r-Process nucleosynthesis in neutron star mergers with SkyNet

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Caltech

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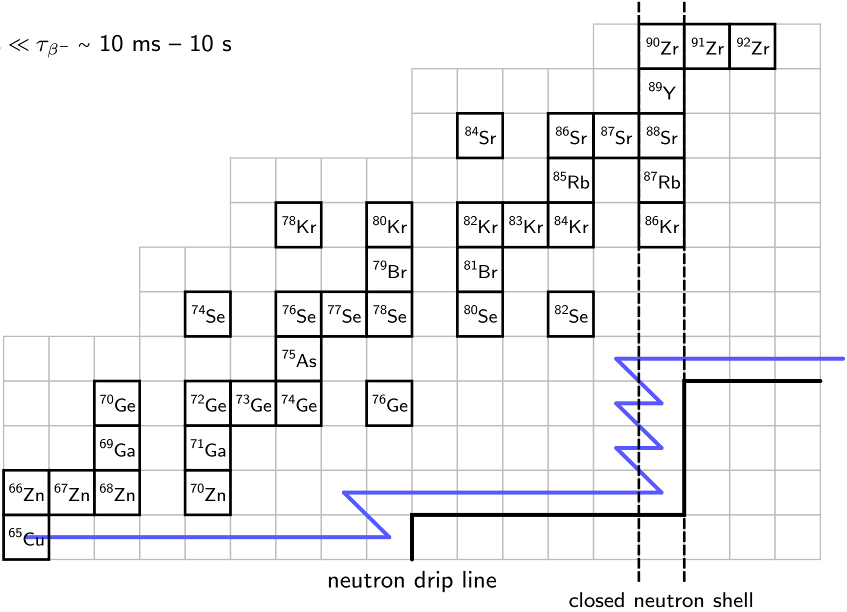
Outline

1. r-Process recap
2. SkyNet
3. Parametrized r-process study
4. r-Process in accretion disk outflow
5. r-Process in NSBH dynamical ejecta (time permitting)

r-Process recap

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



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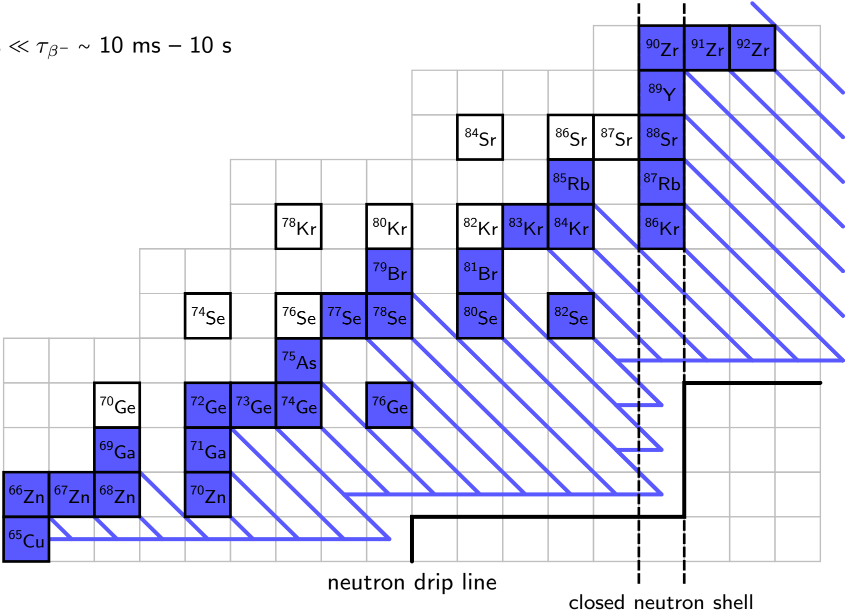
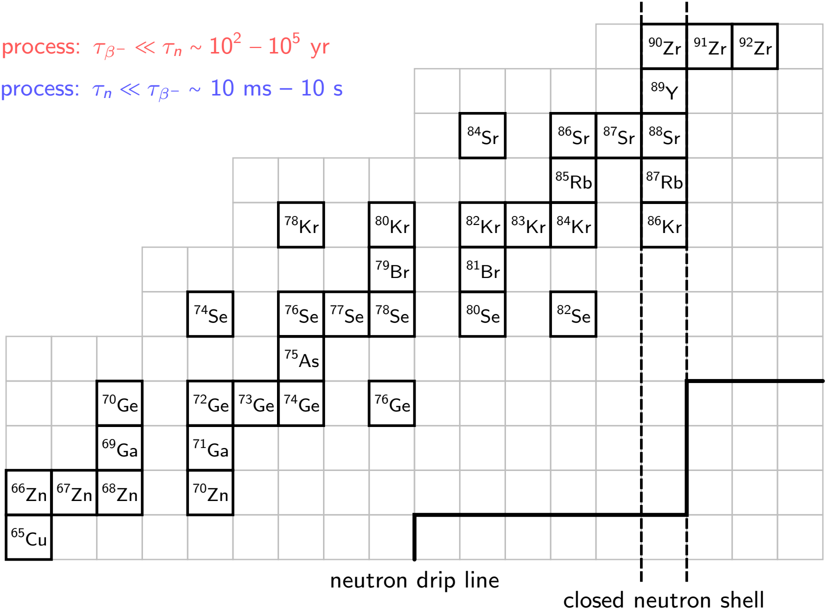


r-Process recap

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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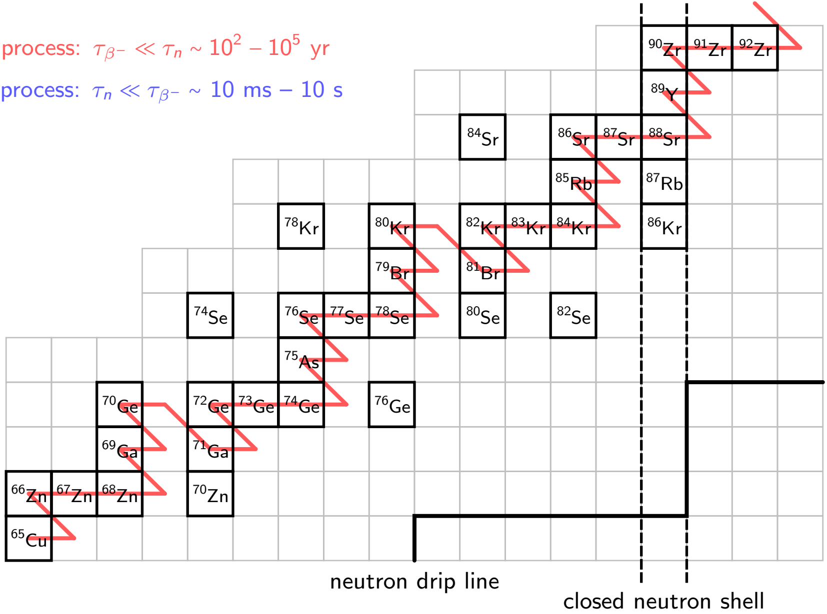

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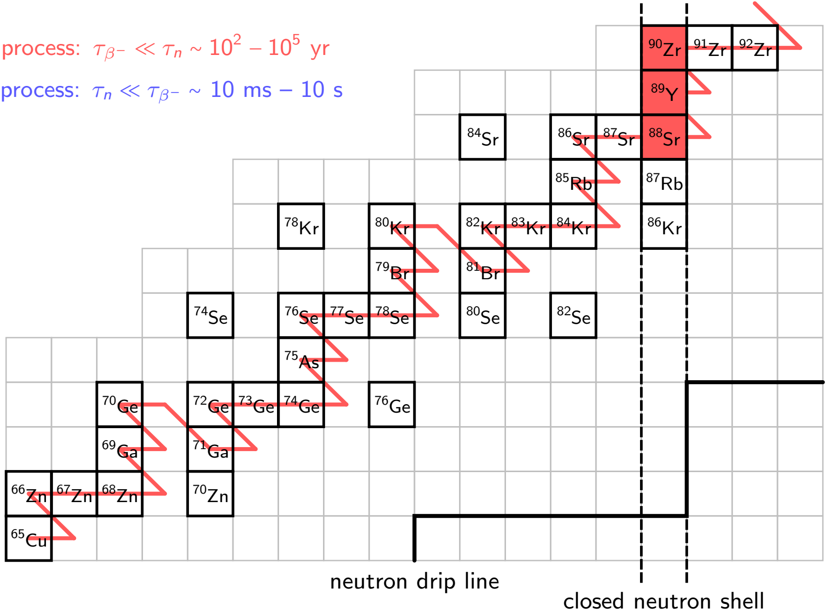

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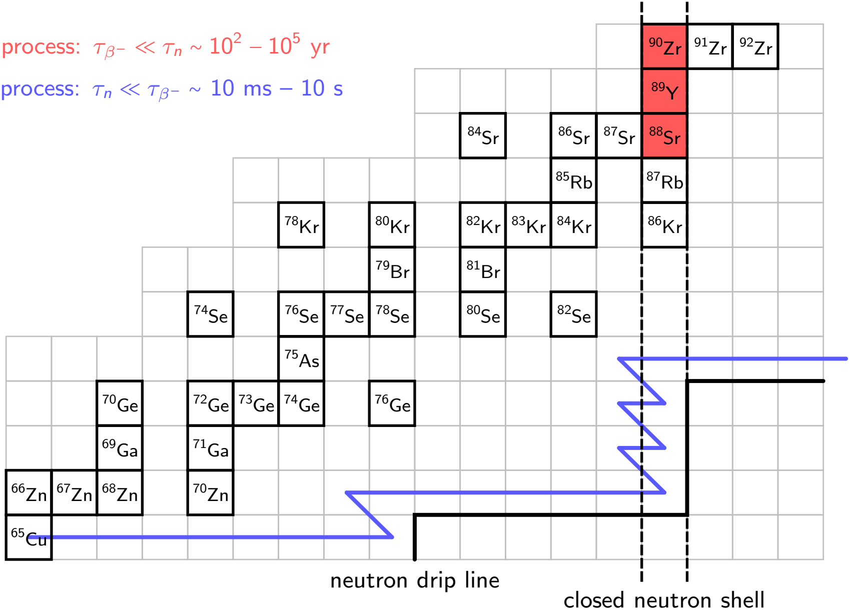

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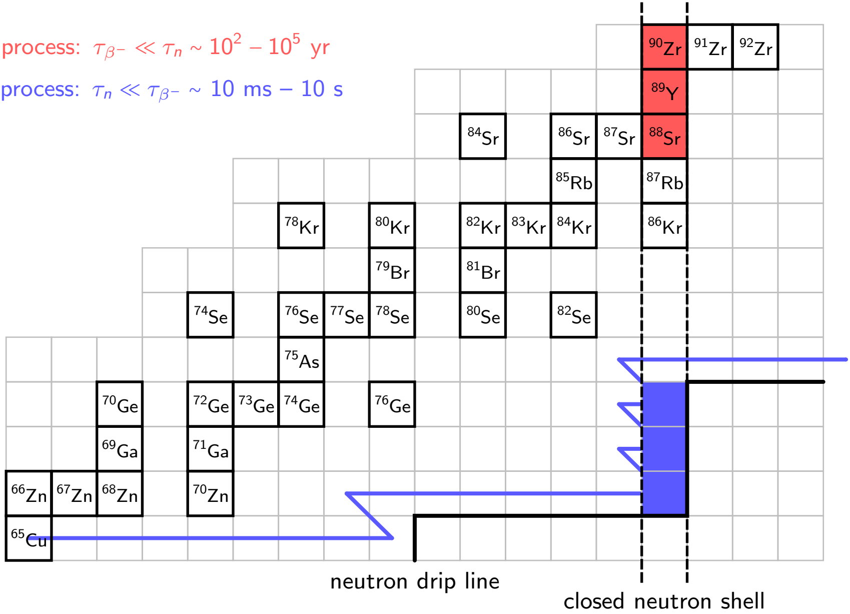

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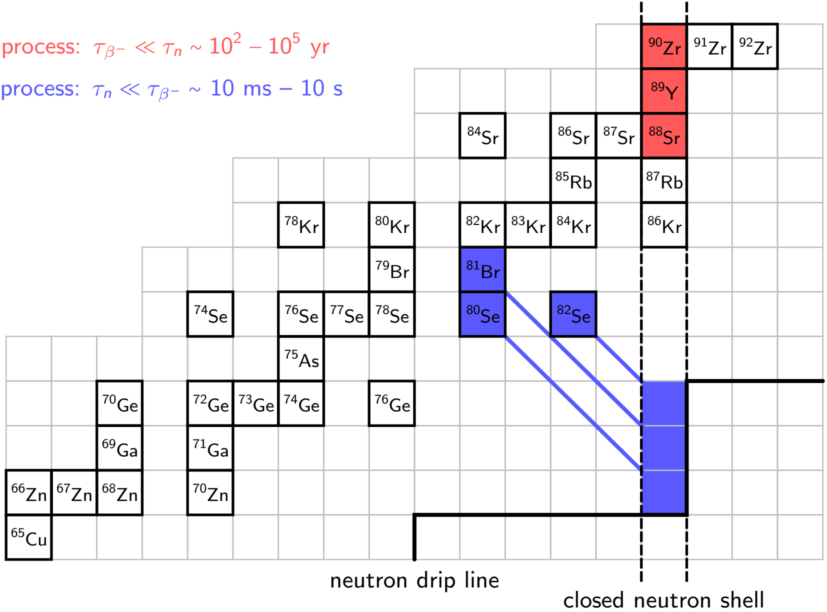
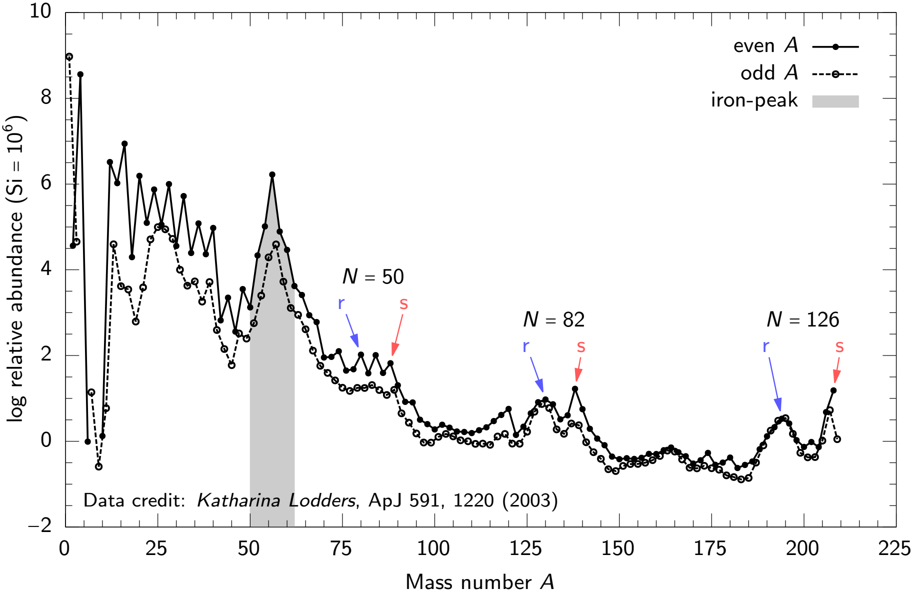


Solar system abundances



SkyNet

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 (soon)

JL, Roberts 2016, *in prep.*

Define abundance

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

Consider reaction

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

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

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

SkyNet reaction types

Strong

- Ordinary: n + ^{196}Au $\rightarrow$ ^{197}Au (REACLIB, Cyburt+10)
- Neutron induced fission: n + ^{235}U $\rightarrow$ ^{118}Pd + ^{118}Pd (Panov+10, Mamdouh+01, Wahl02)
- Spontaneous fission: ^{301}Md $\rightarrow$ ^{121}Ag + ^{180}Xe (Frankel+47)

Weak

- Beta decays: ^{86}Br $\rightarrow$ ^{86}Kr + e$^-$ + $\bar{\nu}_e$ (REACLIB, Fuller+82)
- Electron capture: ^{26}Al + e$^-$ $\rightarrow$ ^{26}Mg + ν_e (REACLIB, Fuller+82)
- Neutrino interactions and e$^-$/e$^+$ capture on free nucleons: n + ν_e $\rightarrow$ p + e$^-$ (Arcones+02)
  - $\lambda_{\nu_e} \propto \int_{w_{ec}}^{\infty} dE\, E^2 (E - Q)^2 (1 - f_e) f_{\nu_e}$

SkyNet additional features

Science

- Expanded Helmholtz equation of state
- Calculate nuclear statistical equilibrium (NSE)
- Calculate inverse rates from *detailed balance* to be consistent with NSE
- NSE evolution mode
- Implementing screening with chemical potential corrections

Code

- Adaptive time stepping
- Python bindings
- Extendible reaction class
- Make movie with chart of nuclides

Parametrized r-process study

Parametrized r-process

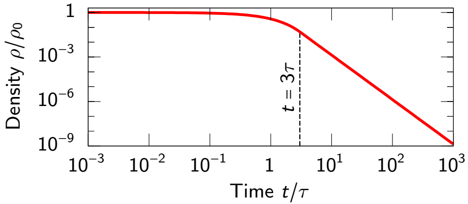
Lippuner & Roberts, 2015, ApJ, 815, 82, arXiv:1508.03133

Parameters

$0.01 \leq Y_e \leq 0.50$	initial electron fraction
$1\,k_B\,\text{baryon}^{-1} \leq s \leq 100\,k_B\,\text{baryon}^{-1}$	initial specific entropy
$0.1\,\text{ms} \leq \tau \leq 500\,\text{ms}$	expansion time scale

Density profile

$$\rho(t,\tau) = \begin{cases} \rho_0 e^{-t/\tau} & t \leq 3\tau \\ \rho_0 \left(\dfrac{3\tau}{te}\right)^3 & t \geq 3\tau \end{cases}$$

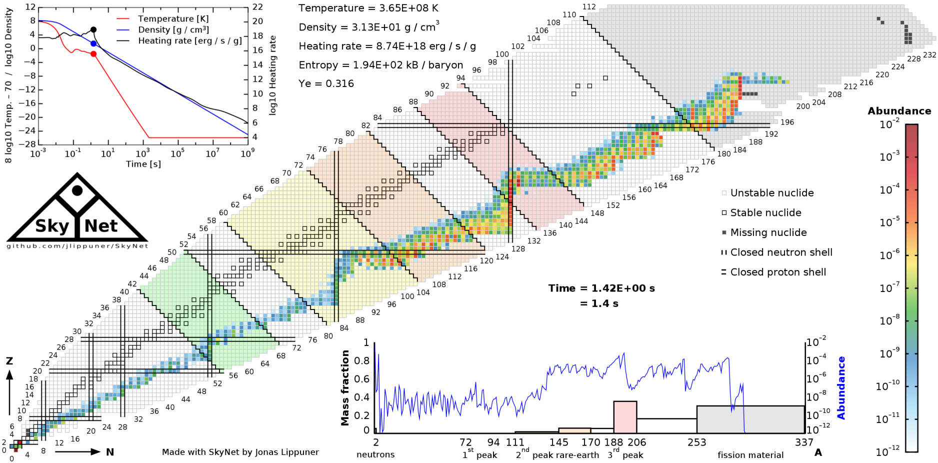


Initial conditions

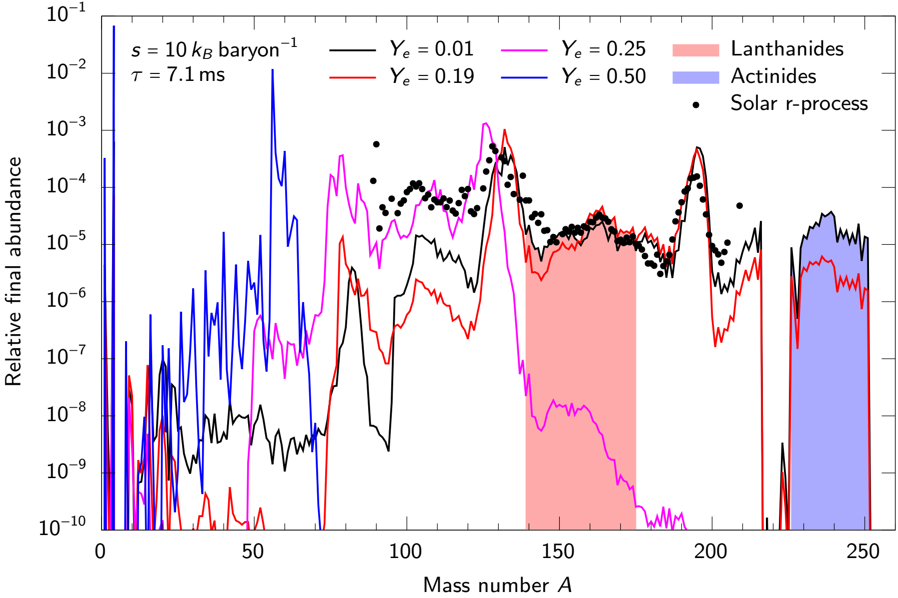
- Choose initial temperature $T_0 = 6\,\text{GK}$
- Find ρ_0 by solving for NSE at T_0 and Y_e that produces specified s

Movies

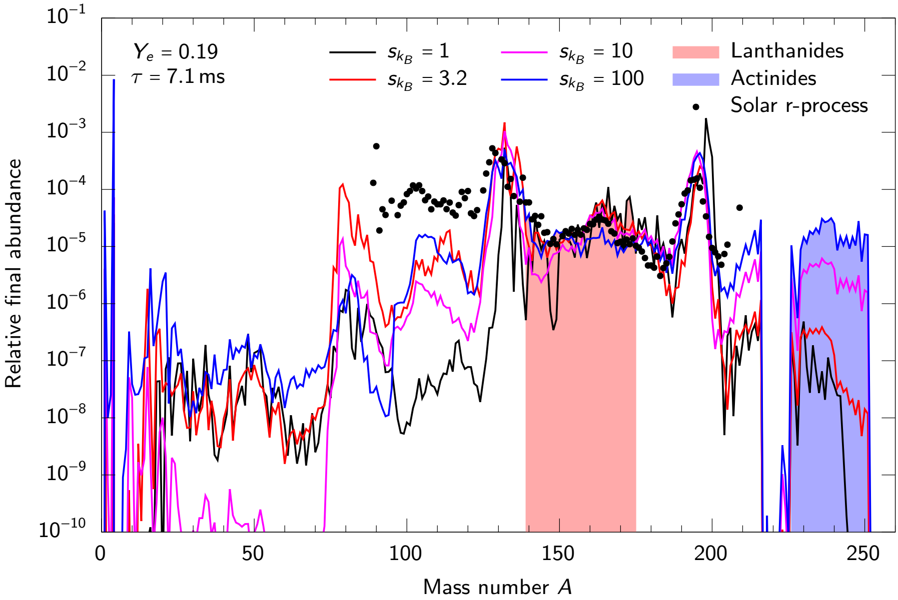
http://lippuner.ca/skynet/SkyNet_Ye_0.010_s_010.000_tau_007.100.mp4
http://lippuner.ca/skynet/SkyNet_Ye_0.250_s_010.000_tau_007.100.mp4



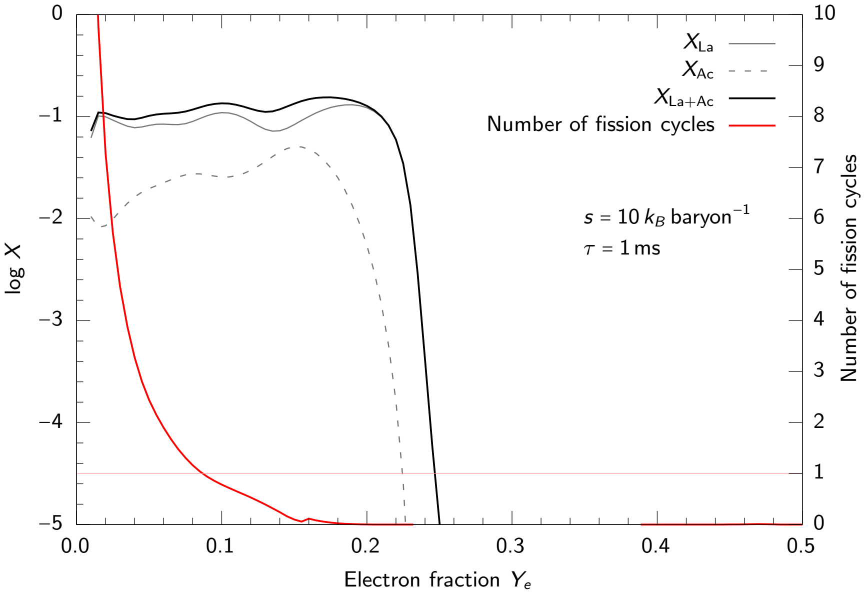
Final abundances vs. electron fraction



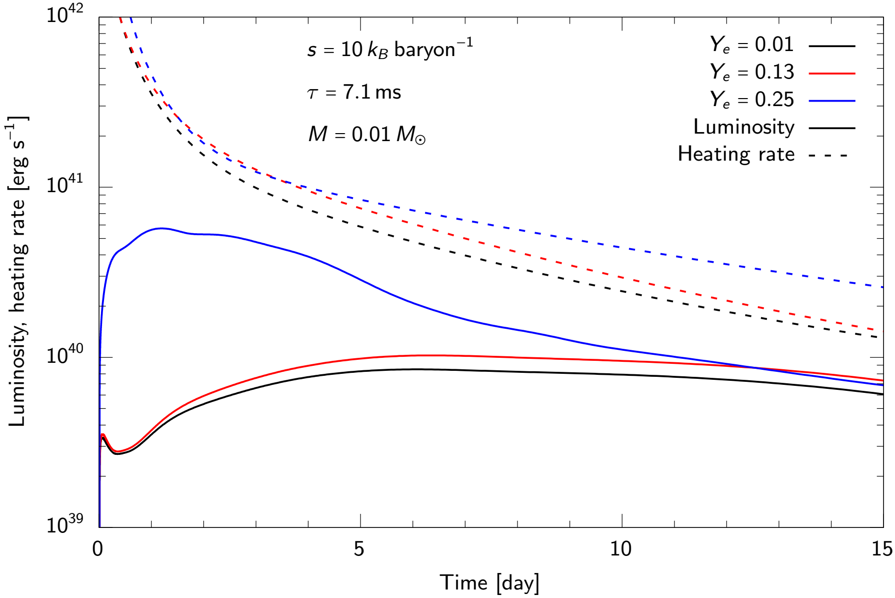
Final abundances vs. entropy



Impact of electron fraction



Example light curves



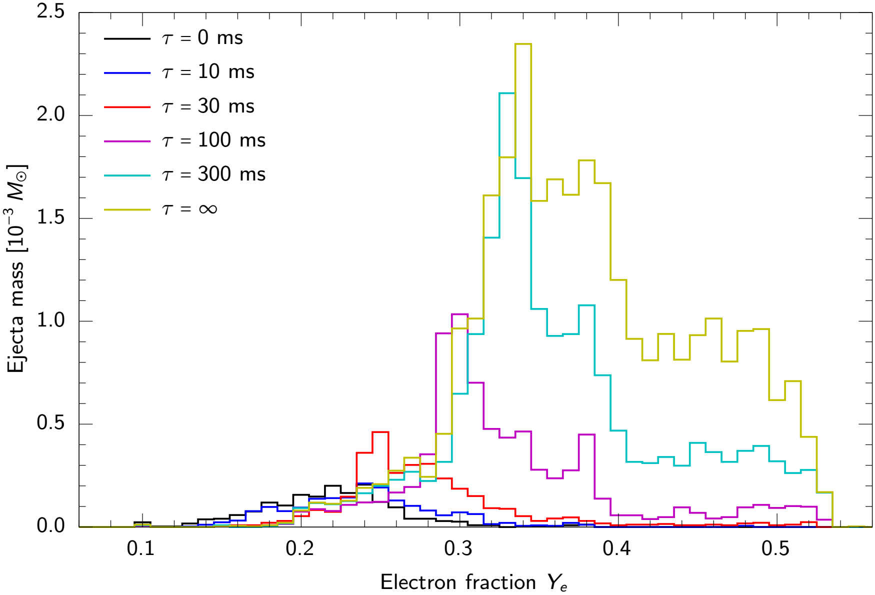
r-Process in accretion disk outflow

Ejecta mass

τ [ms]	M_{ej} $[10^{-3}\,M_\odot]$	$M_{\mathrm{ej},Y_e\leq 0.25}$ $[10^{-3}\,M_\odot]$
0	1.8	1.36
10	1.9	1.07
30	3.3	0.83
100	7.8	0.52
300	18.0	0.67
∞	29.6	0.69

JL, Fernández, Roberts, et al. 2016, *in prep.*

Y_e distribution vs. HMNS lifetime



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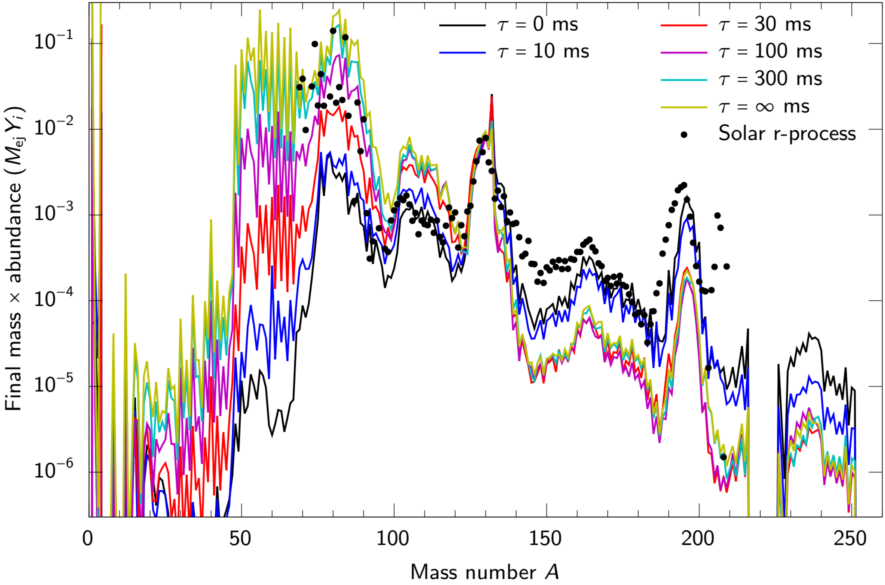
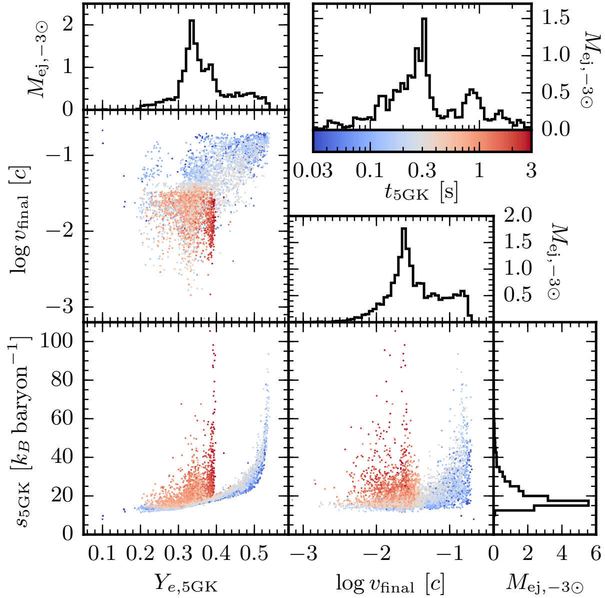


τ = 300 ms ejecta properties



r-Process in NSBH dynamical ejecta

Neutron star–black hole merger

1. Full GR simulation of NS–BH
   Francois Foucart (LBL), Foucart+14
2. Ejecta in SPH code,
   Matt Duez (WSU)
3. Nucleosynthesis with SkyNet and varying neutrino luminosity
   JL and Luke Roberts (Caltech)

Roberts, JL, Duez, et al. 2016, *MNRAS in press*, arXiv:1601.07942

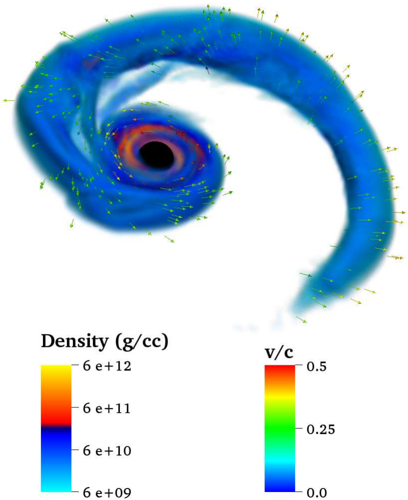
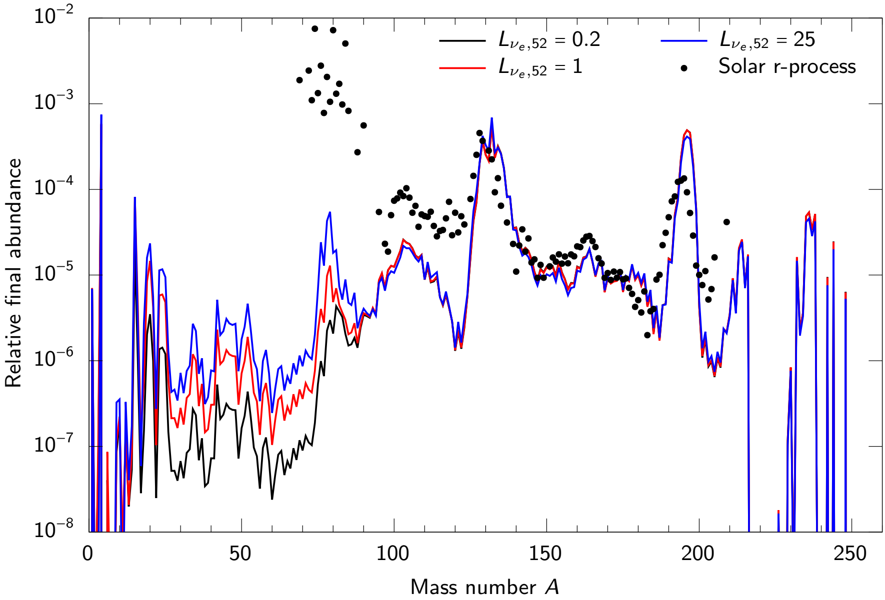
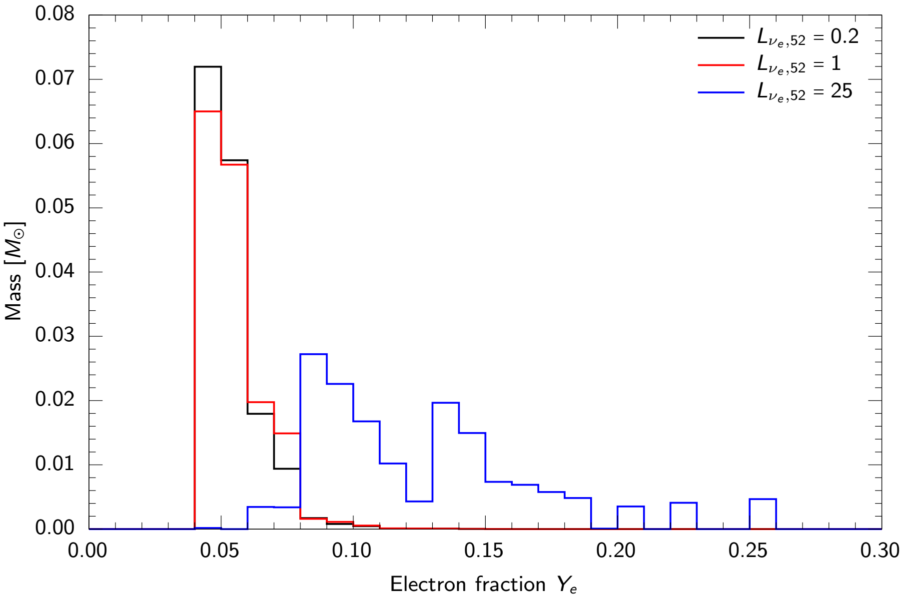


Figure credit: F. Foucart

BHNS: Final abundances vs. neutrino luminosity



BHNS: Electron fraction distribution



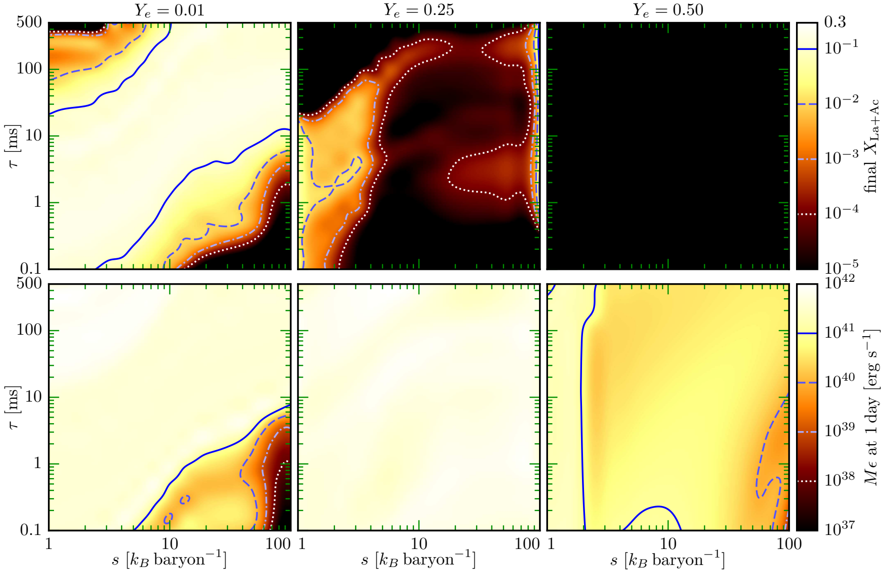
BHNS: New first peak production mechanism

- Original seeds: $A \sim 80 \rightarrow$ full r-process
- With neutrinos:
  - $\nu_e + \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^-$
  - $2\,\mathrm{p} + 2\,\mathrm{n} \rightarrow {}^4\mathrm{He}$
  - $3\,{}^4\mathrm{He} + \mathrm{n} \rightarrow {}^{12}\mathrm{C} + \mathrm{n}$
- Additional low-mass seed nuclei $\rightarrow$ enhanced 1st peak
- No combination of complete and incomplete r-process

Summary

- SkyNet is a flexible reaction network that will be open source
- $Y_e \sim 0.25$ is the critical value for lanthanide production
- Heating rate is fairly uniform
- Disk outflow after neutron star merger produces 3rd peak regardless of τ, but 3rd peak under-produced for $\tau \gtrsim 10$ ms
- Black hole-neutron star merger produces very strong 3rd peak
- Neutrino irradiation can enhance 1st peak via low-mass seed nuclei

Extra slides



$Y_e = 0.01$
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500
100
10
1
0.1
τ [ms]
1
10
100
s [k_B baryon^{-1}]
0.3
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
final $X_{\mathrm{La+Ac}}$
10^{42}
10^{41}
10^{40}
10^{39}
10^{38}
10^{37}
$M\epsilon$ at 1 day [erg s^{-1}]

Nuclear reaction network

Consider reaction

$$[\mathrm{j}] + [\mathrm{k}] \to [\mathrm{m}] \tag{4}$$

$$\begin{aligned}\text{cross section} = \sigma &= \frac{\#\text{ of reactions per target [j] per second}}{\text{flux of projectiles [k]}} \\ &= \frac{R/(Vn_j)}{n_k v} = \frac{r}{n_j n_k v},\end{aligned} \tag{5}$$

and so

$$r = \frac{R}{V} = \sigma v n_j n_k = \#\text{ of reactions per second per volume}, \tag{6}$$

where

$$\begin{aligned} R &= \#\text{ of reactions per second}, \\ V &= \text{volume}, \\ n_{j,k} &= \text{number density of species [j], [k]}, \\ v &= \text{relative speed between [j] and [k]}. \end{aligned}$$

In general

$$r_{j,k} = \int \sigma(\|\boldsymbol{v}_j - \boldsymbol{v}_k\|)\|\boldsymbol{v}_j - \boldsymbol{v}_k\| d^3 n_j d^3 n_k, \tag{7}$$

using Boltzmann distribution

$$r_{j,k} = n_j n_k \langle \sigma v \rangle_{j,k} = n_j n_k \left(\frac{8}{\mu\pi}\right)^{1/2} (k_B T)^{-3/2} \int_0^\infty E\sigma(E) e^{-E/(k_B T)} dE, \tag{8}$$

where

$$\mu = \text{reduced mass} = \frac{m_j m_k}{m_j + m_k},$$

$$T = \text{temperature},$$

$$k_B = \text{Boltzmann constant}.$$

Note that $\langle \sigma v \rangle_{j,k} = \langle \sigma v \rangle_{j,k}(T)$.

Nuclear reaction network

Define *abundance*

$$Y_i = \frac{n_i}{n_B} = \frac{\#\text{ of species [i]}}{\#\text{ of baryons}}, \tag{9}$$

where n_B is baryon number density, then for [j] + [k] → [m]

$$\dot{Y}_m = \frac{r_{j,k}V}{\#\text{ of baryons}} = \frac{r_{j,k}}{n_B} = \frac{Y_j n_B Y_k n_B \langle\sigma v\rangle_{j,k}}{n_B} = Y_j Y_k \lambda_{j,k}, \tag{10}$$

where

$$\lambda_{j,k} = n_B\langle\sigma v\rangle_{j,k} = N_A\rho\langle\sigma v\rangle_{j,k}(T) = \lambda_{j,k}(T,\rho), \tag{11}$$

where N_A is Avogadro's number, and ρ is the mass density.

And, of course

$$\dot{Y}_j = \dot{Y}_k = -\dot{Y}_m. \tag{12}$$

SkyNet

In general

$$\dot{Y}_i = \sum_\alpha N_i^\alpha \lambda_\alpha(T,\rho) \prod_{m\in\mathcal{R}_\alpha} Y_m^{|N_m^\alpha|}, \tag{13}$$

where

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\end{aligned}$$

Example:

$$\dot{Y}_{^4\mathrm{He}} = \underbrace{\qquad\qquad}_{\substack{\text{decay} \\ ^4\mathrm{He}\to 2\,\mathrm{d}}} \quad \underbrace{\qquad\qquad\qquad}_{\substack{\text{producing reaction} \\ \mathrm{p}+{}^7\mathrm{Li}\to 2\,{}^4\mathrm{He}}} \quad \underbrace{\qquad\qquad\qquad\qquad}_{\substack{\text{destroying reaction} \\ \mathrm{n}+\mathrm{p}+2\,{}^4\mathrm{He}\to {}^7\mathrm{Li}+{}^3\mathrm{He}}} + \cdots \tag{14}$$

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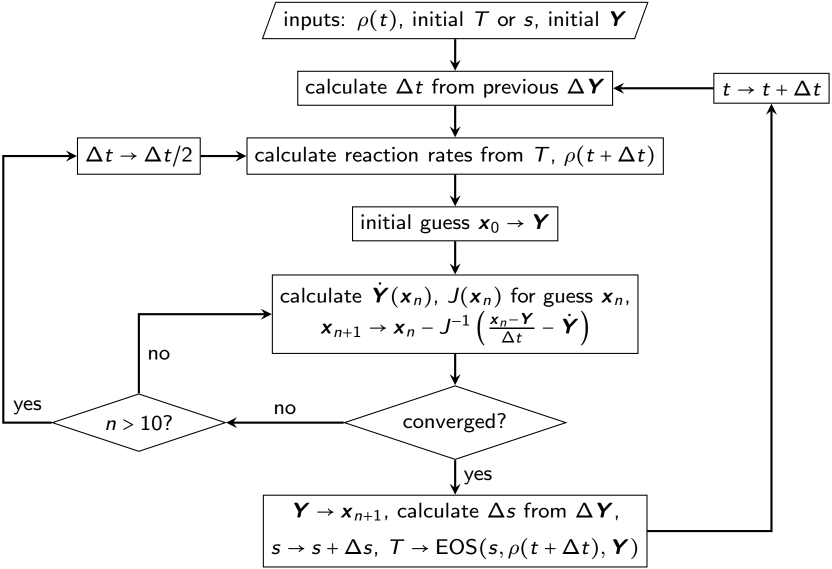
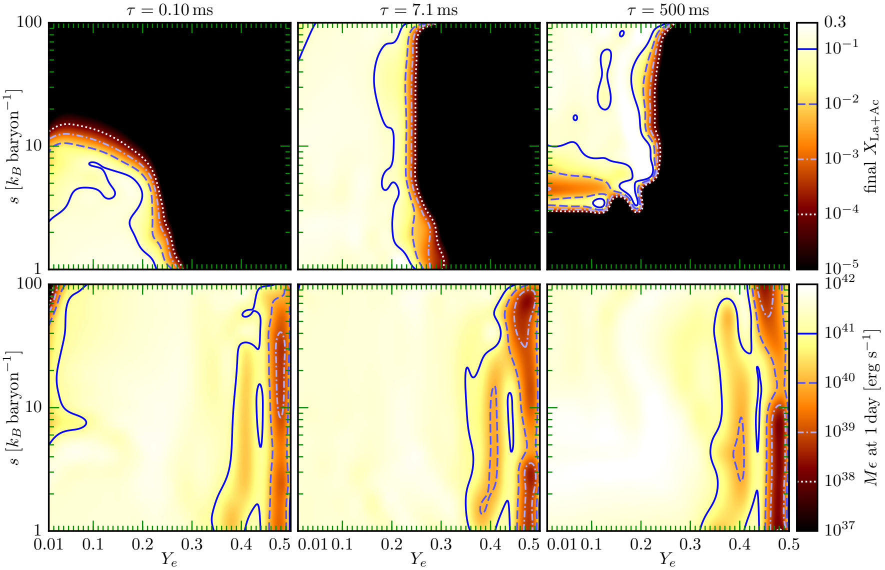
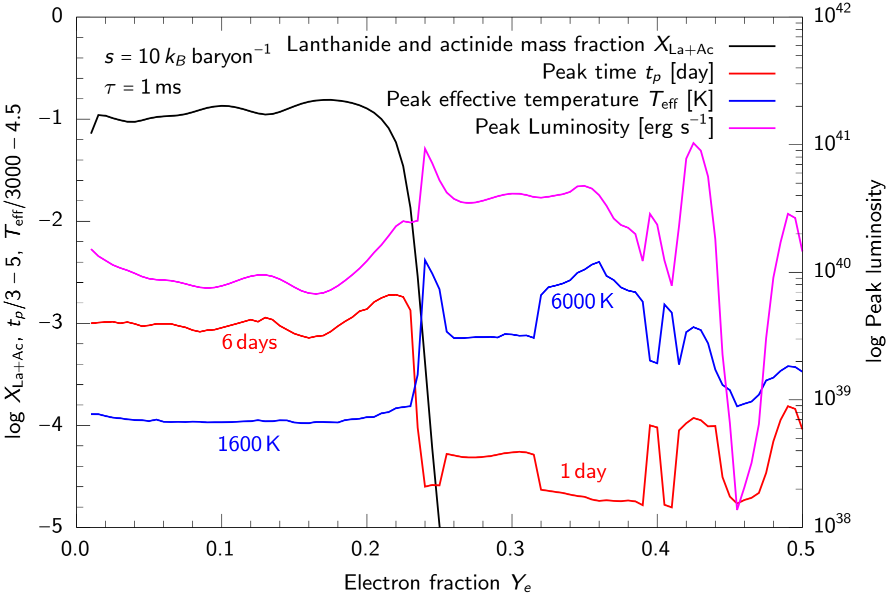
Time stepping method



τ slices


$\tau = 0.10\,\mathrm{ms}$
$\tau = 7.1\,\mathrm{ms}$
$\tau = 500\,\mathrm{ms}$
$s\ [k_B\ \mathrm{baryon}^{-1}]$
100
10
1
Y_e
0.01 0.1 0.2 0.3 0.4 0.5
final $X_{\mathrm{La+Ac}}$
0.3
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$M\epsilon$ at 1 day $[\mathrm{erg\ s^{-1}}]$
10^{42}
10^{41}
10^{40}
10^{39}
10^{38}
10^{37}

Light curves vs. electron fraction



Light curves vs. electron fraction