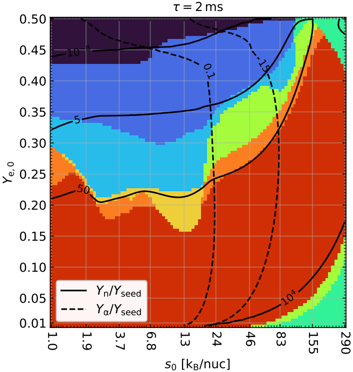
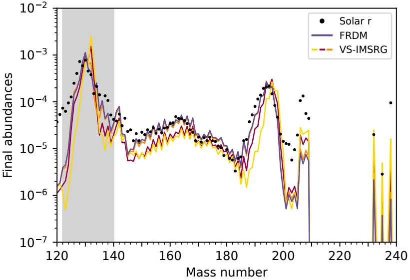
ASTROPHYSICAL AND NUCLEAR UNCERTAINTIES OF THE R-PROCESS



June 13th, 2025

Jan Kuske
(TU Darmstadt)

with:
Almudena Arcones
Takayuki Miyagi
Moritz Reichert
Achim Schwenk



r-Process Calculations

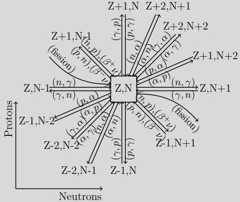
Ingredients

Reaction network code (WinNet)

$$\frac{dY_i(t)}{dt} = \sum_j N^i_j \lambda_j Y_j \quad \text{(one-body)}$$

$$+ \sum_{j,k} \frac{N^i_{j,k}}{1+\delta_{jk}} \rho N_A \langle \sigma v \rangle_{j,k} Y_j Y_k \quad \text{(two-body)}$$

$$+ \sum_{j,k,l} \frac{N^i_{j,k,l}}{1+\Delta_{jkl}} \rho^2 N_A^2 \langle \sigma v \rangle_{j,k,l} Y_j Y_k Y_l \quad \text{(three-body)}$$



WinNet + Fig.: M. Reichert et al. 2023, ApJS 268:66

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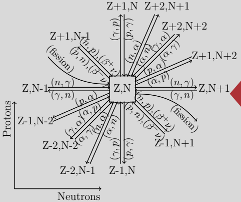

Nuclear inputs

- **masses**
- reaction rates
- β−decays
- fission
- ...

WINNET + Fig.: M. Reichert et al. 2023, ApJS 268:66

r-Process Calculations

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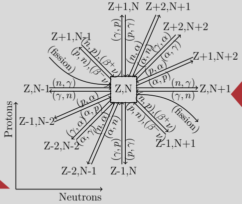

Nuclear inputs

- **masses**
- reaction rates
- $\beta-$decays
- fission
- ...

Astrophysical inputs

- $\rho(t)$, $T(t)$, $Y_\mathrm{e}(t)$, $s(t)$, $\ldots \rightarrow$ Lagrangian tracers from hydrodynamical simulations or **parametric models**

Lagrangian tracers:

\+ most realistic
\- extremely computationally expensive
\- important physics still unclear: nuclear EOS, neutrino interactions, progenitors, ...

Parametric models:

\- not only realistic conditions
\+ computationally cheap
\+ systematic variation of conditions possible
$\Longrightarrow$ nuclear sensitivity studies

r-Process Calculations

Ingredients

Reaction network code (WINNET)

$$\frac{dY_i(t)}{dt} = \sum_j N^i_j \lambda_j Y_j \qquad \text{(one-body)}$$

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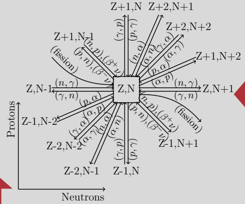


Nuclear inputs — Part II

- **masses**
- reaction rates
- $\beta-$decays
- fission
- ...

Astrophysical inputs — Part I

- $\rho(t)$, $T(t)$, $Y_\mathrm{e}(t)$, $s(t)$, ... $\rightarrow$ Lagrangian tracers from hydrodynamical simulations or **parametric models**

+ most realistic
- extremely computationally expensive
- important physics still unclear: nuclear EOS, neutrino interactions, progenitors, ...

- not only realistic conditions
+ computationally cheap
+ systematic variation of conditions possible
  $\Longrightarrow$ nuclear sensitivity studies

Part I - Astrophysical Uncertainties

Complete survey of r-process conditions

Image: NASA/DOE/Fermi LAT Collaboration

Model for Astrophysical Conditions

based on J. Lippuner & L. Roberts, ApJ 815 82 (2015)

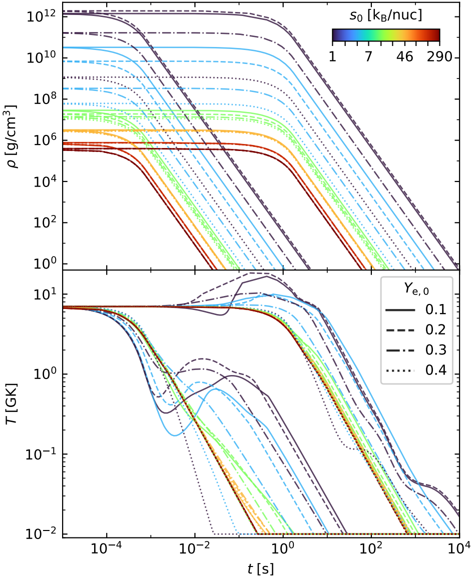
see also: R. Hoffman, S. Woosley & Y.-Z. Qian, ApJ 482 951 (1997)
B. S. Meyer & J. S. Brown, ApJS 112 199 (1997)
C. Freiburghaus, J. Rembges, T. Rauscher et al., ApJ, 516 381 (1999)

- 3 parameters: $\left.\begin{matrix} Y_{e,0} \\ s_0 \end{matrix}\right\} T_0 = 7\,\mathrm{GK} \Rightarrow \rho_0$
  τ
- density evolution:

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

- adiabatic expansion + nuclear energy generation
- parameter space: $100 \times Y_{e,0}, 100 \times s_0, 12 \times \tau$

$\Rightarrow$ **120 000 total conditions**



J. Kuske, A. Arcones, M. Reichert, arXiv:2506.00092

Comparison to Trajectories

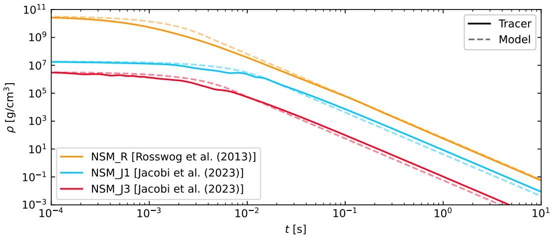
From Hydrodynamical Simulations

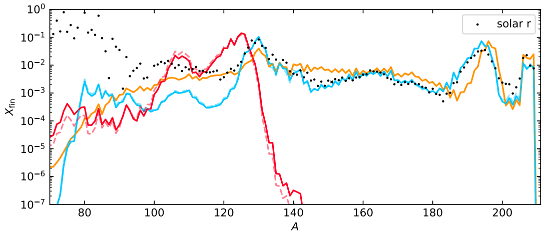
- 22 models of different astrophysical sites with up to 100 trajectories each
- map trajectories to parameter space:

$$\left.\begin{array}{l} Y_{\mathrm{e},0} \\ s_0 \end{array}\right\} \Rightarrow \text{from interpolation to 7 GK}$$

$$\tau \quad \Rightarrow \text{from fit to density profile}$$

- **good agreement** for $\approx 98\,\%$ of trajectories





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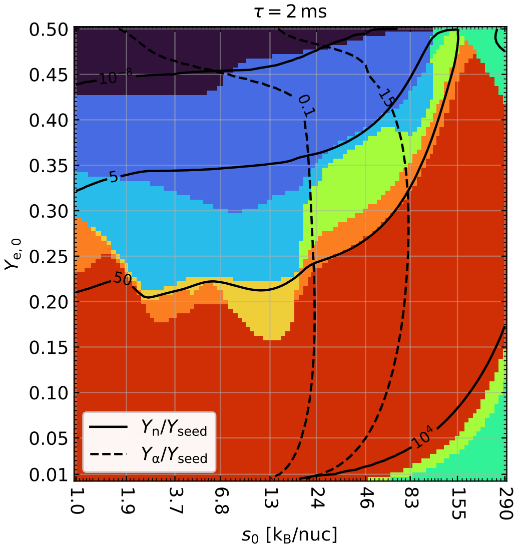
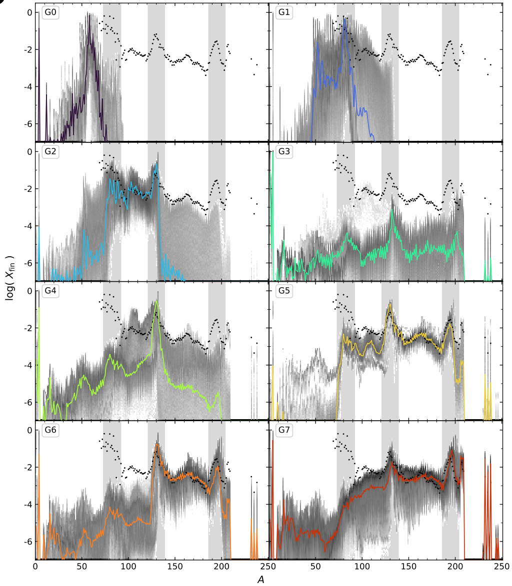
Nucleosynthesis Groups





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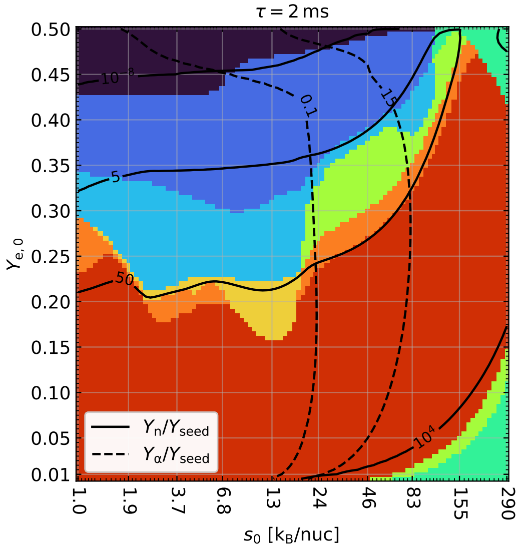

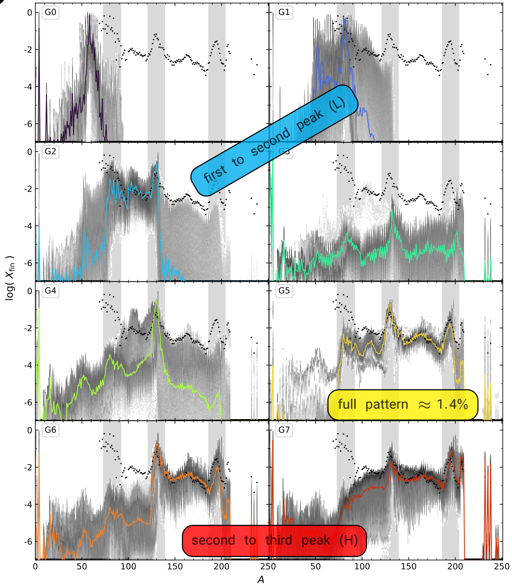

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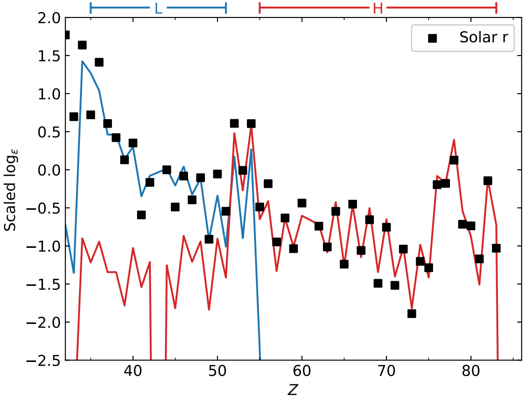
Comparison to Solar

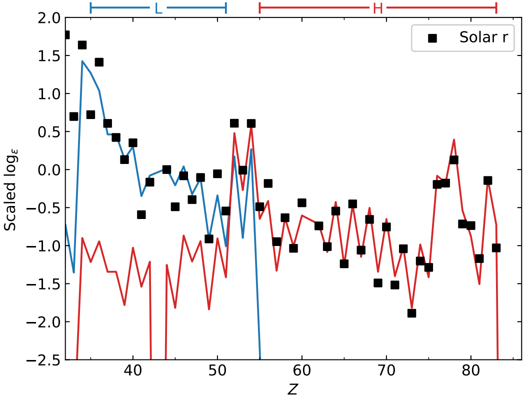
2 Component Model: L + H

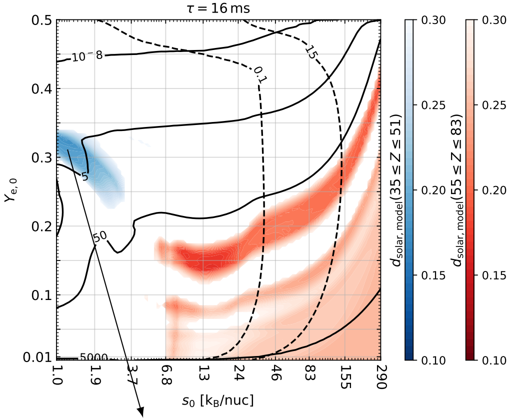


$$d = \frac{1}{\Delta Z} \sum_Z \left| \log\left(X_{\mathrm{solar}}(Z)\right) - \log\left(X_{\mathrm{model}}(Z)\right) \right|$$

Comparison to Solar

2 Component Model: L + H





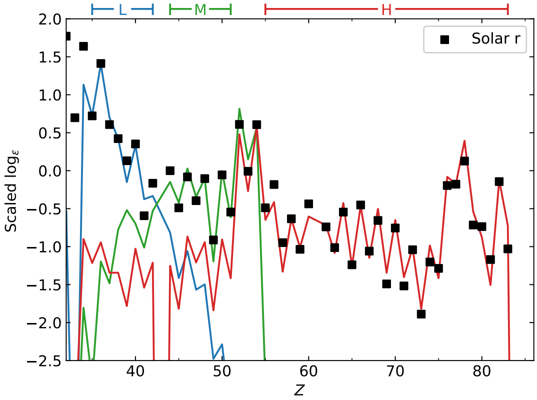
$$d = \frac{1}{\Delta Z} \sum_Z \left| \log\left(X_{\text{solar}}(Z)\right) - \log\left(X_{\text{model}}(Z)\right) \right|$$

L-component not produced in simulations! → add additional M-component

J. Kuske, A. Arcones, M. Reichert, arXiv:2506.00092

Comparison to Solar

3 Component Model: L + M + H



see also: Y.-Z. Qian & G. J. Wasserburg, ApJ 559 925 (2001)
C. J. Hansen, F. Montes & A. Arcones, ApJ 797 123 (2014)

Comparison to Solar

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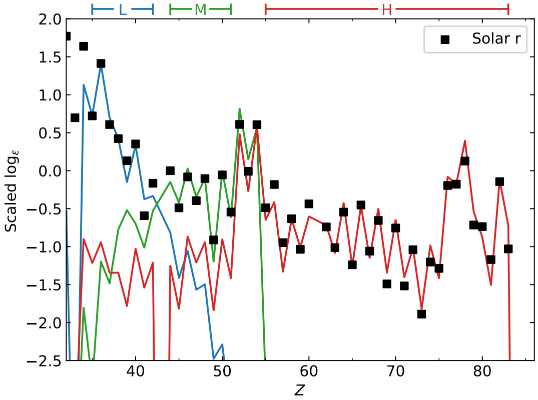
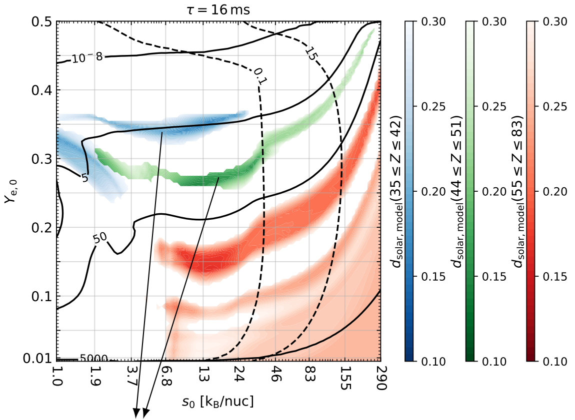


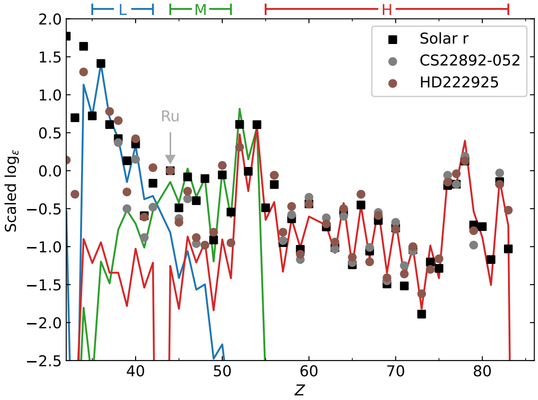


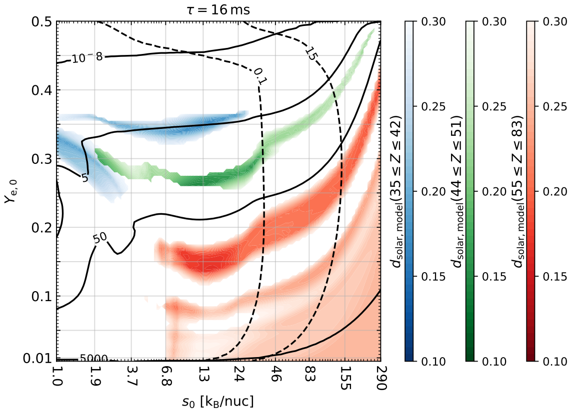
✓ conditions produced in simulations

see also: Y.-Z. Qian & G. J. Wasserburg, ApJ 559 925 (2001)
C. J. Hansen, F. Montes & A. Arcones, ApJ 797 123 (2014)

Comparison to Metal-Poor Stars

3 Component Model: L + M + H





- very similar for main r-process stars

⇒ **robust** mass ratios of L/M/H: 50%/25%/25%

Solar r: C. Sneden, J. J. Cowan & R. Gallino, AnnuRevAstro 46:241-288 (2008)
CS22892-052: C. Sneden, J. J. Cowan, J. E. Lawler et al., ApJ 591 936 (2003)
HD222925: I. U. Roederer, J. E. Lawler, E. A. Den Hartog et al., ApJS 260 27 (2022)

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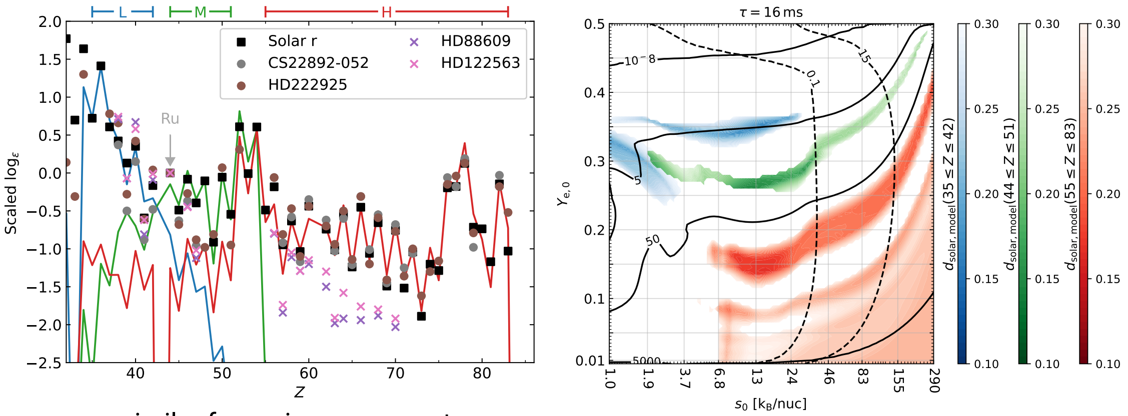


- very similar for main r-process stars

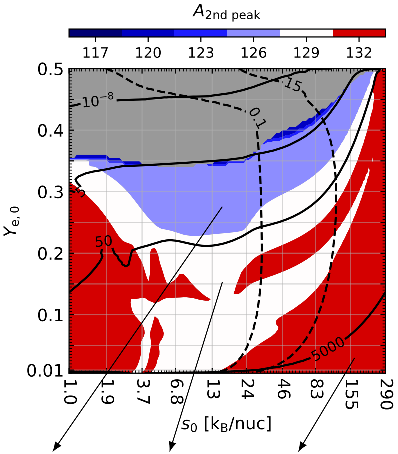
⇒ **robust** mass ratios of L/M/H: 50%/25%/25%

- H-component 1 dex lower for Honda stars

Solar r: C. Sneden, J. J. Cowan & R. Gallino, AnnuRevAstro 46:241-288 (2008)
CS22892-052: C. Sneden, J. J. Cowan, J. E. Lawler et al., ApJ 591 936 (2003)
HD222925: I. U. Roederer, J. E. Lawler, E. A. Den Hartog et al., ApJS 260 27 (2022)
HD88609 & HD122563: S. Honda, W. Aoki, Y. Ishimaru et al., ApJ 666 1189 (2007)

r-Process Peaks

see also: B. S. Meyer & J. S. Brown, ApJS 112 199 (1997)



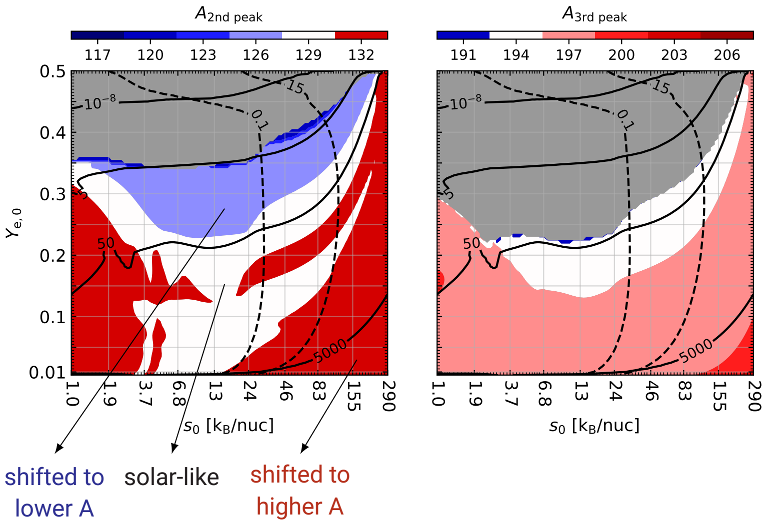
shifted to lower A

solar-like

shifted to higher A

r-Process Peaks

see also: B. S. Meyer & J. S. Brown, ApJS 112 199 (1997)



J. Kuske, A. Arcones, M. Reichert, arXiv:2506.00092

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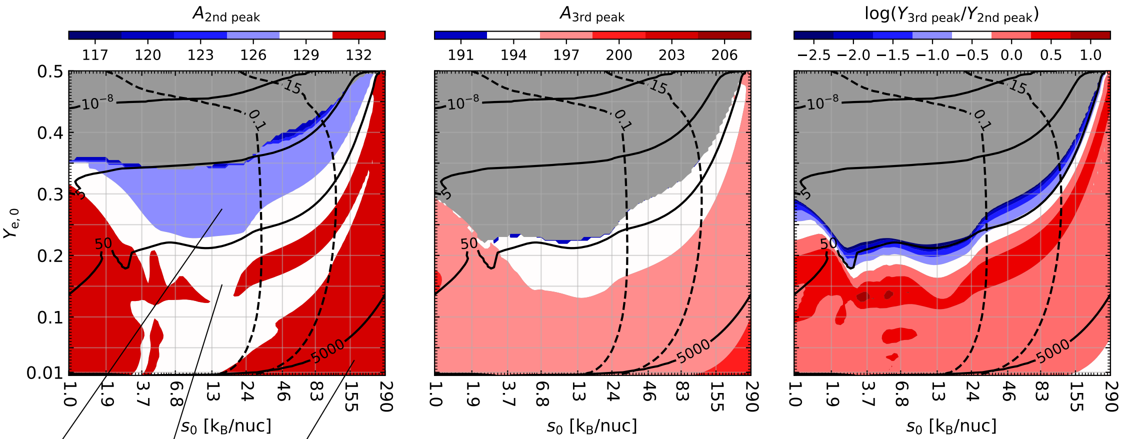


shifted to lower A

solar-like

shifted to higher A

✓ good agreement with solar when $Y_n/Y_{seed} \approx 50$

✗ strong dependency on nuclear physics

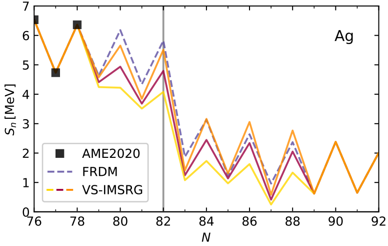
Part II - Nuclear Uncertainties

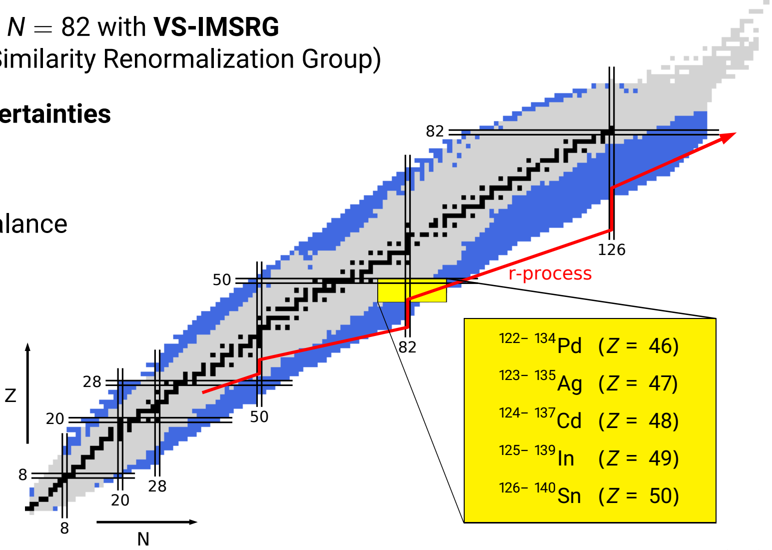
Ab-initio masses from VS-IMSRG

Image: ChatGPT

Ab-Initio Masses

- masses for 70 nuclei around $N = 82$ with **VS-IMSRG** (Valence Space In-Medium Similarity Renormalization Group)
- including valence space **uncertainties**
- (n, γ)–rates from *TALYS*
- (γ, n)–rates from detailed balance





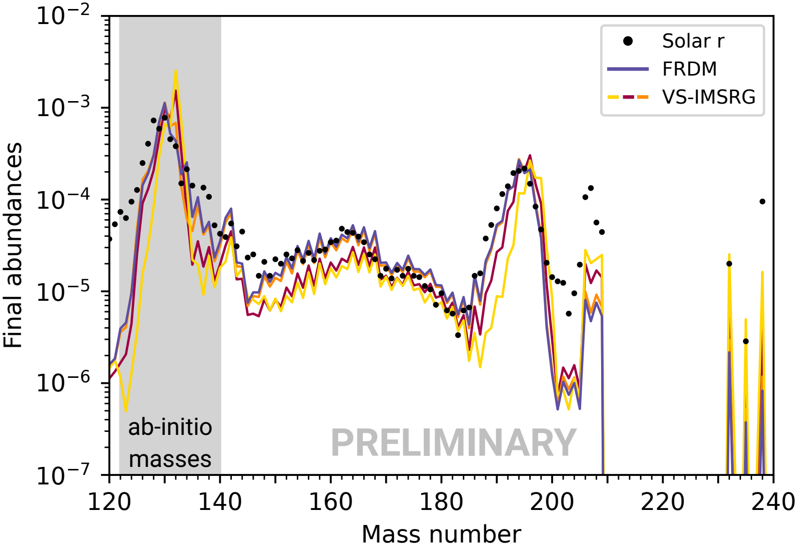
VS-IMSRG: T. Miyagi et al., Phys. Rev. C 105, 014302 (2022)
Fig. (mod.): A. Arcones & F. Thielemann, Astron Astrophys Rev 31, 1 (2023)

Nucleosynthesis Results

VS-IMSRG vs. FRDM2012

- ↘ lower S_n
- ↘ lower (n, γ)−rates
- ⇒ **stronger waiting point**
- ↘ lower abundances beyond second peak
- ↗ higher $Y_n / Y_{\mathrm{seed(A>140)}}$
- ⇒ **more Pb and actinides**

J. Kuske, T. Miyagi, A. Arcones, A. Schwenk (in prep.)



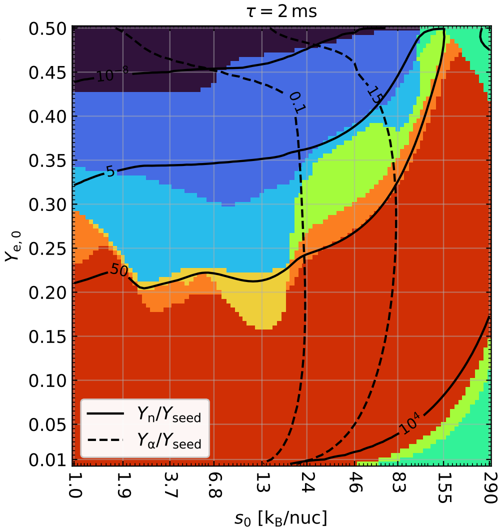
NSM simulation: M. Jacobi et al., MNRAS 527, 3 (2024)

Summary & Outlook

Part I - Complete r-process study

- second-to-third peak produced **robustly** for many conditions
- full r-process pattern requires **superposition** of at least 2–3 different conditions

⇒ more details: *J. Kuske, A. Arcones, M. Reichert (submitted to ApJ), arXiv:2506.00092*



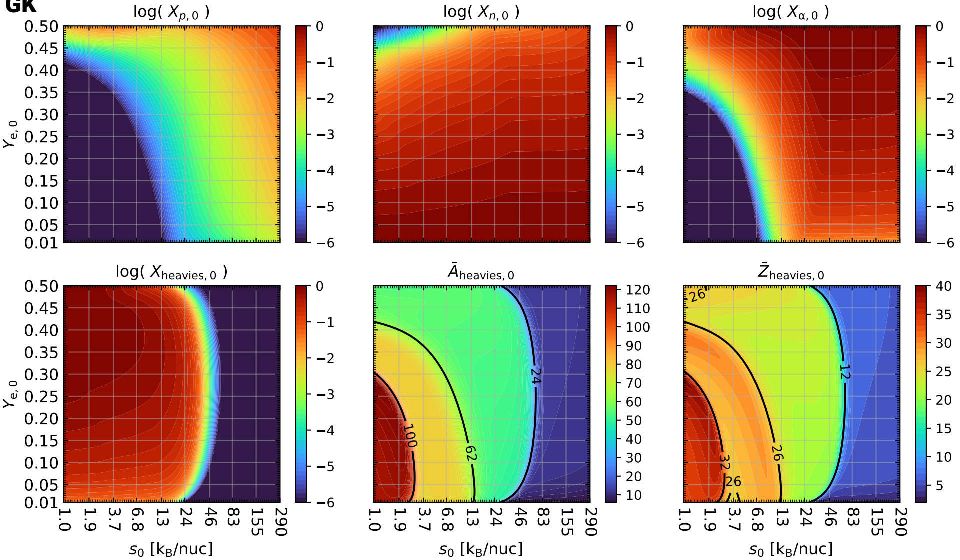
Part II - Ab-initio masses from VS-IMSRG

- first application in r-process calculations

⇒ coming soon: *J. Kuske, T. Miyagi, A. Arcones, A. Schwenk (in prep.)*

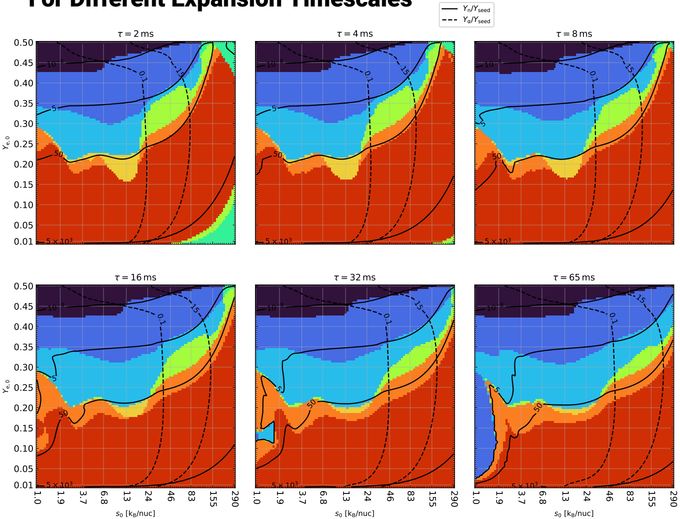
Initial Conditions

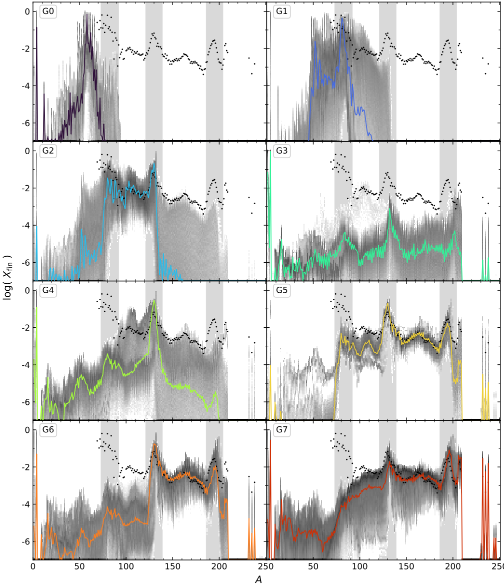
NSE at 7 GK



Nucleosynthesis Groups

For Different Expansion Timescales





$$\bar{A}_{fin} \approx \bar{A}_{seed} + \frac{Y_n}{Y_{seed}}$$

J. Kuske, A. Arcones, M. Reichert, arXiv:2506.00092

Comparison to Trajectories
From Hydrodynamical Simulations

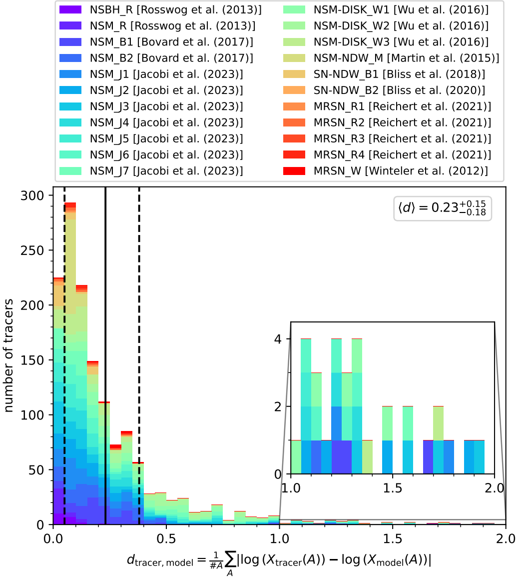
- map trajectory to $Y_{\mathrm{e},0}-s_0-\tau-$space:

$$\left.\begin{matrix} Y_{\mathrm{e},0} \\ s_0 \end{matrix}\right\} \Rightarrow \text{ from interpolation to } 7\,\mathrm{GK}$$
$$\tau \quad \Rightarrow \text{ from fit to density profile}$$

- metric for comparing final mass fractions:

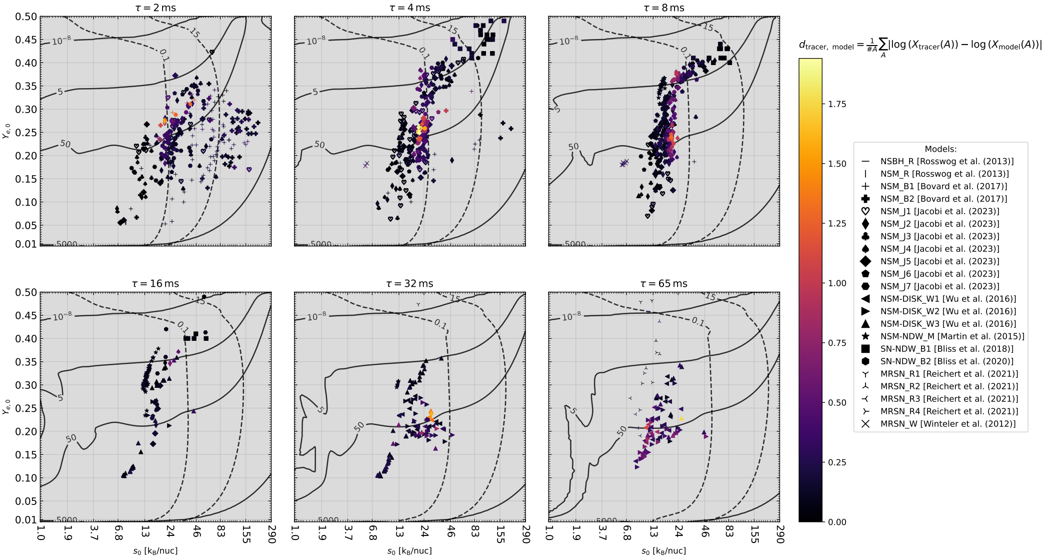
$$d_{\mathrm{tracer,model}} = \frac{1}{\#A} \sum_A \left| \log\left(X_{\mathrm{tracer}}(A)\right) - \log\left(X_{\mathrm{model}}(A)\right) \right|$$

- 22 models of different astrophysical sites with up to 100 trajectories each



J. Kuske, A. Arcones, M. Reichert, arXiv:2506.00092

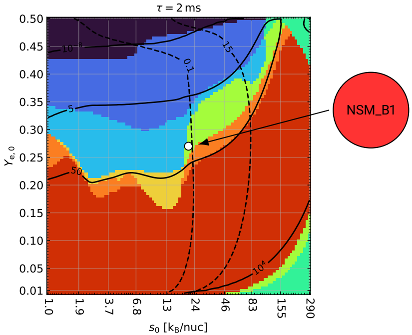
Comparison to Trajectories

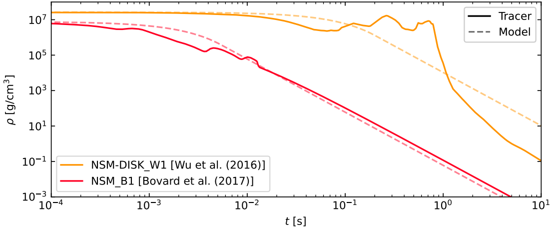


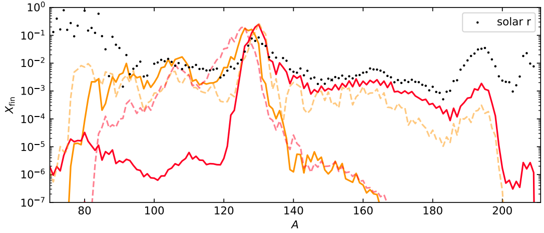
Comparison to Trajectories

From Hydrodynamical Simulations

- **good agreement** for $\approx 98\,\%$ of trajectories
- large discrepancies for some trajectories due to:
  1) non-monotonic density evolution: **hydrodynamical shocks**
  2) **sensitive conditions**: between two nucleosynthesis groups







J. Kuske, A. Arcones, M. Reichert, arXiv:2506.00092