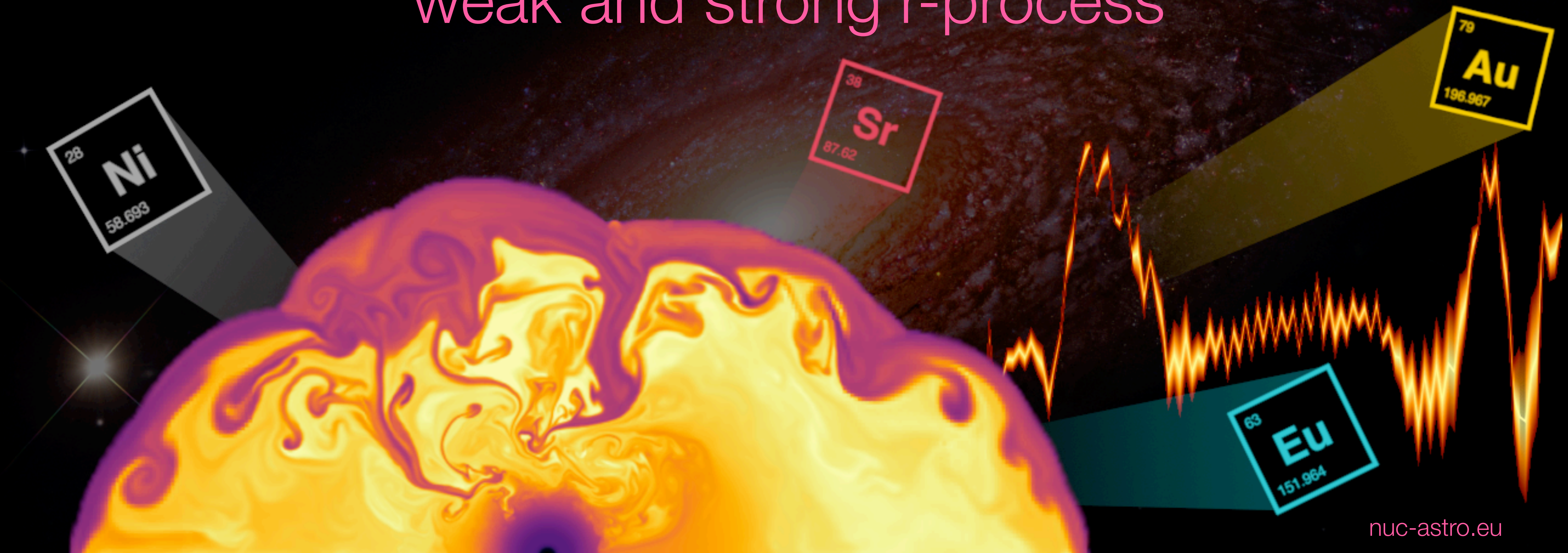


Nuclear physics uncertainties in the weak and strong r-process



nuc-astro.eu

NEUTRON-CAPTURE REACTIONS
FOR ASTROPHYSICAL PROCESSES

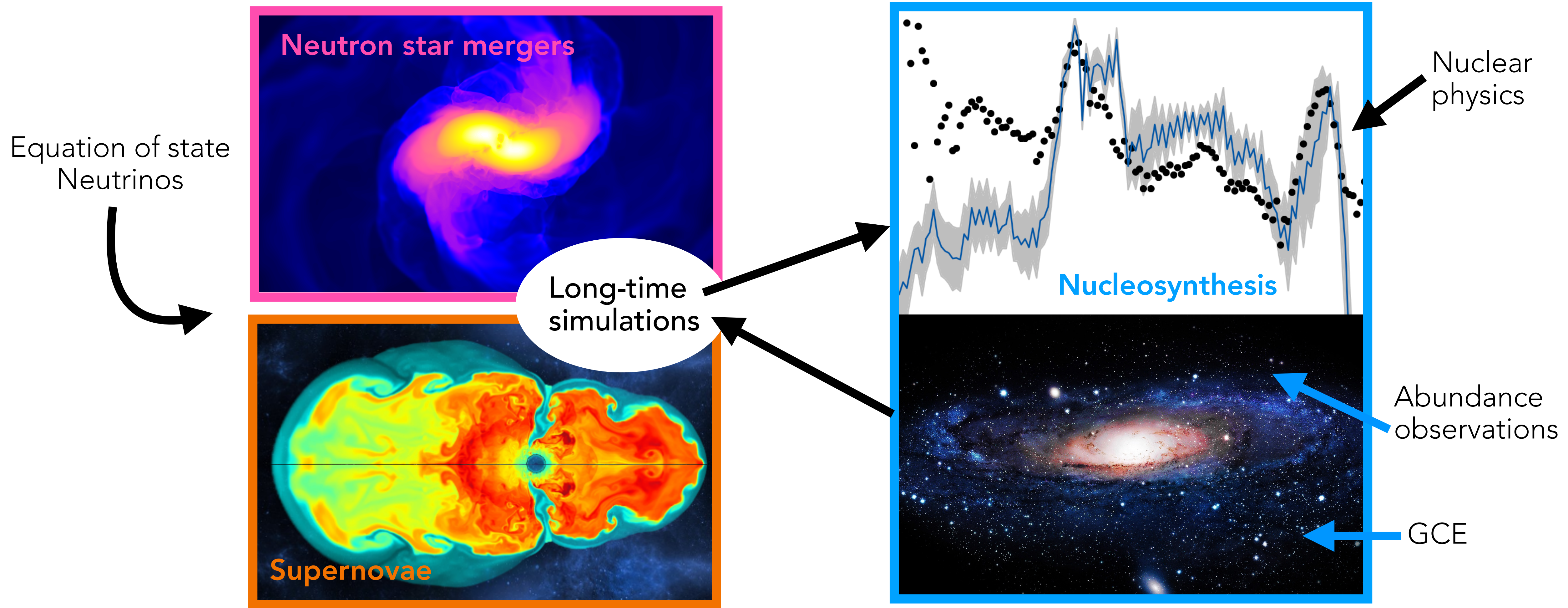
Almudena Arcones



TECHNISCHE
UNIVERSITÄT
DARMSTADT



Connecting astrophysics and nuclear physics



Nucleosynthesis network



<https://github.com/nuc-astro>
Reichert et al. 2023

$$\frac{dY}{dt} = \dot{Y}(Z, N) =$$

$$\lambda_{(n,\gamma)} Y(Z, N-1) + \lambda_{(\gamma,n)} Y(Z, N+1) + \lambda_{\beta} Y(Z-1, N-1)$$

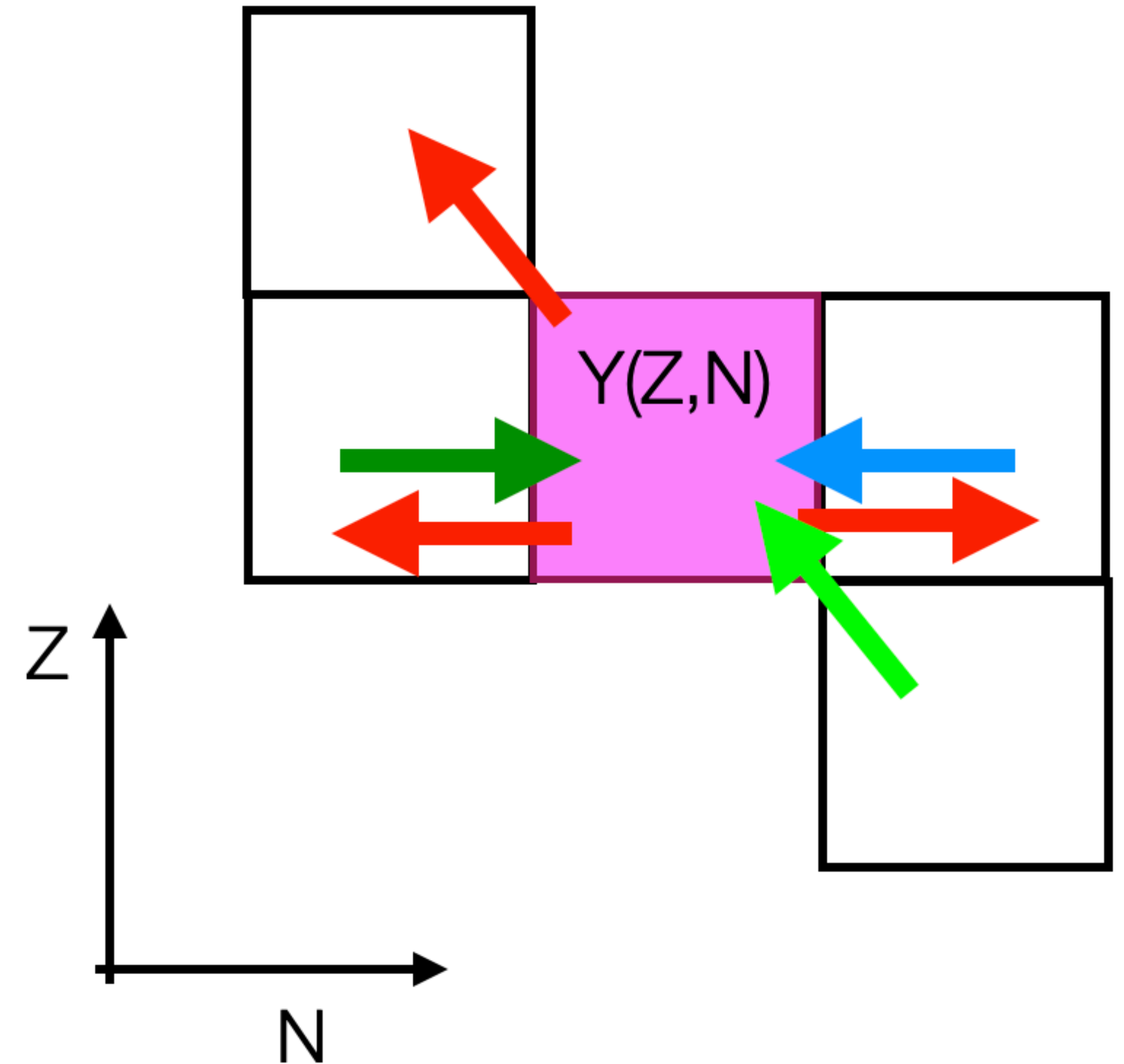
$$-(\lambda_{(n,\gamma)} + \lambda_{(\gamma,n)} + \lambda_{\beta}) Y(Z, N)$$

Nuclear physics:

masses, beta decays, reaction rates,
fission (barriers and yield distribution)

Astrophysics:

density and temperature evolution: $\rho(t), T(t)$
initial composition (at high T: NSE $\Rightarrow Y(Z, N) = f(\rho, T, Y_e)$)



Nucleosynthesis network



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Reichert et al. 2023

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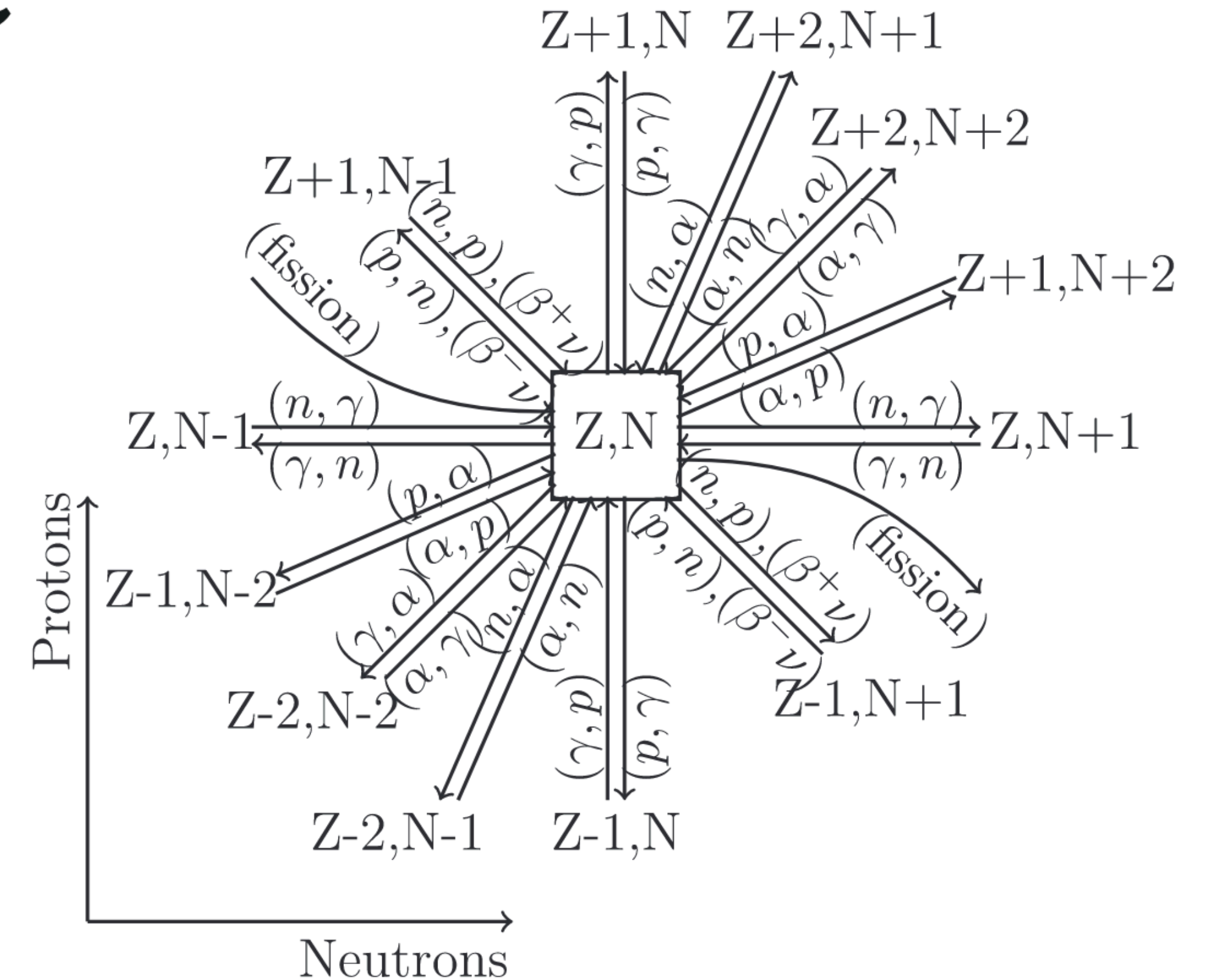
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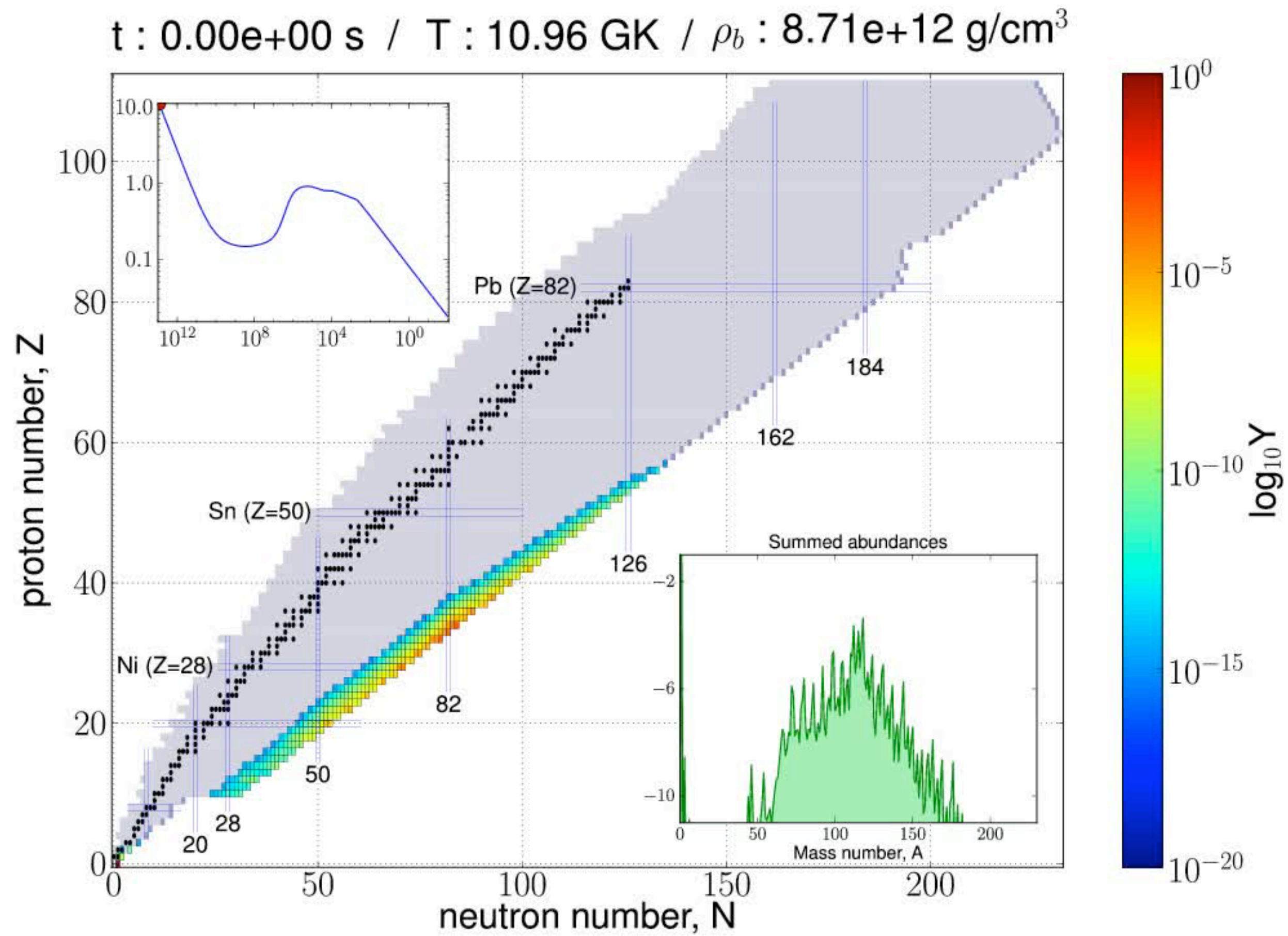
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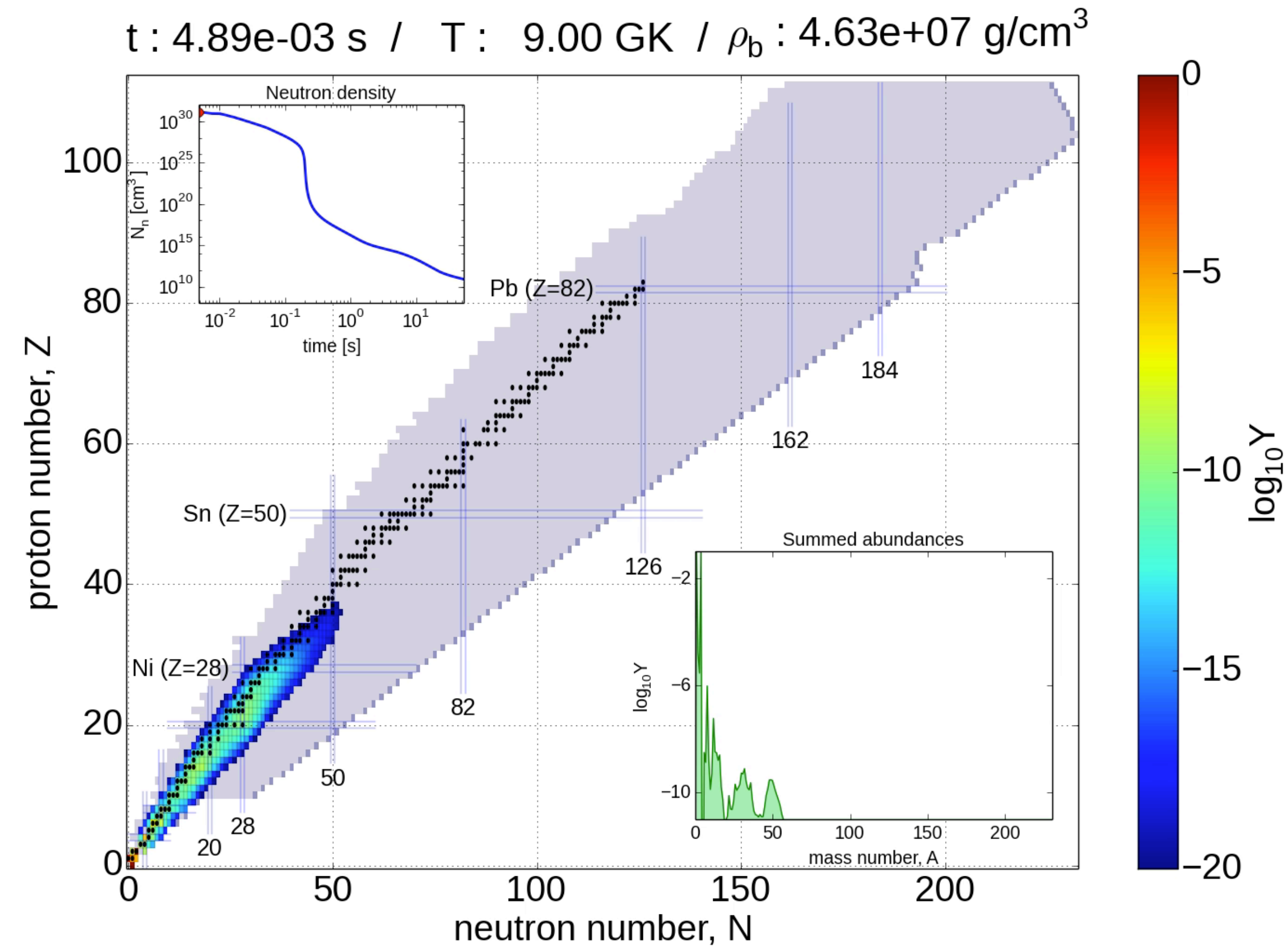
R-processes

Strong r-process



Korobkin et al. MNRAS (2012)

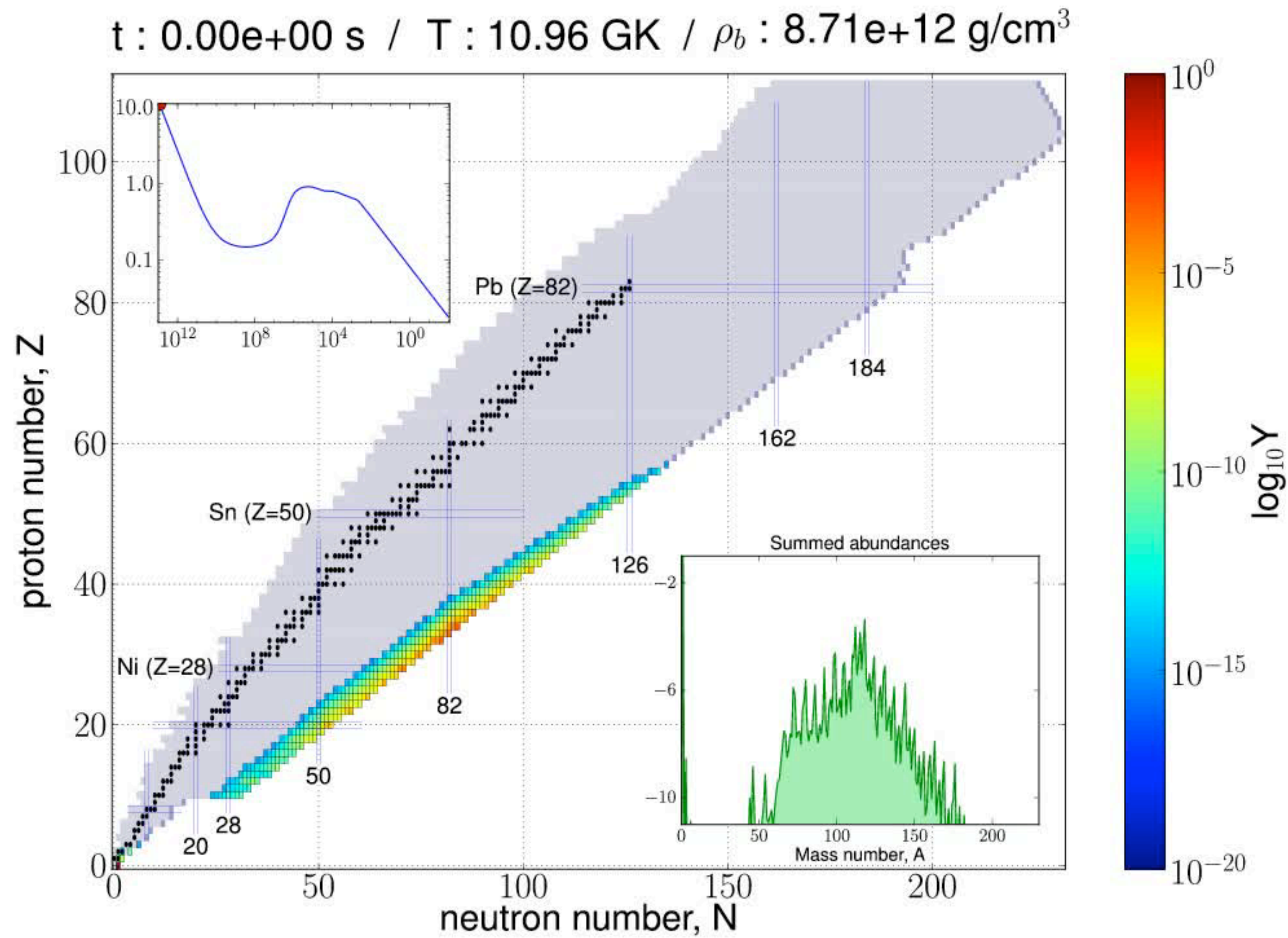
Weak r-process



Martin et al. ApJ (2015), Perego et al. MNRAS (2014)

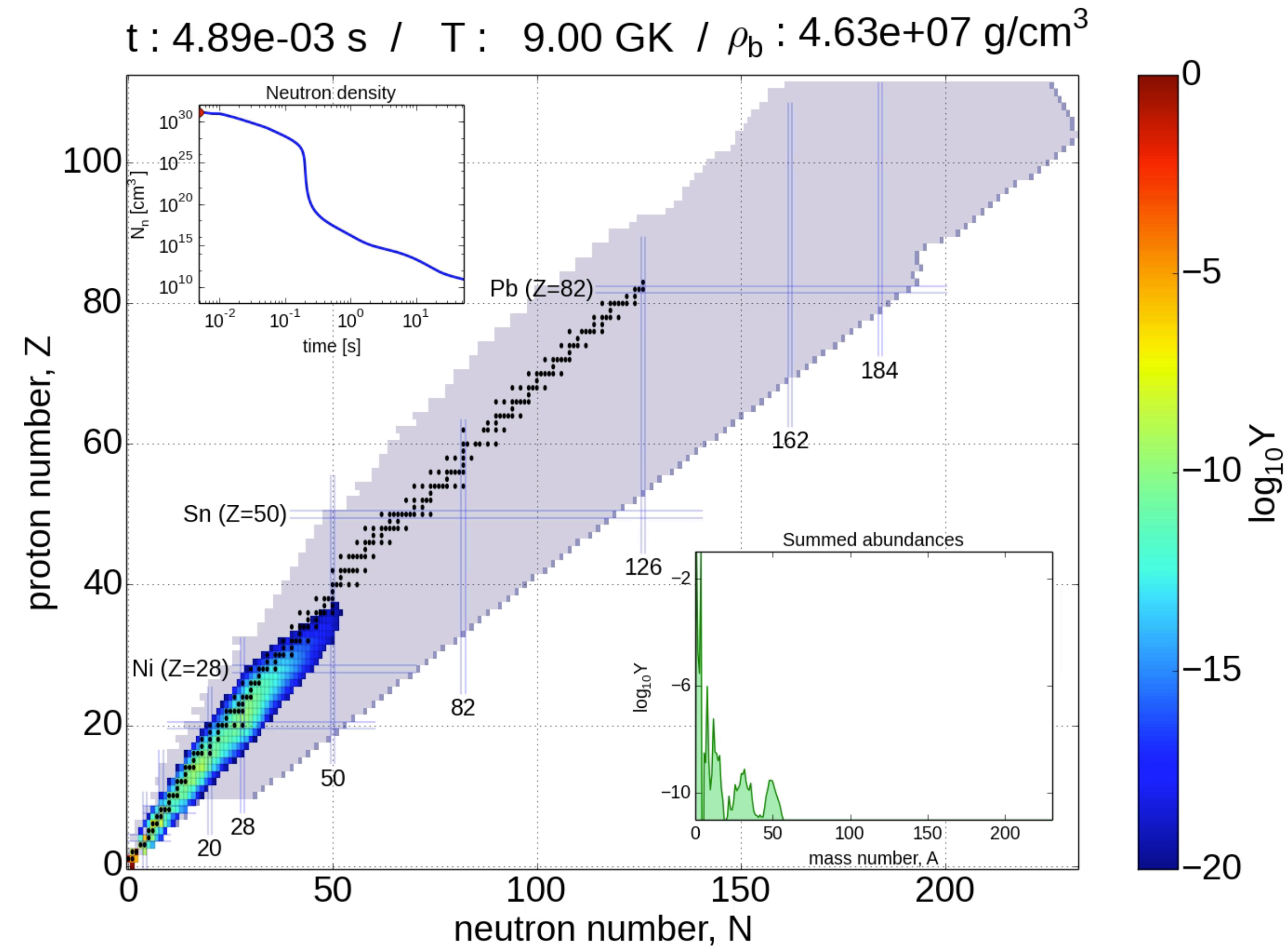
R-processes

Strong r-process



Korobkin et al. MNRAS (2012)

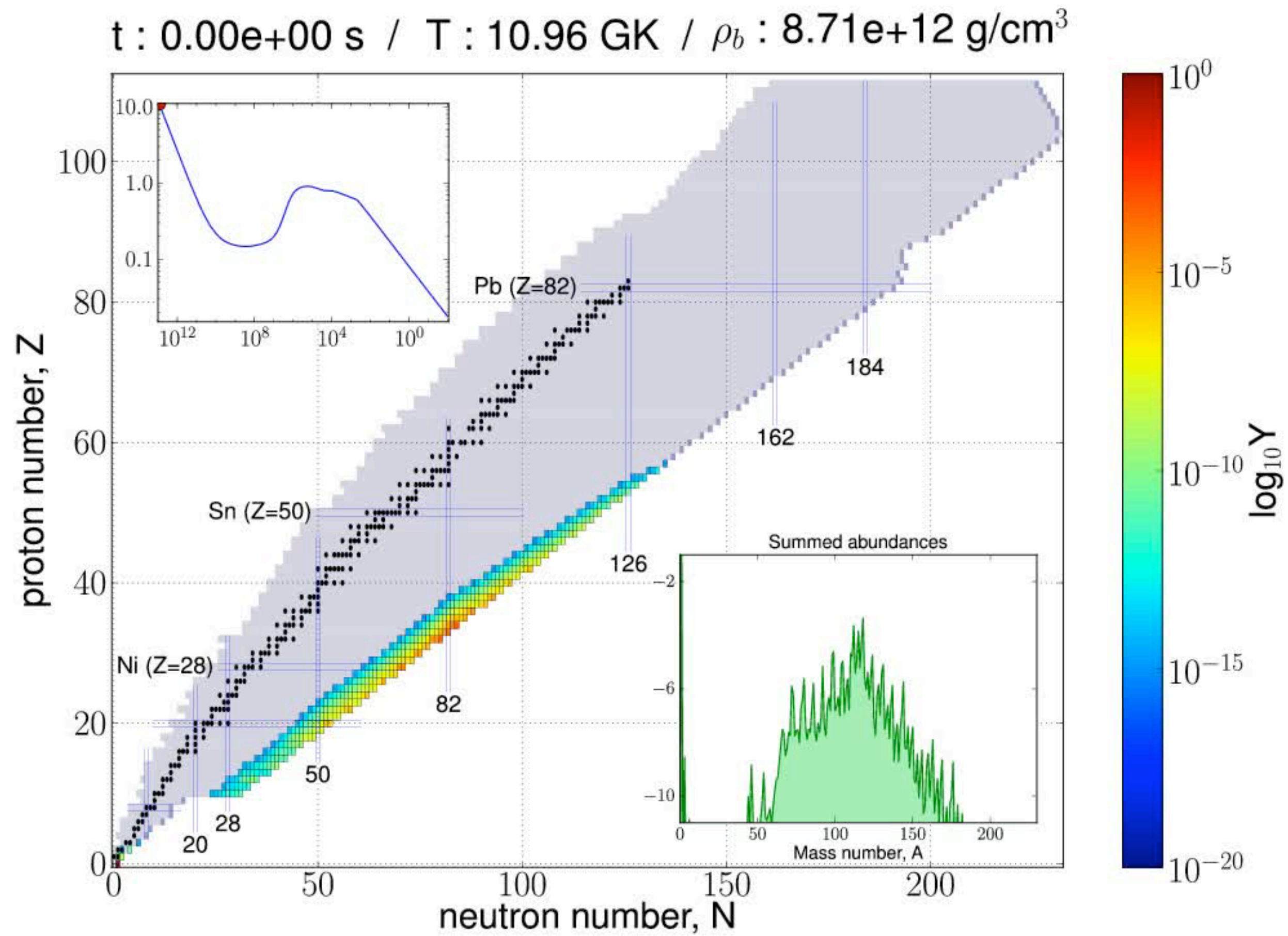
Weak r-process



Martin et al. ApJ (2015), Perego et al. MNRAS (2014)

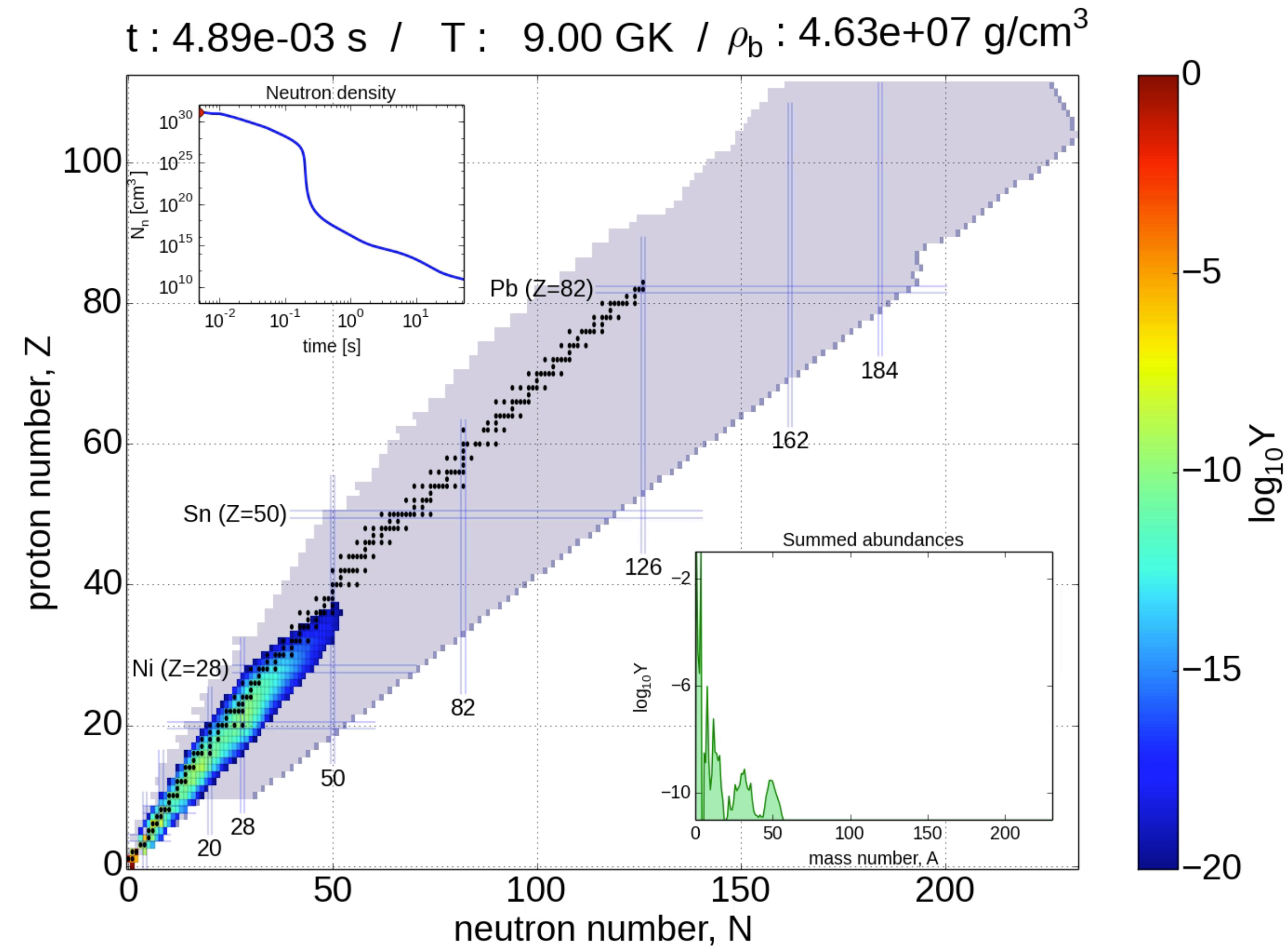
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Strong r-process



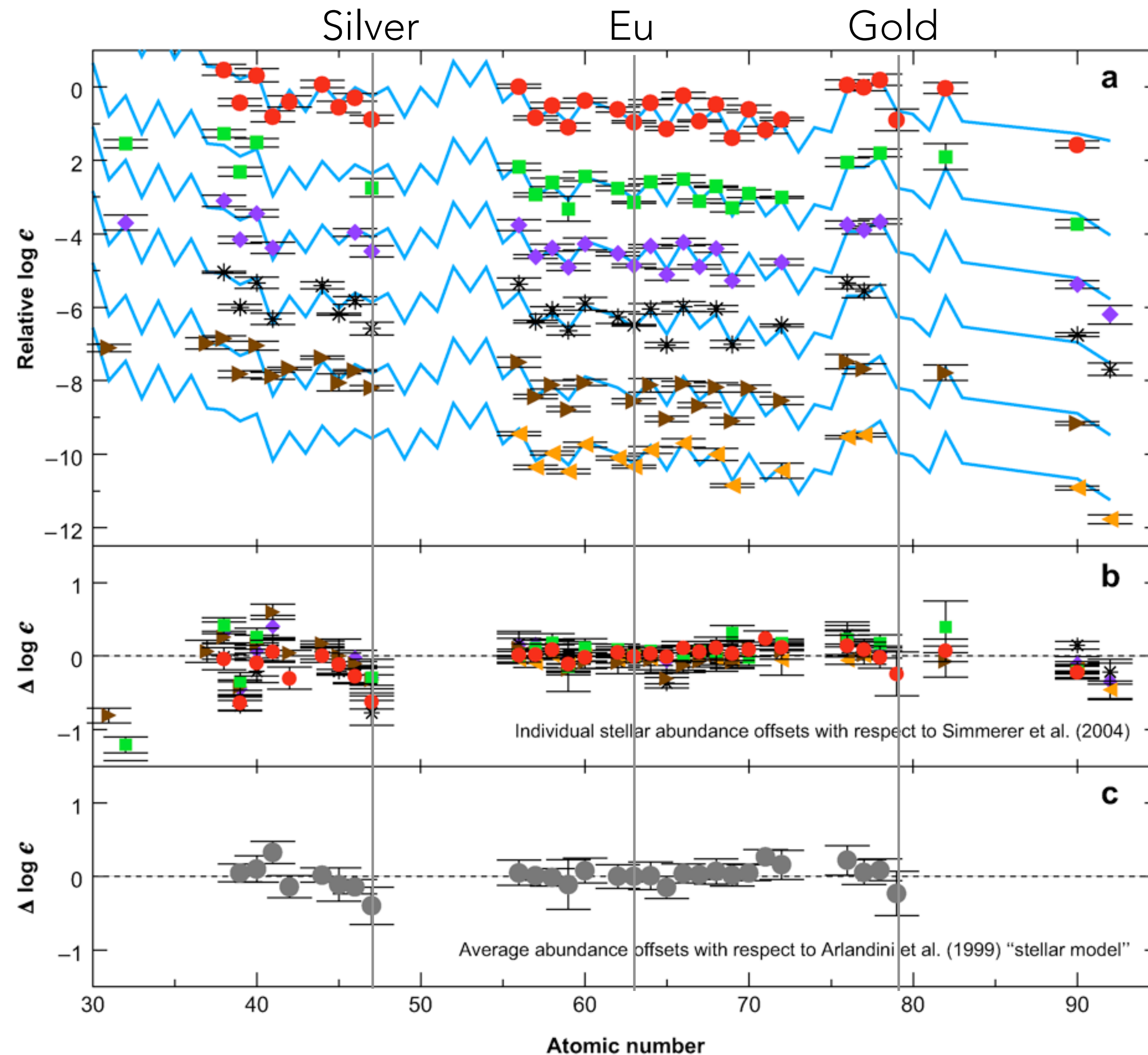
Korobkin et al. MNRAS (2012)

Weak r-process



Martin et al. ApJ (2015), Perego et al. MNRAS (2014)

R-process in ultra metal-poor stars



Abundances of r-process elements:

- ultra metal-poor stars and

- r-process solar system: $N_{\text{solar}} - N_s$

Robust r-process for $56 < Z < 83$

Scatter for lighter heavy elements, $Z \sim 40$

Ac-boost stars

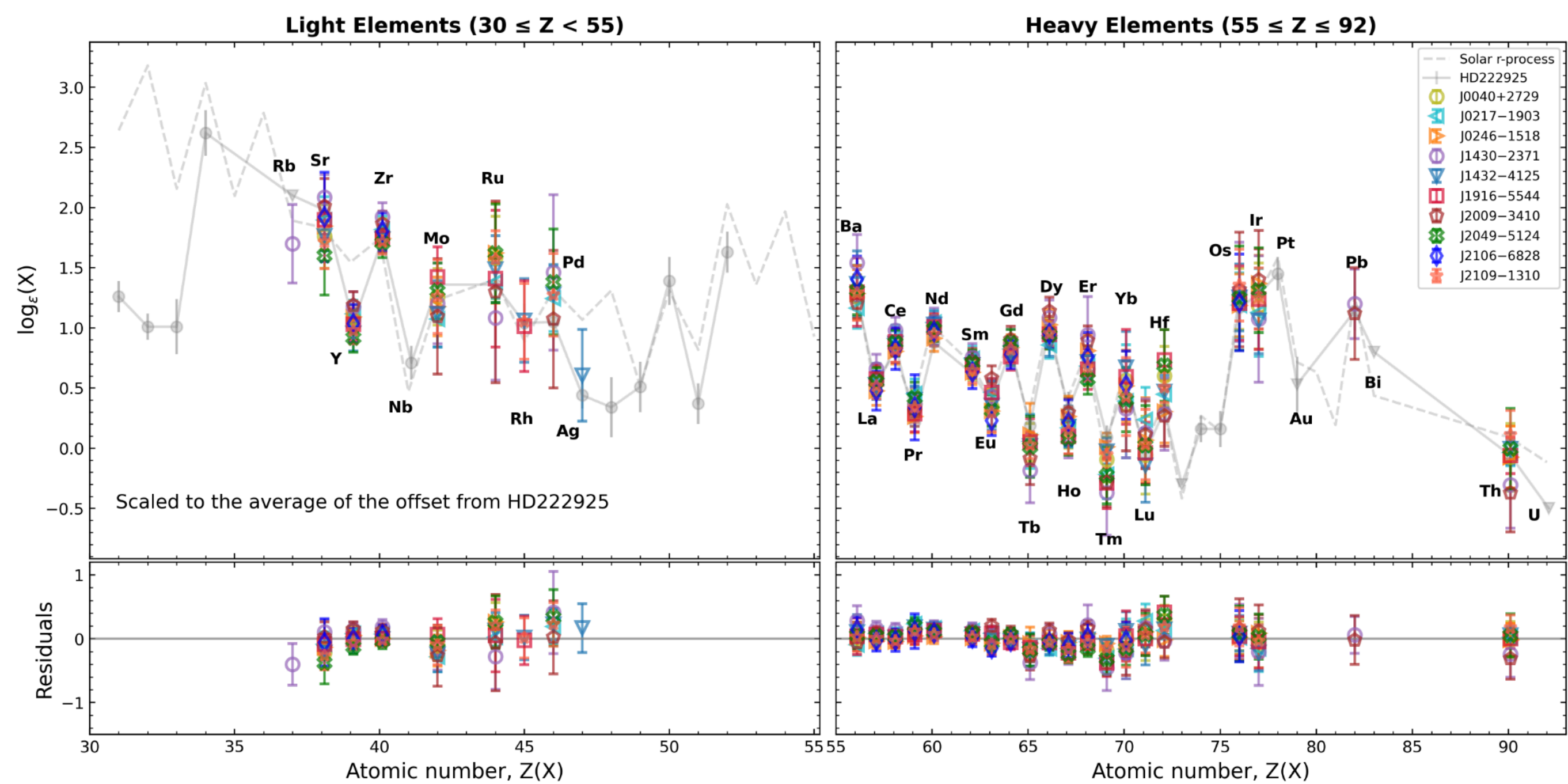
(Eichler et al. 2019, Holmbeck et al. 2018)

Sneden, Cowan, Gallino 2008

- CS 22892-052: Sneden et al. (2003)
- HD 115444: Westin et al. (2000)
- ◆ BD+17°324817: Cowan et al. (2002)
- * CS 31082-001: Hill et al. (2002)
- ▲ HD 221170: Ivans et al. (2006)
- ▼ HE 1523-0901: Frebel et al. (2007)

$$\log(\epsilon(E)) = \log(N_E/N_H) + 12$$

R-process in ultra metal-poor stars



Abundances of r-process elements:

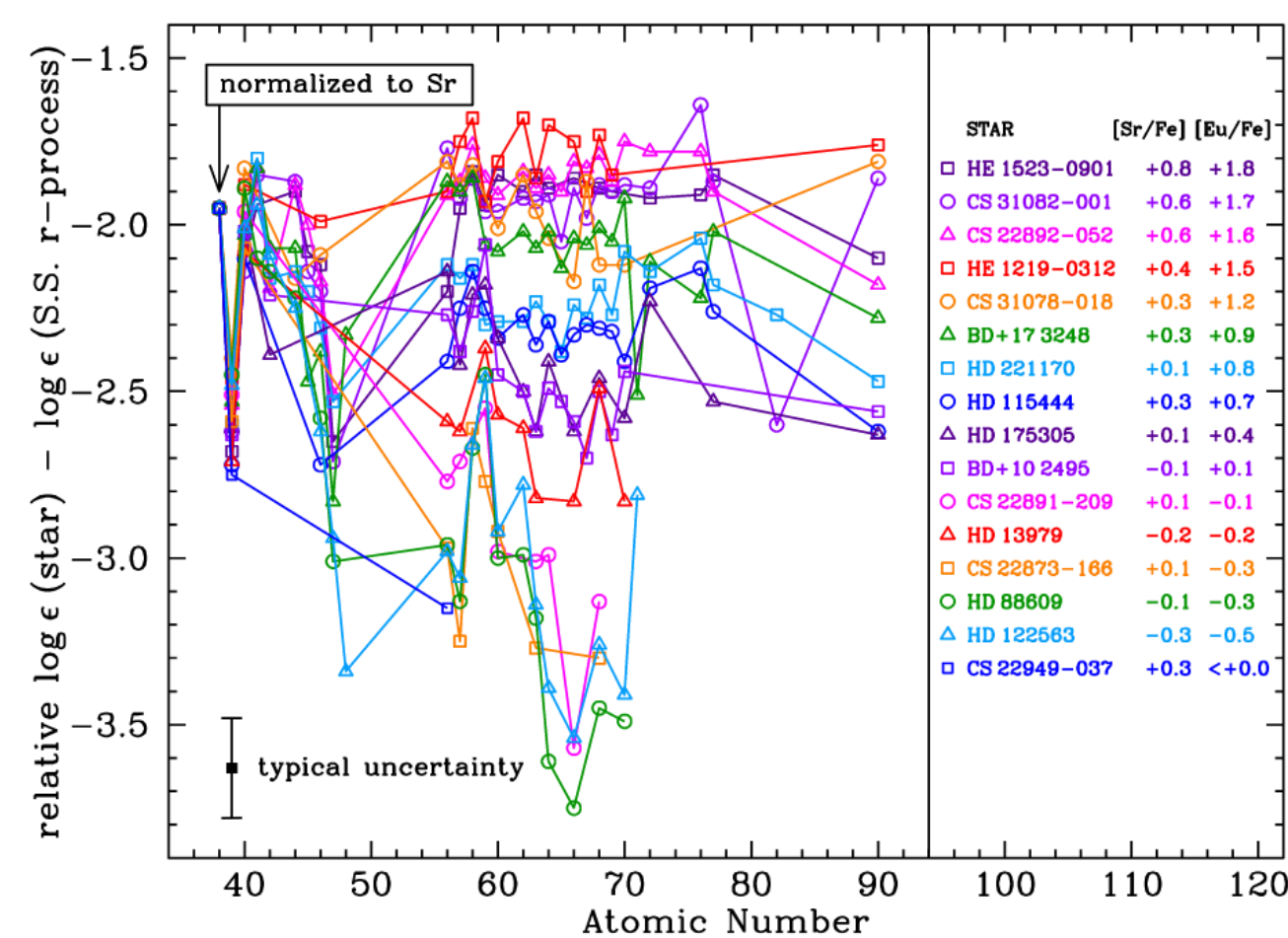
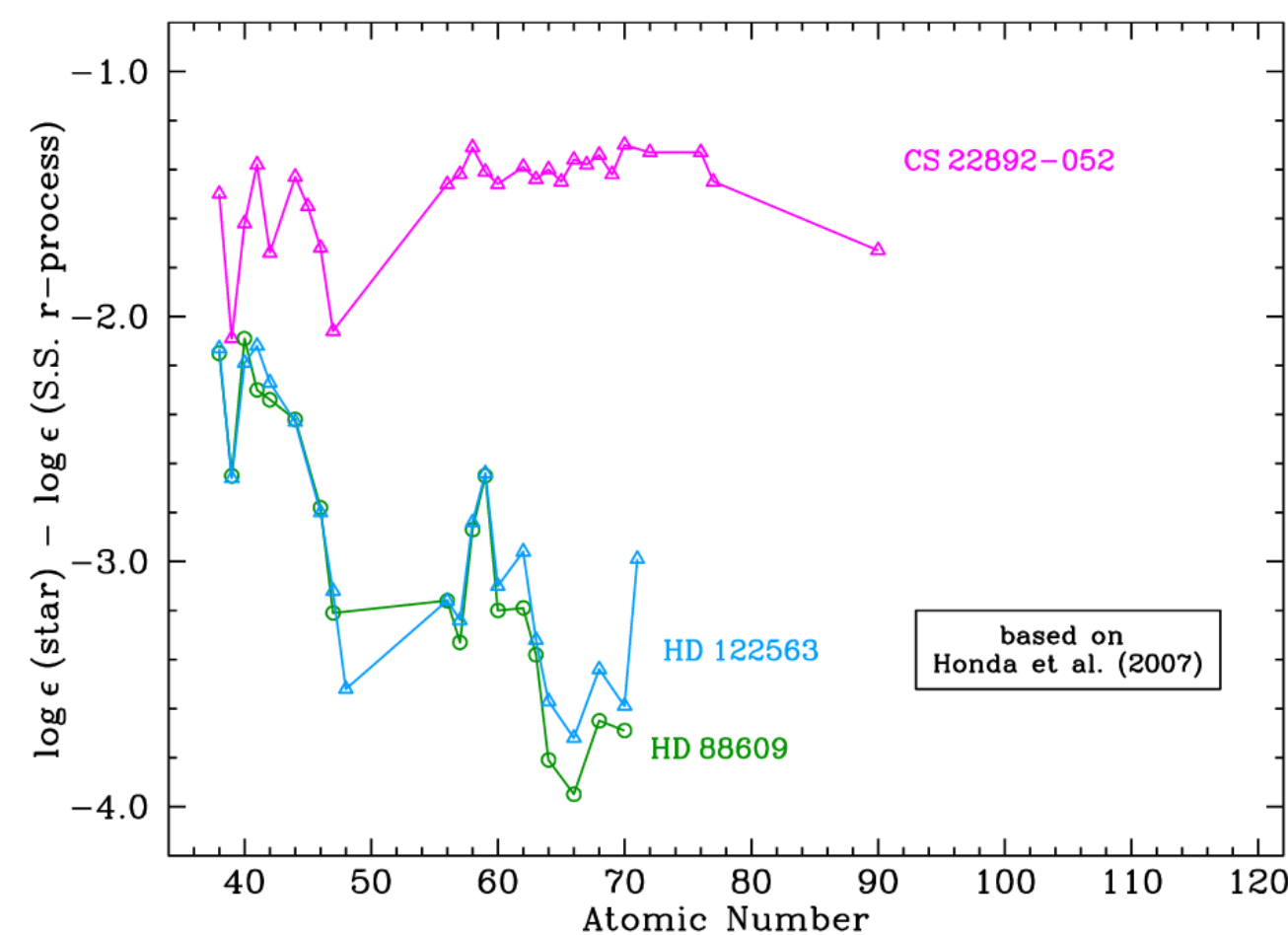
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([Eichler et al. 2019](#), [Holmbeck et al. 2018](#))

Racca, T. T. Hansen, R-Process Alliance [arxiv:2510.25500]

R-process in ultra metal-poor stars



Roederer et al. ApJ (2010)

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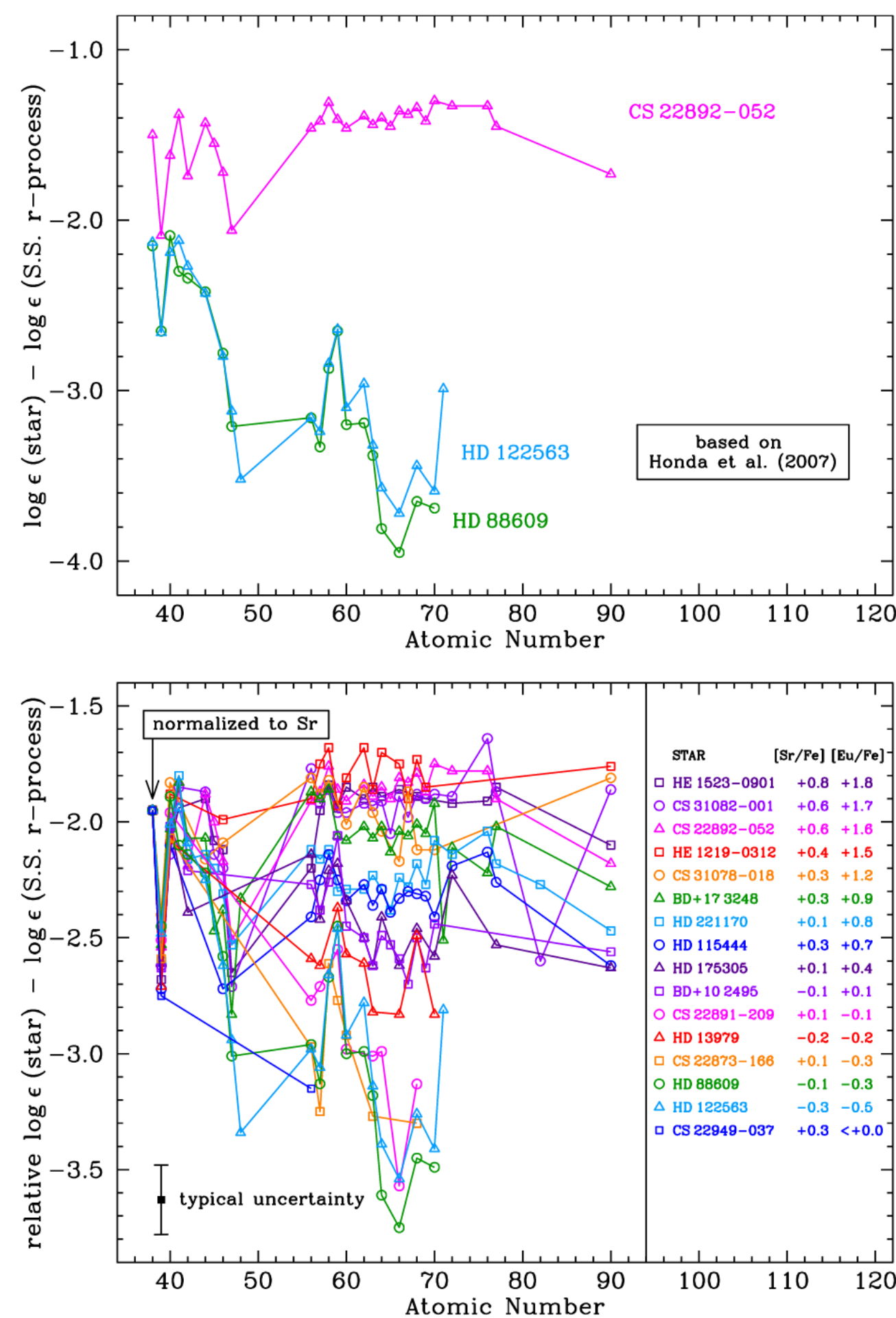
Robust r-process for $56 < Z < 83$

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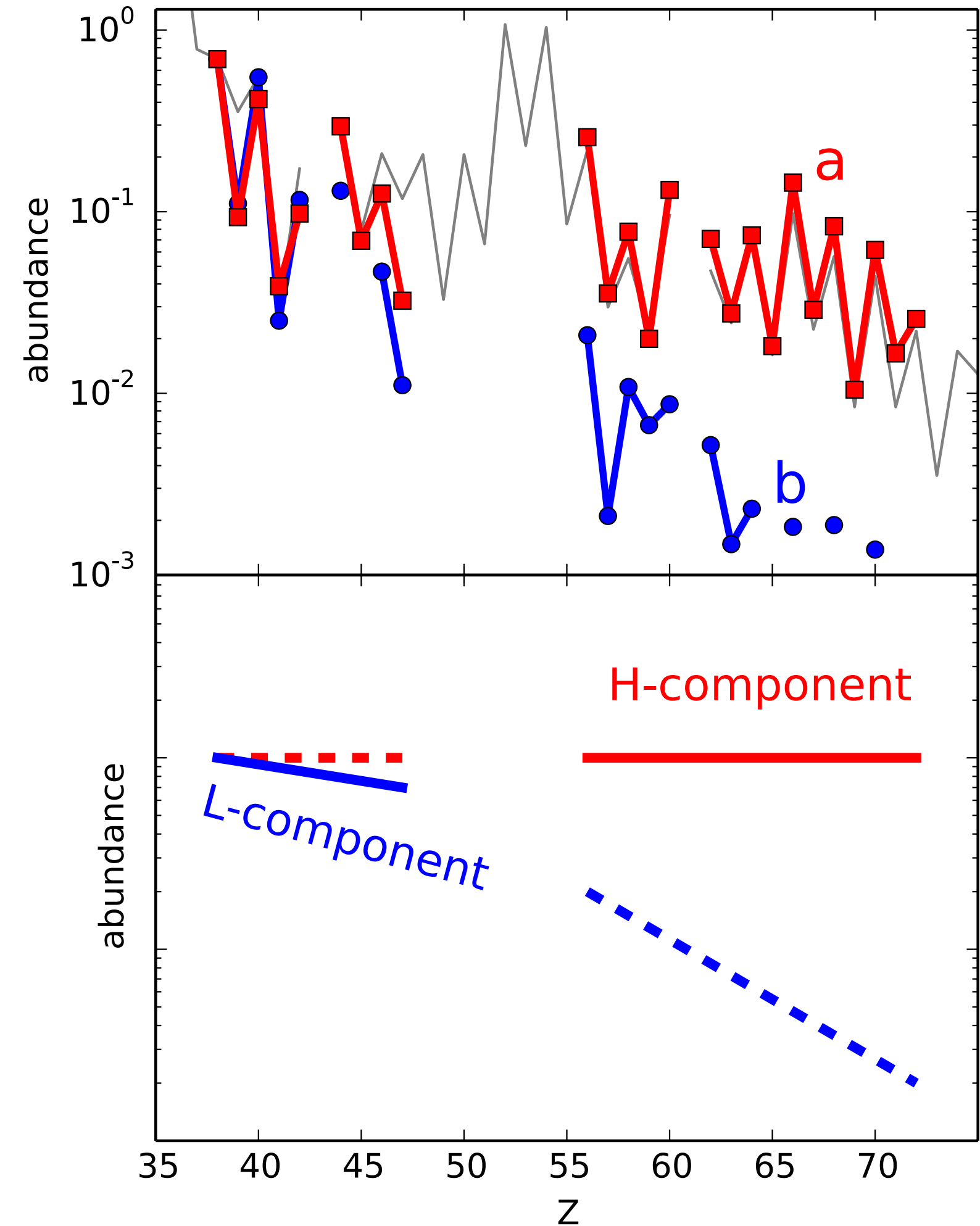
Ac-boost stars

(Eichler et al. 2019, Holmbeck et al. 2018)

R-process in ultra metal-poor stars



Roederer et al. ApJ (2010)



C.J. Hansen, Montes, Arcones (2014)

Abundances of r-process elements:

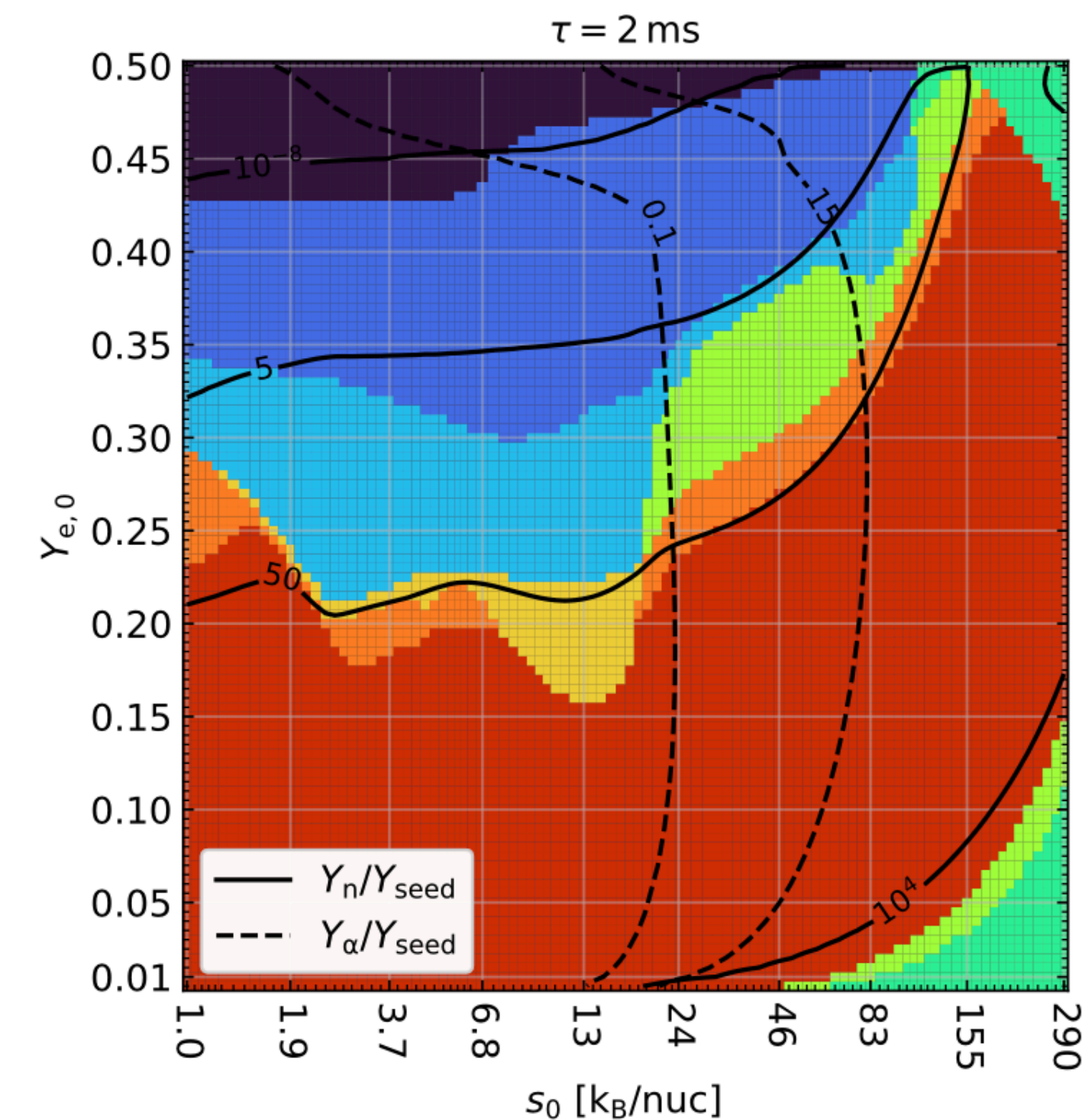
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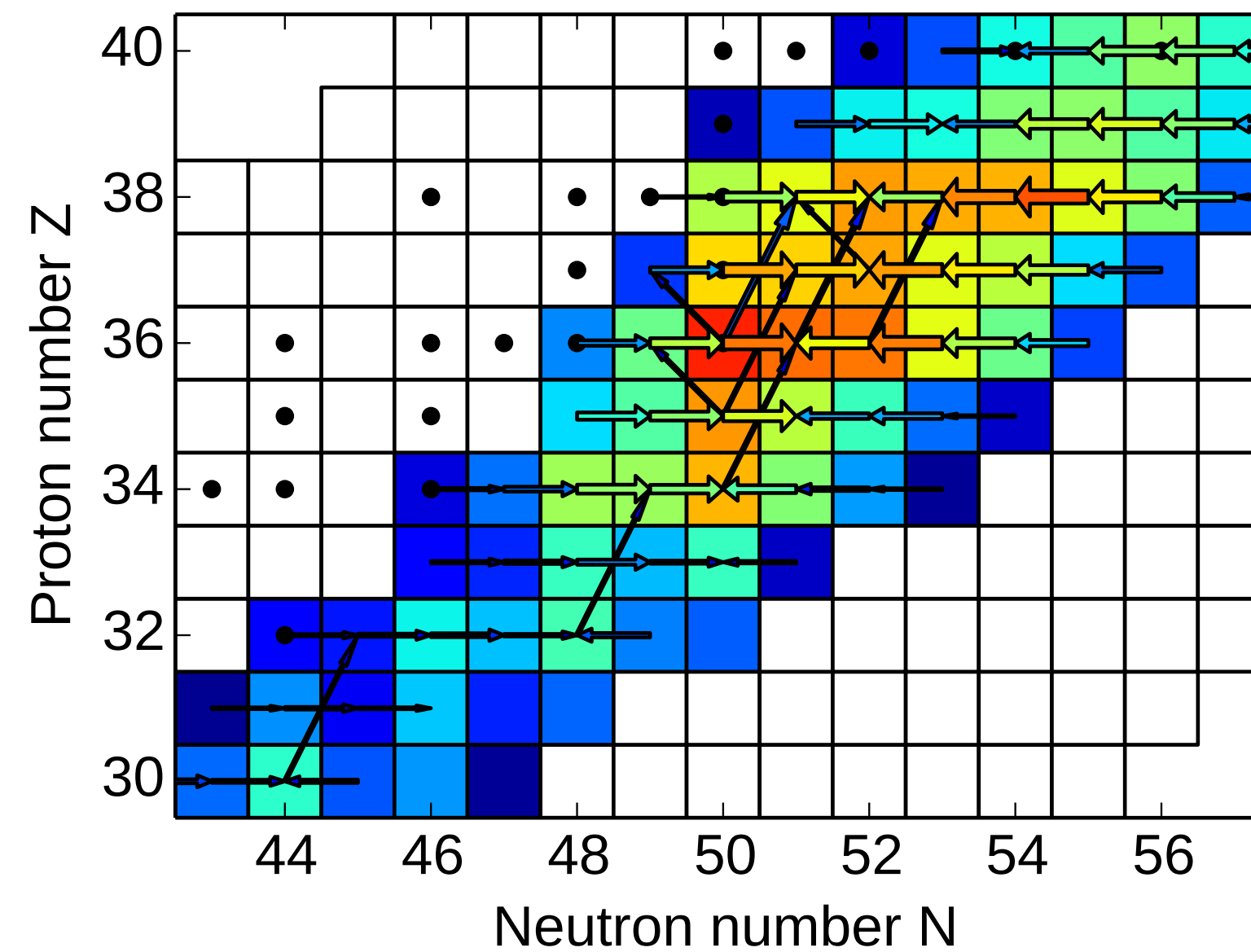
Ac-boost stars
(Eichler et al. 2019, Holmbeck et al. 2018)

Nuclear physics uncertainties in the weak and strong r-process

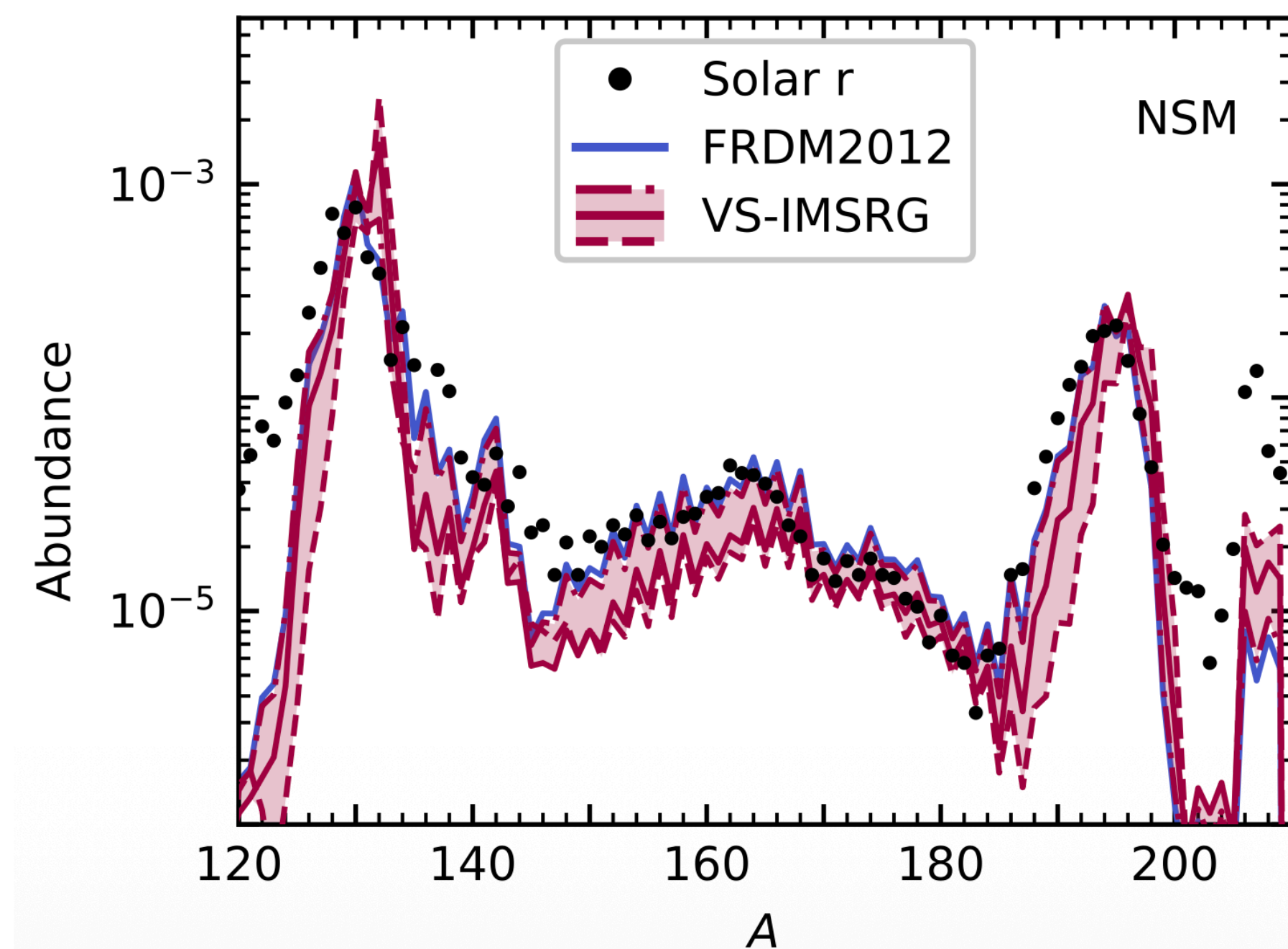
Complete survey of
r-process conditions



Weak r-process and
 (α, n) reactions

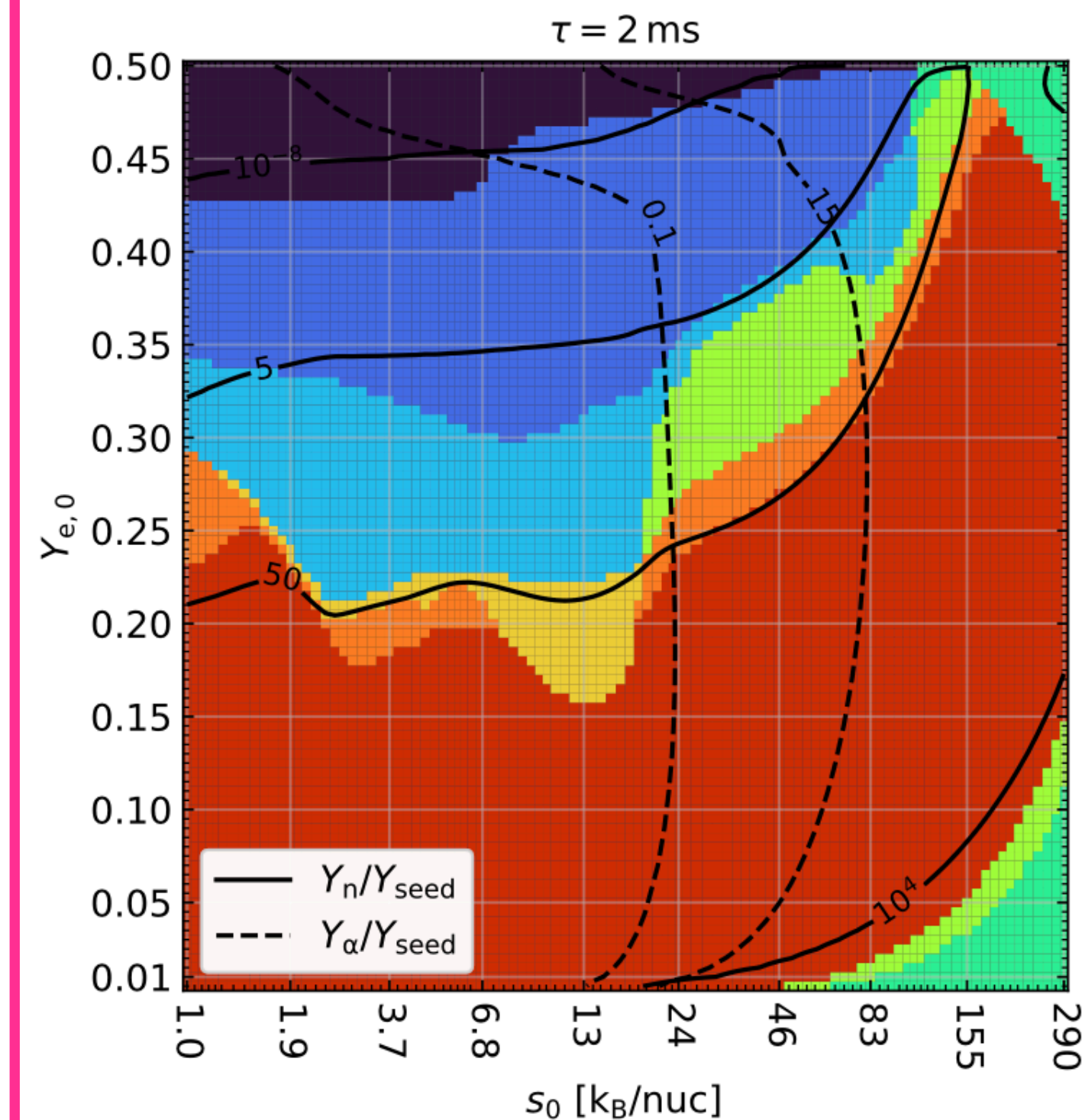


R-process with
ab-initio nuclear masses

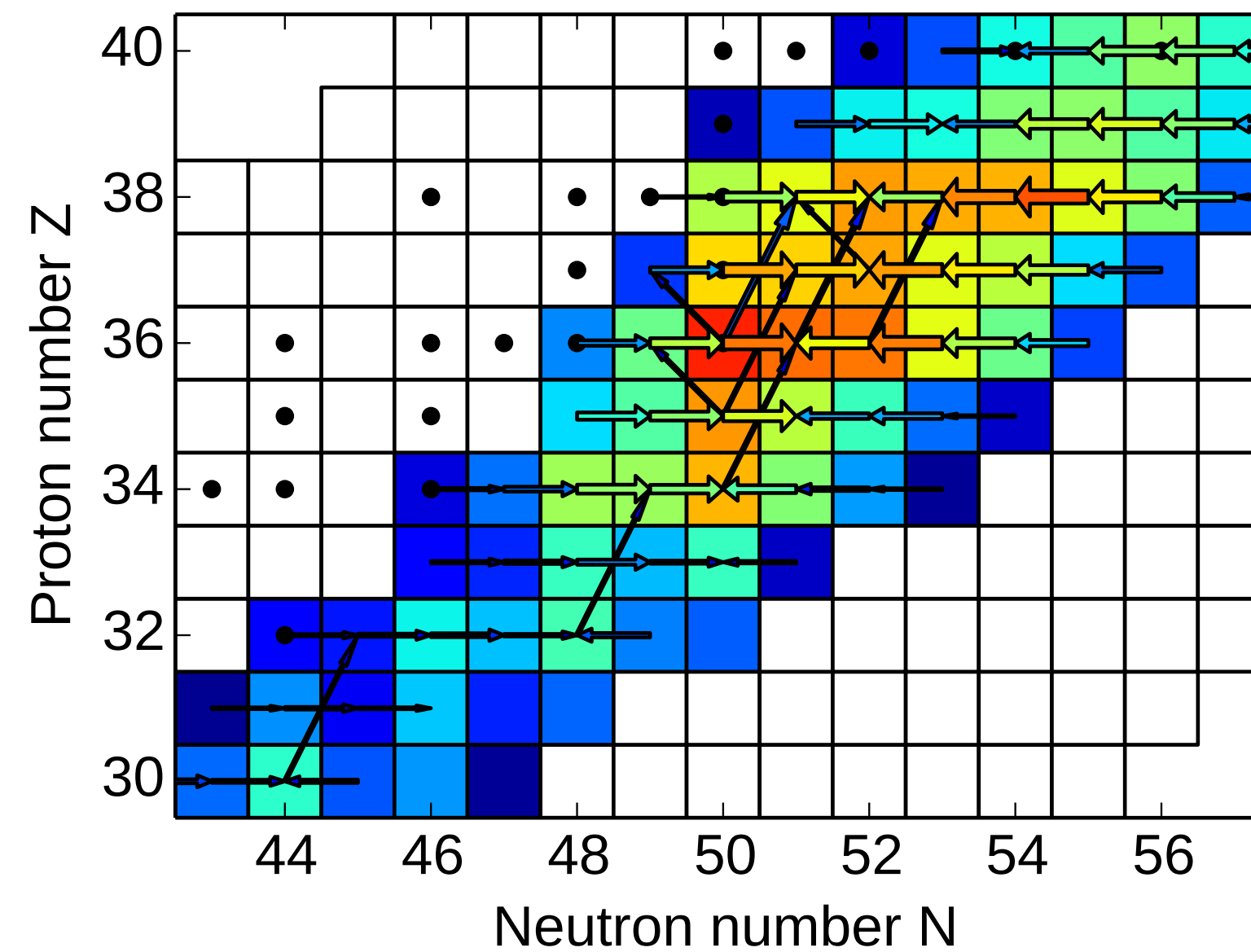


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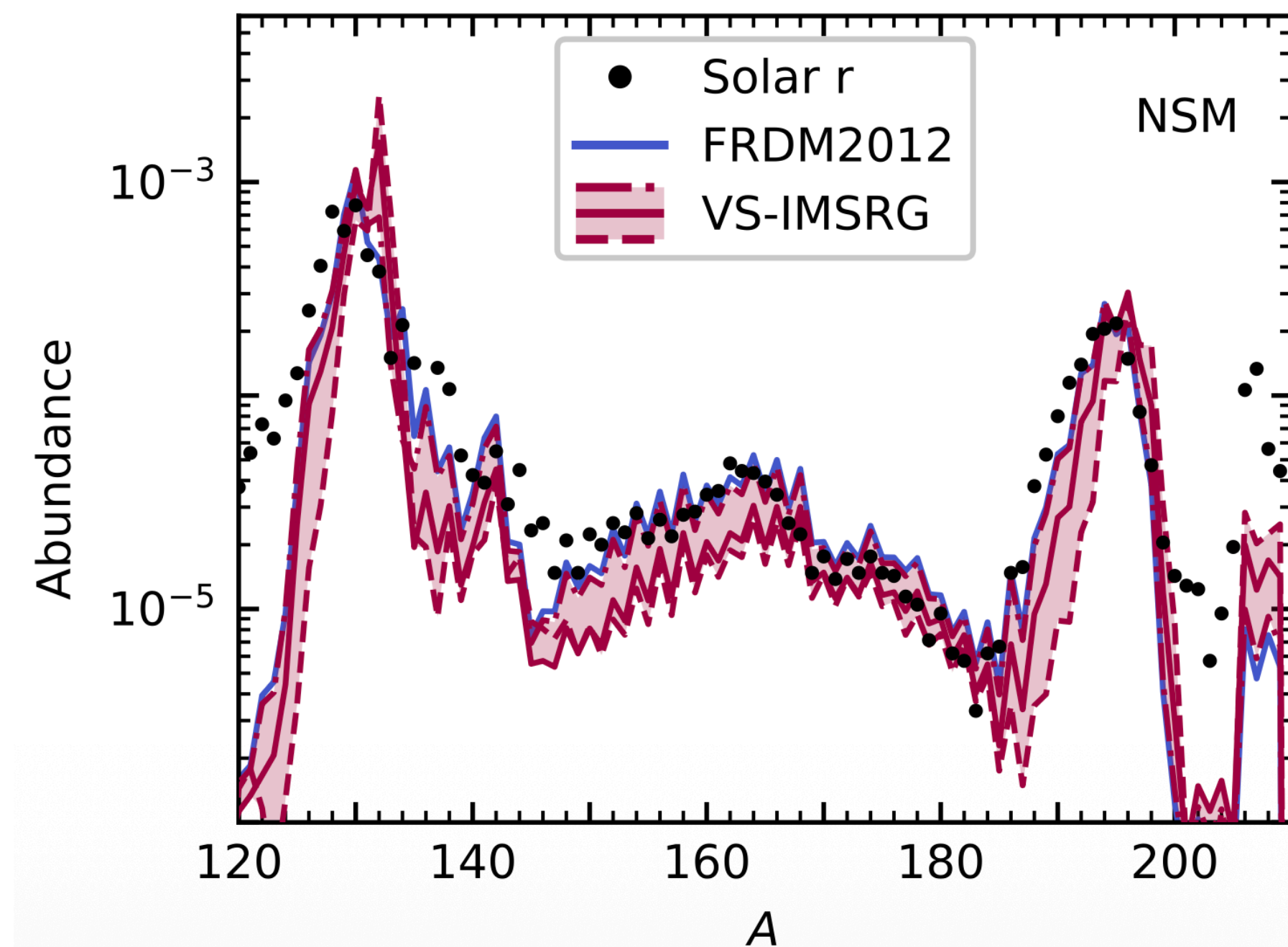
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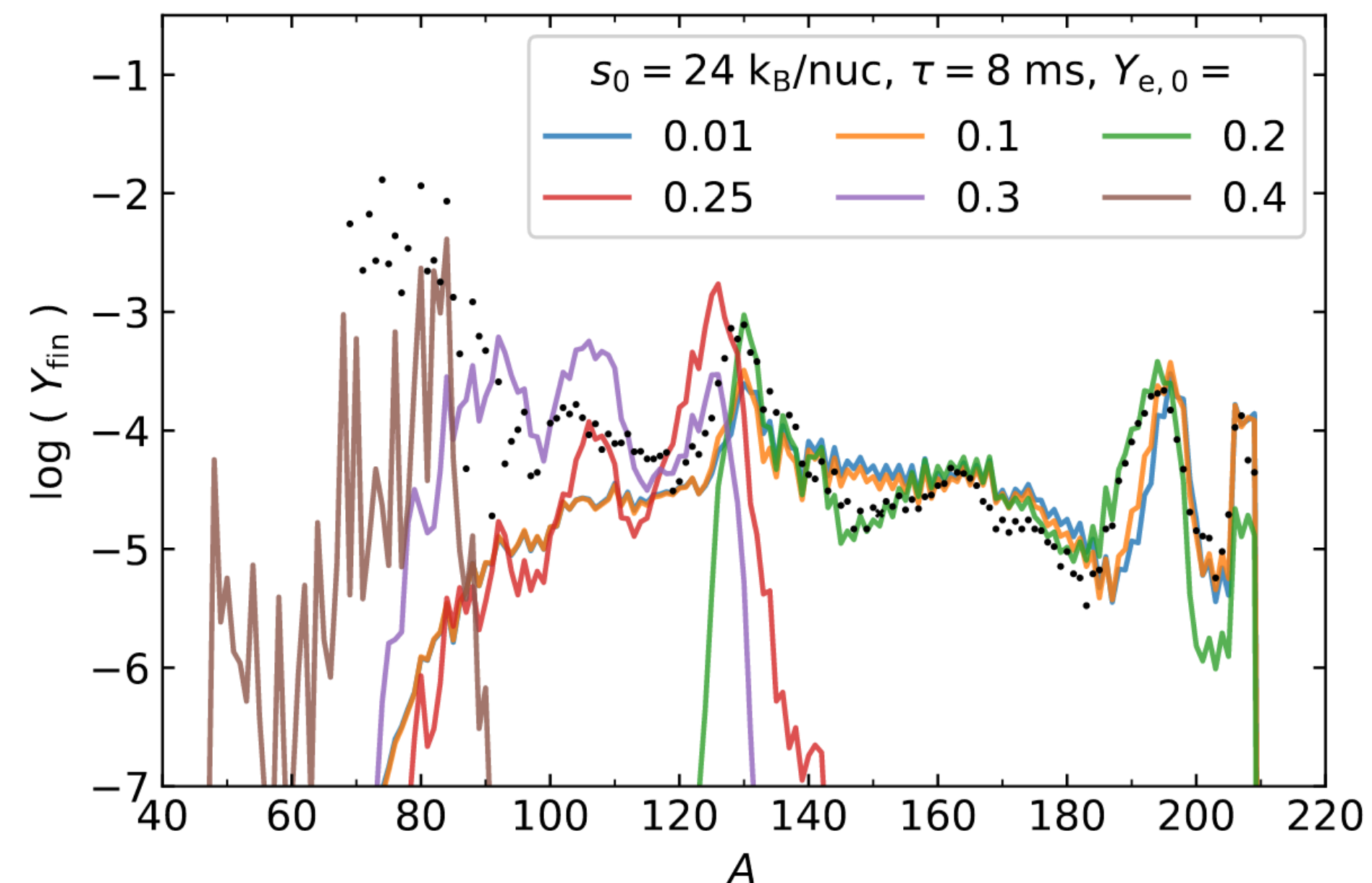


Complete survey of r-process conditions

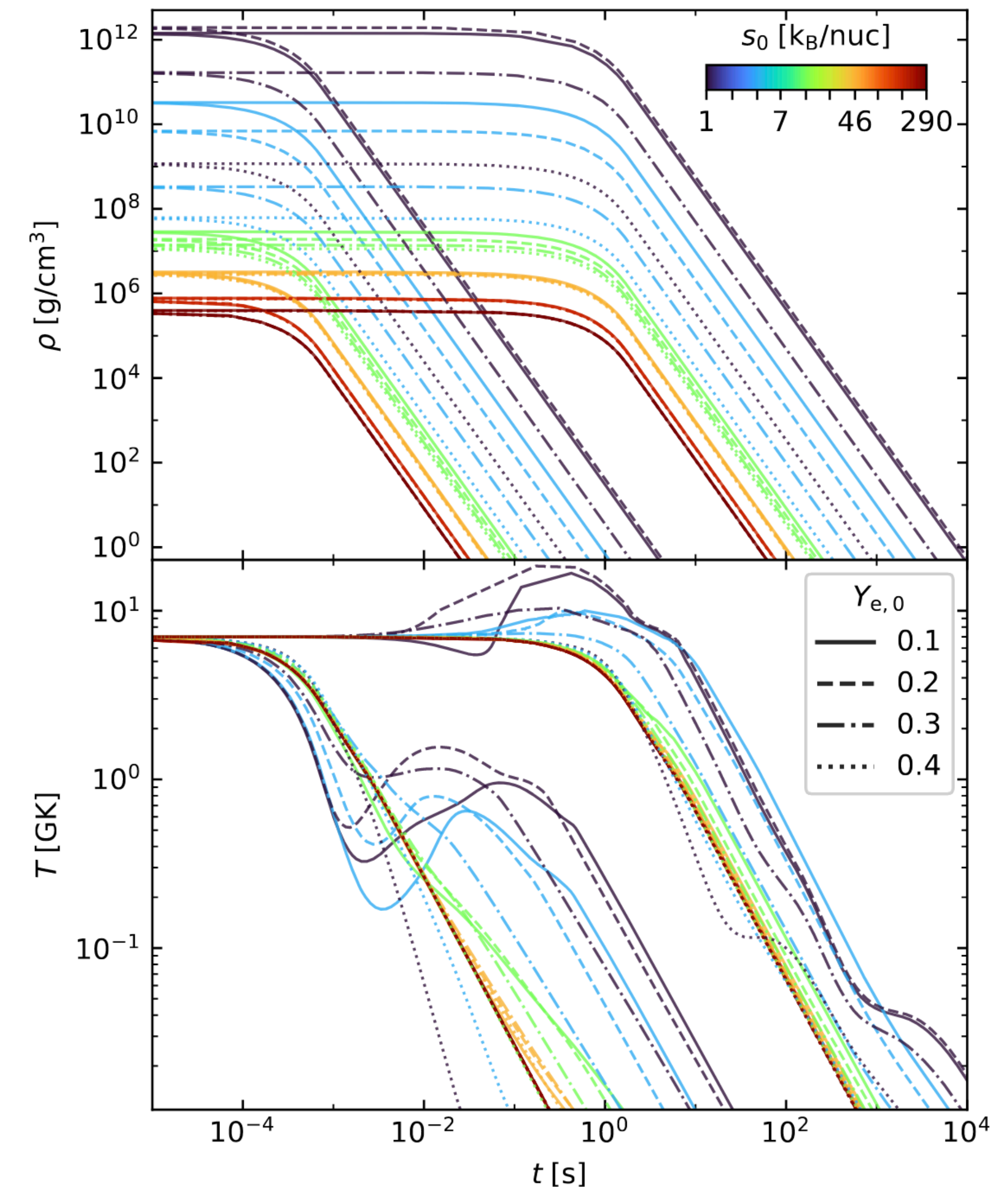
Parametric trajectories:
entropy and Y_e at 7GK, expansion time scale

(Lippuner & Roberts 2015)

$$\rho(t) = \rho_0 \begin{cases} \exp\left(-\frac{t}{\tau}\right) & \text{if } t \leq 3\tau \\ \left(\frac{3\tau}{et}\right)^3 & \text{if } t \geq 3\tau \end{cases}$$



Kuske, Arcones, Reichert ApJ (2025)

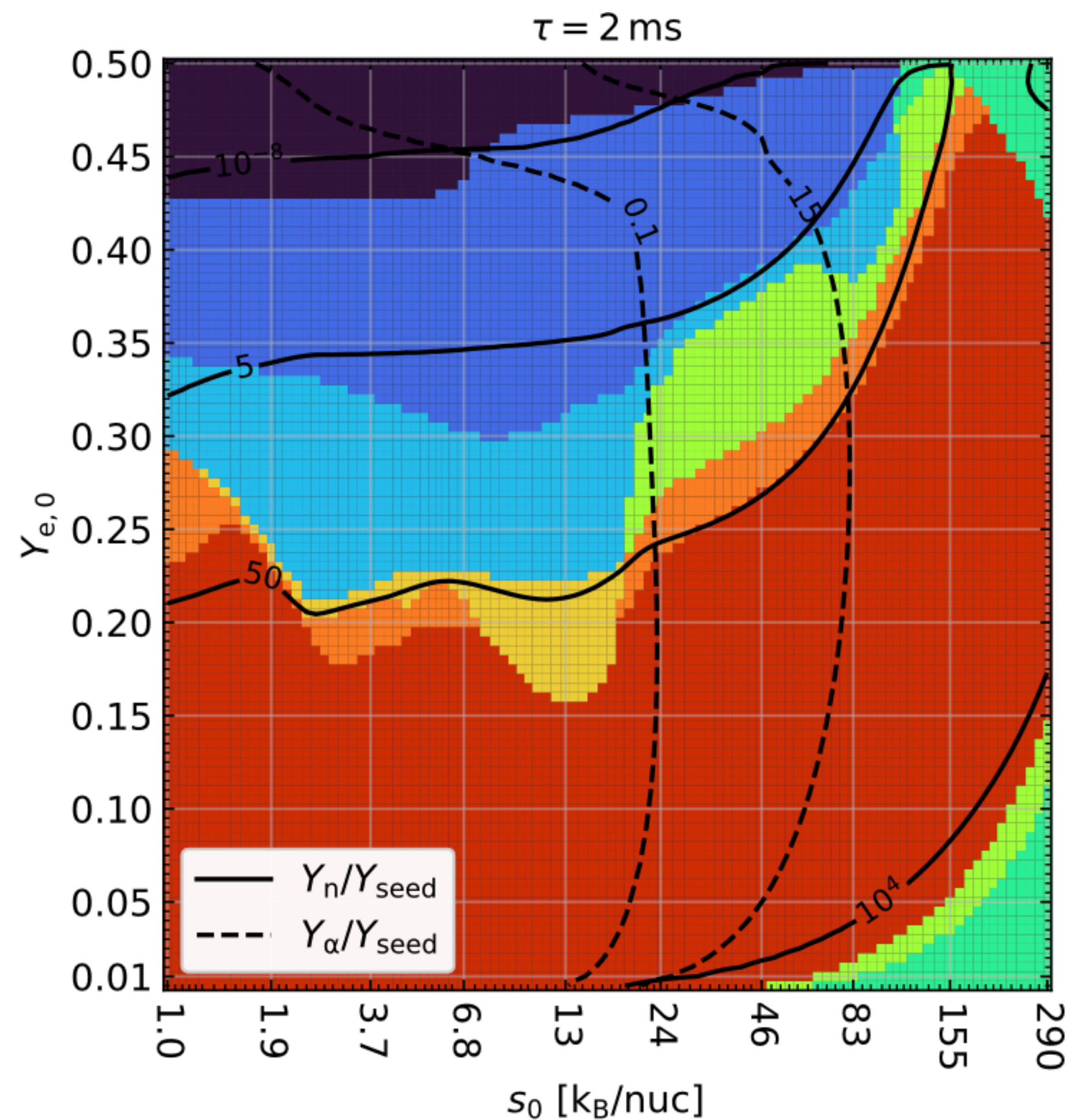


Complete survey of r-process conditions

Parametric trajectories:

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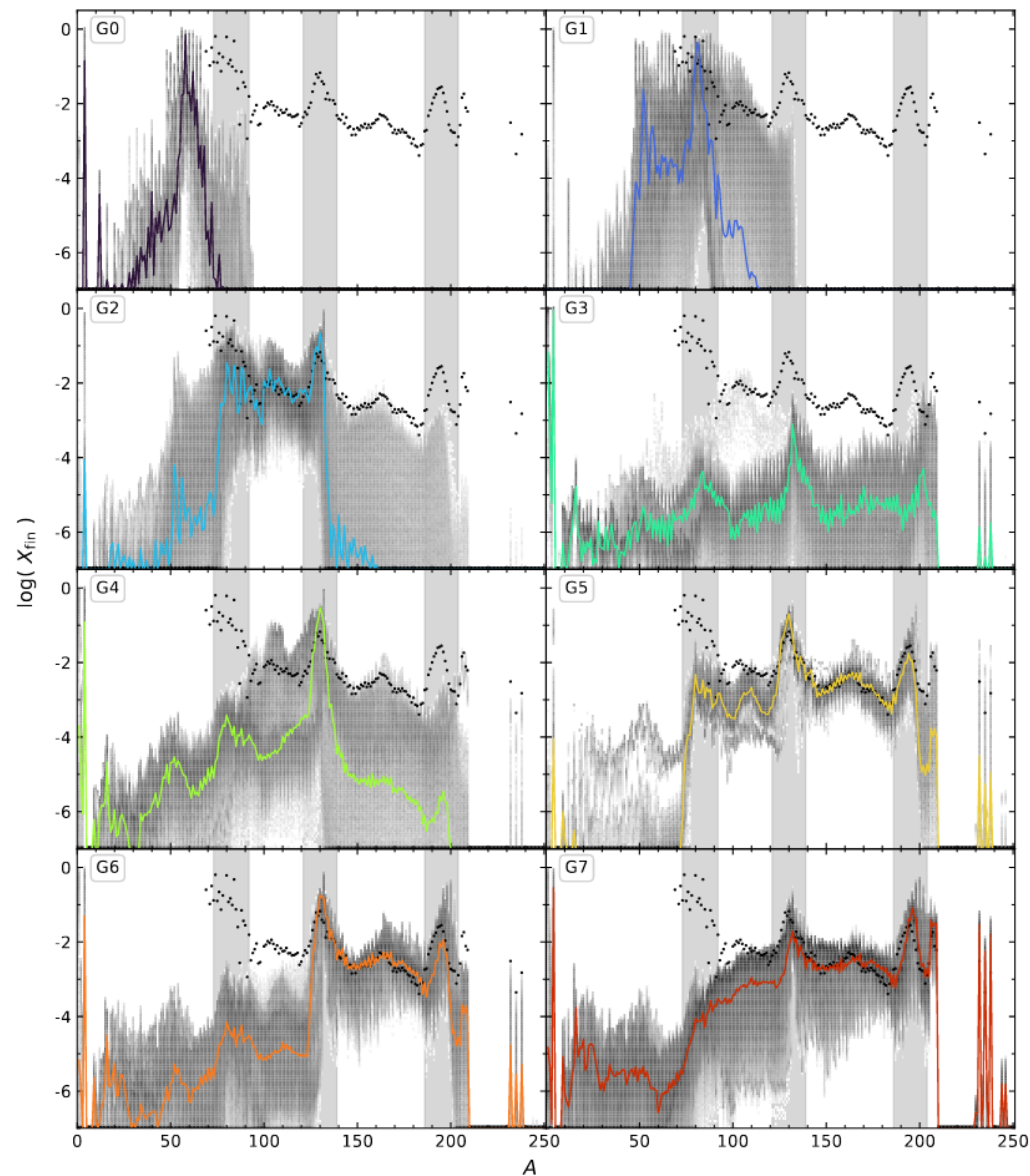
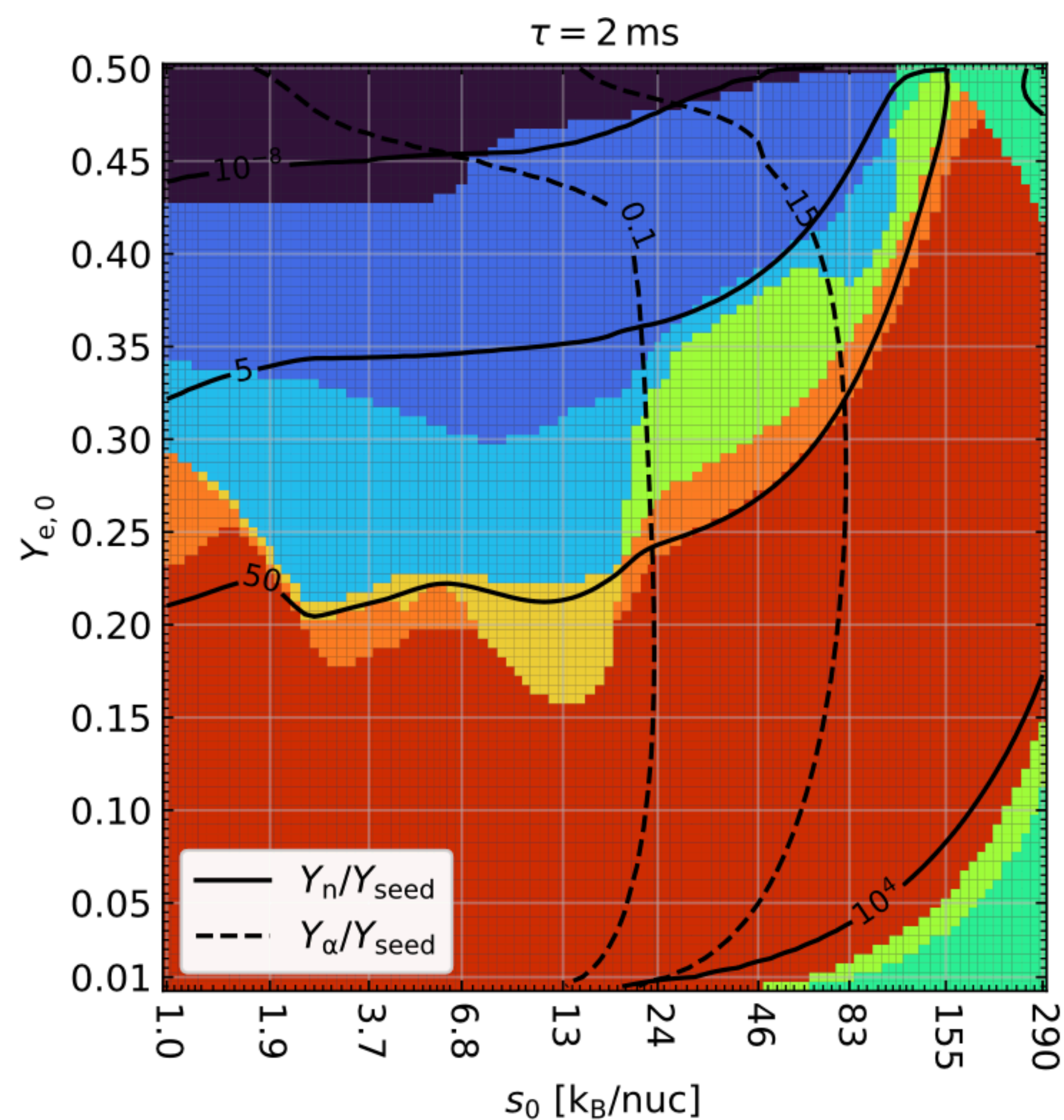
(Lippuner & Roberts 2015)

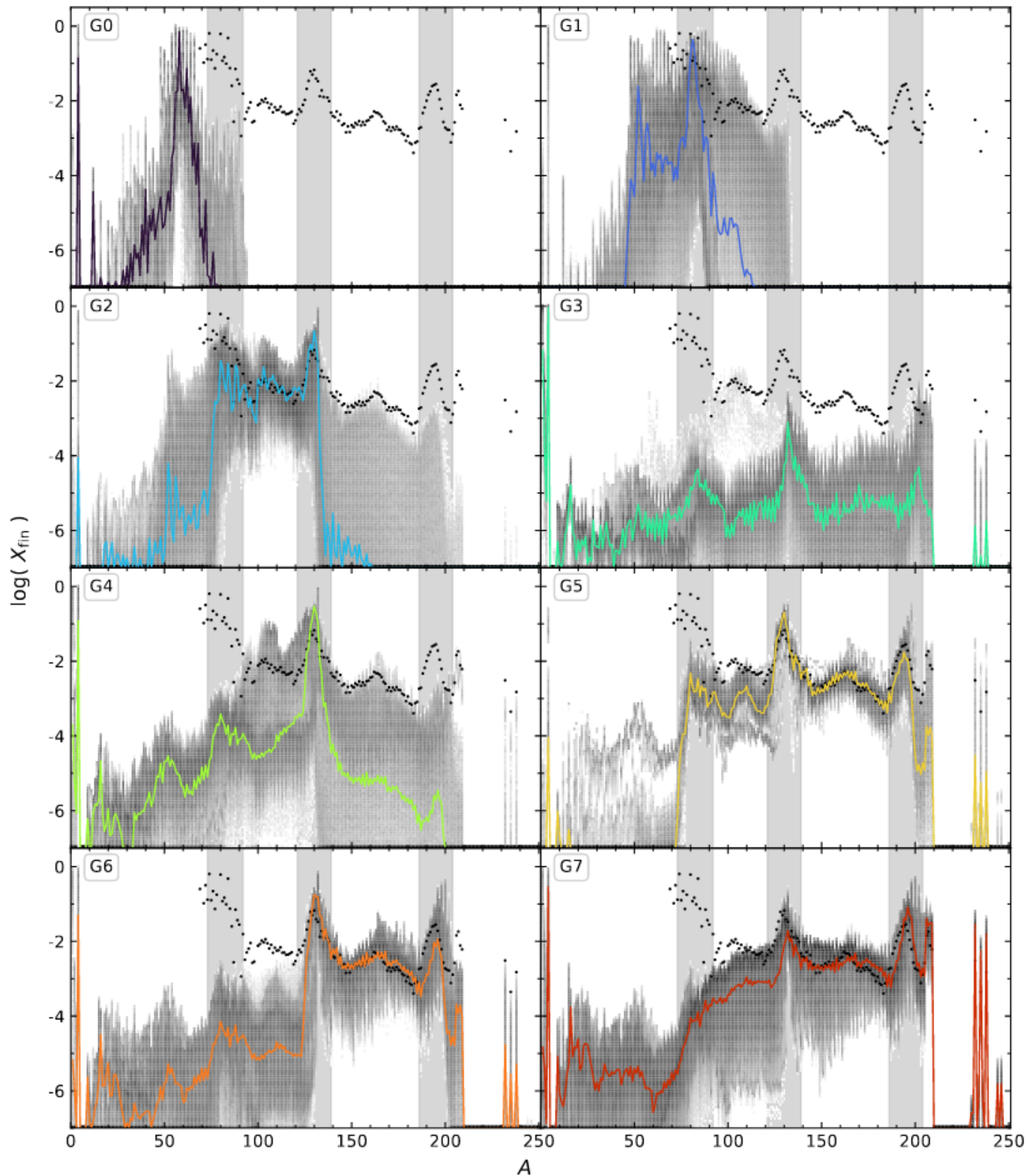
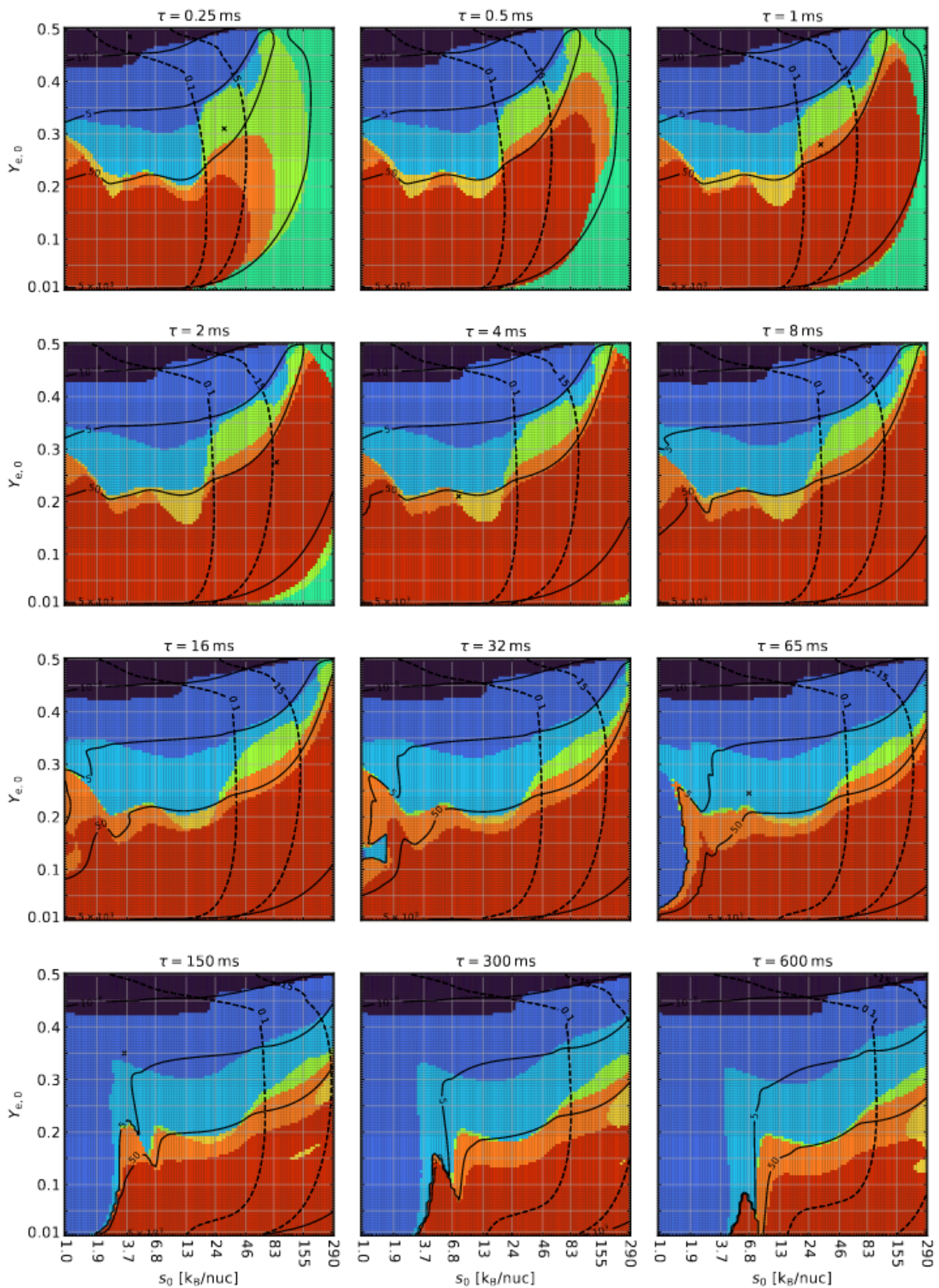


Complete survey of r-process conditions

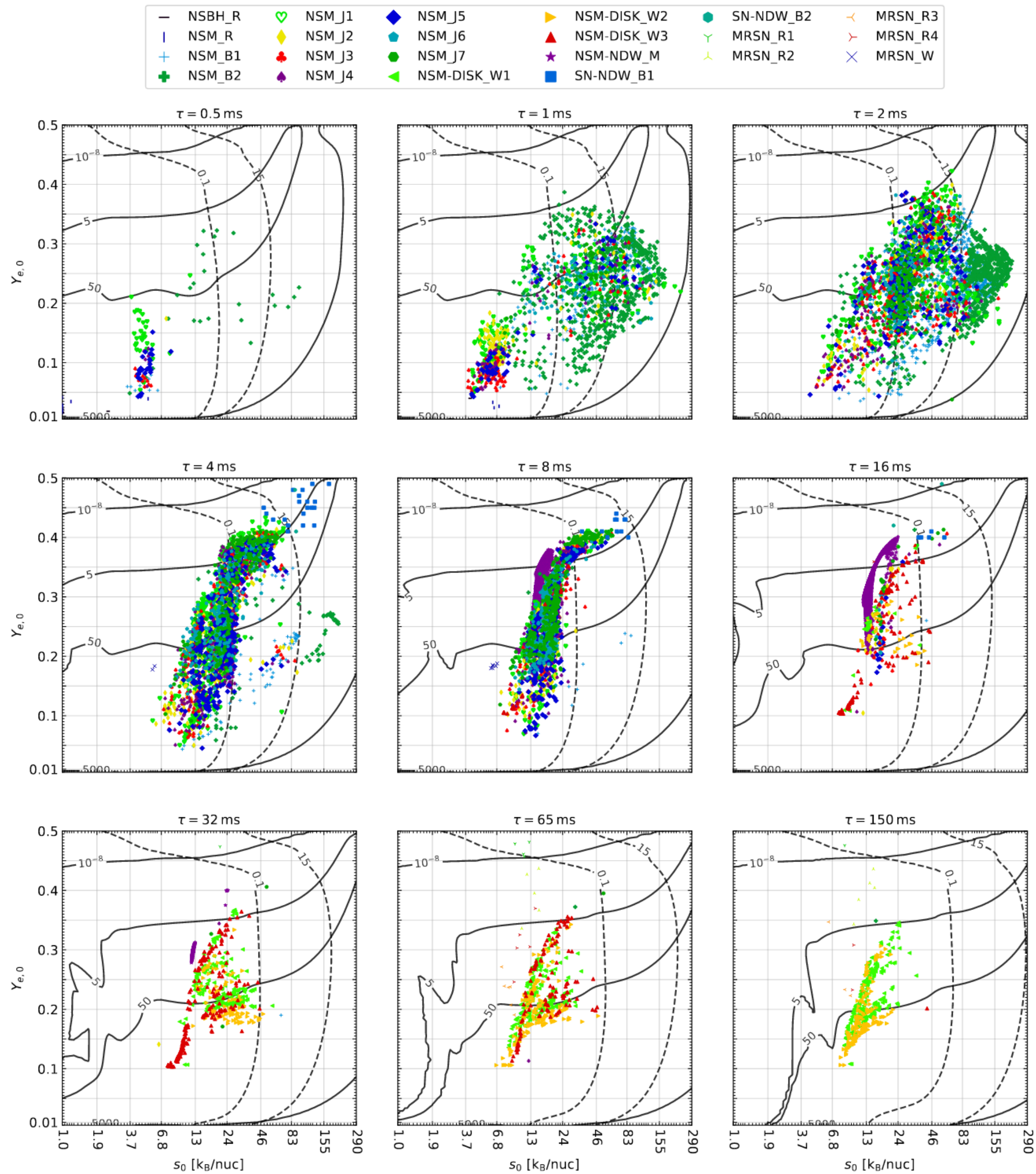
Parametric trajectories:
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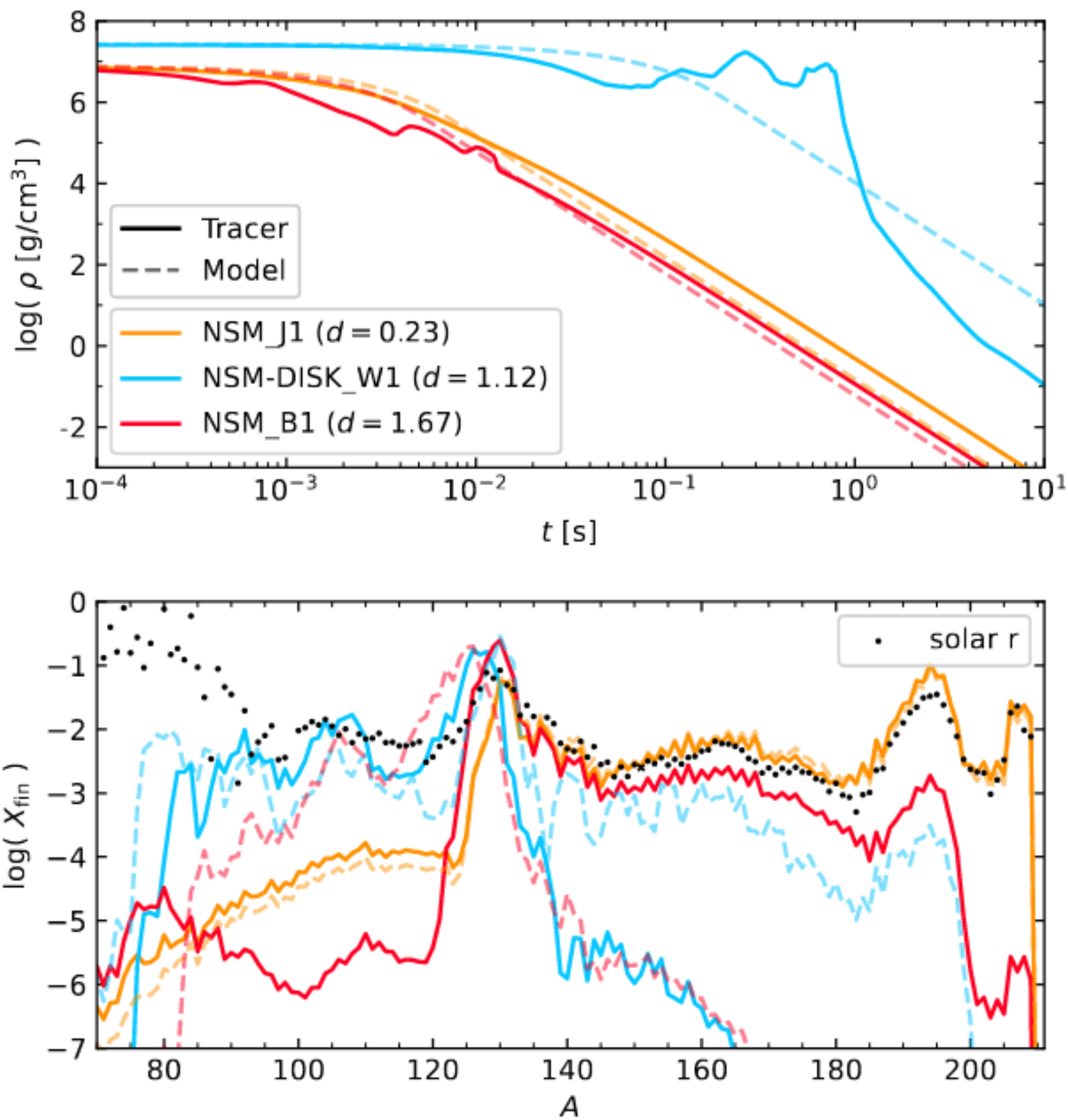




Parametric trajectories vs. Simulation trajectories

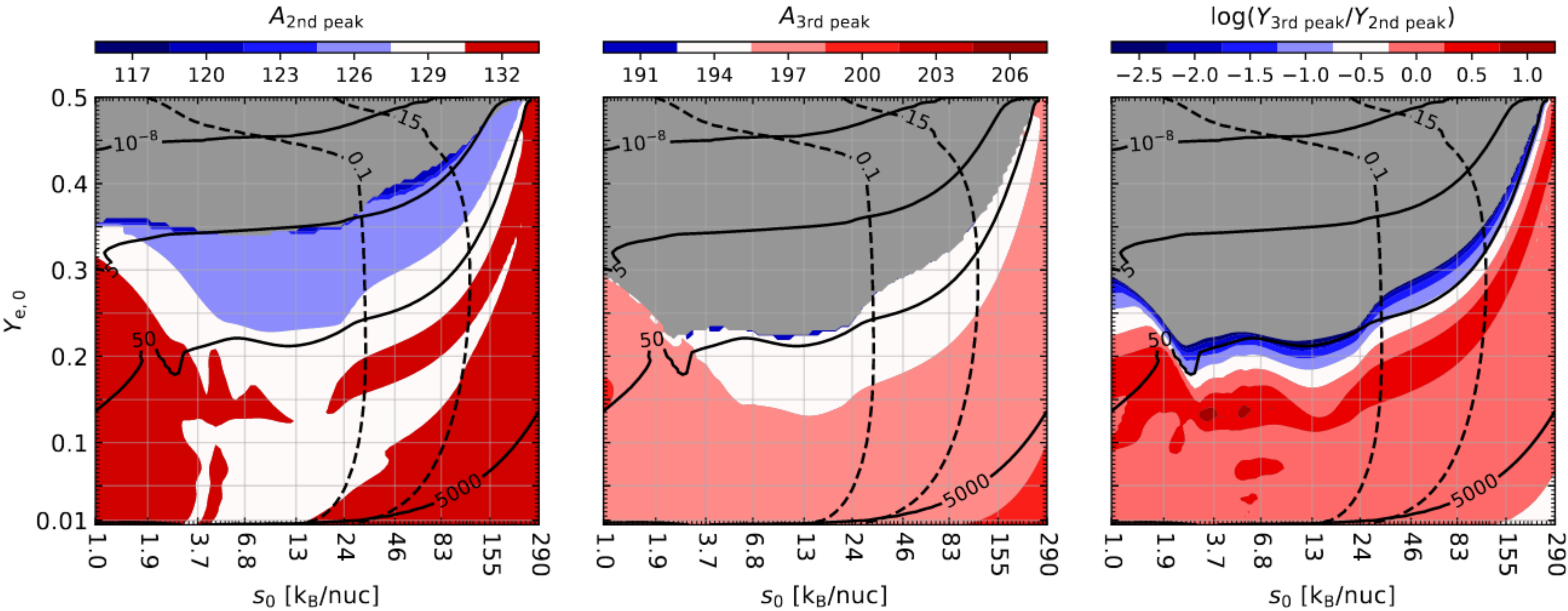


Good agreement for over 98%



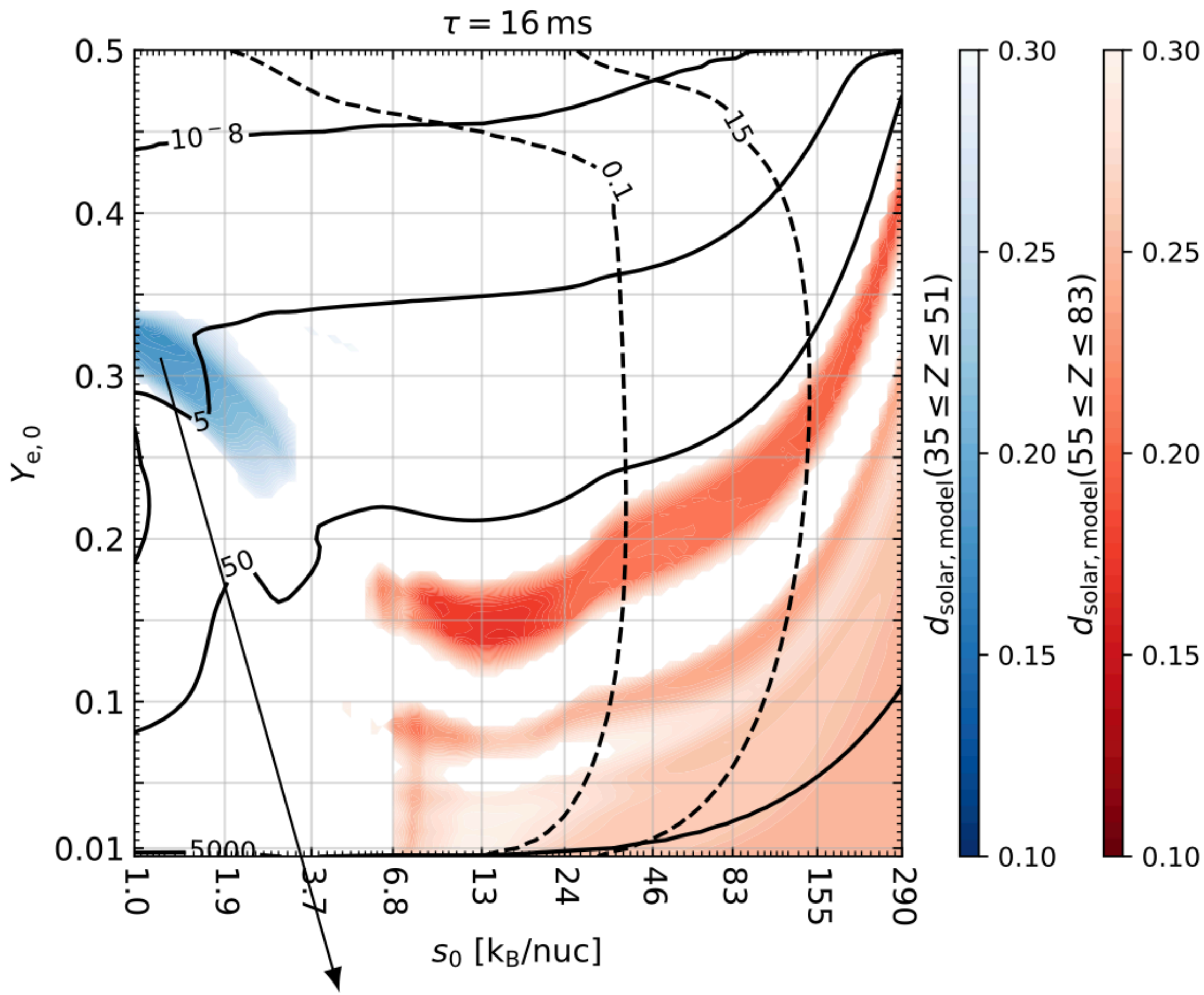
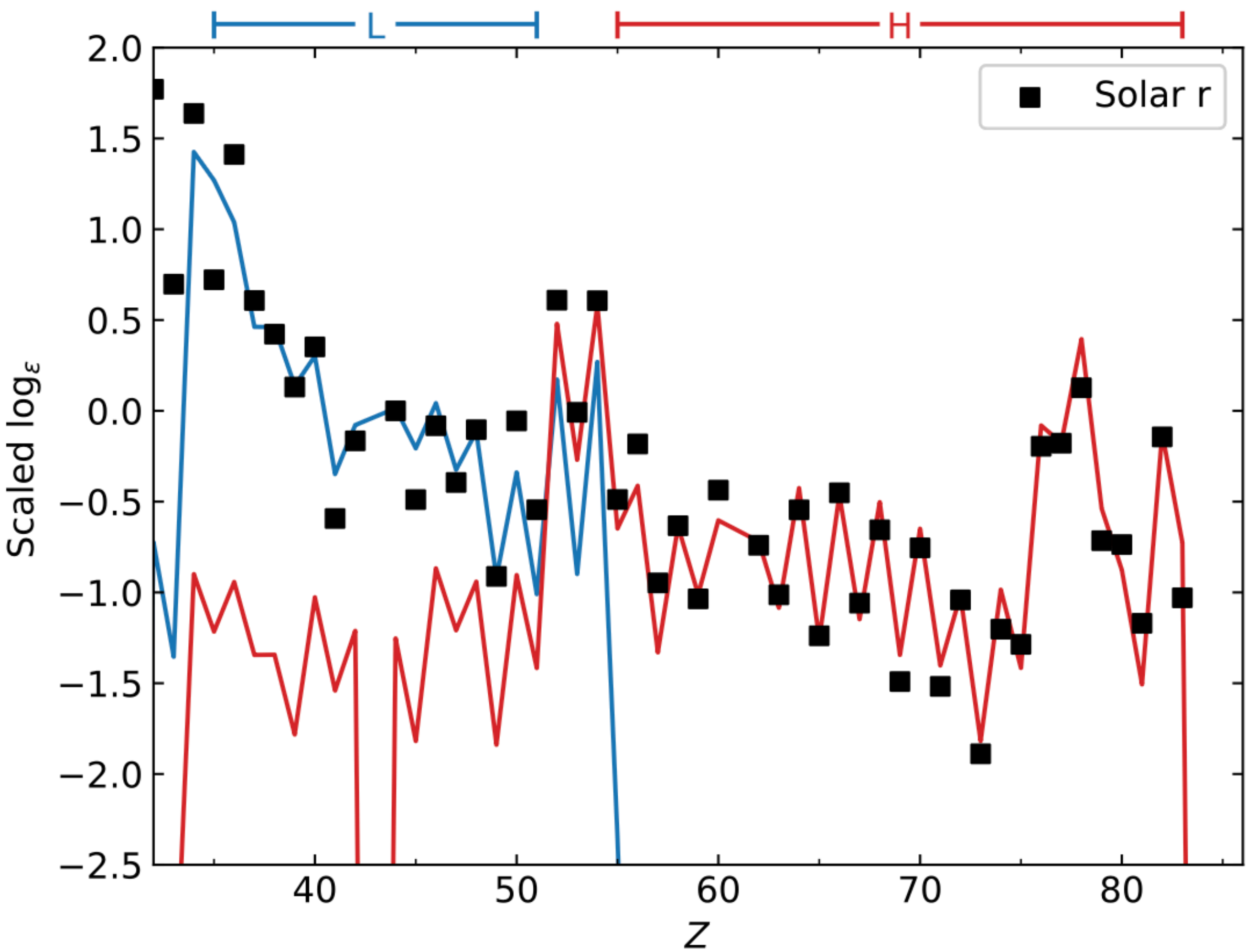
Comparison to observations

Solar system peaks: position and relative abundances



Comparison to observations

Two components

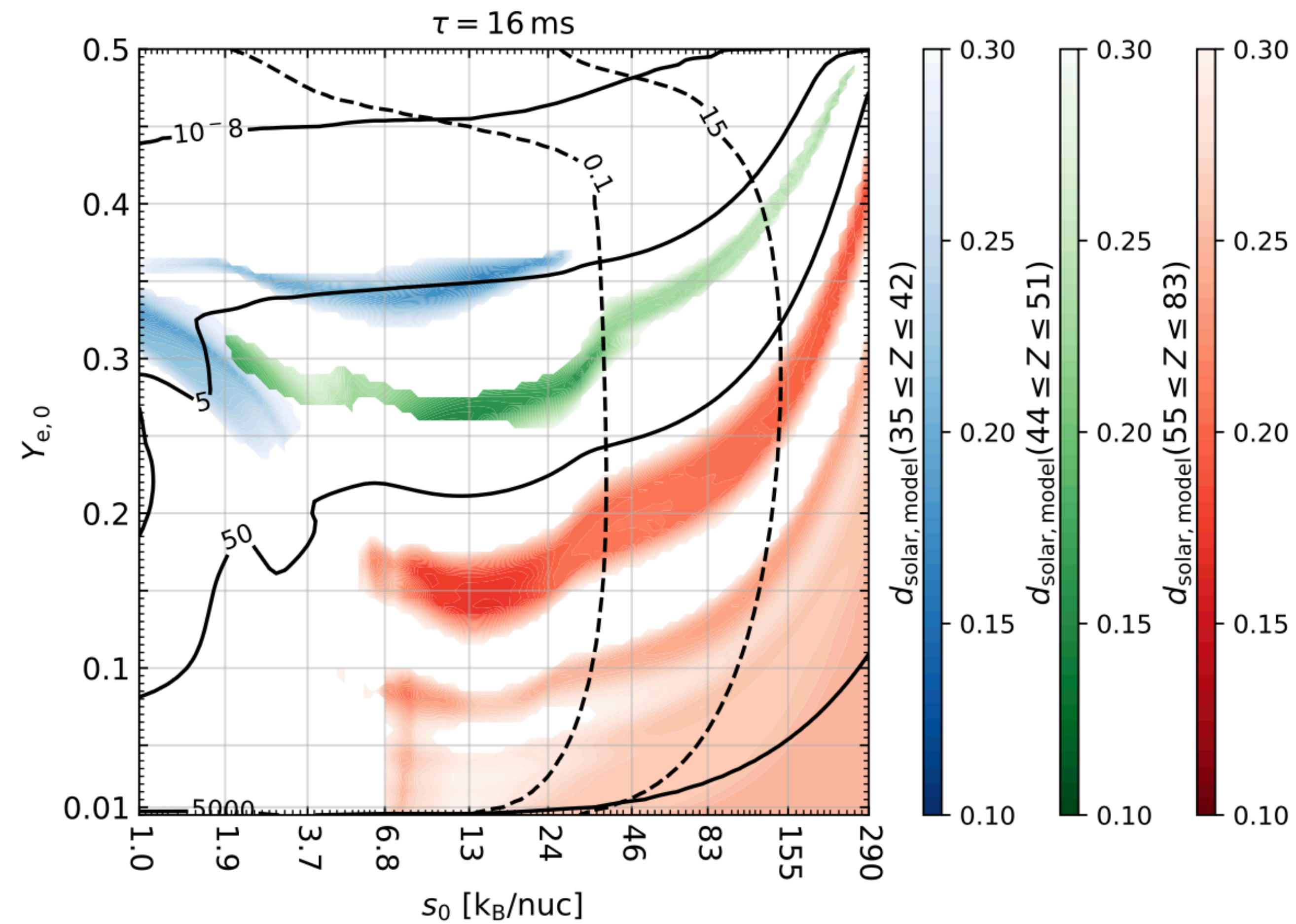
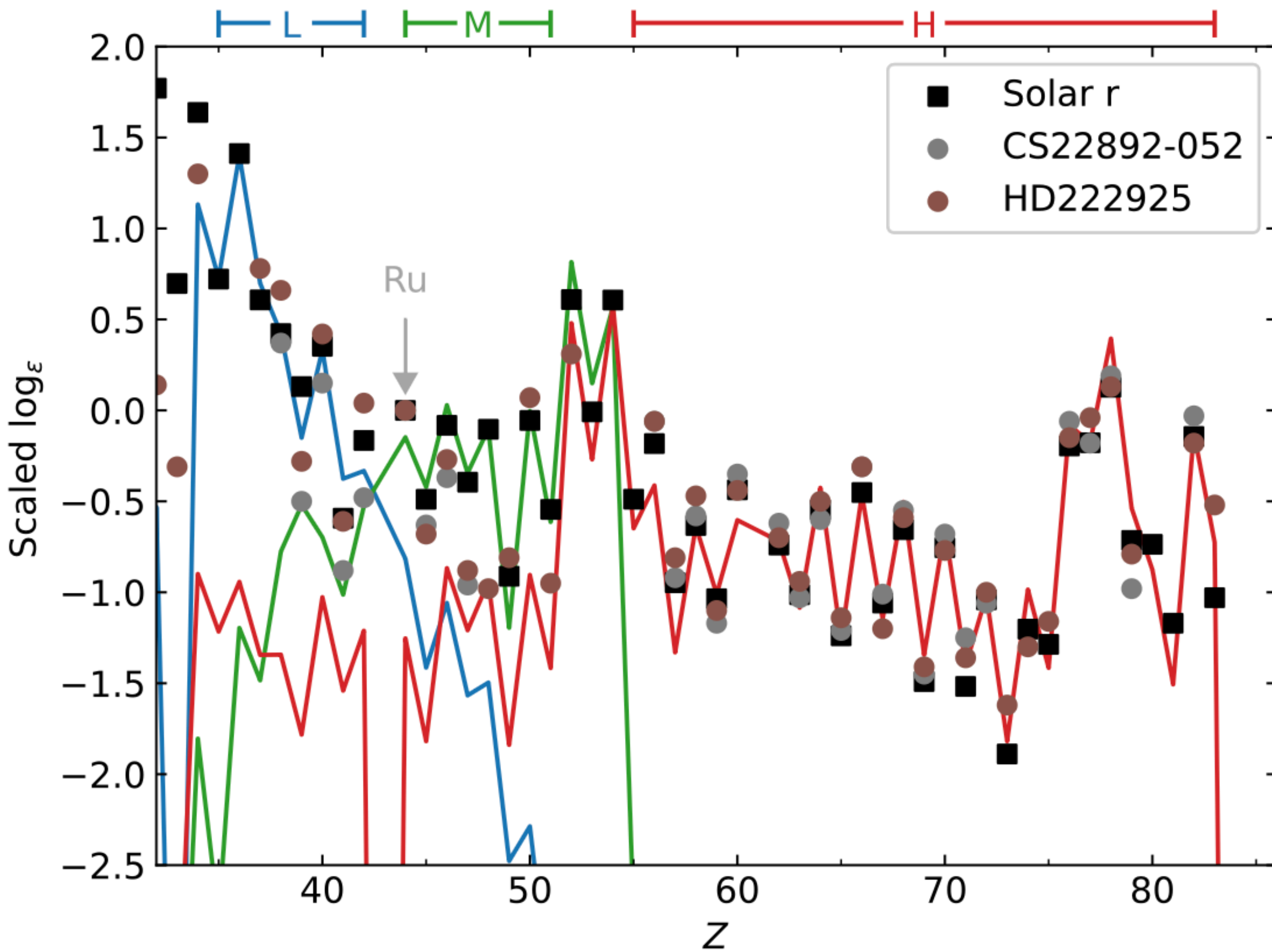


Conditions not found in simulations

Comparison to observations

Kuske, Arcones, Reichert ApJ (2025)

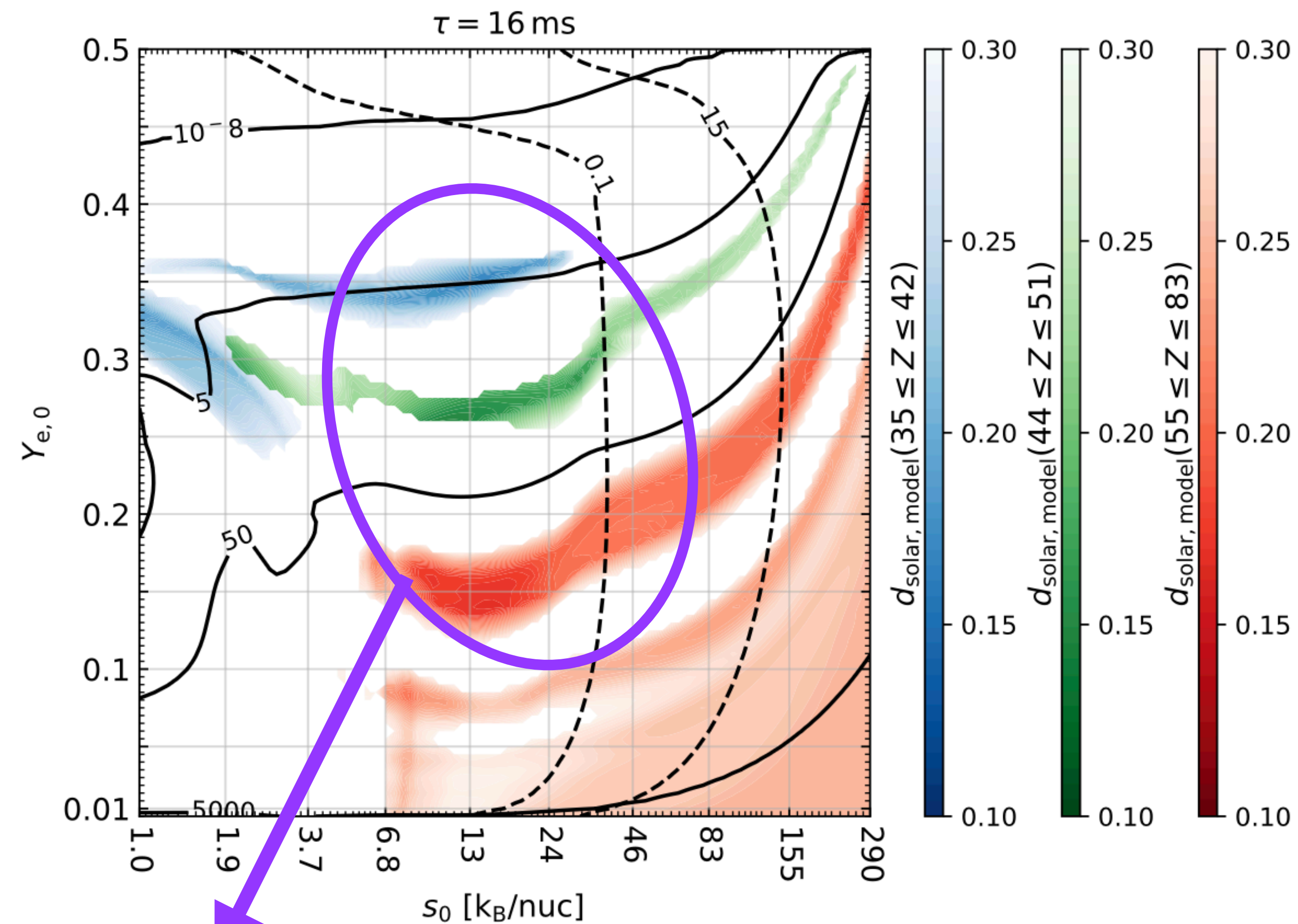
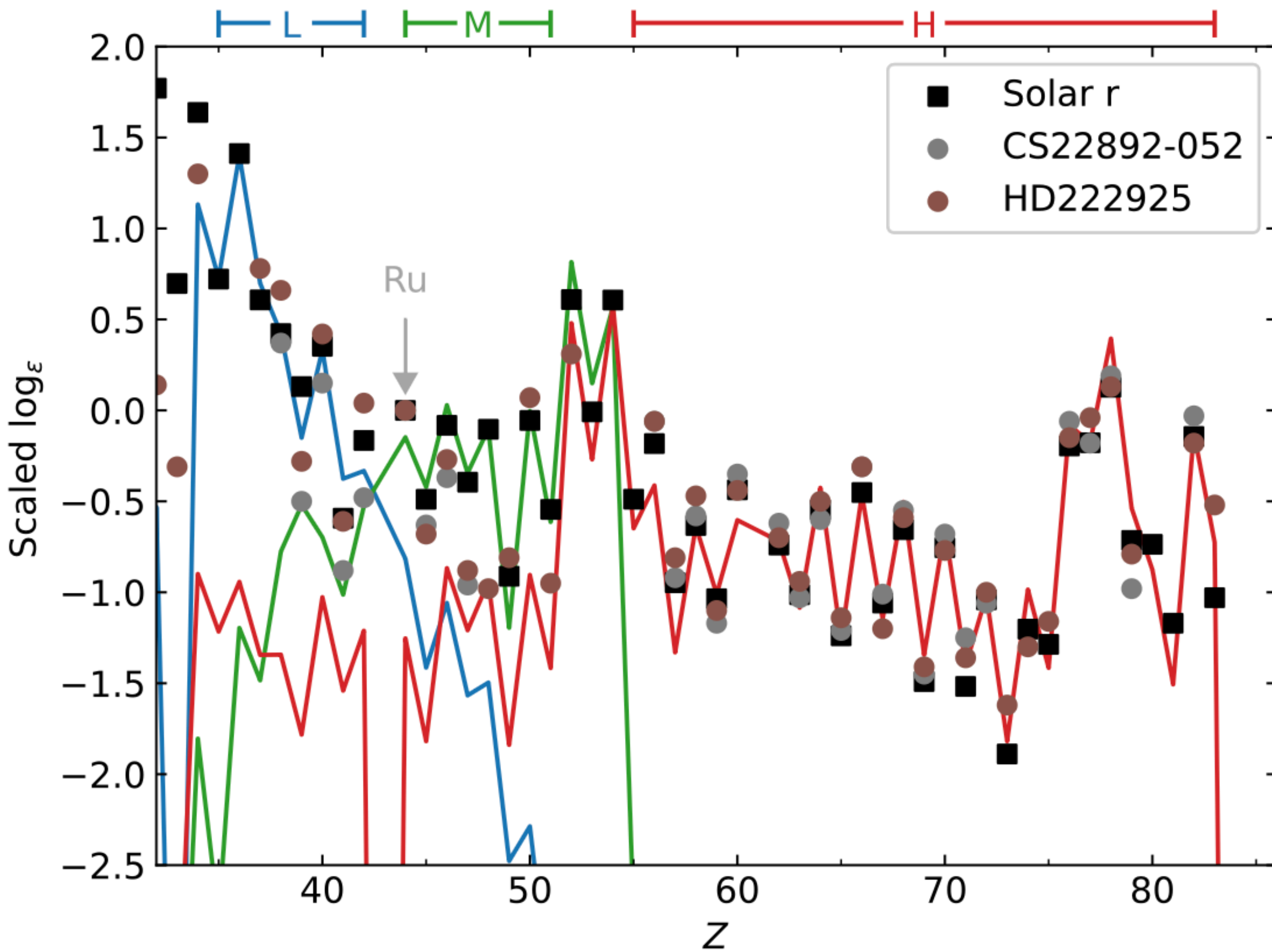
Three components



Comparison to observations

Kuske, Arcones, Reichert ApJ (2025)

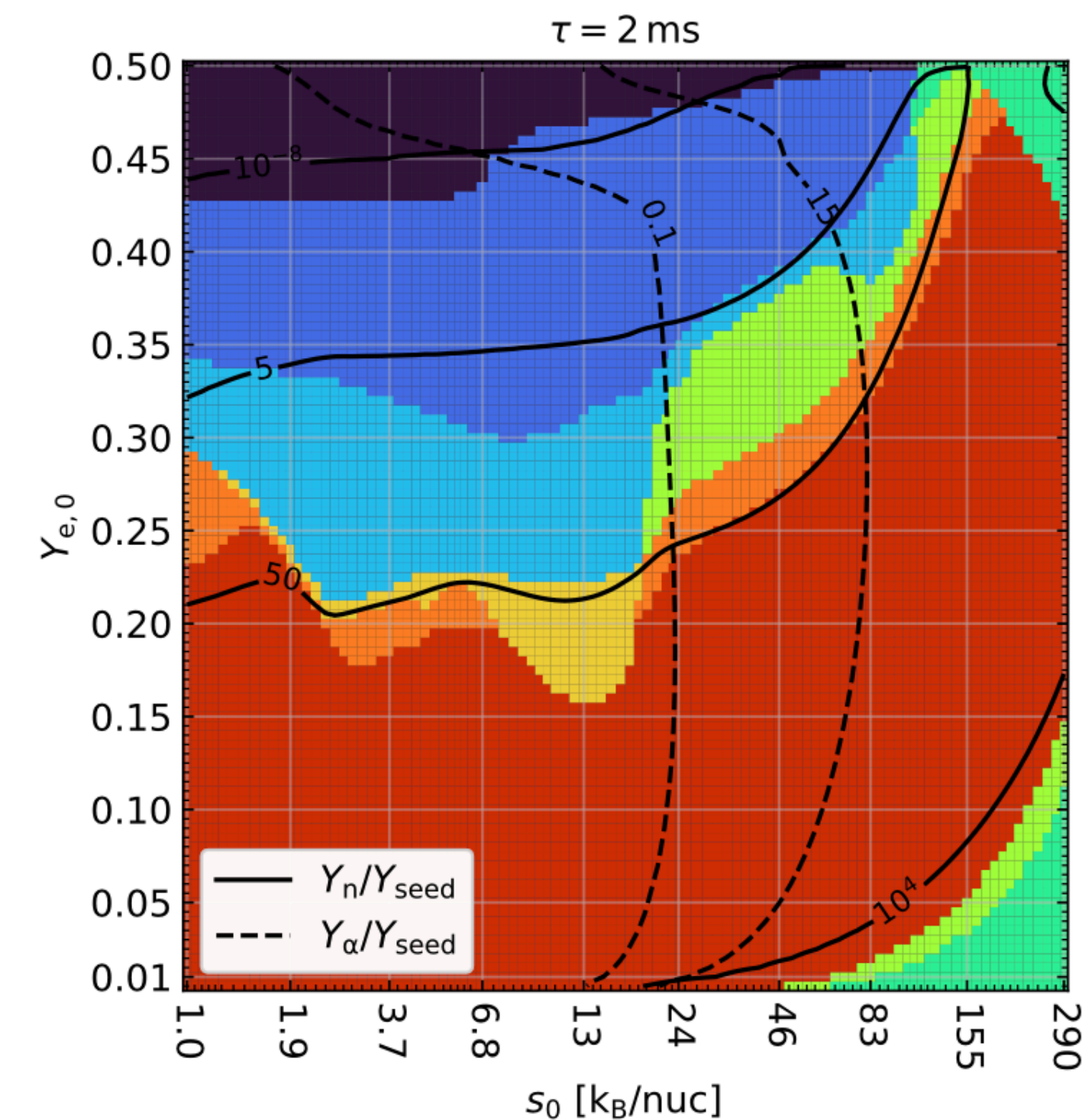
Three components



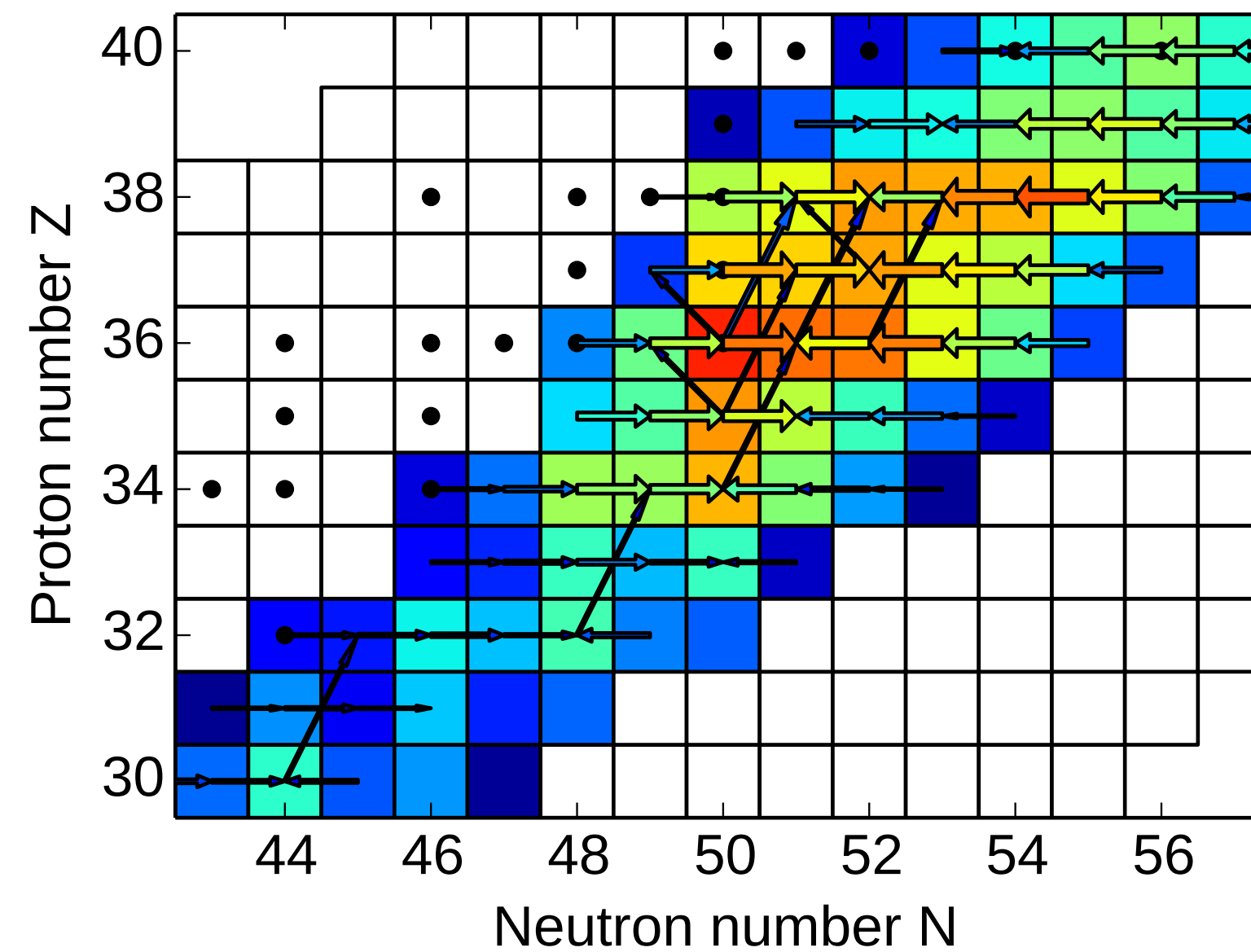
Conditions found in simulations

Nuclear physics uncertainties in the weak and strong r-process

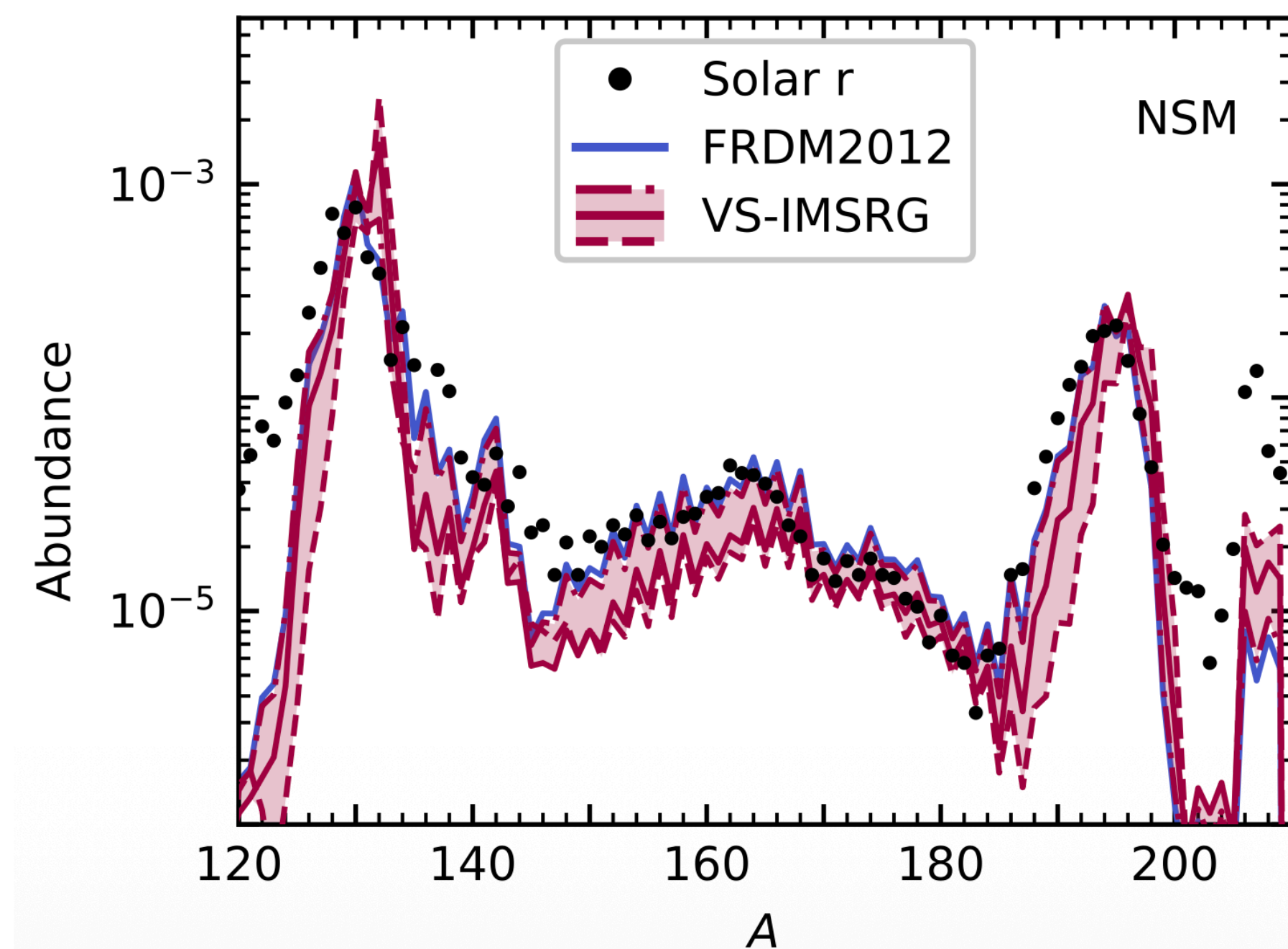
Complete survey of
r-process conditions



Weak r-process and
 (α, n) reactions

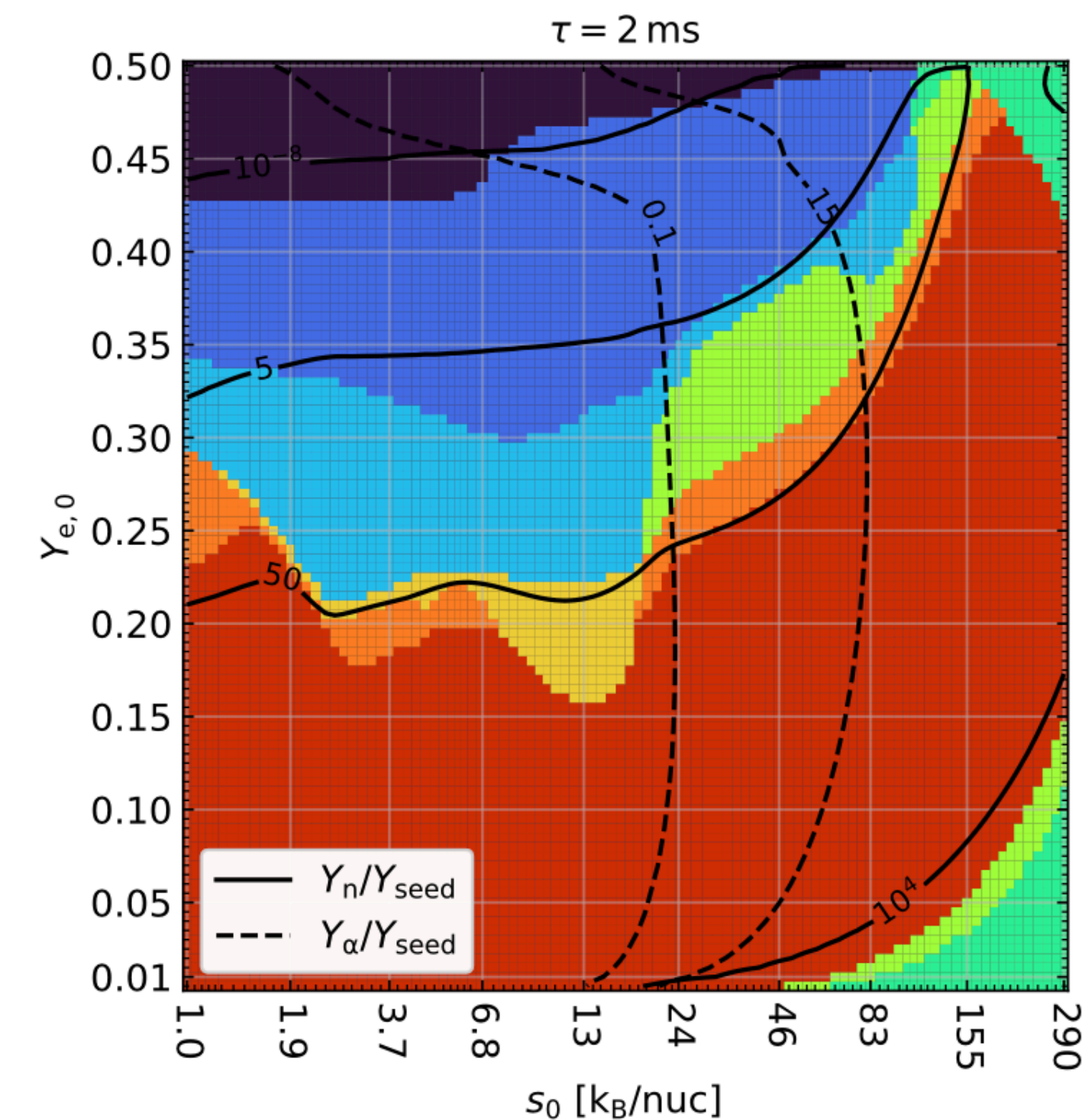


R-process with
ab-initio nuclear masses

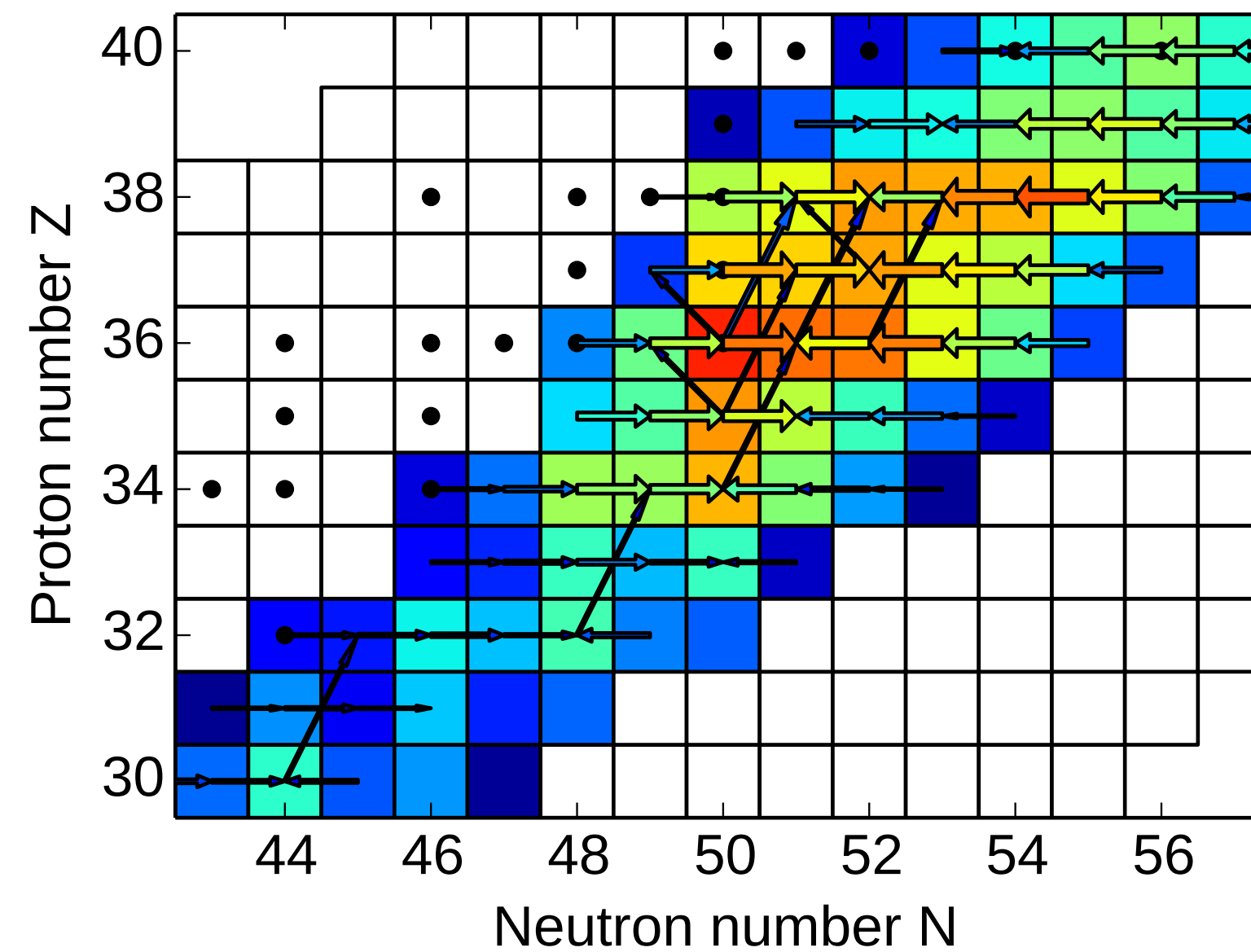


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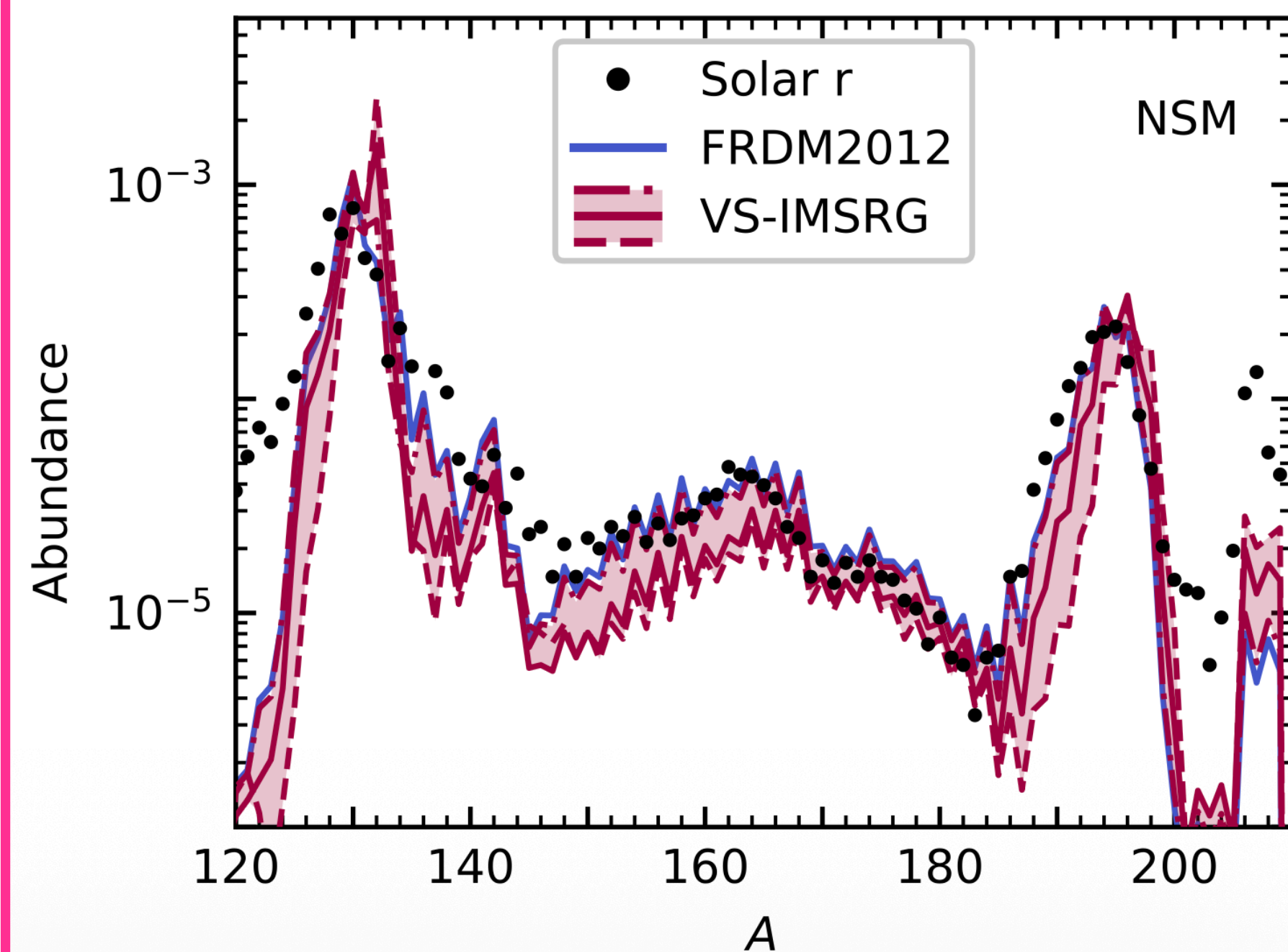
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Weak r-process and
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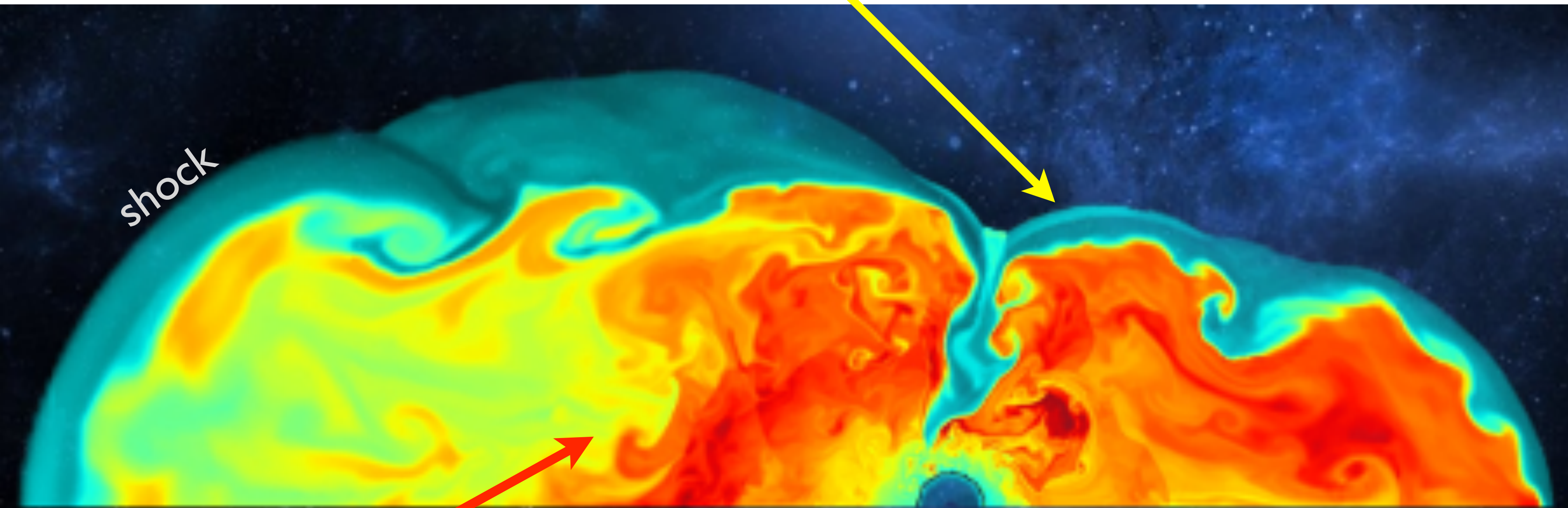


R-process with
ab-initio nuclear masses



Supernova nucleosynthesis

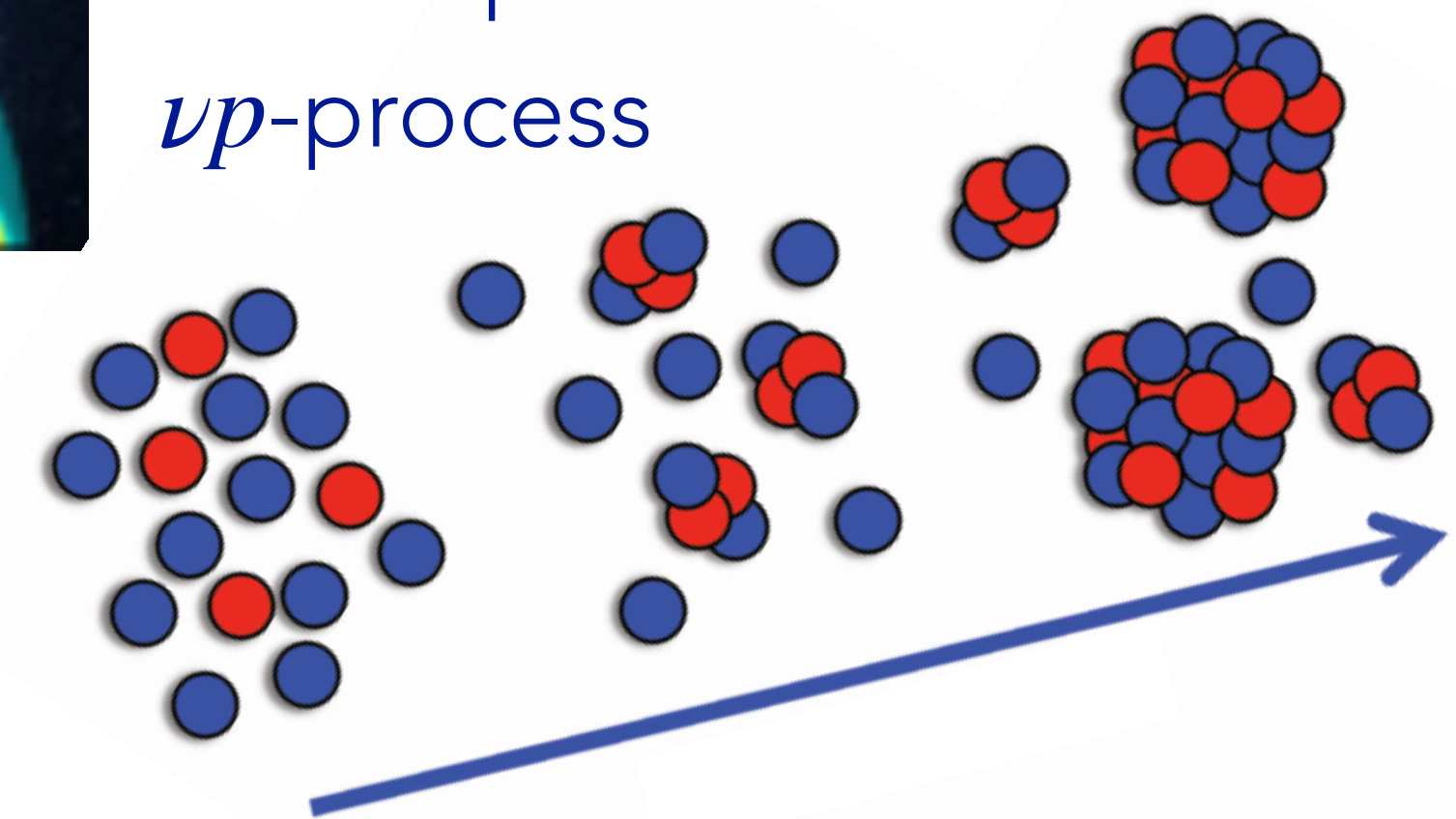
Explosive nucleosynthesis: O, Mg, Si, S, Ca, Ti, Fe
shock wave heats falling matter



Nuclear statistical
equilibrium
(NSE)

charged particle reactions
 α -process

r-process
weak r-process
 νp -process



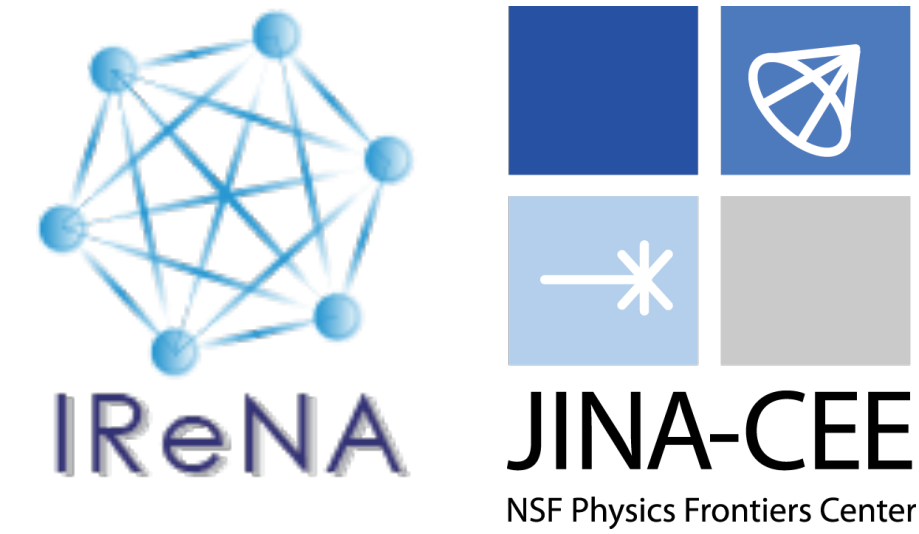
neutrino-driven ejecta

Core-collapse supernova: weak r-process

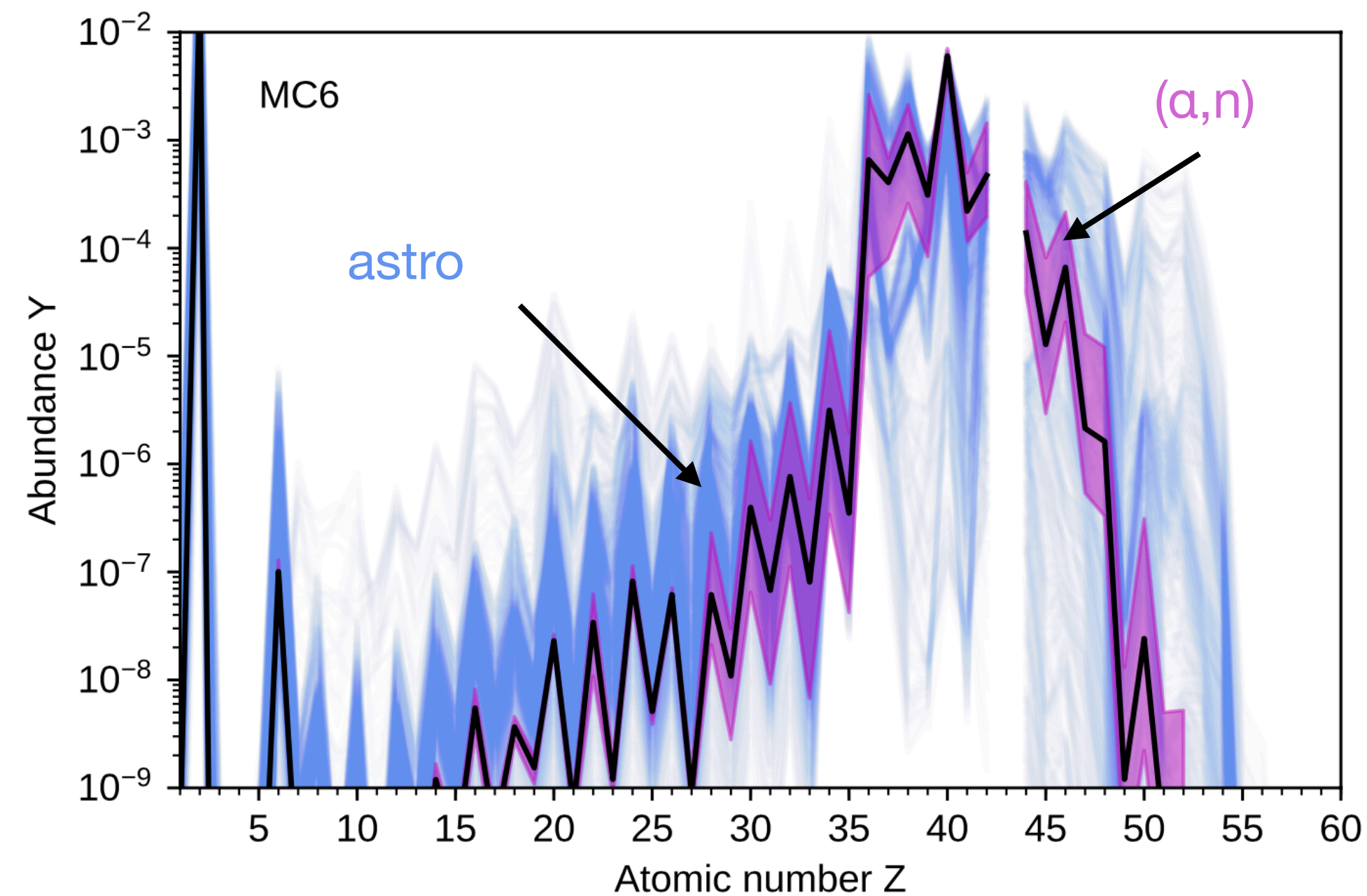
Neutrino-driven supernovae: elements up to Ag

Combine astrophysics and nuclear physics uncertainties

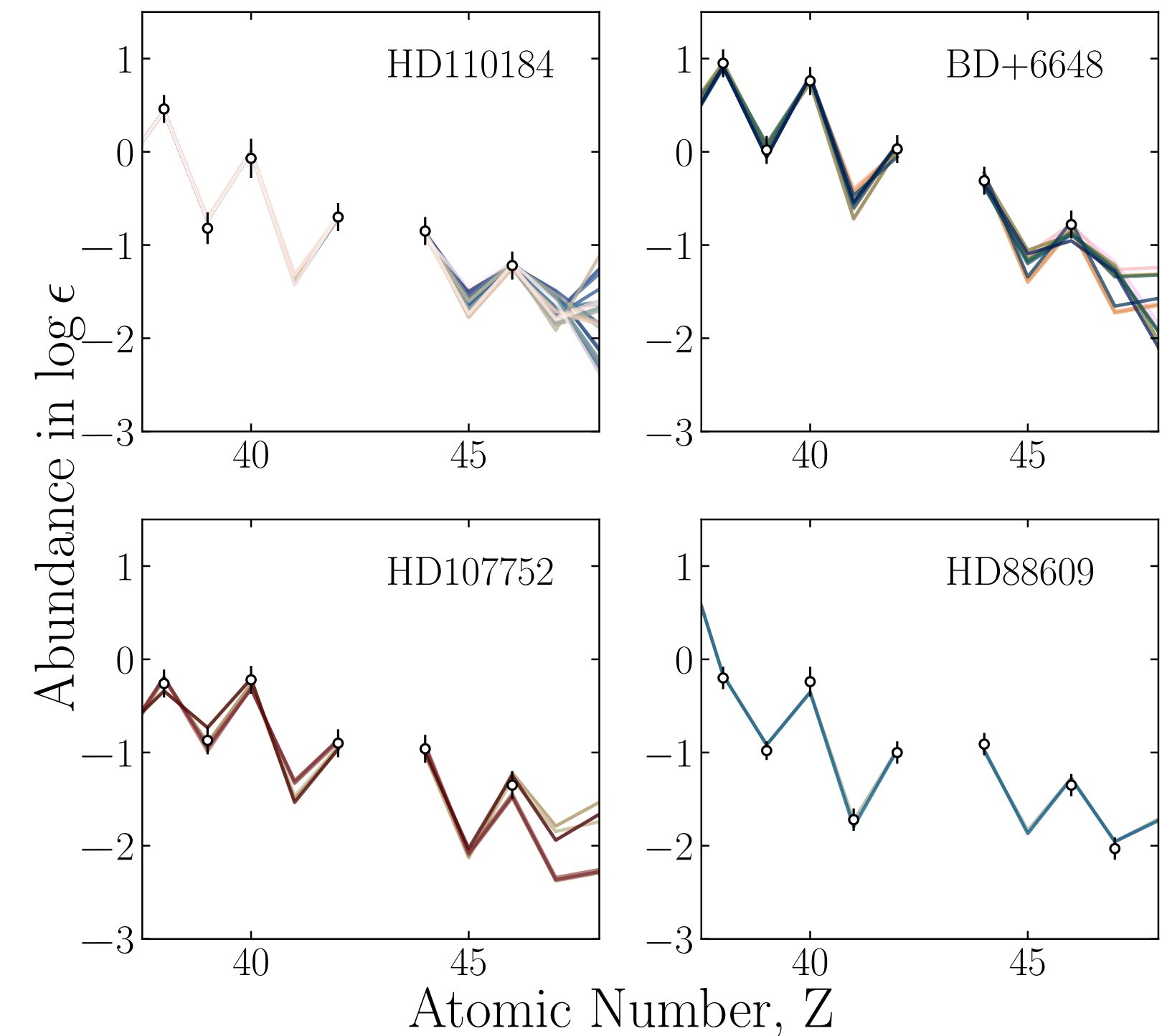
Motivation and support for experiments at NSCL, ANL, TRIUMF, ATOMKI



Bliss et al. JPG (2017), Bliss et al. ApJ (2018), Bliss et al. PRC (2020)



Psaltis et al. ApJ (2022), Psaltis et al. ApJ (2024)

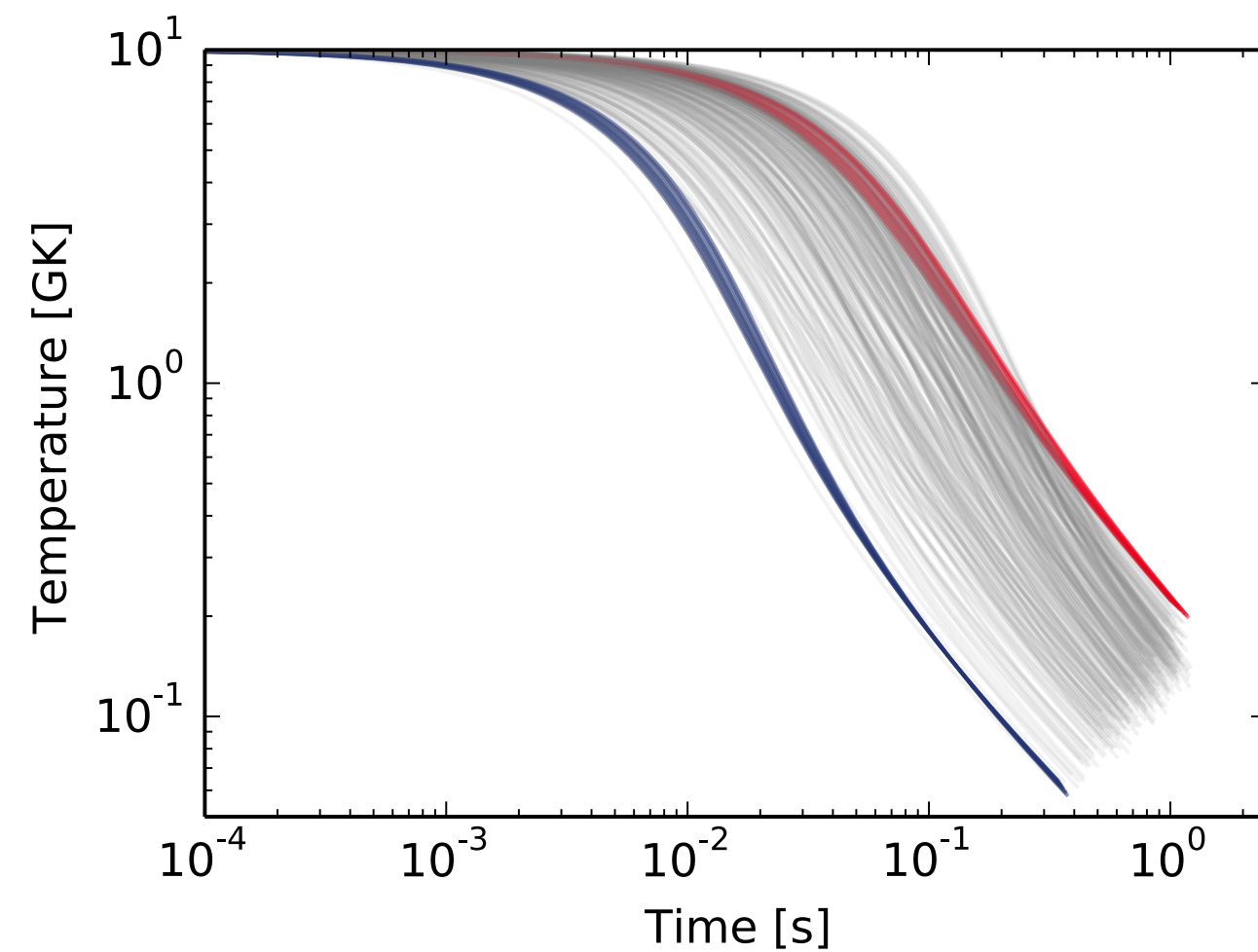
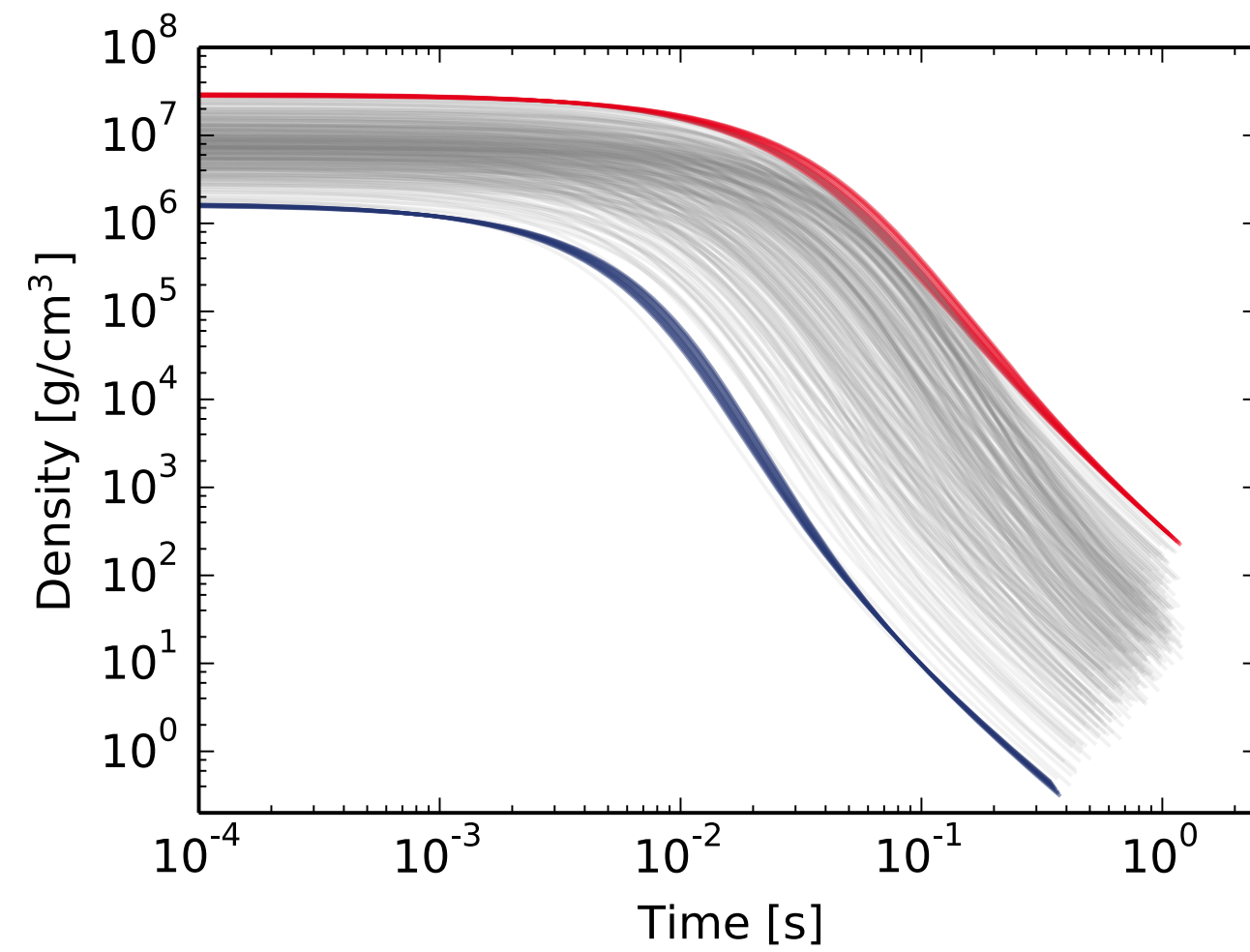


Astrophysics uncertainties/variability

Bliss, Witt, Arcones, Montes, Pereira (2018)

Steady-state model: all possible conditions and nucleosynthesis pattern in neutrino-driven ejecta

Based on Otsuki et al. 2000: study of 3 000 trajectories



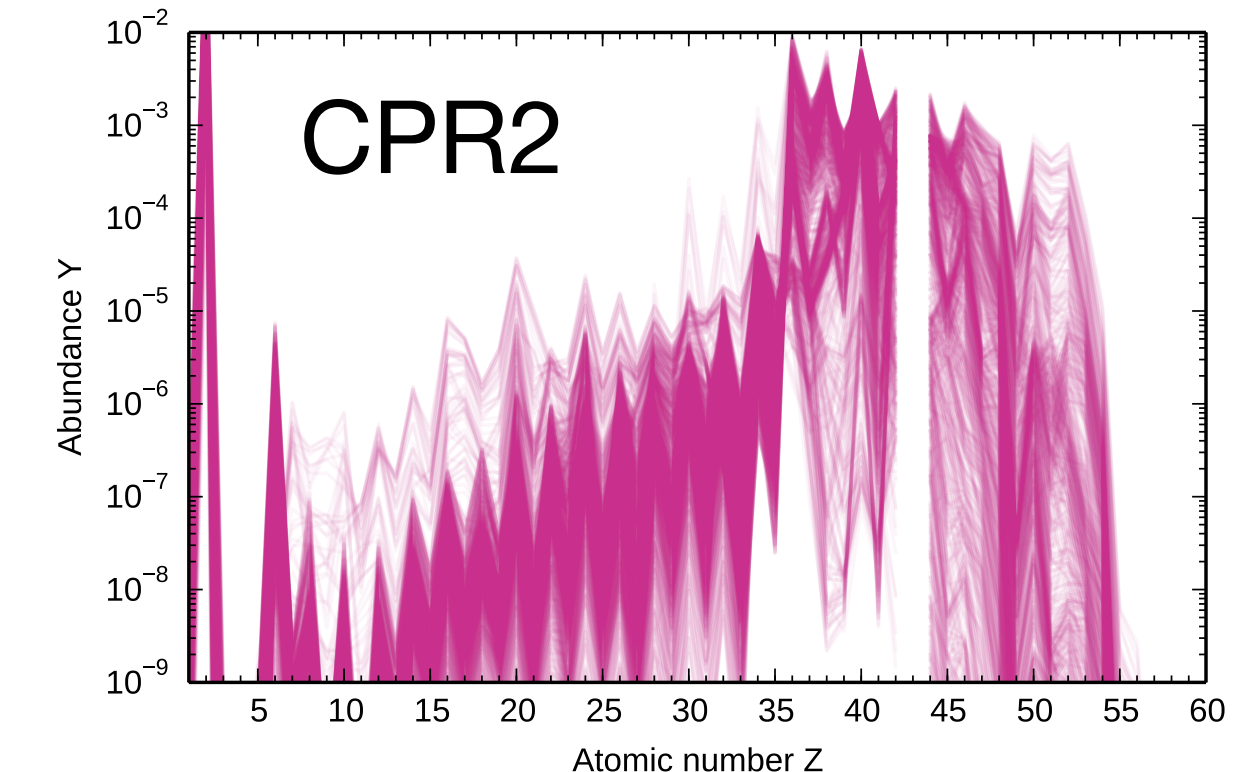
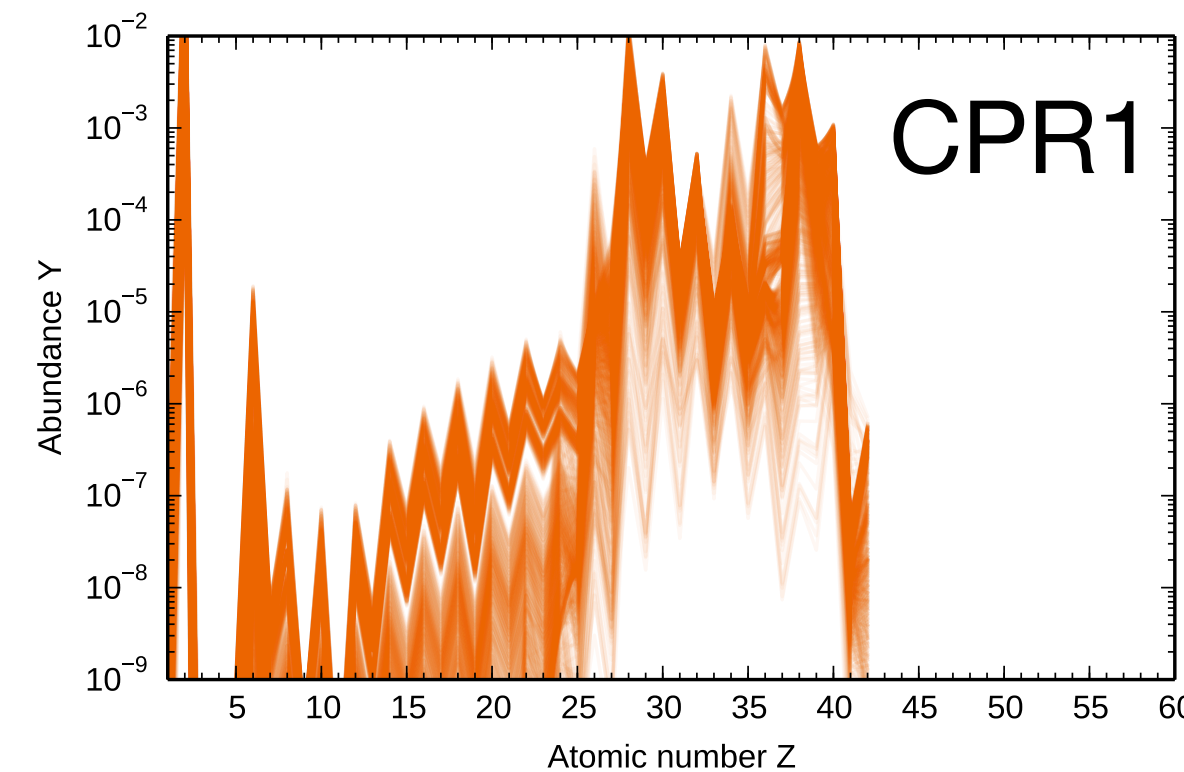
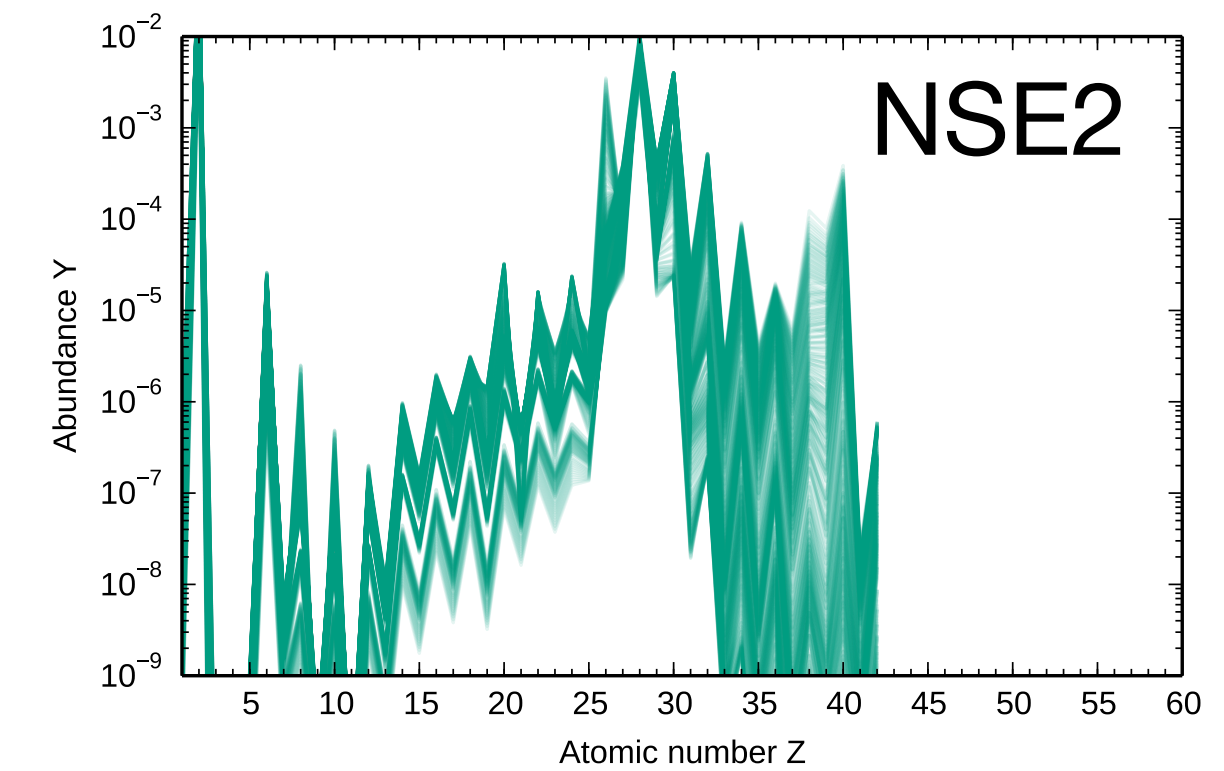
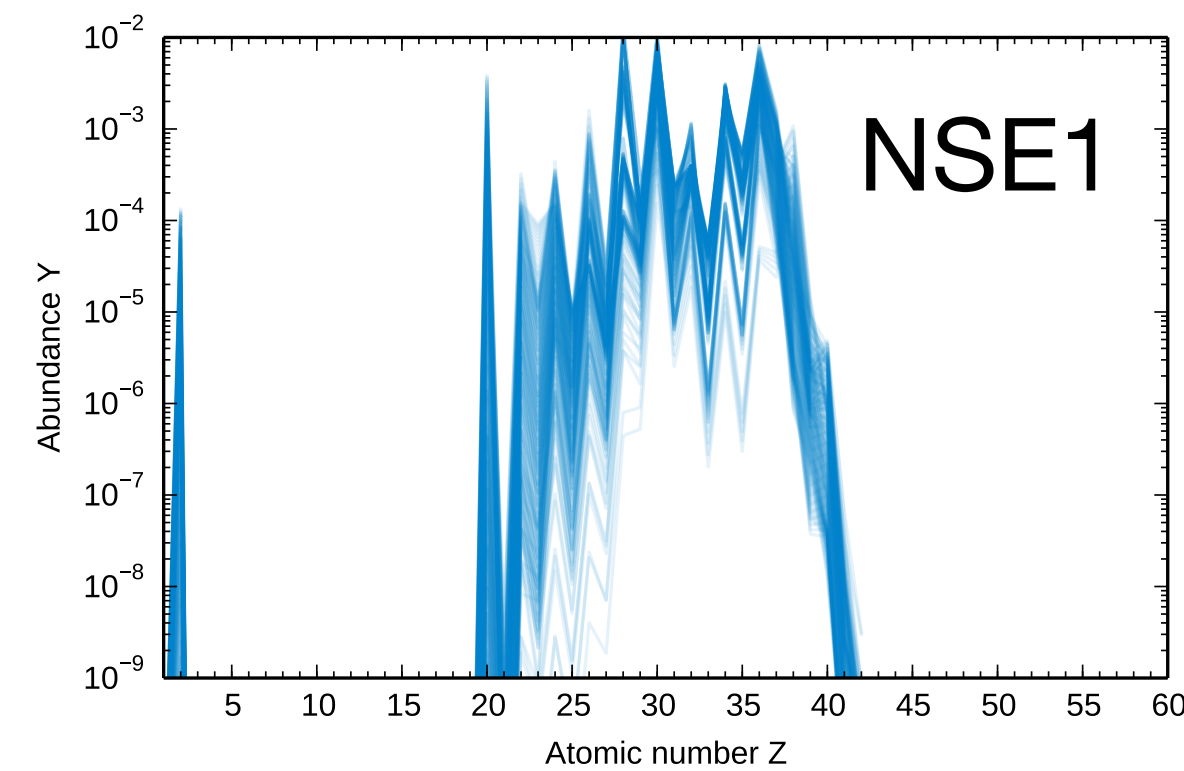
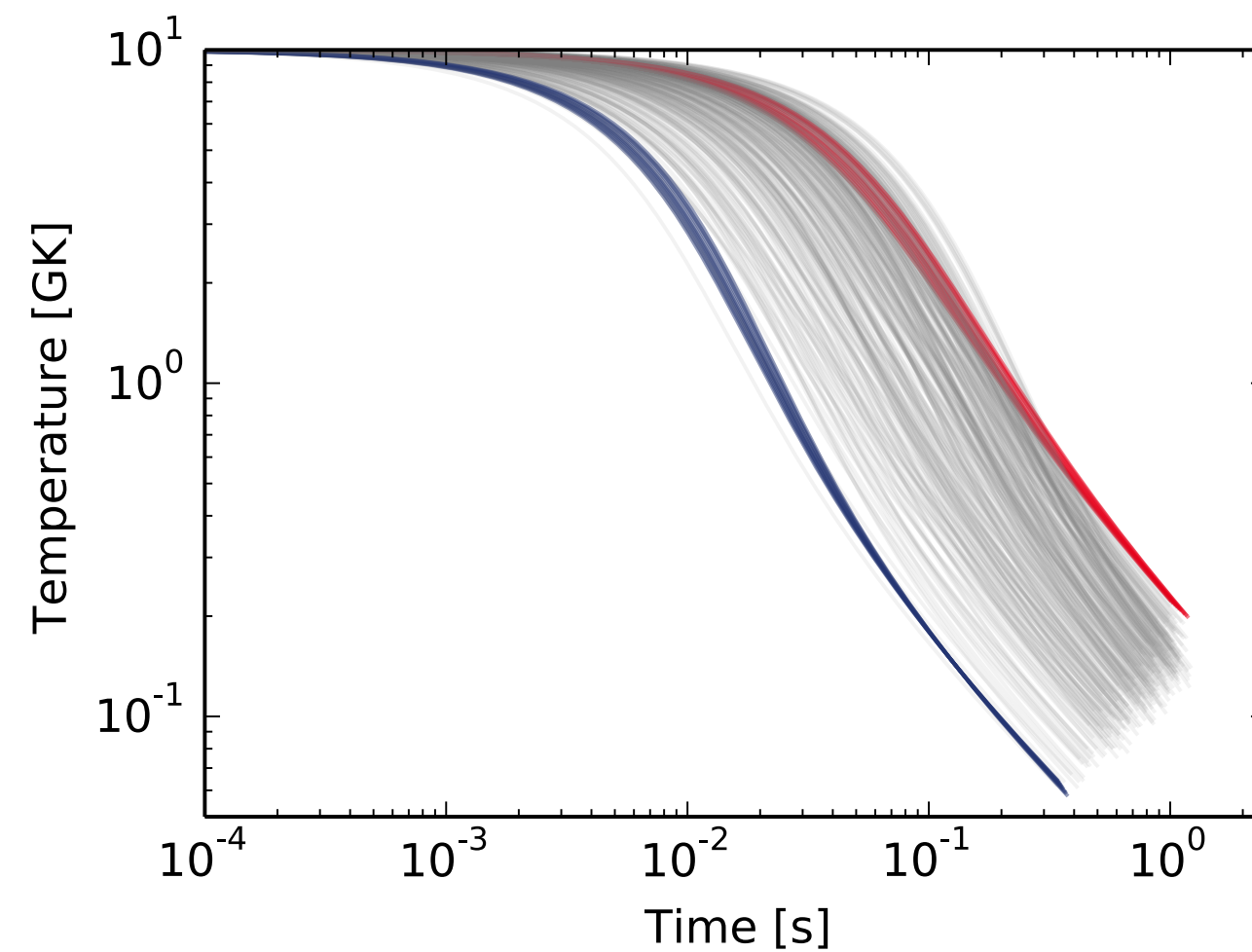
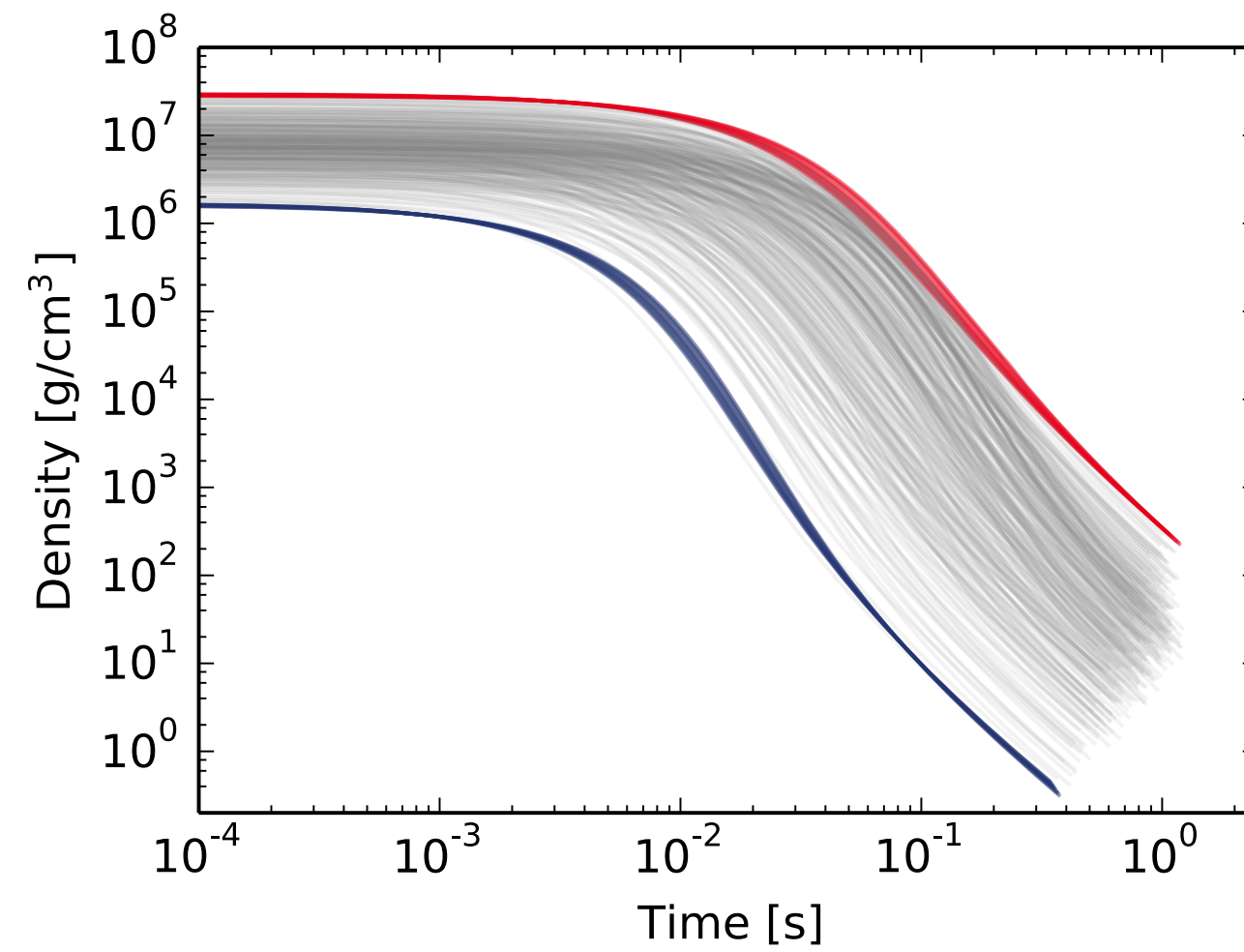
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Four characteristic patterns



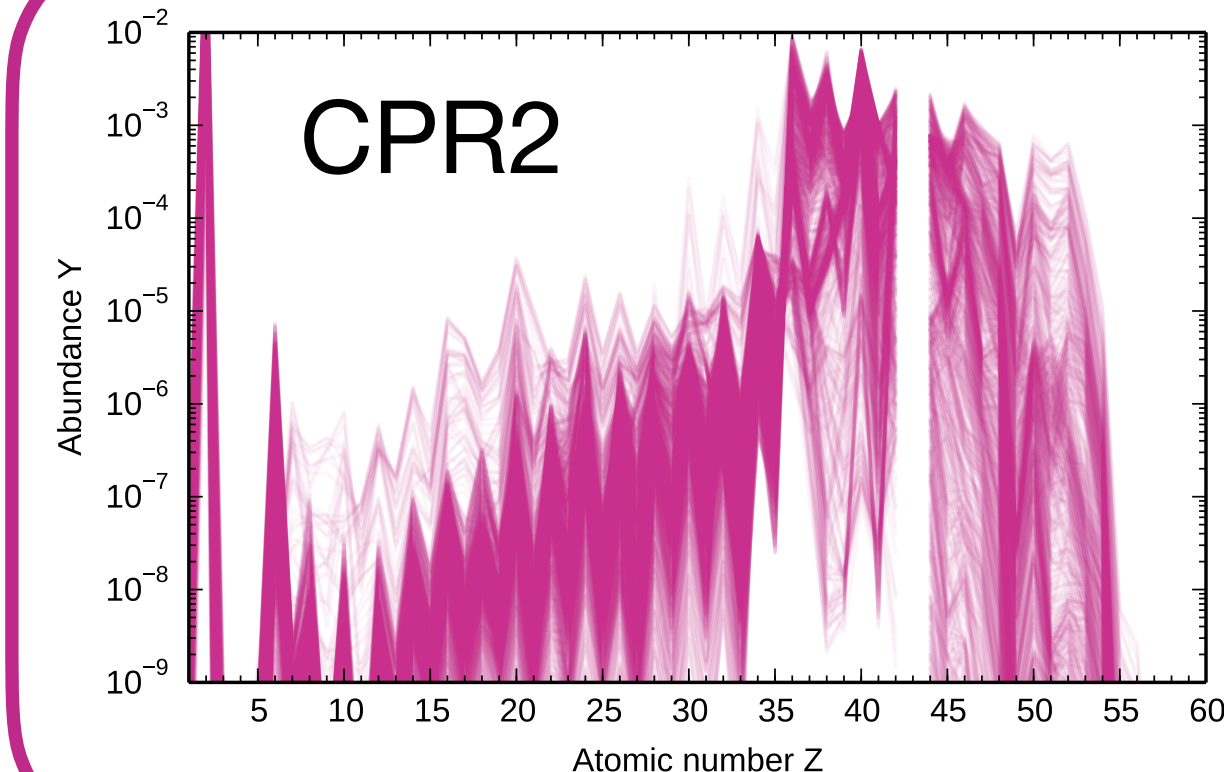
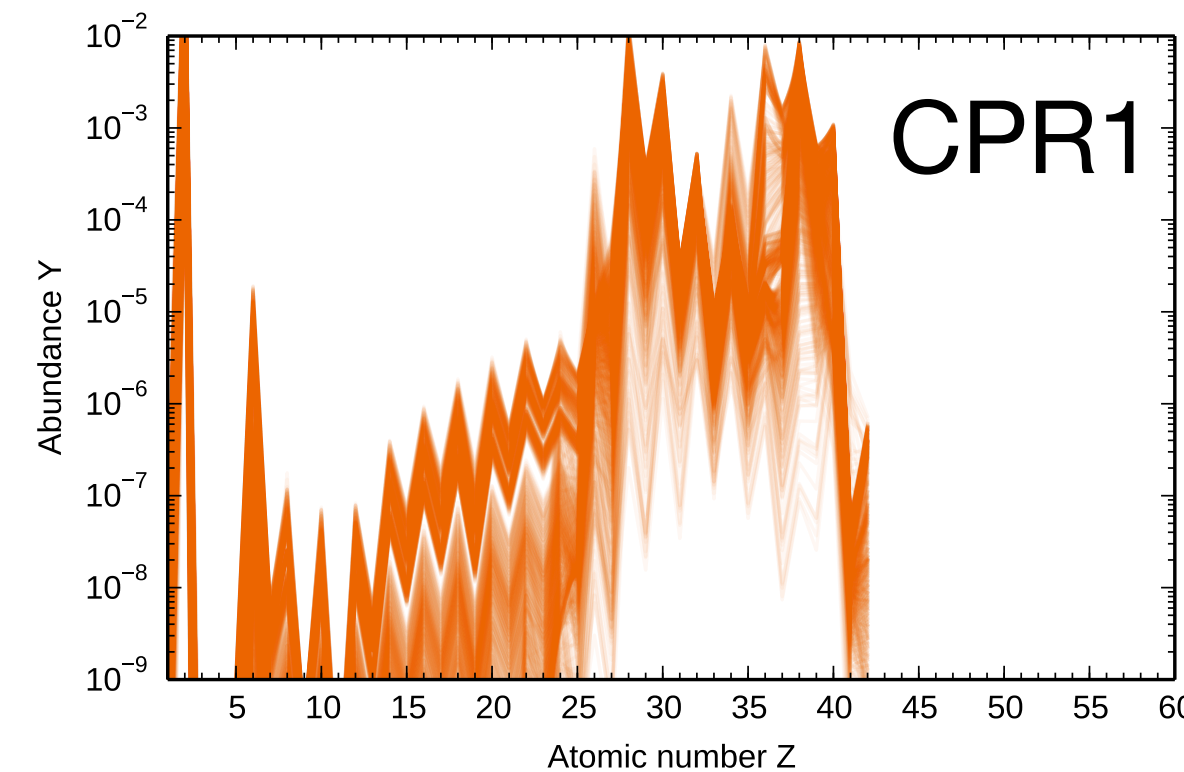
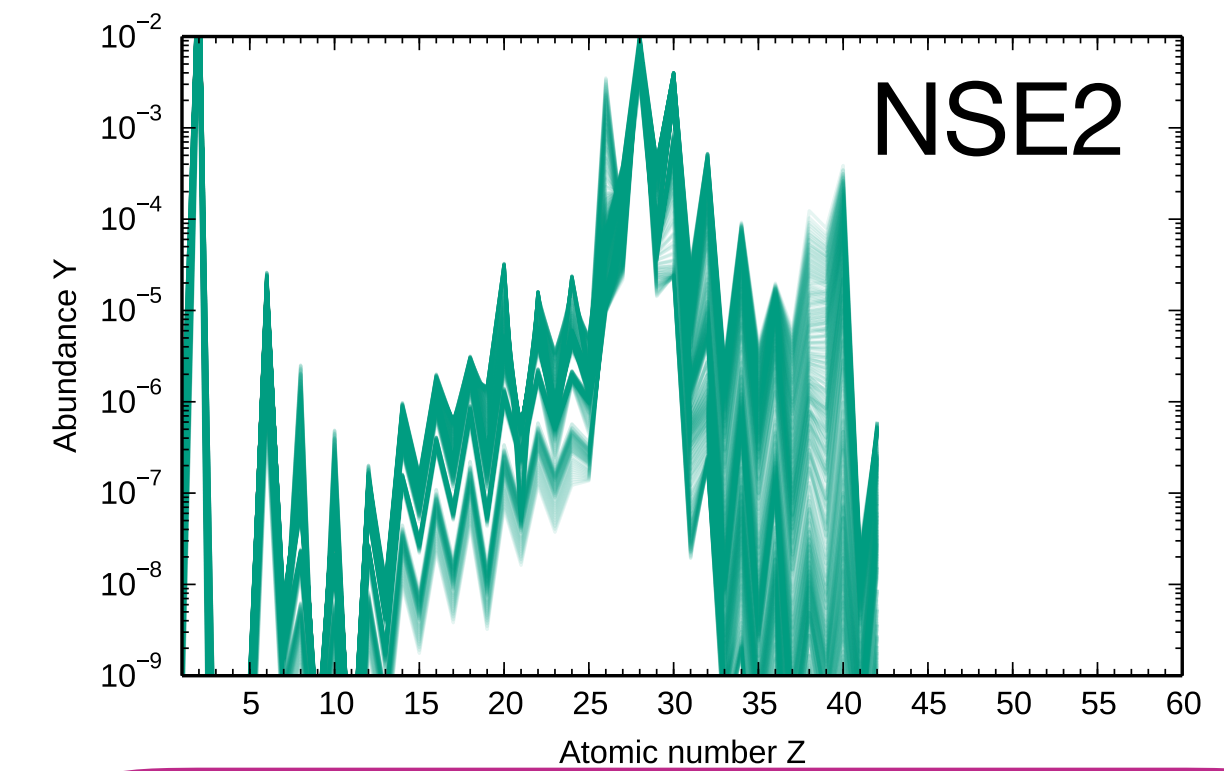
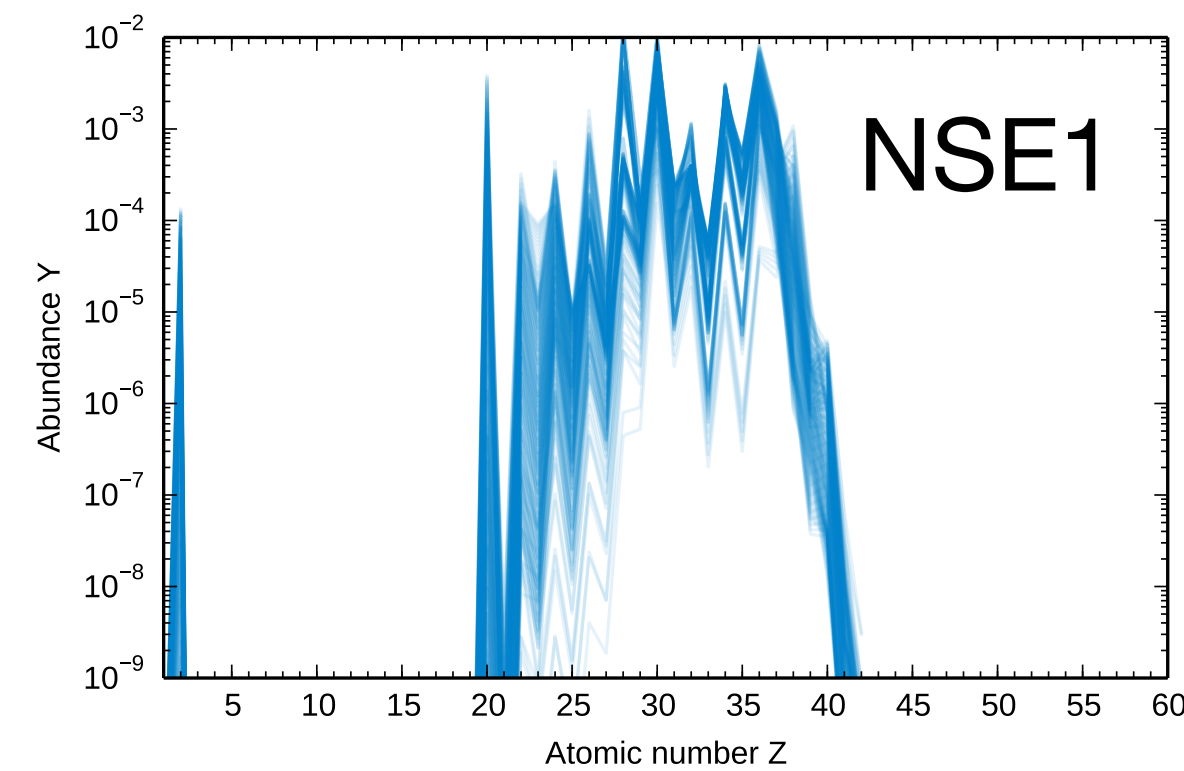
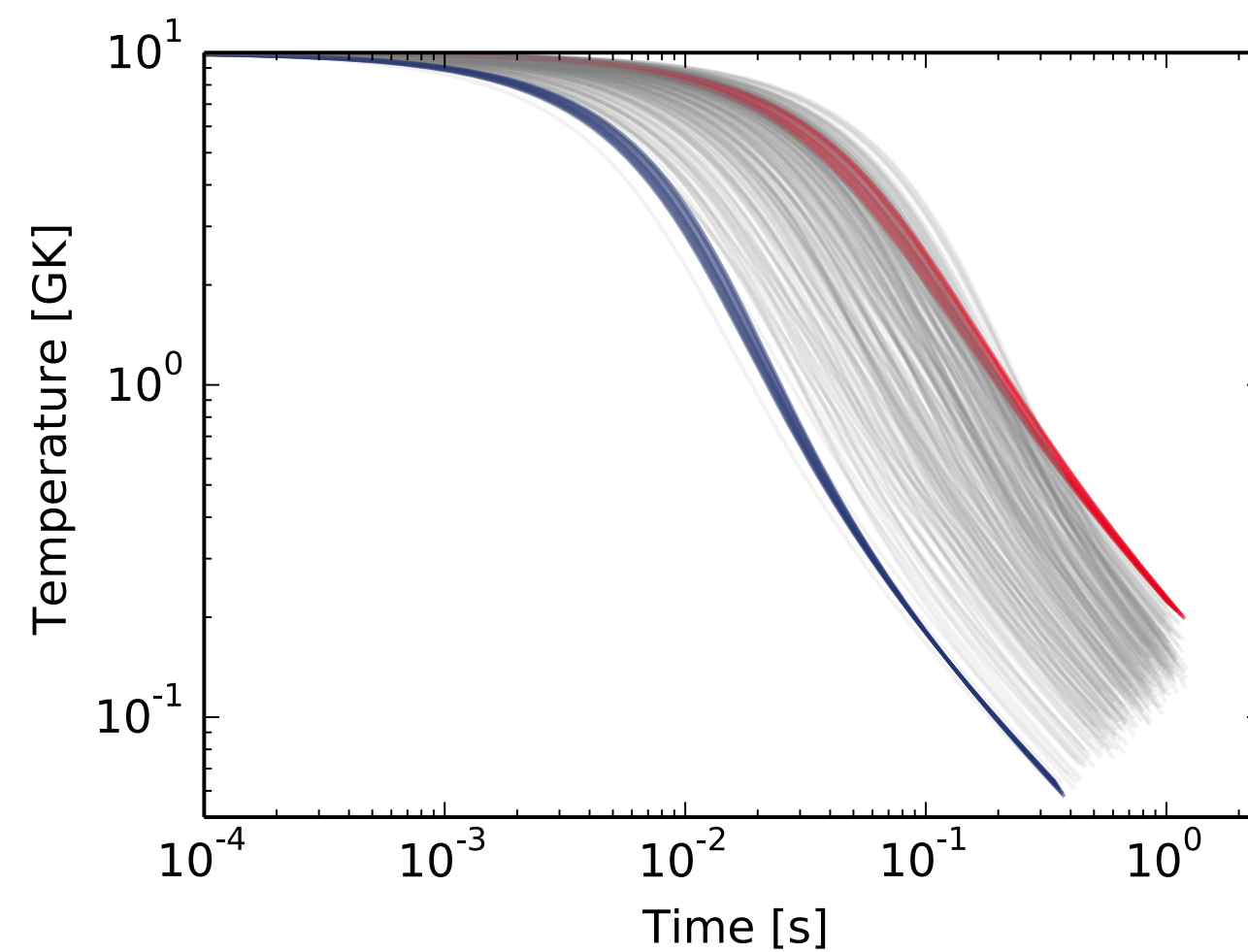
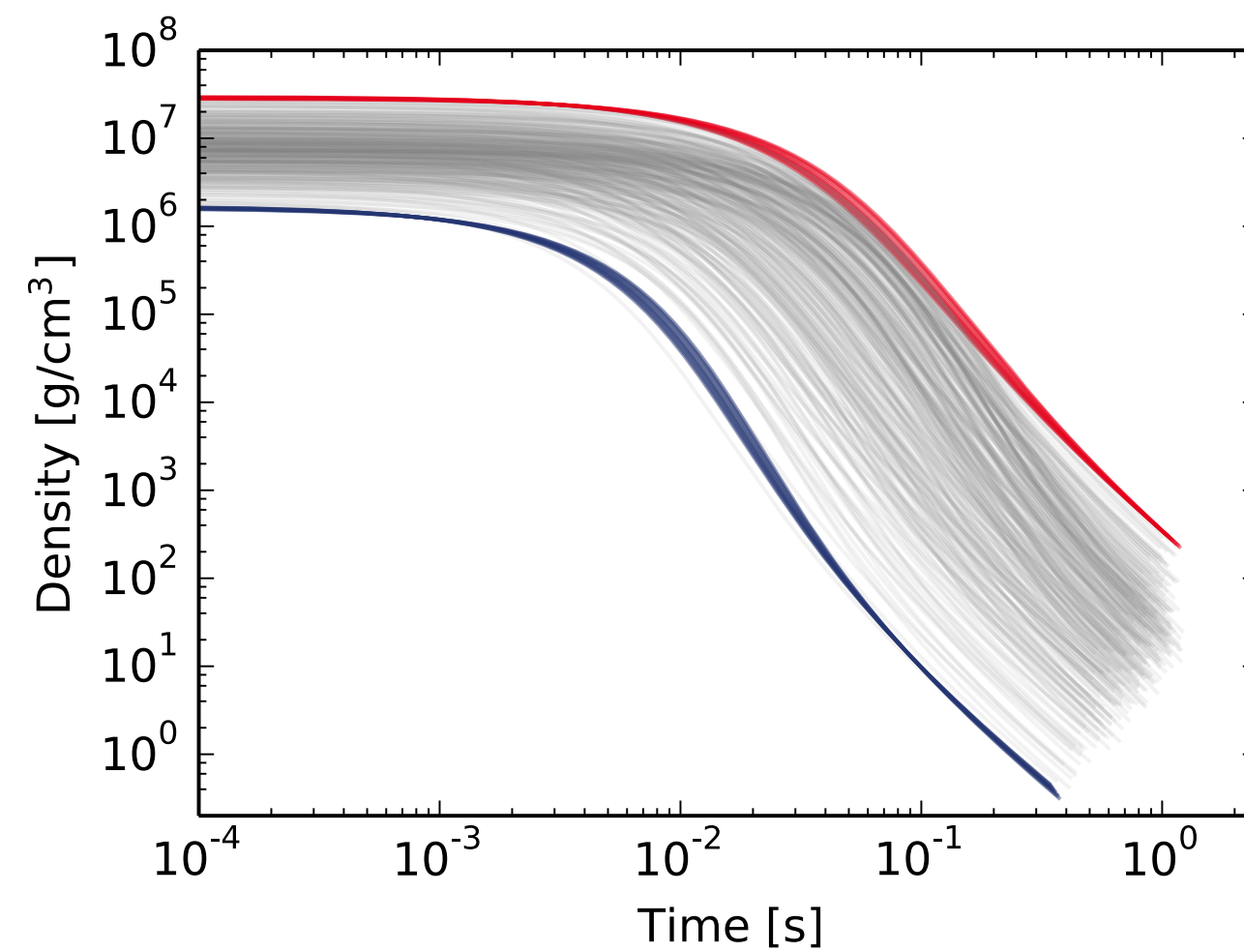
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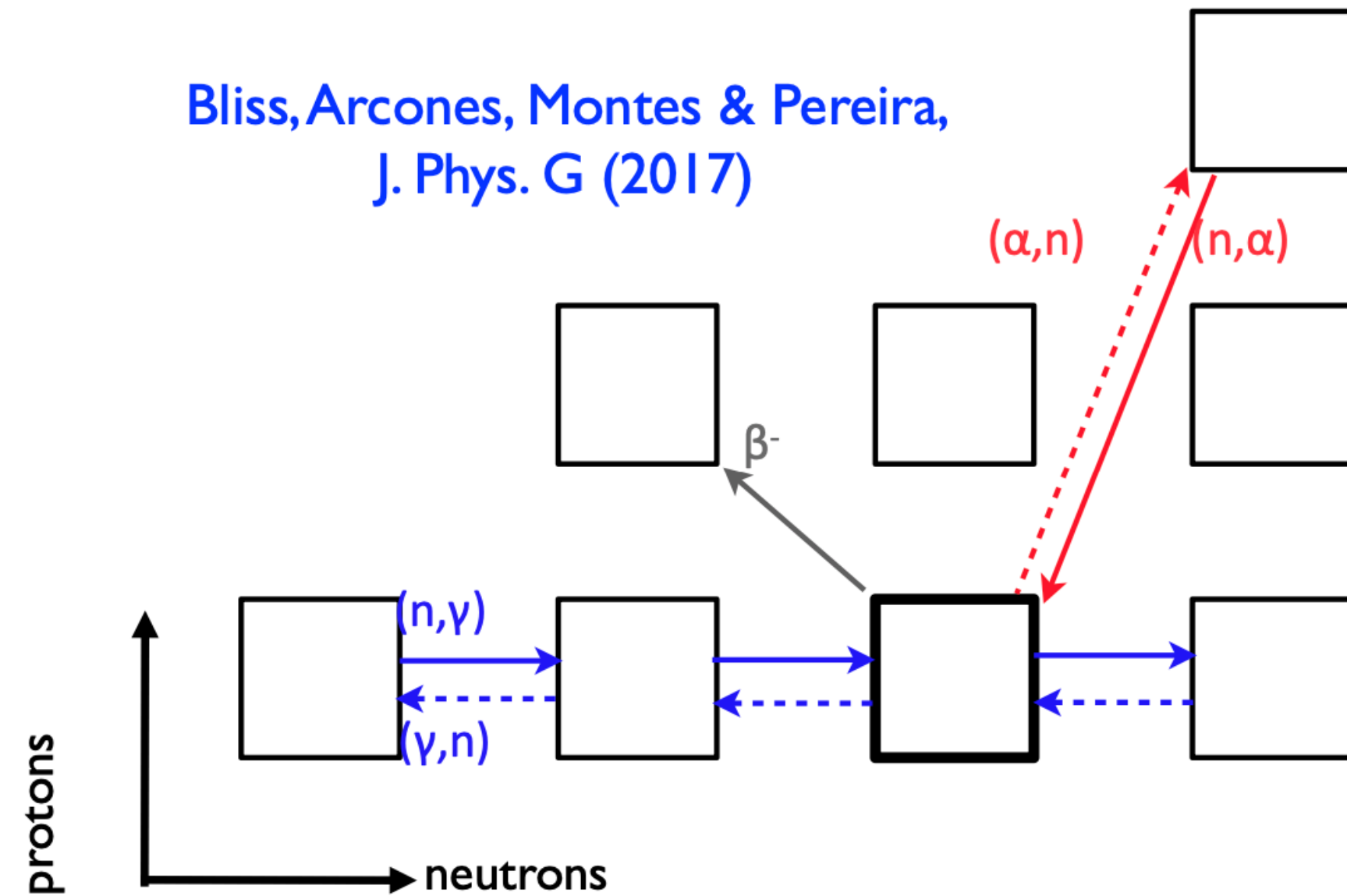
Four characteristic patterns



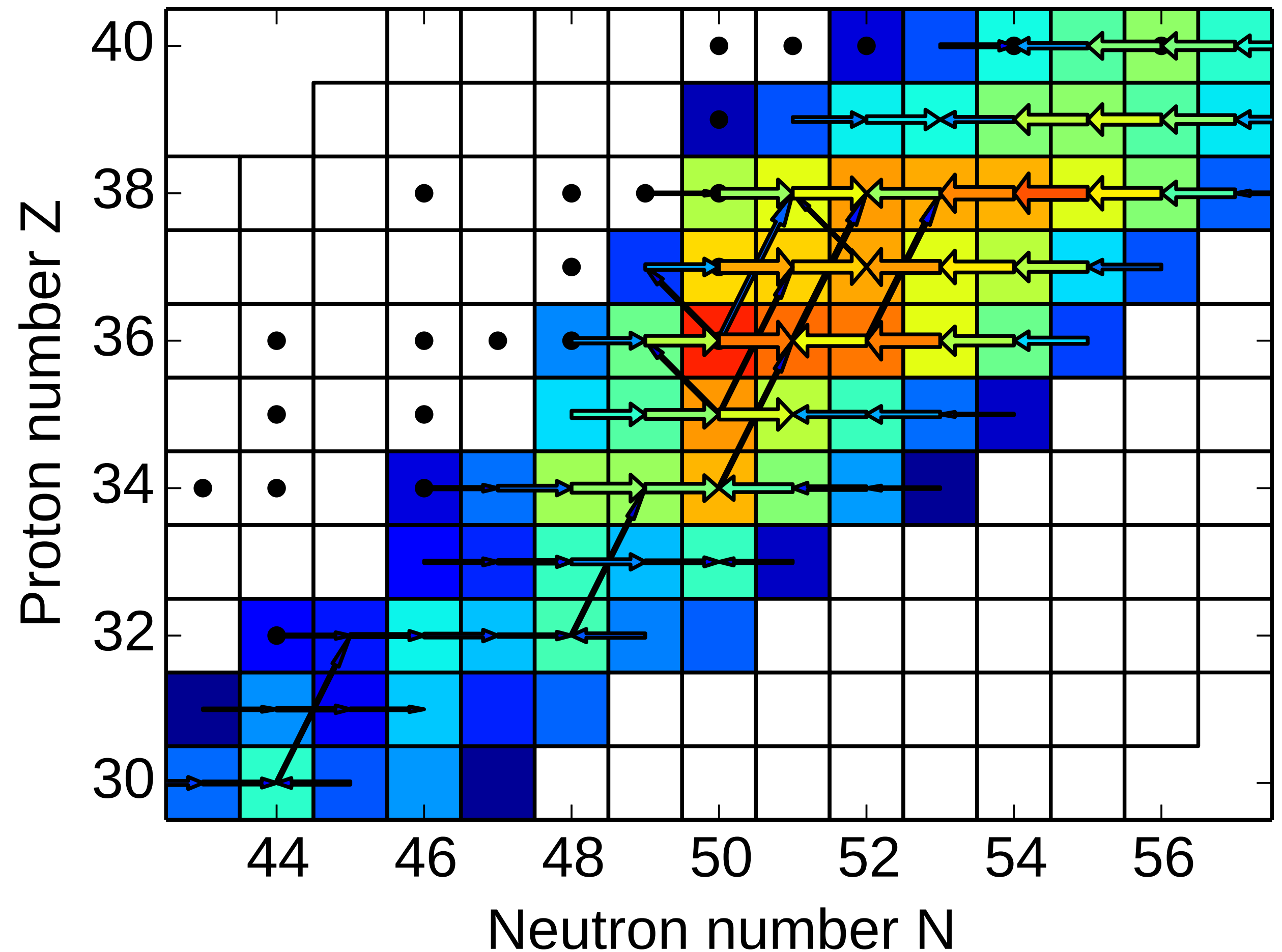
Nuclear physics uncertainty

Path close to stability:

- masses and beta decays known
- beta decays slow
- (α, n) reactions move matter to higher Z



time : 9.936e-03 s, T : 4.193e+00 GK, ρ : 2.481e+05 g/cm³

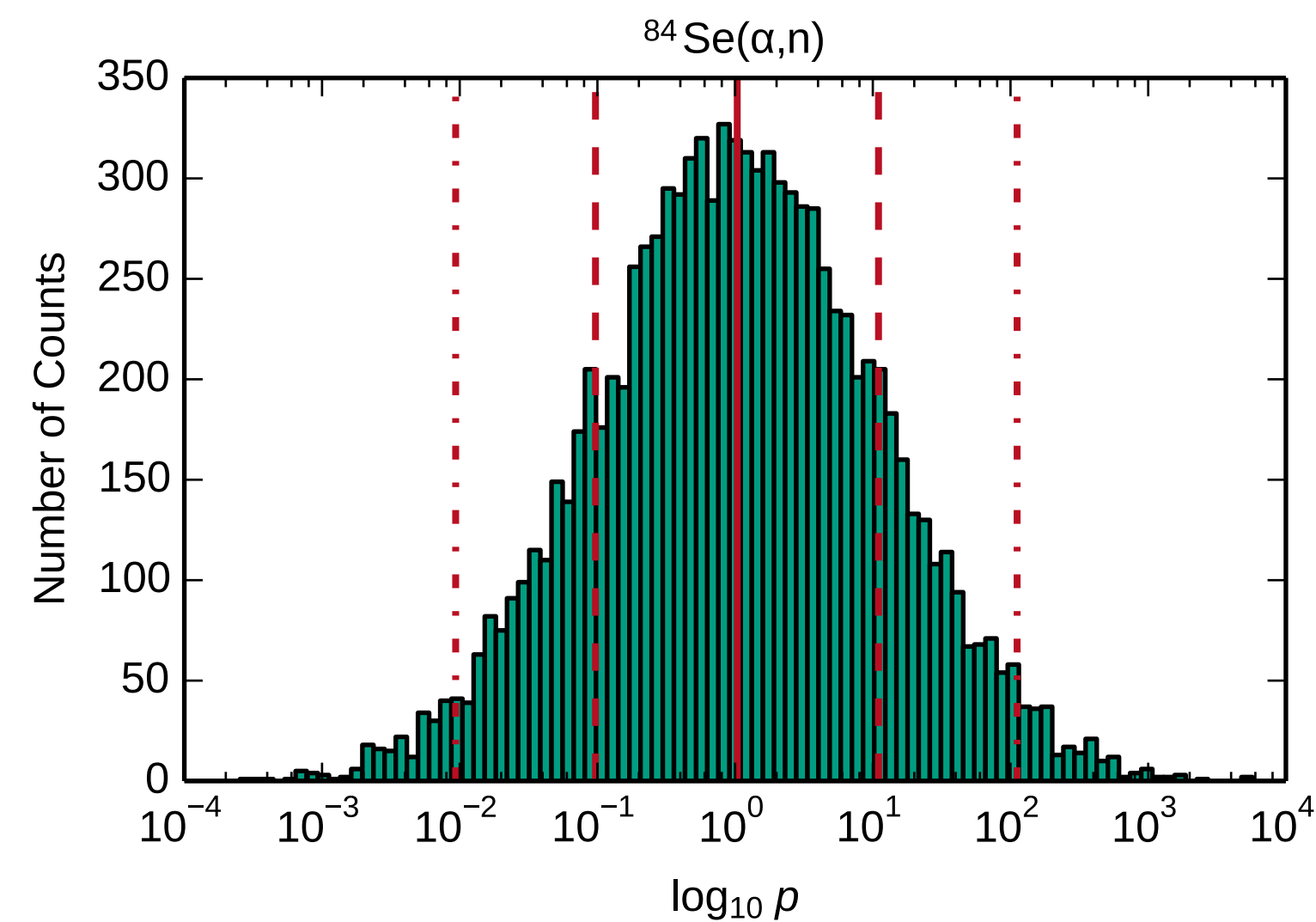


Sensitivity study

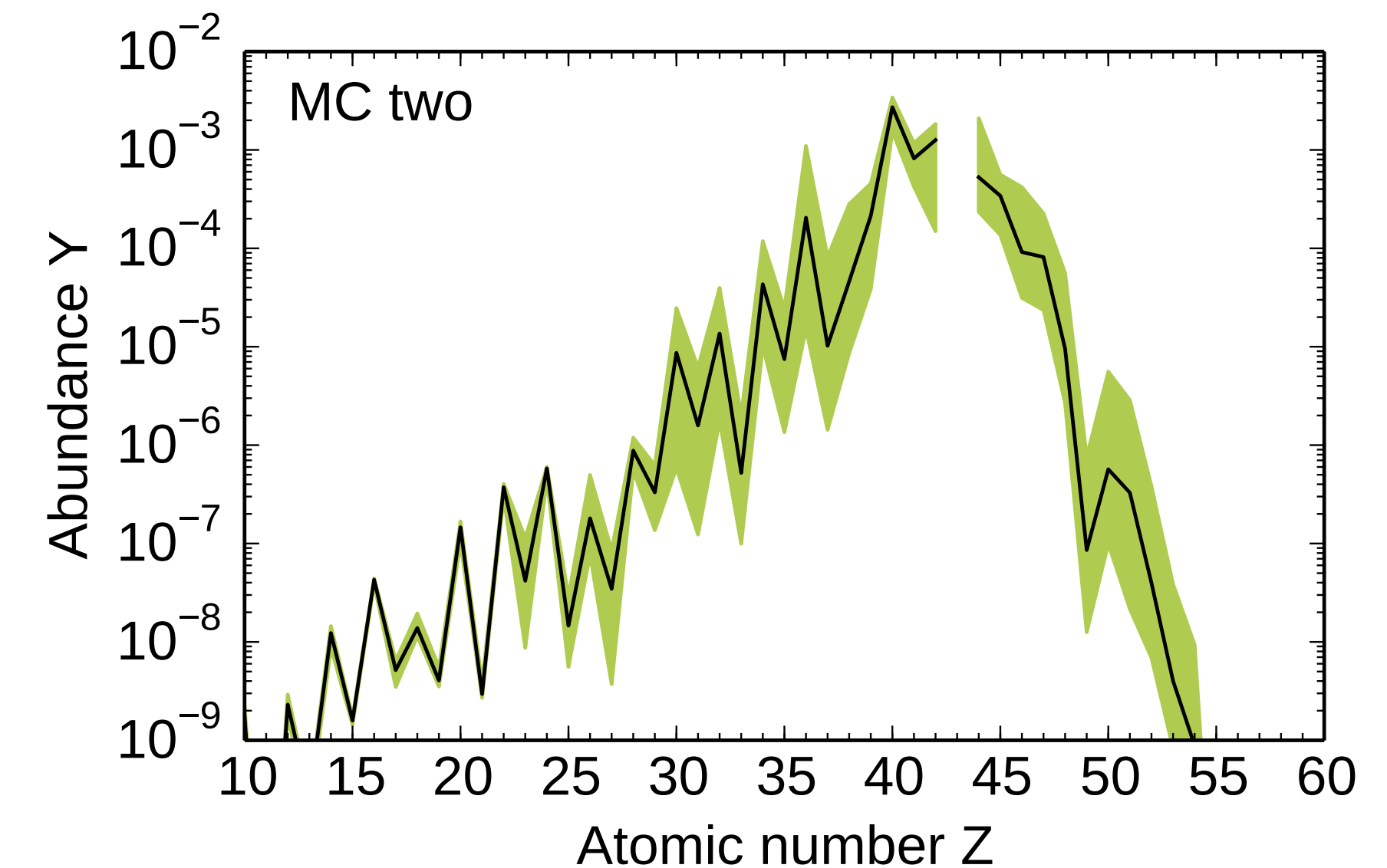
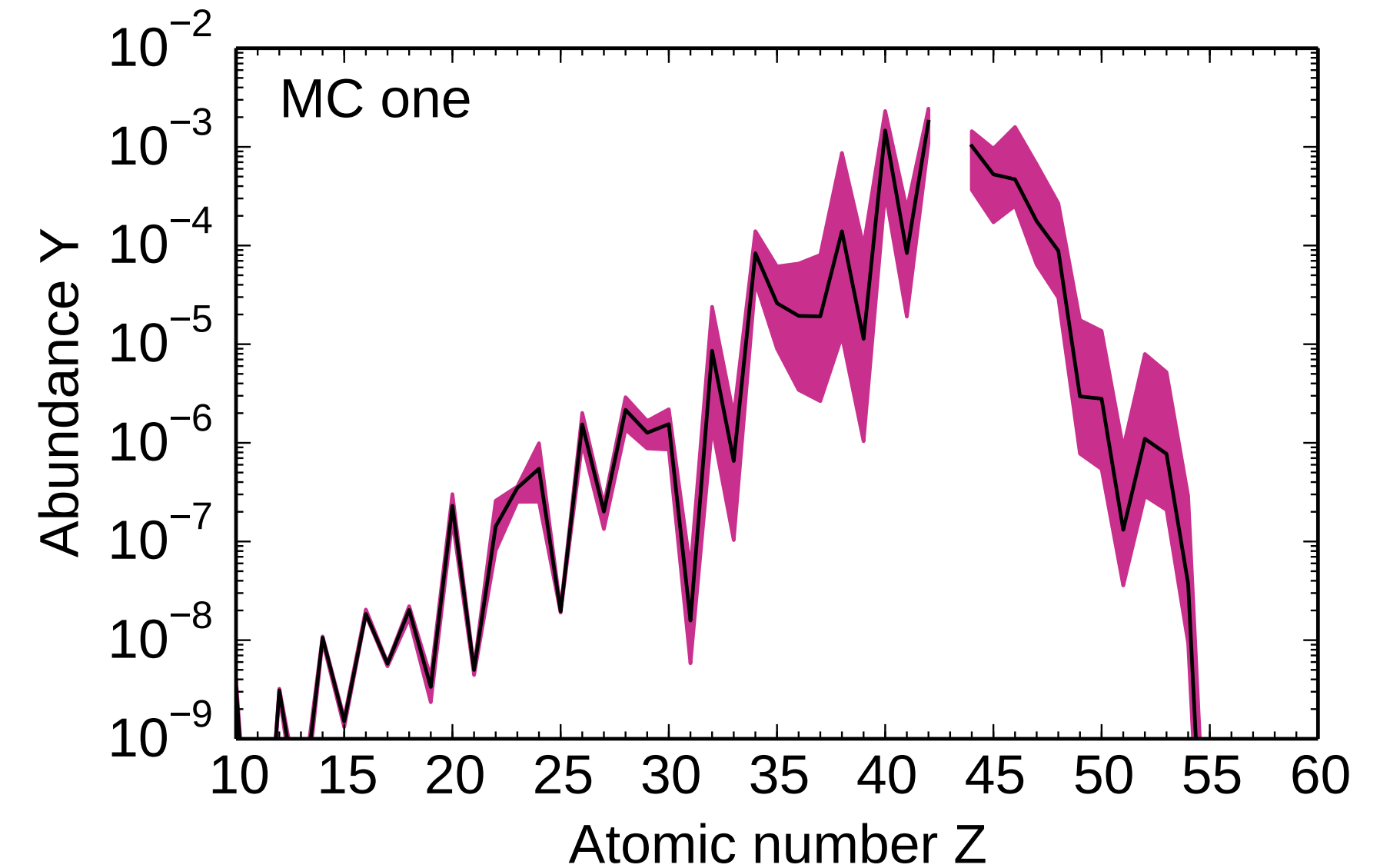
Bliss et al., PRC (2020)

Independently vary each (α, n) reaction rate between Fe and Rh by a random factor

Include theoretical and experimental uncertainties
→ log-normal distributed rates ($\mu = 0, \sigma = 2.3$)

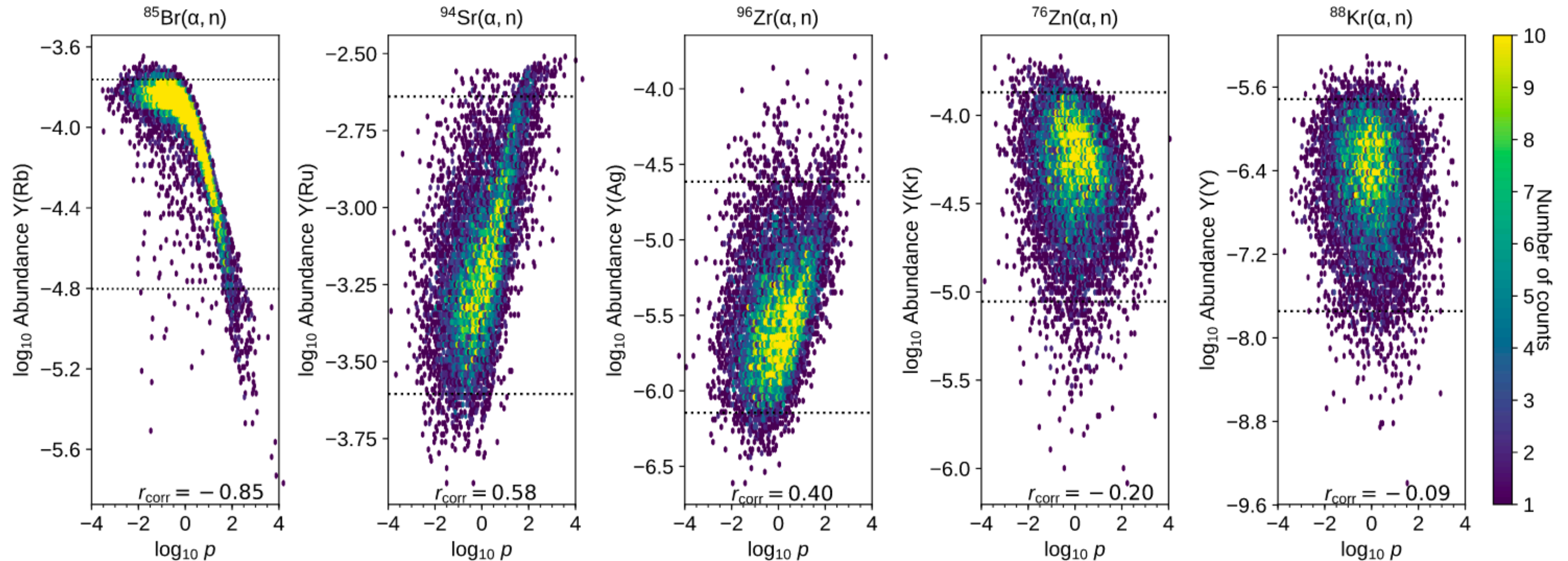


36 representative trajectories of group CPR2,
10 000 Monte Carlo runs



Sensitivity study: key reactions

Bliss et al., PRC (2020)



Spearman rank order correlation

$$\rho_{\text{corr}} = \frac{\sum_{i=1}^n (R(p_i) - \overline{R(p)}) (R(y_i) - \overline{R(y)})}{\sqrt{\sum_{i=1}^n (R(p_i) - \overline{R(p)})^2} \sqrt{\sum_{i=1}^n (R(y_i) - \overline{R(y)})^2}}$$

→ Monotonic changes

→ $-1 \leq \rho_{\text{corr}} \leq +1$

Sensitivity study: key reactions

Bliss et al., PRC (2020)

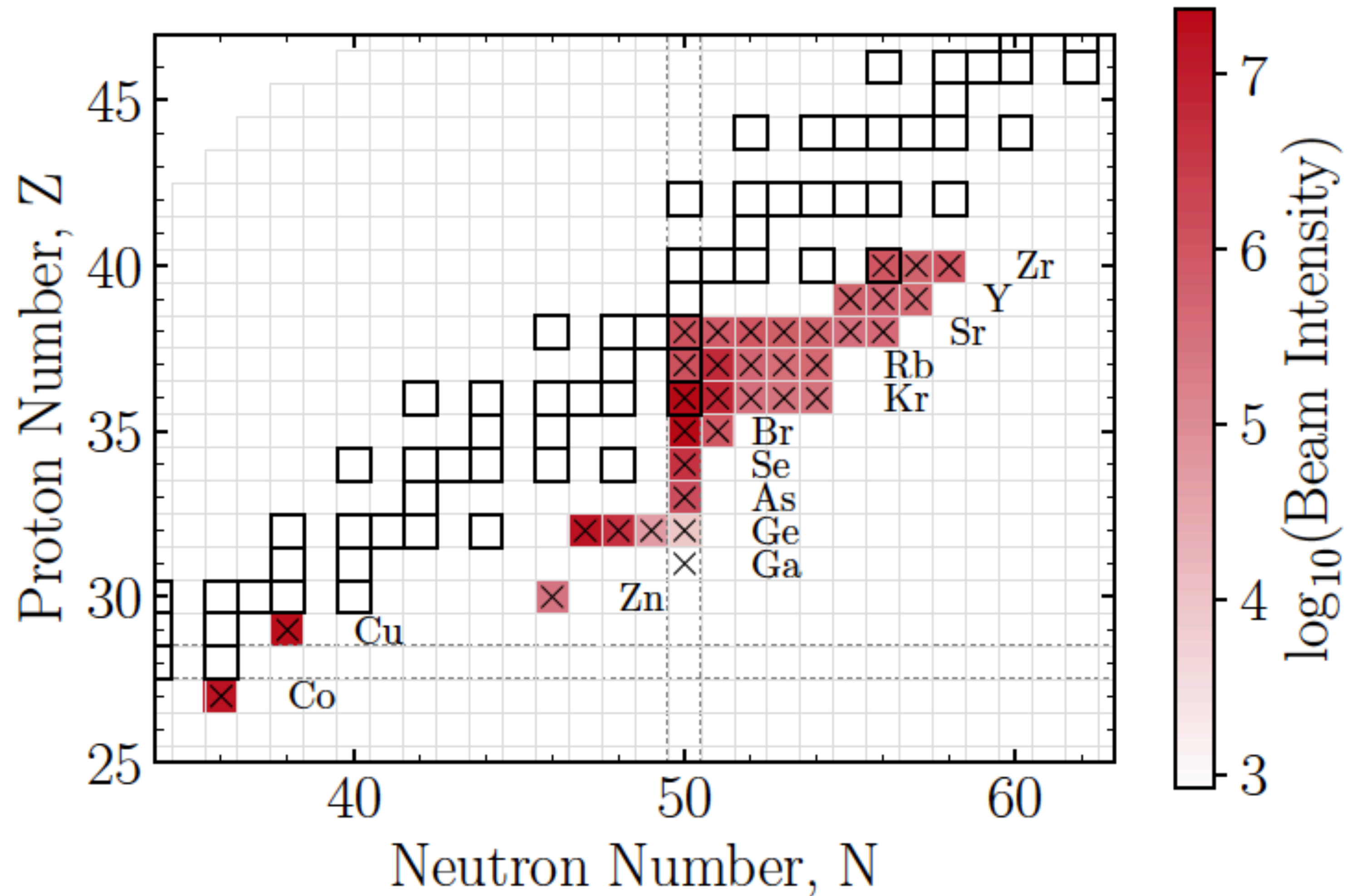
Key reactions $\Rightarrow$ large correlation + significant impact on abundance for several astro conditions

Reaction	Z	MC tracers
$^{59}\text{Fe}(\alpha, n)^{62}\text{Ni}$	39 – 42, 45	34, 36
$^{68}\text{Fe}(\alpha, n)^{71}\text{Ni}$	36, 37	3
$^{63}\text{Co}(\alpha, n)^{66}\text{Cu}$	39–42, 45	20, 34, 36
$^{71}\text{Co}(\alpha, n)^{74}\text{Cu}$	36, 37	3
$^{74}\text{Ni}(\alpha, n)^{77}\text{Zn}$	36–42	2, 3, 17, 18, 32
$^{76}\text{Ni}(\alpha, n)^{79}\text{Zn}$	36–42	2, 3, 18, 32
$^{67}\text{Cu}(\alpha, n)^{70}\text{Ga}$	47	35
$^{77}\text{Cu}(\alpha, n)^{80}\text{Ga}$	37	3
$^{72}\text{Zn}(\alpha, n)^{75}\text{Ge}$	39–42	36
$^{76}\text{Zn}(\alpha, n)^{79}\text{Ge}$	36, 37–42	2, 3, 17, 18, 32
$^{78}\text{Zn}(\alpha, n)^{81}\text{Ge}$	36, 37–42	2, 3, 17, 18, 32
$^{79}\text{Zn}(\alpha, n)^{82}\text{Ge}$	36, 37–42	2, 3, 18, 32
$^{80}\text{Zn}(\alpha, n)^{83}\text{Ge}$	36, 37, 39–42	2, 3, 18, 32
$^{81}\text{Ga}(\alpha, n)^{84}\text{As}$	36, 38, 39, 41	17, 32
$^{78}\text{Ge}(\alpha, n)^{81}\text{Se}$	39–42	36
$^{80}\text{Ge}(\alpha, n)^{83}\text{Se}$	36–39, 42	28, 33, 36
$^{82}\text{Ge}(\alpha, n)^{85}\text{Se}$	36–39, 41	11, 17, 19, 27, 28, 33
$^{83}\text{As}(\alpha, n)^{86}\text{Br}$	36, 37, 41	11, 26, 27, 28, 33
$^{84}\text{Se}(\alpha, n)^{87}\text{Kr}$	36–42, 44, 45	2, 6, 7, 8, 9, 10, 11, 18, 19, 20, 22, 23, 24, 26, 27, 28, 29, 30, 31, 33, 34, 36
$^{85}\text{Se}(\alpha, n)^{88}\text{Kr}$	36–42, 44, 45	2, 6, 7, 8, 9, 10, 11, 18, 19, 22, 23, 24, 26, 27, 28, 29, 30, 31
$^{85}\text{Br}(\alpha, n)^{88}\text{Rb}$	37–39	6, 7, 8, 9, 10, 22, 23, 24, 26, 28, 29, 30, 31
$^{87}\text{Br}(\alpha, n)^{90}\text{Rb}$	37, 39	6, 9, 10, 29, 31
$^{88}\text{Br}(\alpha, n)^{91}\text{Rb}$	39	26
$^{86}\text{Kr}(\alpha, n)^{89}\text{Sr}$	38–42, 44, 45, 47	4, 5, 7, 8, 13, 14, 15, 16, 20, 24, 25, 33, 34, 35

Identify key reactions

Key reactions $\Rightarrow$ large correlation + significant impact on abundance ratios

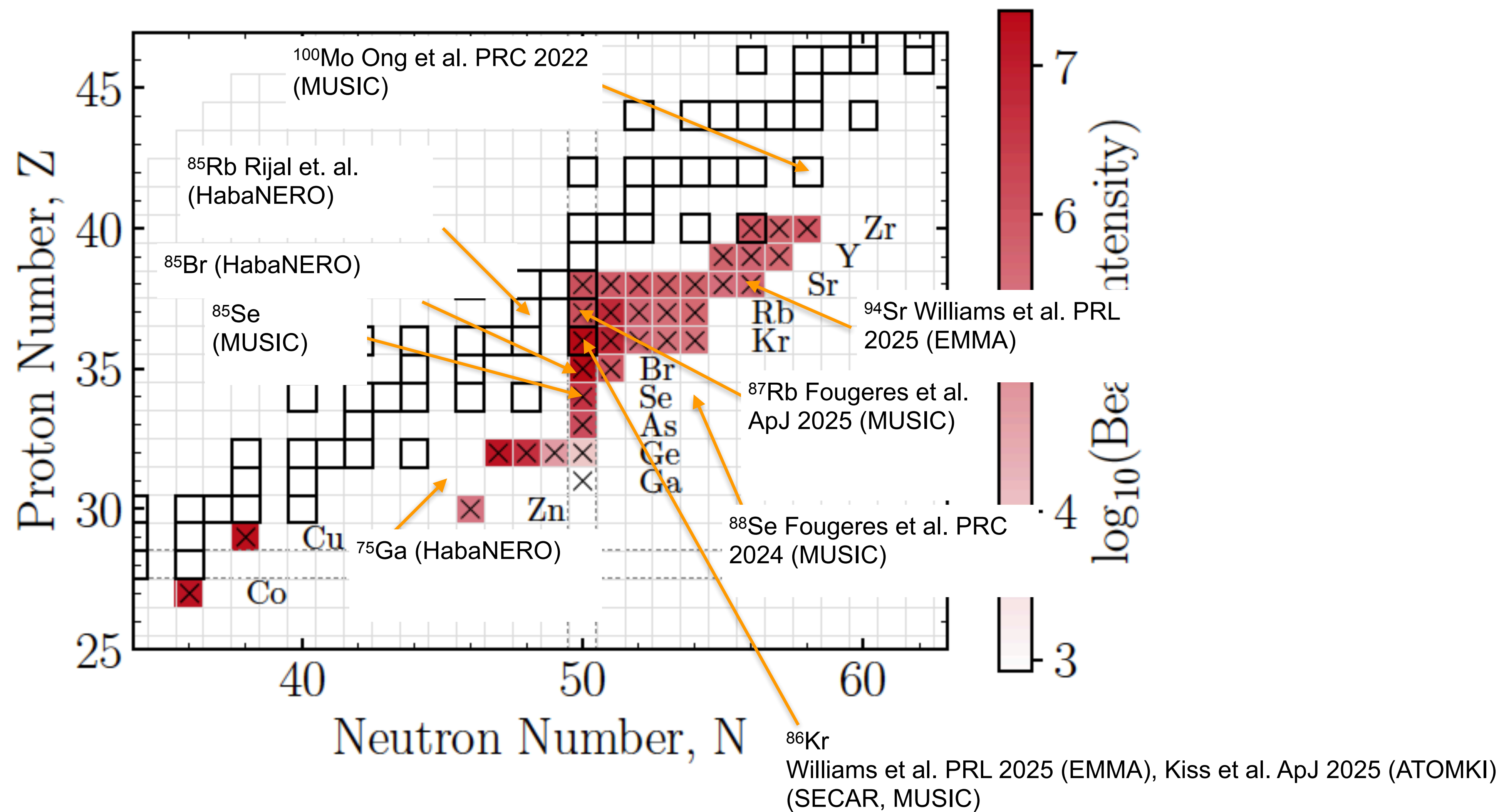
Psaltis et al., ApJ (2022)



Identify key reactions

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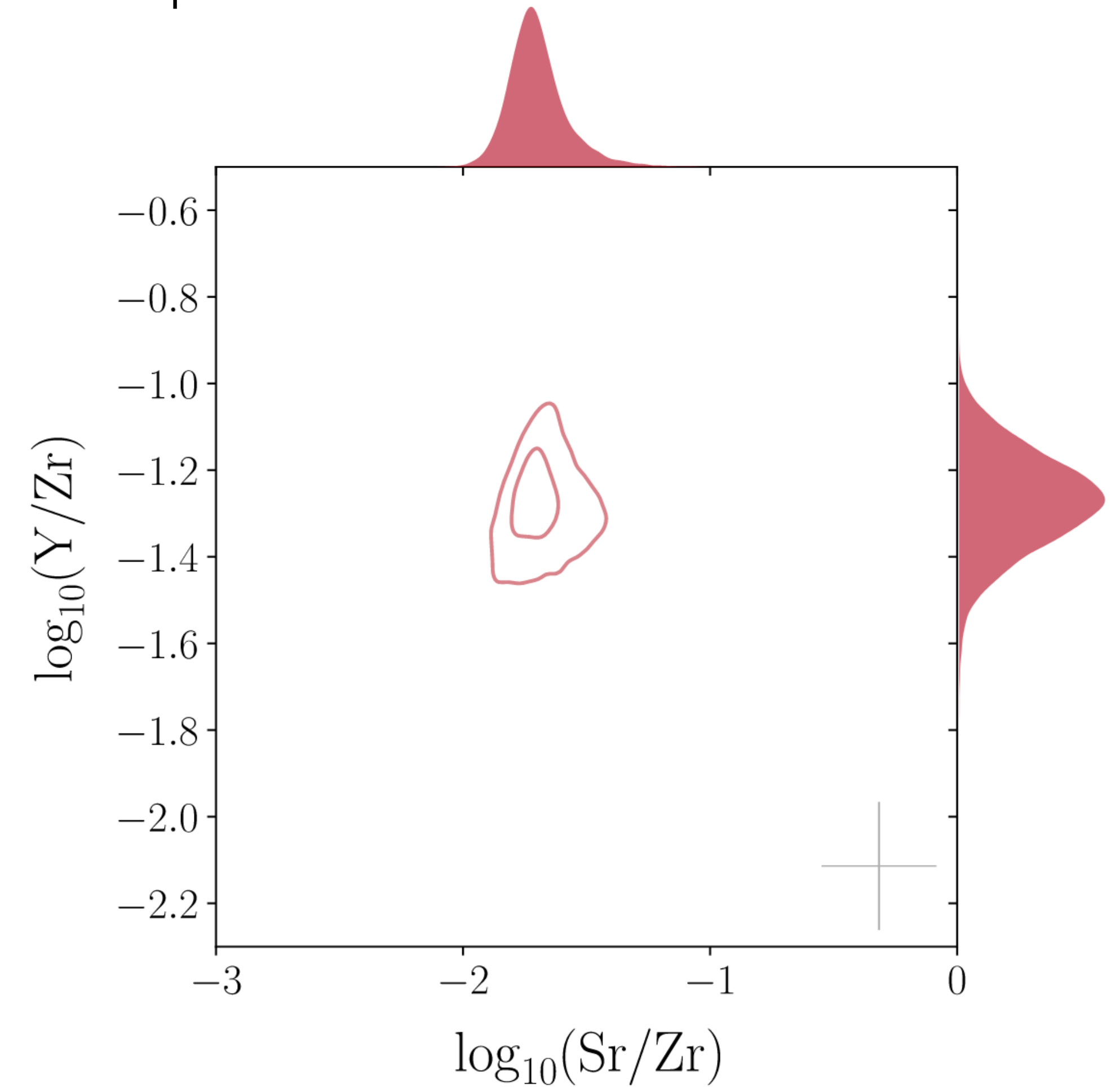
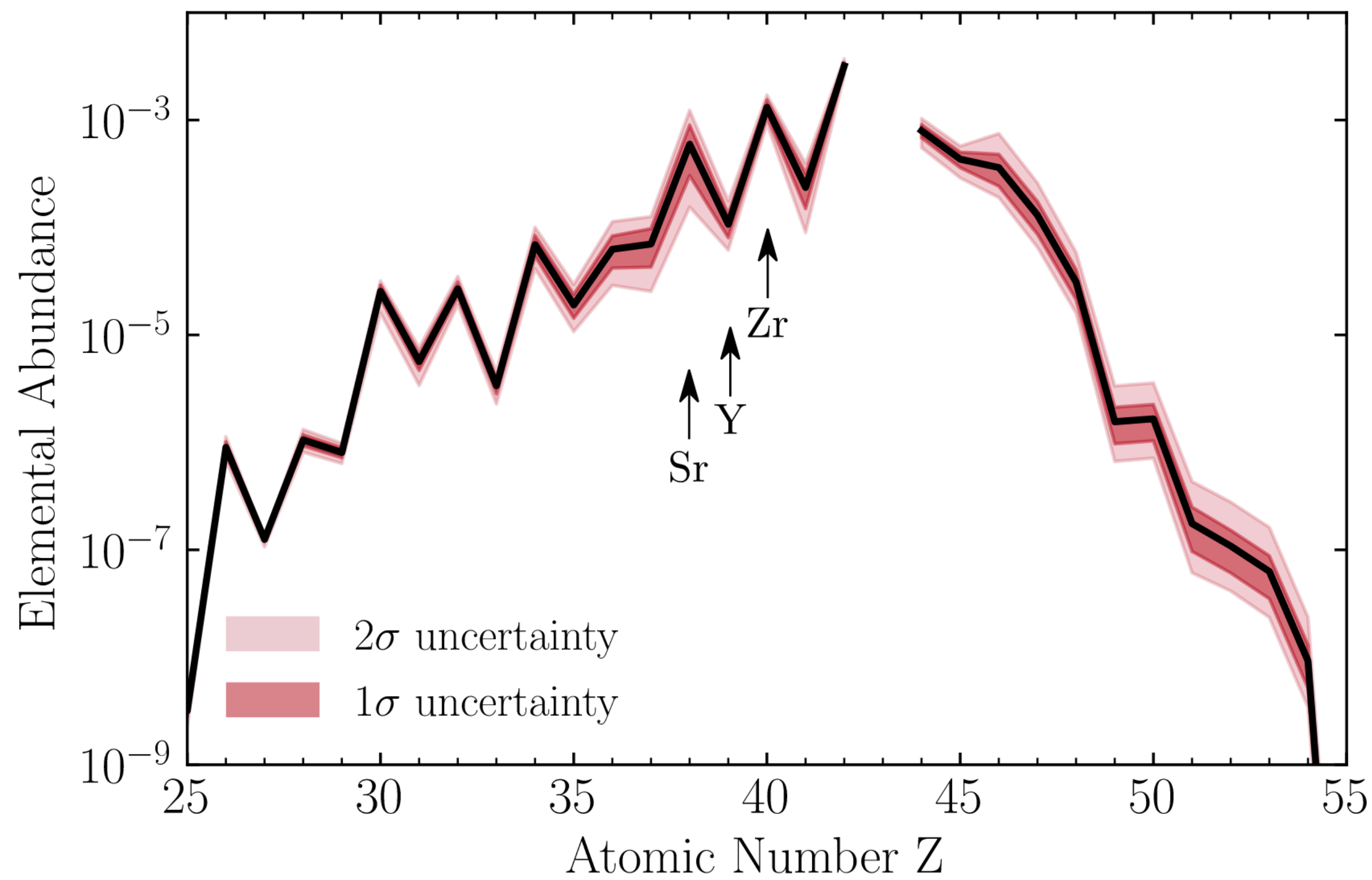
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Comparison to observations

Psaltis et al., ApJ (2022)

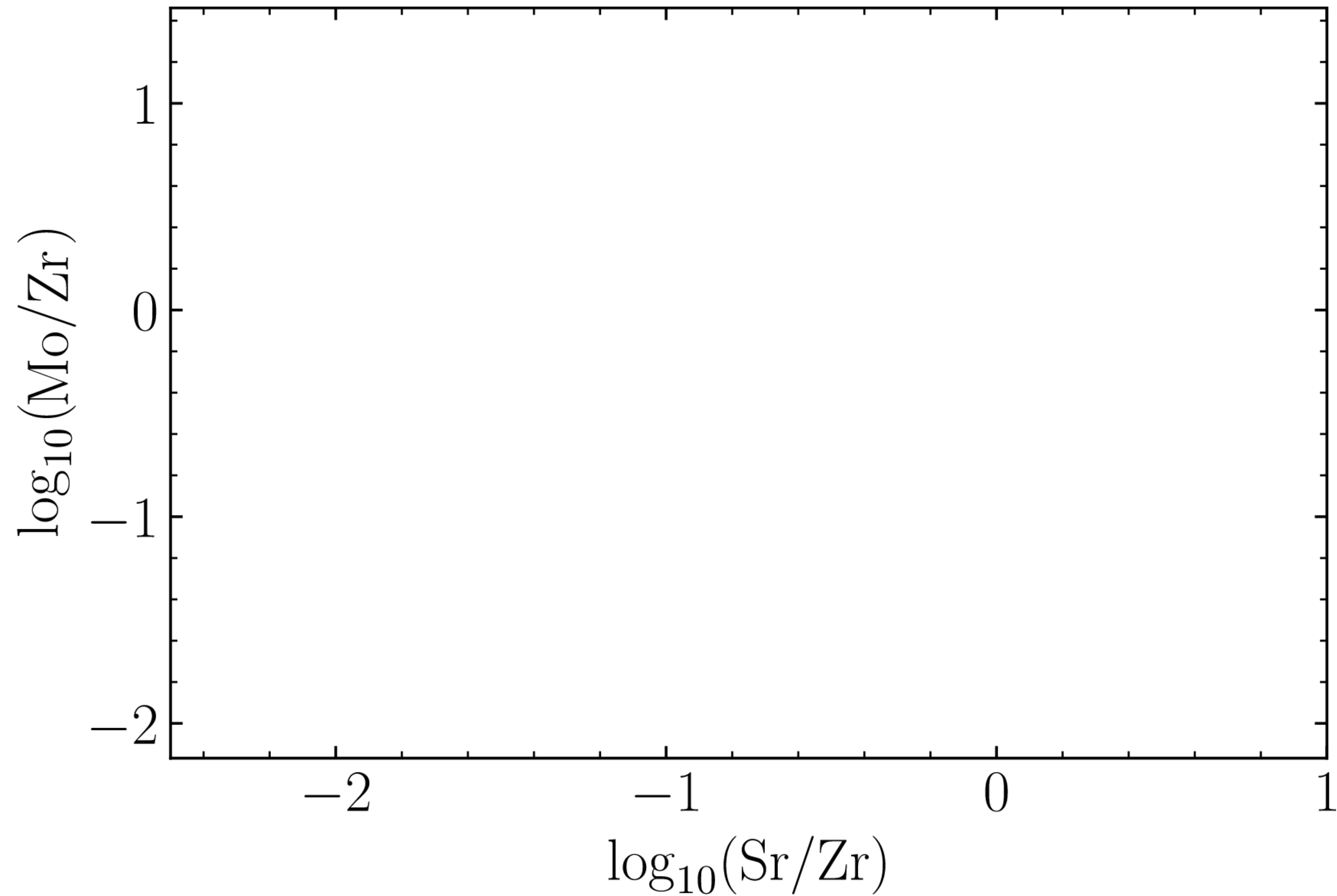
Abundance with uncertainties for several astro conditions → compare abundance ratios



Comparison to observations

Psaltis et al., ApJ (2022)

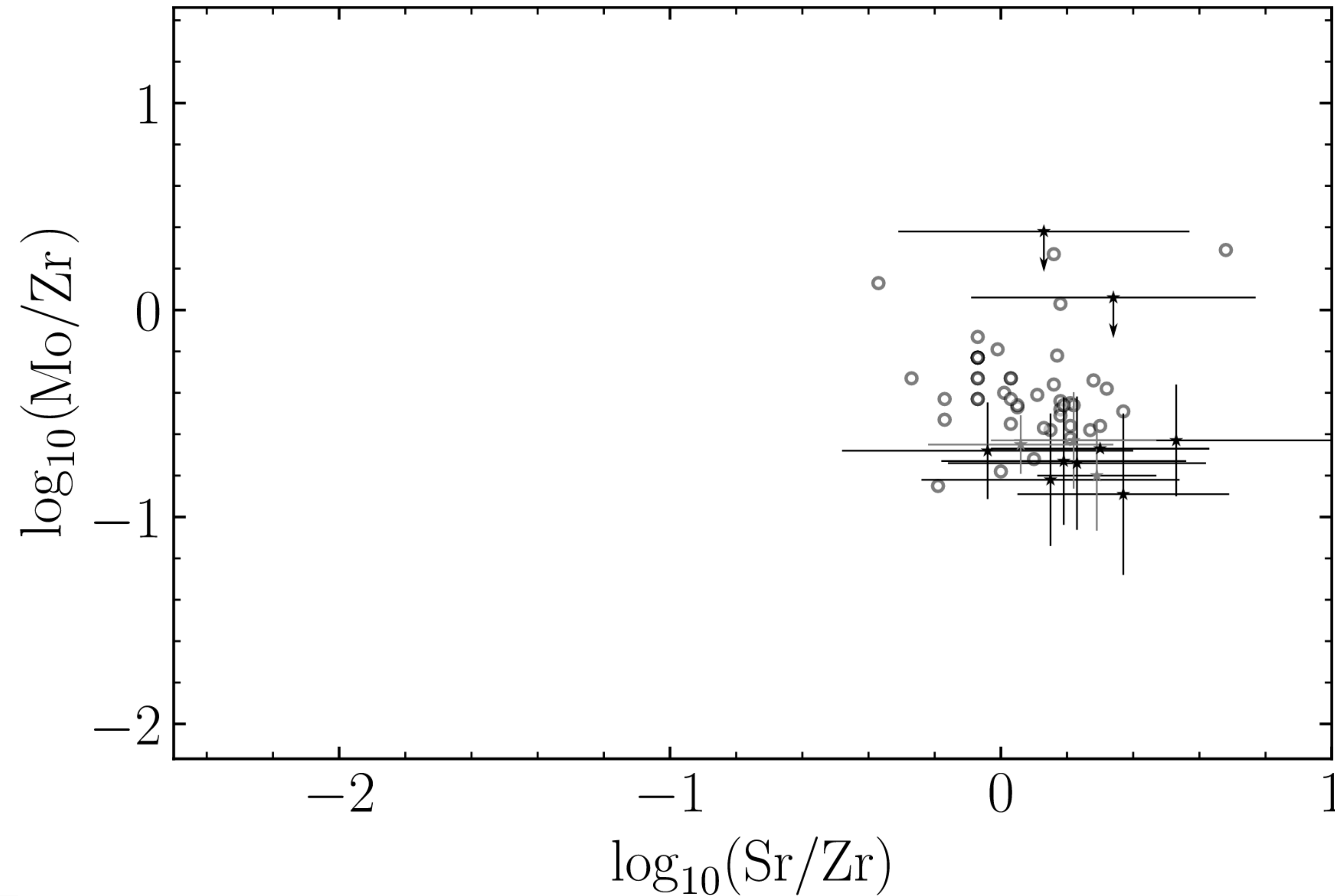
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Comparison to observations

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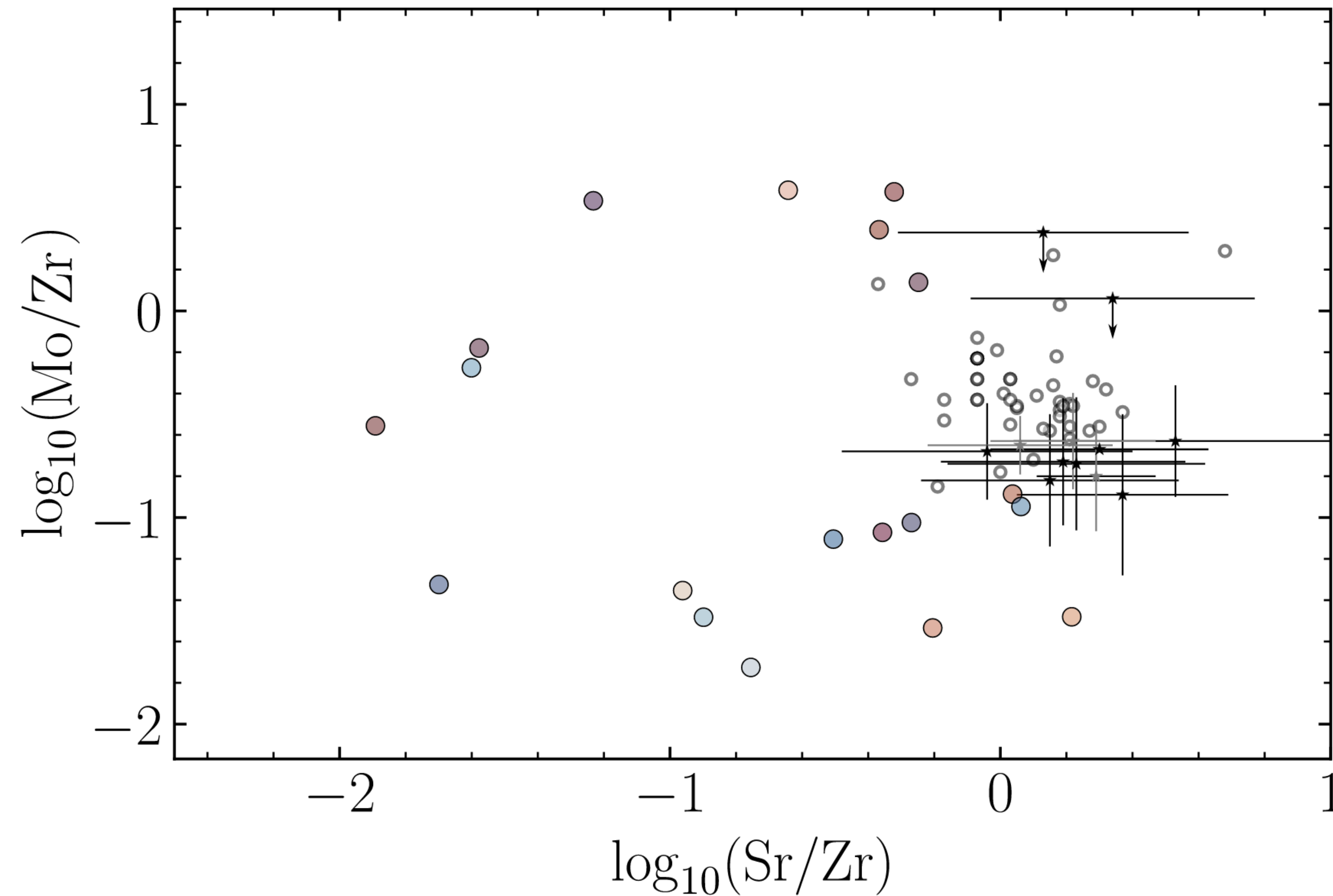
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Psaltis et al., ApJ (2022)

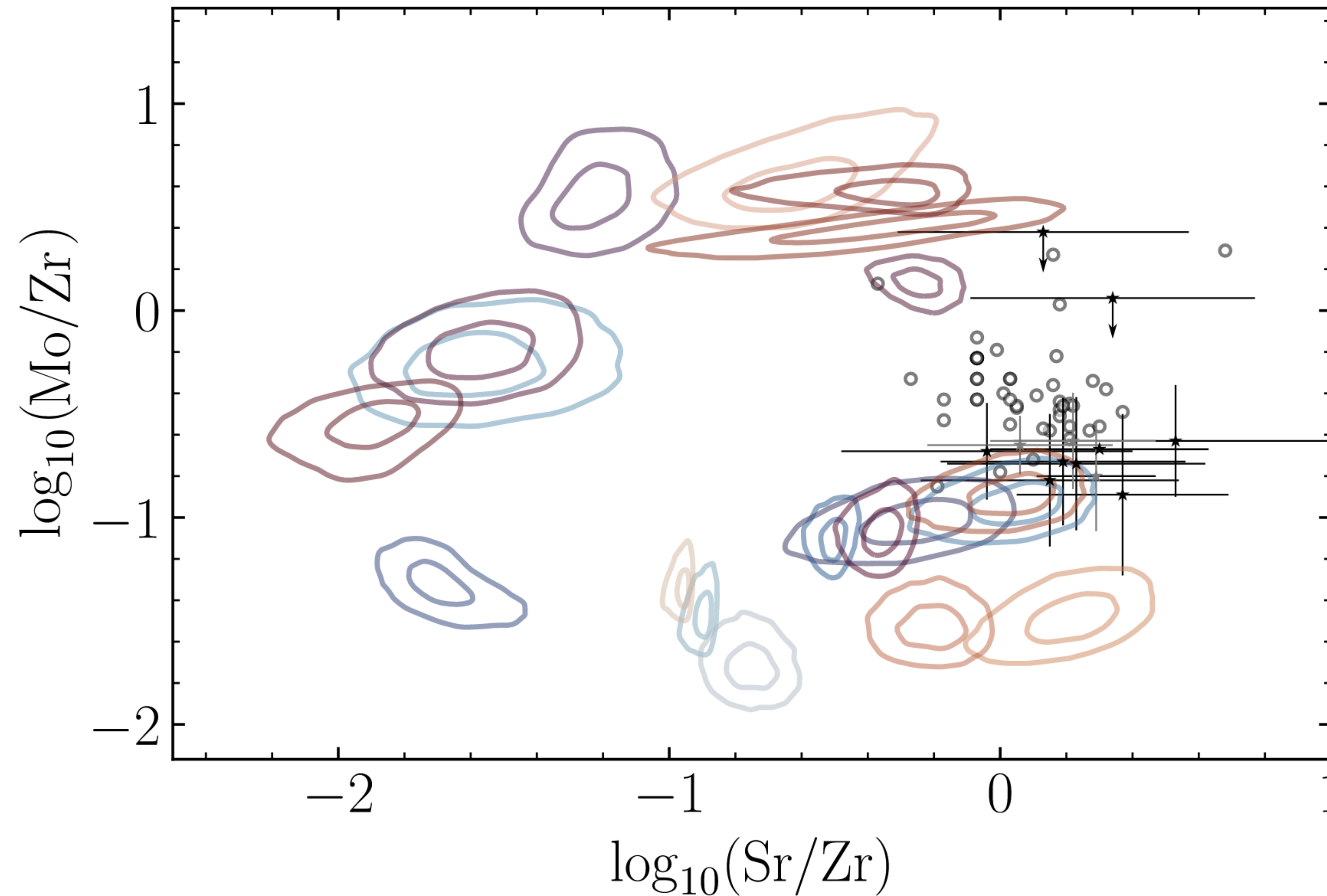
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Comparison to observations

Psaltis et al., ApJ (2022)

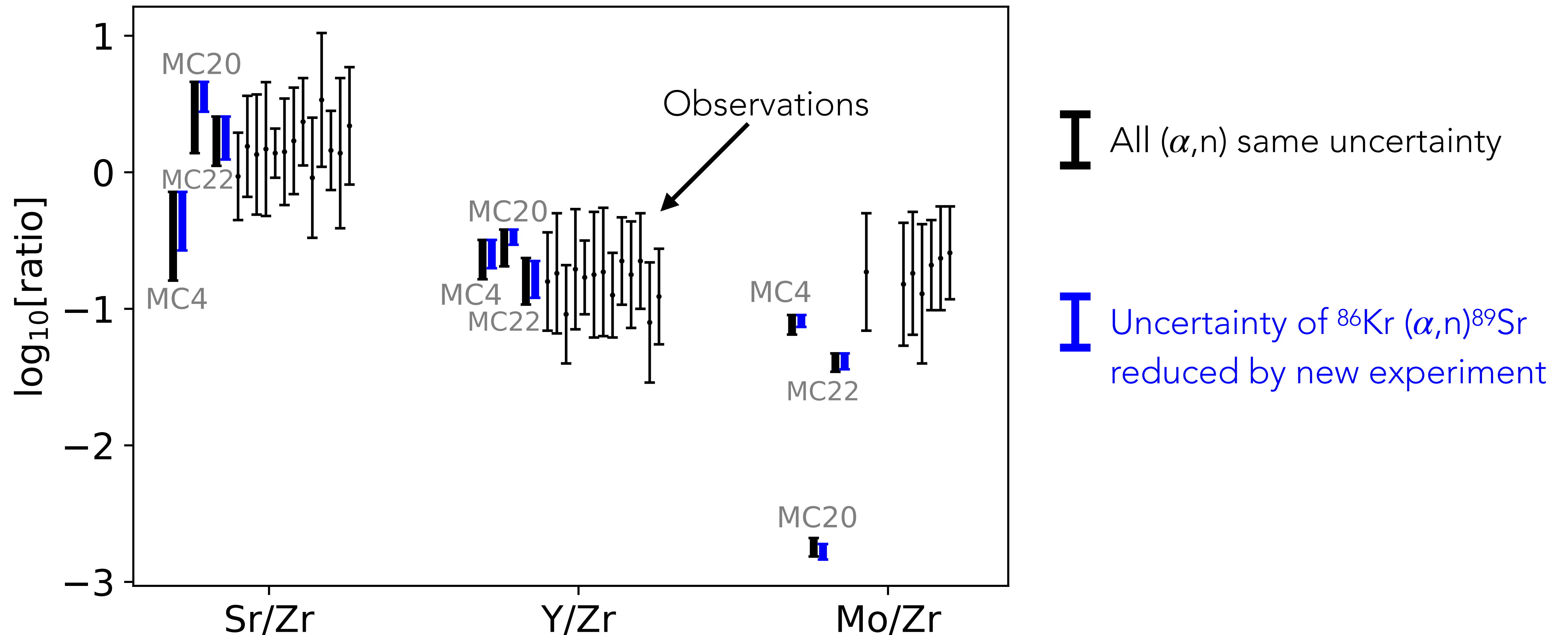
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Comparison to observations

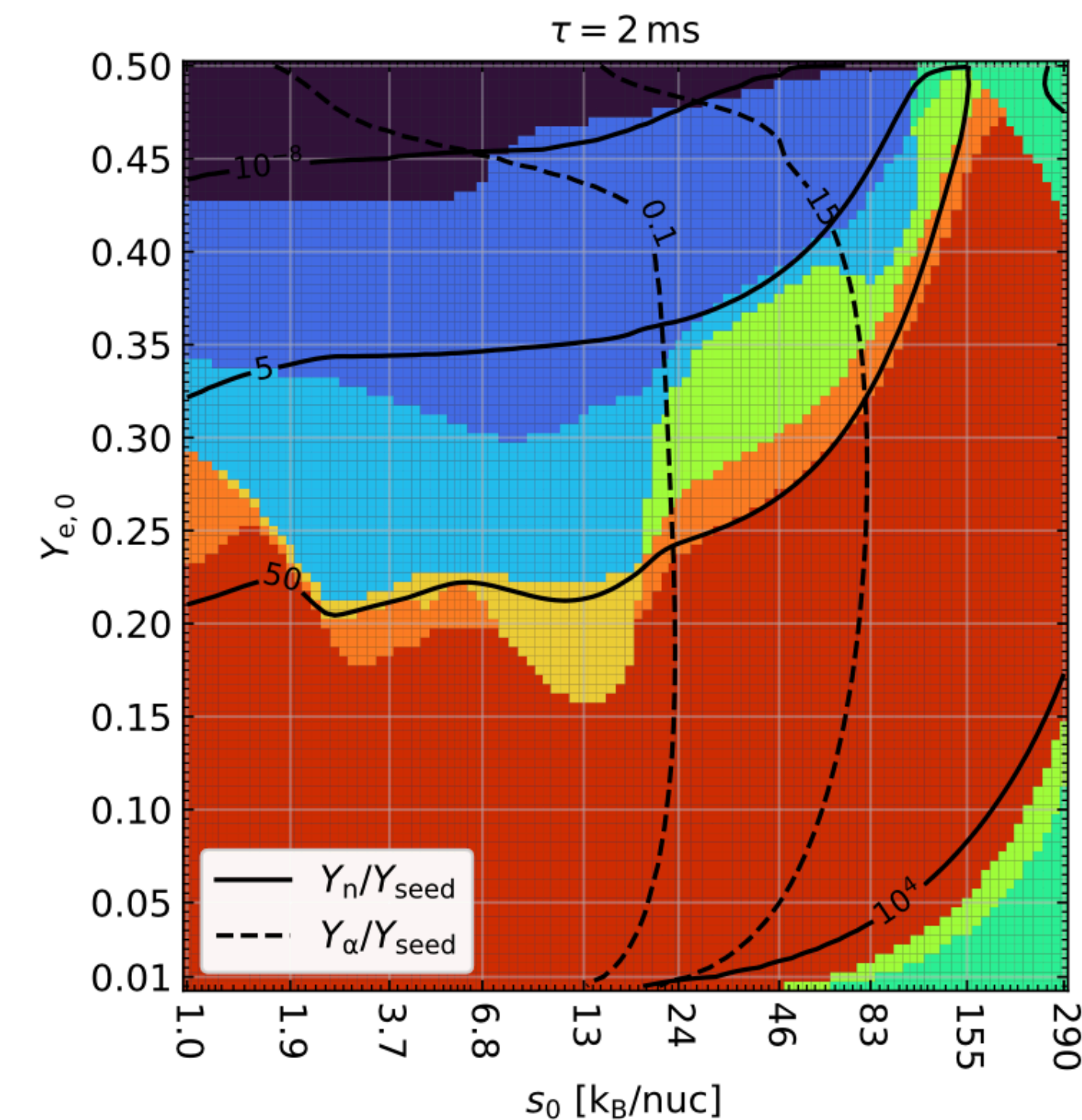
Kiss et al., ApJ (2025)

ATOMKI experiment for $^{86}\text{Kr} (\alpha, n)^{89}\text{Sr}$ $\longrightarrow$ one reaction enough to reduce nuclear uncertainty

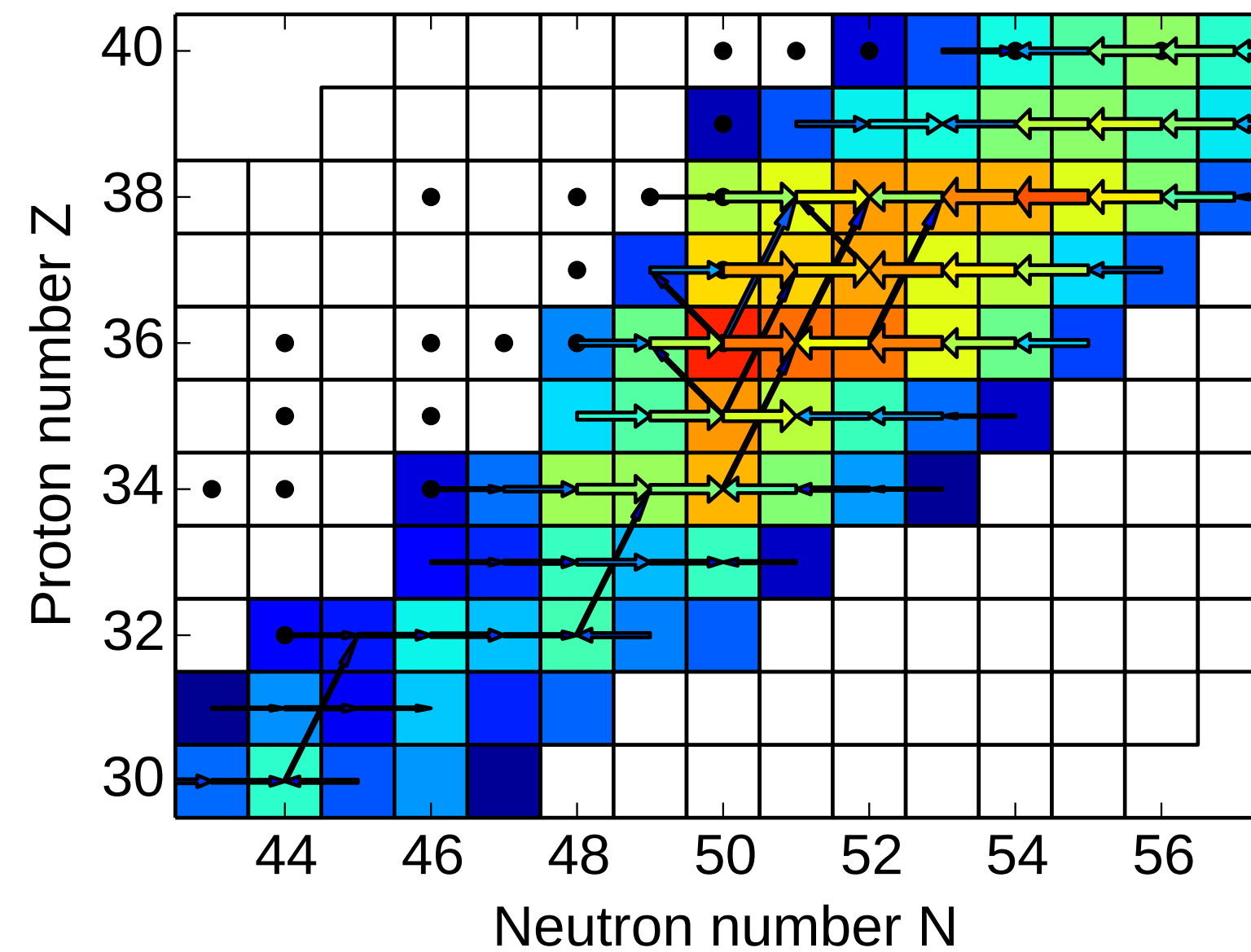


Nuclear physics uncertainties in the weak and strong r-process

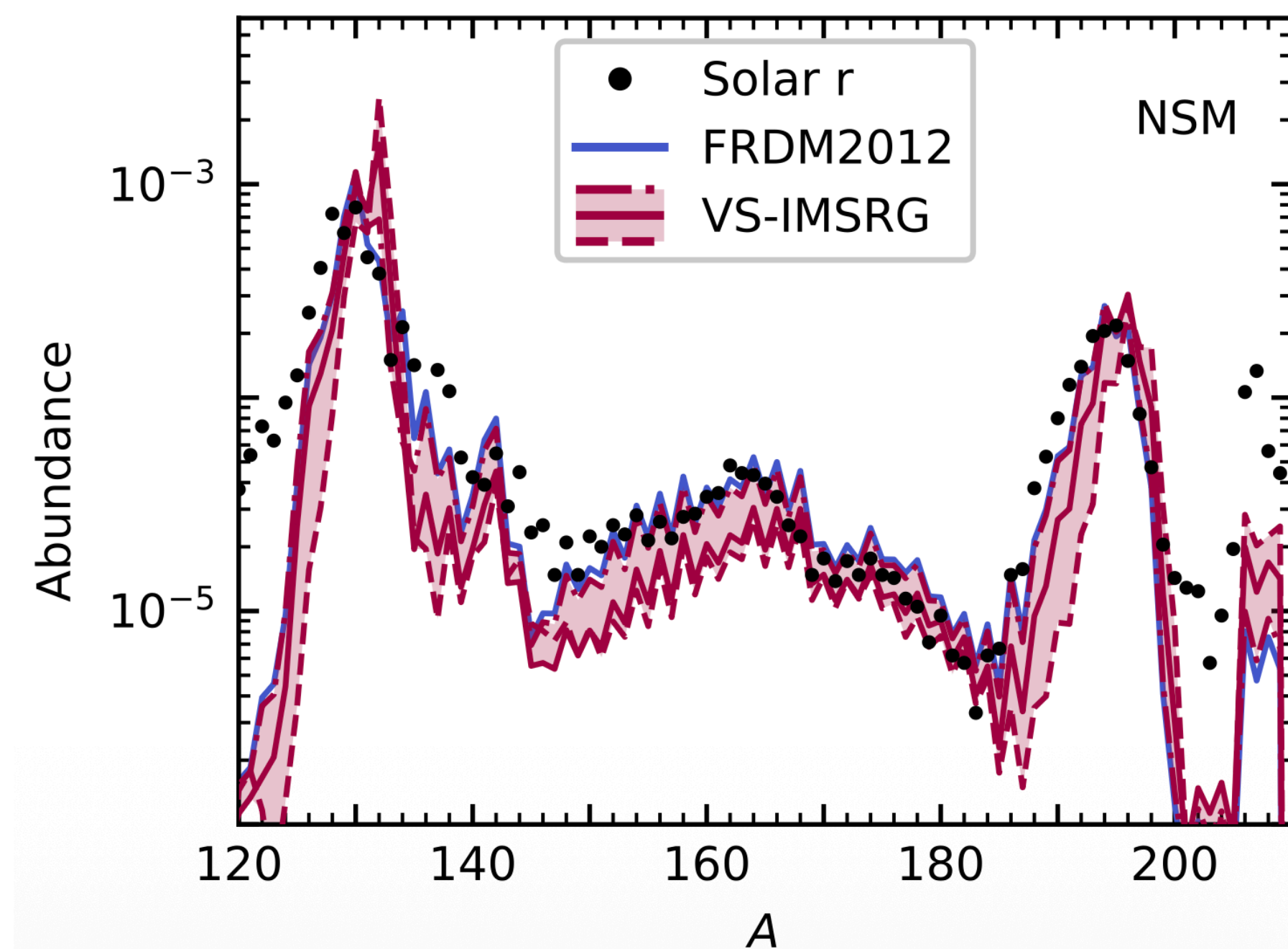
Complete survey of
r-process conditions



Weak r-process and
(α, n) reactions

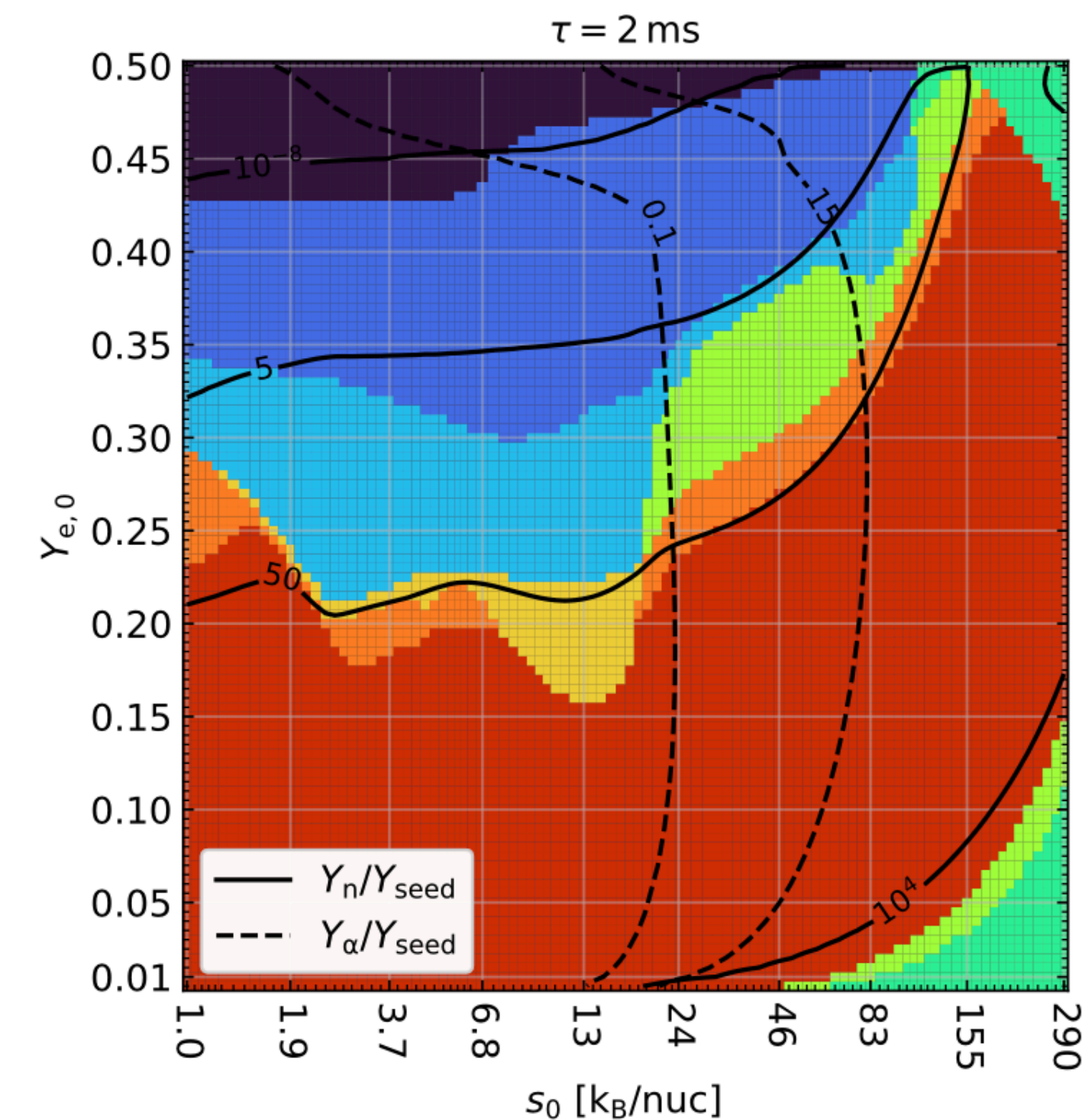


R-process with
ab-initio nuclear masses

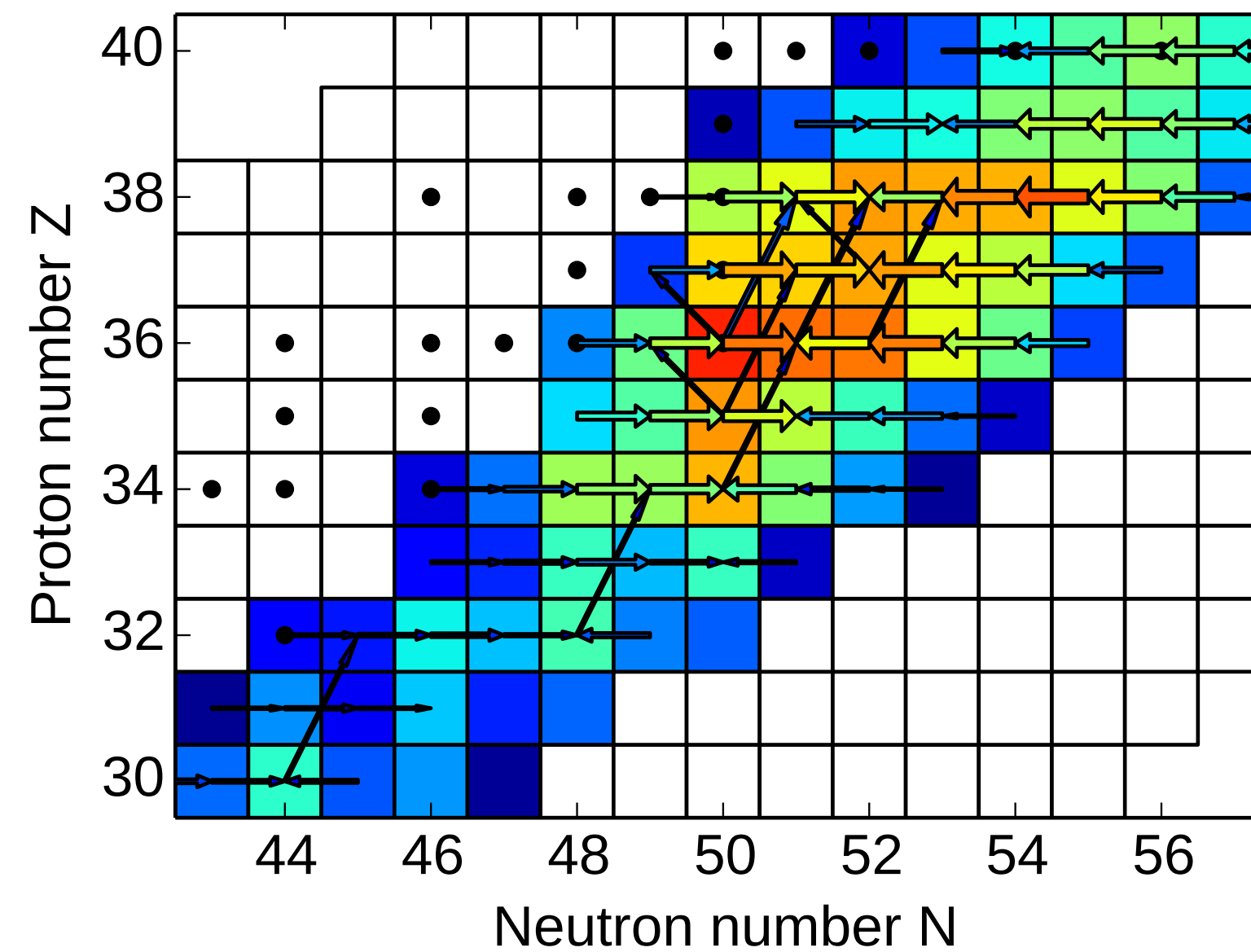


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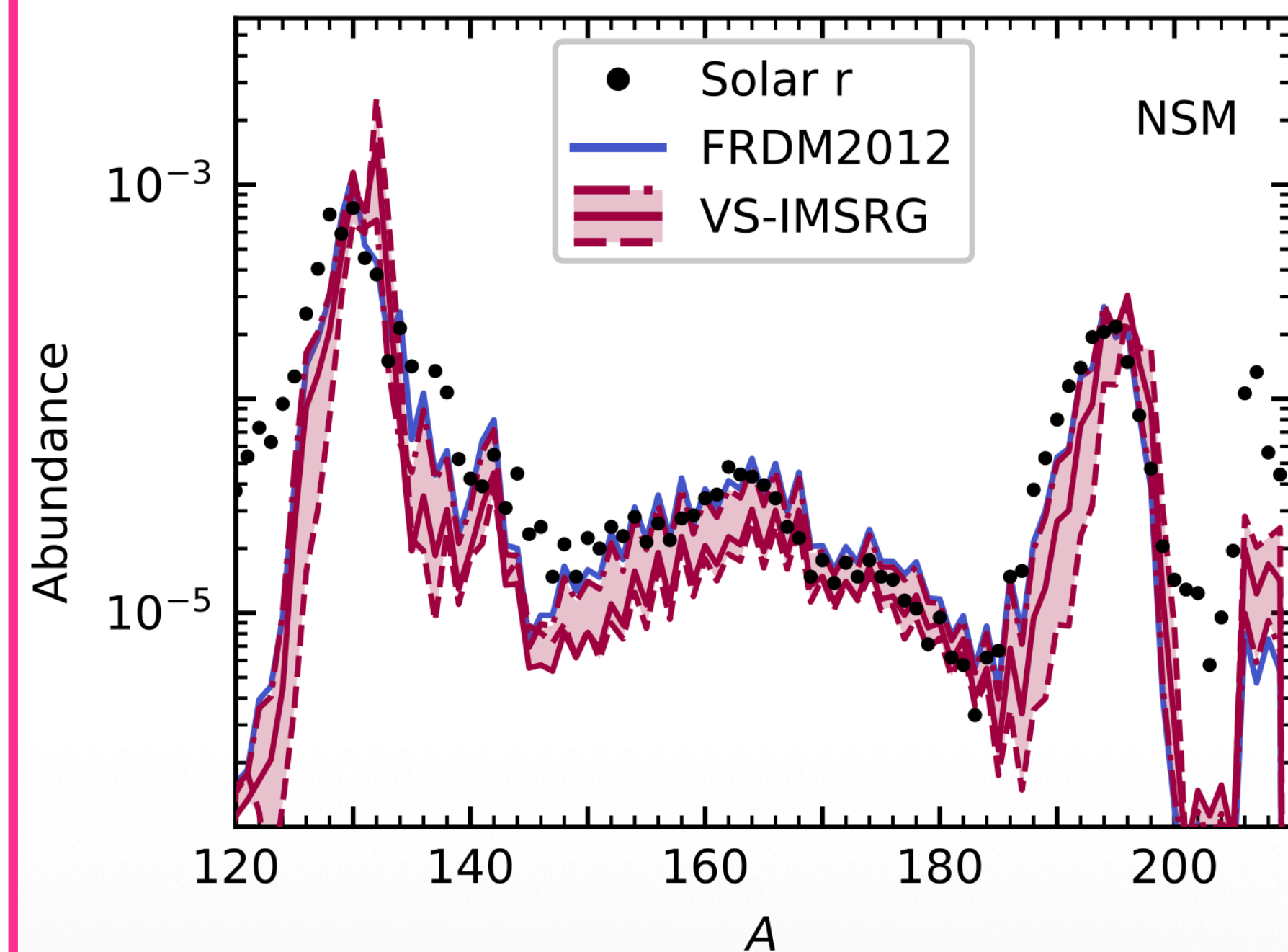
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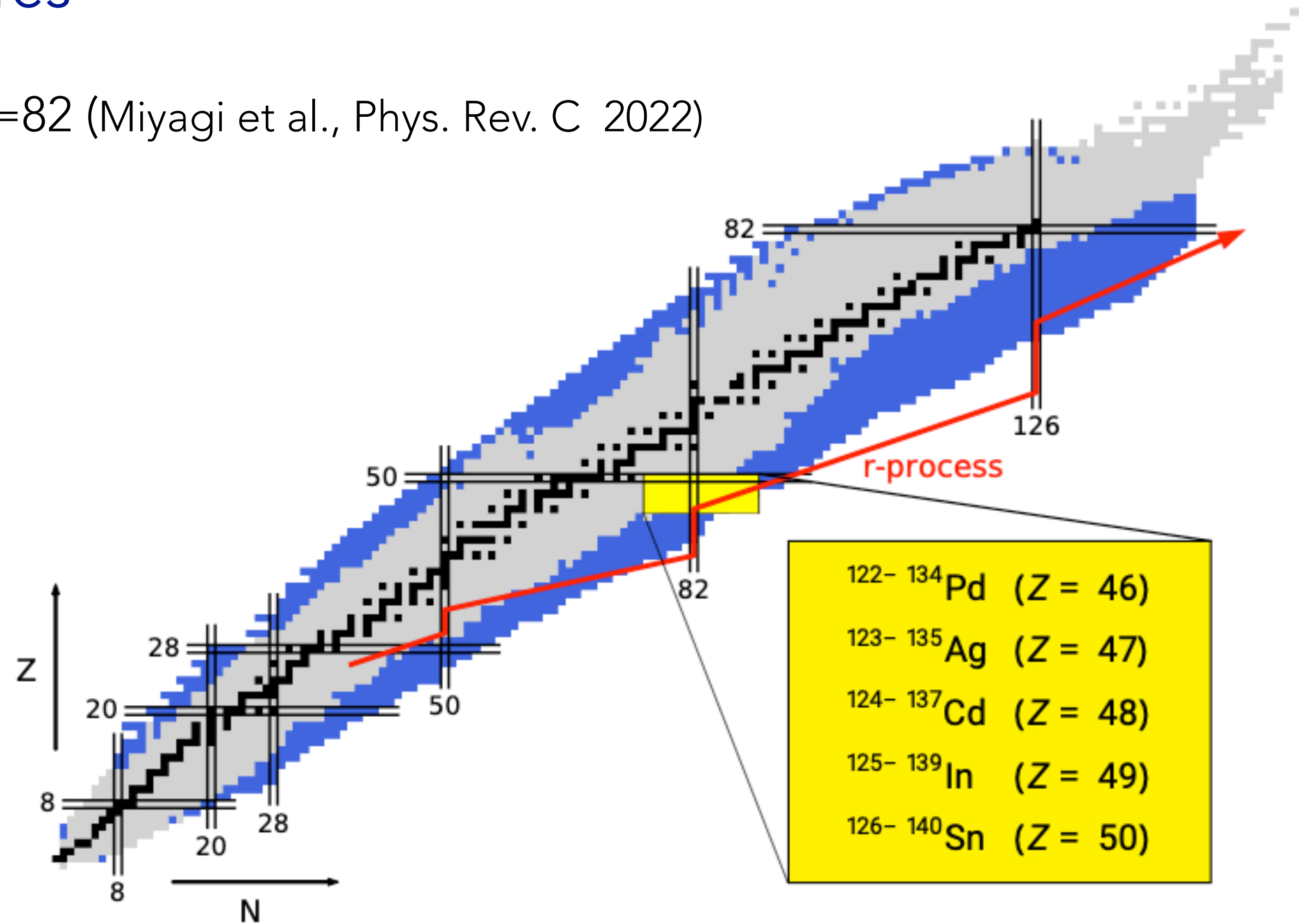
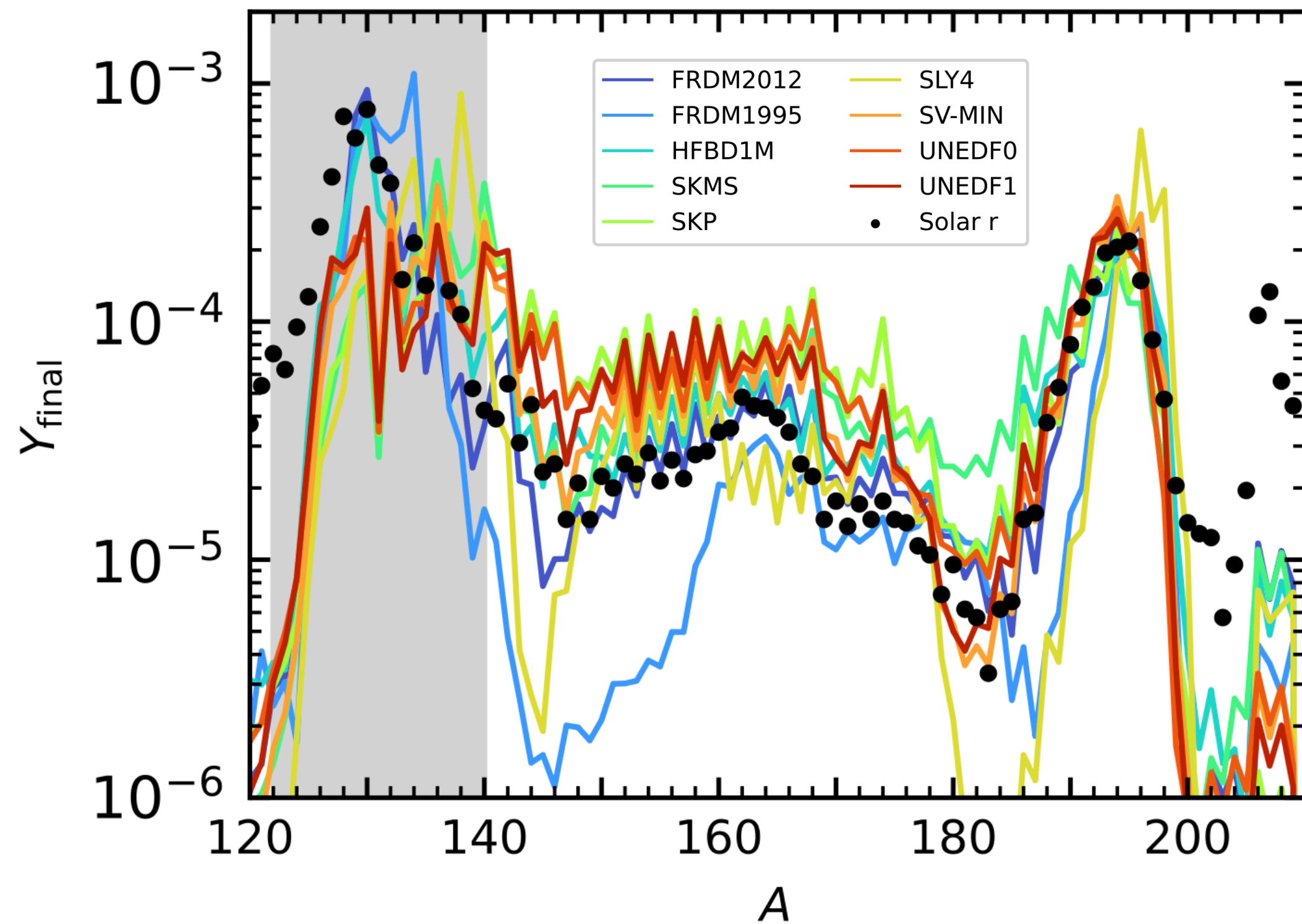


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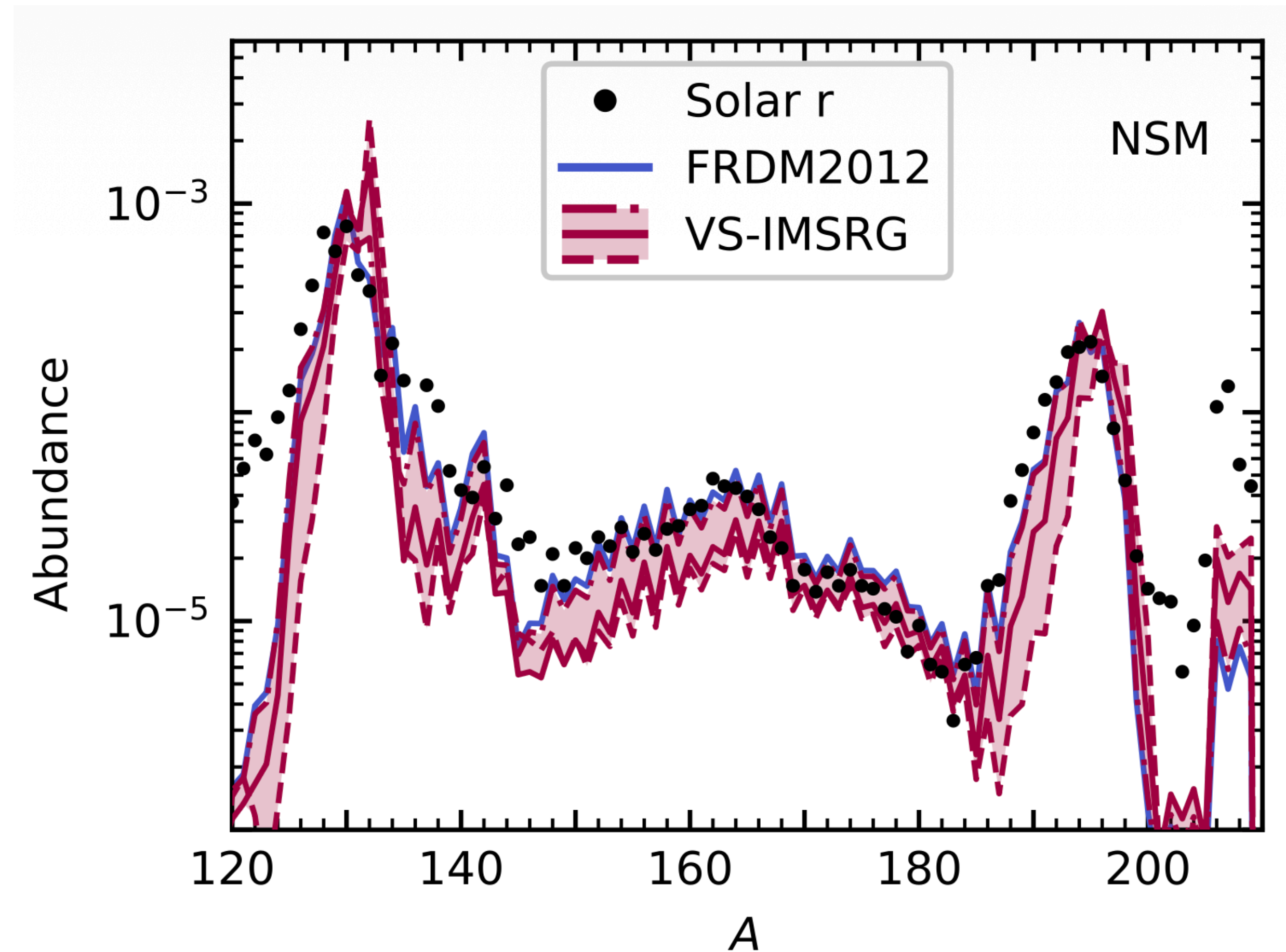
Nuclear masses $\longrightarrow$ neutron captures

Ab-initio masses from VS-IMSRG around $N=82$ (Miyagi et al., Phys. Rev. C 2022)

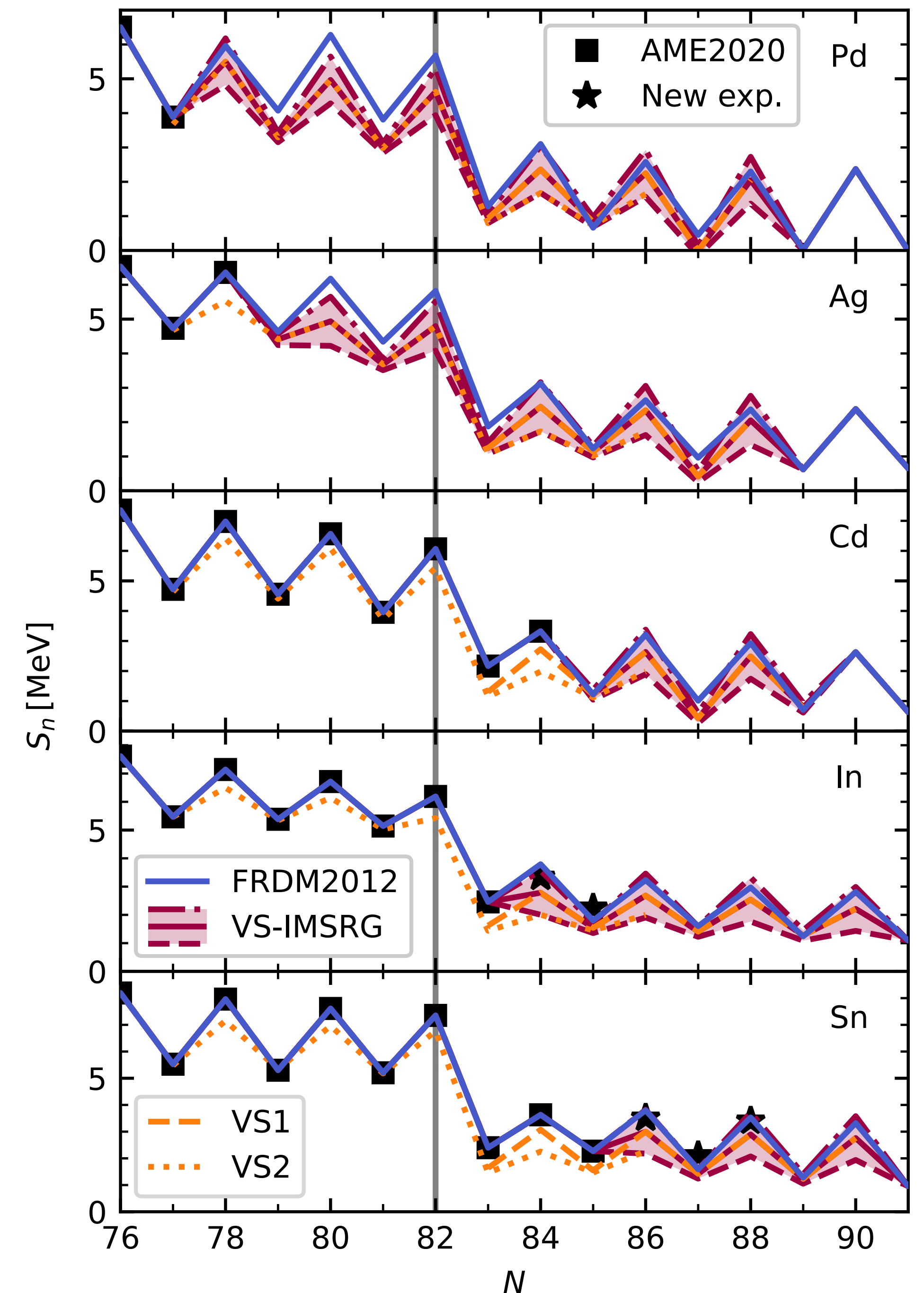


Ab initio masses and nucleosynthesis

Lower S_n matter flows slower (N=86): higher 2nd peak
Slower evolution: lower abundances beyond

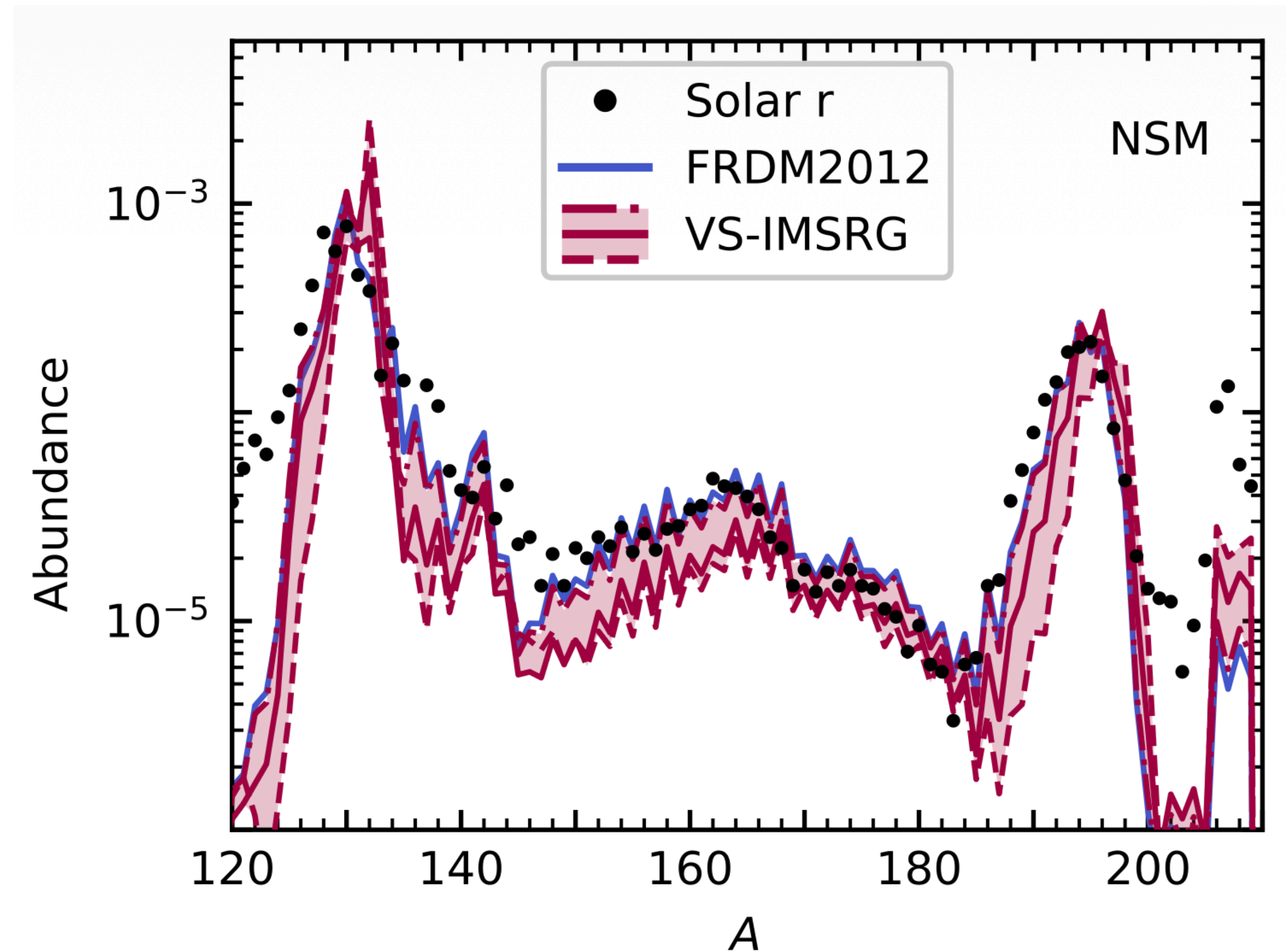
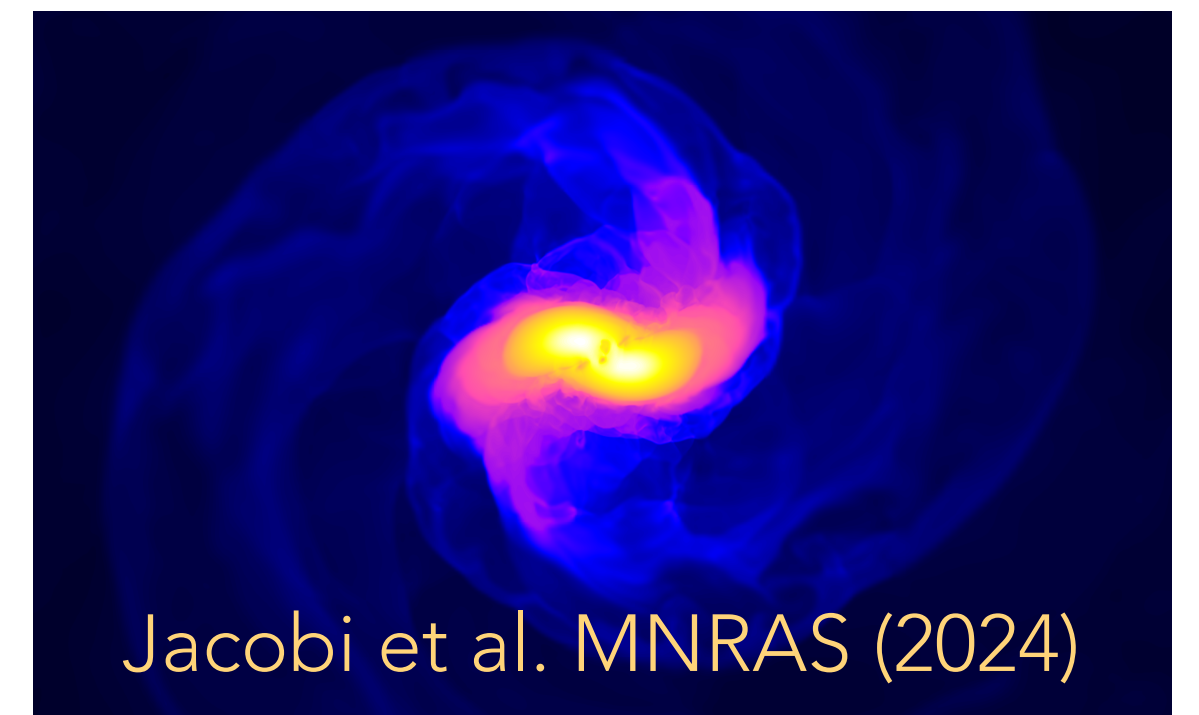


Kuske, Miyagi et al. [arxiv:509.19131]

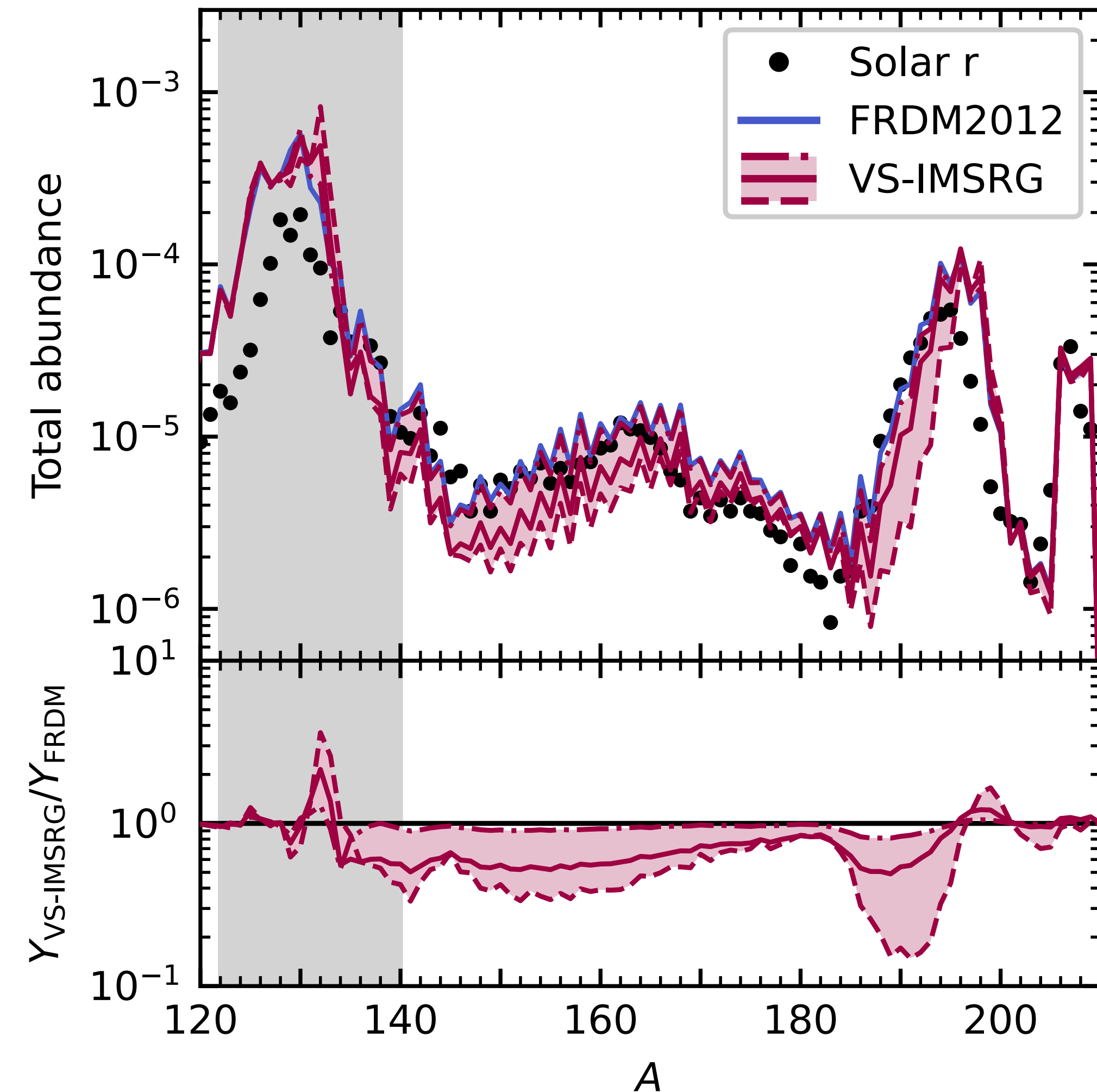


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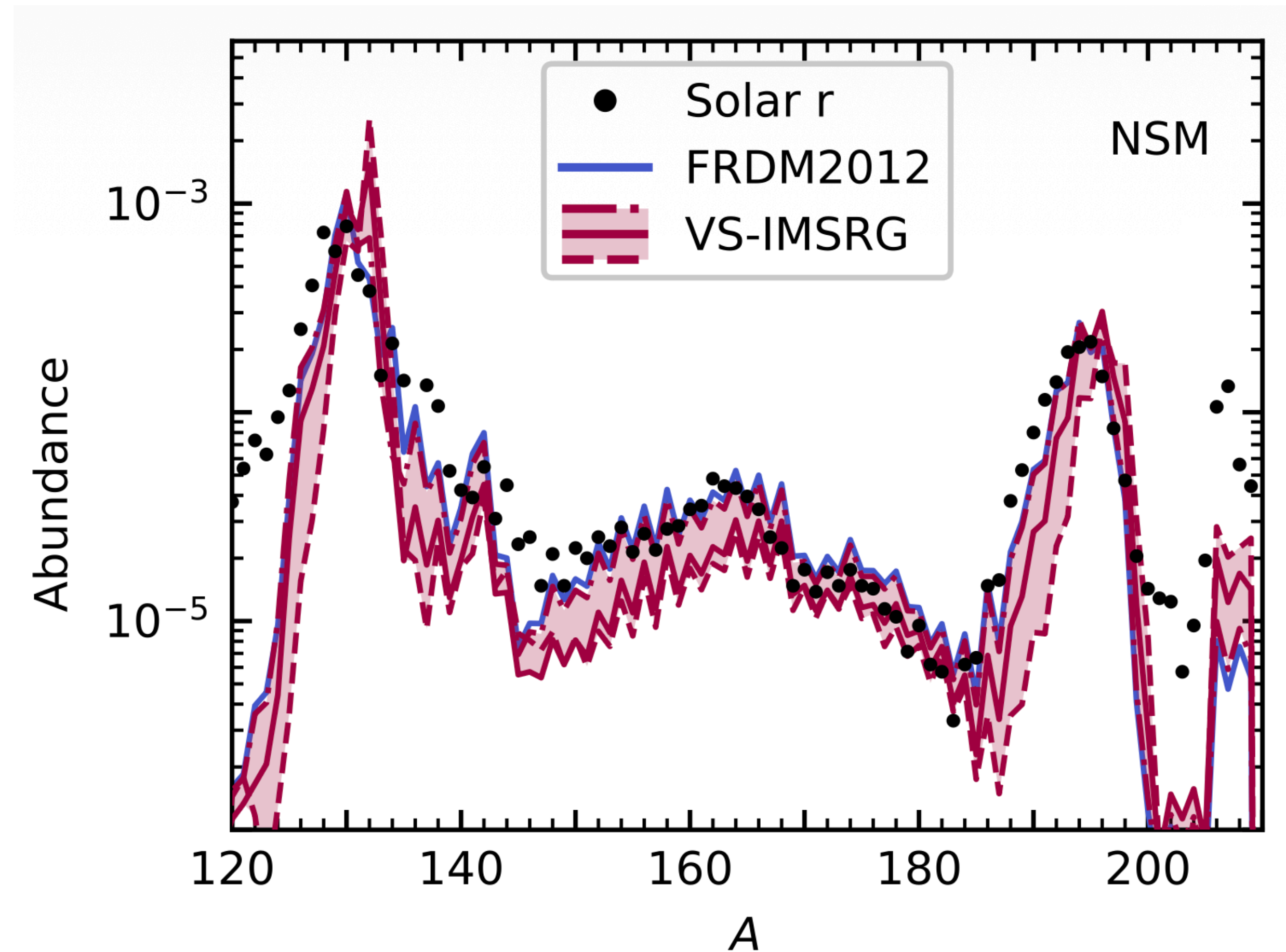


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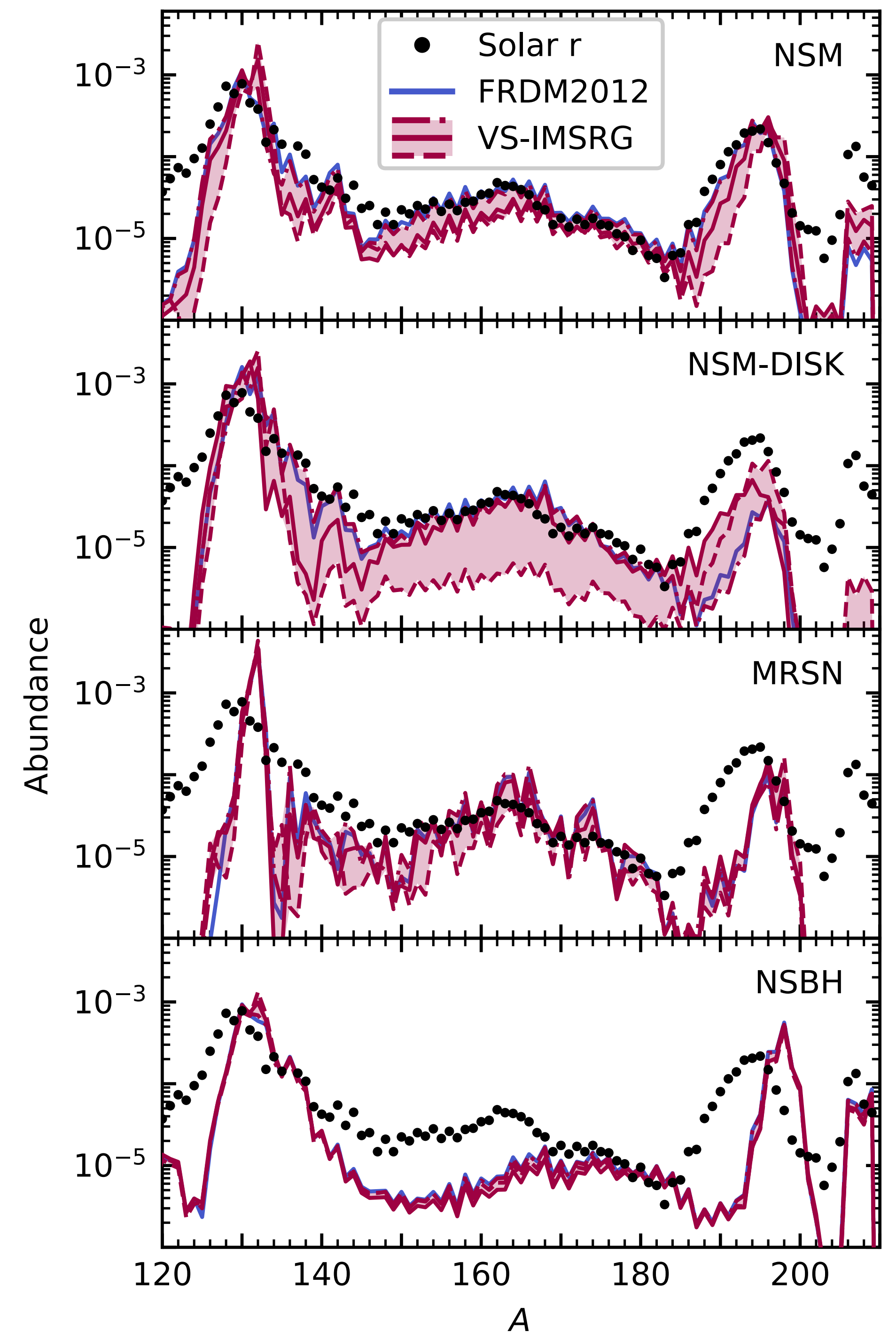


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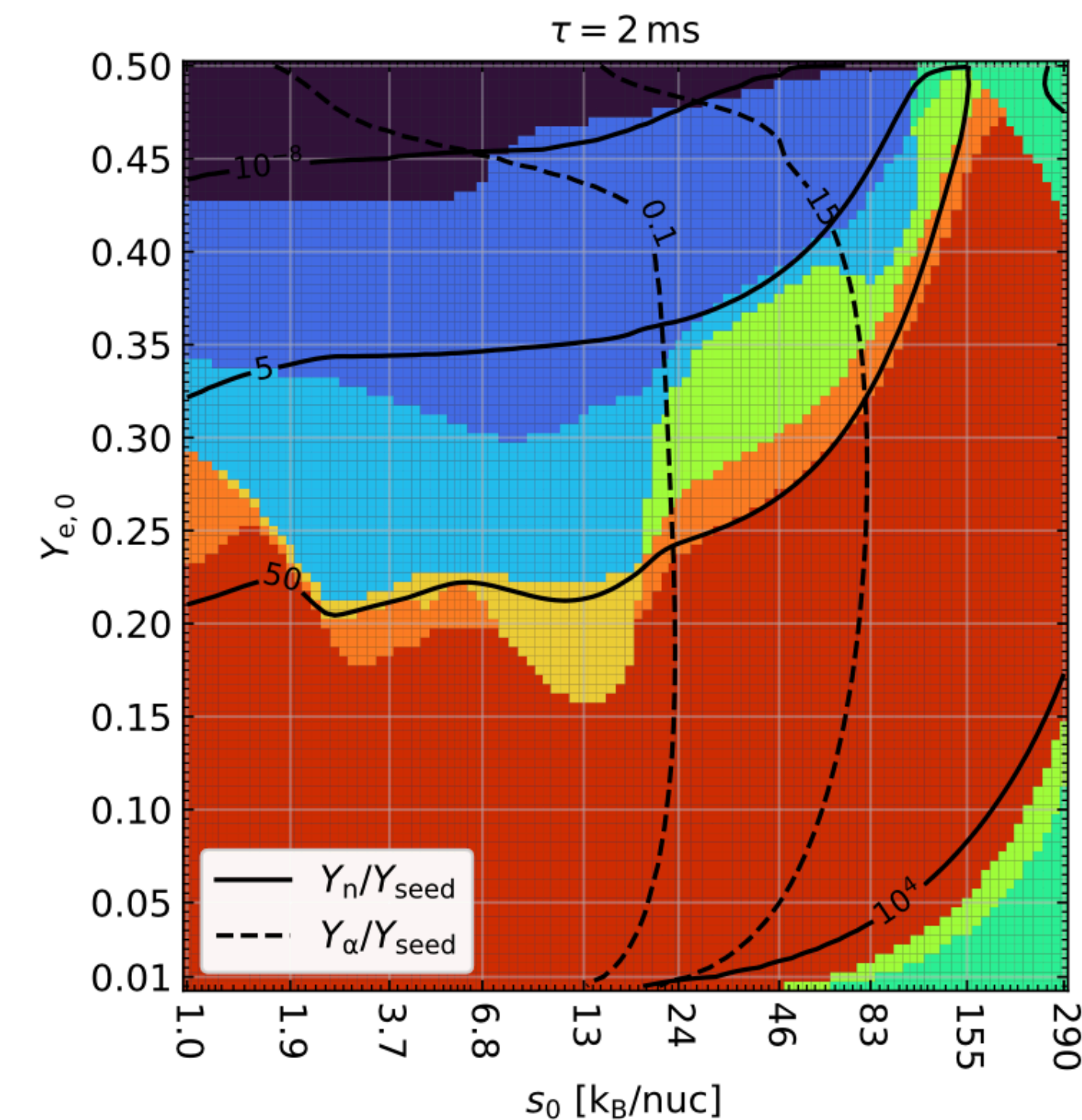


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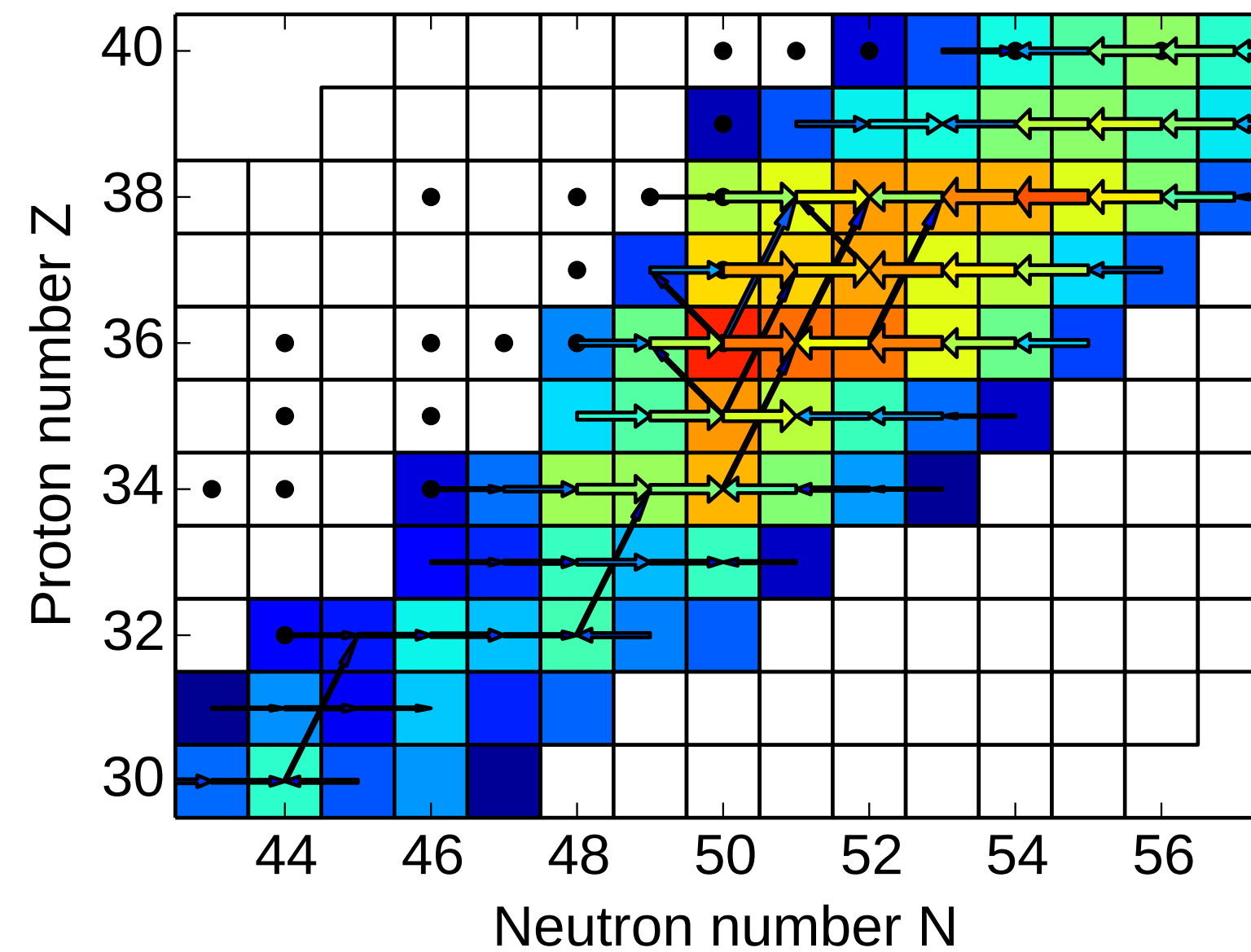


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