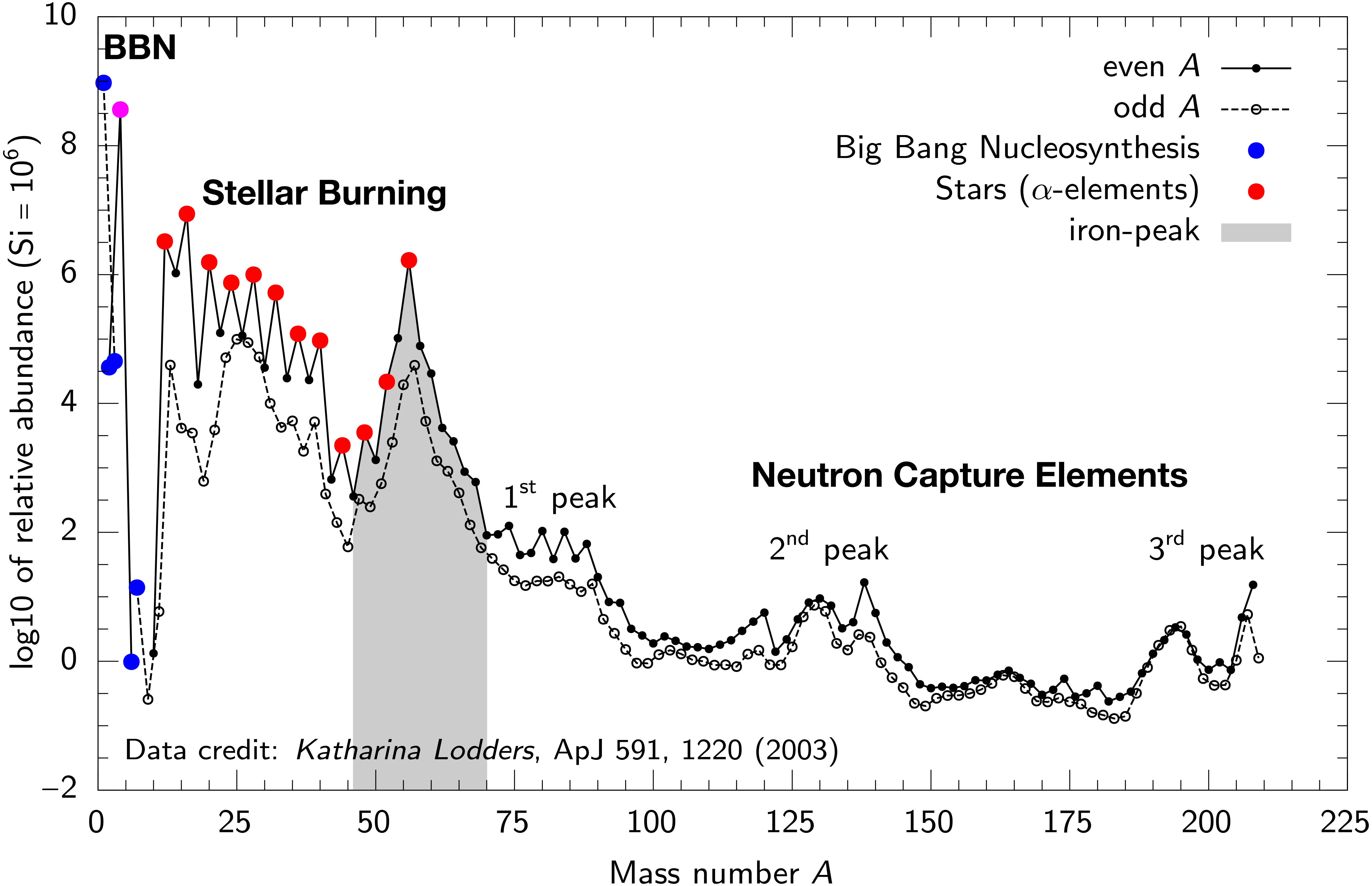
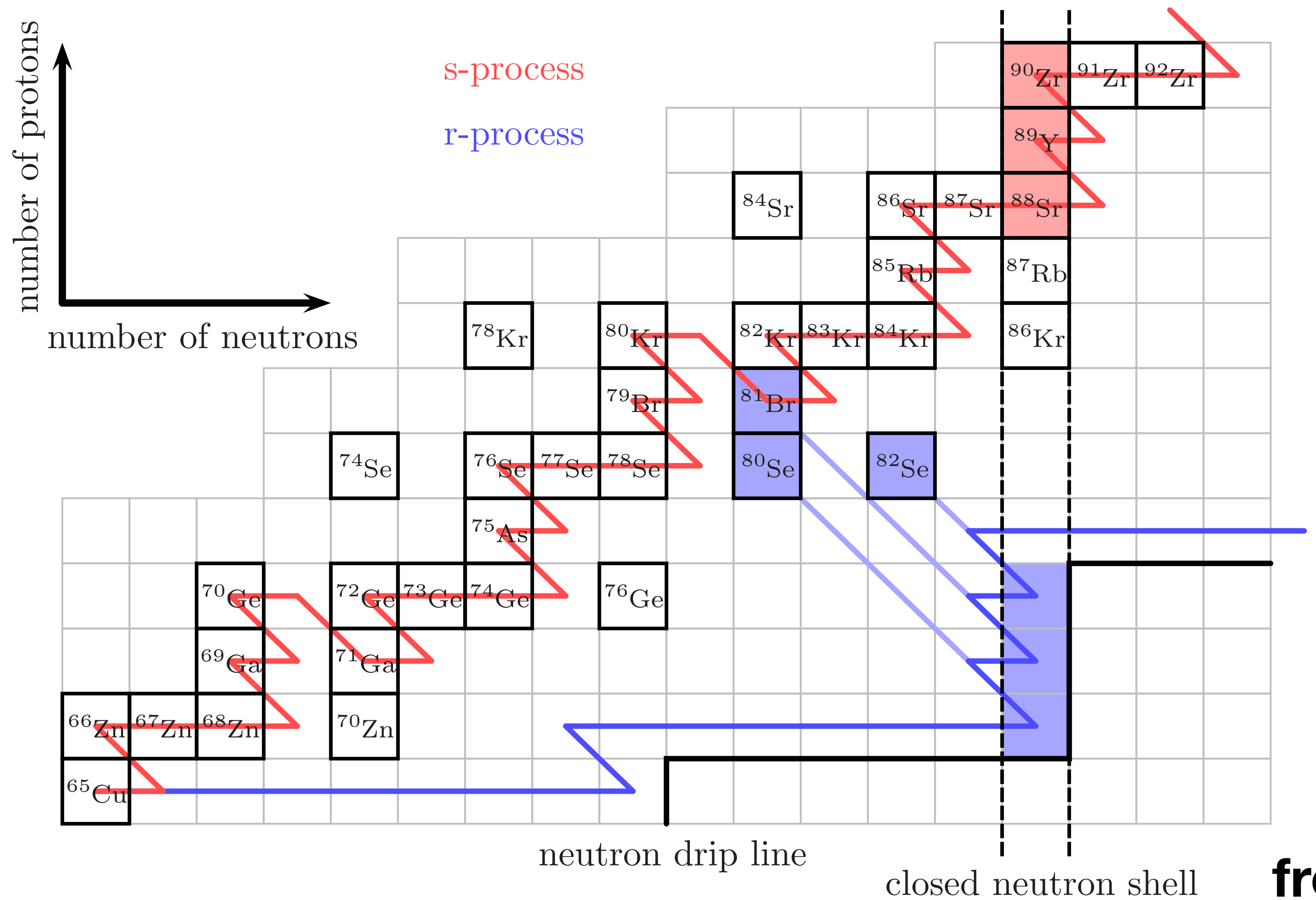
The r-Process and Weak Interactions in Neutron Star Mergers

Luke Roberts, NSCL



BBN
Stellar Burning
Neutron Capture Elements
1st peak
2nd peak
3rd peak
even A
odd A
Big Bang Nucleosynthesis
Stars (α-elements)
iron-peak
Data credit: Katharina Lodders, ApJ 591, 1220 (2003)
log10 of relative abundance (Si = 10^6)
Mass number A
10
8
6
4
2
0
−2
0
25
50
75
100
125
150
175
200
225

Capturing Neutrons



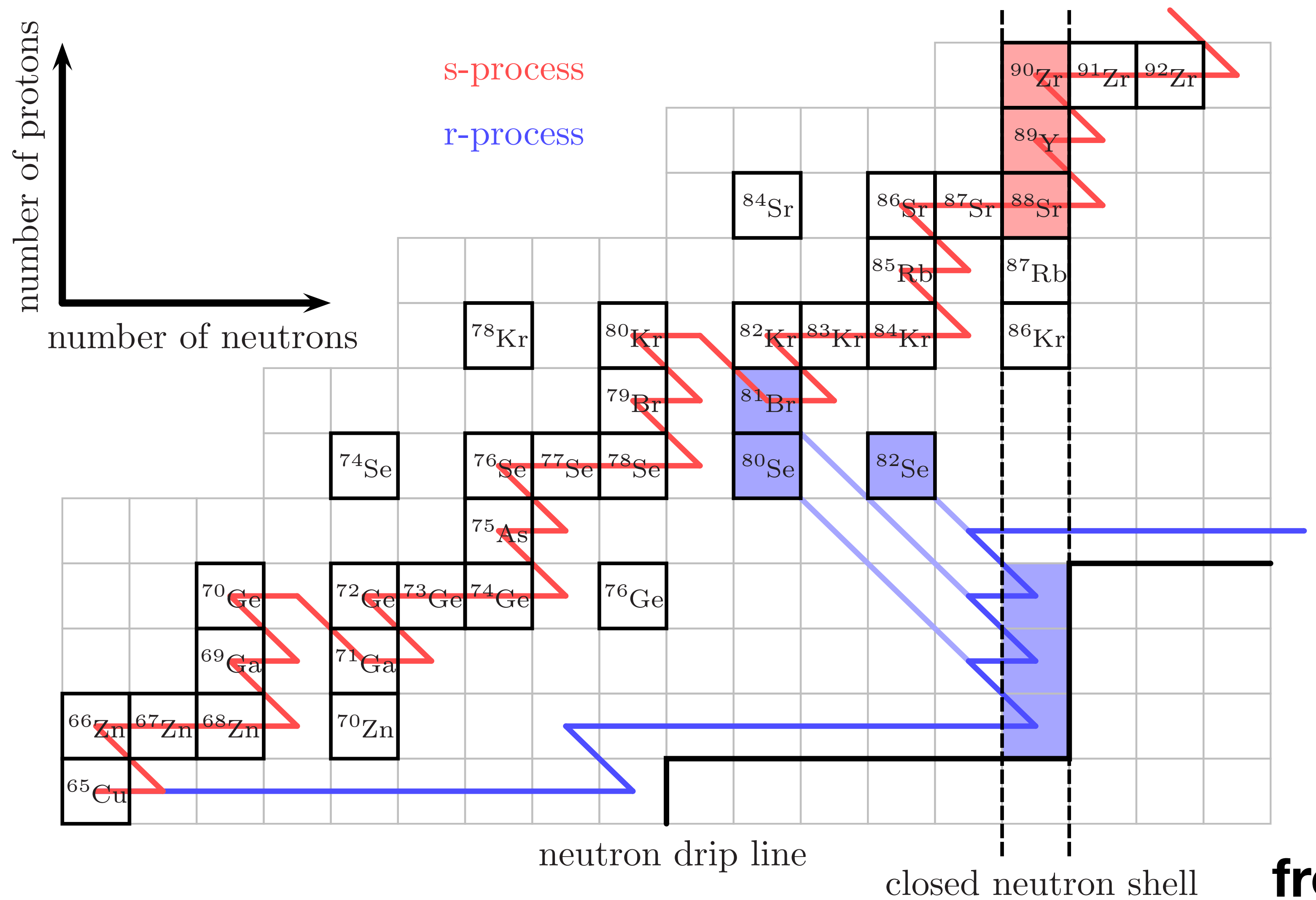
from J. Lippuner

Produce elements beyond iron by series of neutron captures followed by beta-decays:

$$(A, Z) + n \leftrightarrow (A+1, Z) + \gamma$$

$$(A, Z) \rightarrow (A, Z+1) + \bar{\nu}_e + e^-$$

Capturing Neutrons



from J. Lippuner

Two (maybe three) ways to do this:

r-process		**s-process**
$\tau_n \ll \tau_{\beta^-}$	**or**	$\tau_n \gg \tau_{\beta^-}$

(there is also evidence for a possible i-process)

Capturing Neutrons

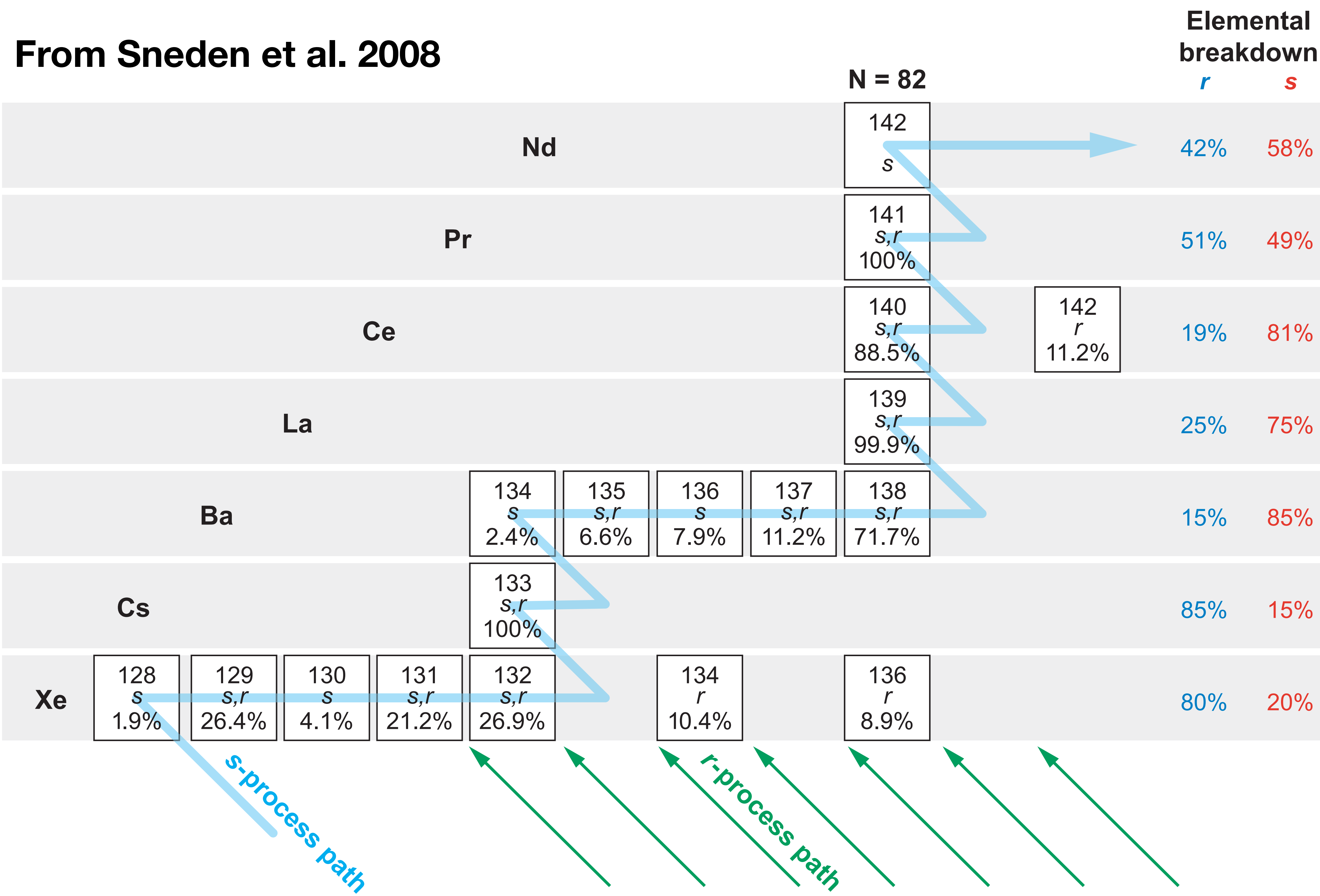
	s-process	r-process
mechanism	neutron capture, β^- decay	No Coulomb barrier!
τ_n	$10^2 - 10^5$ yr	$\ll \tau_{\beta-}$
$\tau_{\beta-}$	$\ll \tau_n$	$0.01 - 10$ s
site	AGB Stars inside massive stars	supernovae? NS-NS/BH mergers?
neutron source	$^{13}\text{C} + {^4}\text{He} \to {^{16}}\text{O} + \text{n}$ $^{22}\text{Ne} + {^4}\text{He} \to {^{25}}\text{Mg} + \text{n}$	
path	valley of stability	neutron drip line
peaks*	$A = 88,\ 138,\ 208$ strontium, barium, lead	$A = 80,\ 130,\ 194$ selenium, xenon, platinum

* due to closed neutron shells at $N = 50,\ 82,\ 126$

from J. Lippuner

Separating s and r

From Sneden et al. 2008

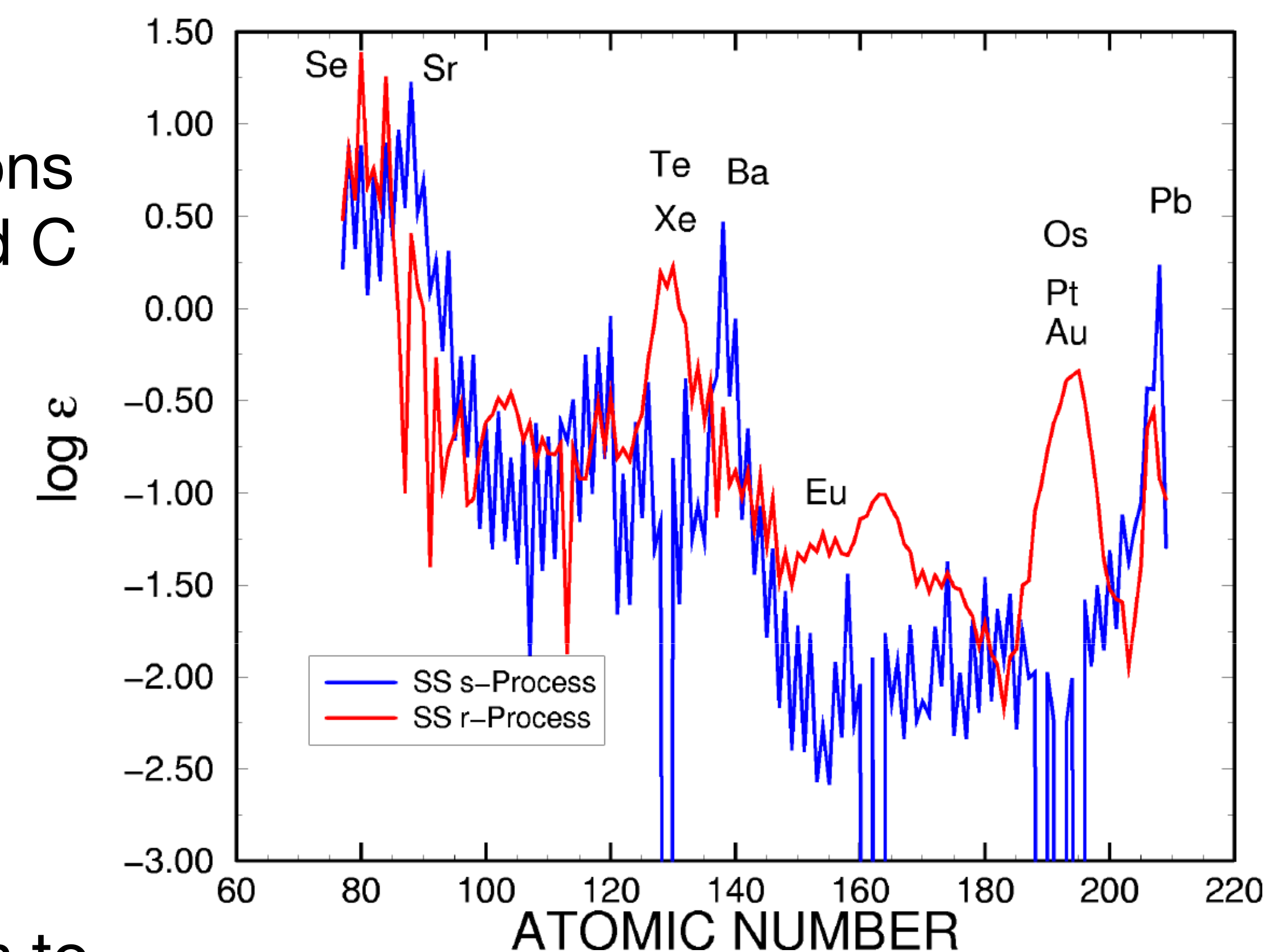


The s-process

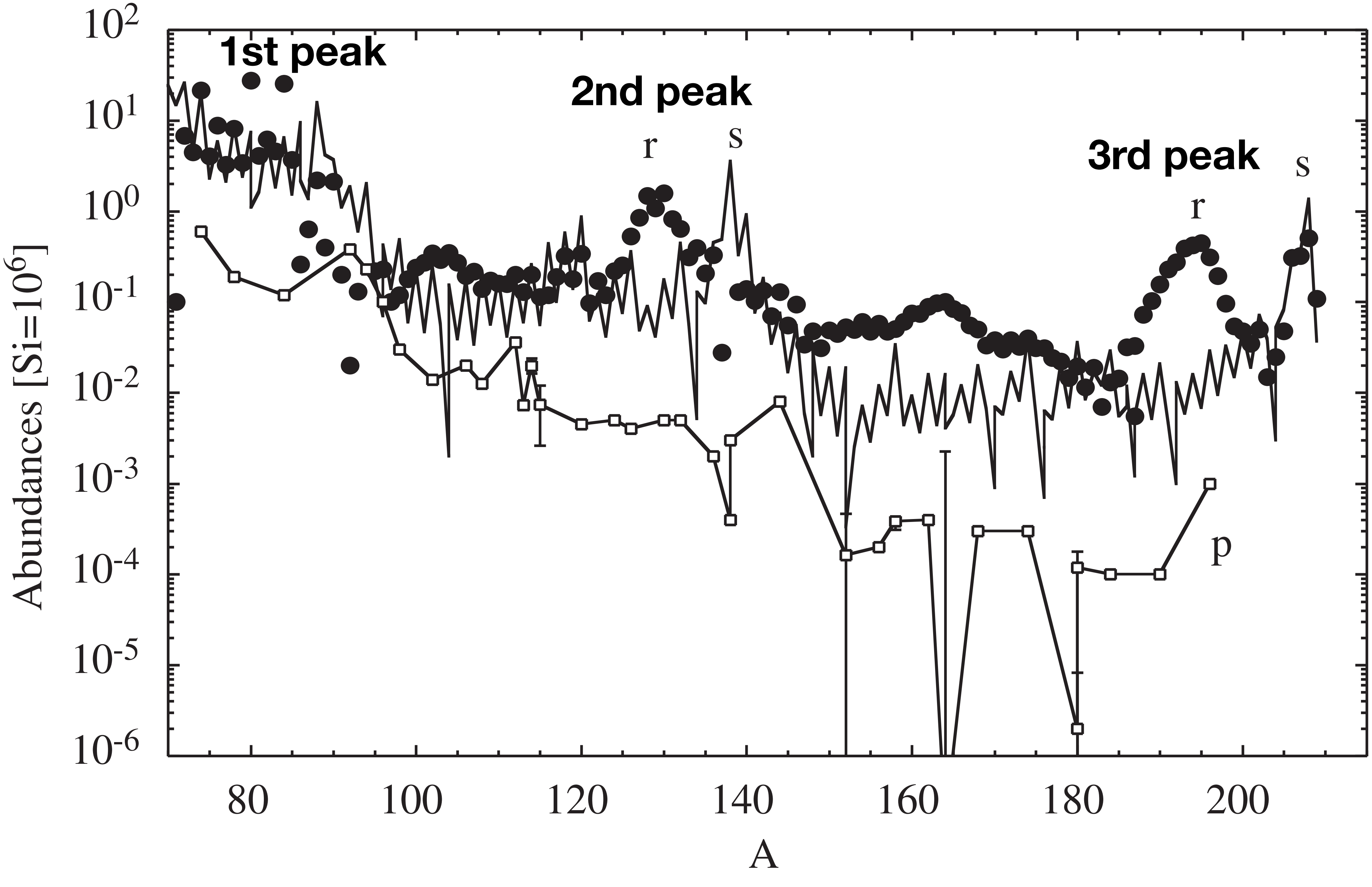
- Secondary process, requires pre-existing seed nuclei to capture neutrons on
- Neutrons slowly produced by reactions in both AGB stars and during He and C burning in massive stars

$$^{13}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \mathrm{n}$$
$$^{22}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{25}\mathrm{Mg} + \mathrm{n}$$

- Flow is mainly sensitive to neutron capture cross sections
- With accurate cross sections, can determine the s-process contribution to the solar abundances

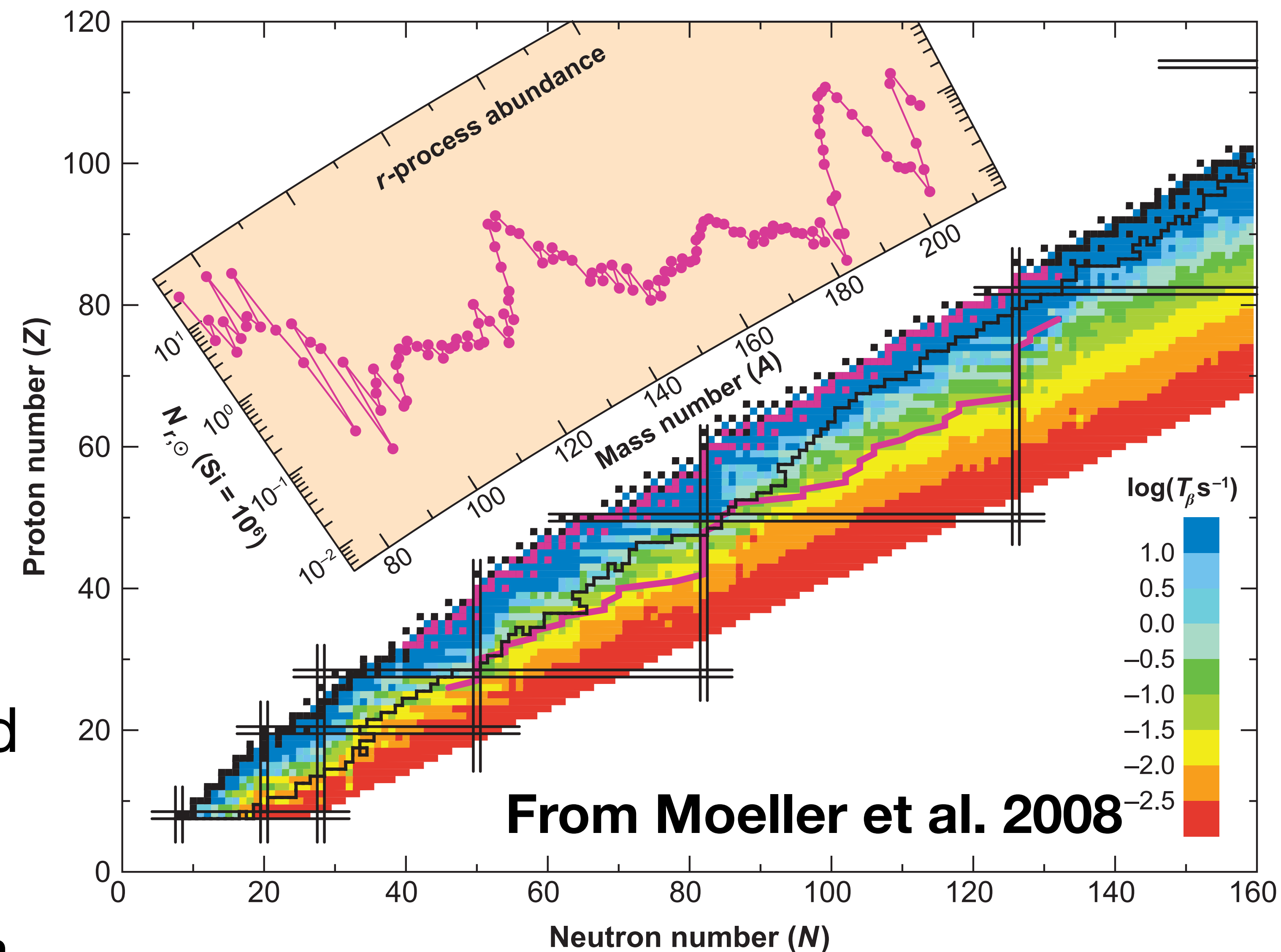


Solar r-process residuals



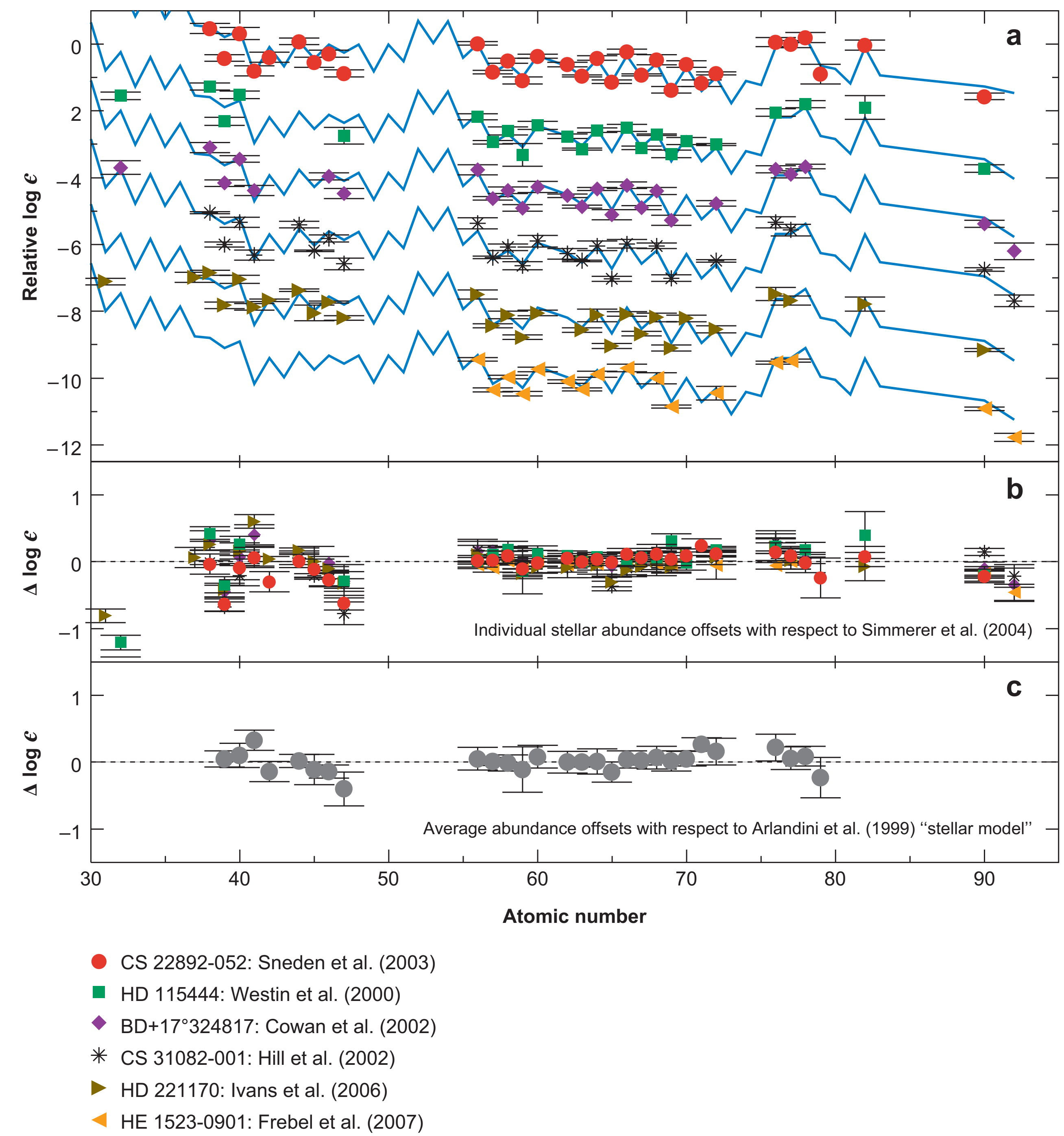
Solar r-process residuals

- Material builds up at neutron closed shells during neutron capture flow
- When neutrons are exhausted, material stays at the same mass number and decays back to stability
- Mass at which flow intersects closed shells is where peaks end up in the r-process distribution
- Different positions of peaks from s-process since intersection points are different, lower mass for r-process



r-process in the galaxy

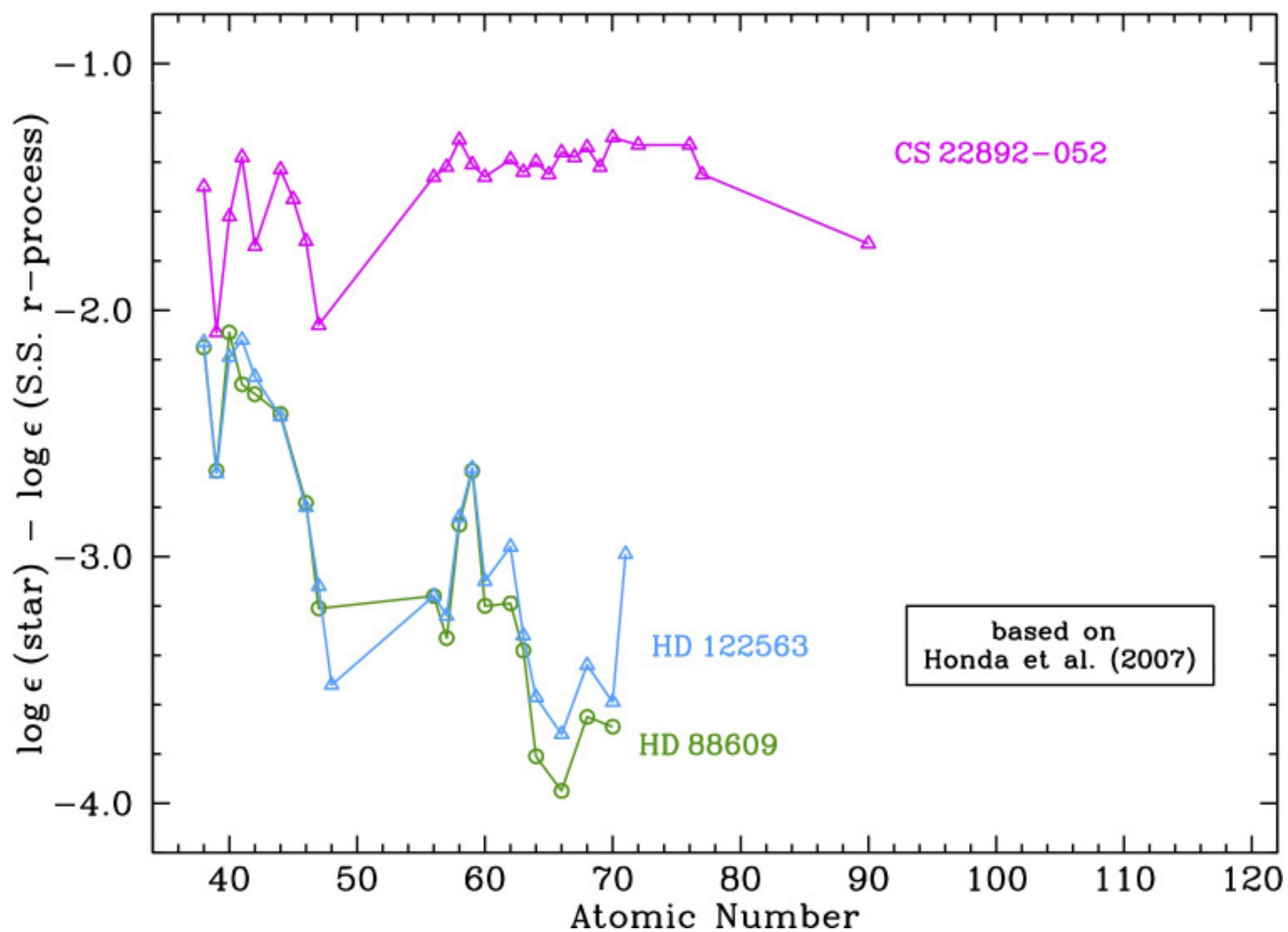
- Can also find low metallicity halo stars with significant enhancement of neutron capture nuclei
- In many stars, the pattern of second and third peak nuclei is very similar to the pattern of r-process residuals, suggesting they only have r-process enrichment
- There is more variation in the first peak r-process abundances among low metallicity halo stars



r-process in the galaxy

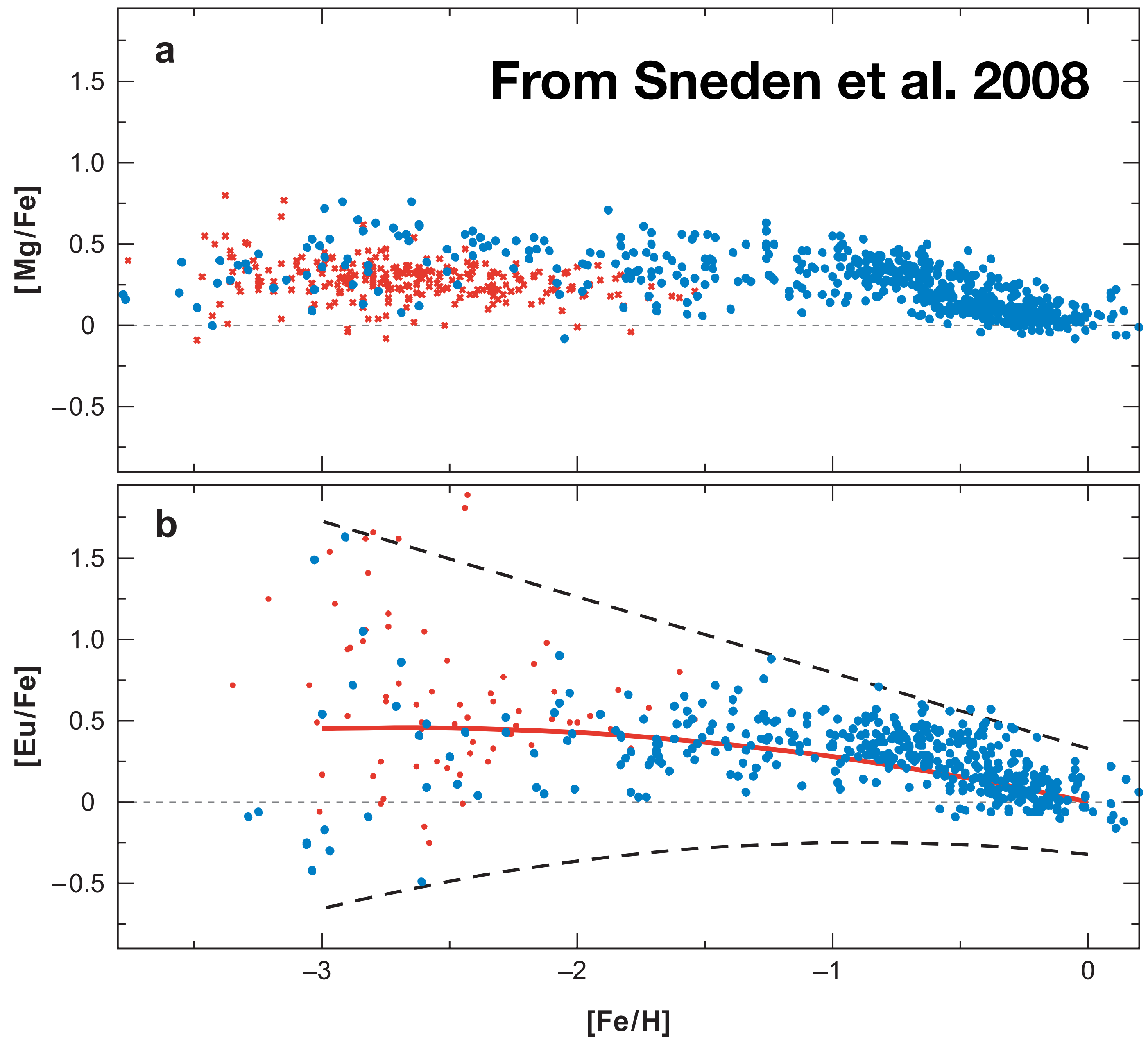
- Also can find some low-metallicity halo stars that are enriched in neutron capture elements that have an abundance pattern that is significantly different than the solar r-process abundance pattern

- Suggests there might need to be two r-process sites:
  - main r-process (up to third peak)
  - weak r-process (dominated by Sr, Y, Zr)



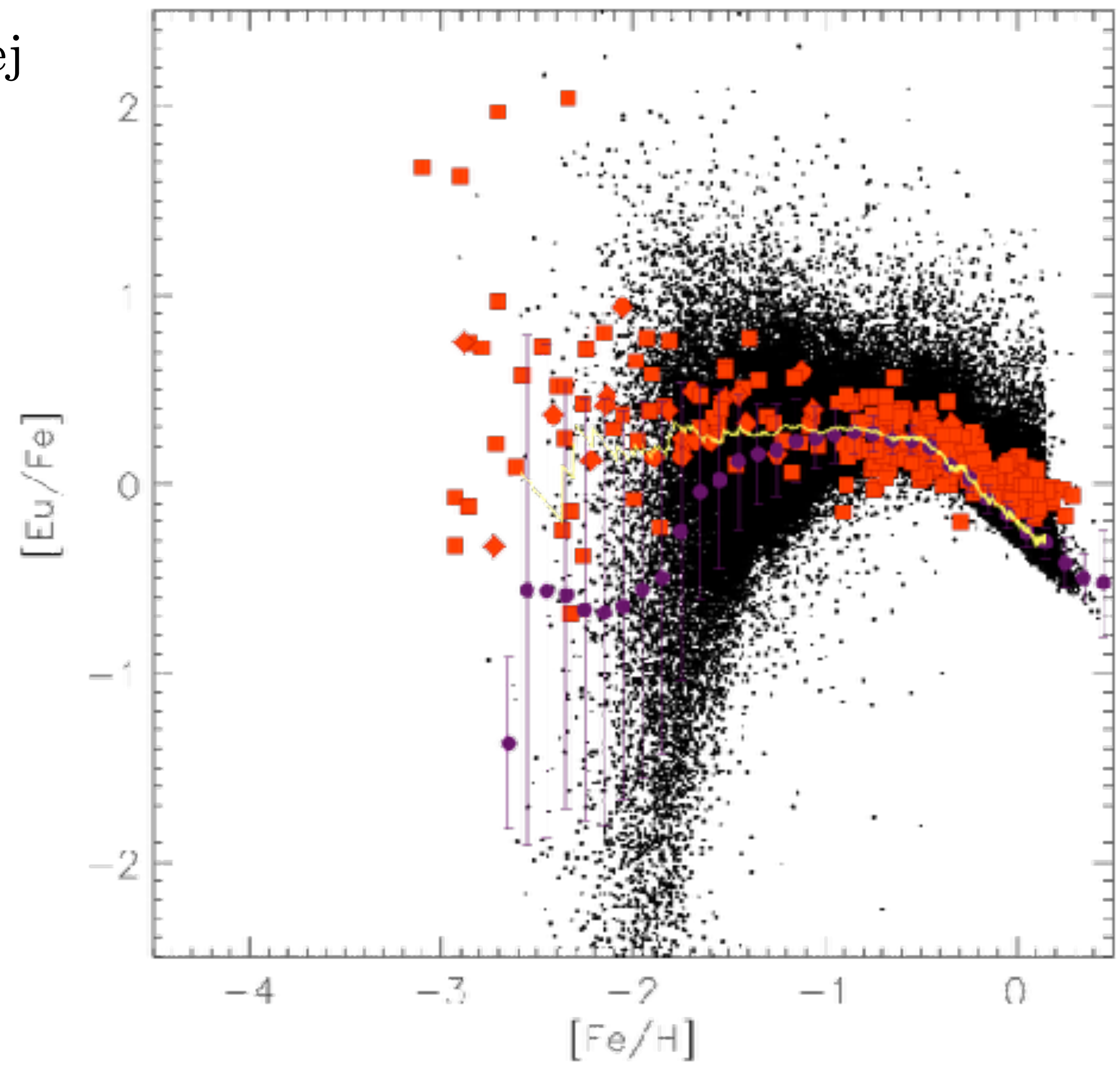
r-process in the galaxy

- r-process enhancement present at very low metallicity, similar to the beginning of enrichment of the ISM by supernovae
- Suggests that r-process must be a primary process
- Maybe an argument in favor of being associated with supernovae



Galactic r-process budget

$$
\begin{aligned}
M_r &\approx t_{MW} \cdot R_{\rm merger} \cdot M_{\rm ej} \\
t_{MW} &\sim 10^{10}\,{\rm yr} \\
R_{\rm merger} &\sim 10^{-4}\,{\rm yr}^{-1} \\
M_{\rm ej} &\sim 0.01\,M_\odot \\
M_{\rm r,merger} &\sim 10^4\,M_\odot \\
\\
M_{\rm r,galaxy} &\sim 10^4\,M_\odot
\end{aligned}
$$



from Argast et al. 2004

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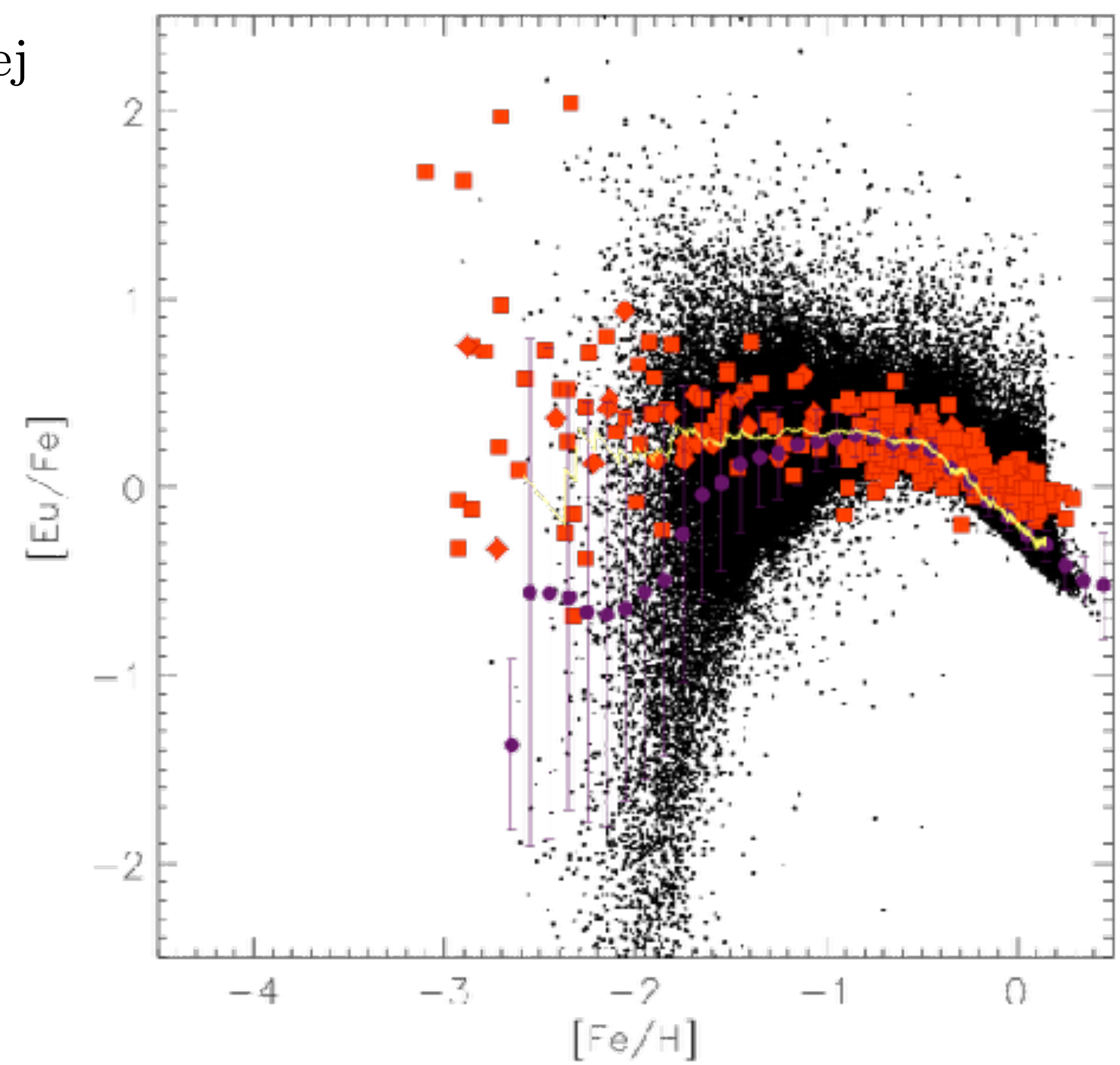
$$

but...

$$t_{coalesce} \approx 10^{6-8}\ yr$$

$$M_{eject} \sim 10^{-2} M_\odot$$



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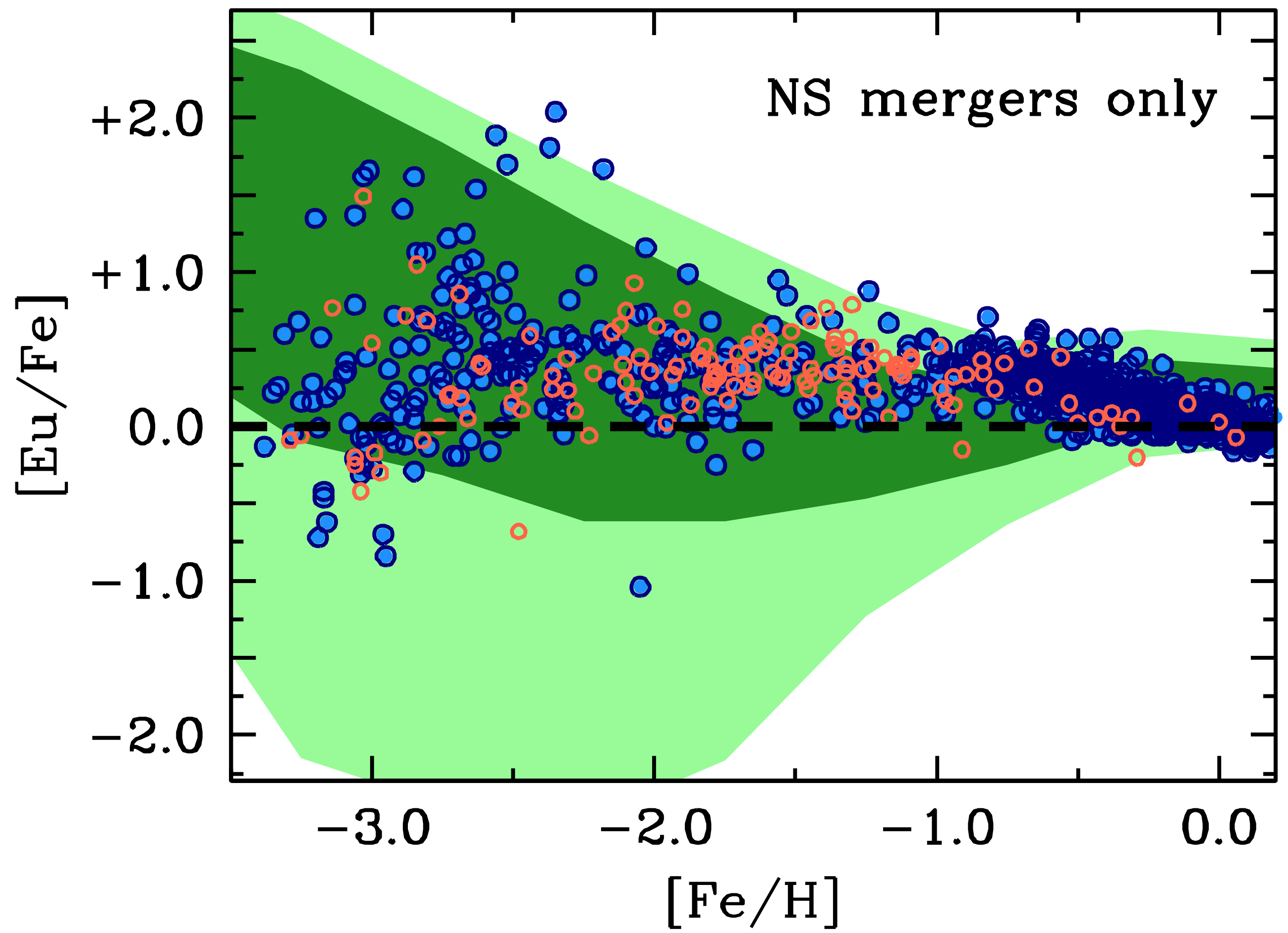
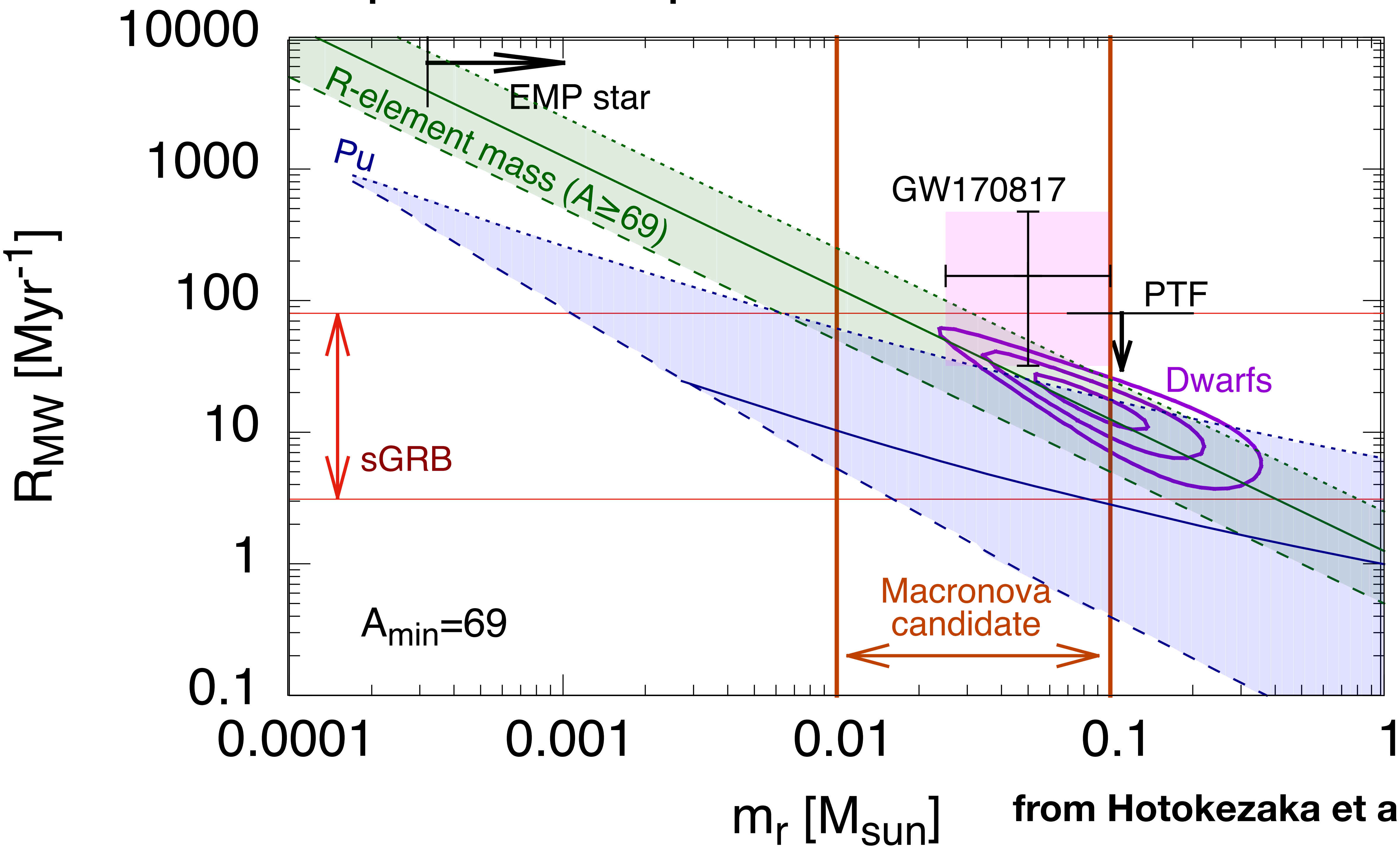


from Shen et al. 2014

Galactic r-process budget

Supernova rate is up here



from Hotokezaka et al. (2017)

r-process conditions

Some Nomenclature

Abundance: $$Y_i = \frac{n_i}{n_b}$$

Number of nuclei of species *i* per baryon in a fluid

Mass fraction: $$X_i = \frac{A_i n_i}{n_b}$$

Fraction of baryons locked in nuclei of species *i*

$$\Rightarrow \quad \sum_i X_i = 1$$

Electron fraction: $$Y_e = \frac{n_{e^-} - n_{e^+}}{n_b}$$

Net number of electrons per baryon

Charge Neutrality $\quad \Rightarrow \quad Y_e = \sum_i Z_i Y_i$

Initial Conditions for the r-process

- In most r-process scenarios, material starts at high density and high temperature
- Therefore, nuclear statistical equilibrium (NSE) holds, where forward and reverse strong reactions are balanced

$$\mu_{(A,Z)} = (A - Z)\mu_n + Z\mu_p$$

Nuclei can be treated as Boltzmann particles:

$$\mu_{(A,Z)} = m_{(A,Z)} + T \ln \left[\frac{n_b Y_{(A,Z)}}{G_{(A,Z)}(T)} \left(\frac{2\pi\hbar^2 c^2}{m_{(A,Z)} T} \right)^{3/2} \right]$$

Initial Conditions for the r-process

$$\mu_{(A,Z)} = (A-Z)\mu_n + Z\mu_p$$

$$\Longrightarrow \qquad Y_{(A,Z)} \approx \frac{G_{(A,Z)}A^{3/2}}{2^A}\left(\frac{n_b}{n_Q}\right)^{A-1} Y_n^N Y_p^Z \exp[BE_{(A,Z)}/T]$$

where

$$BE_{(A,Z)} = (A-Z)m_n + Zm_p - m_{(A,Z)}$$ **and** $$n_Q = \left(\frac{m_n T}{2\pi\hbar^2 c^2}\right)^{3/2}$$

Initial Conditions for the r-process

$$\mu_{(A,Z)} = (A-Z)\mu_n + Z\mu_p$$

$$\Longrightarrow \qquad Y_{(A,Z)} \approx \frac{G_{(A,Z)} A^{3/2}}{2^A} \left(\frac{n_b}{n_Q}\right)^{A-1} Y_n^N Y_p^Z \exp[BE_{(A,Z)}/T]$$

where

$$BE_{(A,Z)} = (A-Z)m_n + Zm_p - m_{(A,Z)}$$

and

$$n_Q = \left(\frac{m_n T}{2\pi\hbar^2 c^2}\right)^{3/2}$$

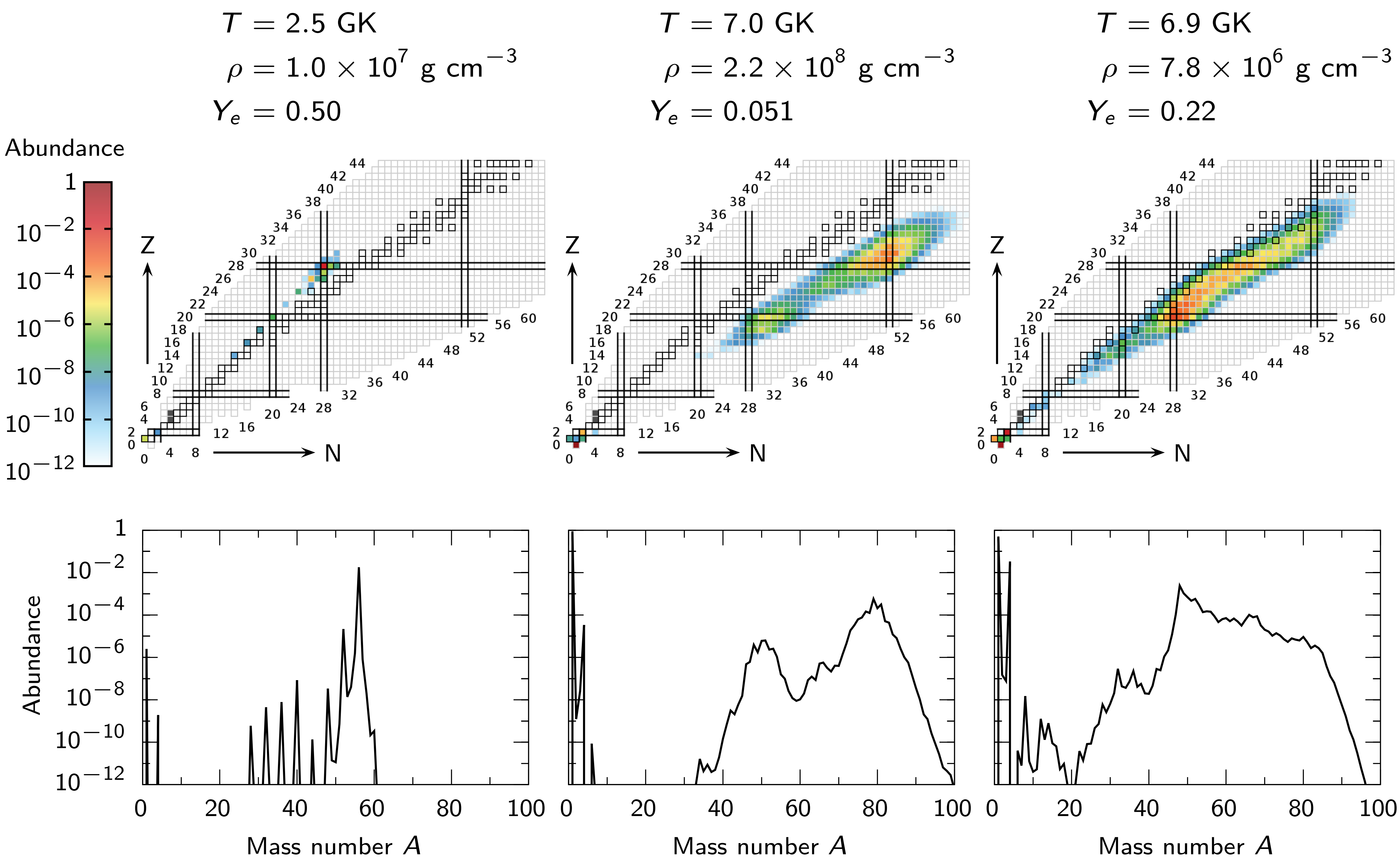
Baryon number conservation and charge neutrality give:

$$Y_e = \sum_i Z_i Y_i \qquad\qquad 1 = \sum_i A_i Y_i$$

So that

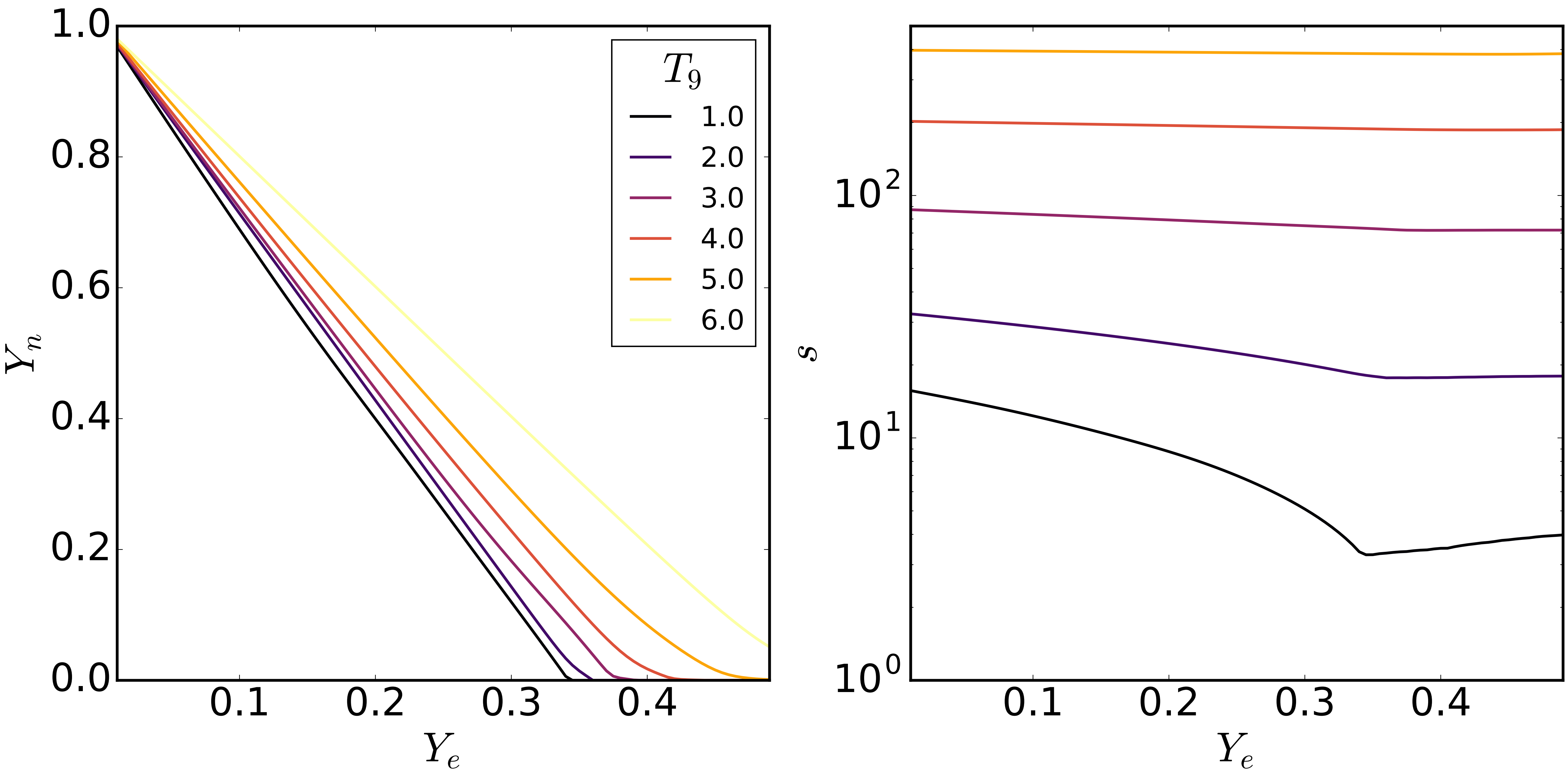
$$\boxed{Y_{(A,Z)} = Y_{(A,Z)}(n_b, Y_e, T)}$$

NSE



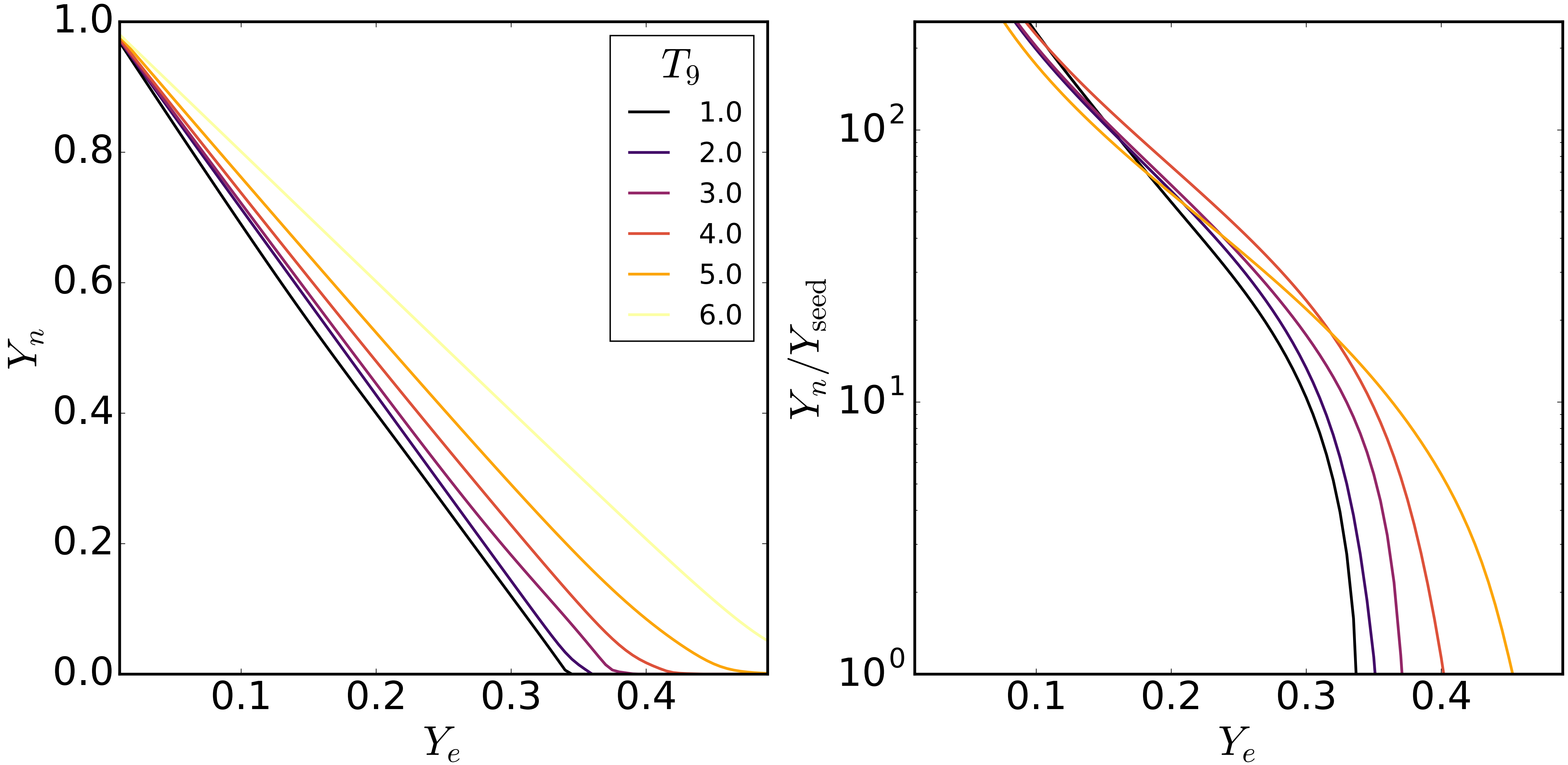
from J. Lippuner

NSE Neutron Fractions



Lower Y_e, higher s result in larger numbers of free neutrons in NSE

Neutron-to-Seed Ratio



The initial neutron-to-seed ratio is a useful metric for wether or not a complete r-process will occur

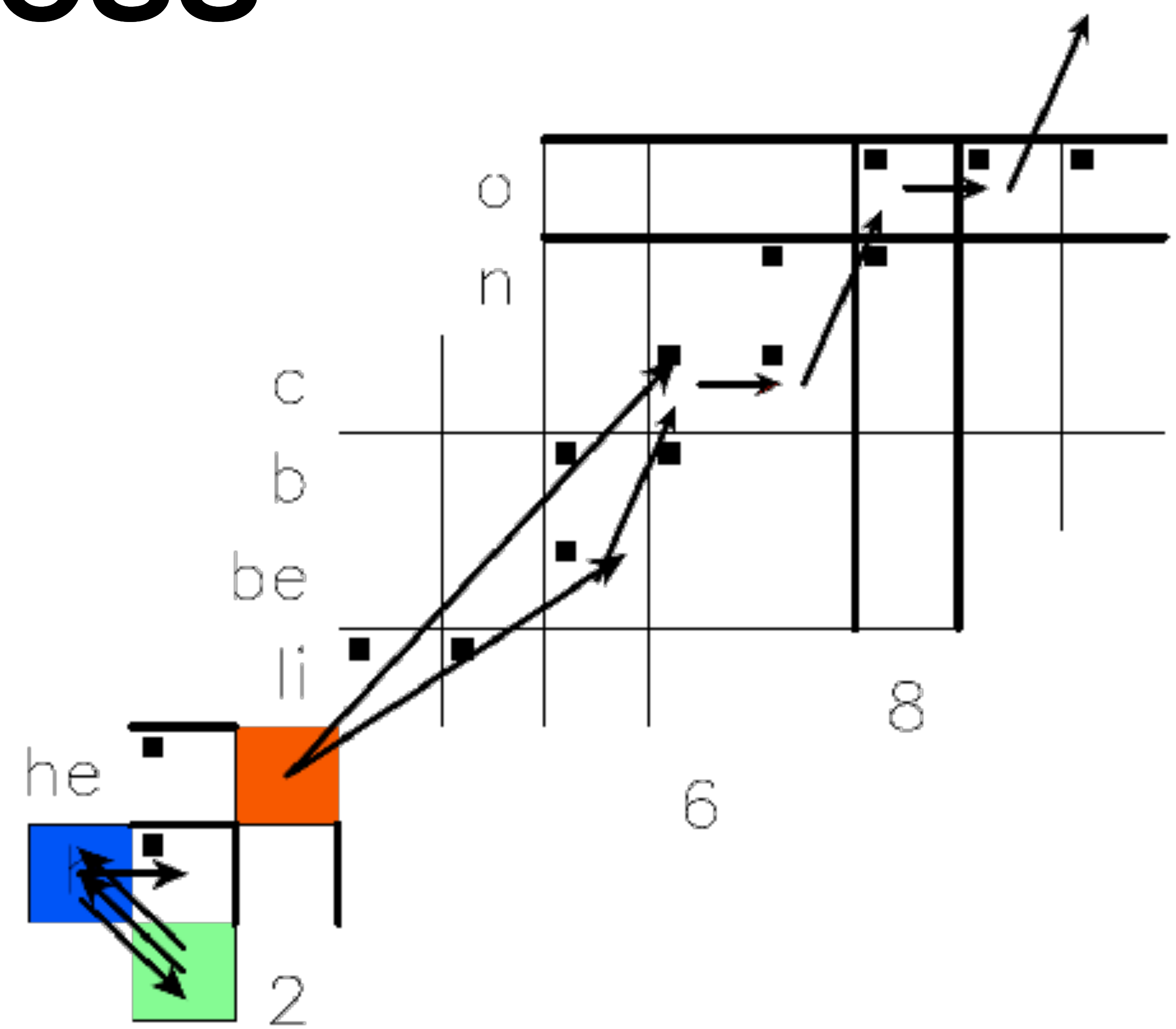
Initial Conditions for the r-process

- In high-entropy material, seeds may not form during NSE
- Instead left with alpha particles and neutrons
- Make seed nuclei via

$$3\alpha \rightarrow^{12} C \rightarrow \ldots$$

or

$$2\alpha + n \rightarrow^{9} Be$$
$$^{9}Be + \alpha \rightarrow n +^{12} C \rightarrow \ldots$$



$$\frac{dY_{\rm seed}}{dt} \propto \rho^3 Y_\alpha^3 Y_n \rightarrow \frac{N_n}{N_{\rm seed}} \propto \frac{s^3}{Y_e^3 \tau_d}$$

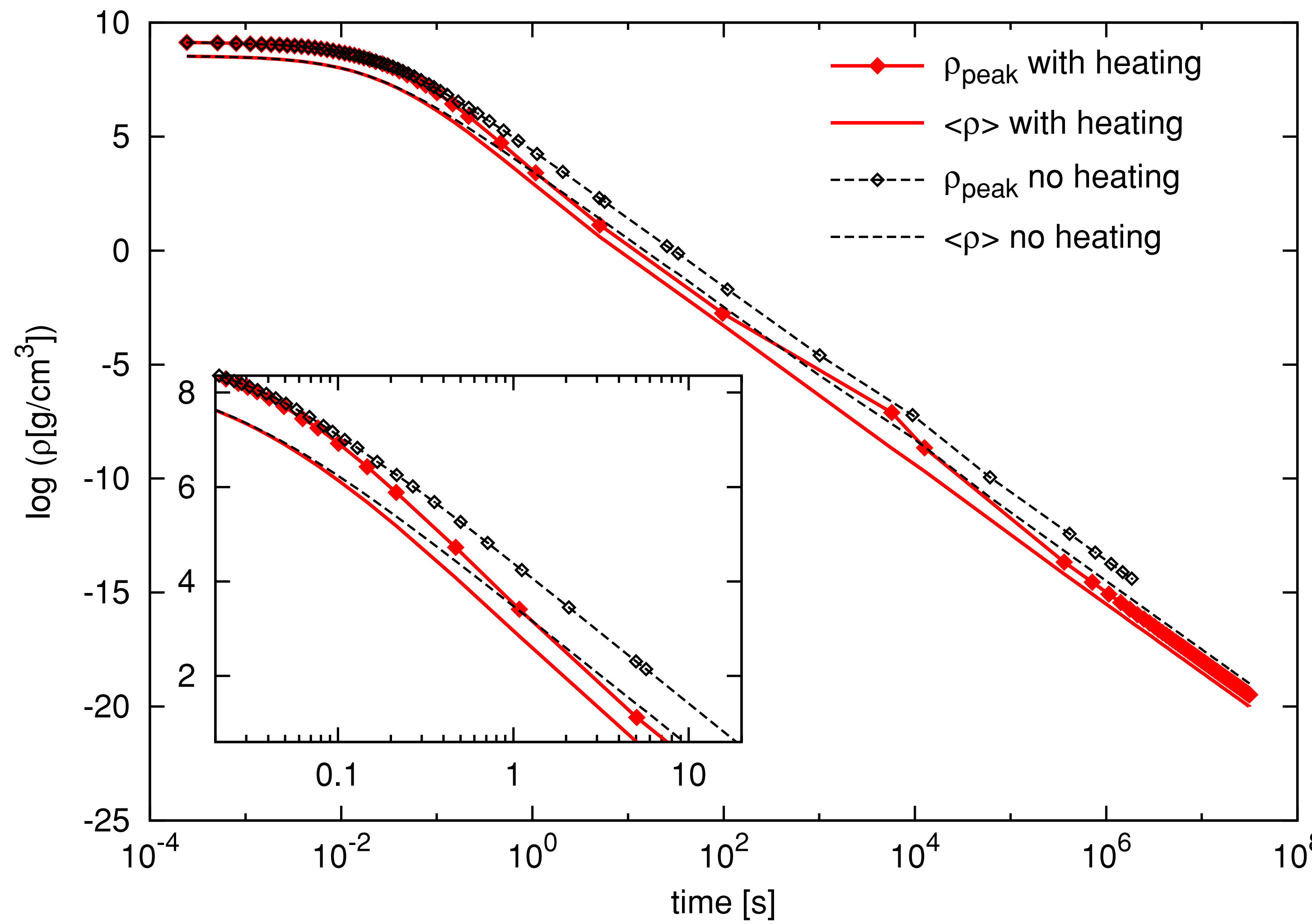
Nucleosynthesis is much more sensitive to the dynamics, but can make r-process nuclei for much higher Y_e

Calculating the r-process

- Time dependent thermodynamic conditions from simulations (if post-processing)
- By the time r-process starts, homologous expansion has set in with:

$$v \propto r$$

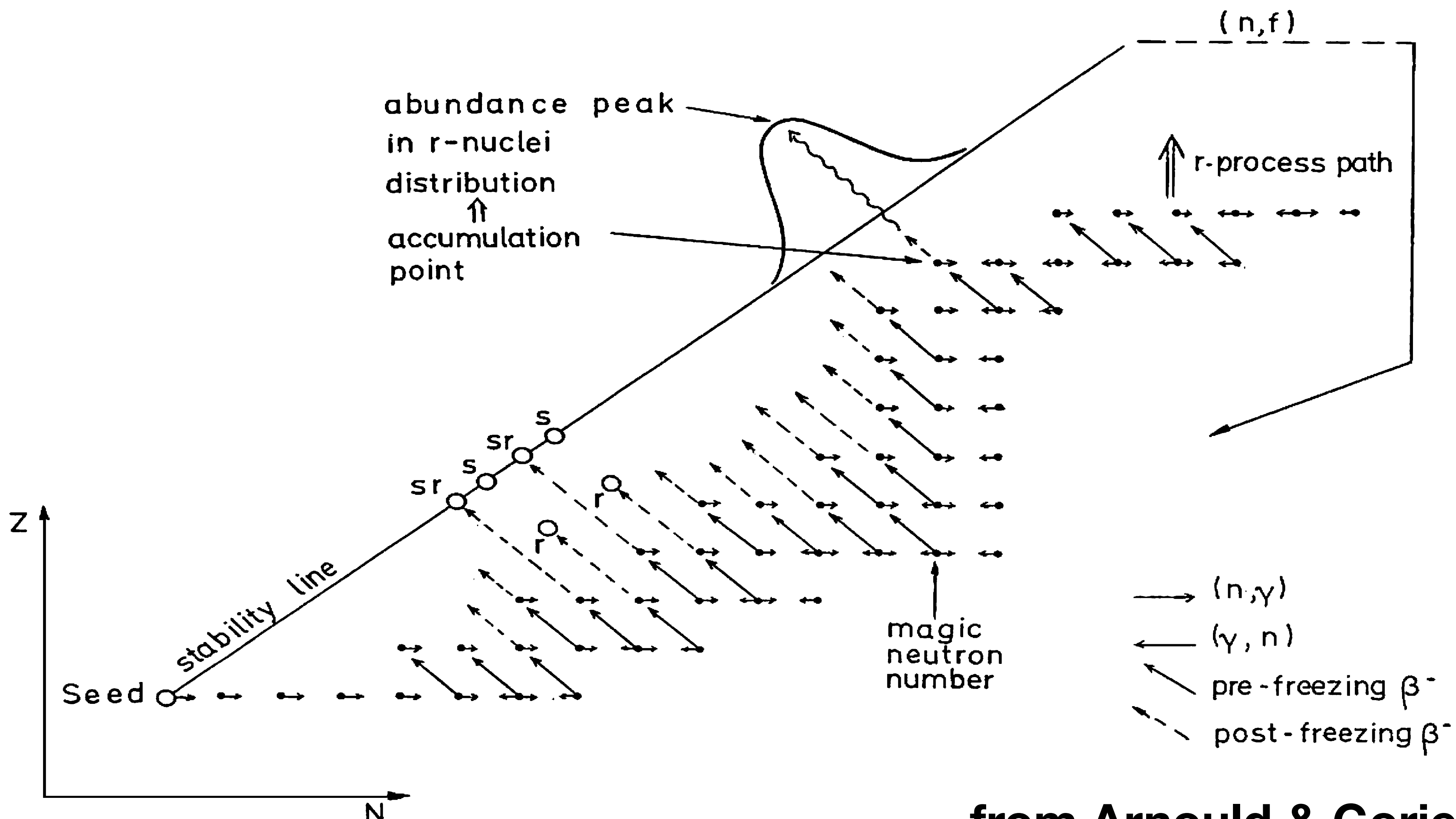
$$\Rightarrow \qquad \rho = \rho_0 \left(\frac{t}{t_0}\right)^{-3}$$



from Rosswog et al. (2014)

R-process Flow

$$
\begin{aligned}
\dot{Y}_{(A,Z)} &= n_b\langle\sigma v\rangle_{n+(A-1,Z)}Y_nY_{(A-1,Z)} - \lambda_{\gamma(A,Z)}Y_{(A,Z)} \\
&\quad -n_b\langle\sigma v\rangle_{n+(A,Z)}Y_nY_{(A,Z)} + \lambda_{\gamma(A+1,Z)}Y_{(A+1,Z)} \\
&\quad +\lambda_{\beta^-(A,Z-1)}Y_{(A,Z-1)} - \lambda_{\beta^-(A,Z)}Y_{(A,Z)}
\end{aligned}
$$



from Arnould & Goriely (2007)

Calculating the r-process

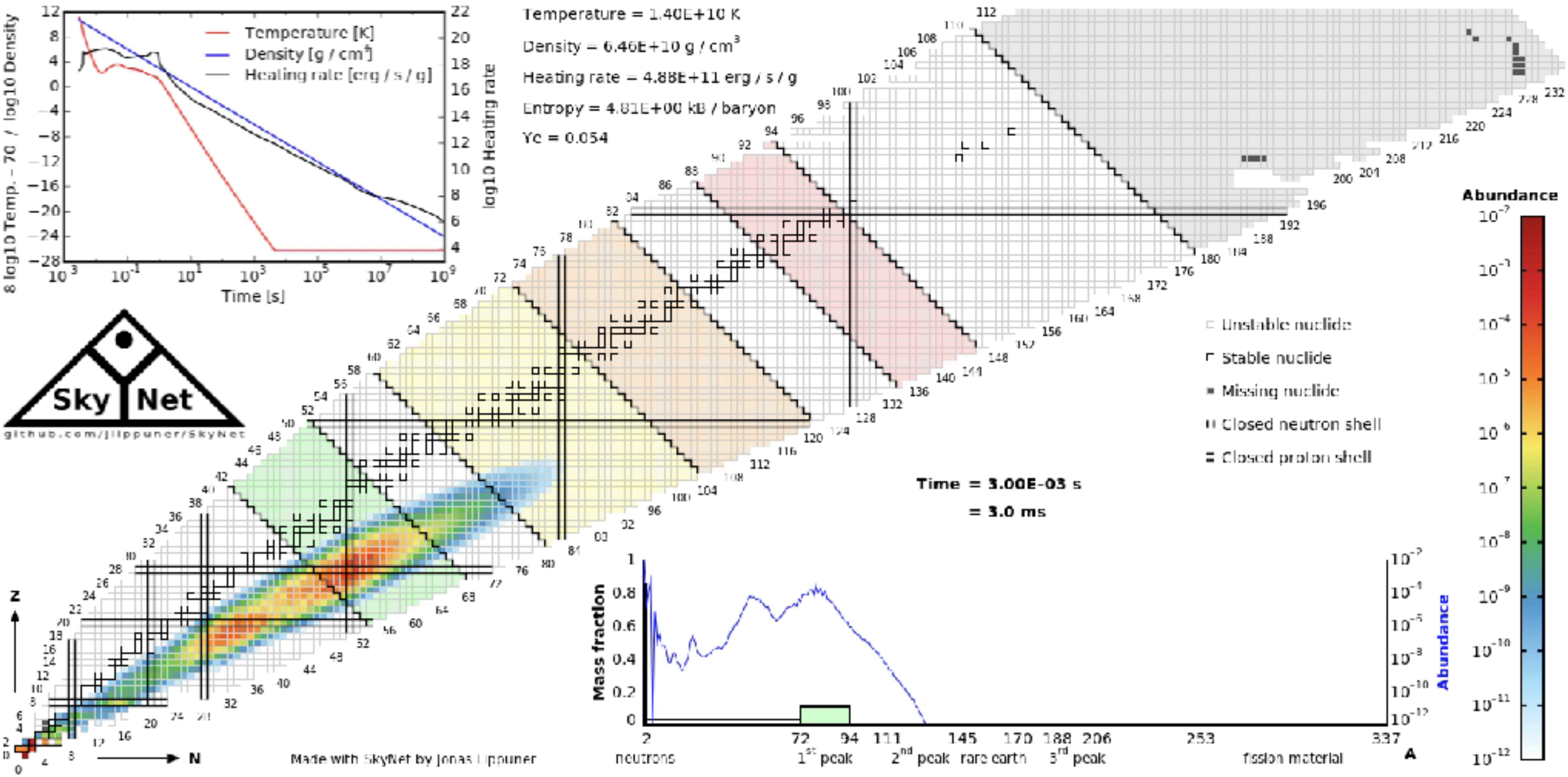
- Large, coupled system of stiff ODEs
- Need to employ implicit methods
- Input nuclear data:
  - masses
  - partition functions
  - beta-decay rates
  - neutron capture rates
  - fission rates
  - …
- Initial composition

$$\begin{aligned}\dot{Y}_{(A,Z)} &= n_b\langle\sigma v\rangle_{n+(A-1,Z)}Y_nY_{(A-1,Z)} - \lambda_{\gamma(A,Z)}Y_{(A,Z)} \\ &\quad -n_b\langle\sigma v\rangle_{n+(A,Z)}Y_nY_{(A,Z)} + \lambda_{\gamma(A+1,Z)}Y_{(A+1,Z)} \\ &\quad +\lambda_{\beta^-(A,Z-1)}Y_{(A,Z-1)} - \lambda_{\beta^-(A,Z)}Y_{(A,Z)}\end{aligned}$$

+ fission + electron capture + …

Velocity averaged cross-section:

$$\langle\sigma_\alpha v_{\rm rel}\rangle = \int_{[1]}\frac{f_1}{n_1}\int_{[2]}\frac{f_2}{n_2}v_{\rm rel}\sigma_\alpha$$



Temperature [K]
Density [g / cm³]
Heating rate [erg / s / g]
Time [s]
8 log10 Temp. − 70 / log10 Density
log10 Heating rate
Temperature = 1.40E+10 K
Density = 6.46E+10 g / cm³
Heating rate = 4.88E+11 erg / s / g
Entropy = 4.81E+00 kB / baryon
Ye = 0.054
Sky Net
github.com/jlippuner/SkyNet
Unstable nuclide
Stable nuclide
Missing nuclide
Closed neutron shell
Closed proton shell
Time = 3.00E-03 s
= 3.0 ms
Abundance
Z
N
Made with SkyNet by Jonas Lippuner
Mass fraction
Abundance
neutrons
1st peak
2nd peak
rare earth
3rd peak
fission material
A

Self-heating

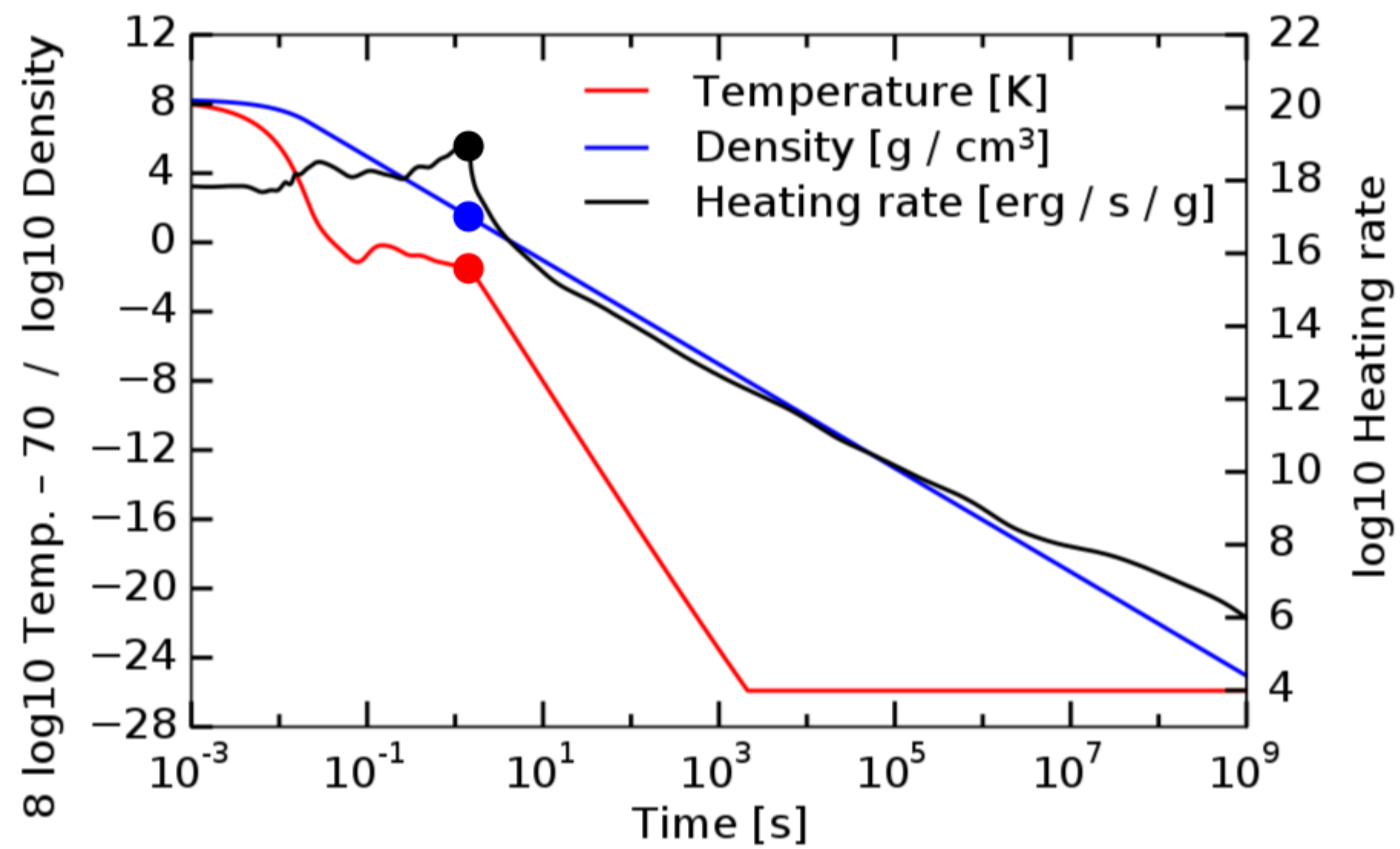
- Neutron captures and beta decays release rest-mass energy

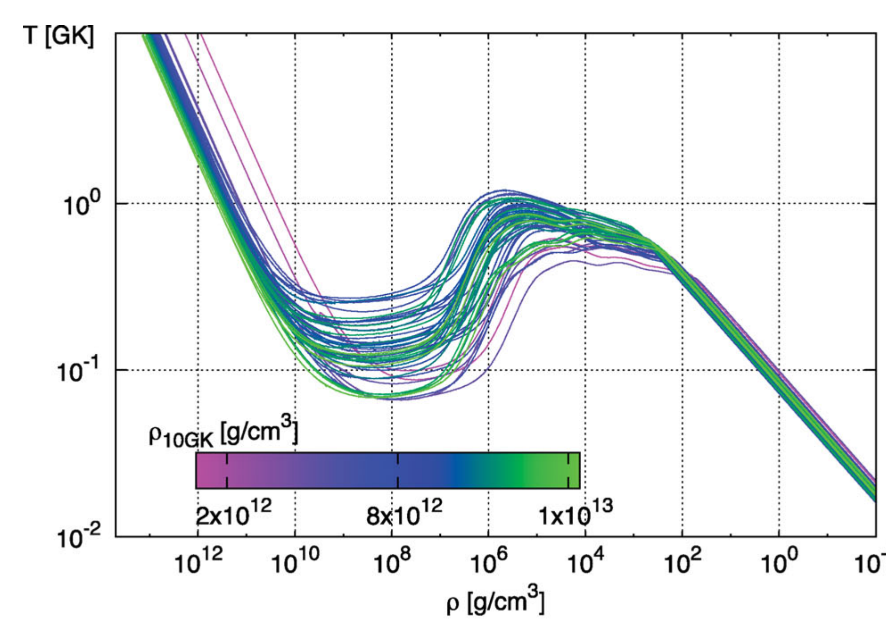
$$d\epsilon = dq_{\mathrm{ext}} - PdV = Tds - PdV + \sum_i \mu_i dY_i + \mu_e dY_e$$

$$\Rightarrow \quad ds = dq_{\mathrm{ext}}/T + \sum_i \frac{\mu_i}{T} dY_i + \frac{\mu_e}{T} dY_e$$

- Increases the entropy of the fluid and keeps the temperature of the expanding gas near constant

- This can substantially impact the path of the r-process





Run r-process Calculations Yourself

Sky Net

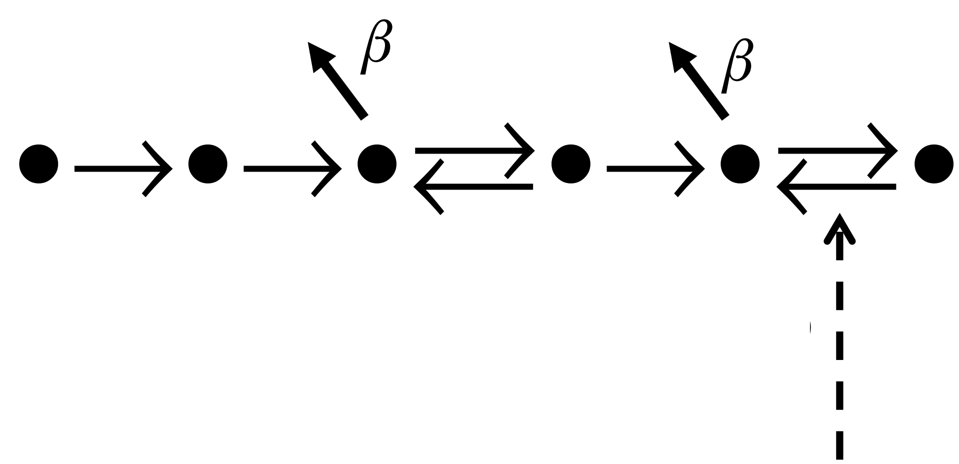
github.com/jlippuner/SkyNet

- General-purpose nuclear reaction network
- $\sim$8000 isotopes, $\sim$140,000 nuclear reactions
- Evolves temperature and entropy based on nuclear reactions
- Input: $\rho(t)$, initial composition, initial entropy or temperature
- Open source

What set the r-process flow

$\tau_n \ll \tau_{\beta^-}$ **and** $\tau_n \ll \tau_d$

Equilibrate: $(A, Z) + n \leftrightarrow (A+1, Z) + \gamma$

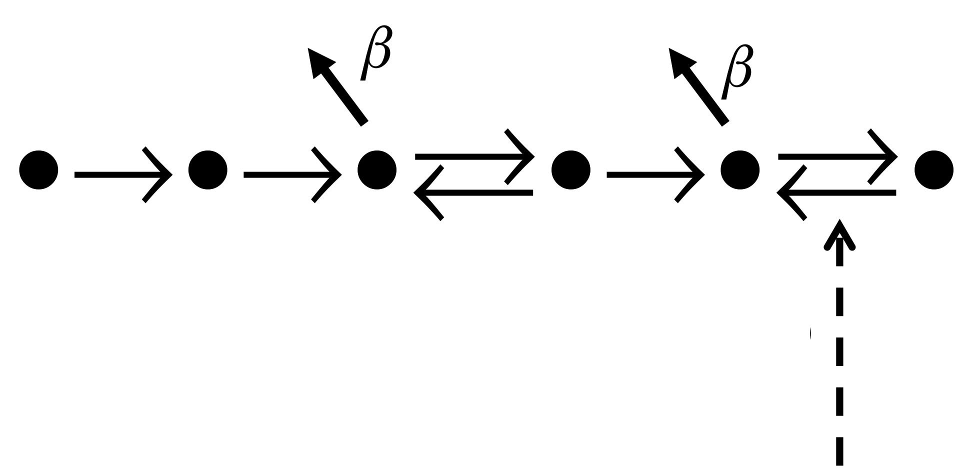


$$Y_{A+1}\lambda_{\gamma n}(A+1) = \rho\, Y_n\, Y_A \lambda_{n\gamma}(A)$$

Waiting Point Approximation

$\tau_n \ll \tau_{\beta^-}$ **and** $\tau_n \ll \tau_d$

Equilibrate: $(A, Z) + n \leftrightarrow (A+1, Z) + \gamma$



$$Y_{A+1}\lambda_{\gamma n}(A+1) = \rho\, Y_n\, Y_A \lambda_{n\gamma}(A)$$

$$\Rightarrow \qquad \mu_{(A,Z)} + \mu_n = \mu_{(A+1,Z)}$$

Waiting Point Approximation

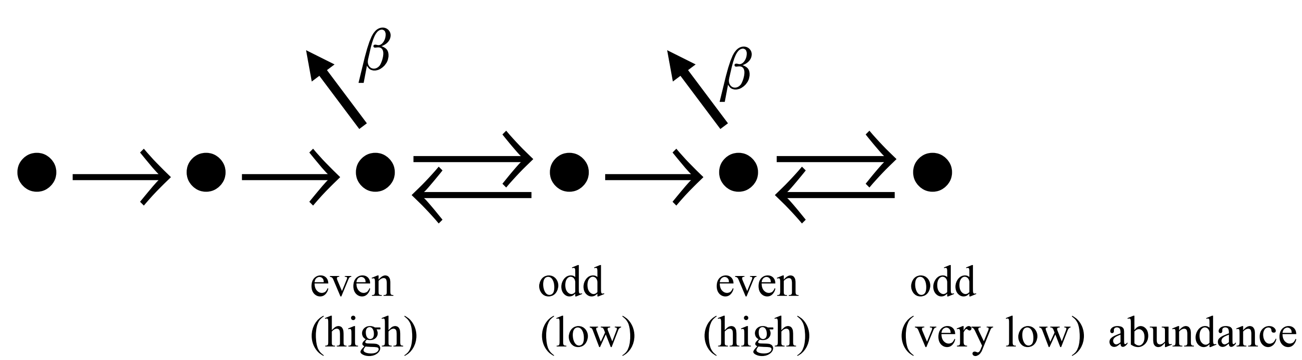
$$\mu_{(A,Z)} + \mu_n = \mu_{(A+1,Z)}$$

$$\mu_{(A,Z)} = m_{(A,Z)} + T \ln \left[\frac{n_b Y_{(A,Z)}}{G_{(A,Z)}(T)} \left(\frac{2\pi\hbar^2 c^2}{m_{(A,Z)} T} \right)^{3/2} \right]$$

$$\Rightarrow \qquad \frac{Y_{(A+1,Z)}}{Y_{(A,Z)}} = n_b Y_n \frac{G_{(A+1,Z)}(T)}{2G_{(A,Z)}(T)} \left(\frac{2\pi\hbar^2 c^2 m_{(A+1,Z)}}{m_n m_{(A,Z)} T} \right)^{3/2} e^{S_{n,(A+1,Z)}/T}$$

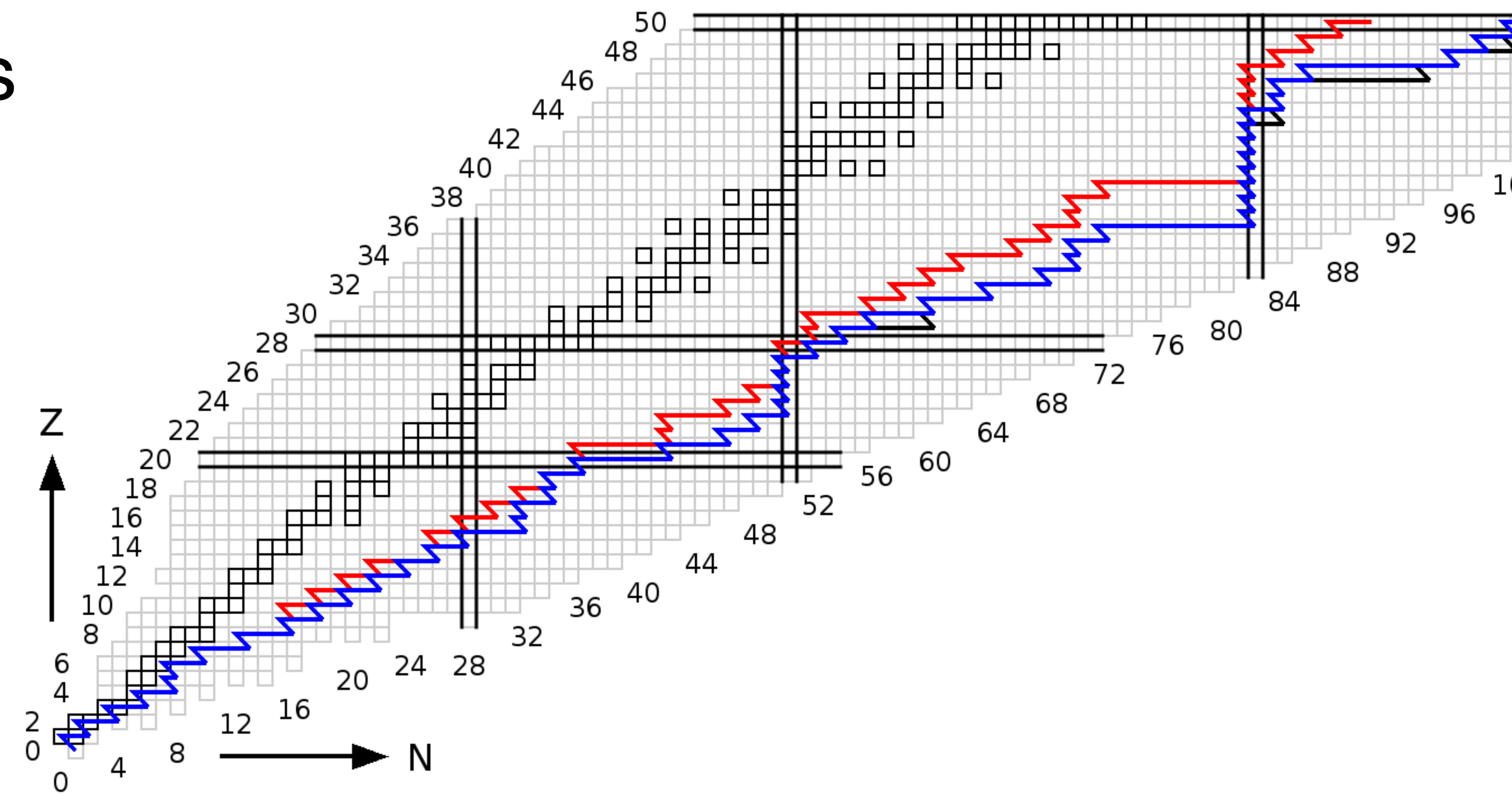
where

Neutron Separation Energy: $S_{n,(A,Z)} = m_{(A,Z)} + m_n - m_{(A+1,Z)}$



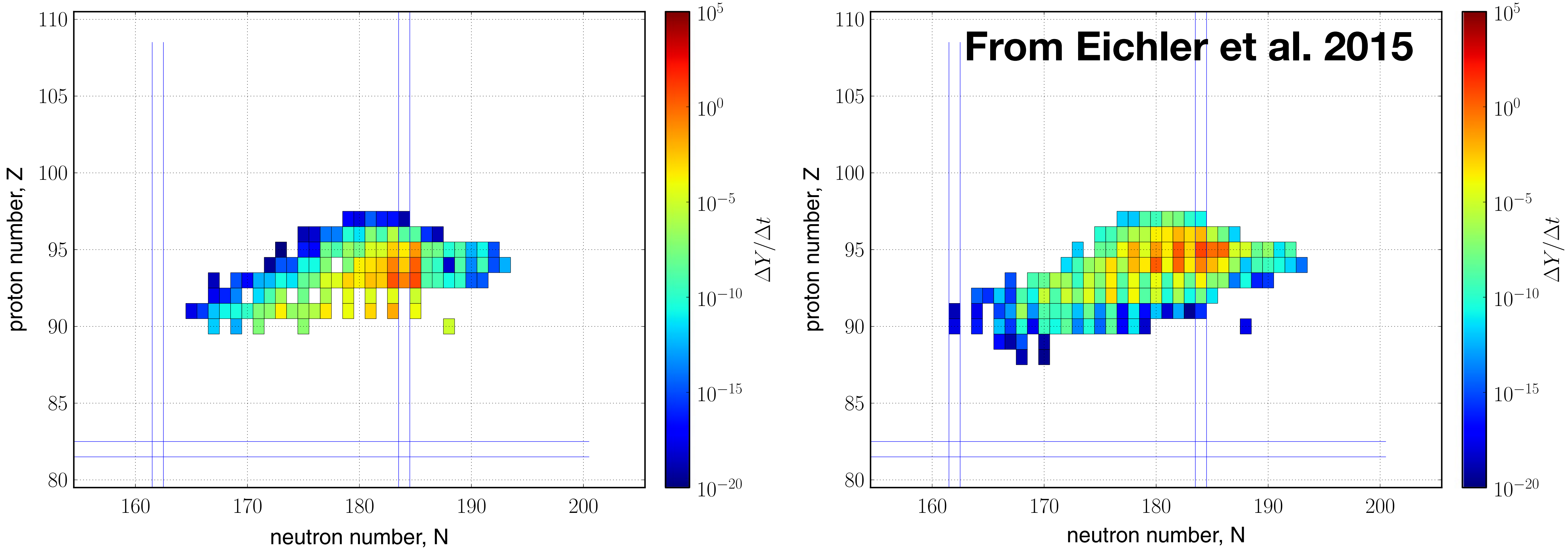
r-process path depends on conditions

- Higher temperature implies path lies closer to stability
- Path particularly sensitive to mass differences
- Neutron separation energies small just beyond neutron closed shells, forces the path to stay along closed shells until closer to stability



r-process paths predicted by the waiting point approximation for two different outflows

Fission: The end of the r-process



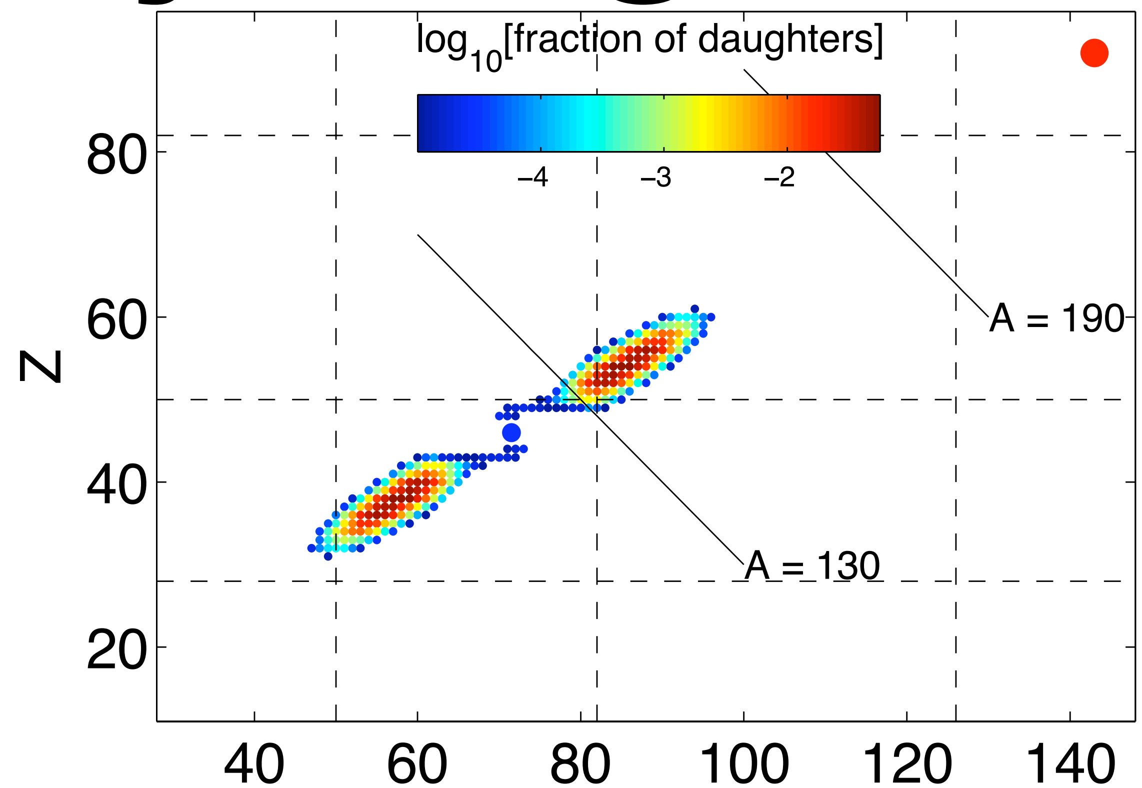
(a) β-delayed fission

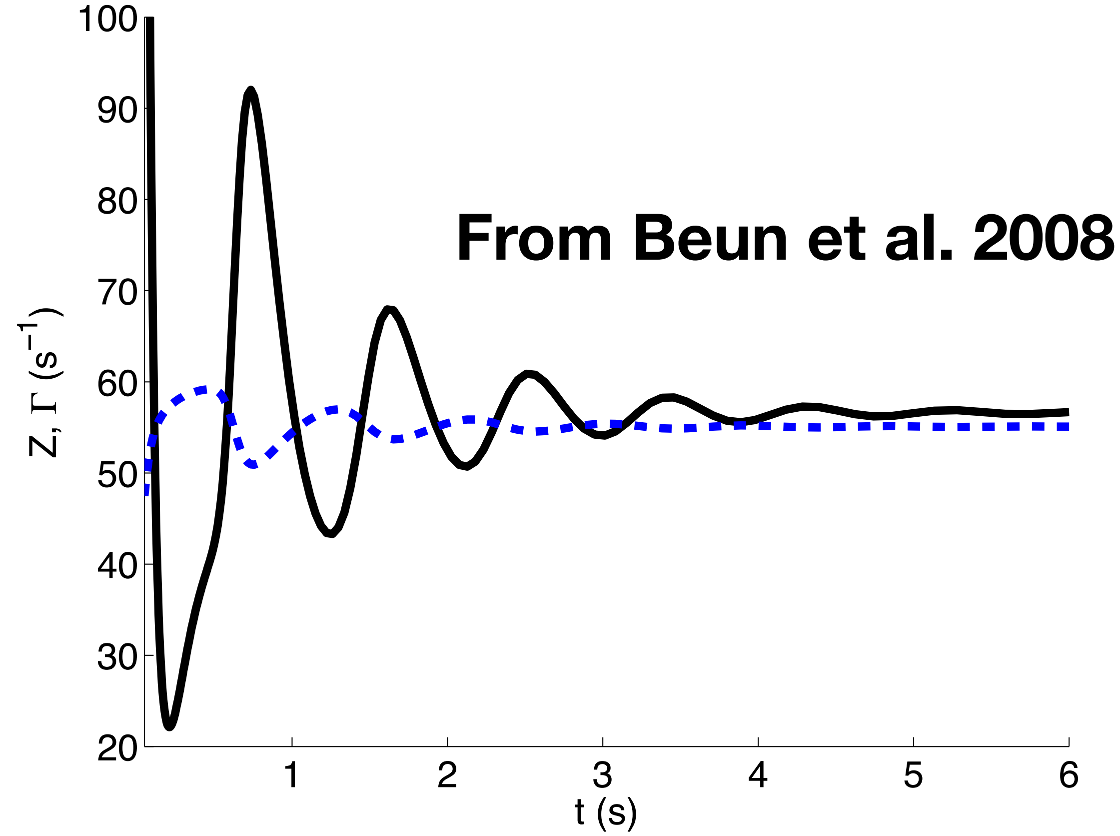
(b) neutron-induced fission

- Once material reaches nuclei susceptible to either neutron induced or beta-delayed fission, the r-process reaches its maximum extent
- Material is pushed back down to lower mass

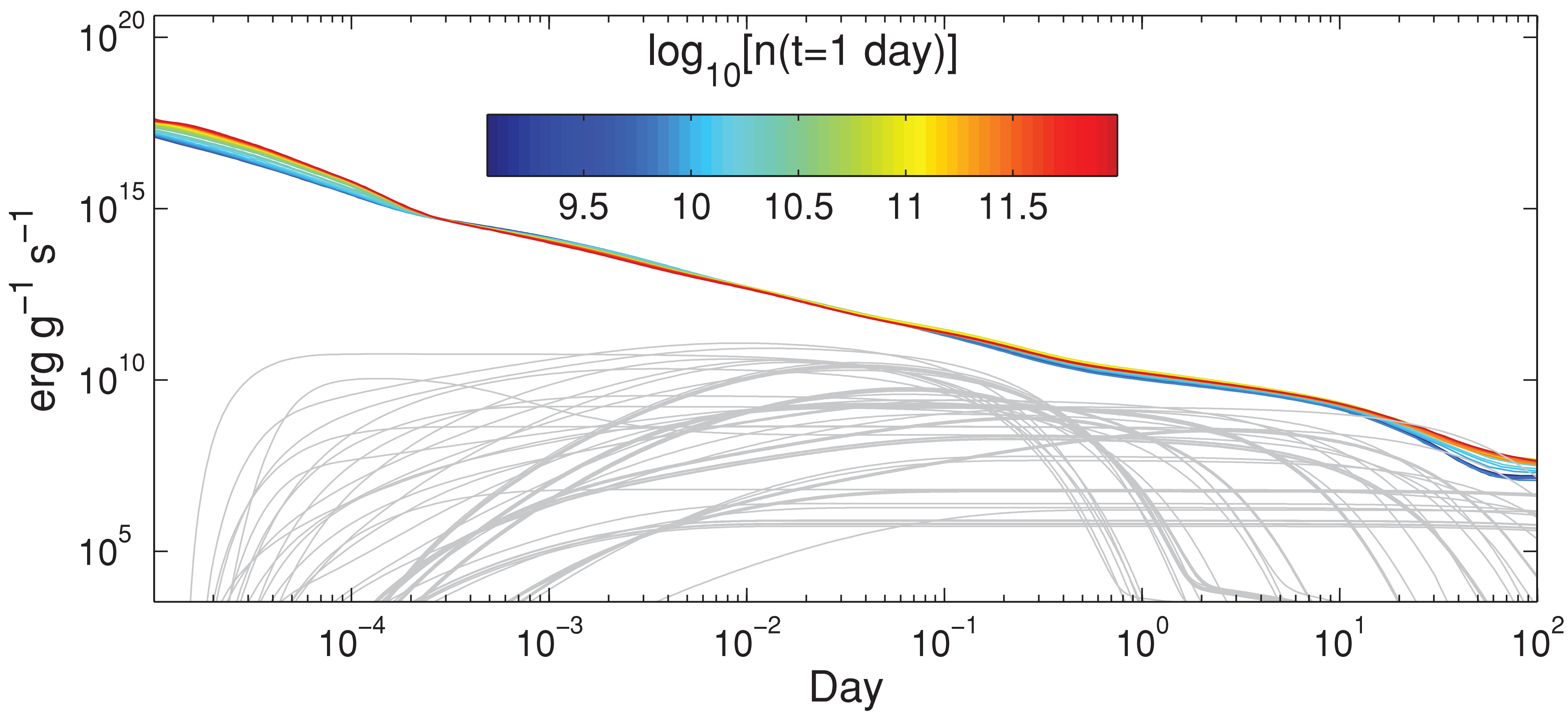
Fission Cycling

- Fission takes single seed, turns it into two back near the first peak
- If the initial neutron-to-seed ratio is high, material can cycle through this process a number of times
- Distribution of daughter nuclei important to final pattern



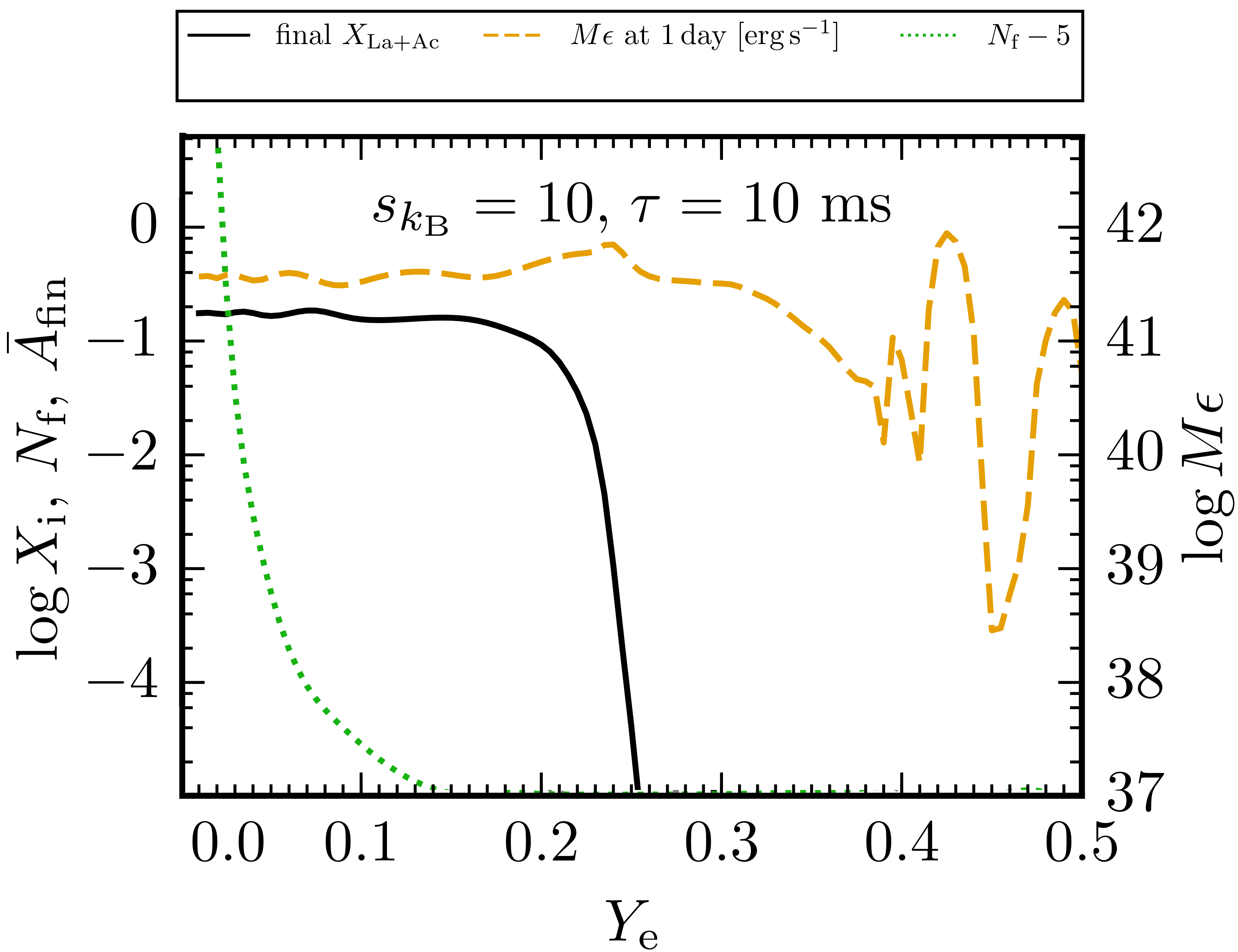


Decay to Stability

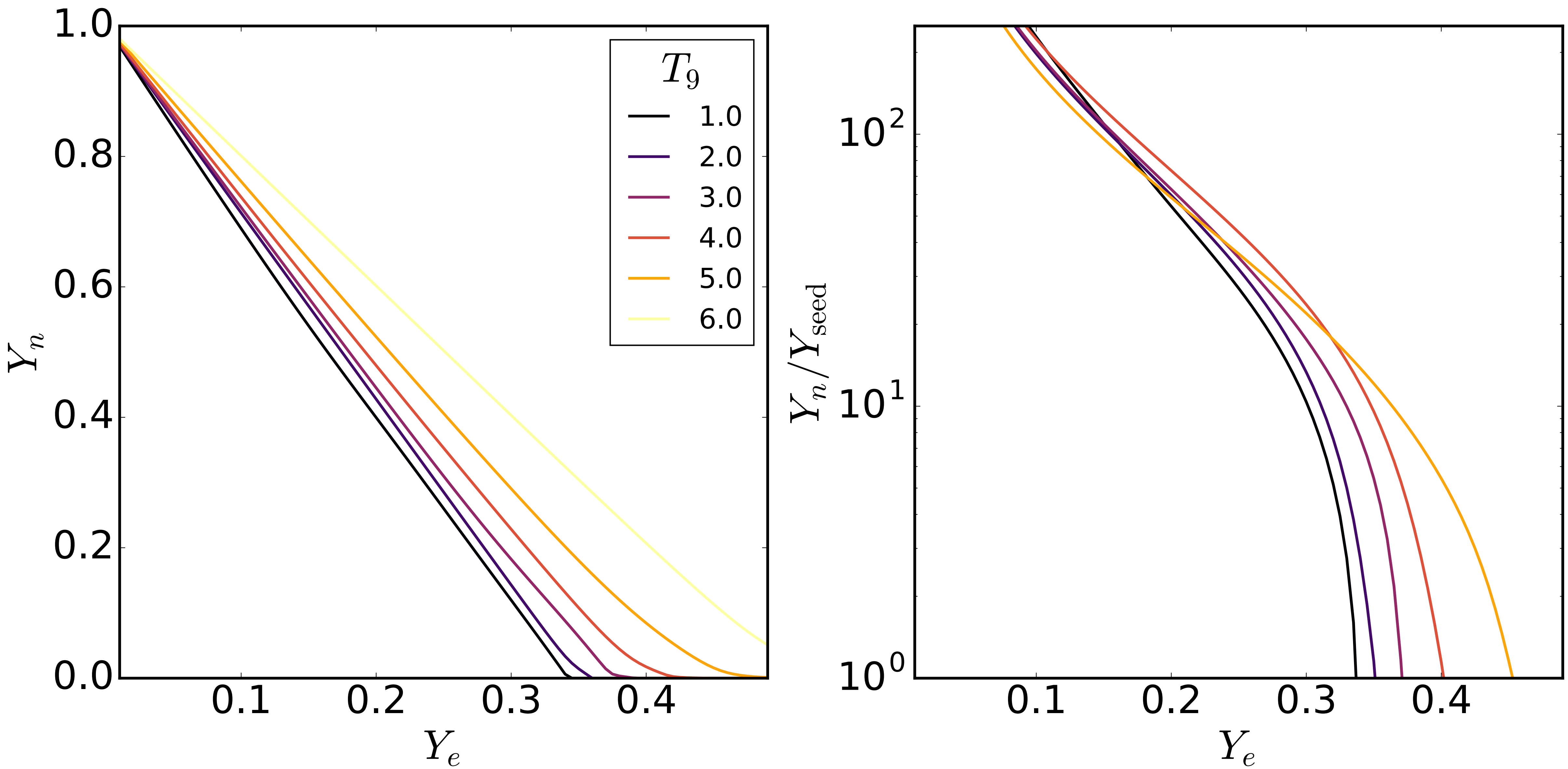


- Beta decays, alpha decays, and fission back towards stability
- Decays move to longer and longer timescales as one gets closer to stability since beta-decay Q values decrease closer to stability
- These decays release energy into the fluid, relevant to kilonovae (see Brian’s lecture)

Dependence of Nucleosynthesis on Initial Conditions



Neutron-to-Seed Ratio

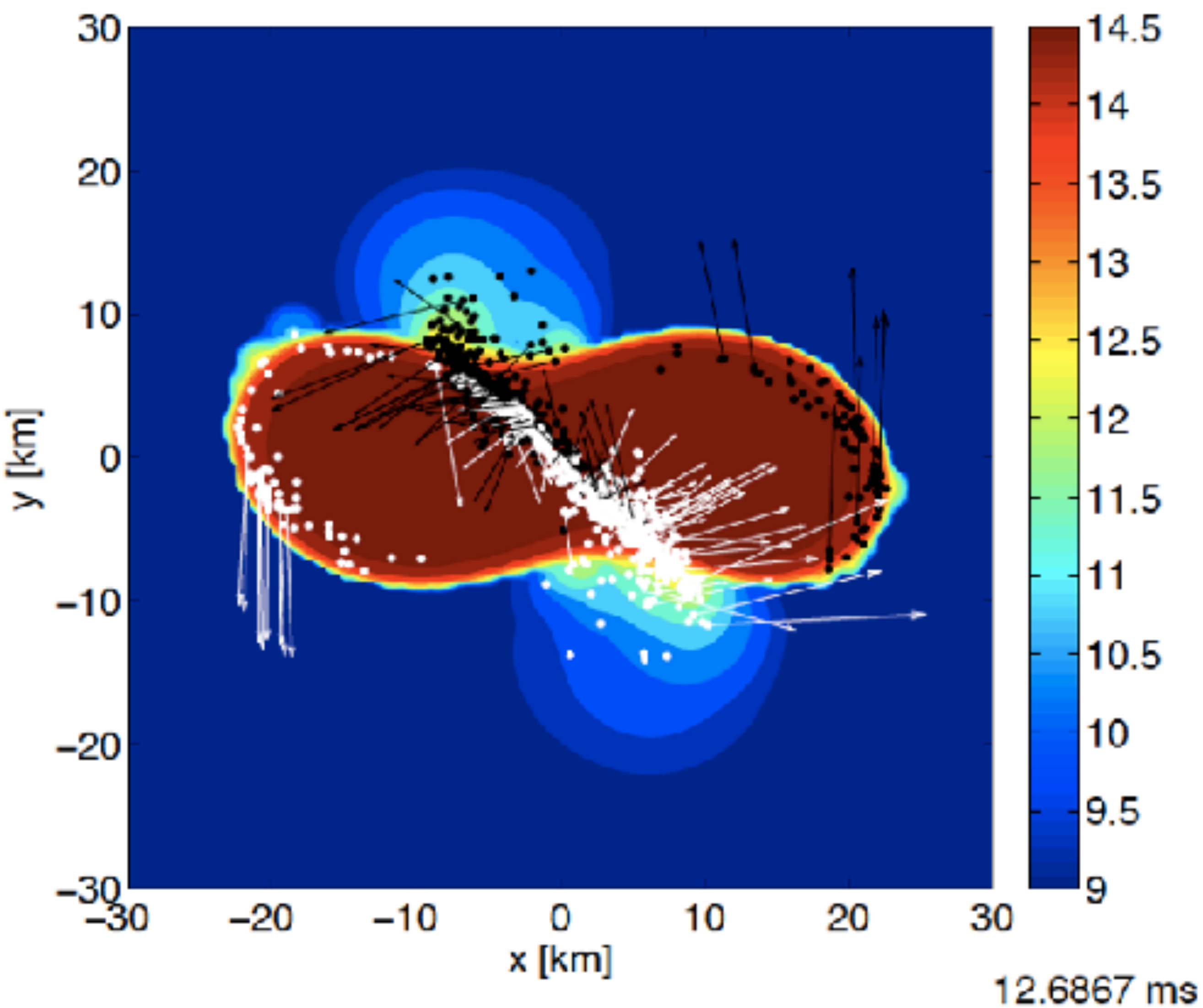


Can pretty easily trace this condition back to the initial conditions

How does Y_e get set in material ejected during NS mergers?

Mass Ejection from NS Mergers

1. Dynamical Ejecta
    - Tidal ejecta
    - Shock heated ejecta
2. Disk winds
3. Disk outflows from viscous heating and alpha recombination

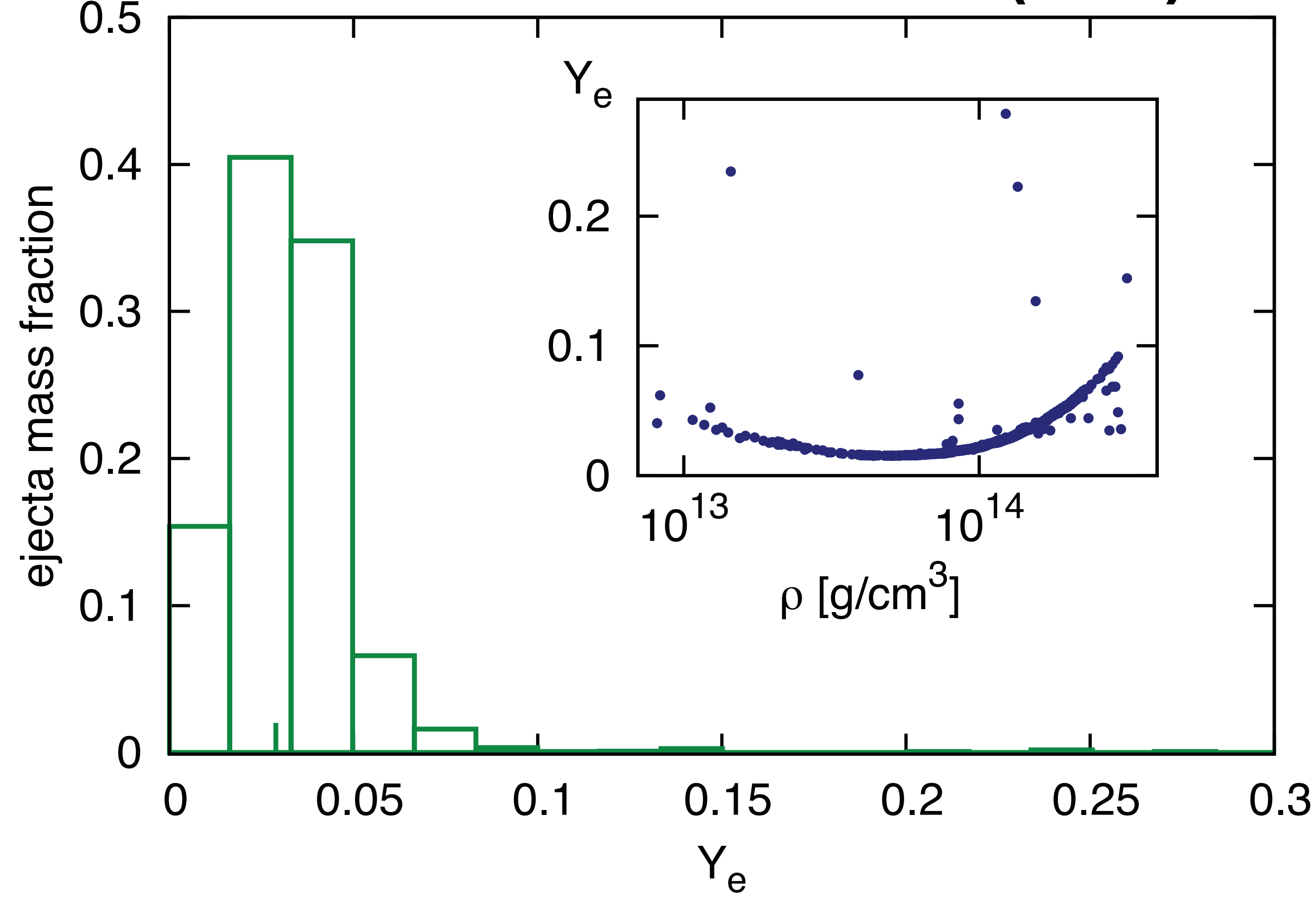


Bauswein et al. ’13

Tidal Ejecta

- Material squeezed through the outer Lagrange points during merger
- Material is not shocked and likely undergoes few weak reactions
- Electron fraction distribution essentially that of the progenitor NS

from Korobkin et al. (2012)



Electron fraction set by beta equilibrium of cold NS:

$$\mu_{e^-} + \mu_p = \mu_n$$

Predicts Y_e<0.1 for most of the material

Changing Y_e for the r-process

At high density before the r-process begins, the electron fraction of the ejecta can be changed by weak interactions:

$$
\begin{aligned}
e^- + p &\quad\leftrightarrow\quad \nu_e + n \\
e^+ + n &\quad\leftrightarrow\quad \bar{\nu}_e + p
\end{aligned}
$$

Rates for these processes are given by integrating over the phase space of the involved particles:

$$\lambda_w = \frac{1}{n_2} g_1 \int \frac{d^3k_1}{(2\pi)^3} g_2 \int \frac{d^3k_2}{(2\pi)^3} \int \frac{d^3k_3}{(2\pi)^3} \int \frac{d^3k_4}{(2\pi)^3} \delta^{(4)}(k_1^\mu + k_2^\mu - k_3^\mu - k_4^\mu)\, \mathscr{r}_w f_1 f_2 (1 - f_3)(1 - f_4)$$

1 and 3: Electrons and neutrinos
2 and 4: Nucleons

Changing Y_e for the r-process

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To a good approximation (ignoring nucleon recoil):

$$\mathscr{r}_w \approx (2\pi)^4 G_F^2 (g_V^2 + 3g_A^2)$$

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To a good approximation (ignoring nucleon recoil):

$$\mathcal{r}_w \approx (2\pi)^4 G_F^2 (g_V^2 + 3g_A^2)$$

For instance: $$\lambda_{e^-} = \frac{G_F^2(g_V^2 + 3g_A^2)}{\pi^3} \int_{\Delta_{np}}^{\infty} dE_e E_e^2 (\underbrace{E_e - \Delta_{np}}_{E_\nu})^2 f_{e^-}(1 - f_{\nu_e})$$

Order of Magnitude Rates

For relativistic electrons:

$$\mu_e \gg T$$

$$\lambda_{e^-} \approx 0.23\,\mathrm{s}^{-1}\mu_{e,\mathrm{MeV}}^5$$

$$\lambda_{e^+} \approx 0.45\,\mathrm{s}^{-1}T_{\mathrm{MeV}}^5 \exp(-\mu_e/T)$$

or

$$\mu_e \ll T$$

$$\lambda_{e^\pm} \approx 0.45\,\mathrm{s}^{-1}T_{\mathrm{MeV}}^5$$

For neutrinos:

$$\lambda_{\nu_e n} \approx 4.83 L_{\nu_e,51}\left(\epsilon_{\nu_e,\mathrm{MeV}} + 2\Delta_{\mathrm{MeV}} + 1.2\,\frac{\Delta_{\mathrm{MeV}}^2}{\epsilon_{\nu_e,\mathrm{MeV}}}\right) r_6^{-2}\ \mathrm{s}^{-1}$$

$$\lambda_{\bar{\nu}_e p} \approx 4.83 L_{\bar{\nu}_e,51}\left(\epsilon_{\bar{\nu}_e,\mathrm{MeV}} - 2\Delta_{\mathrm{MeV}} + 1.2\,\frac{\Delta_{\mathrm{MeV}}^2}{\epsilon_{\bar{\nu}_e,\mathrm{MeV}}}\right) r_6^{-2}\ \mathrm{s}^{-1}$$

where:

$$\epsilon_\nu = \frac{\int_0^\infty dE_\nu E_\nu^4 f_\nu}{\int_0^\infty dE_\nu E_\nu^3 f_\nu}$$

and

$$L_\nu = \frac{cr^2}{2\pi^2(\hbar c)^3}\int_0^\infty dE_\nu E_\nu^3 f_\nu$$

Changing Y_e for the r-process

$$\begin{aligned} e^- + p &\leftrightarrow \nu_e + n \\ e^+ + n &\leftrightarrow \bar{\nu}_e + p \end{aligned}$$

Evolution of the electron fraction is governed by

$$\frac{dY_e}{dt} = (\lambda_{\nu_e} + \lambda_{e^+})Y_n - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})Y_p + \ldots$$

Changing Y_e for the r-process

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$$\frac{dY_e}{dt} = (\lambda_{\nu_e} + \lambda_{e^+})Y_n - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})Y_p + \ldots$$

$$Y_e(t) \approx Y_{e,0}\exp(-t/\tau_w) + [1 - \exp(-t/\tau_w)]Y_{e,eq}$$

where

$$\tau_w = [\lambda_{e^-} + \lambda_{e+} + \lambda_{\nu_e} + \lambda_{\bar{\nu}_e}]^{-1}$$

$$Y_{e,eq} = \frac{\lambda_{\nu_e} + \lambda_{e+}}{\lambda_{\nu_e} + \lambda_{e+} + \lambda_{\bar{\nu}_e} + \lambda_{e-}}$$

Changing Y_e with electrons

- Under degenerate conditions, electron capture dominates and expect small Y_e

- Increase temperature, lift degeneracy, produce pairs (as long as $T > m_e$), positron and electron capture rates are similar and $Y_{e,eq}$~0.5

For relativistic electrons:

$$\mu_e \gg T$$

$$\lambda_{e^-} \approx 8 \times 10^{-3}\,\mathrm{s}^{-1} \left(\frac{\mu_e}{m_e}\right)^5$$

$$\lambda_{e^+} \approx 2 \times 10^{-2}\,\mathrm{s}^{-1} \left(\frac{T}{m_e}\right)^5 \exp(-\mu_e/T)$$

or

$$\mu_e \ll T$$

$$\lambda_{e^\pm} \approx 2 \times 10^{-2}\,\mathrm{s}^{-1} \left(\frac{T}{m_e}\right)^5$$

Setting Y_e by neutrinos

Evolution of the electron fraction is governed by

$$\frac{dY_e}{dt} = (\lambda_{\nu_e} + \lambda_{e^+})Y_n - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})Y_p + \ldots$$

$$Y_e(t) \approx Y_{e,0}\exp(-t/\tau_w) + [1 - \exp(-t/\tau_w)]Y_{e,eq}$$

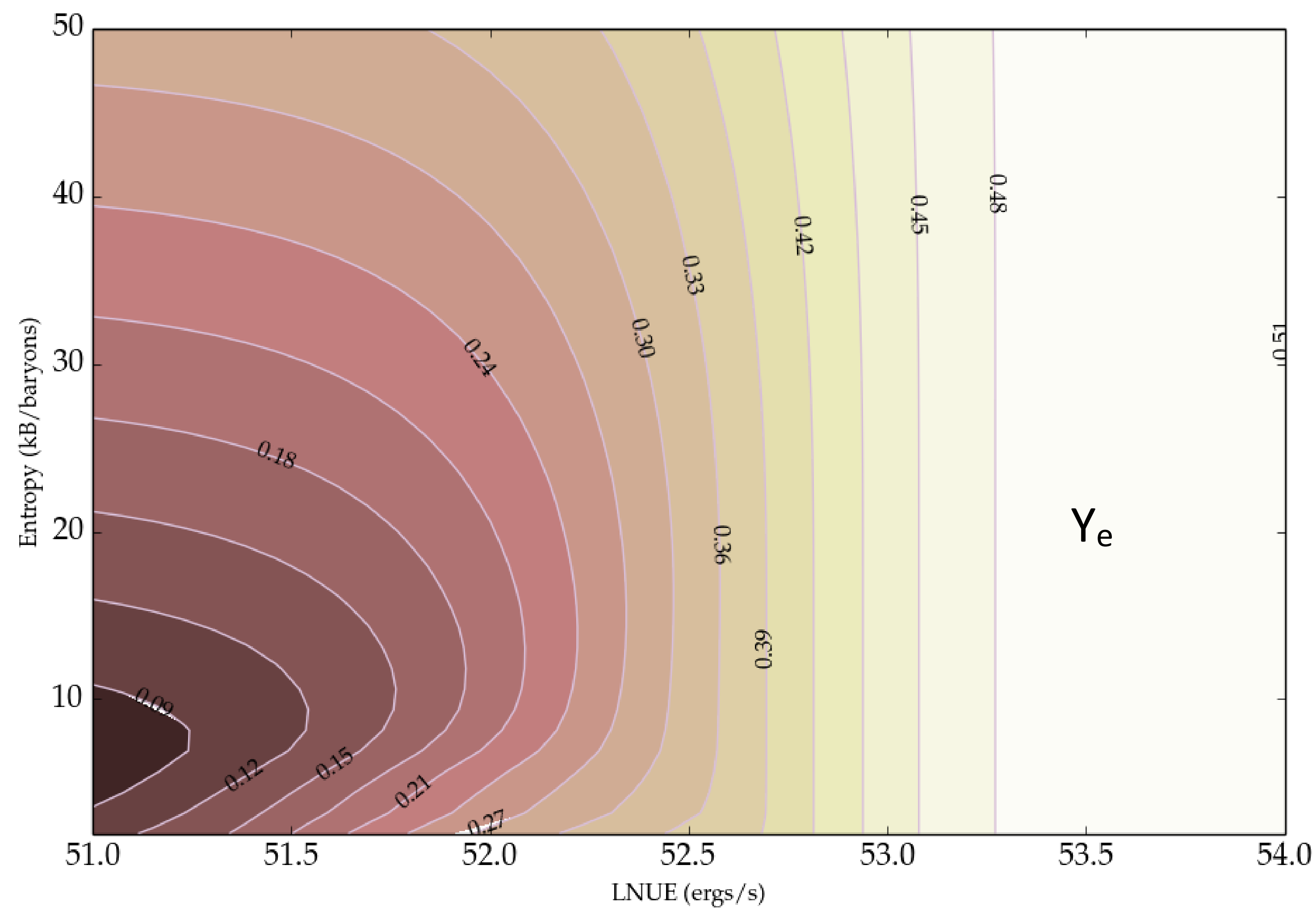
When we have:

$$\lambda_\nu \gg \lambda_{e^+,e^-}$$

$$\Rightarrow \qquad Y_{e,eq} \approx \frac{\lambda_{\nu_e}}{\lambda_{\nu_e} + \lambda_{\bar{\nu}_e}}$$

Weak Interactions in NS Mergers

- Contours of Y_e for fixed time dependent density
- Hierarchy of neutrino energies similar to proto-NS neutrino emission because neutrino decoupling physics is similar



Neutrino Transport

Neutrinos are out of equilibrium outside of the dense remnant. Therefore, their distribution functions become non-thermal and the evolution of the neutrinos must be tracked explicitly in phase space. Evolution of neutrino distribution function is described by the Boltzmann equation:

$$\frac{\partial f(\vec{x}, \hat{n}, E_\nu, t)}{\partial \lambda} = \left(\frac{df}{d\tau} \right)_{\mathrm{coll}}$$

LHS evolution of distribution on characteristic path through phase space. In the absence of interactions, distribution function is conserved on characteristics.

RHS describes microscopic interactions of neutrinos with the background nuclear medium.

Deceptively simple!

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$$p^\beta \left(\frac{\partial f}{\partial x^\beta} - \Gamma^\alpha_{\beta\gamma} p^\gamma \frac{\partial f}{\partial p^\alpha} \right) = \left(\frac{df}{d\tau} \right)_{\text{coll}}$$

LHS describes evolution of the neutrino p^ν is constrained to be on mass shell, so this is a 7-d PDE which must be solved for each neutrino species.

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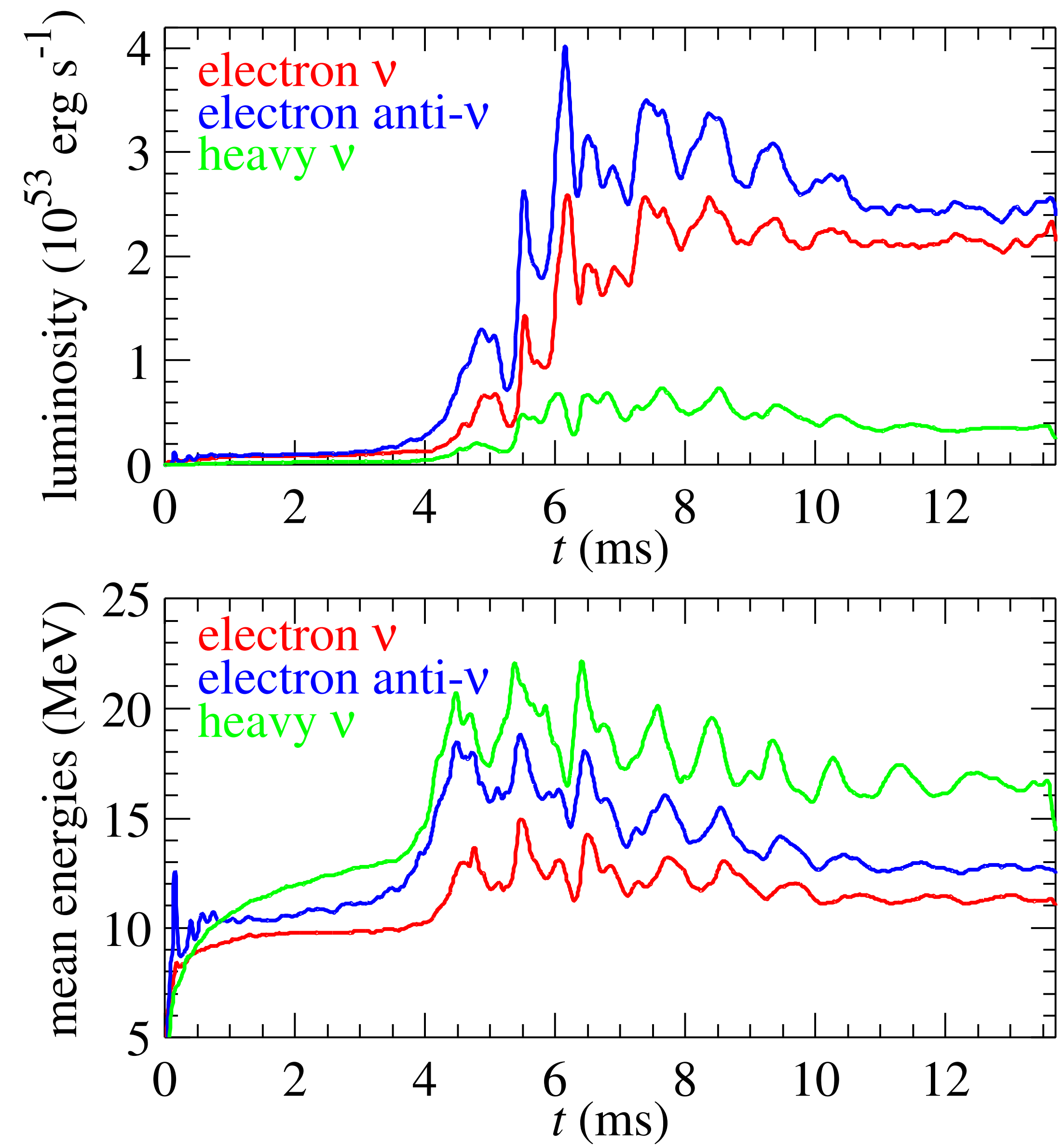
Methods for treating neutrino transport:

- Leakage
- Gray Moment based approaches
- Spectral moment based approaches
- Monte Carlo
- S_n methods

Weak Interactions in the Dynamical Ejecta

- Large neutrino luminosities provided by central remnant of the NS merger
- Re-leptonizing, so largest emission is in electron antineutrinos
- Hierarchy of neutrino energies similar to proto-NS neutrino emission because neutrino decoupling physics is similar



from Wanajo (2014)

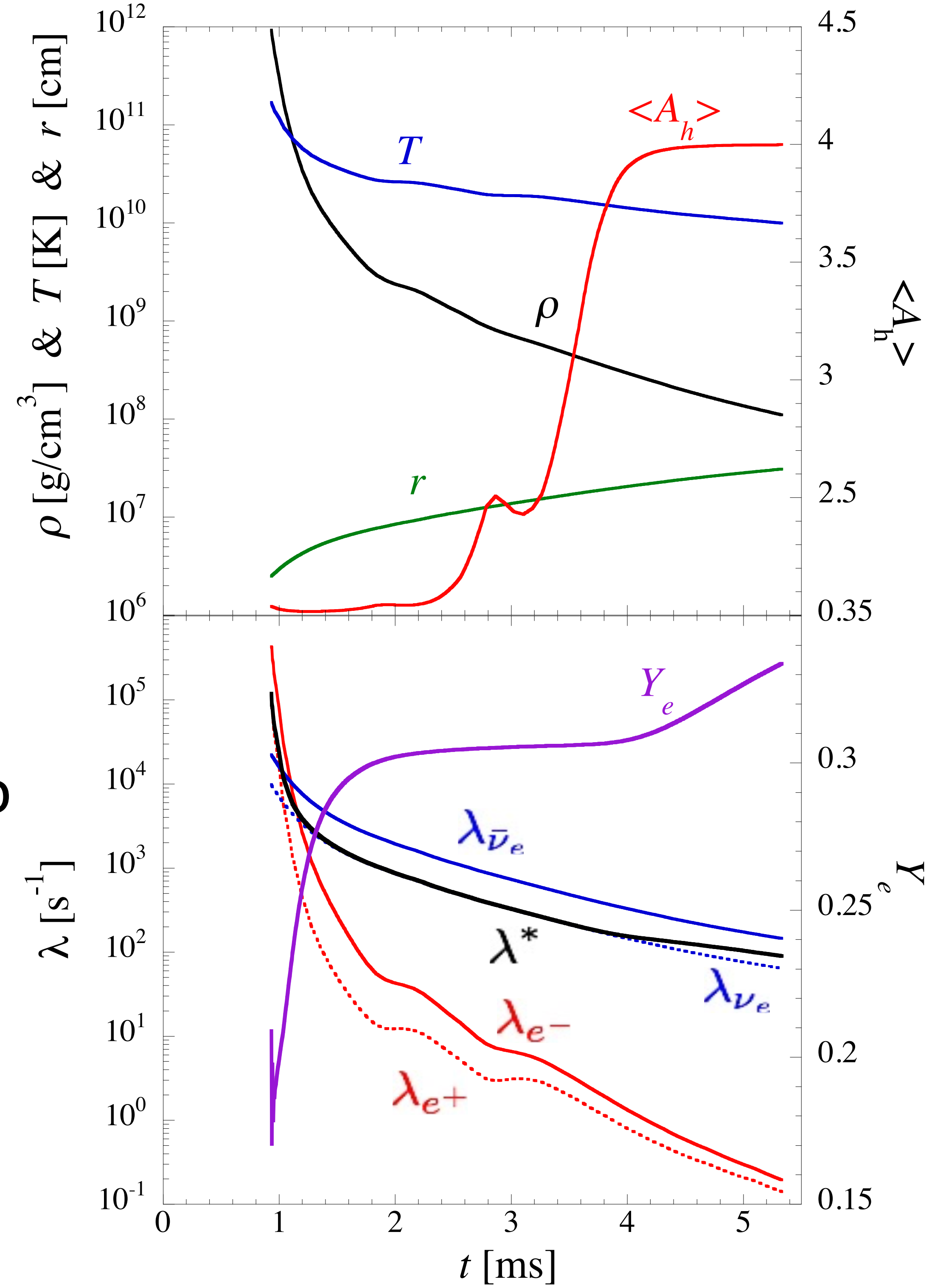
Weak Interactions in NS Mergers

Destroy neutron at early times in hot, neutrino rich environment at early times via:

$$\{\nu_e, e^+\} + n \rightarrow p + \{e^-, \bar{\nu}_e\}$$

Early on at high density electron capture dominates, but as density falls off neutrino capture pushes Y_e up

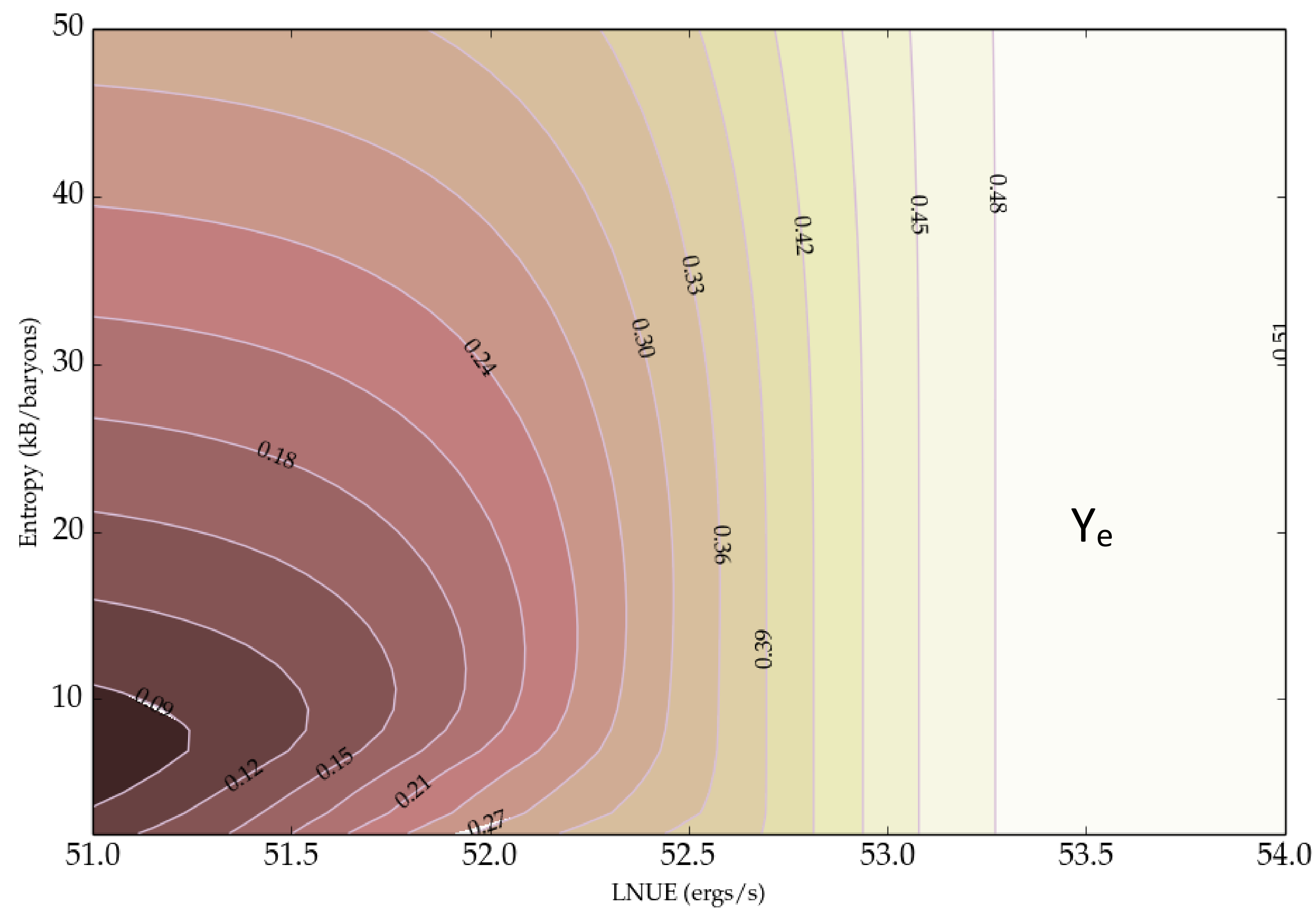
Can push Y_e to values at which a complete r-process is no longer made



from Goriely et al. (2015)

Weak Interactions in NS Mergers

- Contours of Y_e for fixed time dependent density
- Hierarchy of neutrino energies similar to proto-NS neutrino emission because neutrino decoupling physics is similar



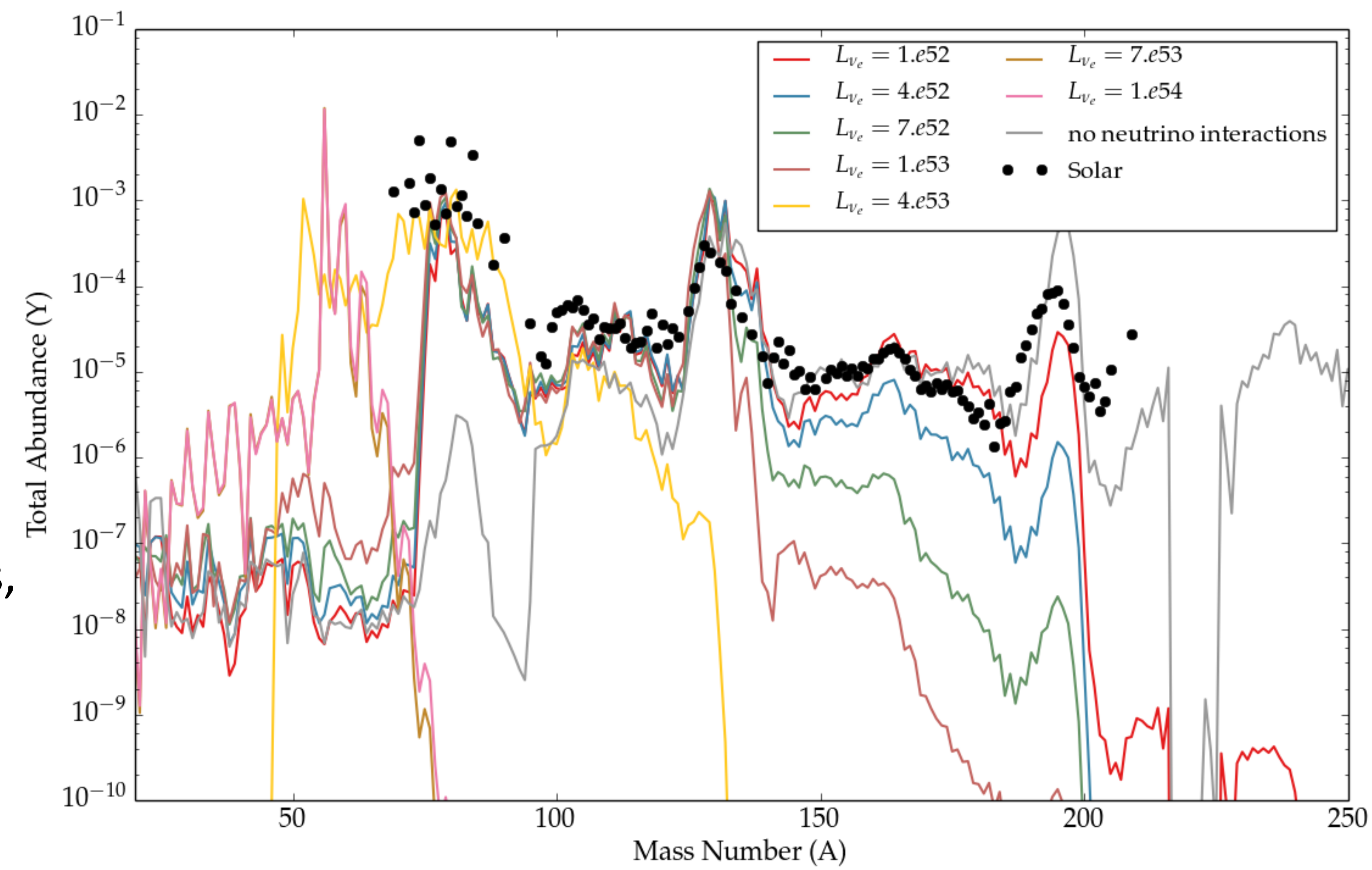
Weak Interactions in NS Mergers

Destroy neutron at early times in hot, neutrino rich environment at early times via:

$$\{\nu_e, e^+\} + n \rightarrow p + \{e^-, \bar{\nu}_e\}$$

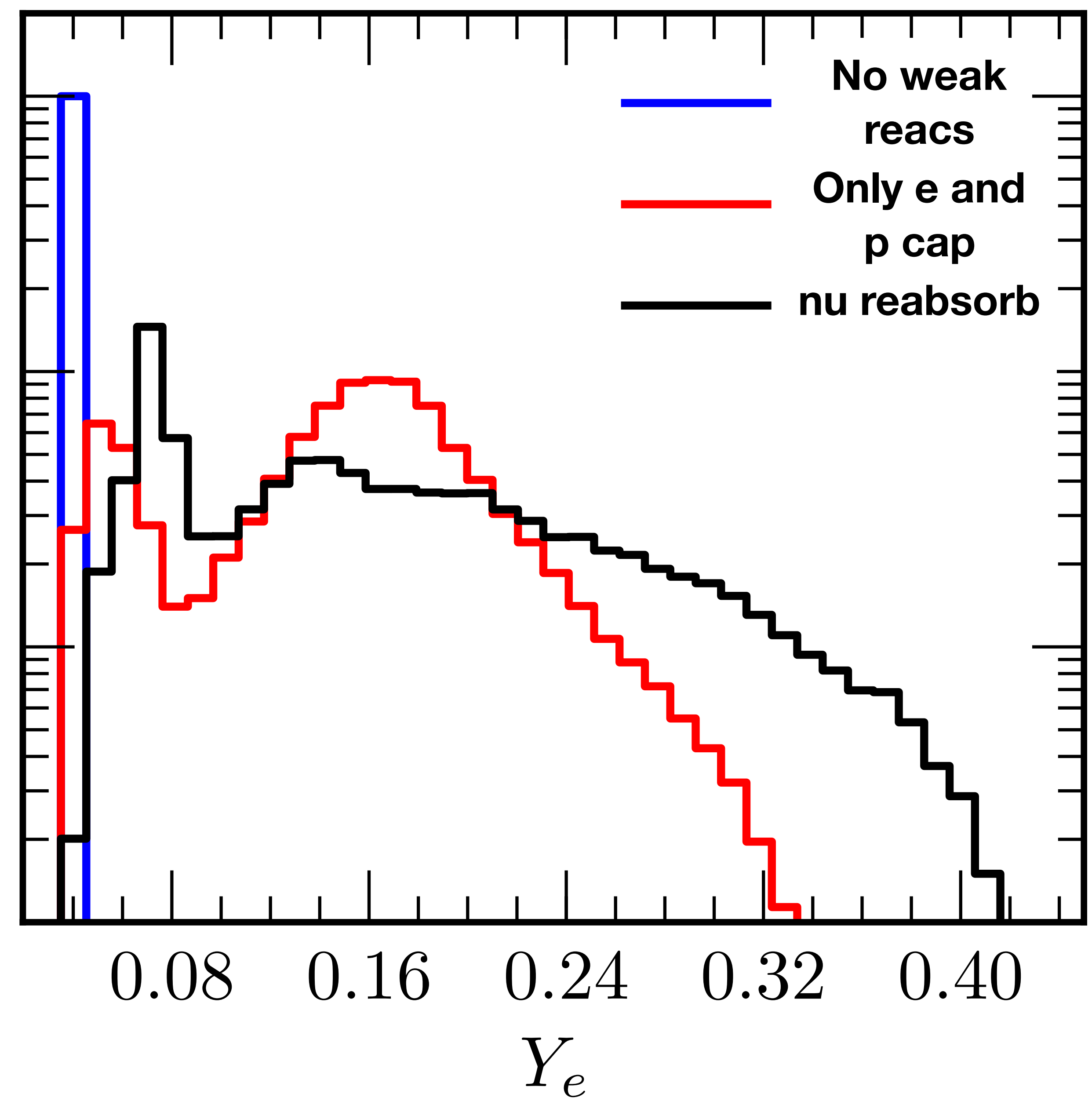
NSE favors more seed nuclei, fewer neutrons, thereby gives lower neutron to seed ratio

Incomplete r-process, material builds up at first peak



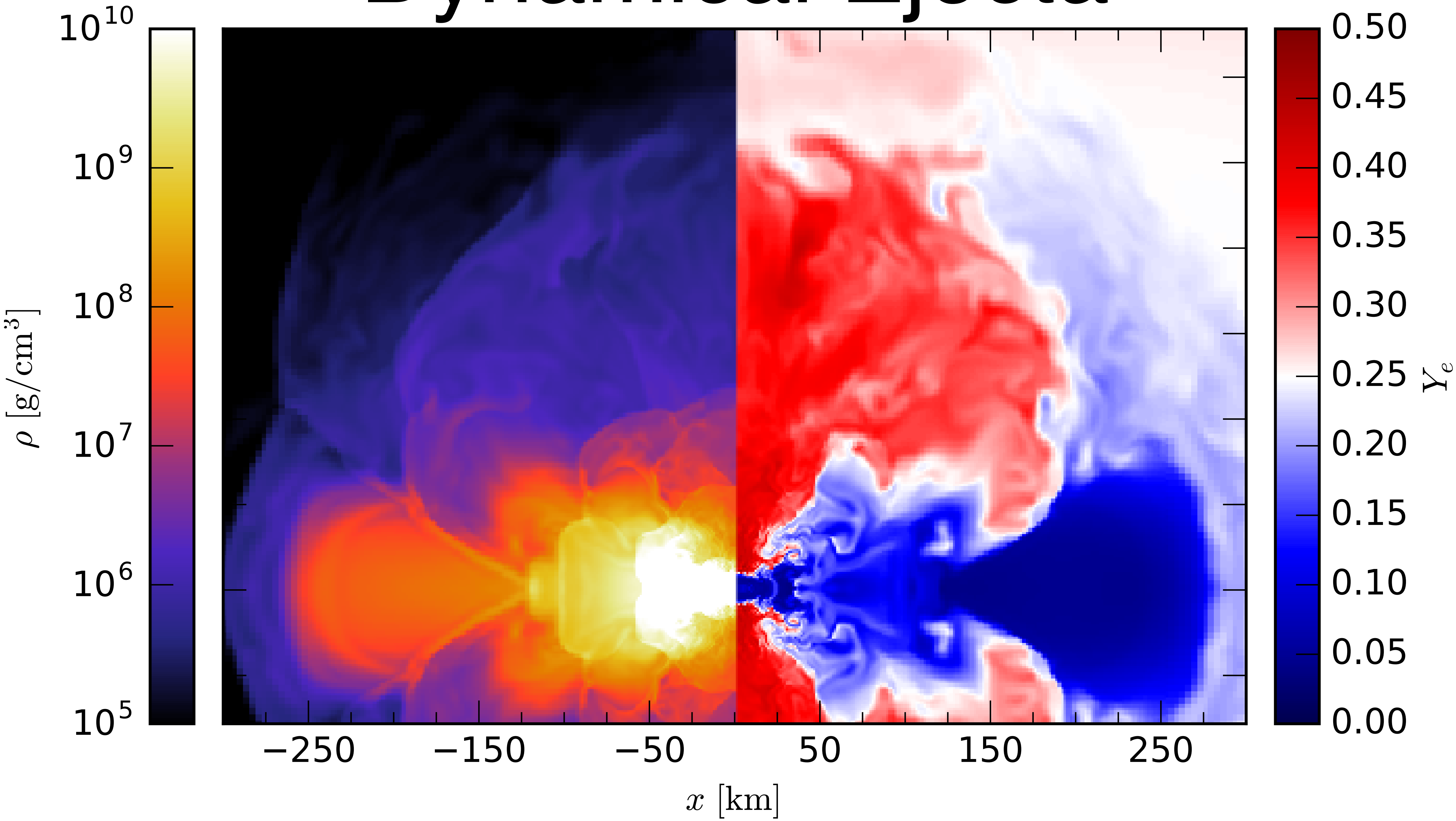
Weak Interactions in the Dynamical Ejecta

- Shock heating lifts electron degeneracy and allows for pair capture, increasing Y_e by positron capture
- Additionally, neutrino capture alters Y_e
- Neutrino luminosities and average energies fairly similar



from Radice et al. (2016)

Weak Interactions in the Dynamical Ejecta

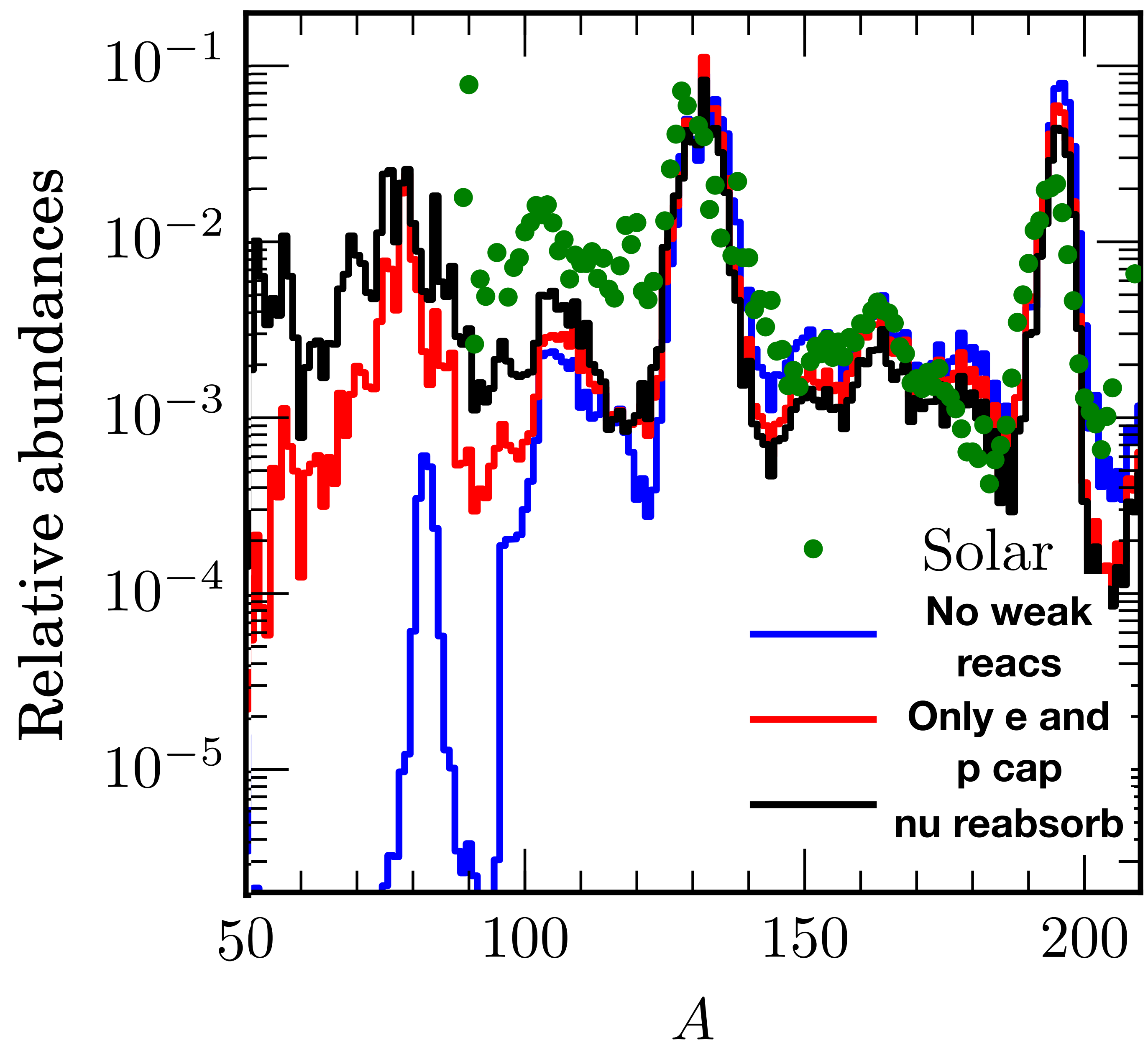


from Radice et al. (2016)

Weak Interactions in the Dynamical Ejecta

- Nevertheless, still produce quite a bit of material with $Y_e < 0.25$ so second and third peak still produced

- Weak interactions have a significant impact on the amount of first peak production



from Radice et al. (2016)

Weak interactions in BHNS dynamical ejecta

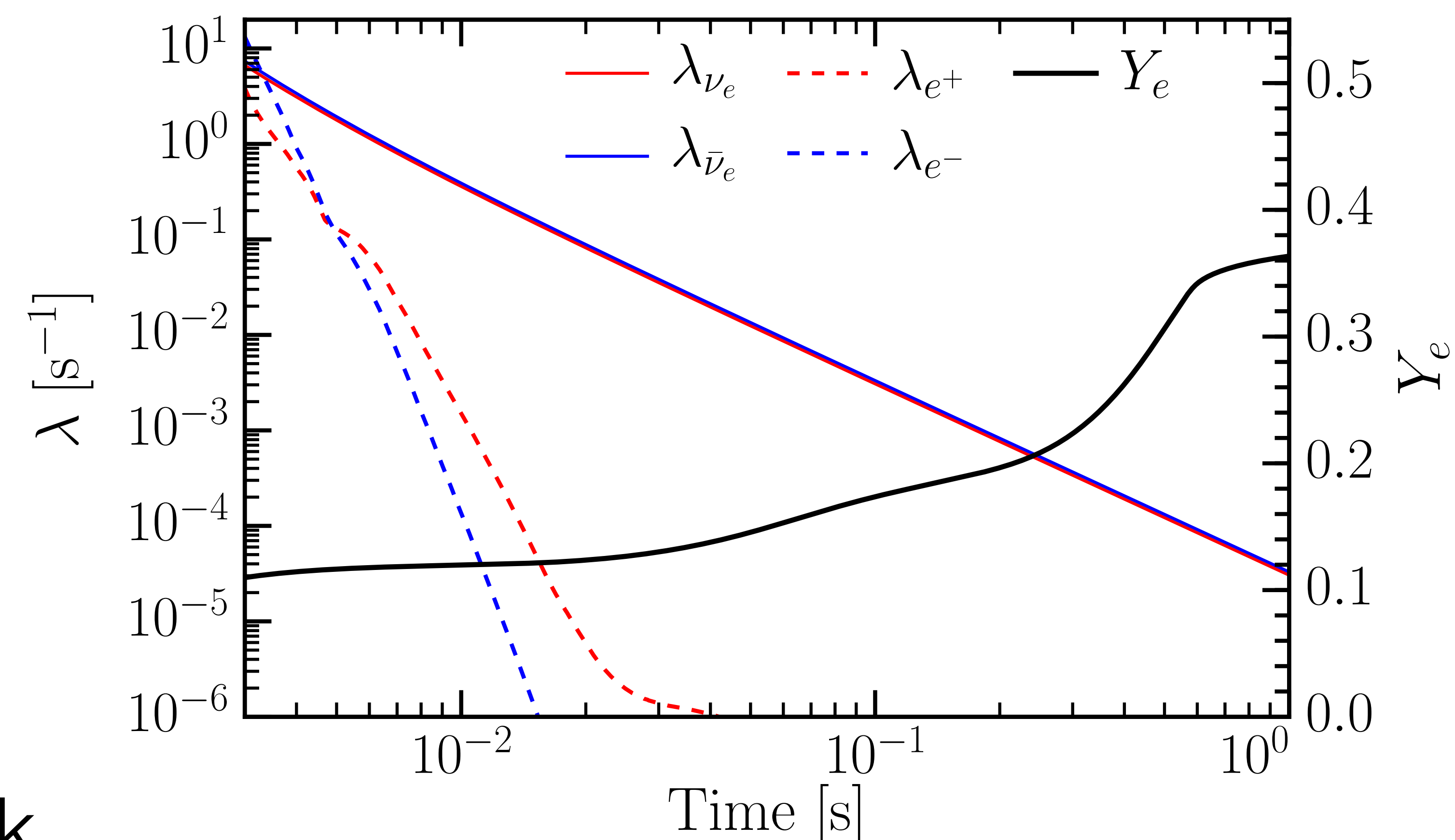
Low entropy tidal ejecta -> small electron/positron capture rates

Neutrino reactions are somewhat faster

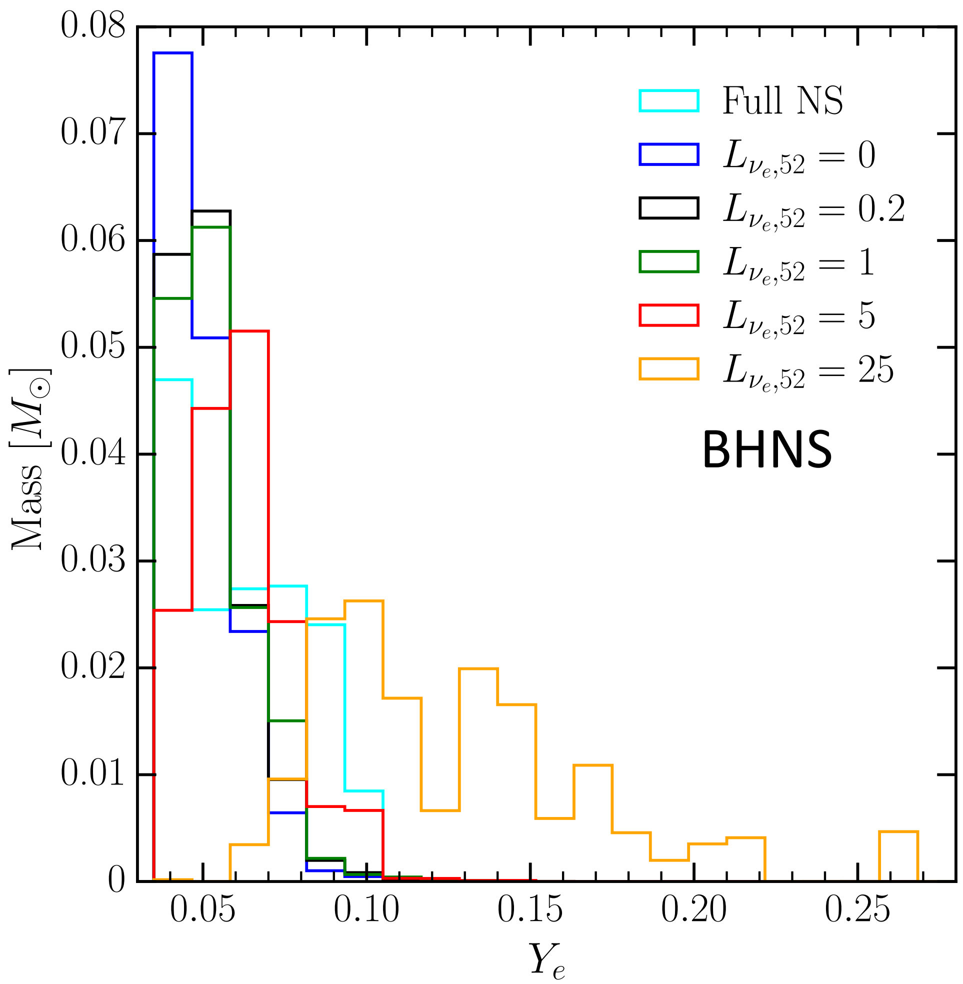
$$\tau_\nu(r) \approx 67.8\,\mathrm{ms}\left(\frac{r}{250\,\mathrm{km}}\right)^2 L^{-1}_{\nu_e,53} T^{-1}_{\nu_e,5}$$

Still to slow to impact Y_e significantly,

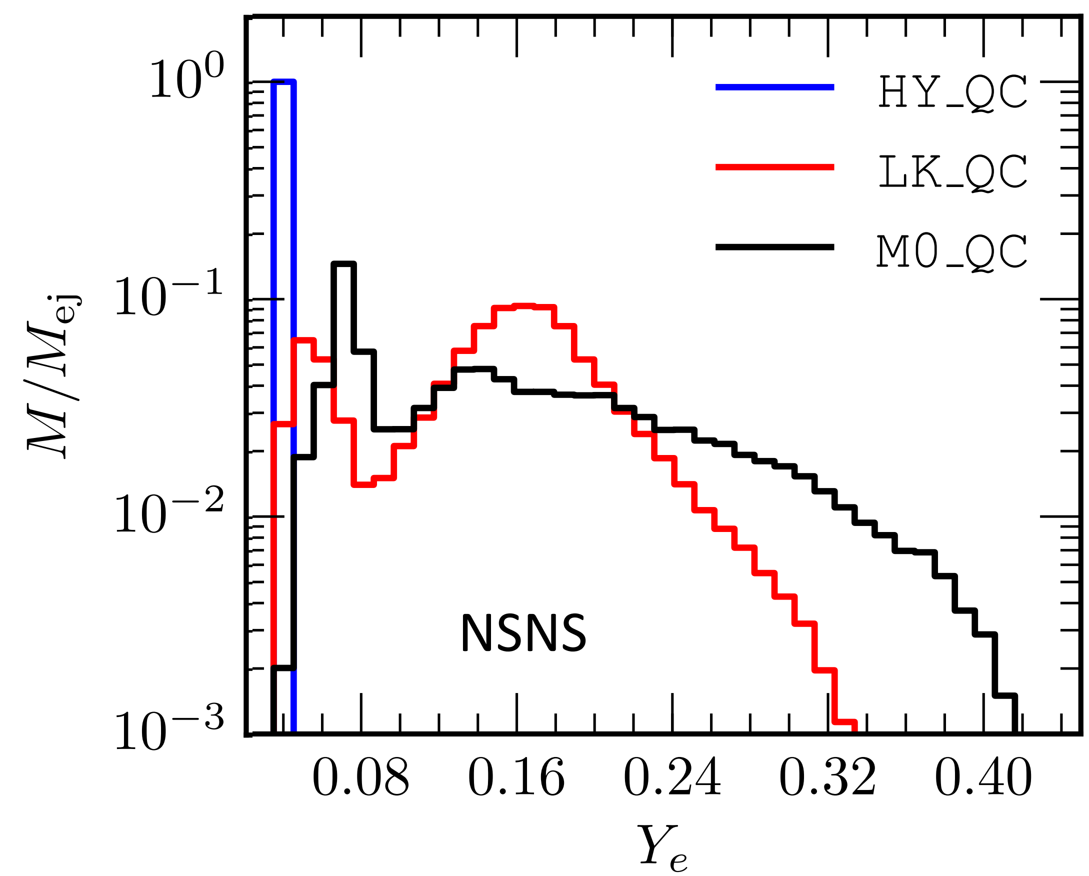
but can impact the first peak nucleosynthesis in the dynamical ejecta



Dynamical Ejecta in BHNS mergers vs NSNS mergers



LR, et al. ‘16



Radice, ..., LR et al. ’16