Nucleosynthesis

Jonas Lippuner

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TCAN Meeting 2021
BNS/BH-NS Merger Workshop

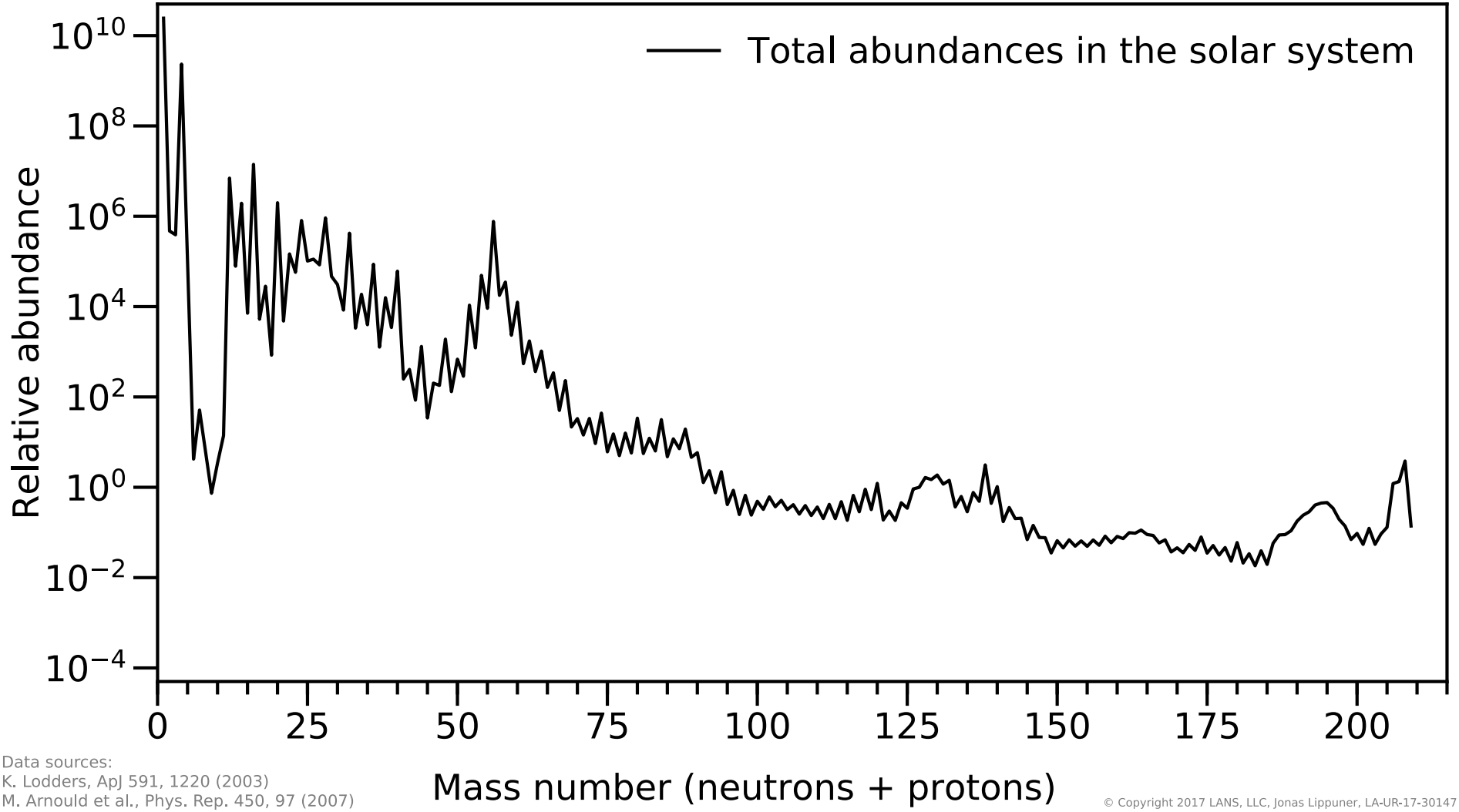
Los Alamos
NATIONAL LABORATORY
EST. 1943

National Nuclear Security Administration
Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

Outline

1. Brief nucleosynthesis overview
2. Nuclear reaction networks
3. r-Process in neutron star mergers

Solar system abundances



Data sources:
K. Lodders, ApJ 591, 1220 (2003)
M. Arnould et al., Phys. Rep. 450, 97 (2007)

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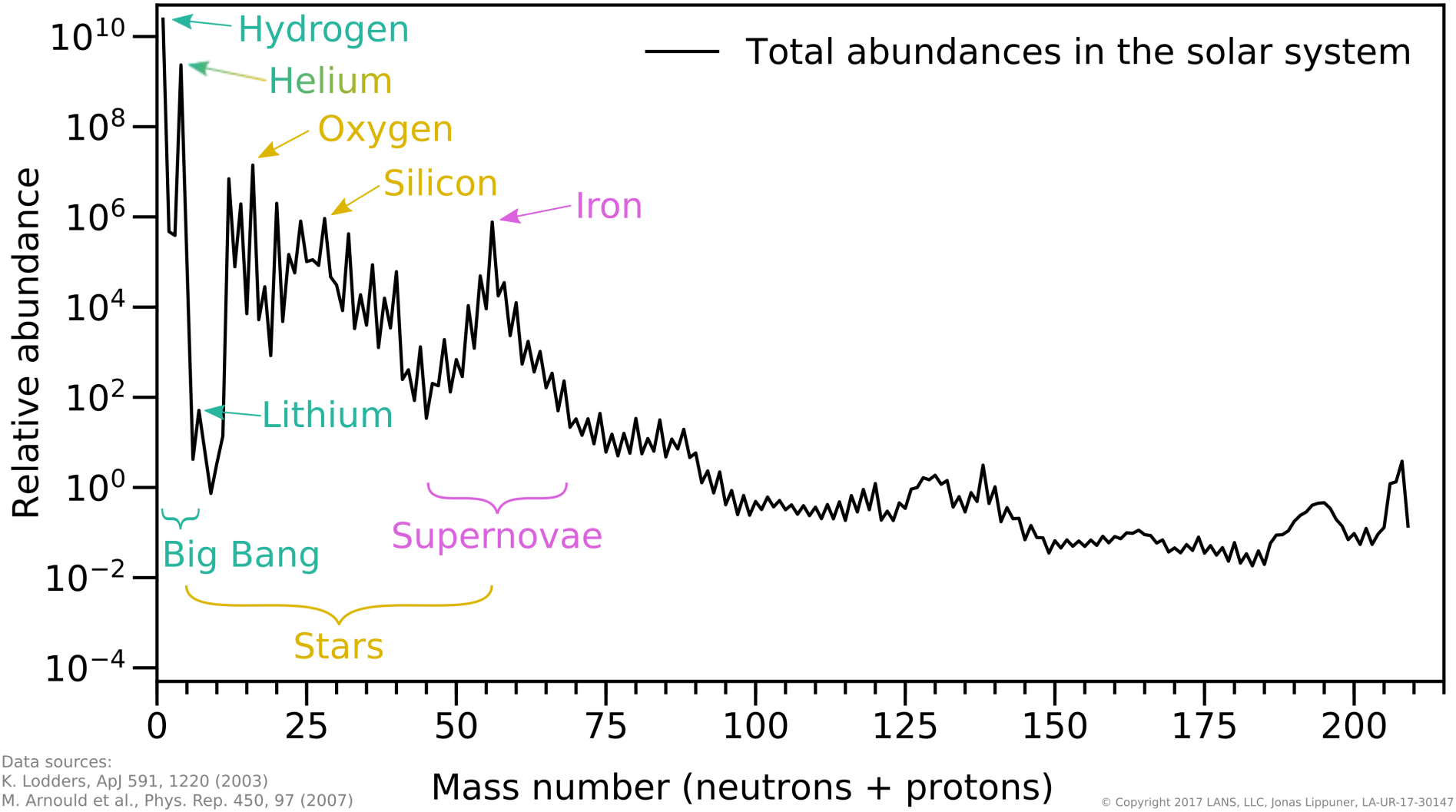

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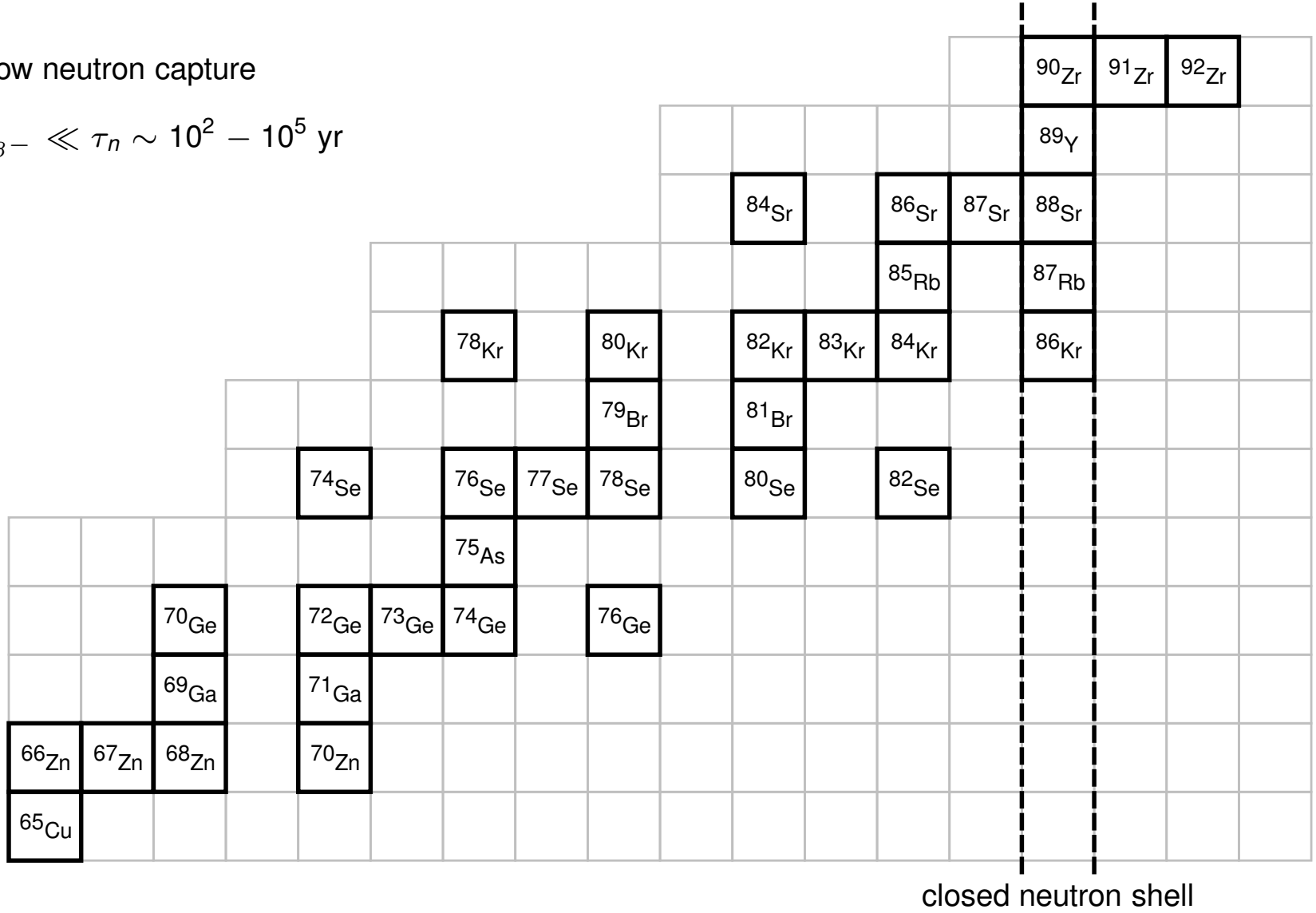
The s-process

slow neutron capture

$\tau_{\beta-} \ll \tau_n \sim 10^2 - 10^5$ yr



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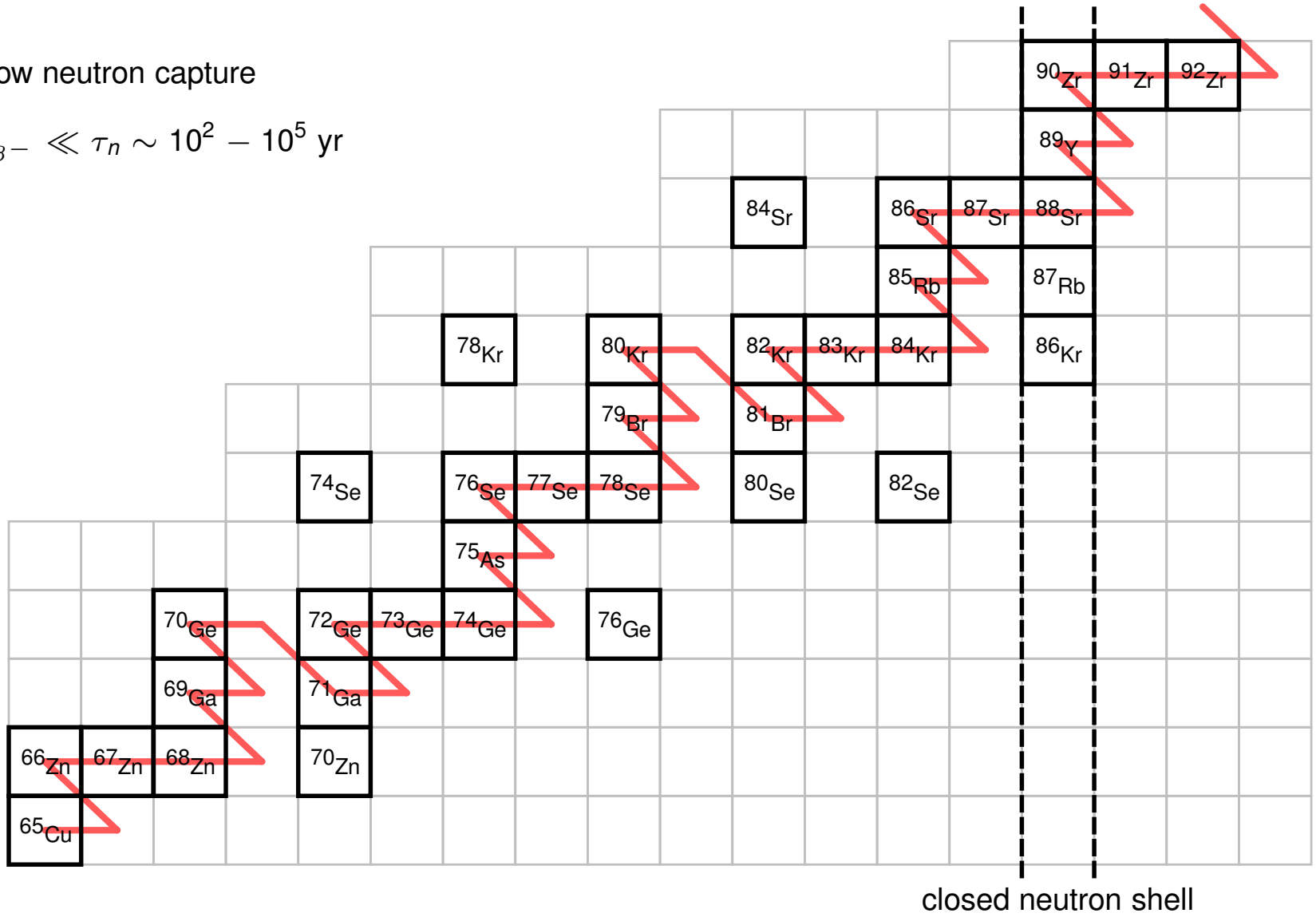

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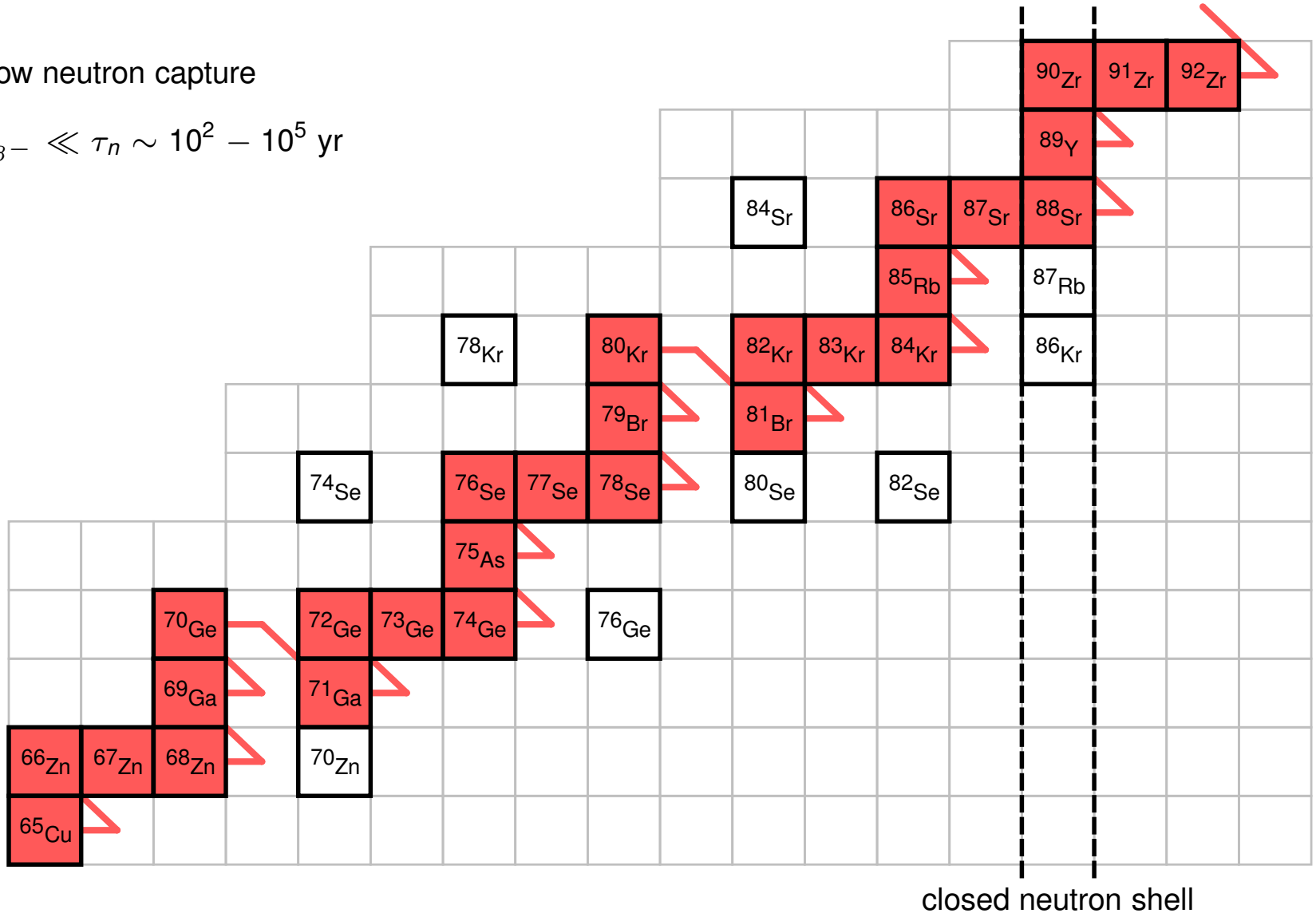
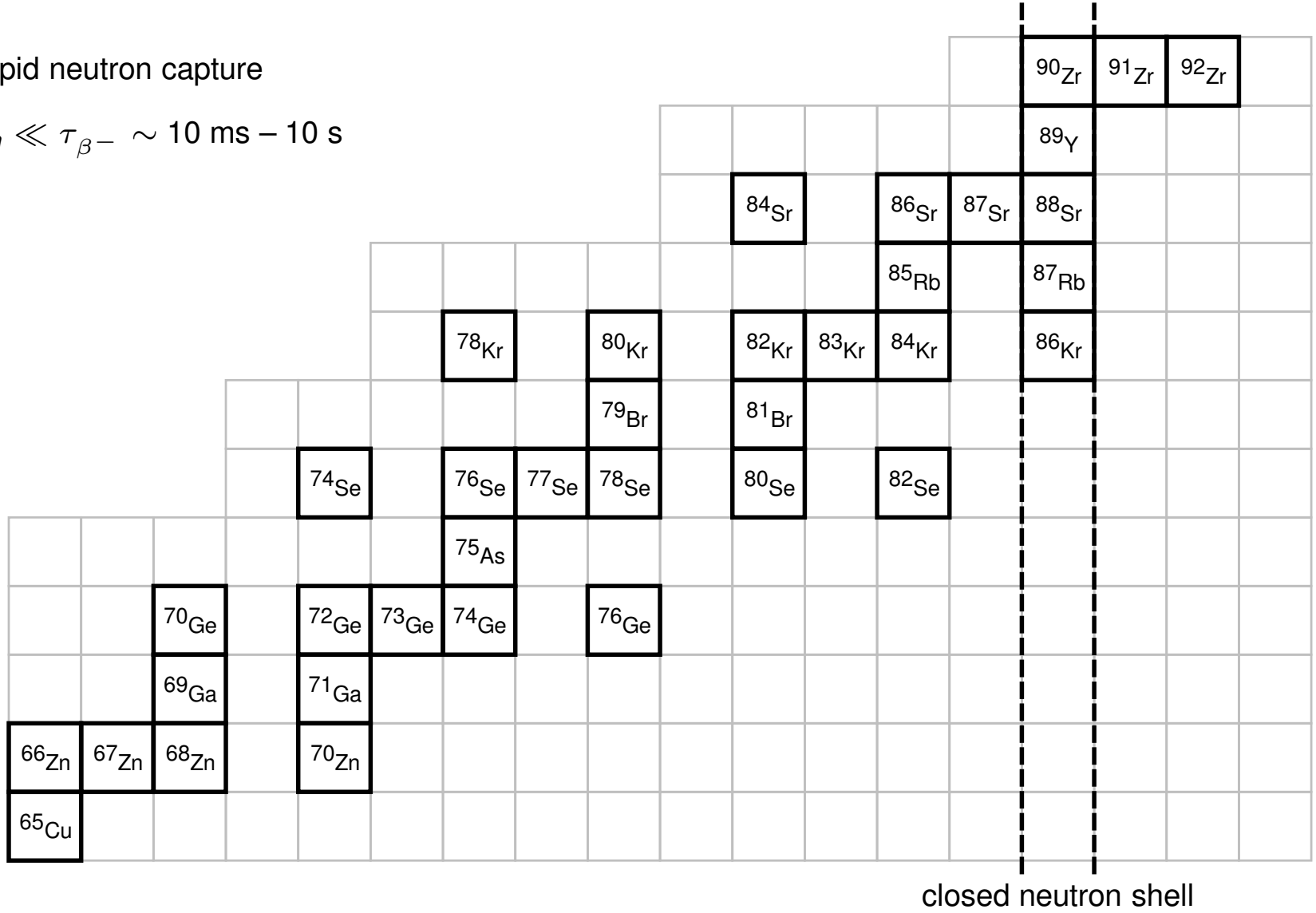


The r-process

rapid neutron capture

$\tau_n \ll \tau_{\beta-} \sim 10$ ms – 10 s



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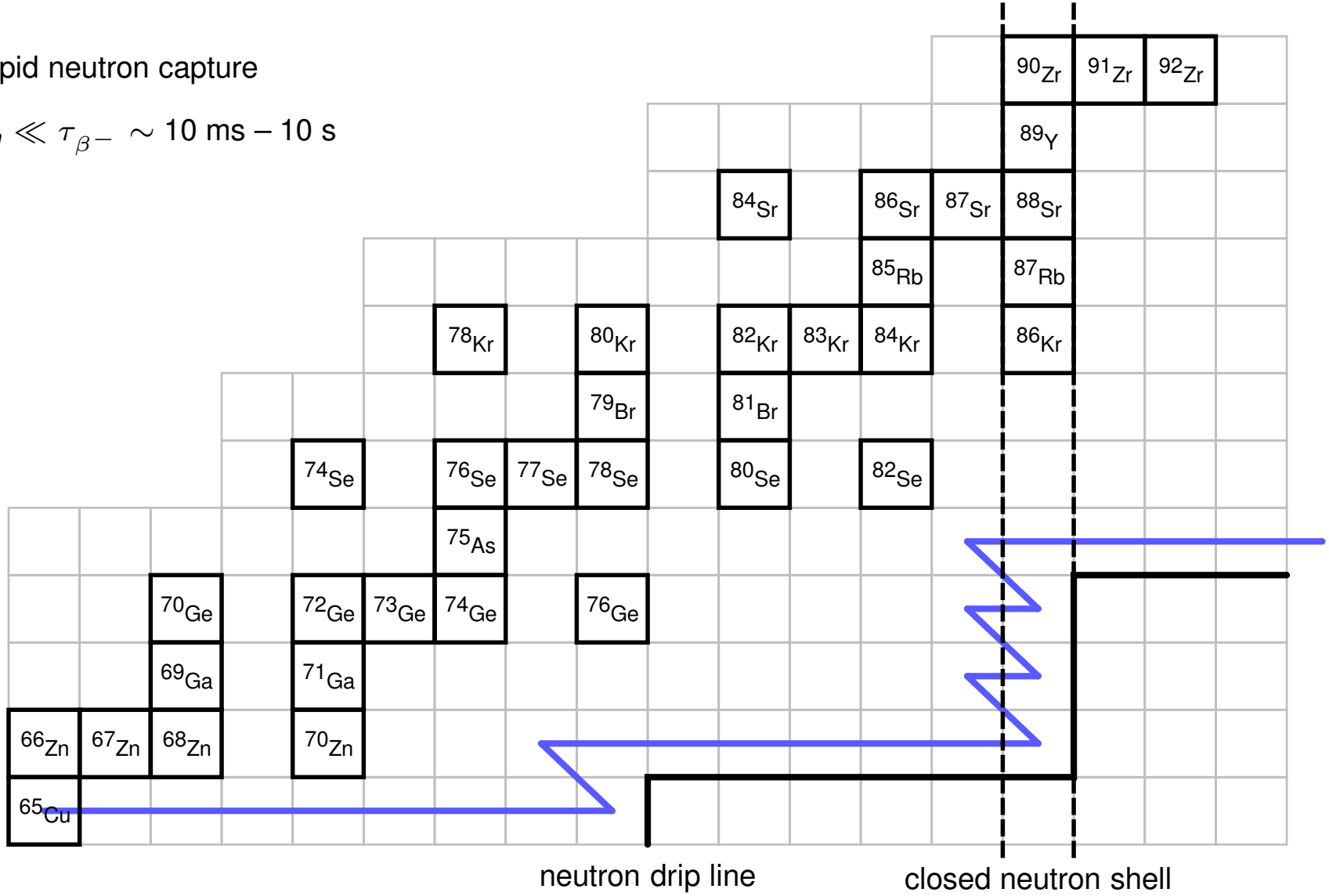

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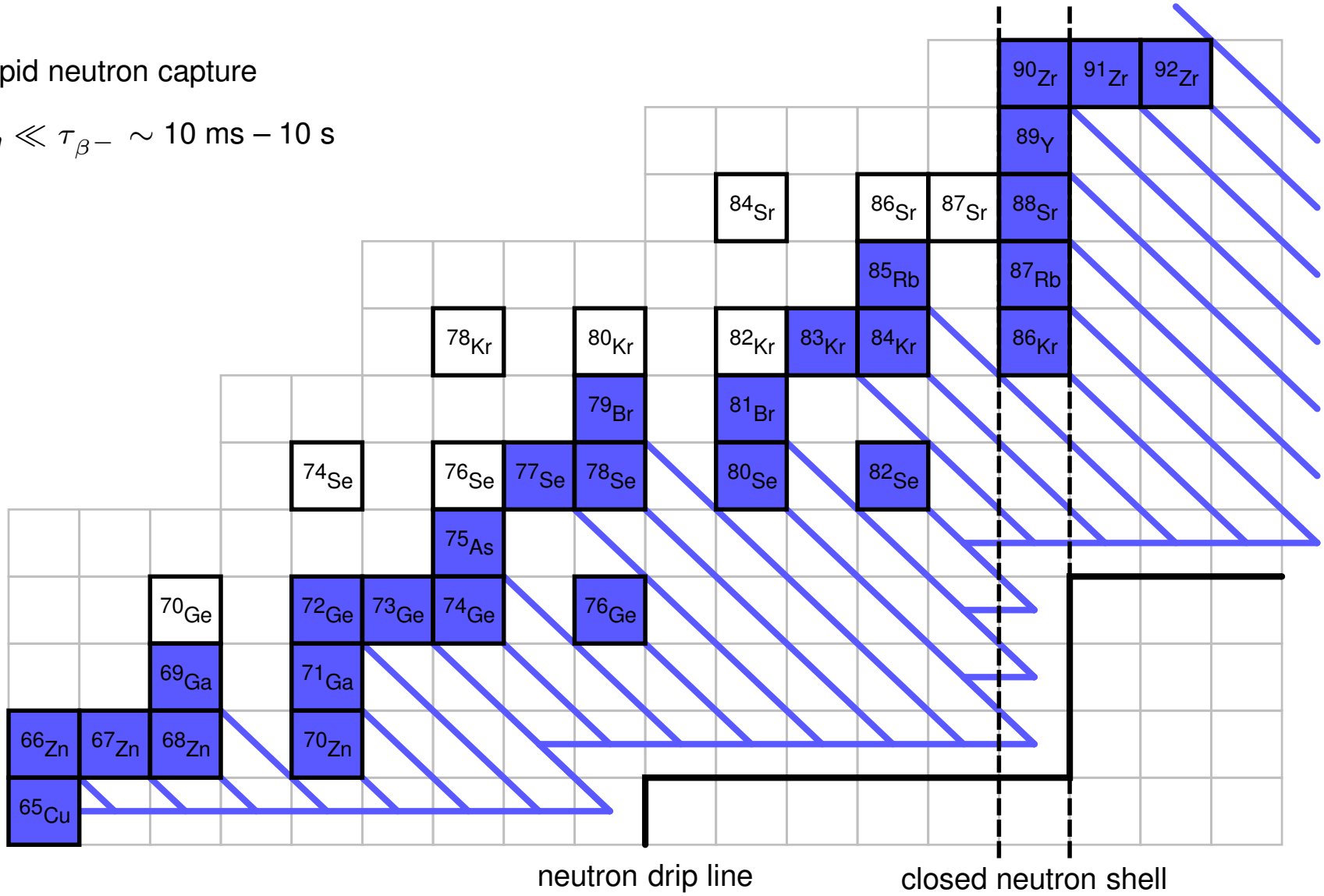
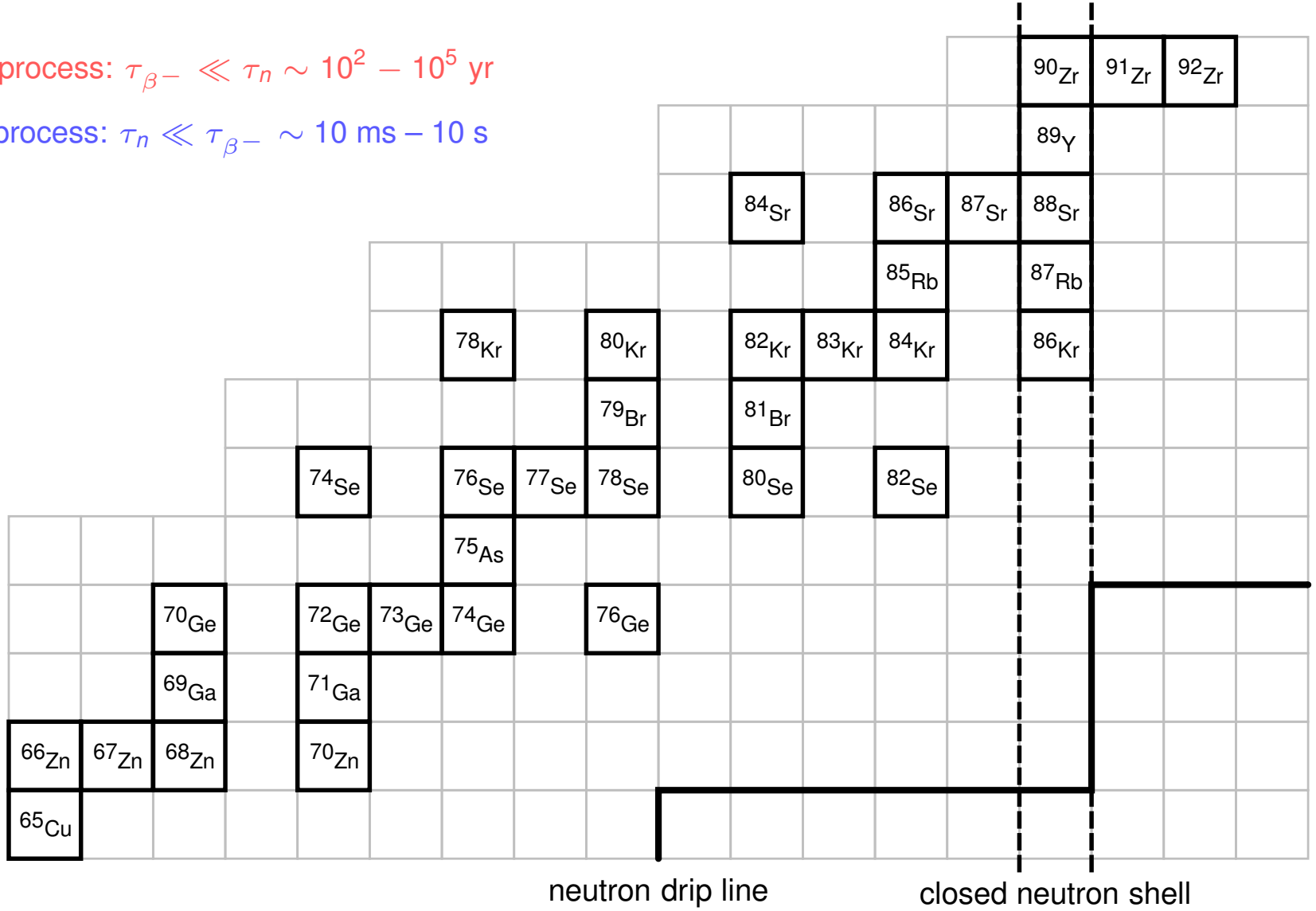


Double peaks due to closed neutron shells

s-process: $\tau_{\beta-} \ll \tau_n \sim 10^2 - 10^5$ yr

r-process: $\tau_n \ll \tau_{\beta-} \sim 10$ ms – 10 s



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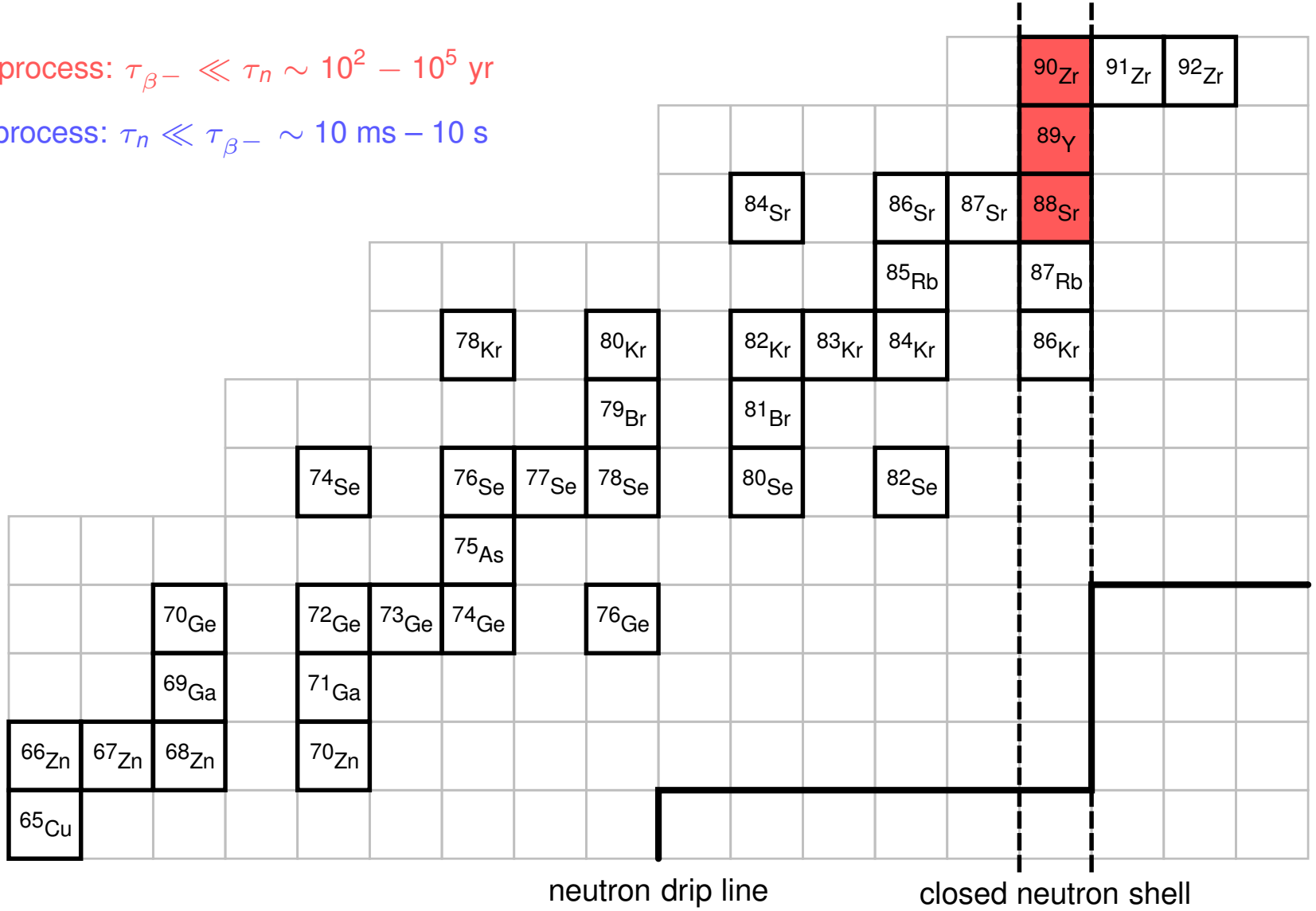

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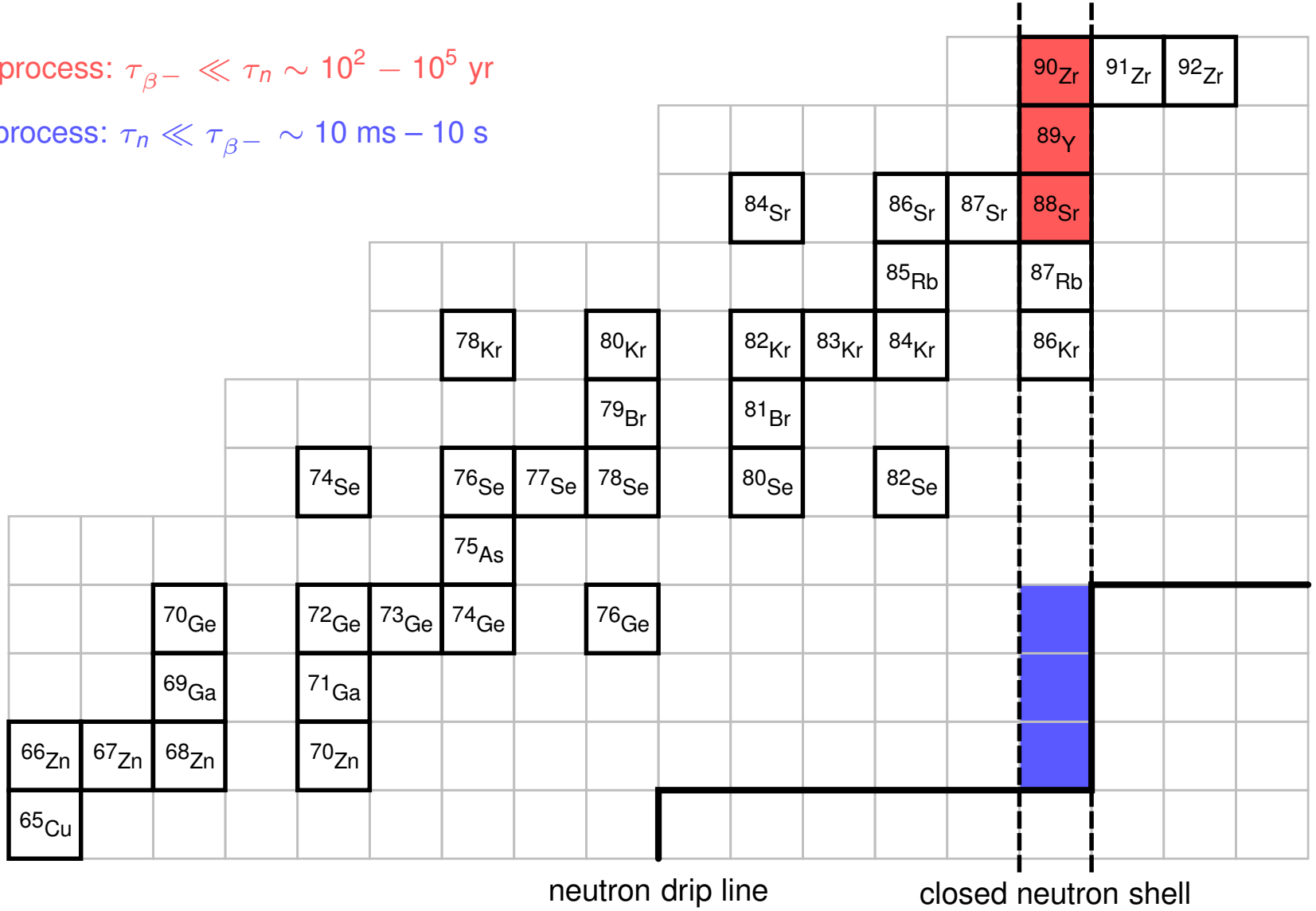

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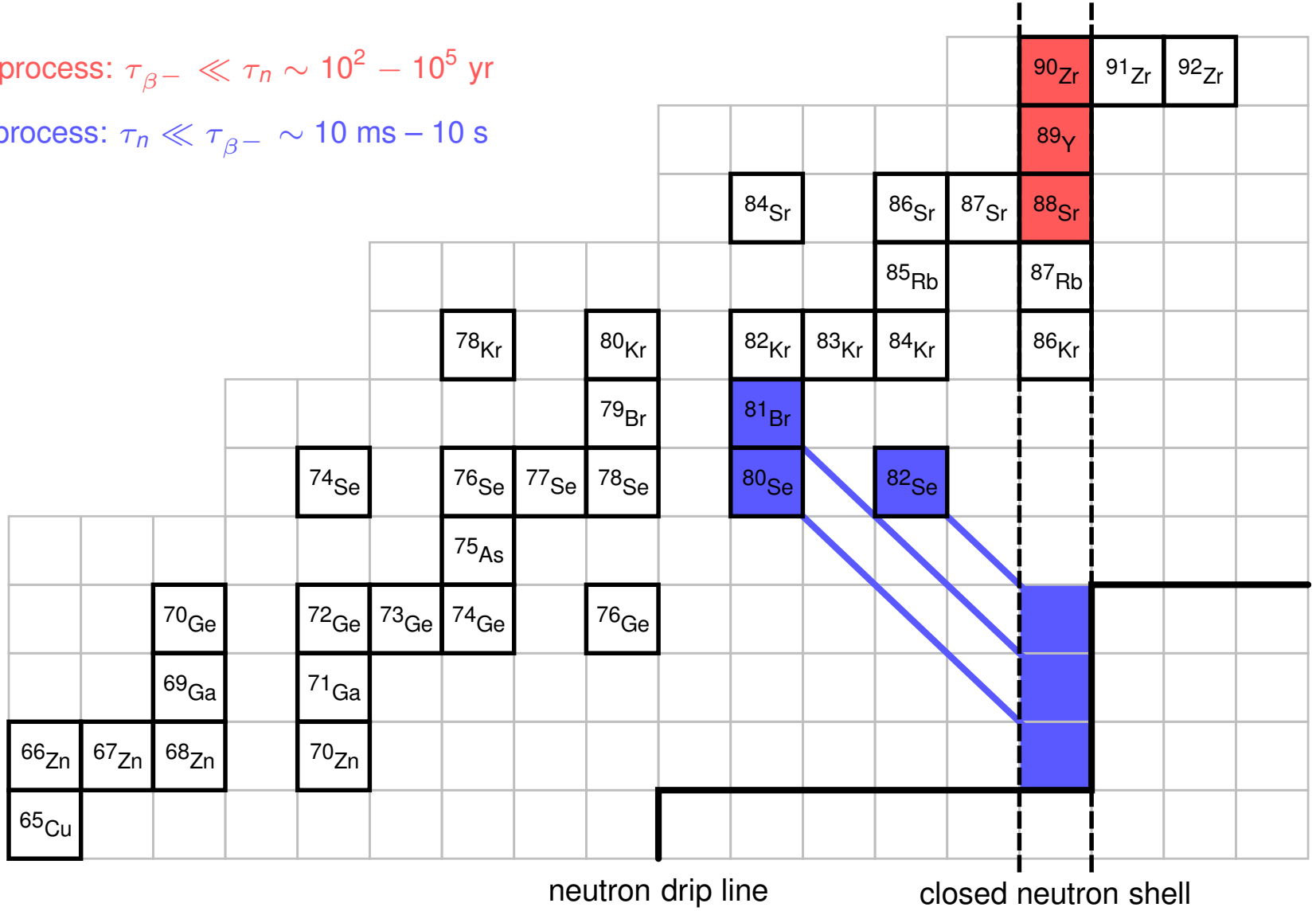
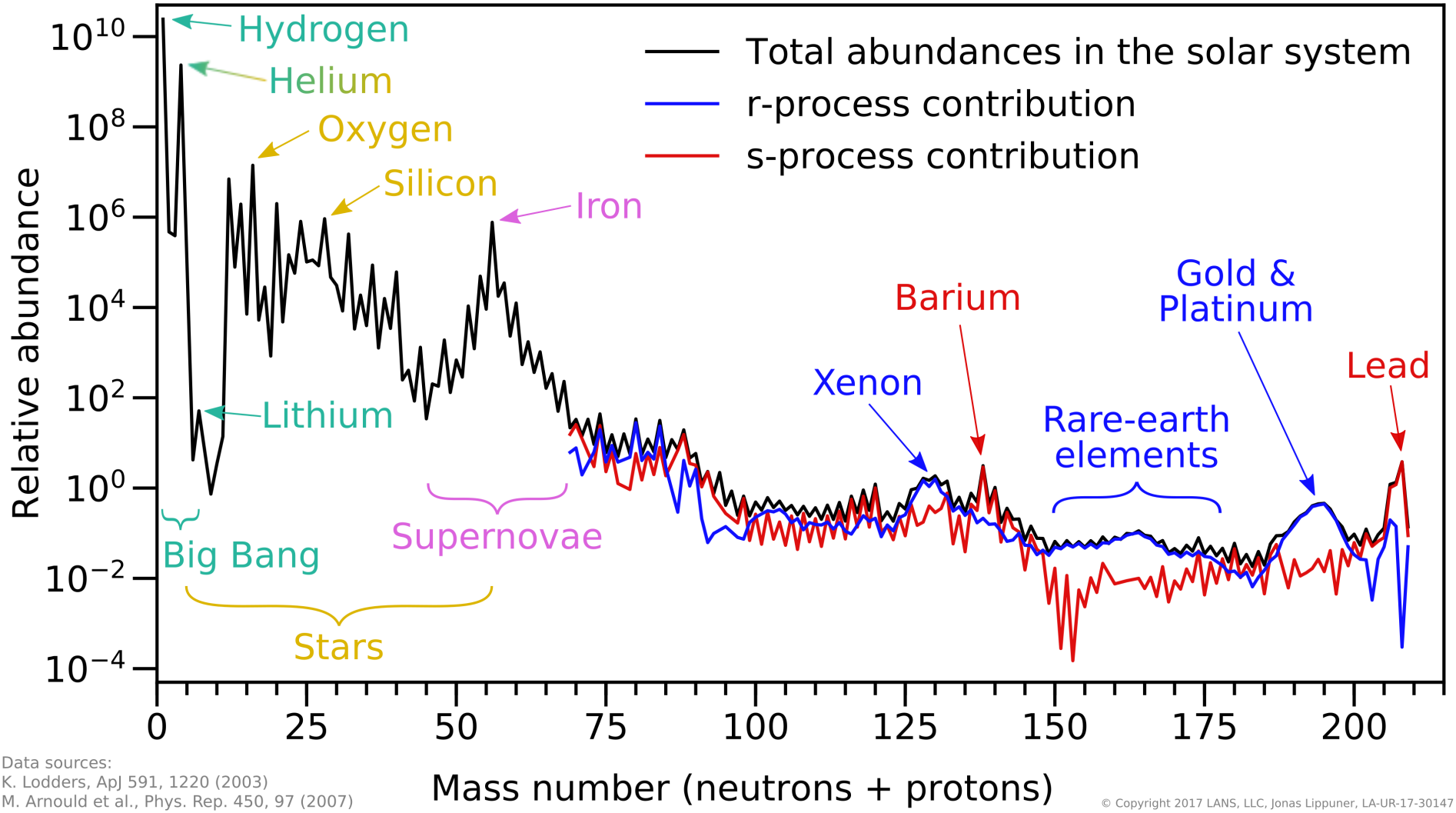


Solar system abundances



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Outline

1. Brief nucleosynthesis overview
2. **Nuclear reaction networks**
3. r-Process in neutron star mergers

SkyNet

SkyNet

bitbucket.org/jlippuner/skynet

- General-purpose nuclear reaction network
- $\sim$8000 isotopes, $\sim$140,000 nuclear reactions
- Written in C++ with Python bindings
- Open source

Lippuner, J. and Roberts, L. F., ApJS 233, 18 (2017)

SkyNet

Define abundance

$$Y_i = \frac{n_i}{n_B}. \tag{1}$$

Consider reaction

$$\mathrm{p} + {}^7\mathrm{Li} \rightarrow 2\,{}^4\mathrm{He} \tag{2}$$

with rate $\lambda = \lambda(T, \rho)$. Then

$$\begin{aligned} \dot{Y}_{^4\mathrm{He}} &= 2\lambda Y_\mathrm{p} Y_{^7\mathrm{Li}} + \cdots\,, \\ \dot{Y}_\mathrm{p} &= -\lambda Y_\mathrm{p} Y_{^7\mathrm{Li}} + \cdots\,, \\ \dot{Y}_{^7\mathrm{Li}} &= -\lambda Y_\mathrm{p} Y_{^7\mathrm{Li}} + \cdots \end{aligned} \tag{3}$$

Need to solve big, stiff, non-linear system of ODEs

SkyNet features

Physics

- Extended Timmes equation of state (EOS)
- Calculate nuclear statistical equilibrium (NSE)
- NSE evolution mode
- Self-heating
- Calculate inverse rates from *detailed balance* to be consistent with NSE
- Electron screening with smooth transition between weak and strong screening (reactions and NSE)

Code

- Adaptive time stepping
- Python bindings
- Modularity
- Extendible reaction class (currently REACLIB, table, neutrino)
- Make movies

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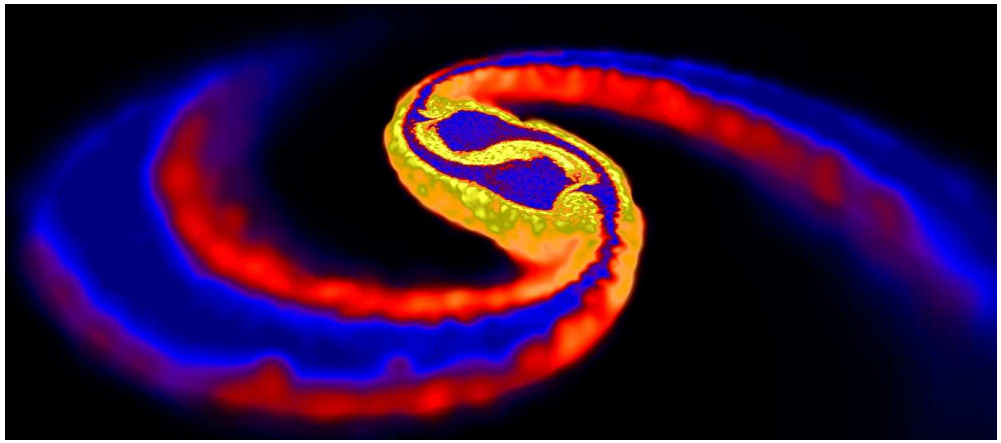
Two types of merger ejecta



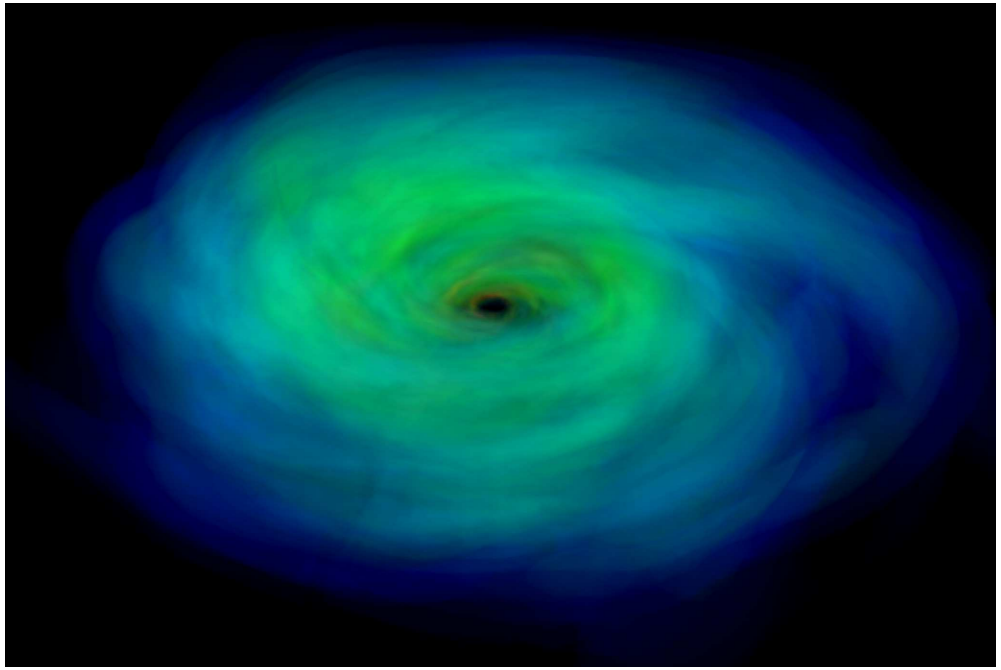
Dynamical tidal tail ejecta

Typically very neutron-rich

$M_{\rm ej} \sim 10^{-4} - \text{few} \times 10^{-2} M_\odot$

See: Bauswein+13, Hotokezaka+13, Foucart+14, Sekiguchi+15, Kyutoku+15, Radice+16

Figure credit: Price+06



Disk outflow

Typically neutron-poor

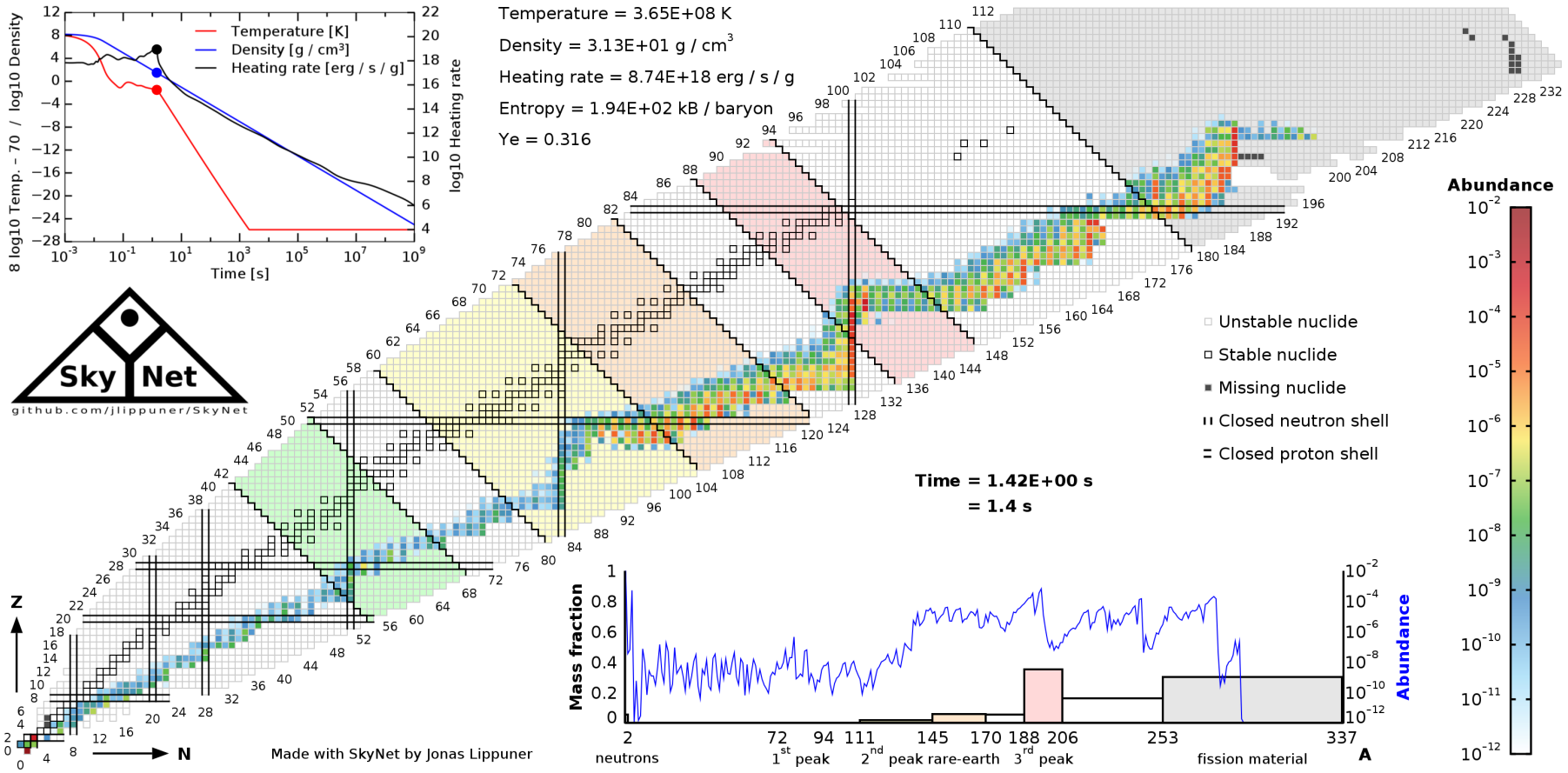
$M_{\rm ej} \sim \text{few} \times 10^{-3} M_\odot$

See: Surman+08, Wanajo+11, Fernández+13, Perego+14, Just+15, Foucart+15, Siegel+17, Siegel+18, Miller+19

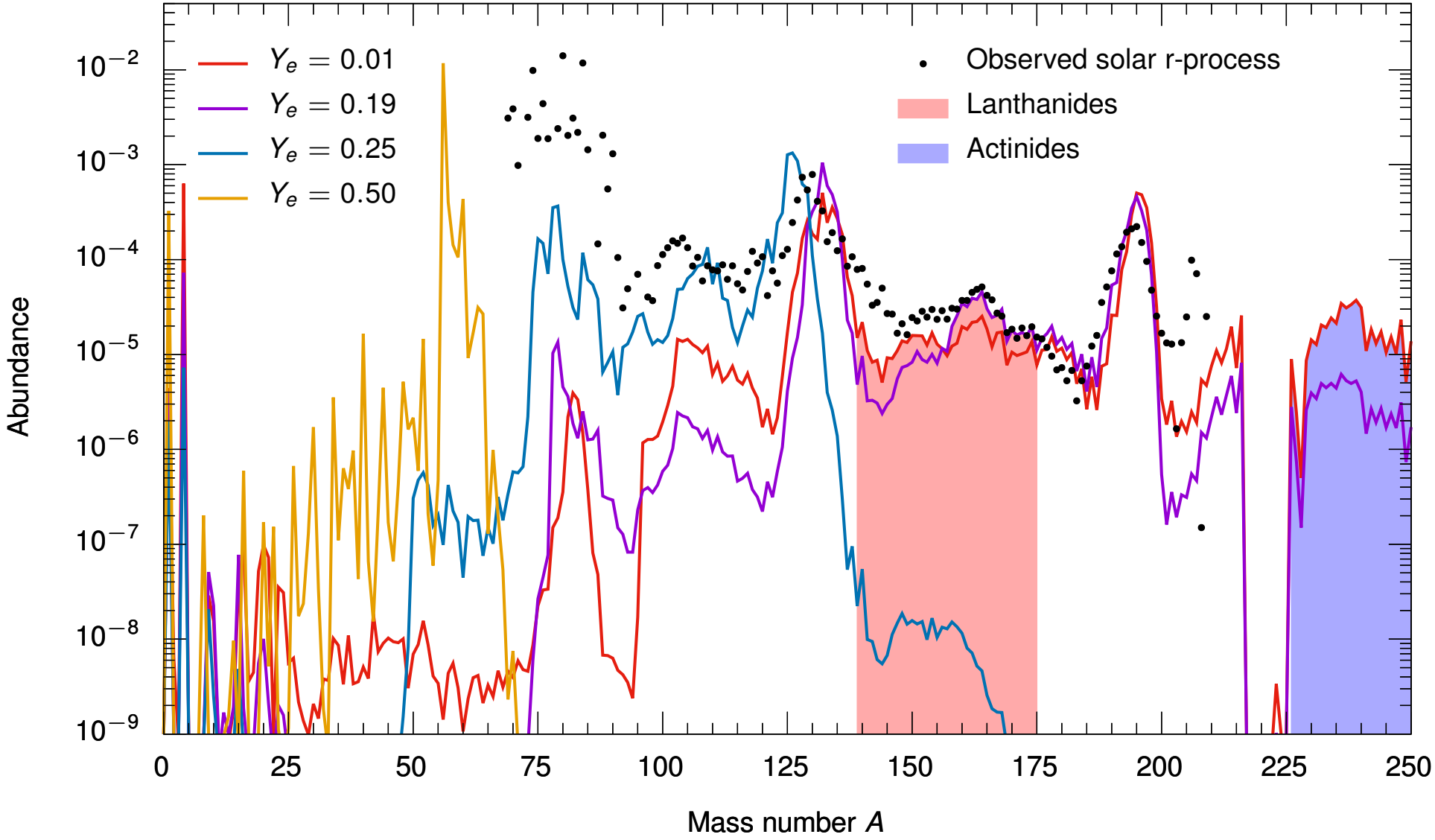
Figure credit: Miller+19

SkyNet results

http://jonaslippuner.com/skynet/SkyNet_Ye_0.010_s_010.000_tau_007.100.mp4
http://jonaslippuner.com/skynet/SkyNet_Ye_0.250_s_010.000_tau_007.100.mp4

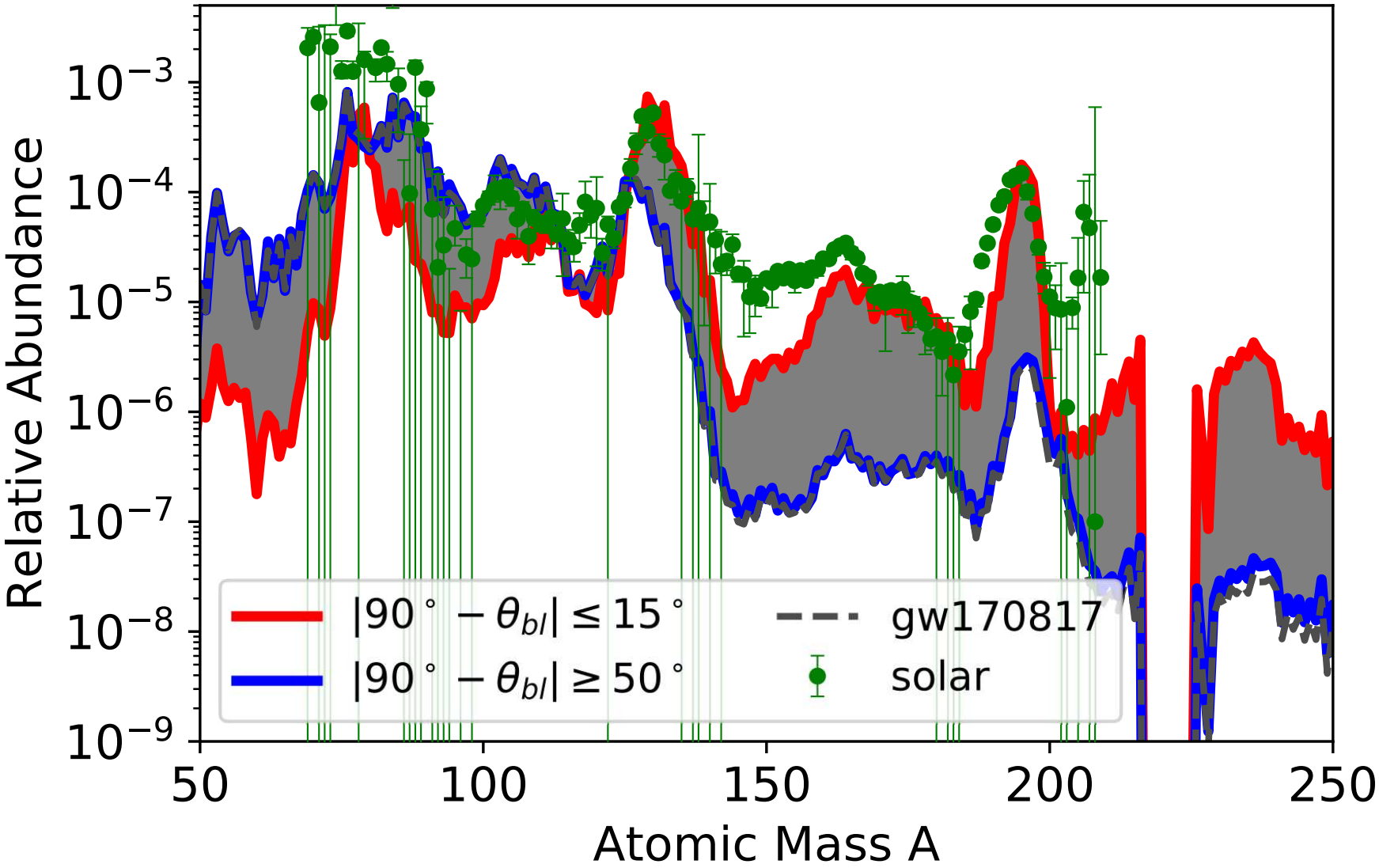


SkyNet results



JL, Roberts 2015, ApJ 815, 82, arXiv:1508.03133

Final abundances from accretion disk outflow



Miller+19

Nucleosynthesis in HMNS disk outflow

- 3 $M_\odot$ central HMNS or BH, 0.03 $M_\odot$ accretion disk
- Variable HMNS lifetime, neutrino leakage, α viscosity

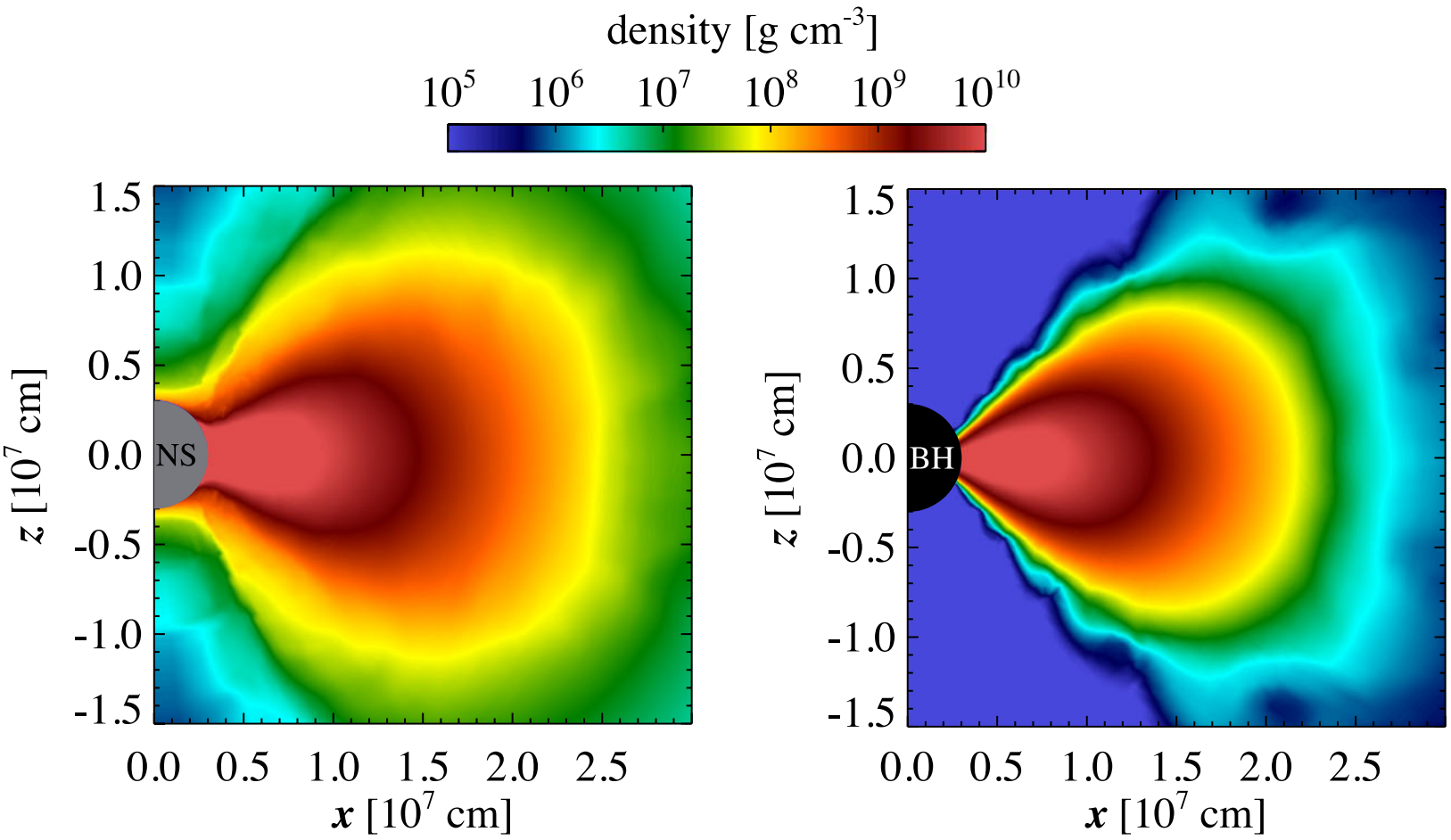
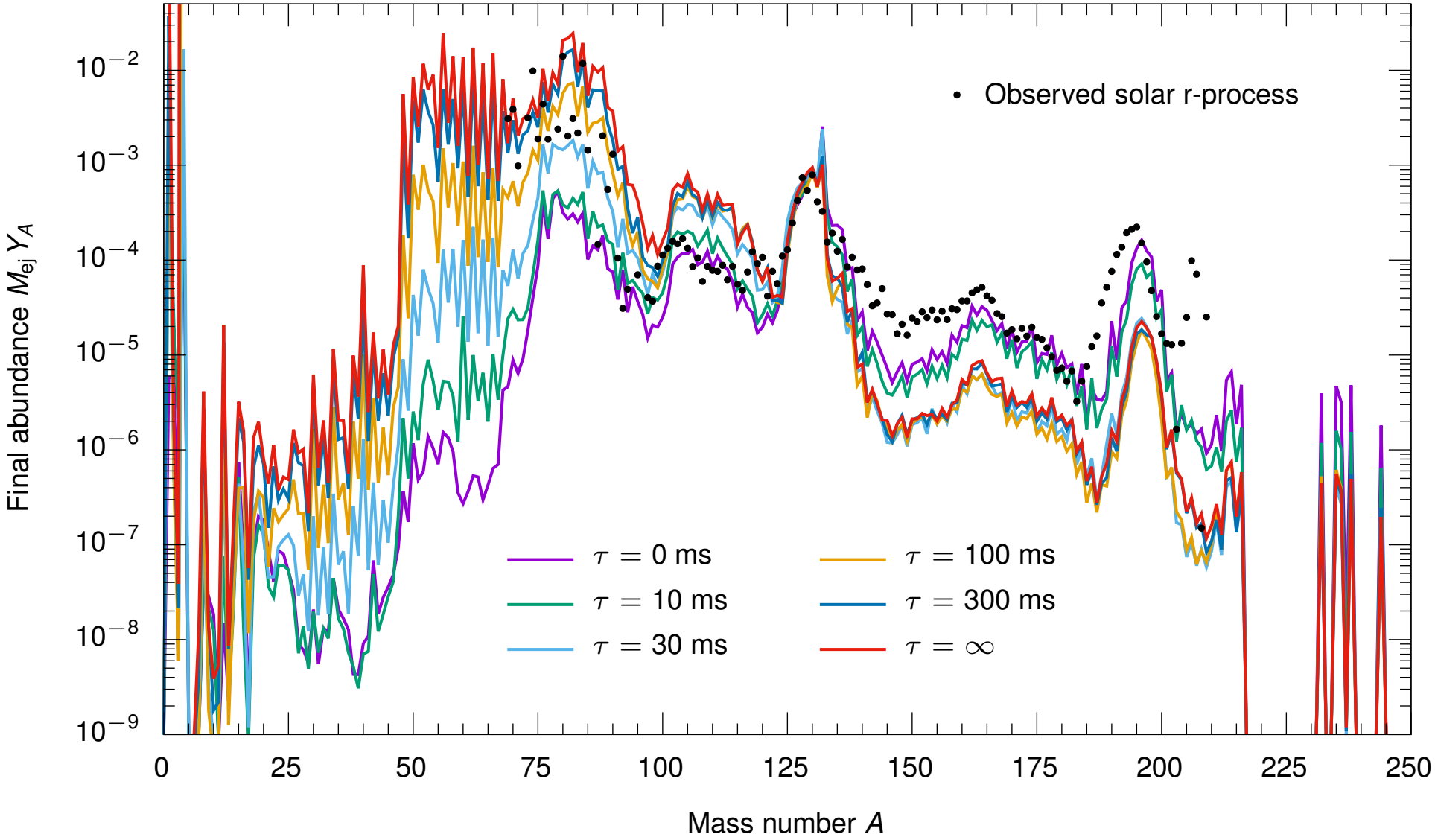


Figure from Metzger & Fernández (2014)

Final abundances vs. HMNS life time



JL, Fernández, Roberts, et al. 2017, MNRAS 472, 904, arXiv:1703.06216

Black hole–neutron star merger

Roberts, JL, Duez, et al. 2017, *MNRAS* 464, 3907, arXiv:1601.07942

1. Full GR simulation of BH–NS
   Francois Foucart (UNH), *Foucart et al.*, Phys. Rev. D 90, 024026 (2014)
2. Evolve ejecta in SPH code
   Matt Duez (WSU)
3. Nucleosynthesis with varying neutrino luminosity
   JL and Luke Roberts (MSU)

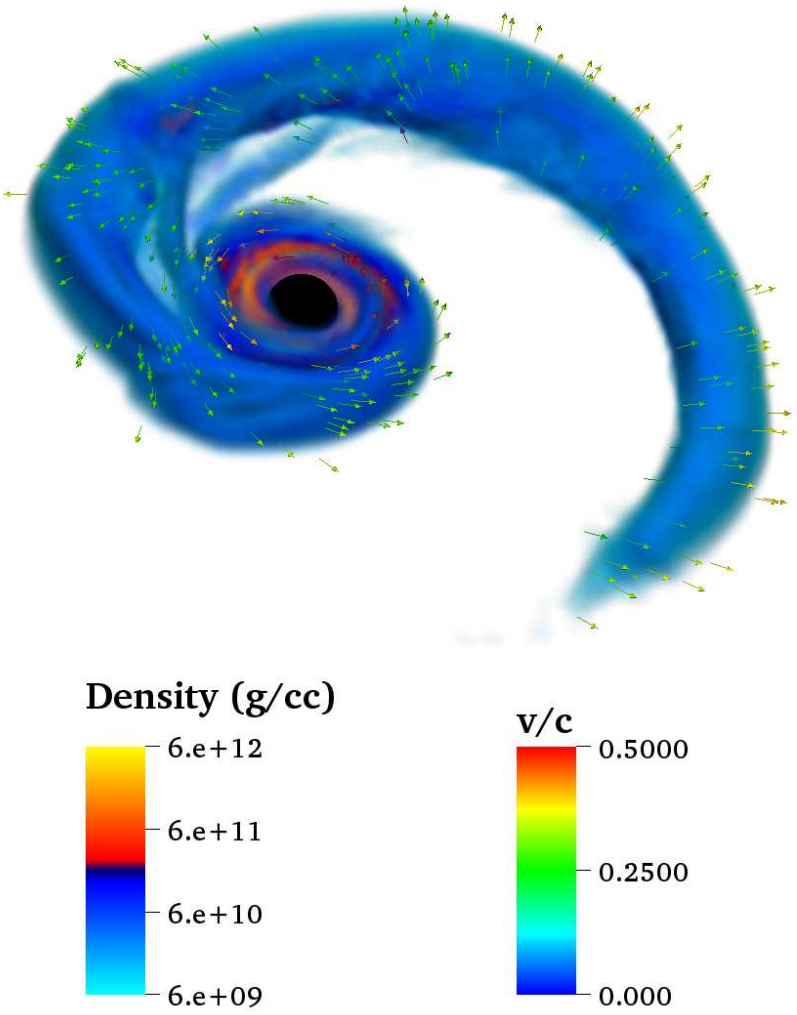
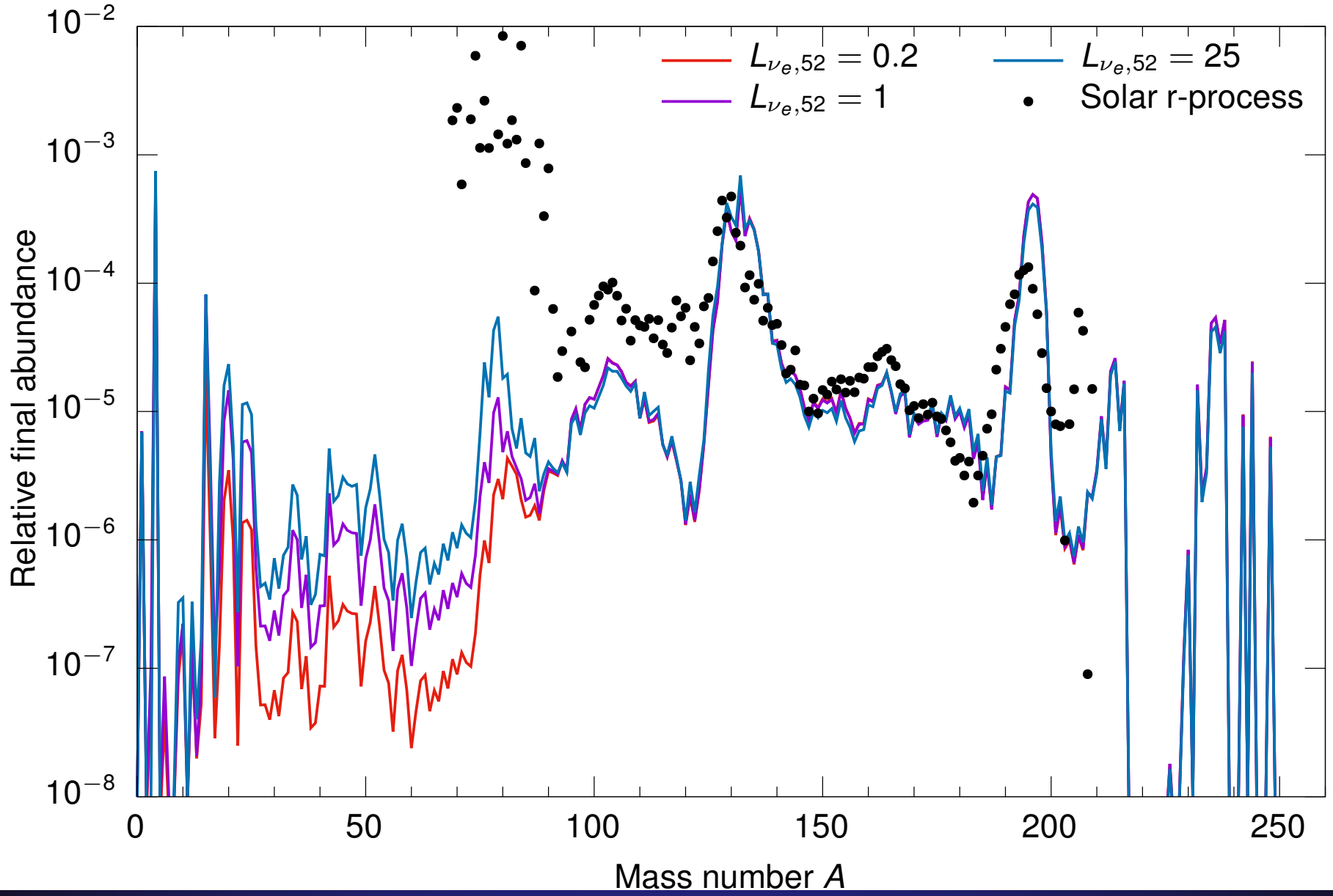
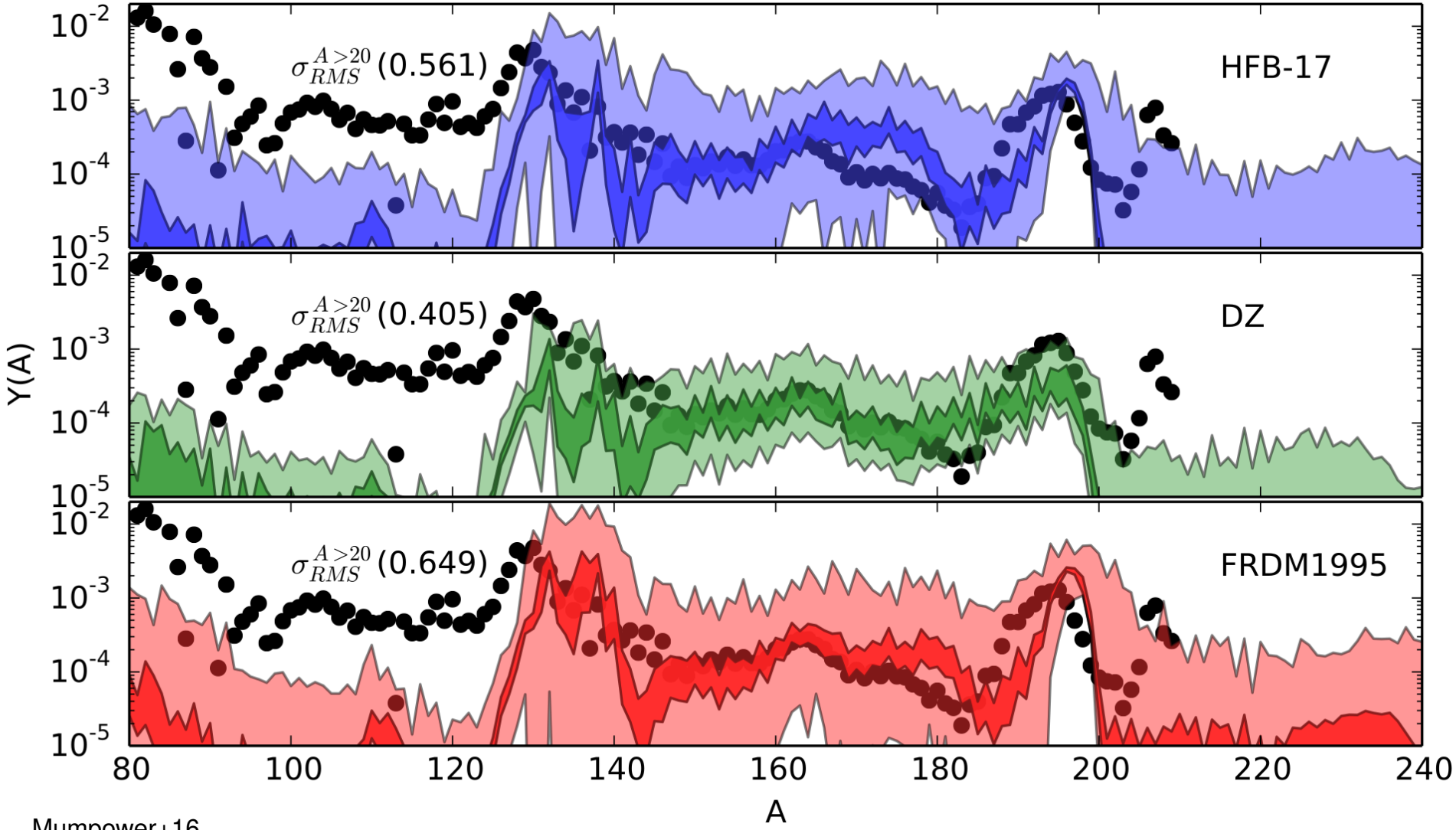


Figure credit: F. Foucart

BHNS: Final abundances vs. neutrino luminosity



Uncertainties



Mumpower+16

Conclusions

- r-Process produces about half of heavy elements
- Nuclear reaction network calculations require lots of nuclear data
- SkyNet is an open source reaction network for r-process calculations
- Tidal tail ejecta from neutron star mergers (NS-NS and BH-NS) robustly makes full r-process
- Disk outflow may or may not make full r-process
- Lifetime of hypermassive neutron star might can affect nucleosynthesis
- Uncertainties in nuclear data can produce large uncertainties in network calculations

Extra slides

Nuclear reaction network

Abundance: Let n_i be the number density of the nuclide of species i (e.g. ^{12}C, ^{56}Fe, ^{197}Au), then the abundance Y_i is

$$Y_i = \frac{n_i}{n_B}, \tag{4}$$

where n_B is the number density of baryons (total number conserved).

Composition: Set of abundances denoted by $\vec{Y}(t)$

Goal: Compute $\vec{Y}(t)$ for a given thermodynamic history

Ingredients

- Initial composition $\vec{Y}(t = 0)$
- Thermodynamic history $T(t)$ and $\rho(t)$
- Time derivatives of abundances $\dot{Y}_i$

Nuclear reaction network

Initial composition: Assume Nuclear Statistical Equilibrium (NSE) at some initial electron fraction Y_e, temperature, and entropy per baryon

Time derivatives of abundances: Let's consider a few reactions involving ^{197}Au:

Reaction	Forward rate	Reverse rate
$^{197}\mathrm{Pt} \rightarrow {}^{197}\mathrm{Au}$	λ_1	0
$\mathrm{n} + {}^{196}\mathrm{Au} \leftrightarrow {}^{197}\mathrm{Au}$	λ_2	λ_2'
$\mathrm{n} + {}^{197}\mathrm{Au} \leftrightarrow {}^{4}\mathrm{He} + {}^{194}\mathrm{Ir}$	λ_3	λ_3'

Where all rates $\lambda = \lambda(T, \rho)$. Then we have

$$\begin{aligned} \dot{Y}_{^{197}\mathrm{Au}} = \quad & \lambda_1 Y_{^{197}\mathrm{Pt}} \\ & + \lambda_2 Y_\mathrm{n} Y_{^{196}\mathrm{Au}} - \lambda_2' Y_{^{197}\mathrm{Au}} \\ & - \lambda_3 Y_\mathrm{n} Y_{^{197}\mathrm{Au}} + \lambda_3' Y_{^{4}\mathrm{He}} Y_{^{194}\mathrm{Ir}} \\ & + \cdots \end{aligned} \tag{5}$$

Nuclear reaction network

In general, for species i we have

$$\dot{Y}_i(t) = \sum_\alpha \lambda_\alpha(T,\rho) N_i^\alpha \prod_{m\in\mathcal{R}_\alpha} Y_m(t) = \dot{Y}_i(\vec{Y}, T, \rho), \tag{6}$$

where α runs over all reactions, $\lambda_\alpha(T,\rho)$ is the reaction rate, N_i^α is the number of i created/destroyed, and $\mathcal{R}_\alpha$ is the set of reactants of reaction α (with duplicates).

This is a big **system of coupled, non-linear ODEs**. It is usually very stiff, so use implicit method

$$\dot{\vec{Y}}(t+\Delta t) = \frac{\vec{Y}(t+\Delta t) - \vec{Y}(t)}{\Delta t} = \dot{\vec{Y}}(\vec{Y}(t+\Delta t), T, \rho). \tag{7}$$

Write as root finding problem in $\vec{X} = \vec{Y}(t+\Delta t)$

$$0 = \dot{\vec{Y}}(\vec{X}, T, \rho) - \frac{\vec{X} - \vec{Y}(t)}{\Delta t}. \tag{8}$$

Solve using iterative Newton–Raphson method, which requires a sparse matrix solver for Jacobian matrix

$$J_{ij} = \frac{\partial \dot{Y}_i}{\partial Y_j} - \frac{\delta_{ij}}{\Delta t}. \tag{9}$$

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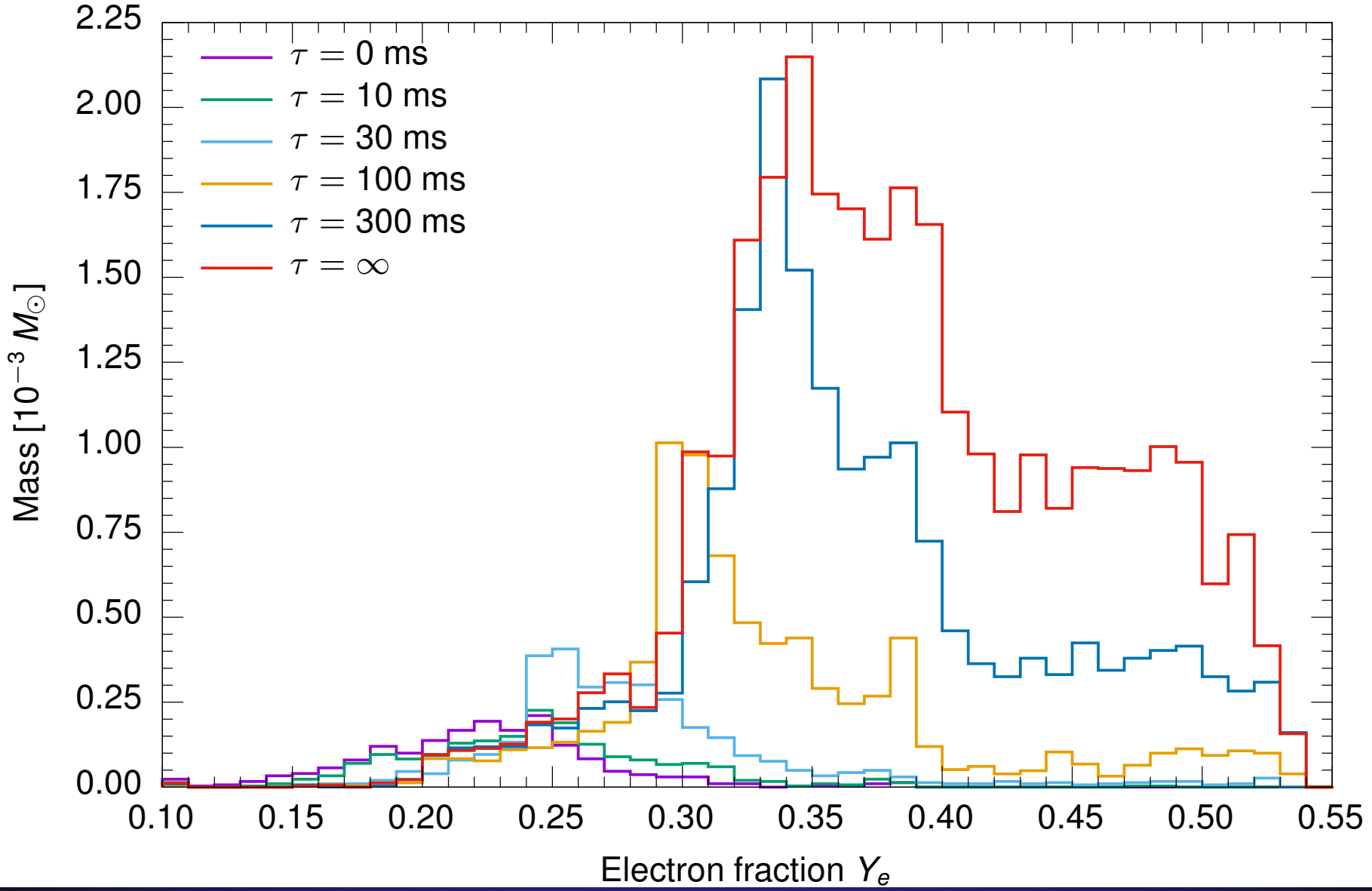
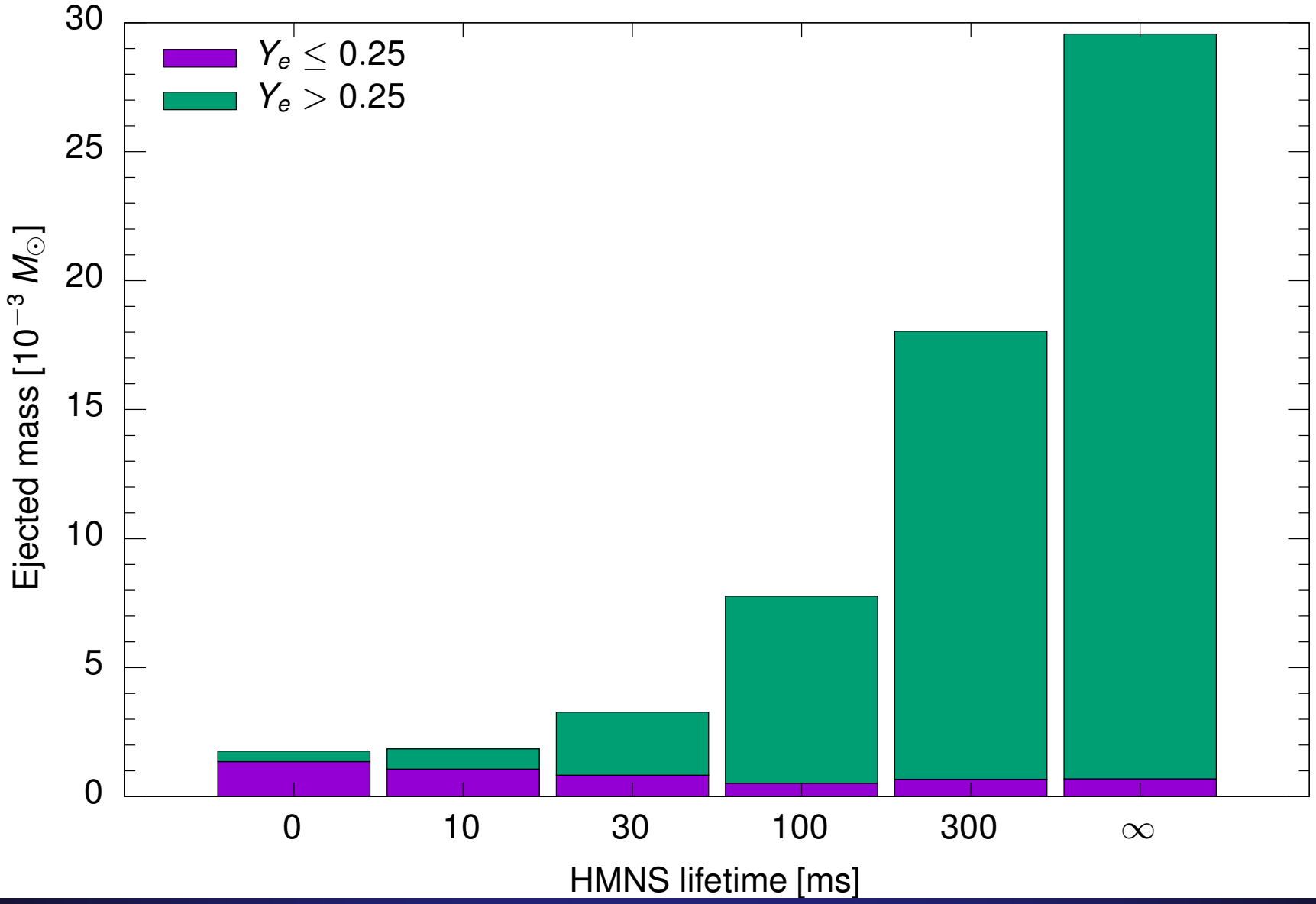
HMNS: Electron fraction distribution



HMNS: Ejected mass



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