Astrophysics of gravitational wave sources

Lecture 10: Electromagnetic signatures of merger & r-process

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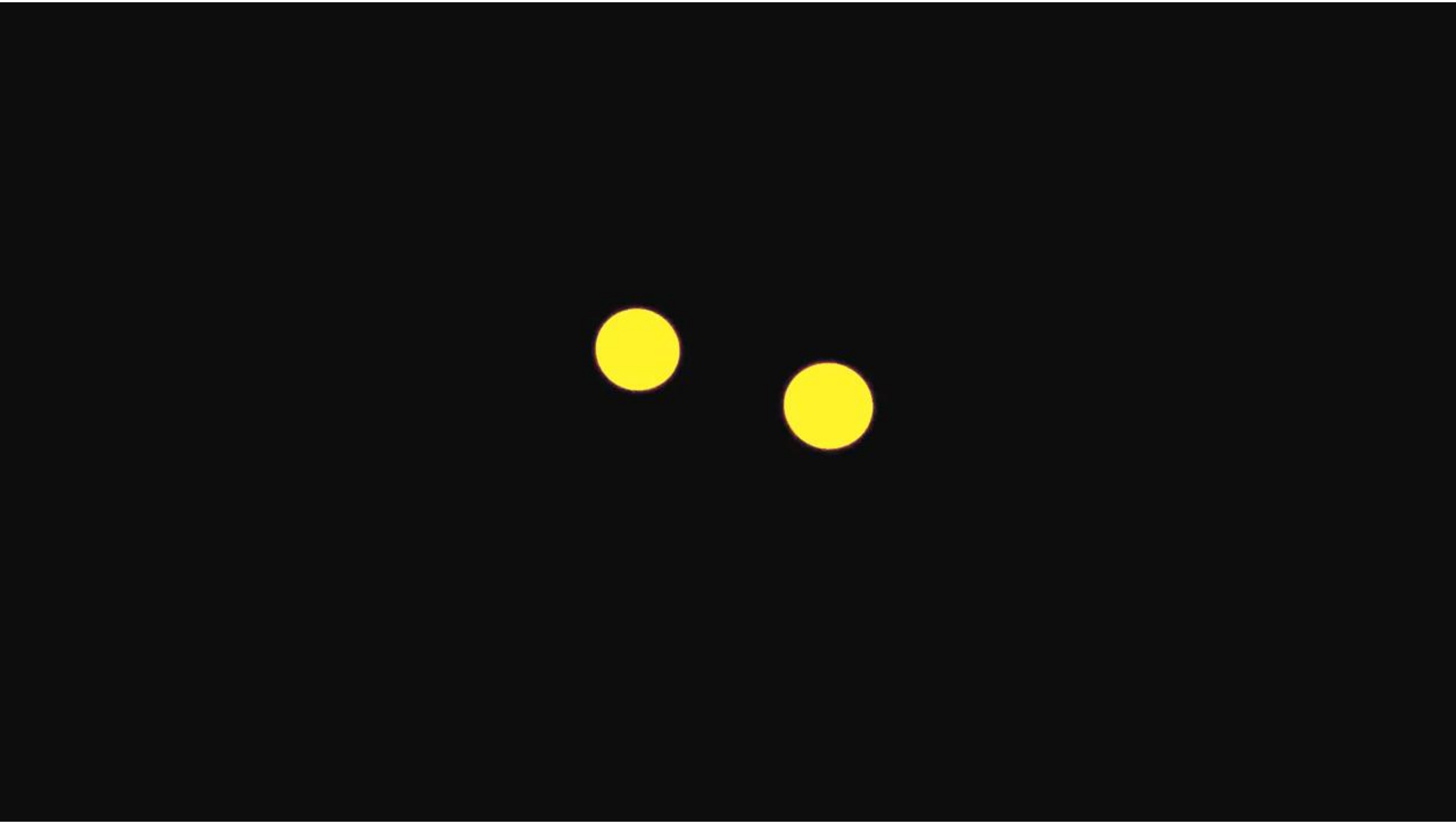
Binary neutron star merger



Radice et al.

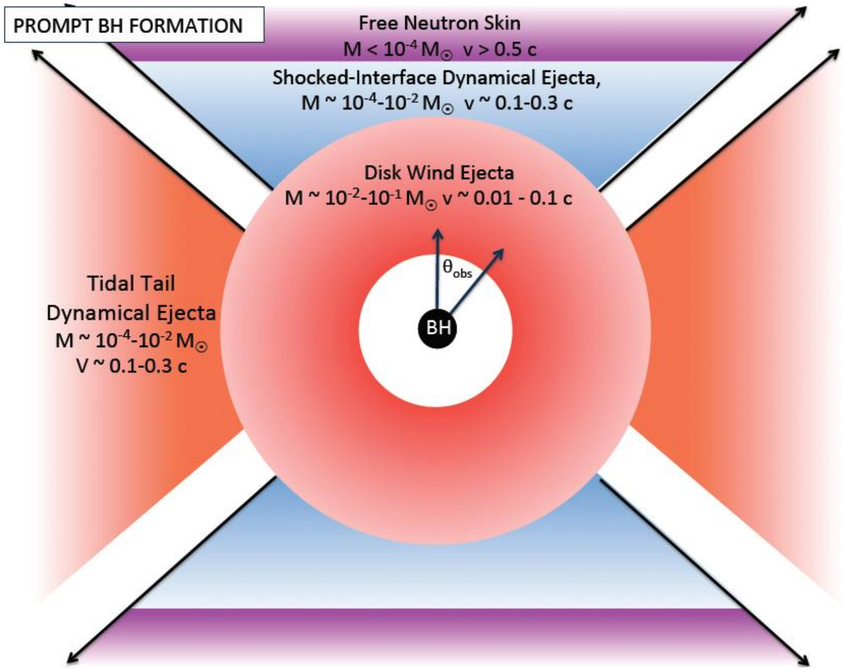
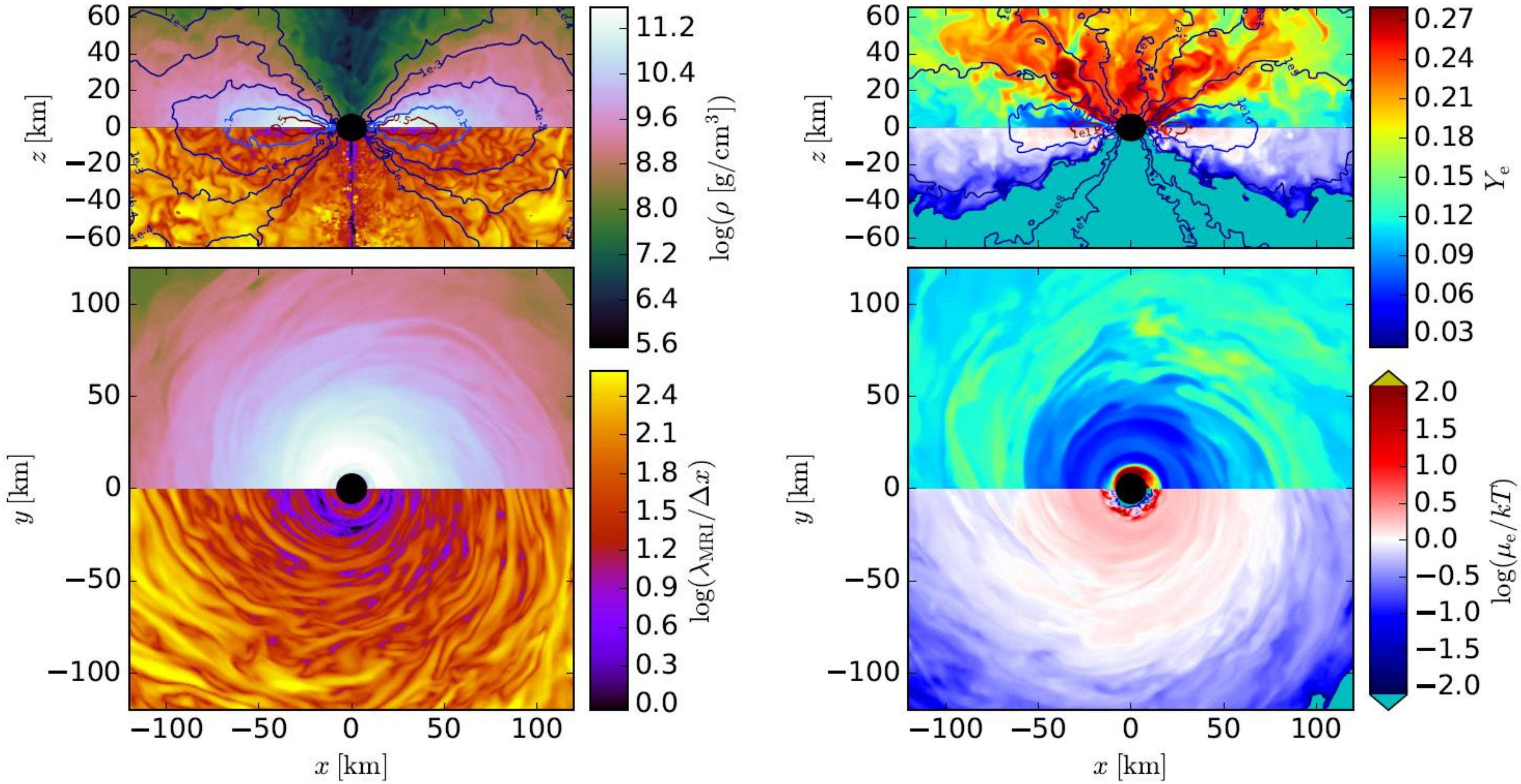


Table 2: Sources of r-Process Ejecta in Binary Neutron Star Mergers

Ejecta Type	$M_{\rm ej}(M_\odot)$	$v_{\rm ej}(c)$	Color	$M_{\rm ej}$ decreases with	References
Tidal Tails	$\sim 10^{-4} - 10^{-2}$	$0.15 - 0.35$	Red (NIR)	$q = M_2/M_1$	e.g., 1,2
Polar Shocked	$\sim 10^{-4} - 10^{-2}$	$0.15 - 0.35$	Blue (visual)	$M_{\rm rem}/M_{\rm max}$, $R_{\rm ns}$	e.g., 3–5
Disk Outflows	$10^{-4} - 0.07$	$0.03 - 0.1$	Blue+Red	$M_{\rm rem}/M_{\rm max}$	e.g., 6–8

Metzger (2017)



Siegel & Metzger (2017)

Nuclear statistical equilibrium

$$Y_i = G_i(\rho N_\mathrm{A})^{A_i-1}\frac{A_i^{3/2}}{2^{A_i}}\left(\frac{2\pi\hbar^2}{m_u k_b T}\right)^{3/2(A_i-1)} \exp(B_i/k_b T)Y_n^{N_i}Y_p^{Z_i}.$$

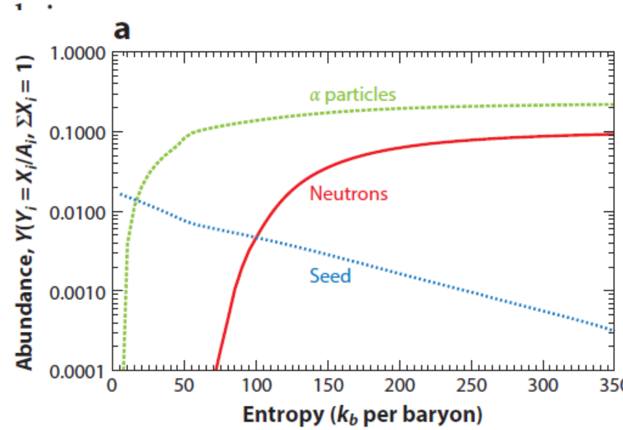
Thielemann et al. (2017)

As a function of time, NSE follows density, temperature and Ye

very high densities favor large nuclei, due to the high power of ρ^{A_i-1}

very high temperatures favor light nuclei, due to $(k_b T)^{-3/2(A_i-1)}$

intermediate regime, $\exp(B_i/k_b T)$ favors tightly bound r

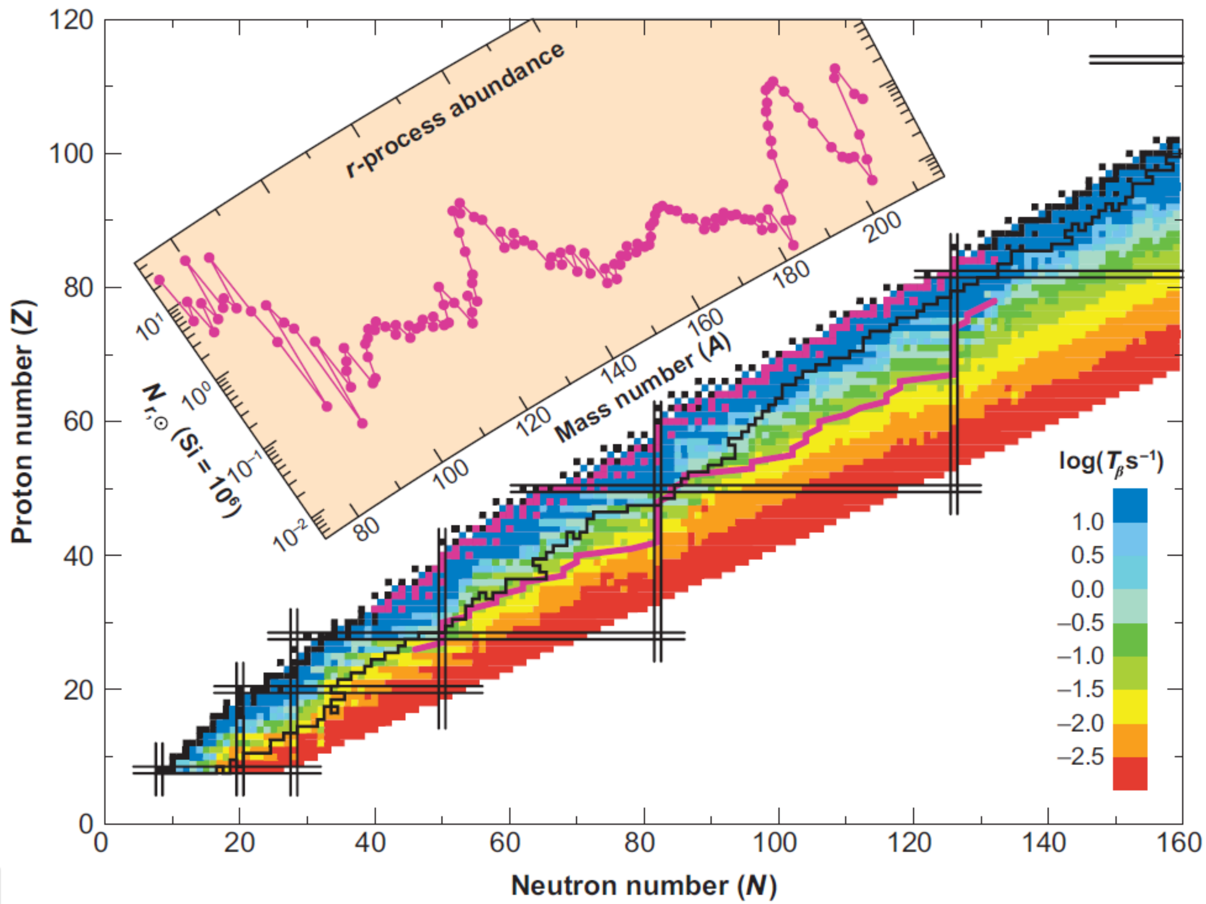


$$\frac{\mathrm{BE}}{A\cdot\mathrm{MeV}} = a - \frac{b}{A^{1/3}} - \frac{cZ^2}{A^{4/3}} - \frac{d(N-Z)^2}{A^2} \pm \frac{e}{A^{7/4}}$$

$\alpha+\alpha+\alpha \rightarrow {}^{12}\mathrm{C}$ or $\alpha+\alpha+n \rightarrow {}^{9}\mathrm{Be}$

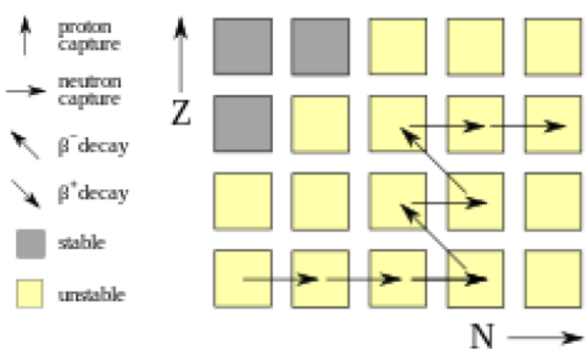
Bottleneck, works only at high density

At low density: alpha-rich freezeout: H, He, A~90



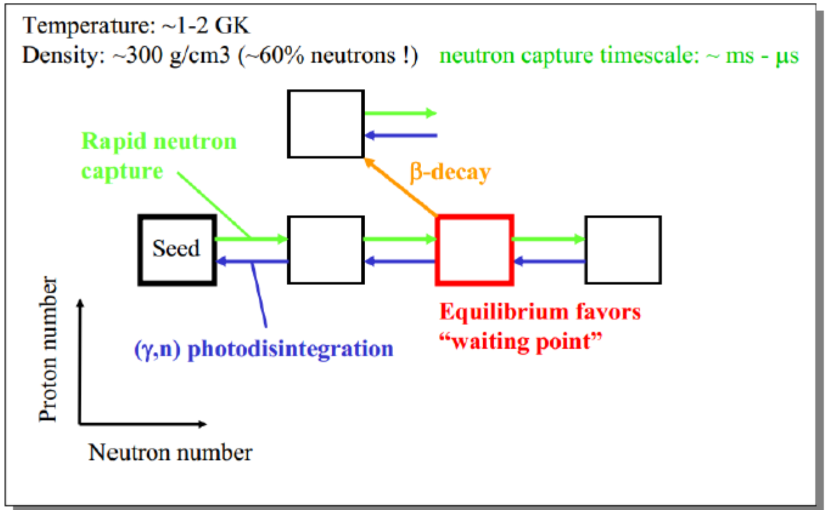
r-process
rapid neutron captures

X(n,γ)Y



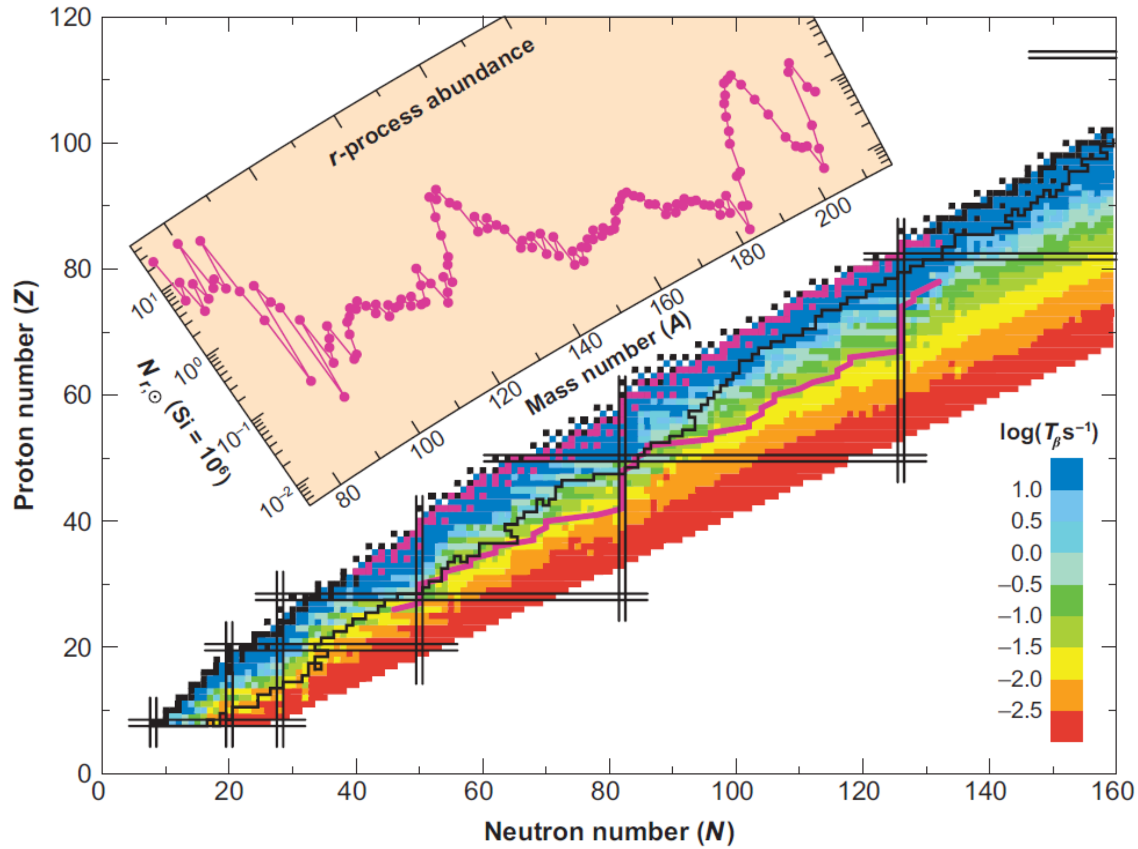
synthesis of neutron-rich nuclei
A > 60

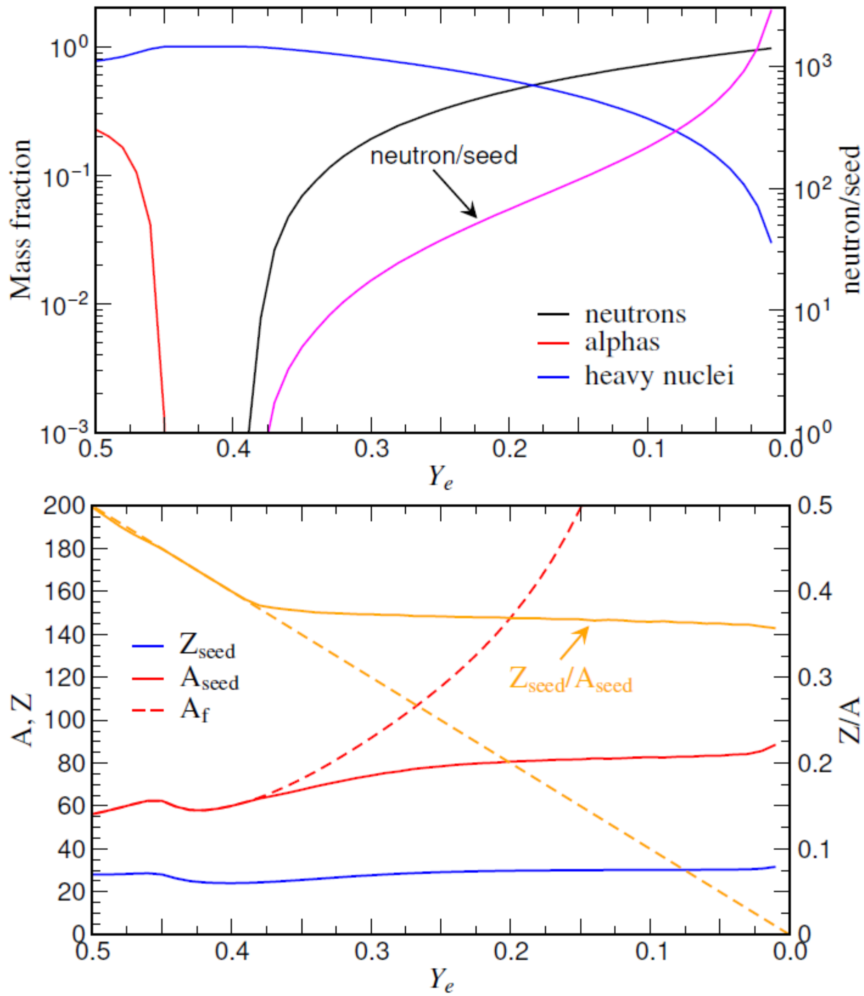
Sneden et al. (2008)



https://www.asc.ohio-state.edu/physics/ntg/6805/slides/rprocess.pdf

Fission terminates r-process -> recycling





$$A_f = A_{\rm seed} + n_s$$

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

$$Y_e = Y_{e,\rm eq} = \left[1 + \frac{L_{\bar{\nu}_e} W_{\bar{\nu}_e}}{L_{\nu_e} W_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2\Delta + \Delta^2/\langle E_{\bar{\nu}_e}\rangle}{\varepsilon_{\nu_e} + 2\Delta + \Delta^2/\langle E_{\nu_e}\rangle}\right]^{-1}$$

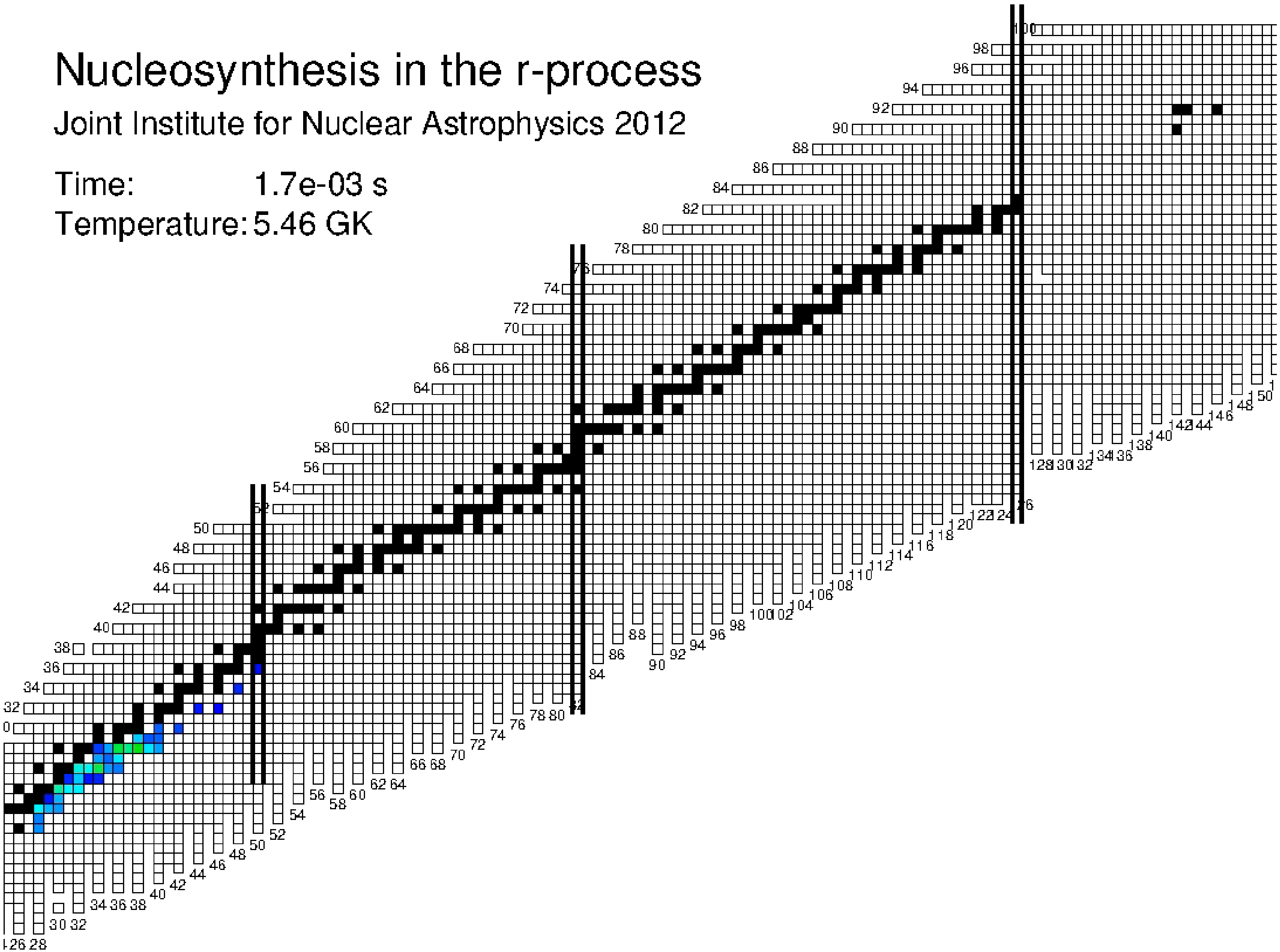
$$\varepsilon_\nu = \langle E_\nu^2\rangle / \langle E_\nu \rangle$$

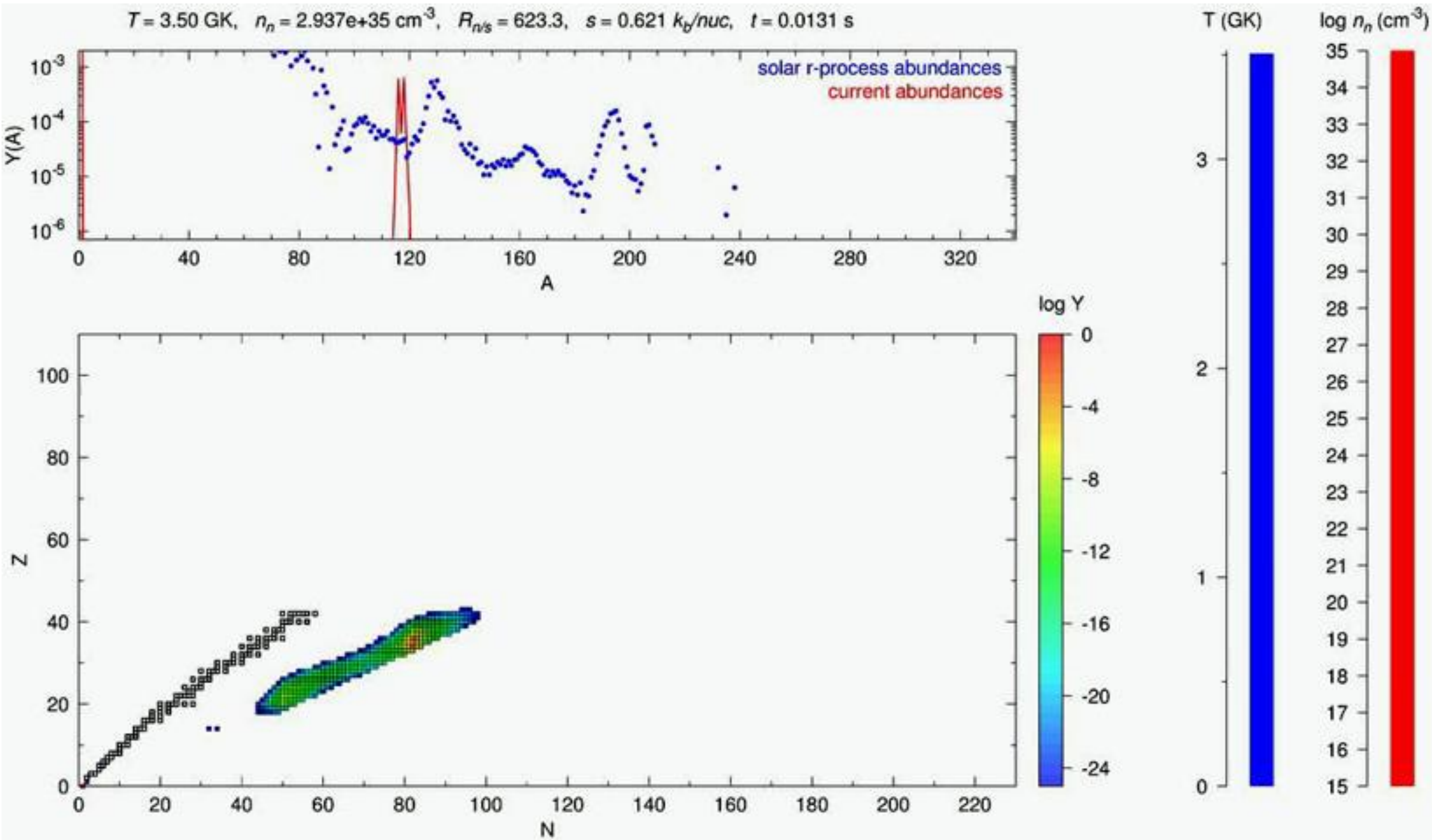
$$W_\nu \approx 1 + 1.01\langle E_\nu\rangle/(m_n c^2),\ W_{\bar{\nu}} \approx 1 - 7.22\langle E_{\bar{\nu}}\rangle/(m_n c^2)$$

Δ =1.2933 MeV the neutron-proton mass difference

Thielemann et al. (2019)

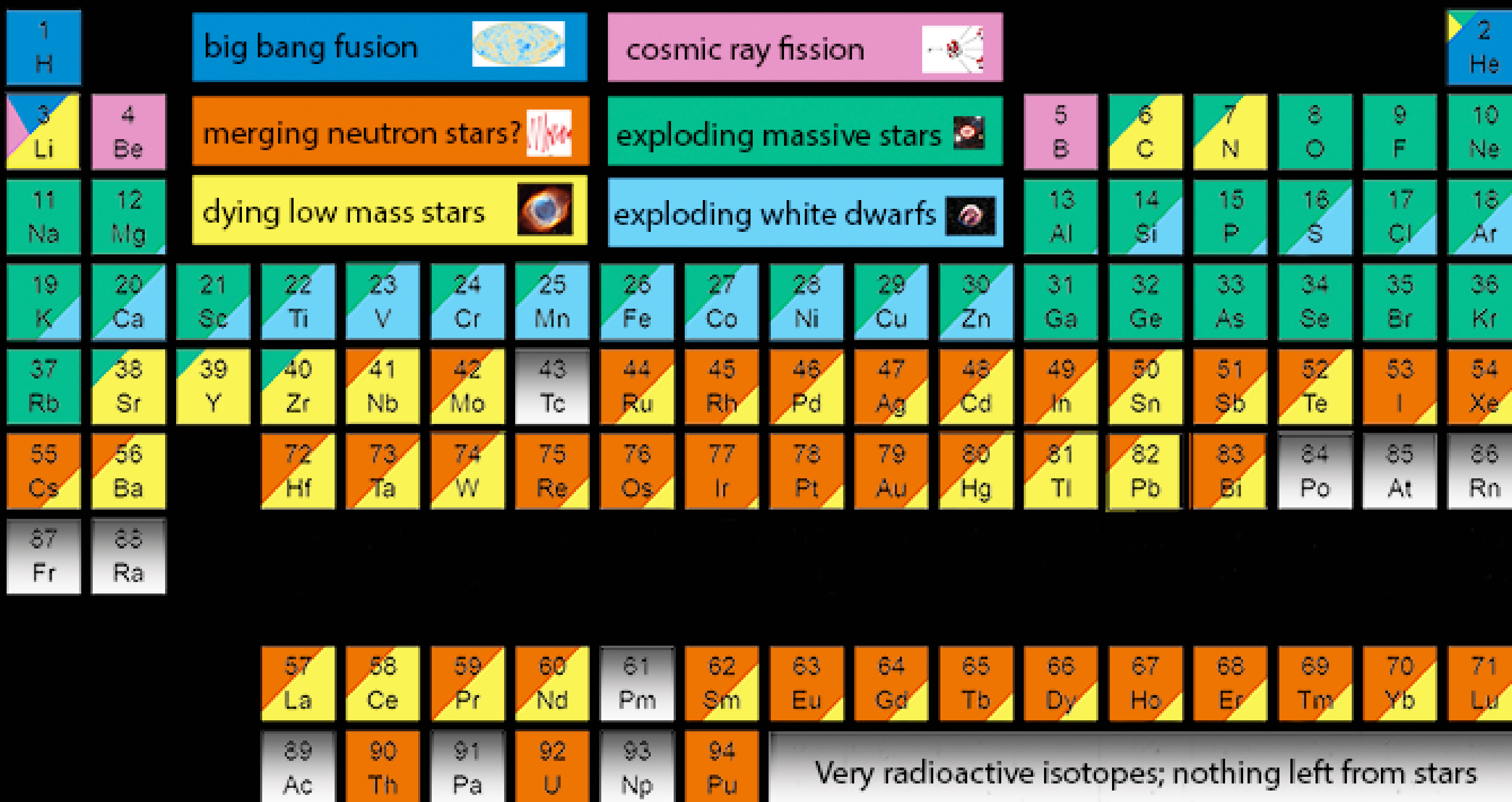
R process


Nucleosynthesis in the r-process
Joint Institute for Nuclear Astrophysics 2012
Time: 1.7e-03 s
Temperature: 5.46 GK



https://www.youtube.com/watch?v=T44B9j3Vzxw

The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

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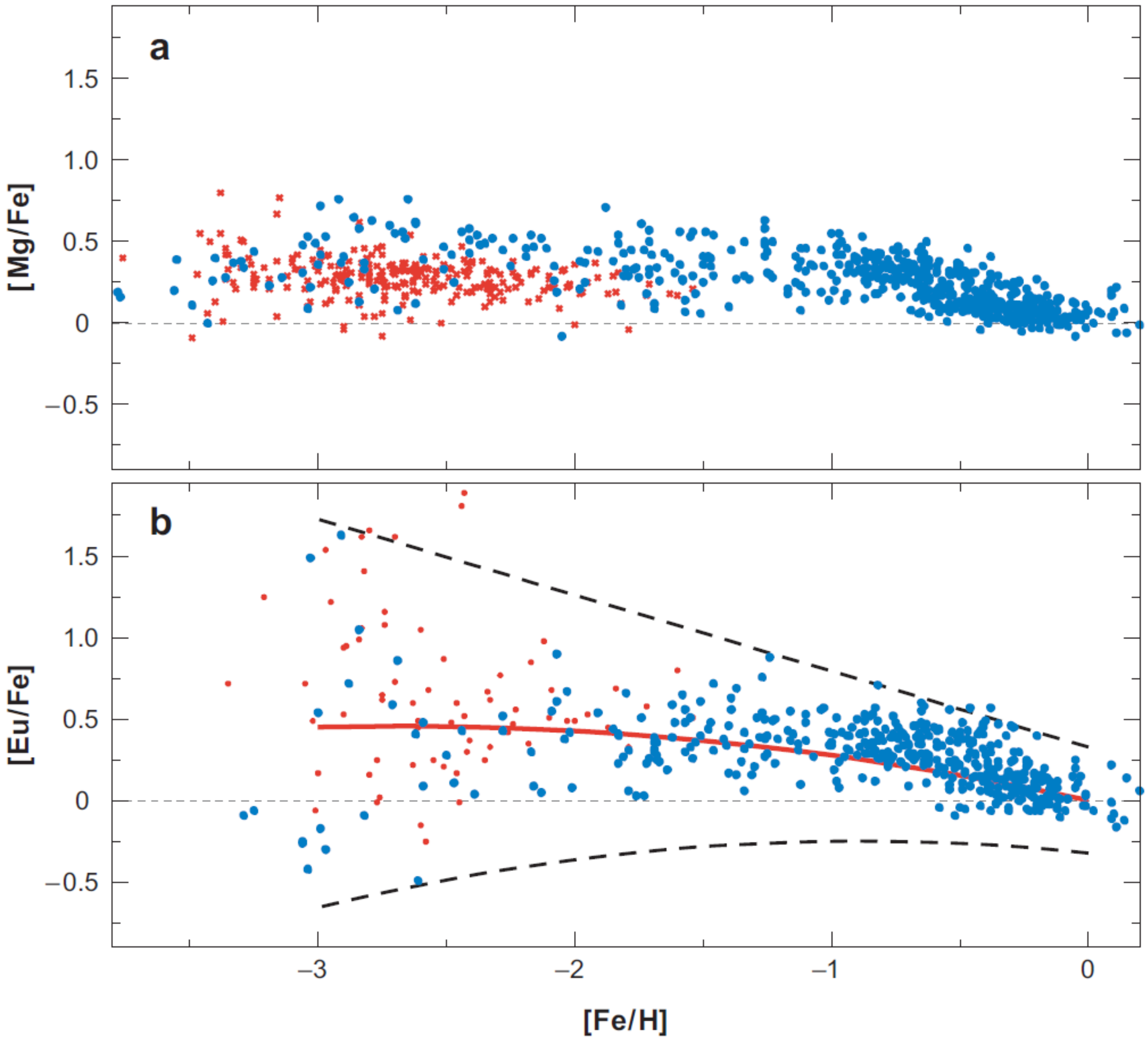

Sneden et al. (2008)