r-process nucleosynthesis: conditions, sites, and heating rates

Marius Eichler

Technische Universität Darmstadt

August 14, 2017

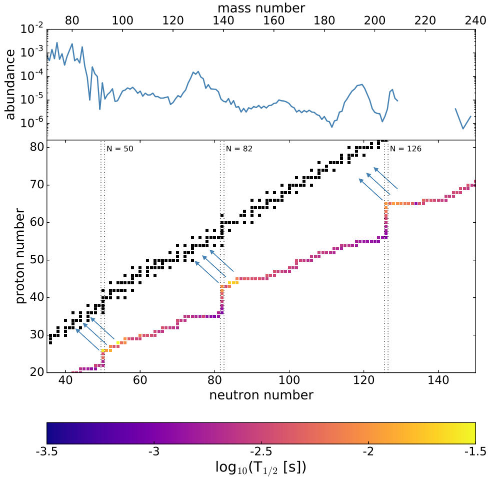
SWISS NATIONAL SCIENCE FOUNDATION

TECHNISCHE UNIVERSITÄT DARMSTADT

HELMHOLTZ GEMEINSCHAFT

SFB 1245

The (solar) r-process abundance pattern



Uncertainties for r-process calculations:

- nuclear properties
  - neutron capture cross sections
  - β-decay rates
  - fission rates & fragment distribution
- hydrodyn. conditions
  - $Y_e = \frac{n_p}{n_p + n_n}$
  - temperatures and densities
  - expansion timescales

basic equations

$$\dot{Y}_i = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} \frac{N^i_{j,k}}{1+\delta_{jk}} \rho N_A \langle \sigma v \rangle_{j;k} Y_j Y_k + \sum_{j,k,l} \frac{N^i_{j,k,l}}{1+\Delta_{jkl}} \rho^2 N_A^2 \langle \sigma v \rangle_{j;k;l} Y_j Y_k Y_l$$

nuclear statistical equilibrium:

$\bar{\mu}(Z,N) = Z\bar{\mu}_p + N\bar{\mu}_n$

$$Y(Z,N) = G_{Z,N} (\rho N_A)^{A-1} \frac{A^{3/2}}{2^A} \left(\frac{2\pi\hbar^2}{m_u kT} \right)^{\frac{3}{2}(A-1)} \exp\left(\frac{B_{Z,N}}{kT} \right) Y_n^N Y_p^Z$$

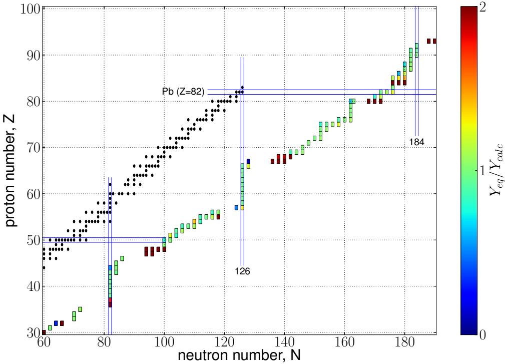
$\sum_i A_i Y_i = 1$

$\sum_i Z_i Y_i = Y_e$

$(n,\gamma) - (\gamma,n)$ equilibrium

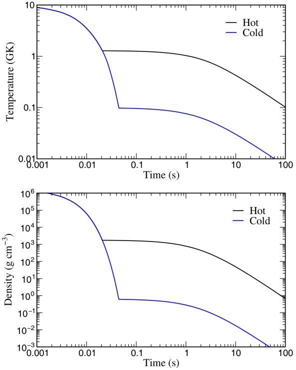
$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{\langle\sigma v\rangle_{n,\gamma}(Z,A)}{\lambda_{\gamma,n}(Z,A+1)} n_n = \frac{G(Z,A+1)}{2G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} n_n \exp[S_n(Z,A+1)/kT]$$

$$\lambda_{\gamma,n}(Z,A+1) = \frac{2G(Z,A)}{G(Z,A+1)} \left(\frac{A}{A+1}\right)^{3/2} \left(\frac{m_u kT}{2\pi\hbar^2}\right)^{3/2} \langle\sigma v\rangle_{n,\gamma}(Z,A) \exp[-S_n(Z,A+1)/kT]$$

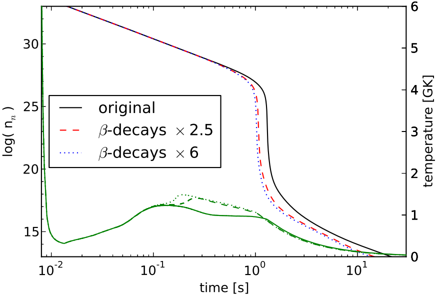


Hot and cold r-process

first defined by Wanajo (2007)



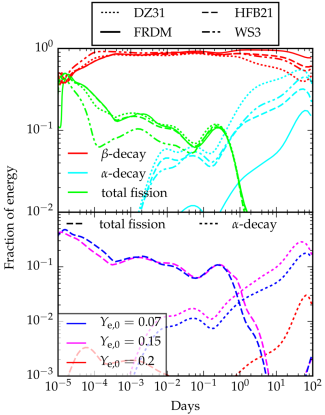
Petermann et al. (2012)



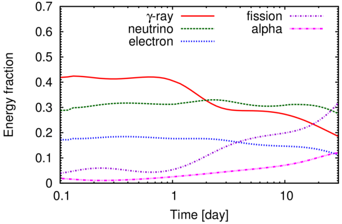
Eichler et al. (2015)

tidal ejecta are a hot r-process scenario if nuclear heating is taken into account

Late-time heating from radioactive decays



Barnes et al. (2016)

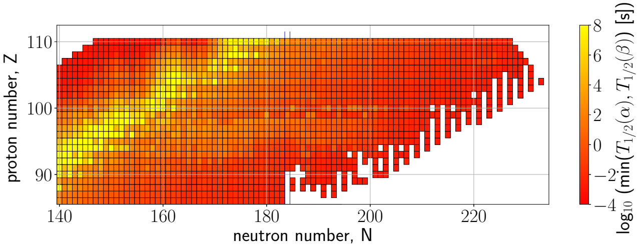


Hotokezaka et al. (2016)

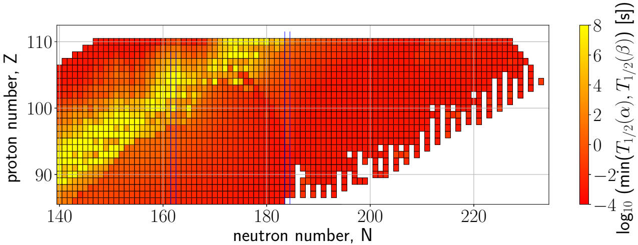
see also Metzger (2014), Lippuner & Roberts (2015), Fernandez & Metzger (2016), Rosswog et al. (2017), Wollaeger et al. (2017)

Survival timescales of heavy nuclei

Möller et al. (2003):

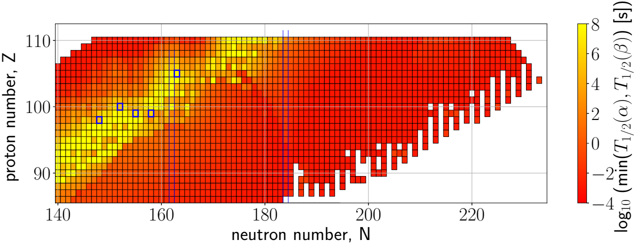


Marketin et al. (2015):



Fission powering kilonova/macronova light curves

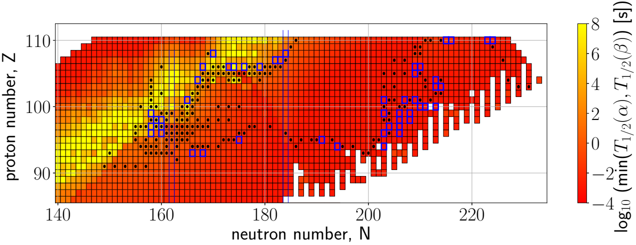
experimentally known SF rates with $1\ \mathrm{d} < \mathrm{T}_{1/2} < 2$ weeks



Phenomenological spontaneous fission rates

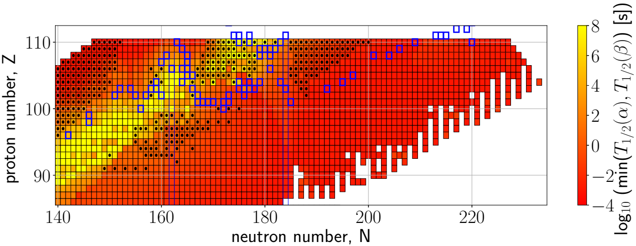
Petermann et al. (2012)

$\log(T_{1/2})[s] = 8.08 B_f - 24.05$



Zagrebaev et al. (2011)

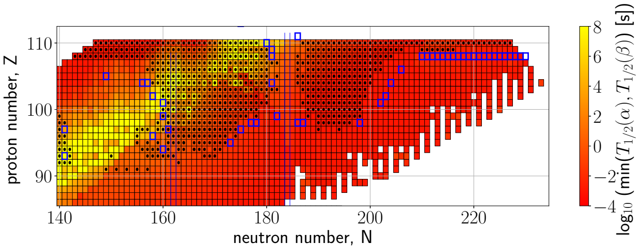
$\log(T_{1/2})[s] = 1146.4 - 75.3\,\frac{Z^2}{A} + 1.638\left(\frac{Z^2}{A}\right)^2 - 0.012\left(\frac{Z^2}{A}\right)^3 + (7.24 - 0.095\frac{Z^2}{A})B_f + C(Z,A)$



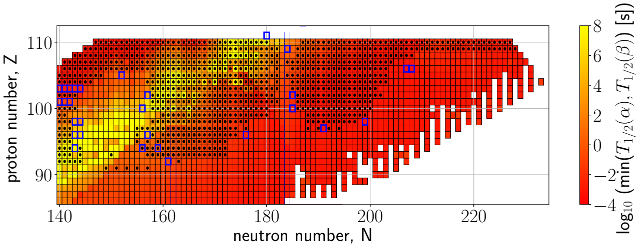
Phenomenological spontaneous fission rates

Based on ETFSI barriers (sets from I. Panov)

$\log(T_{1/2})[s] = 7.77 B_f - 33.3$

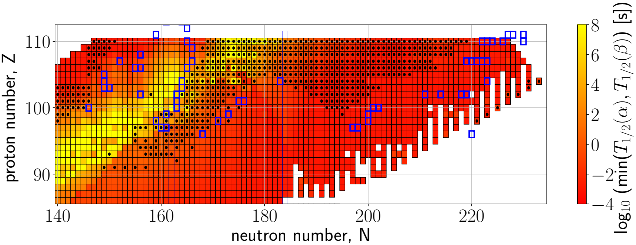


$\log(T_{1/2})[s] = 10.145 B_f - 50.127$



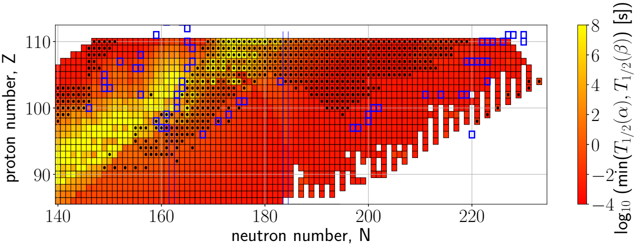
Spontaneous fission rates

Based on BCPM EDF (Giuliani et al. 2017)



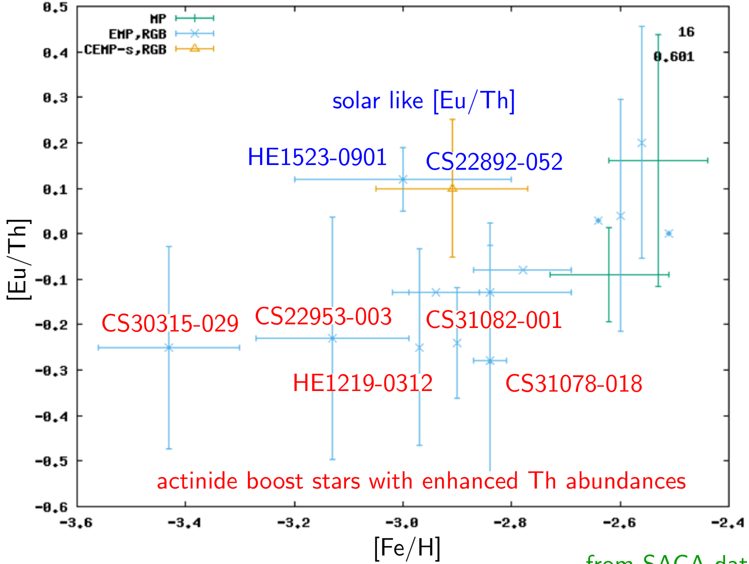
Spontaneous fission rates

Based on BCPM EDF (Giuliani et al. 2017)



based on these models very unlikely that spontaneous fission occurs on timescales between 1 day and 2 weeks

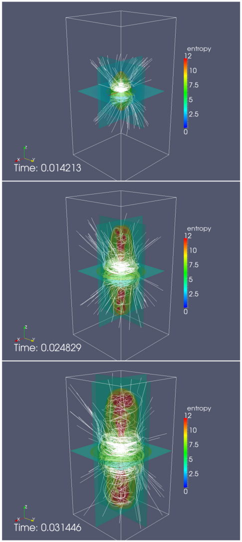
Actinide abundances in Metal-poor stars

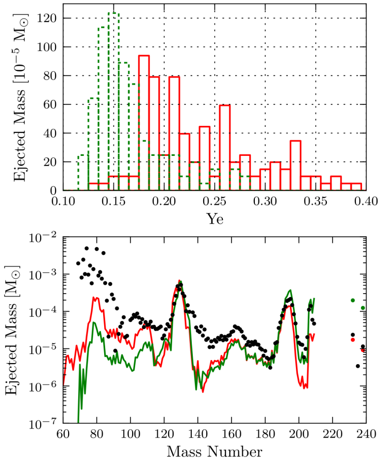


from SAGA database

from Meng-Ru's presentation (10.08.2017)

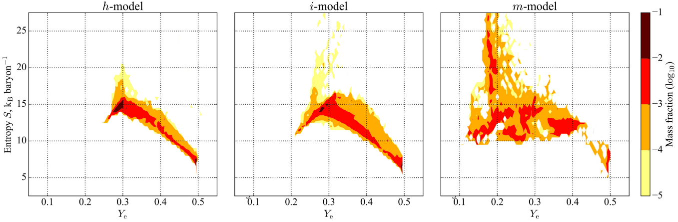
MHD supernovae



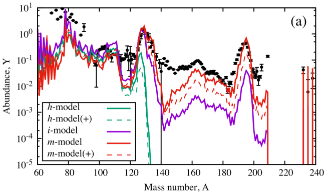


Winteler et al. (2012)

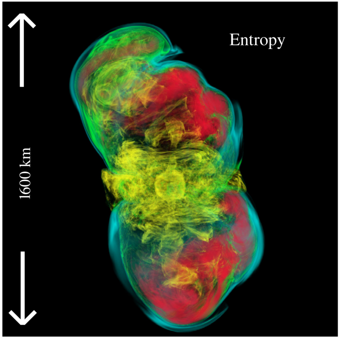
Other models



Nishimura et al. (2017)

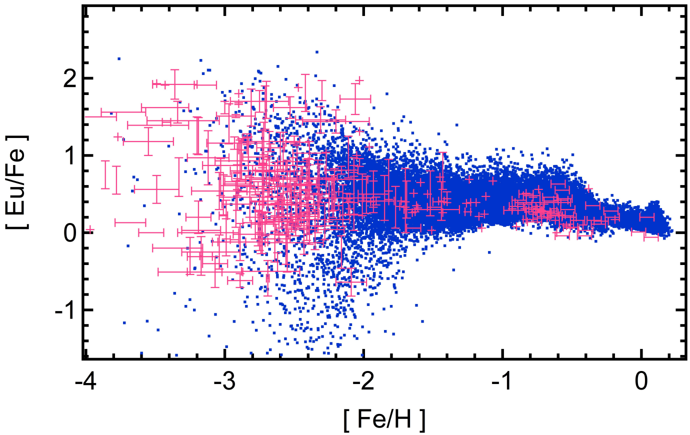


see also Takiwaki et al. (2009)



Mösta et al. (2014)

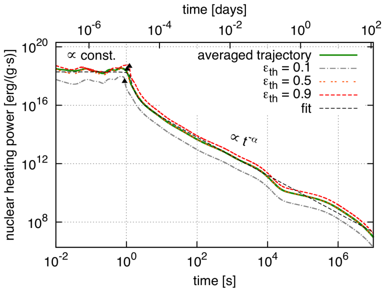
MHD supernovae in GCE



Wehmeyer et al. (2015)

Is there a demand for a reduced r-process network for hydro simulations?

Analytic formula for nuclear heating



Korobkin et al. (2012)

Barnes et al. (2016):

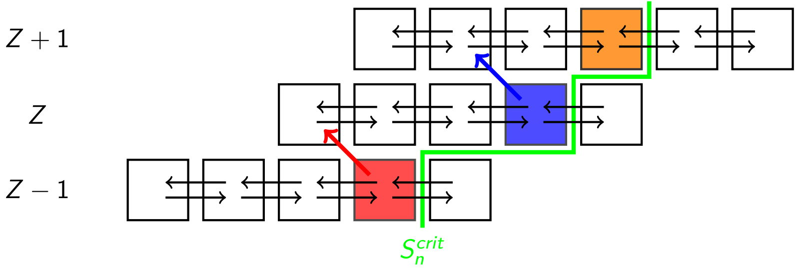
$$f_{tot}(t) = 0.36 \left[\exp(-at) + \frac{\ln(1+2bt^d)}{2bt^d} \right]$$

only valid for FRDM!

Table 1
Analytic fit parameters for $f_{\rm tot}(t)$

Model		Coefficients		
$M/M_\odot$	$v_{\rm ej}/c$	a	b	d
1×10^{-3}	0.1	2.01	0.28	1.12
1×10^{-3}	0.2	4.52	0.62	1.39
1×10^{-3}	0.3	8.16	1.19	1.52
5×10^{-3}	0.1	0.81	0.19	0.86
5×10^{-3}	0.2	1.90	0.28	1.21
5×10^{-3}	0.3	3.20	0.45	1.39
1×10^{-2}	0.1	0.56	0.17	0.74
1×10^{-2}	0.2	1.31	0.21	1.13
1×10^{-2}	0.3	2.19	0.31	1.32
5×10^{-2}	0.1	0.27	0.10	0.60
5×10^{-2}	0.2	0.55	0.13	0.90
5×10^{-2}	0.3	0.95	0.15	1.13

Starting point: waiting point approximation



$$\dot{Y}(Z) = \lambda_\beta(Z-1, N_{Z-1})Y(Z-1) - \lambda_\beta(Z, N_Z)Y(Z)$$

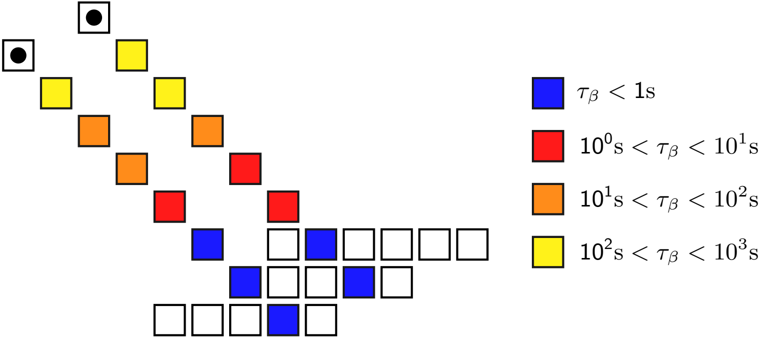
$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{G(Z,A+1)}{2G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} n_n \exp[S_n(Z,A+1)/kT] = 1$$

$$S_n^{crit} = -kT \ln \left[n_n \frac{G(Z,N+1)}{2G(Z,N)} \left(\frac{A+1}{A}\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2}\right];$$

$$S_n(Z, N_Z) > S_n^{crit} > S_n(Z, N_Z+1)$$

Decay to stability

(first) idea: look at isobars and distribute nuclei into bins according to their β-decay timescales



abundances of isobars stay constant for β-decays with $P_n = 0$