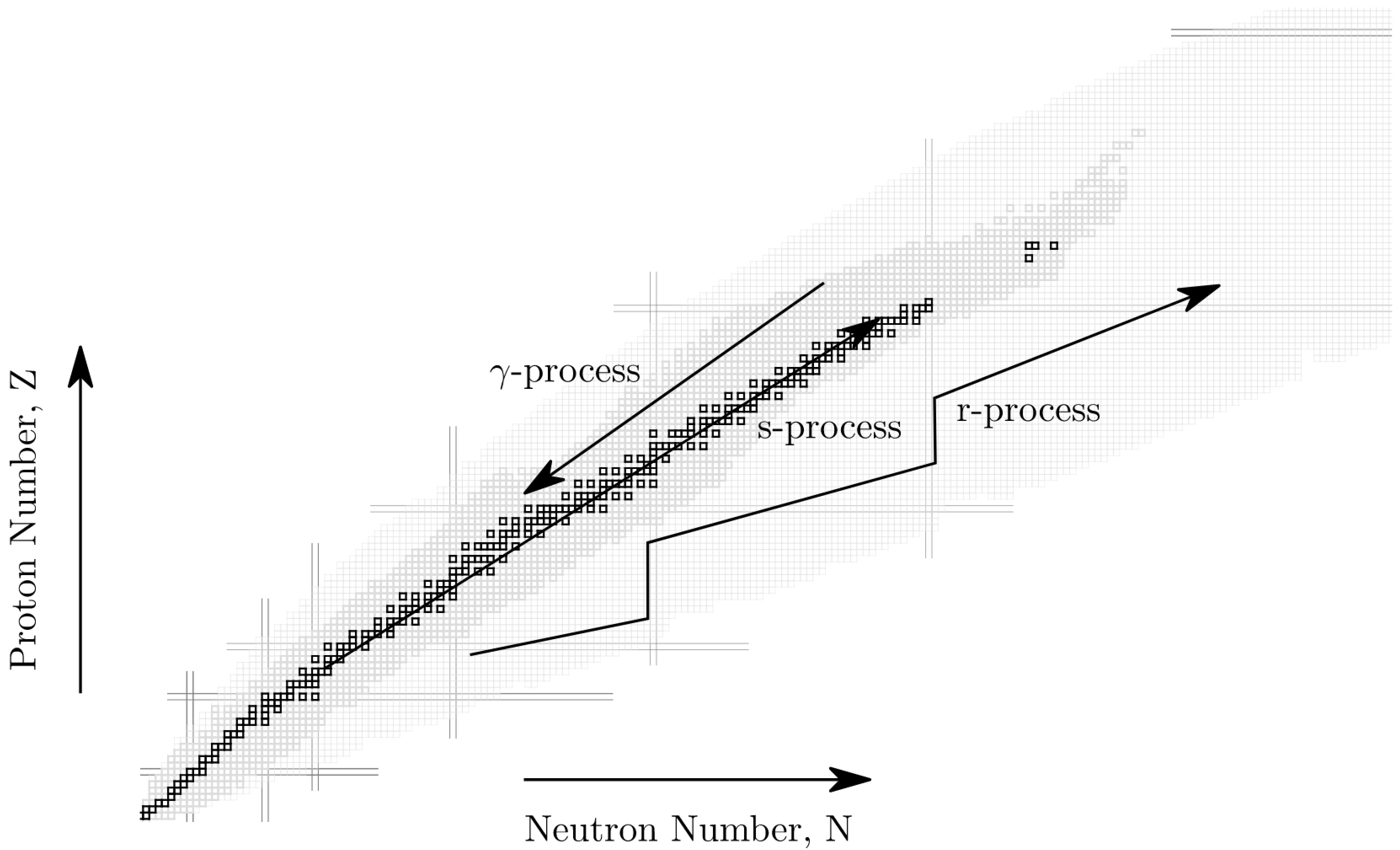
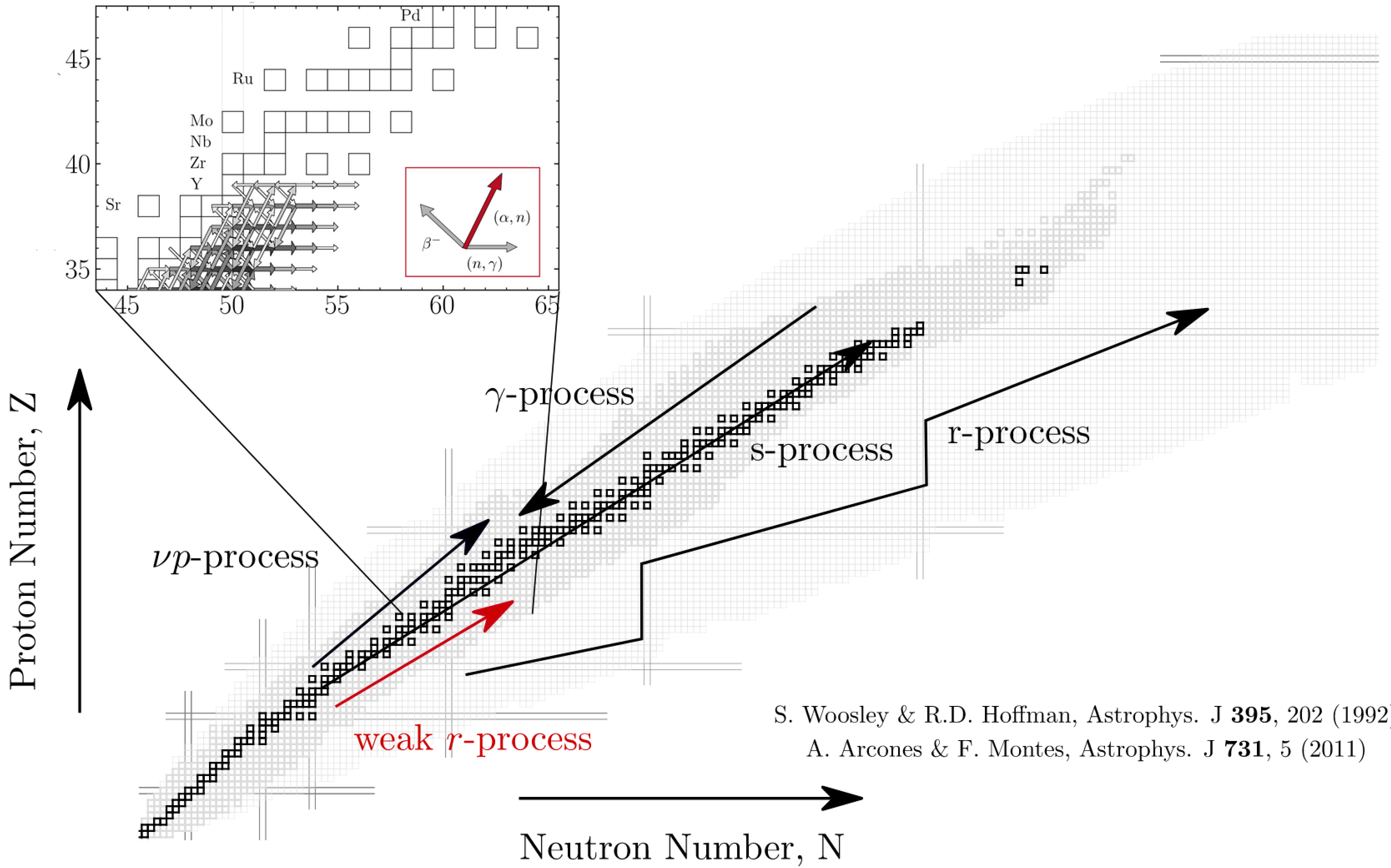
How many processes contribute to the production of elements between strontium and silver?


Proton Number, Z
Neutron Number, N



Proton Number, Z
Neutron Number, N
γ-process
s-process
r-process

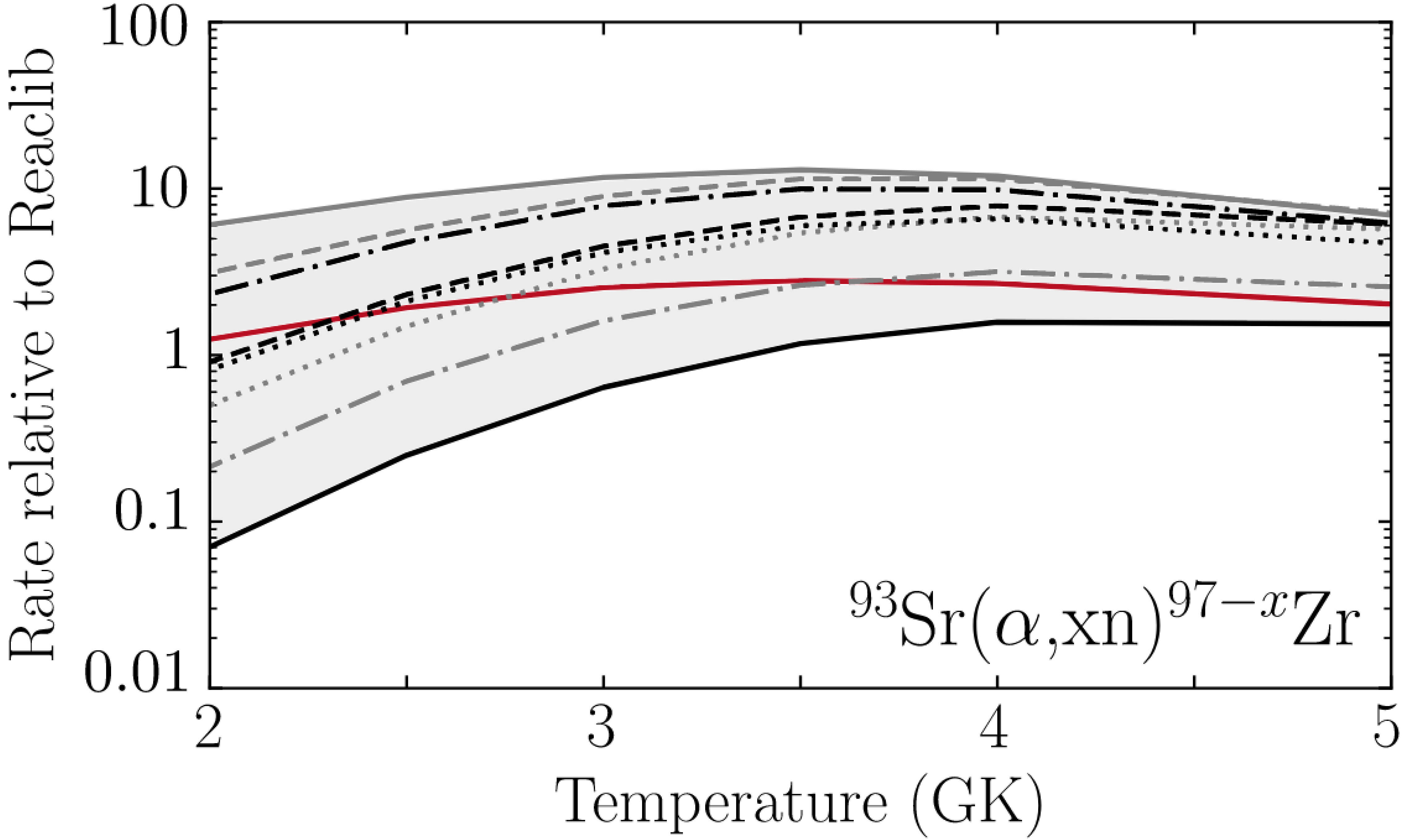


S. Woosley & R.D. Hoffman, Astrophys. J **395**, 202 (1992)
A. Arcones & F. Montes, Astrophys. J **731**, 5 (2011)

What is the impact of the $(\alpha, \mathbf{xn})$ reactions in the weak r-process?

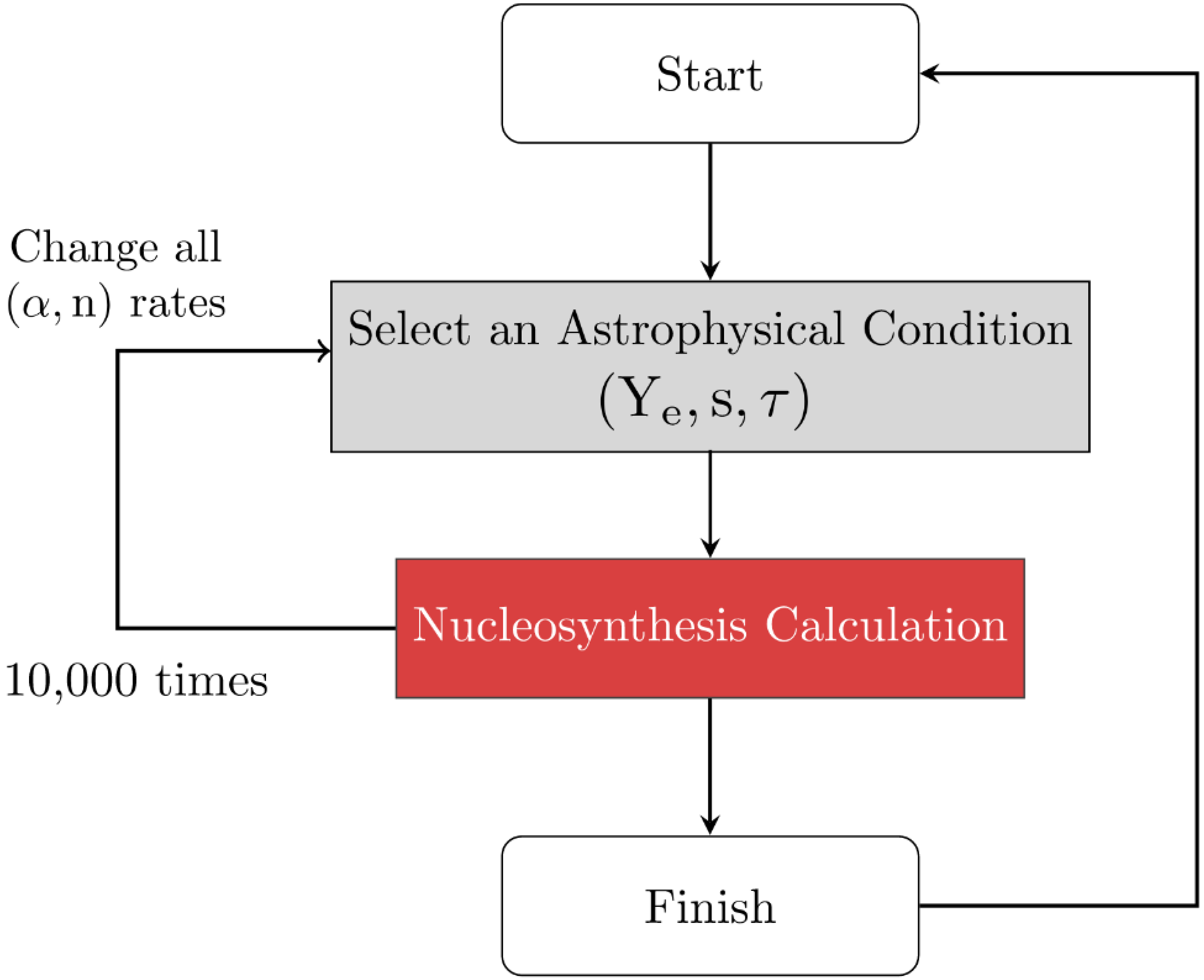
How much do we know the (α, xn) reaction rates?

The (α, xn) reaction rates are sensitive to the α-nucleus potential and their uncertainties can be up to two orders of magnitude.



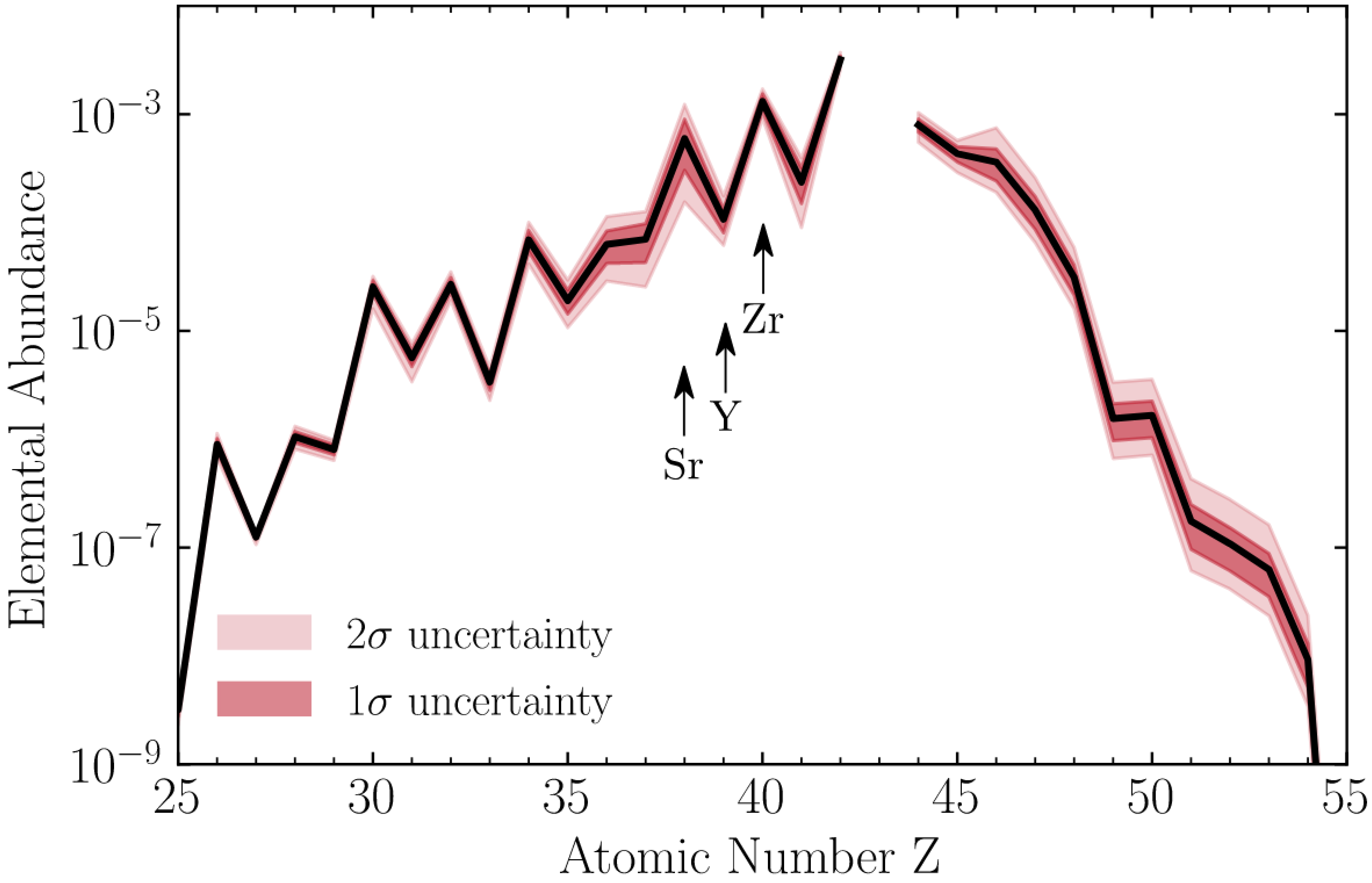
J. Pereira and F. Montes, Phys. Rev. C **93**, 034611 (2016) • P. Mohr, Phys. Rev. C **94**, 35801 (2016)

Framework of the sensitivity study



J. Bliss *et al.*, Astrophys. J **855**, 135 (2018) • P. Mohr *et al.*, At. Data Nucl. Data Tables **132**, 101453 (2021)

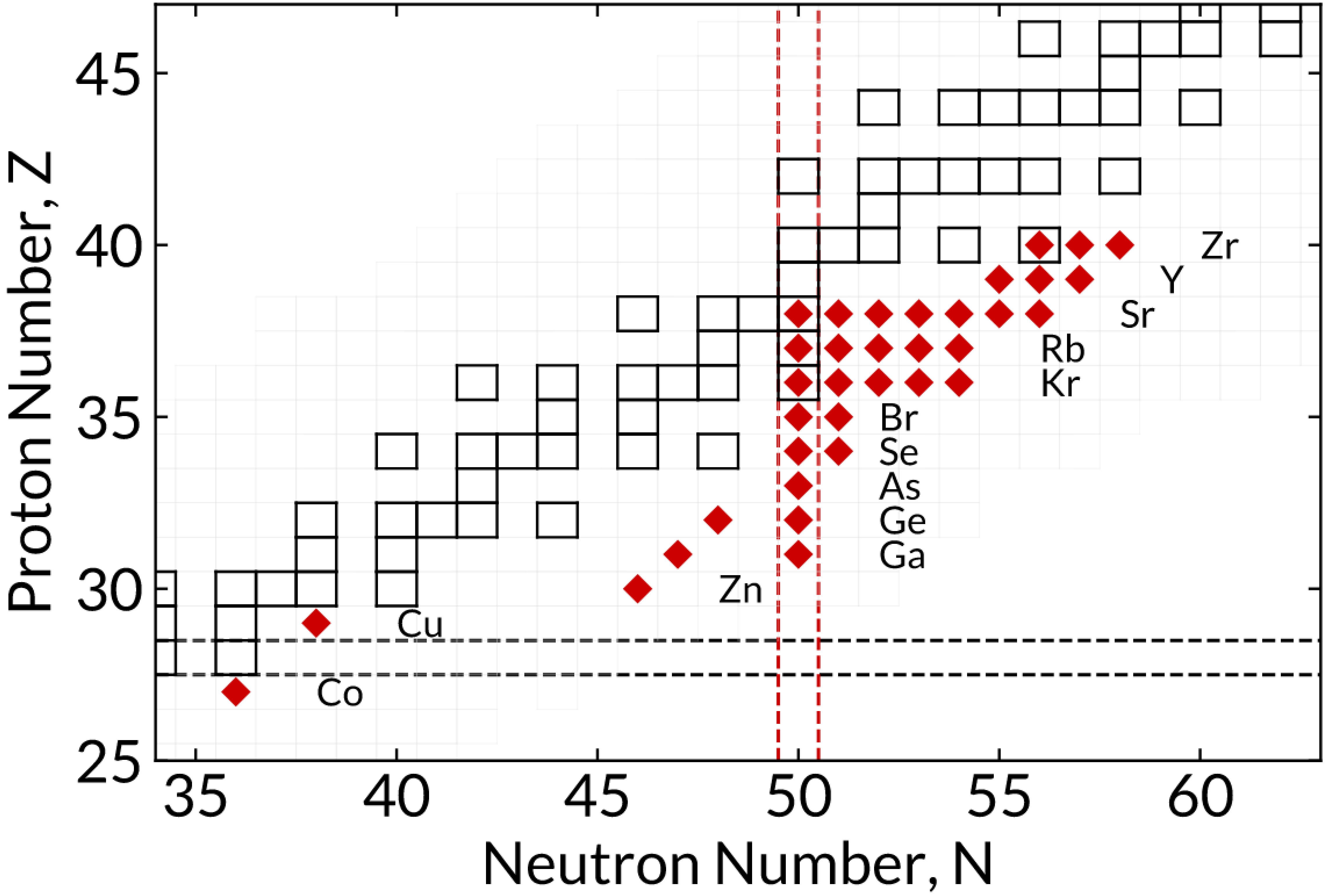
The impact of updated (α, n) reaction rates to elemental abundances



Same model, but different (α, xn) reaction rates!

Which are the most important $(\alpha, \mathbf{xn})$ reactions for the weak r-process?

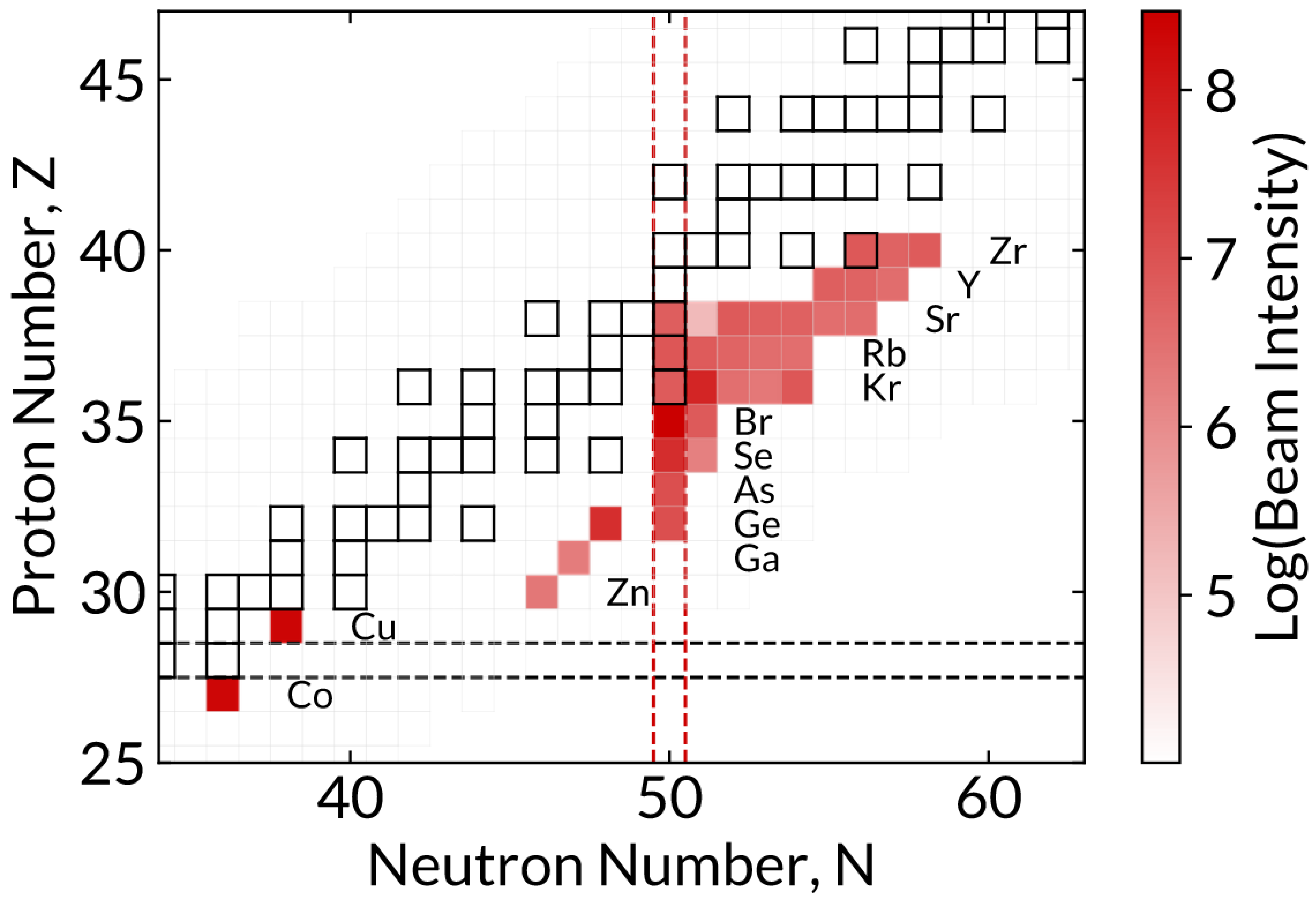
The most important (α, n) reactions for the weak r-process



N=50 shell closure is a bottleneck for T= 4-5 GK due to the $(n, \gamma) \leftrightarrow (\gamma, n)$ equilibrium

Can we study the most important $(\alpha, \mathbf{xn})$ reactions in the lab?

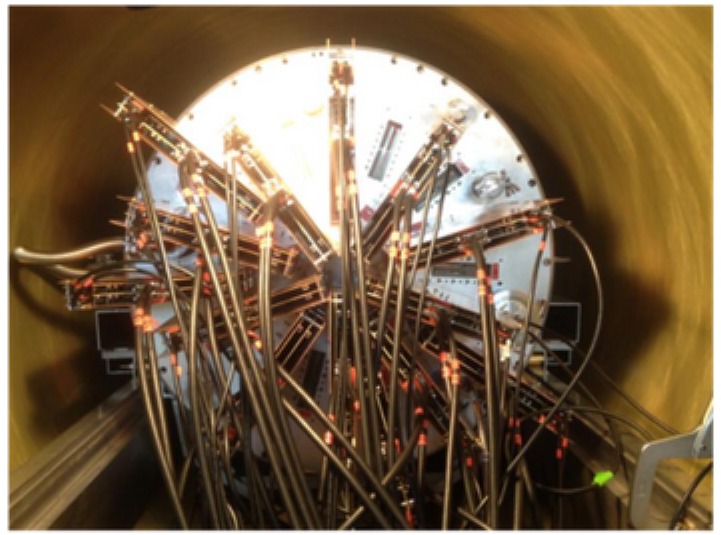
Most of the relevant beams are accessible!



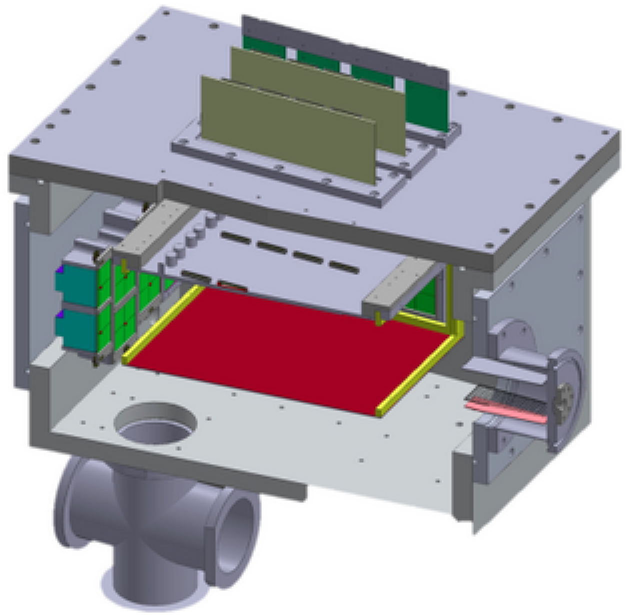
Expected FRIB ultimate beam rates

(Some) experimental setups for (α, n) reaction studies

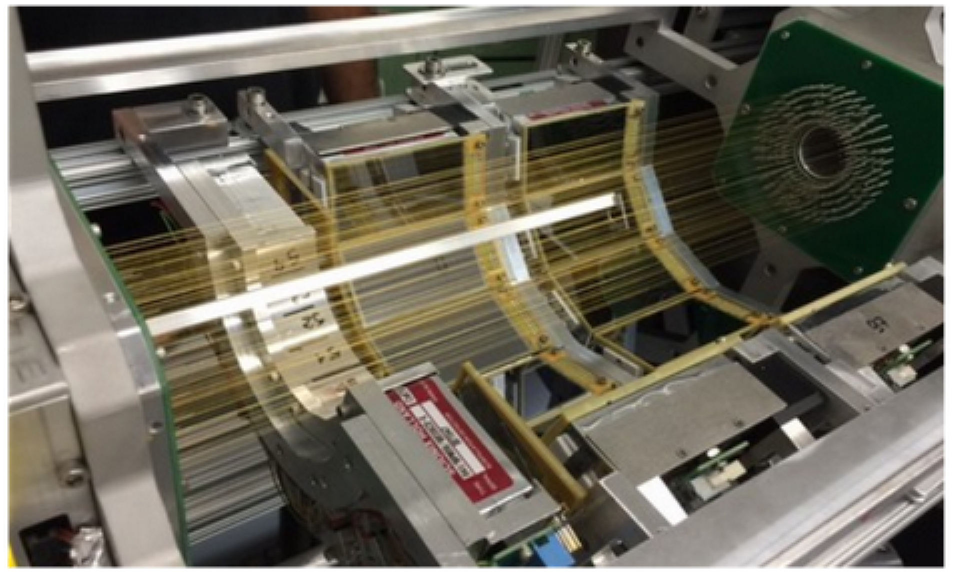
MUSIC @ Argonne



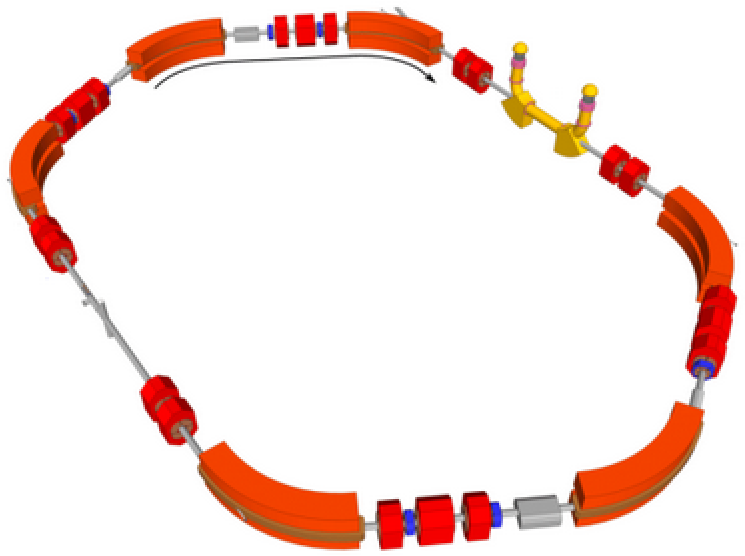
SOLARIS @ FRIB



TexAT @ Texas A&M

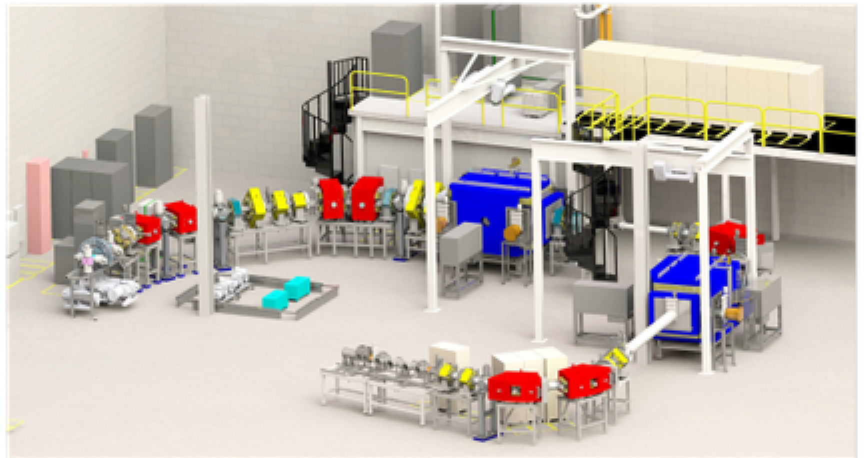


ANASEN @ FSU

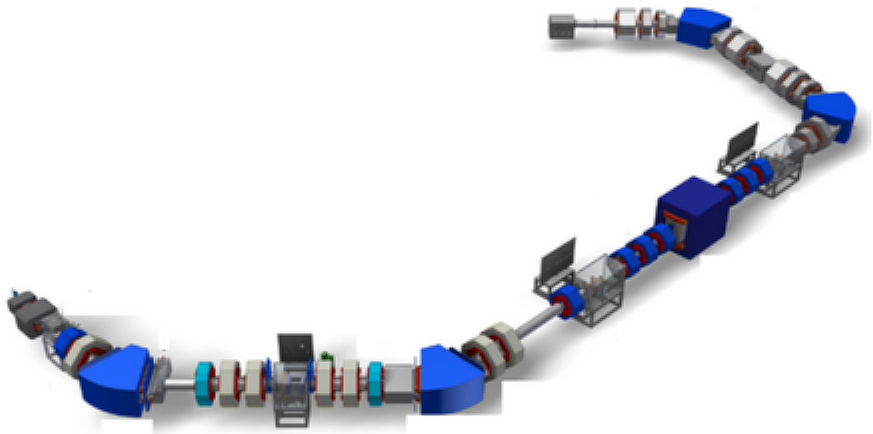


ESR @ GSI/FAIR

DRAGON @ TRIUMF



SECAR @ FRIB



KOBRA @ RAON

... and many more!

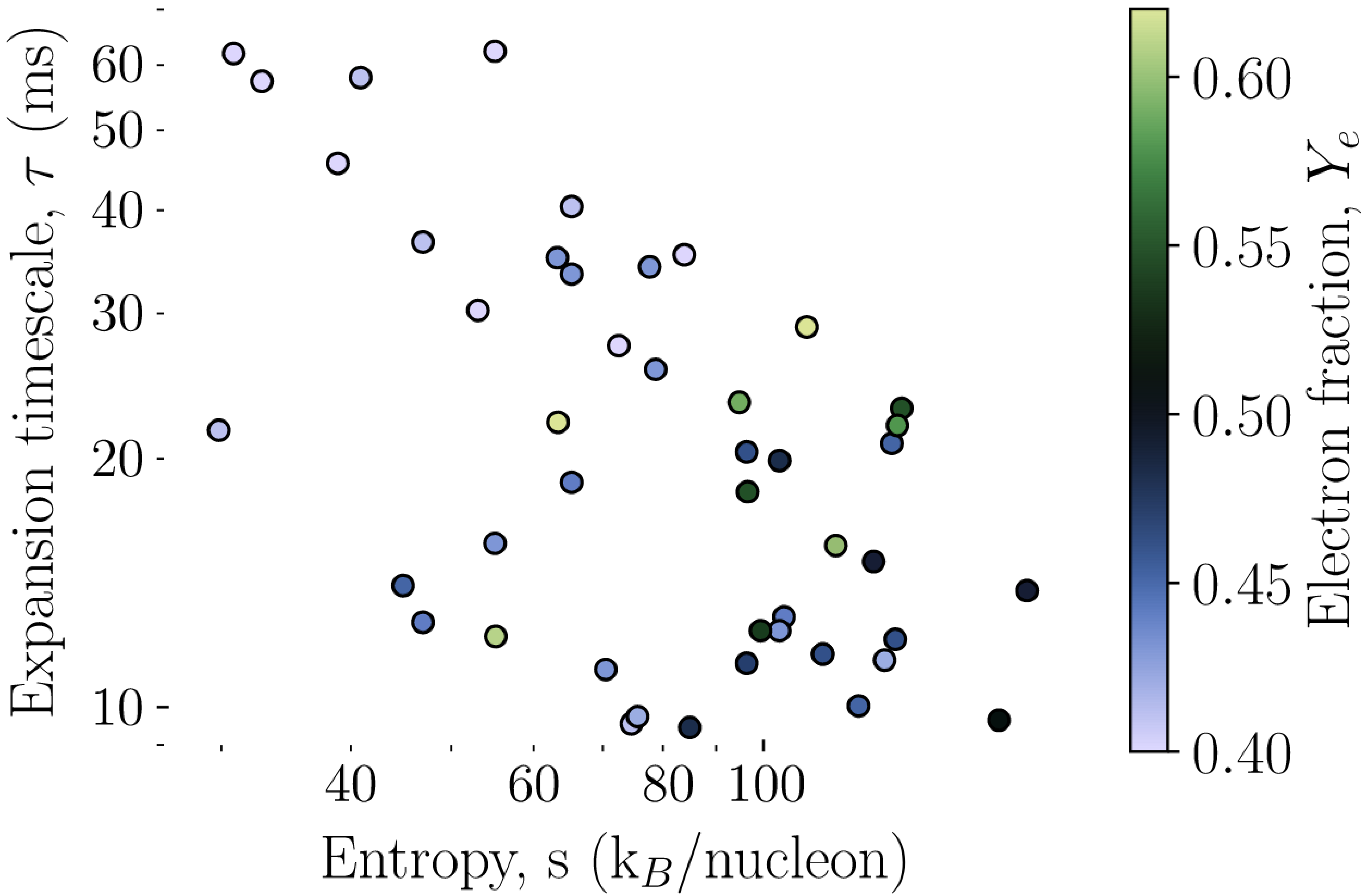
First measurement of the $^{93}\mathrm{Sr}(\alpha, xn)$ reaction at Argonne with MUSIC

Proposal #1923, PI: A. Psaltis, co-PI: W.J. Ong

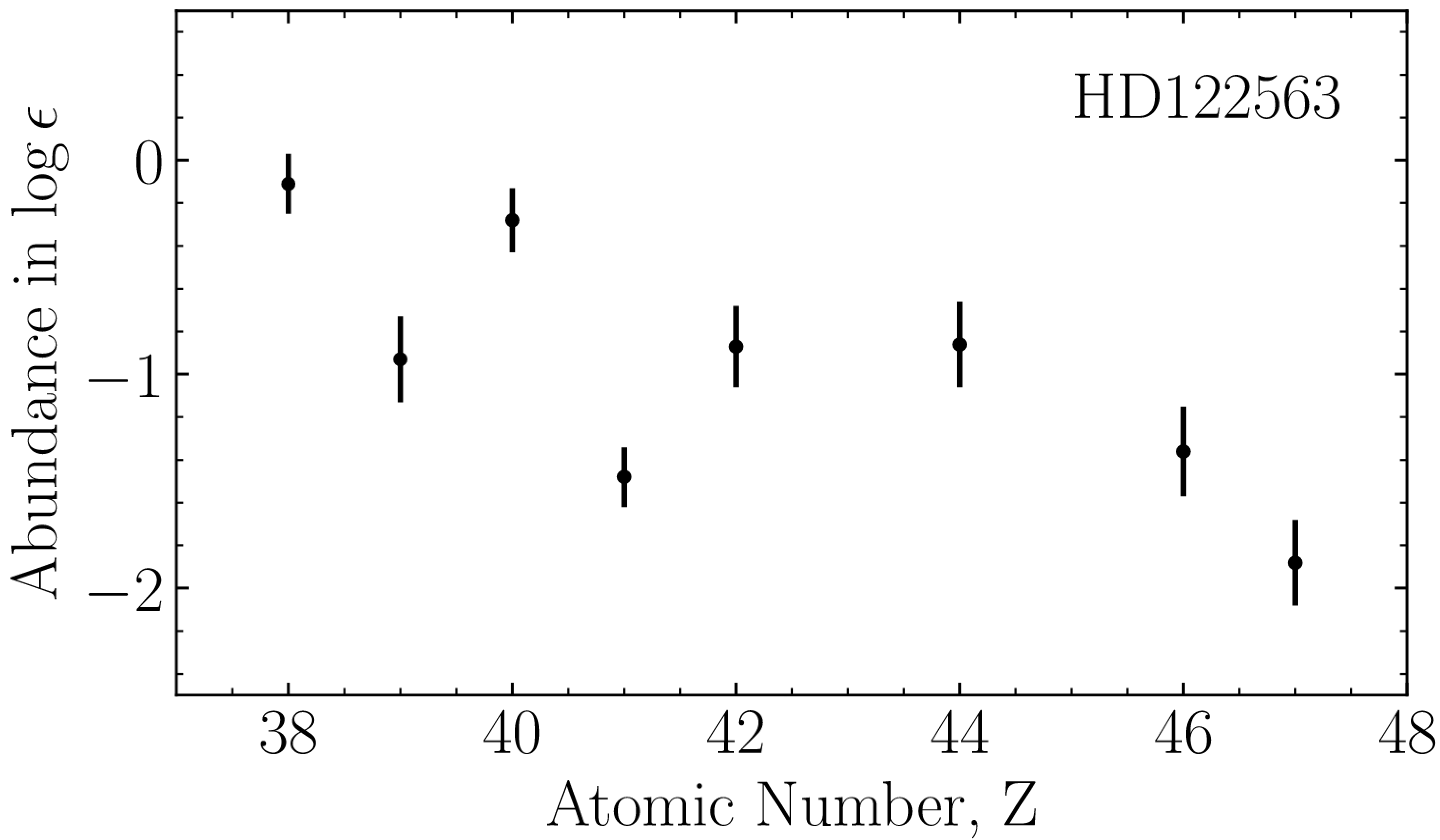
If you are interested in participating, contact me! 😁

Which are the most favourable conditions to produce the light heavy elements in neutrino-driven outflows?

We formed linear combinations using trajectories of various astrophysical conditions to compare with observations of metal-poor stars.



The case of HD122563



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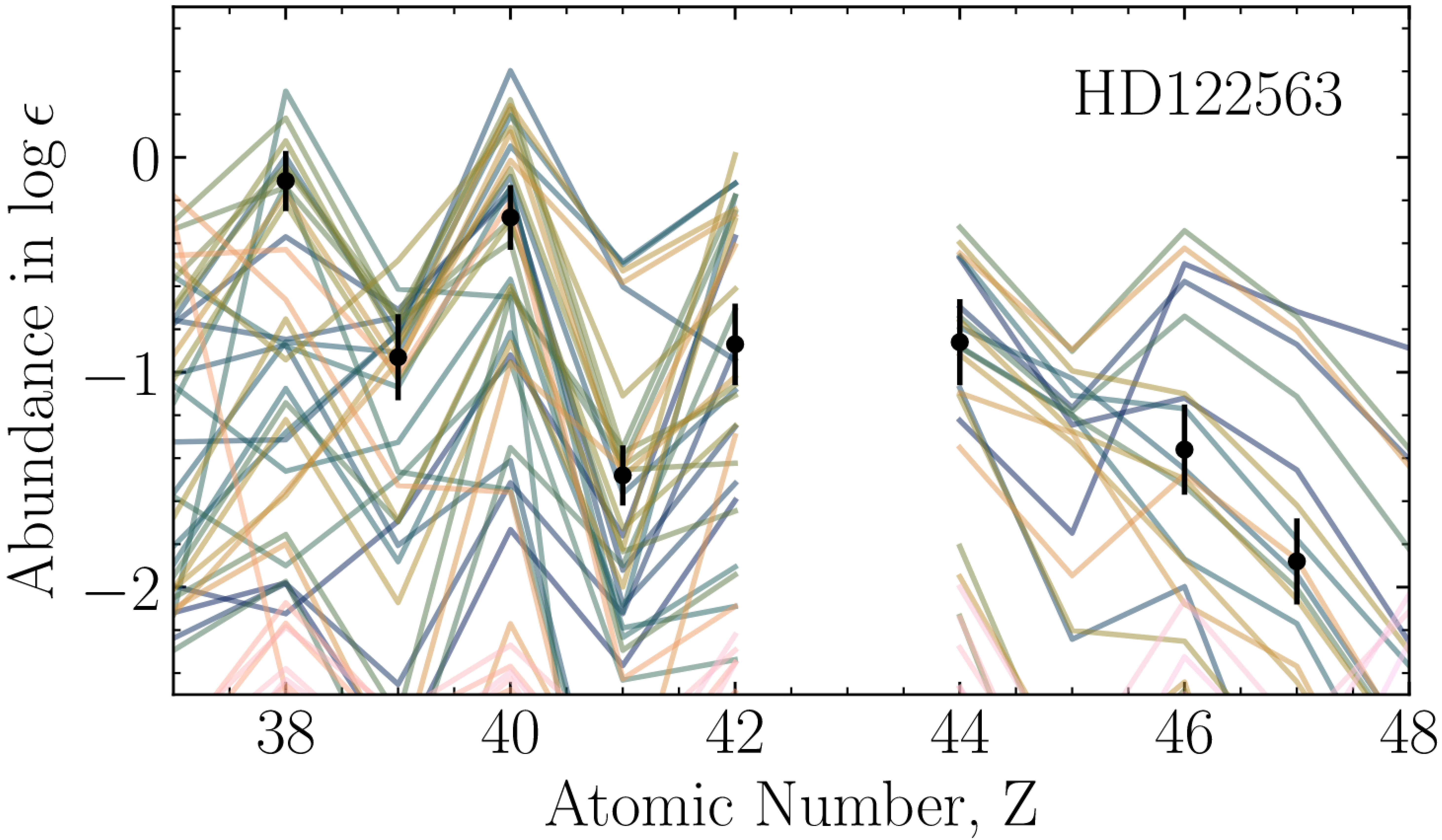
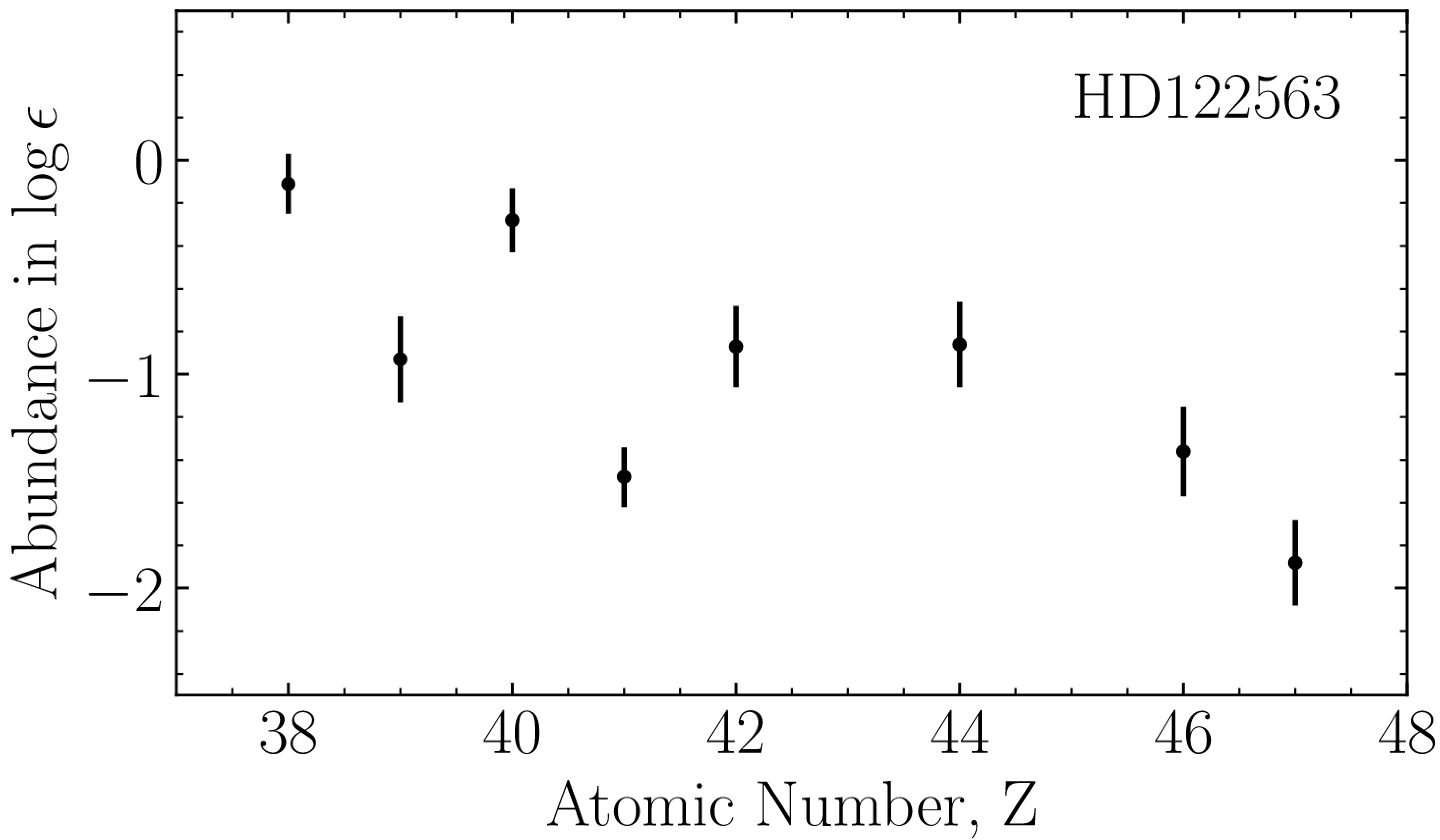


Results for HD122563 using two trajectories



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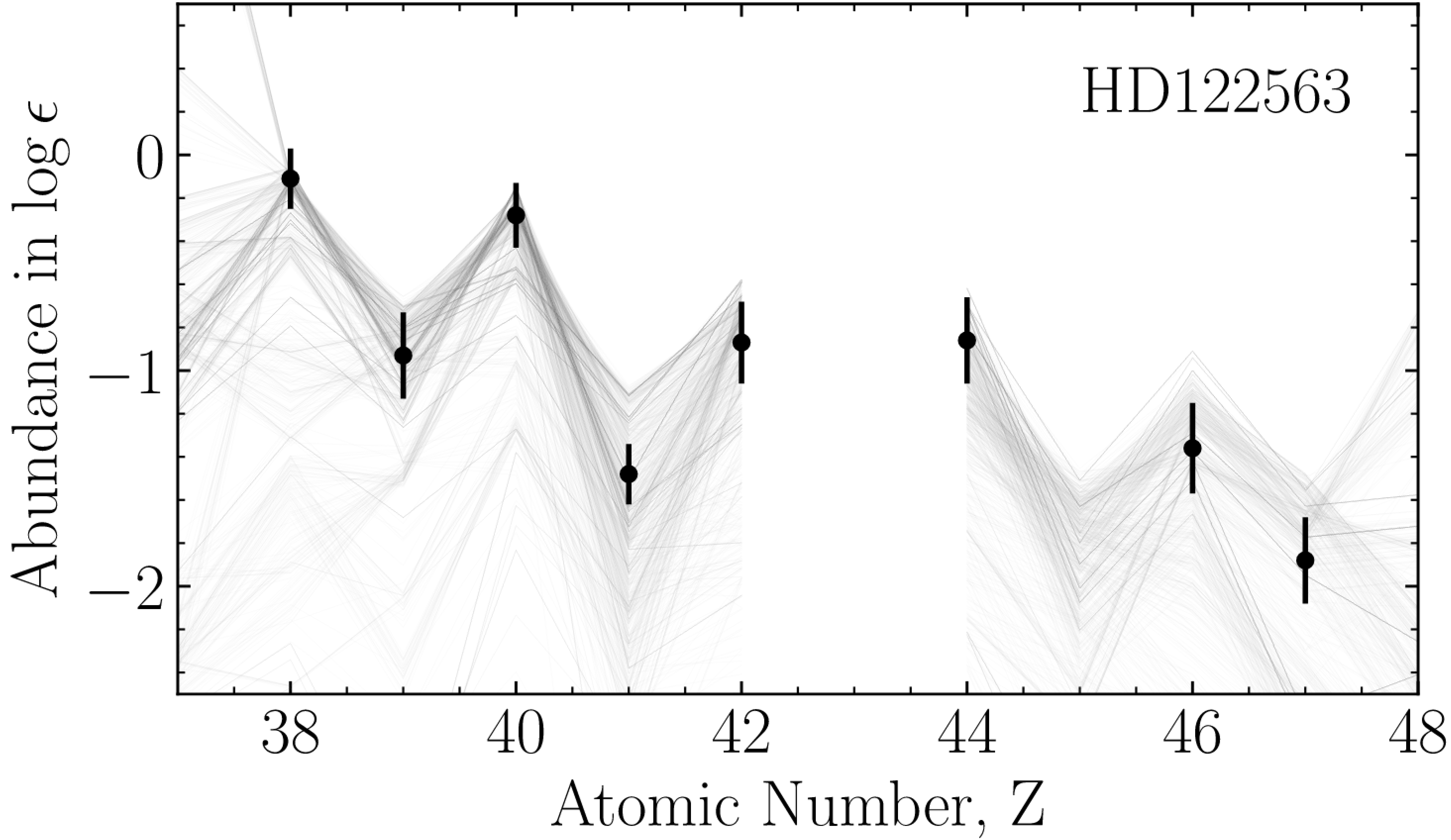

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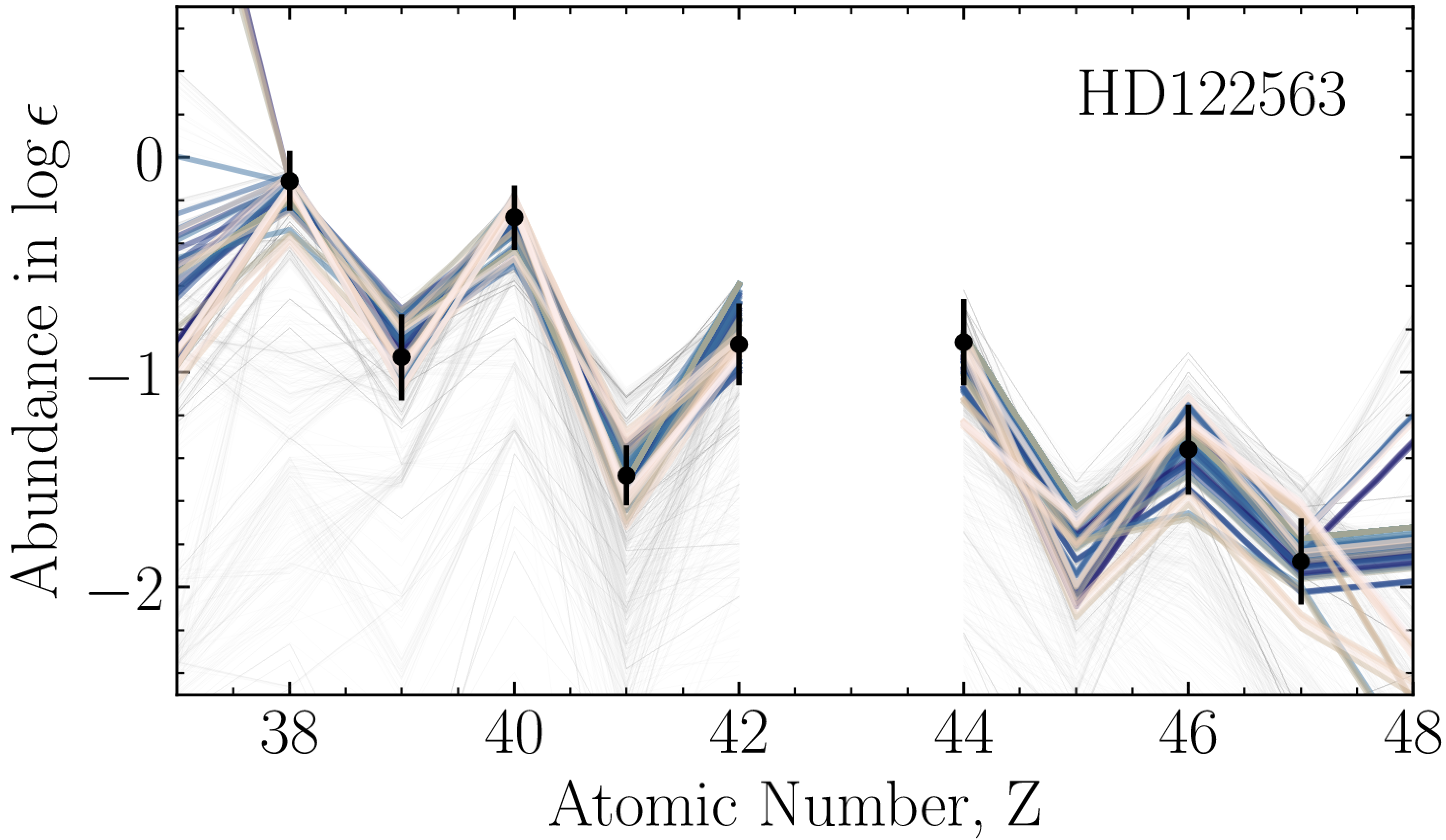
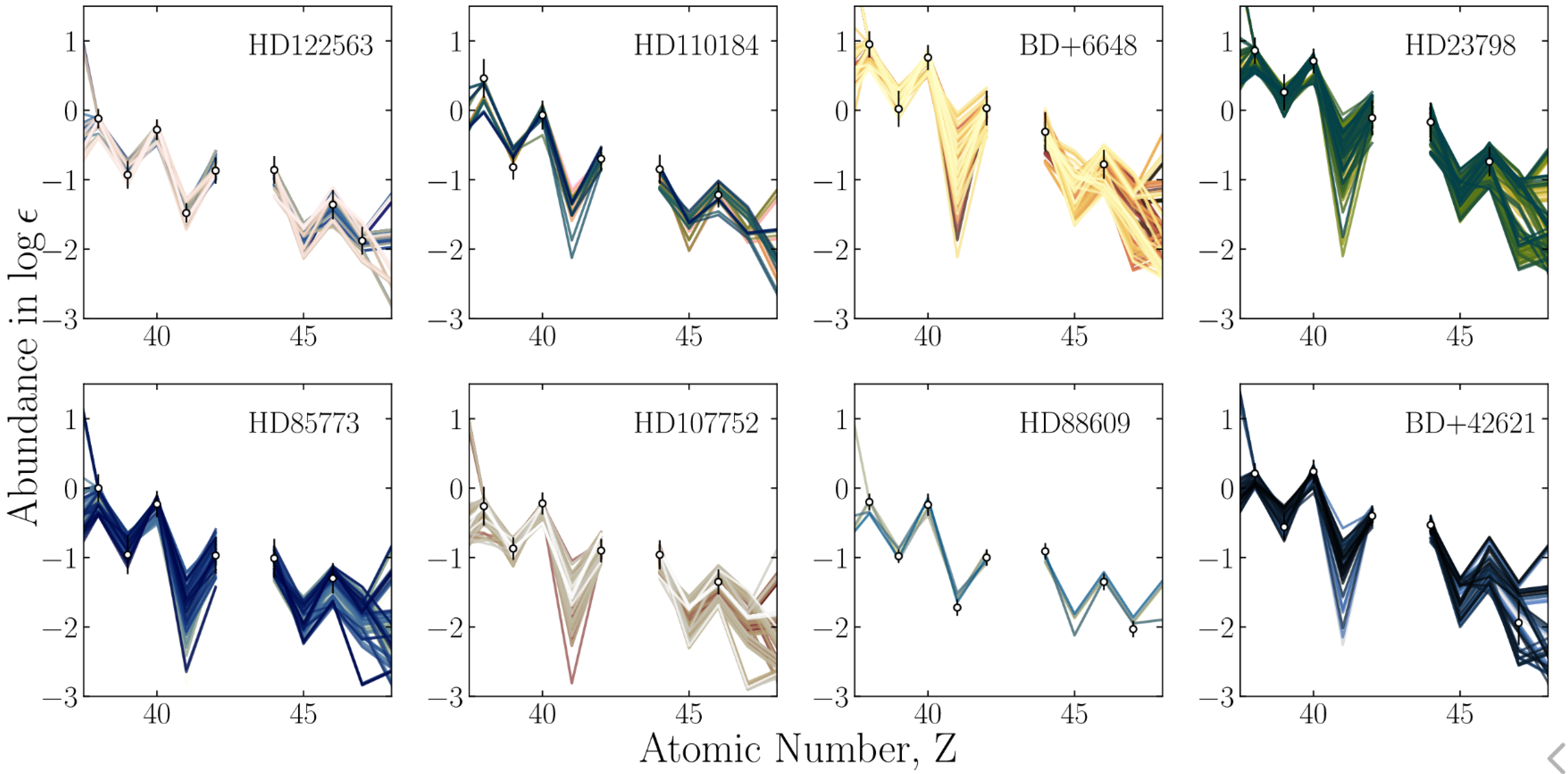
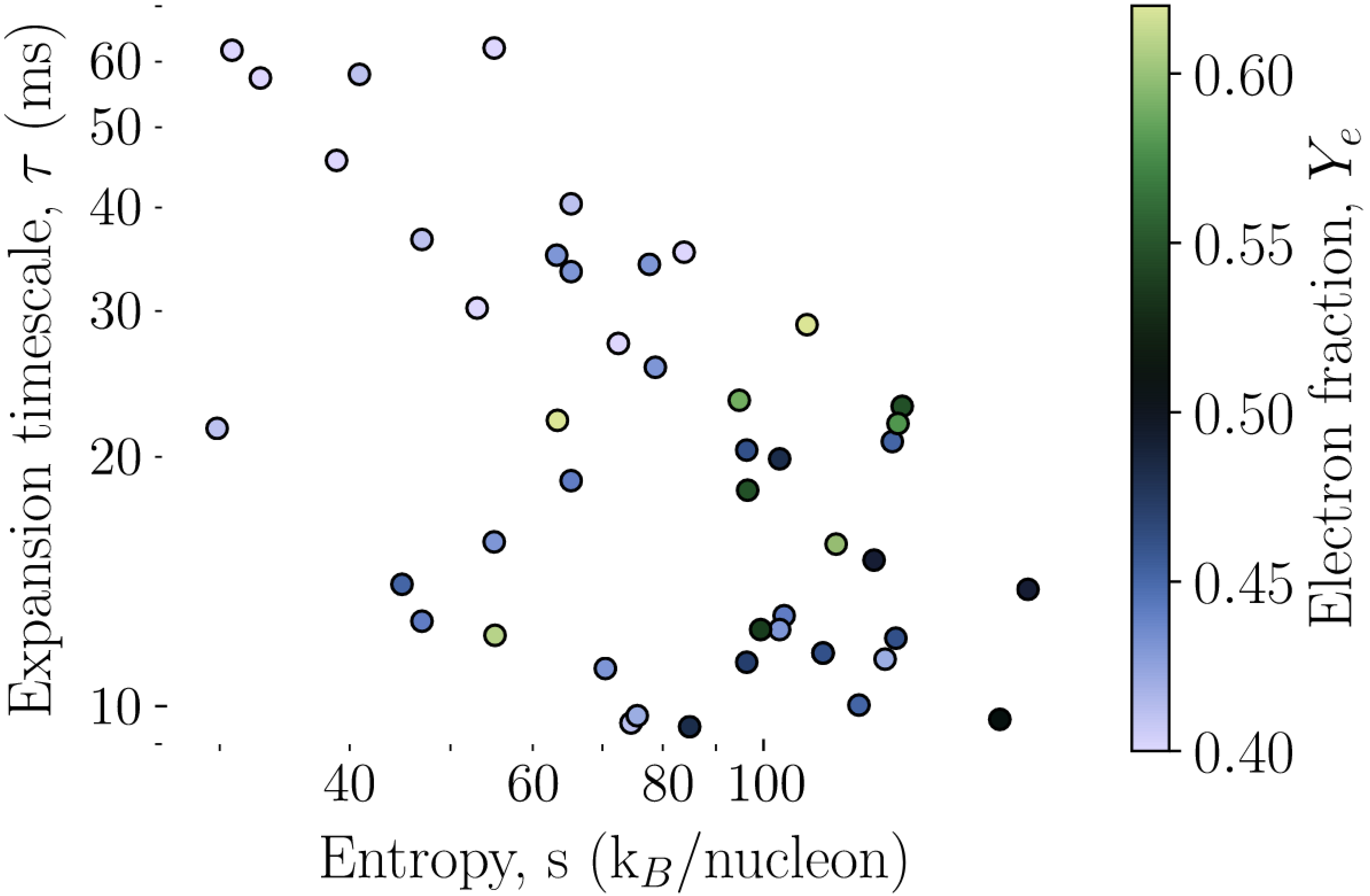


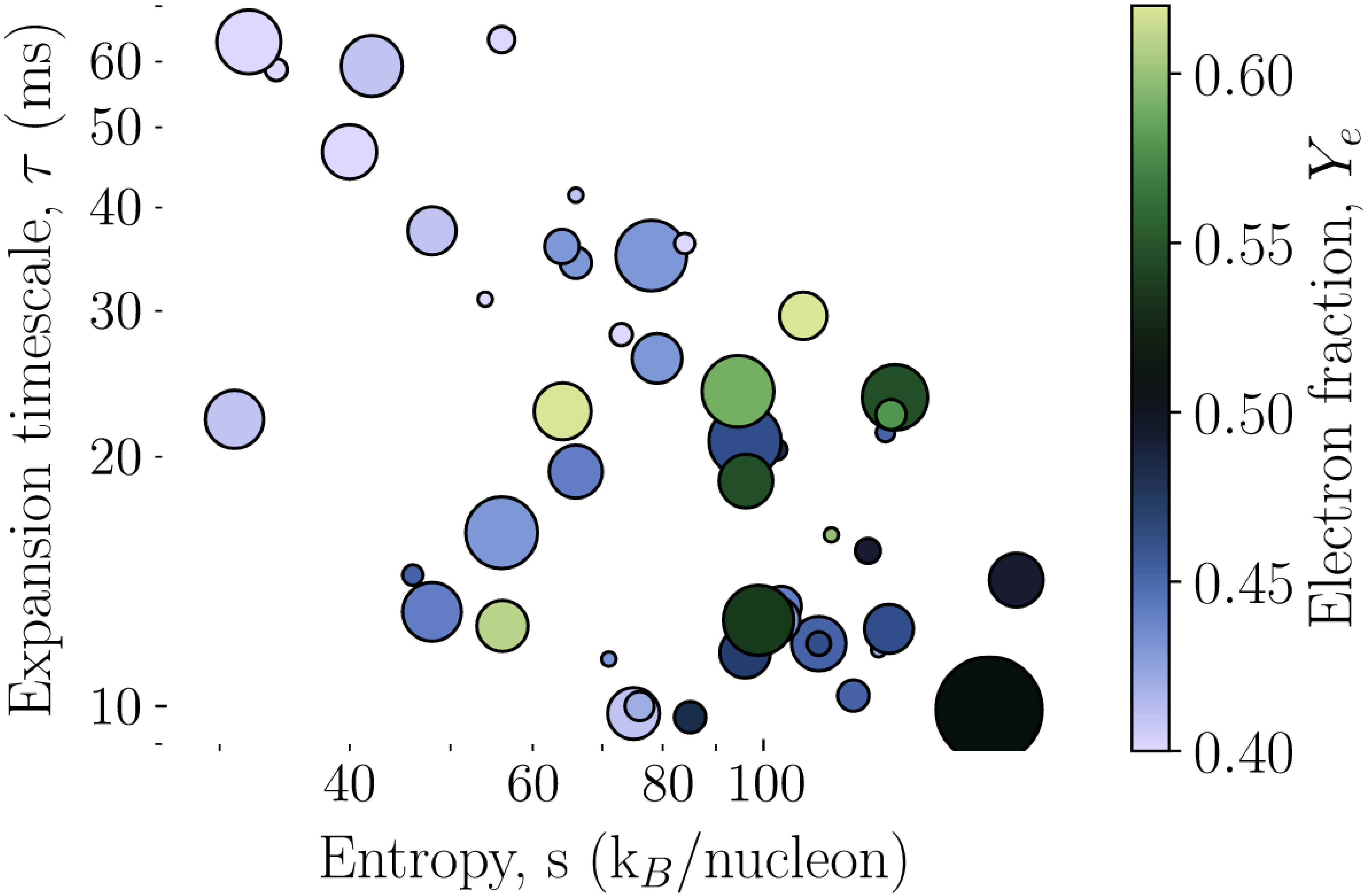
Results using two trajectories for our star sample





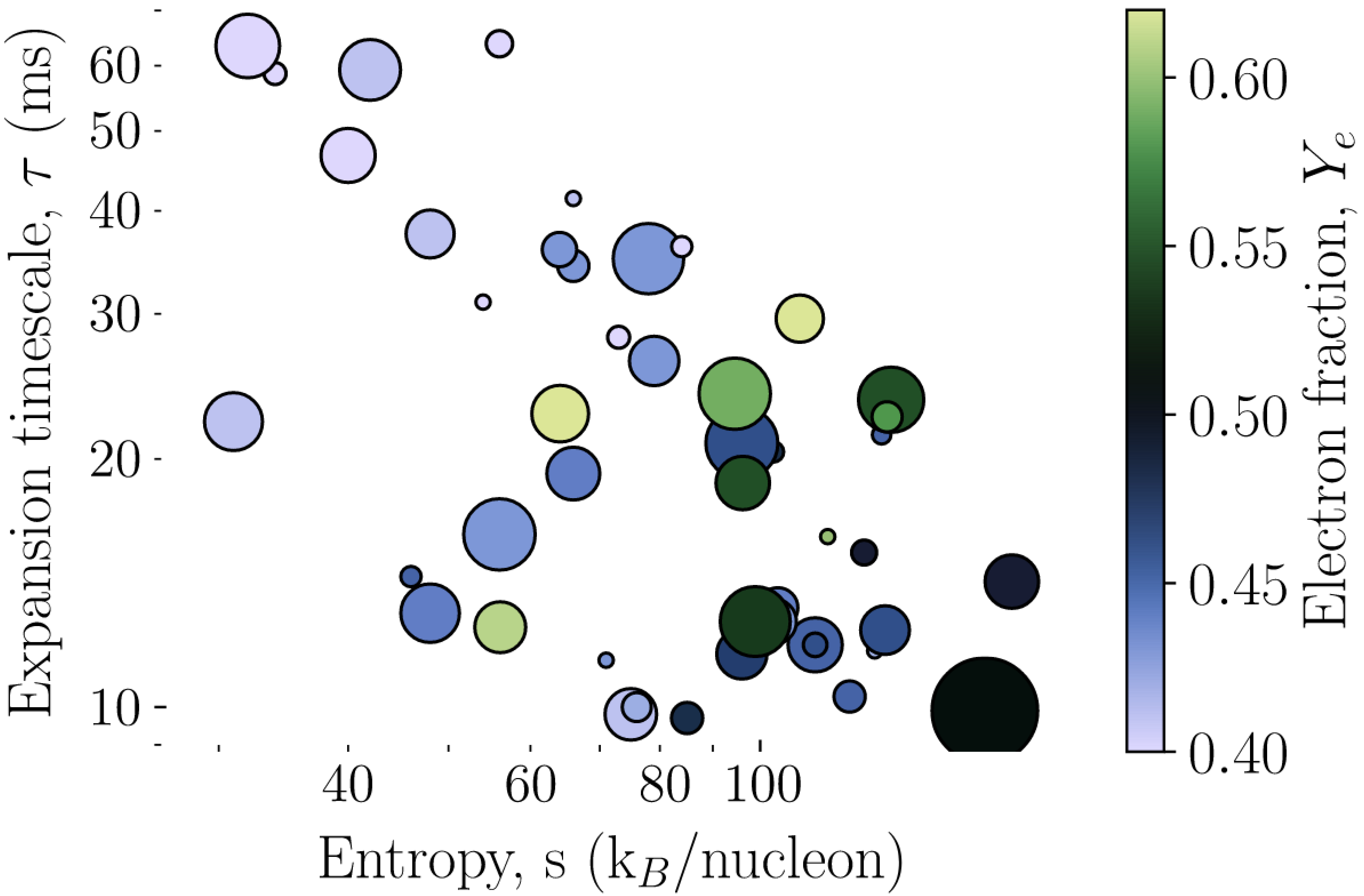
Expansion timescale, τ (ms)
60
50
40
30
20
10
40
60
80
100
Entropy, s (k_B/nucleon)
0.60
0.55
0.50
0.45
0.40
Electron fraction, Y_e

Proton-rich conditions are more favourable than neutron-rich



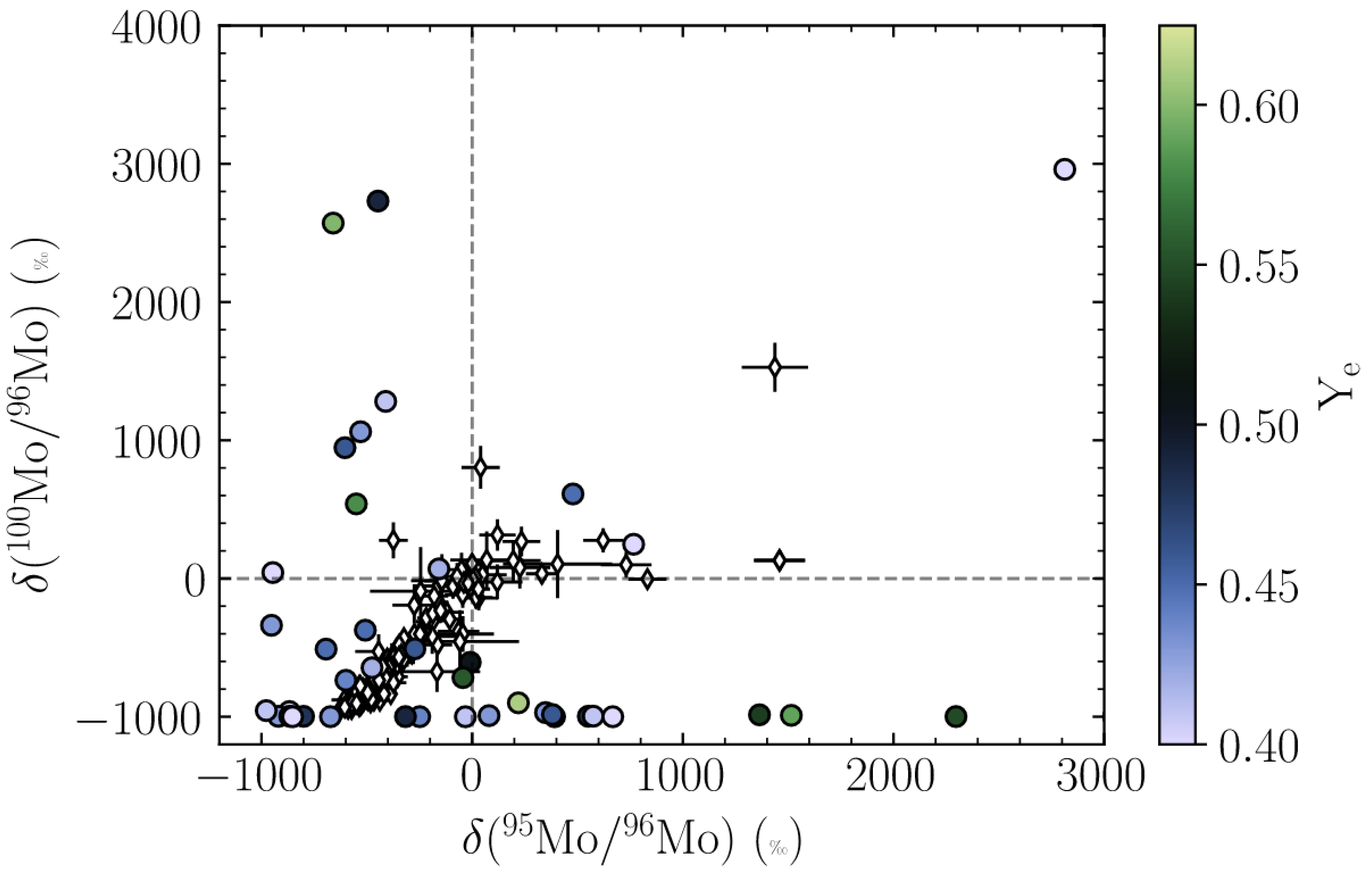
Proton-rich conditions are more favourable than neutron-rich

High entropy and short expansion timescale is preferred



Can *isotopic* abundances from meteorites reveal neutrino-driven nucleosynthesis signatures?

Secrets in the stardust?



A. Psaltis, W.J. Ong *et al.* (in preparation)

What is on the horizon?

New **experimental measurements** of the key (α, xn) reactions and **multi-messenger observations** will help us constrain the contribution of neutrino-driven outflows to the production elements between strontium and silver.

Acknowledgements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Fernando Montes


Wei Jia Ong


Hendrik Schatz

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erc European Research Council Established by the European Commission

EL EM EN TS

Summary

1. The weak r-process in neutrino-driven outflows can contribute to the production of elements between strontium and silver that are observed in Galactic metal-poor stars.

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3. We investigated which are the most common astrophysical conditions of the neutrino-driven outflows that fit the observational patterns of metal-poor stars.

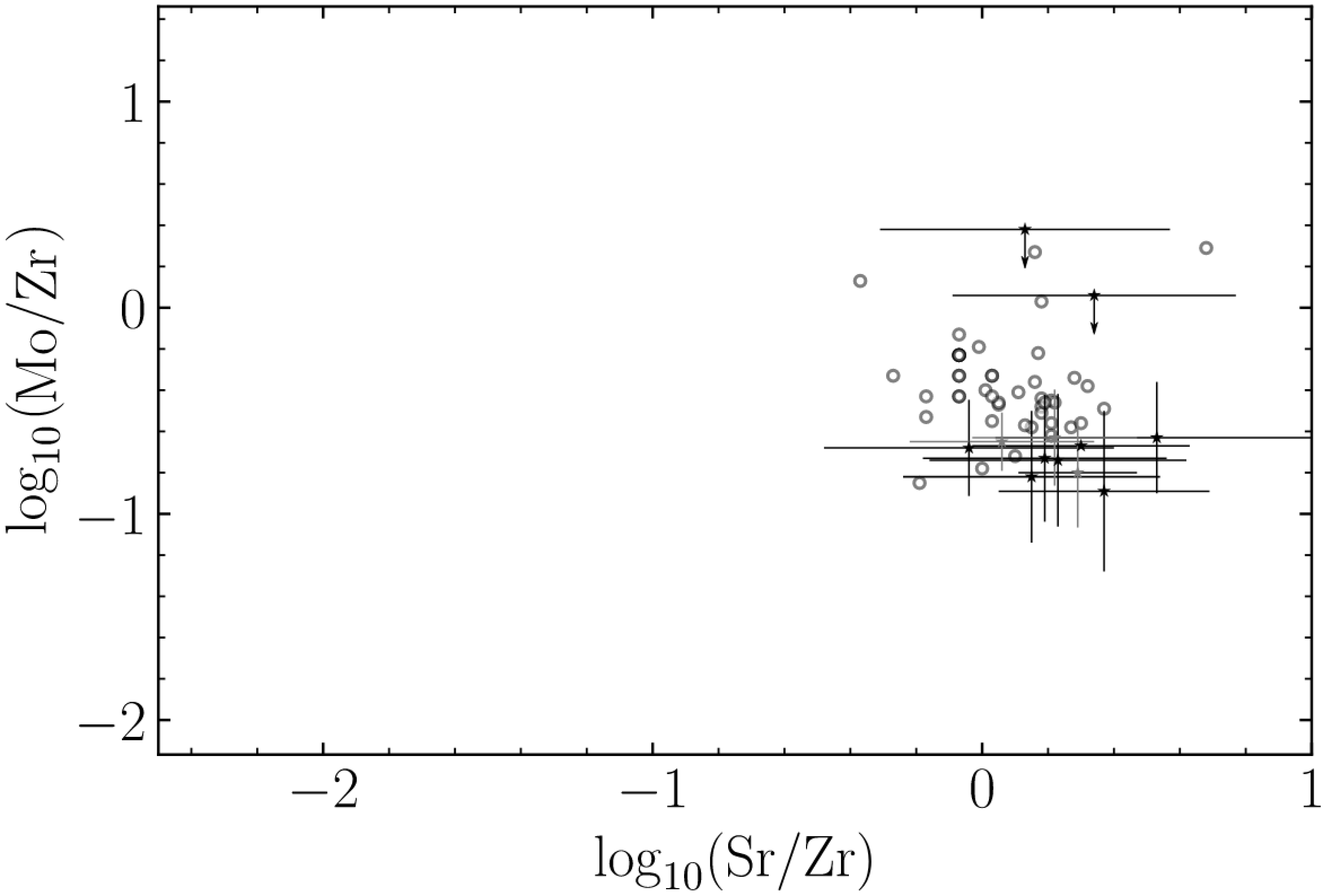
4. Experiments in the current and next-generation RIB facilities, multimessenger observations and theoretical modeling will enhance our understanding of the origin of the light heavy elements.

Thank you!

Slides available at http://psaltisa.github.io/talks

Extra slides

Combine observations, astrophysical modeling and nuclear physics uncertainties



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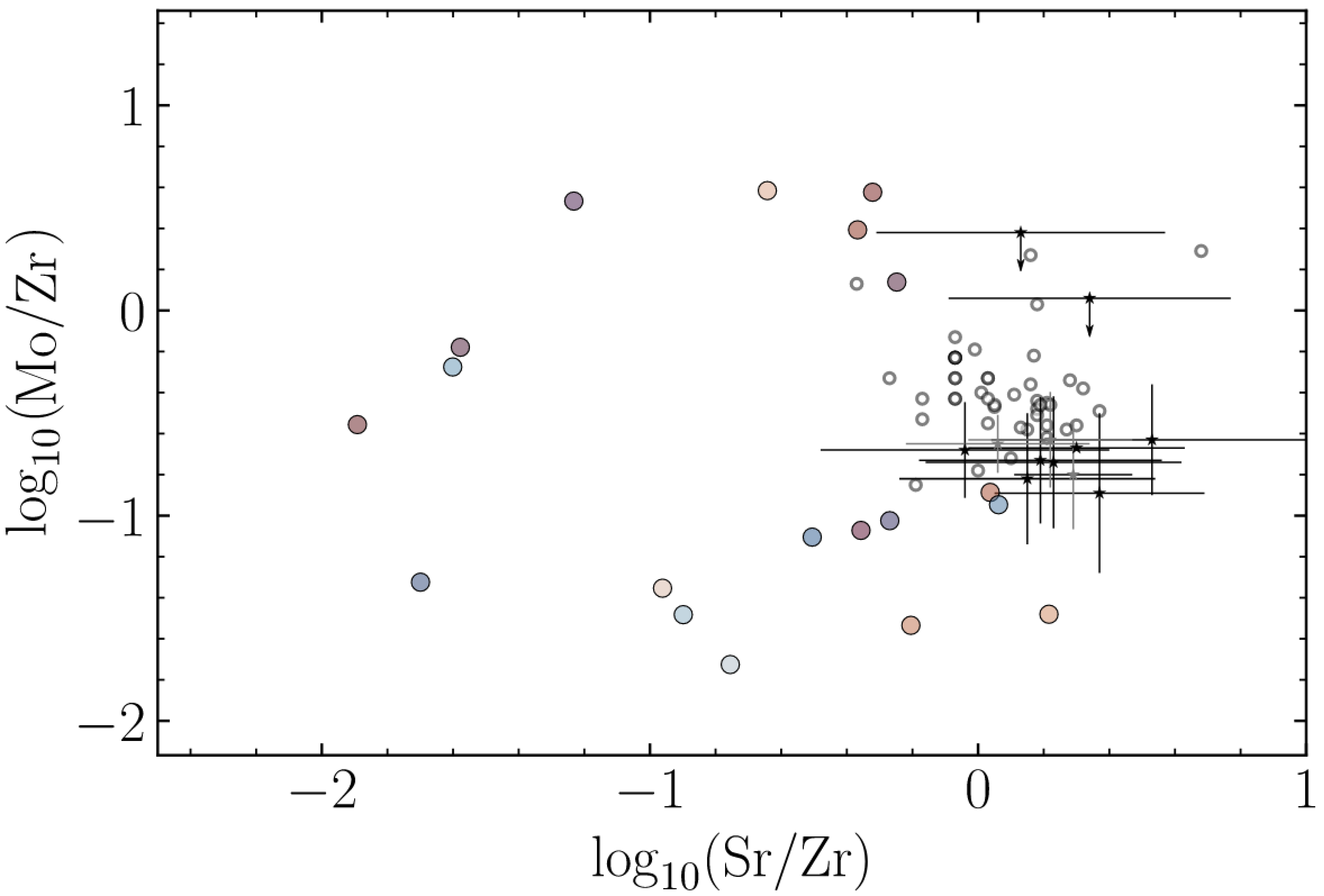

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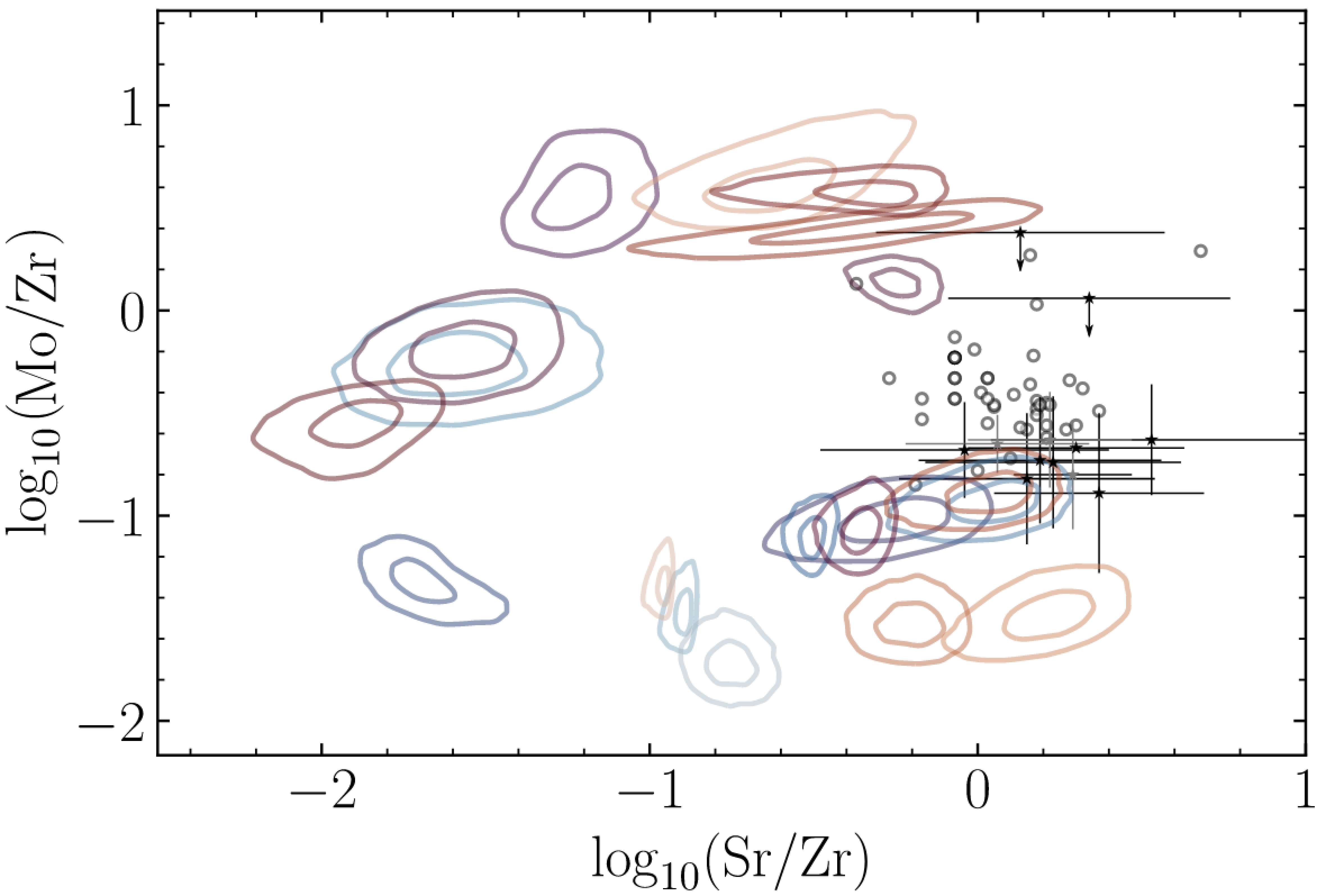

$^{93}\mathrm{Sr}(\alpha, xn)$ at Argonne with MUSIC

M. L. Avila *et al.*, NIM A **859**, 63 (2017)

- Re-accelerated $^{93}\mathrm{Sr}$ beam from νCARIBU.
- MUSIC has close to 100% efficiency due to its segmented anode structure.
- Use a single beam energy to measure a large range of excitation functions of angle integrated cross sections.

Methods

We formed linear combinations using various astrophysical conditions (Y_e, s, τ) to compare with observations of metal-poor stars.

$$P = \sum_{i=1}^{N} w_i Y_i$$

where $w_i > 0$ is a multiplication factor and Y_i is the abundance pattern of the i^{th} trajectory.

Total number of unique combinations: $C_r = N!/r!(N-r)!$

for example 2 trajectories out of 46 yields 1035 unique combinations

Methods

$$\text{minimize } ||Aw - O||^2$$

where O is the observational pattern and

$$A = \begin{bmatrix} Y_{11} & \cdots & Y_{1k} \\ \vdots & \ddots & \vdots \\ Y_{N1} & \cdots & Y_{Nk} \end{bmatrix}, w = \begin{bmatrix} w_1 \\ \vdots \\ w_k \end{bmatrix}$$

Goal: solve the least-squares problem using **`sklearn`**