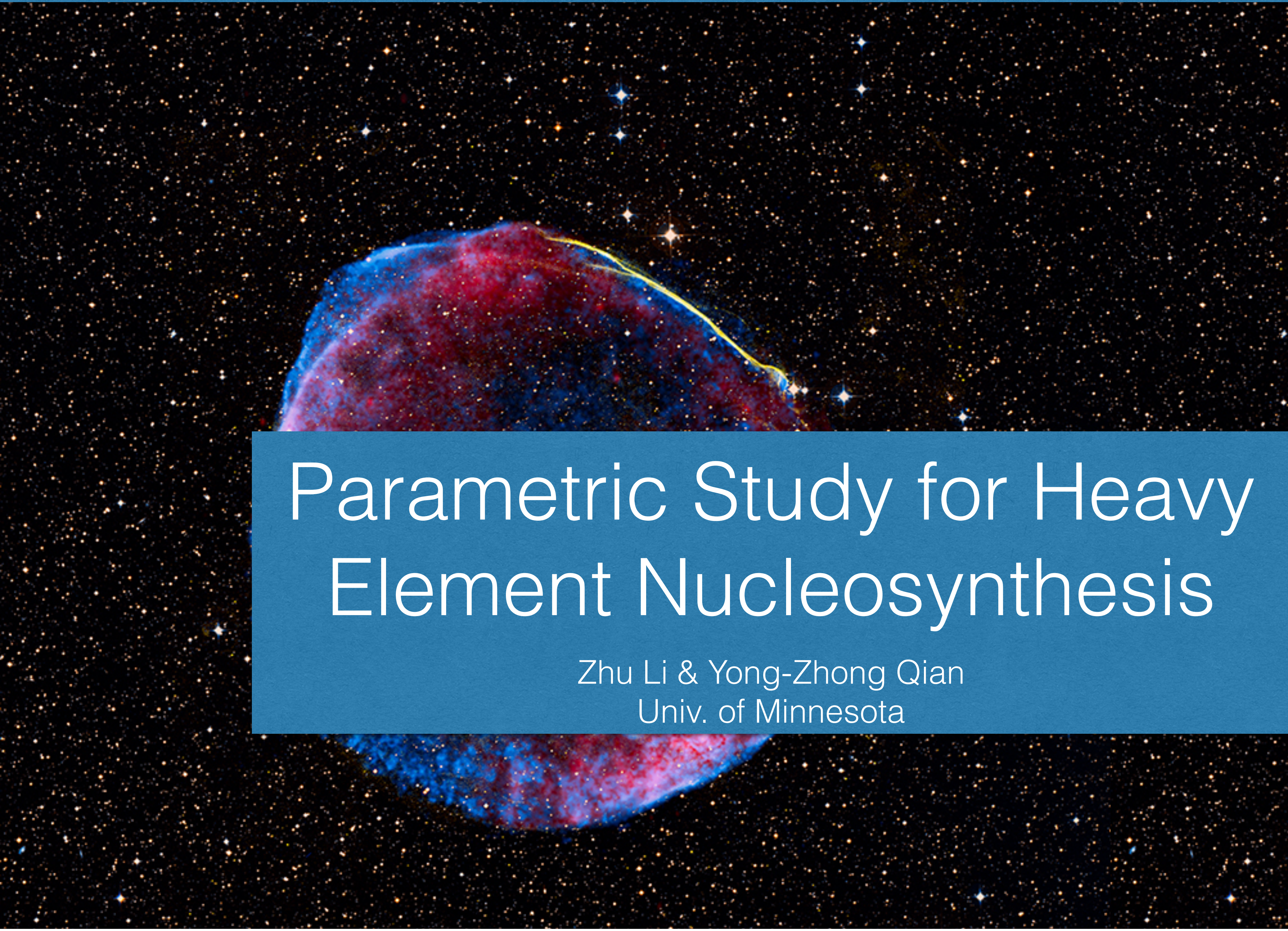


Parametric Study for Heavy Element Nucleosynthesis

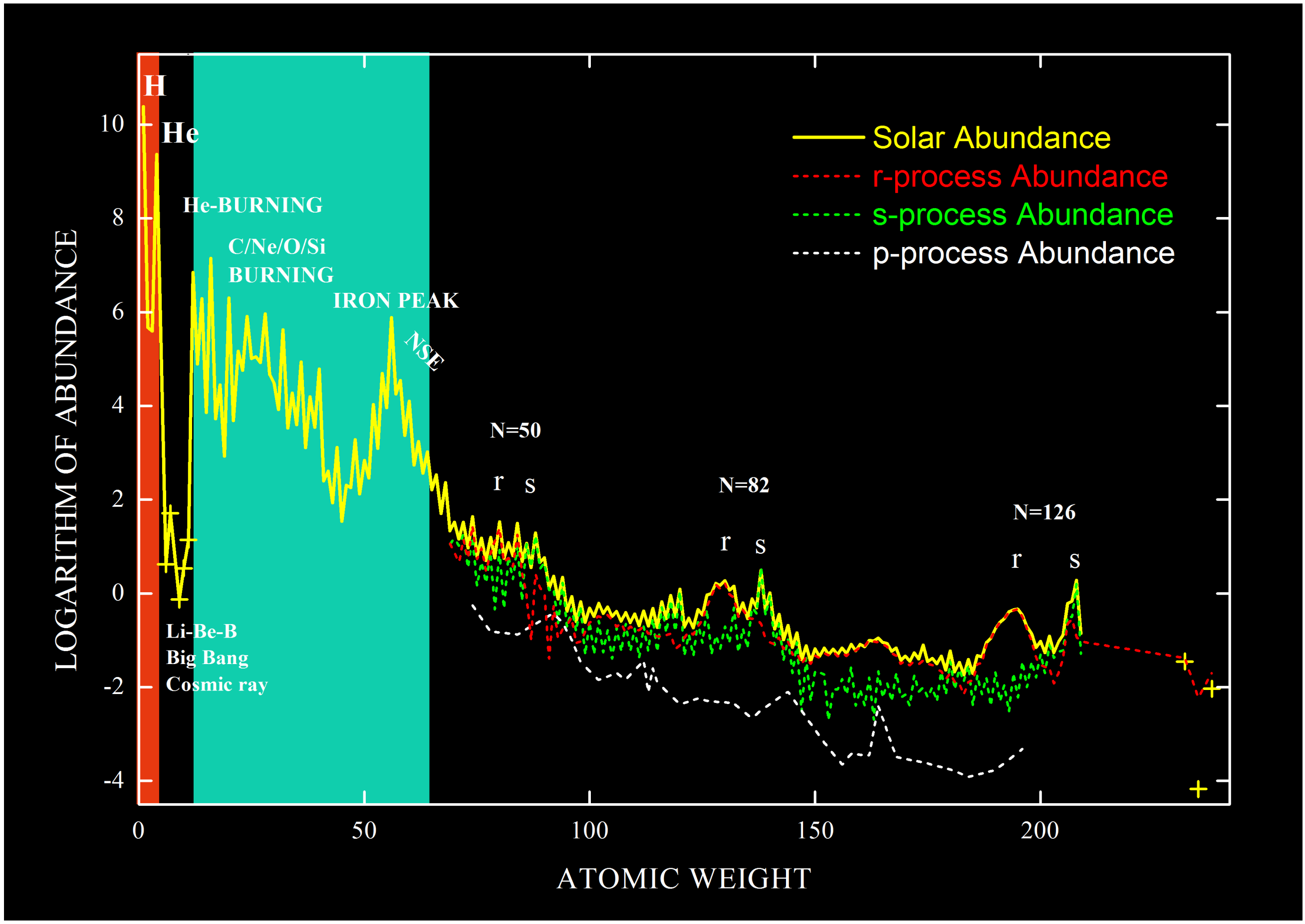
Zhu Li & Yong-Zhong Qian
Univ. of Minnesota

Heavy Elements in Universe

In solar system

- Hydrogen+Helium ~ 98% by mass
  —> proton-rich environment

- “Metal”~2% by mass
  —> “neutron-rich” nuclei



Neutron is needed to produce the heavy nuclei.

Factories for (Neutron Rich) Heavy Elements

Supernovae:

- prompt bounce-back explosion; Hillebrandt 1978
- neutrino-driven wind; Qian & Woosley 1996
- shocked surface of O-Ne-Mg core; Ning et al. 2007
- neutrino-induced in He-shell; Banerjee et al. 2011
- jets; Winteler et al. 2012

Neutron Star Mergers:

- dynamical ejecta; Goriely et al. 2011, Korobkin et al.2012
- evaporation disk; Fernandez & Metzger 2013

High initial temperature and fast adiabatic expansion.

Parametric Model

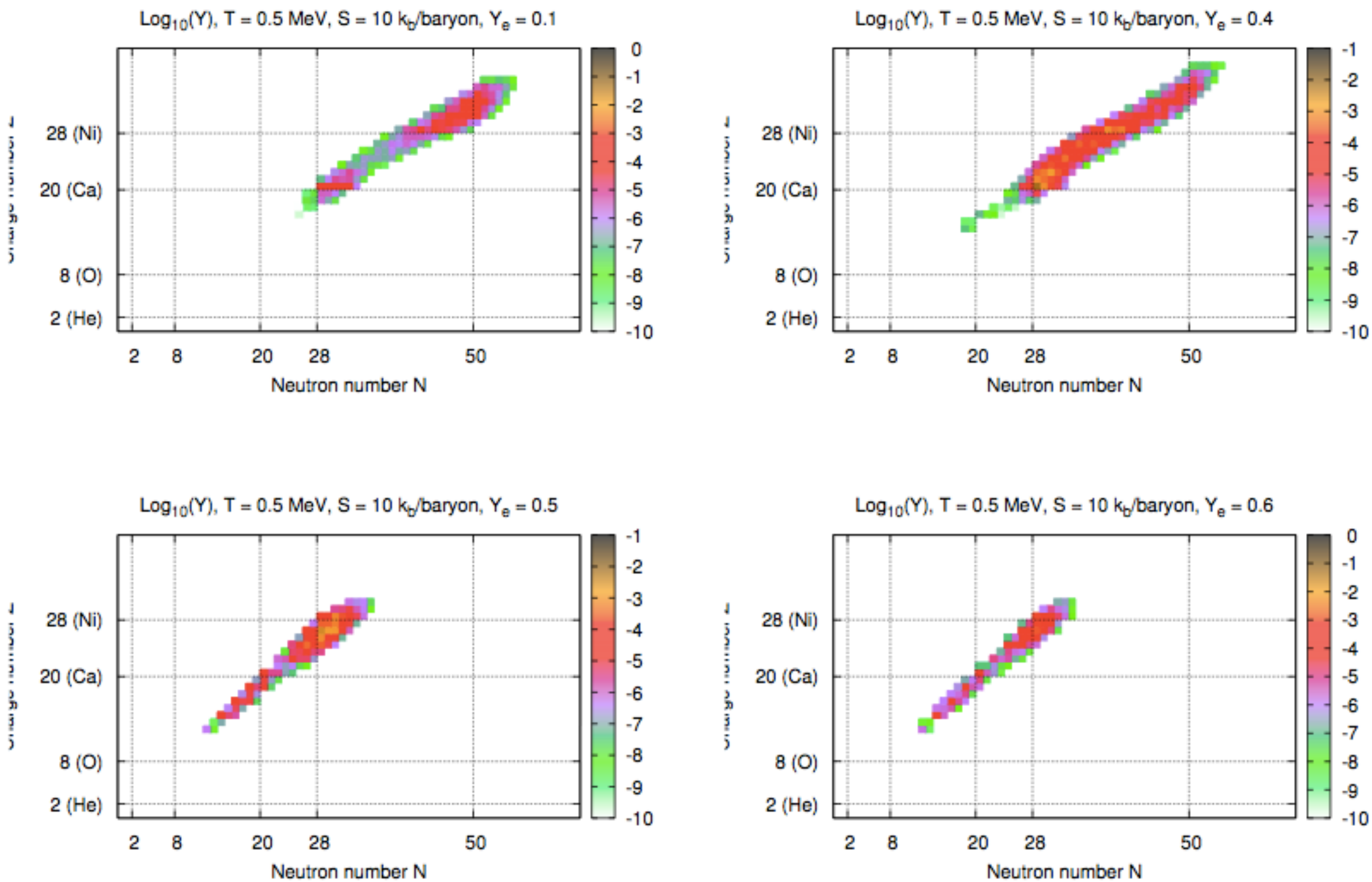
- Dynamical time scale $\tau_{\mathrm{dyn.}}$ for expansion:
  exponential form $T(t) = T_0 \exp(-t/\tau_{\mathrm{dyn.}})$
  power-law form $T(t) = T_0/(1 + t/\tau_{\mathrm{dyn.}})$
- Electron fraction $Y_e = Y_n/(Y_n + Y_p)$
- Entropy stays constant

$$S(t) = S(T(t), \rho(t)) \equiv S_0$$

Any nucleosynthesis model is specified by a set of

$(\tau_{\mathrm{dyn.}},\ T_0,\ S_0,\ Y_e)$

NSE Abundances



T=0.5 MeV, S=10 k**b**/baryon, Y**e**=0.1 / 0.4 / 0.5 / 0.6

Equilibria in NSE: I

Various equilibria exist in NSE process, which favor specified nucleus:

$$(n/p,\gamma) \Leftrightarrow (\gamma, n/p)$$

$$S^*_{n,p} = T_9\{1.052 + 0.198 \times [1.5\log T_9 - \log(\rho_5 Y_{n,p})]\}$$

$$(\alpha,\gamma) \Leftrightarrow (\gamma,\alpha)$$

$$S^*_{\alpha} = T_9\{1.29 + 0.198 \times [1.5\log T_9 - \log(4\rho_5 Y_{\alpha})]\}$$

$$(n,p) \Leftrightarrow (p,n)$$

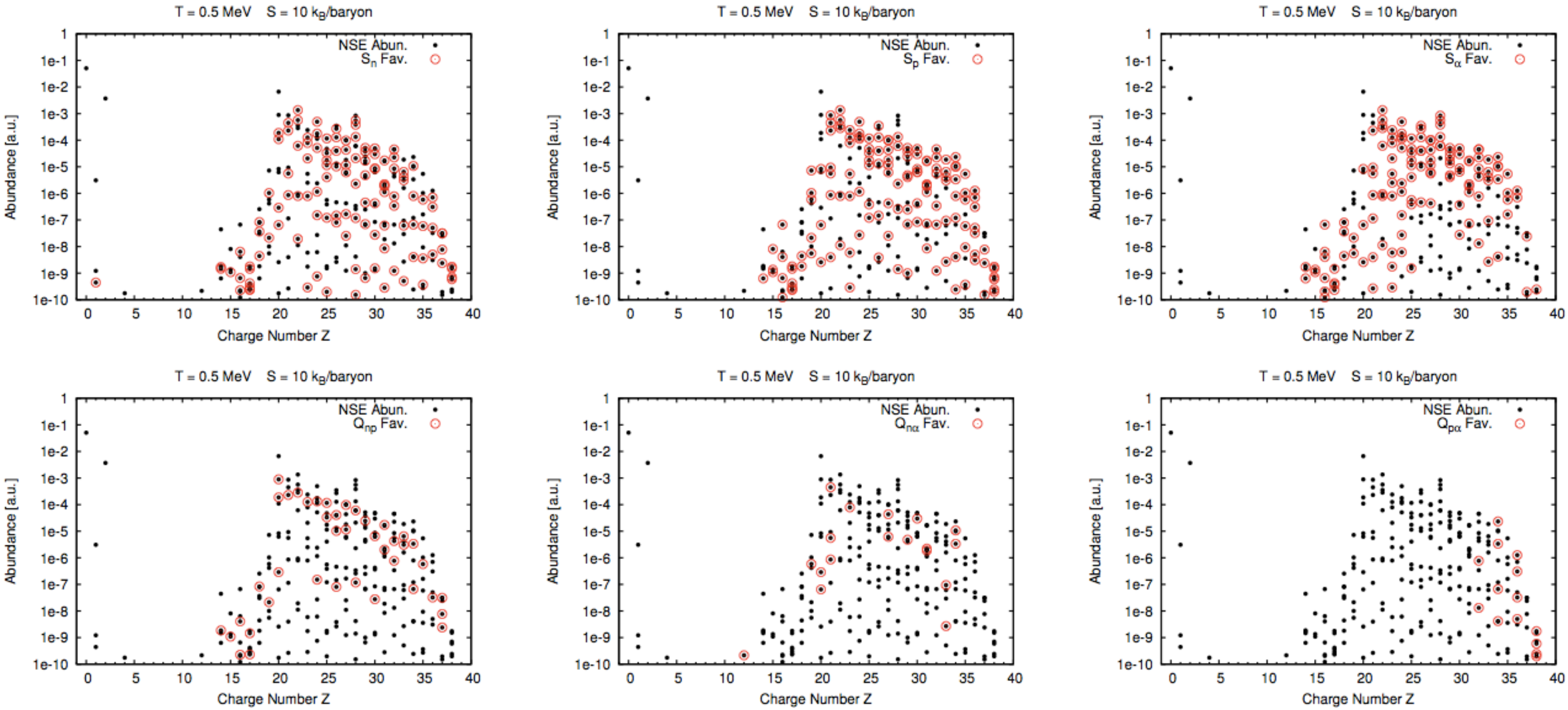
$$Q^*_{(n,p)} = 0.198\ T_9 \log(Y_p/Y_n)$$

$$(n/p,\alpha) \Leftrightarrow (\alpha, n/p)$$

$$S^*_{(n/p,\alpha)} = 0.198\ T_9 \log(Y_\alpha/4Y_{n,p})$$

Equilibria in NSE: II

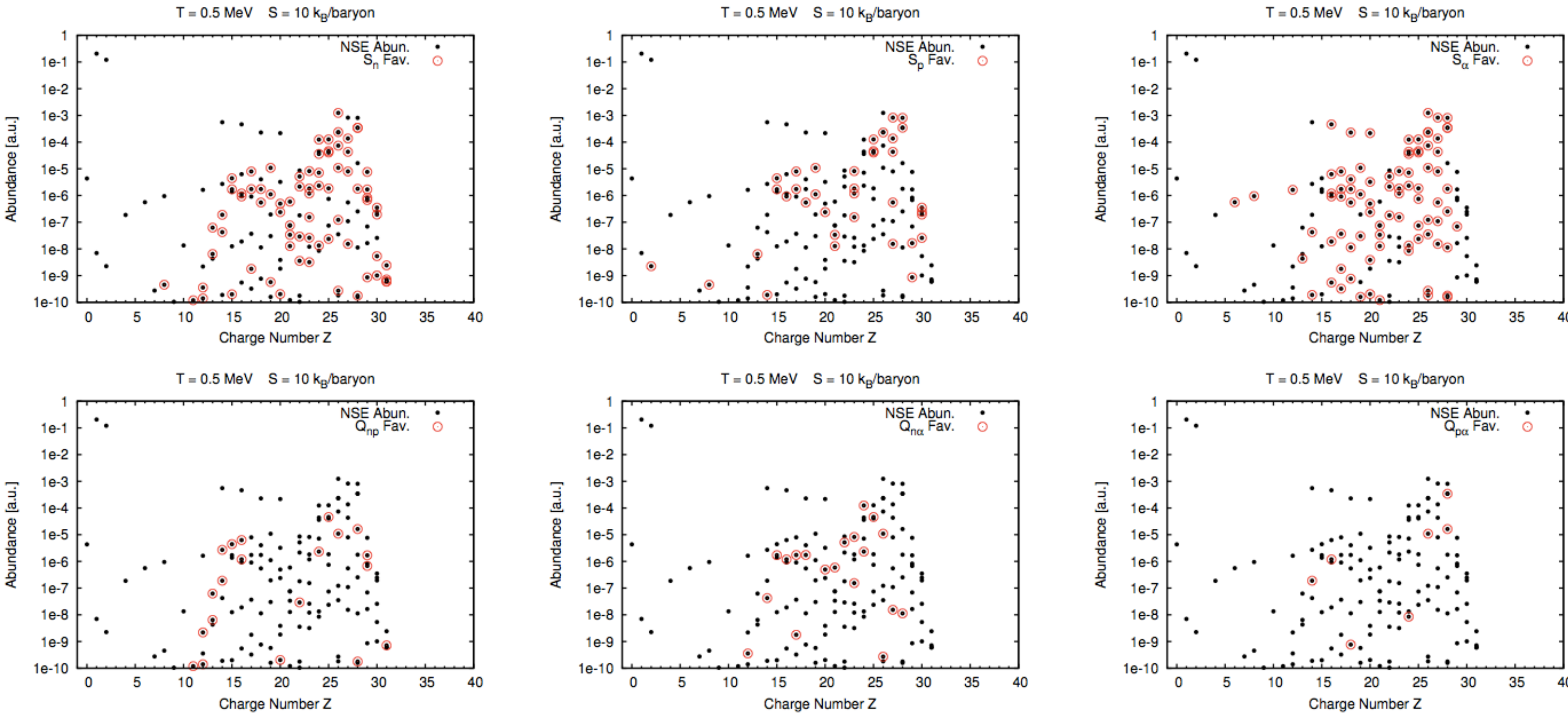
Ye=0.4



Equilibria between capture reactions and photo-disintegration dominate the NSE abundance

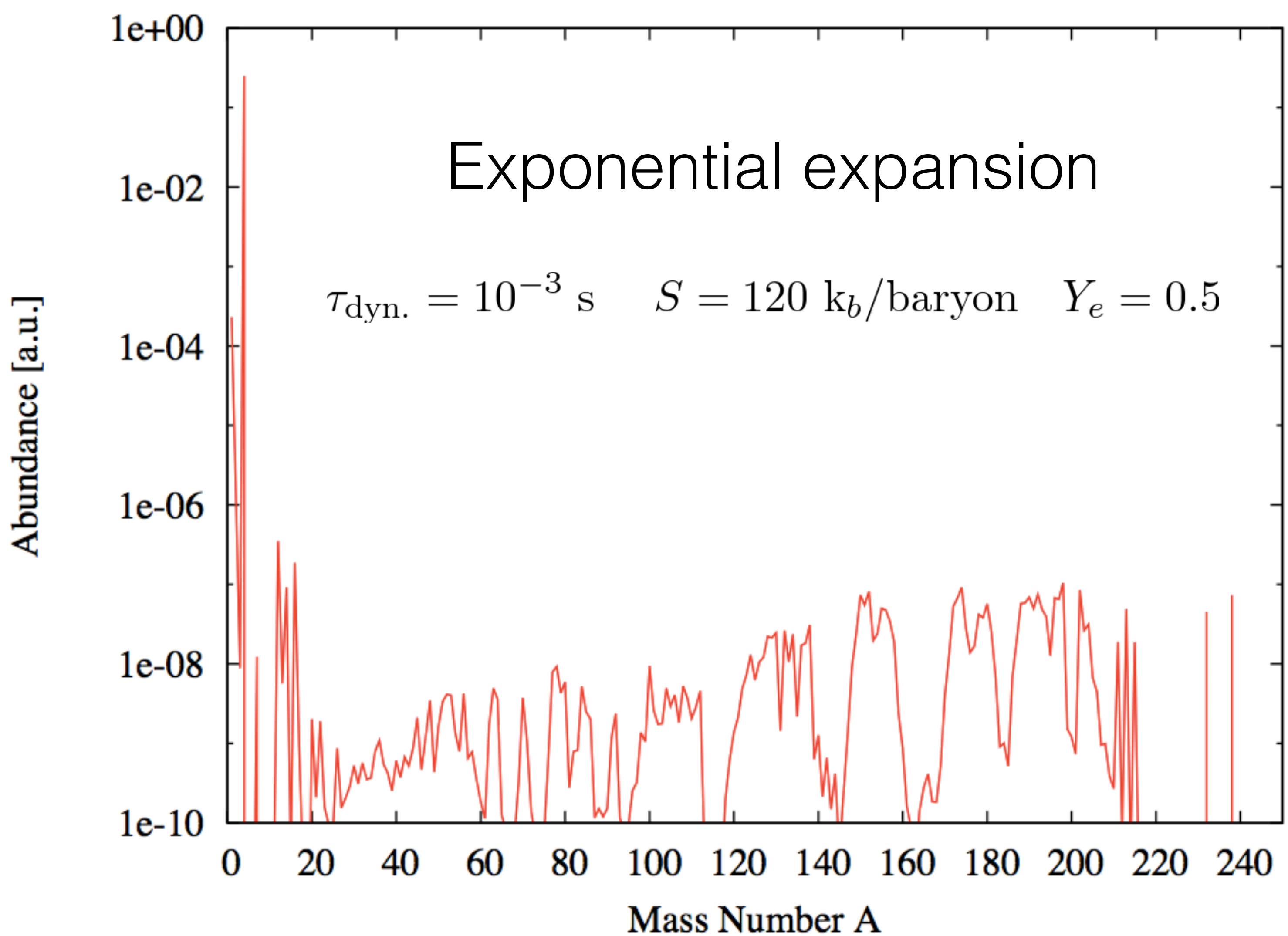
Equilibria in NSE: III

Ye=0.6

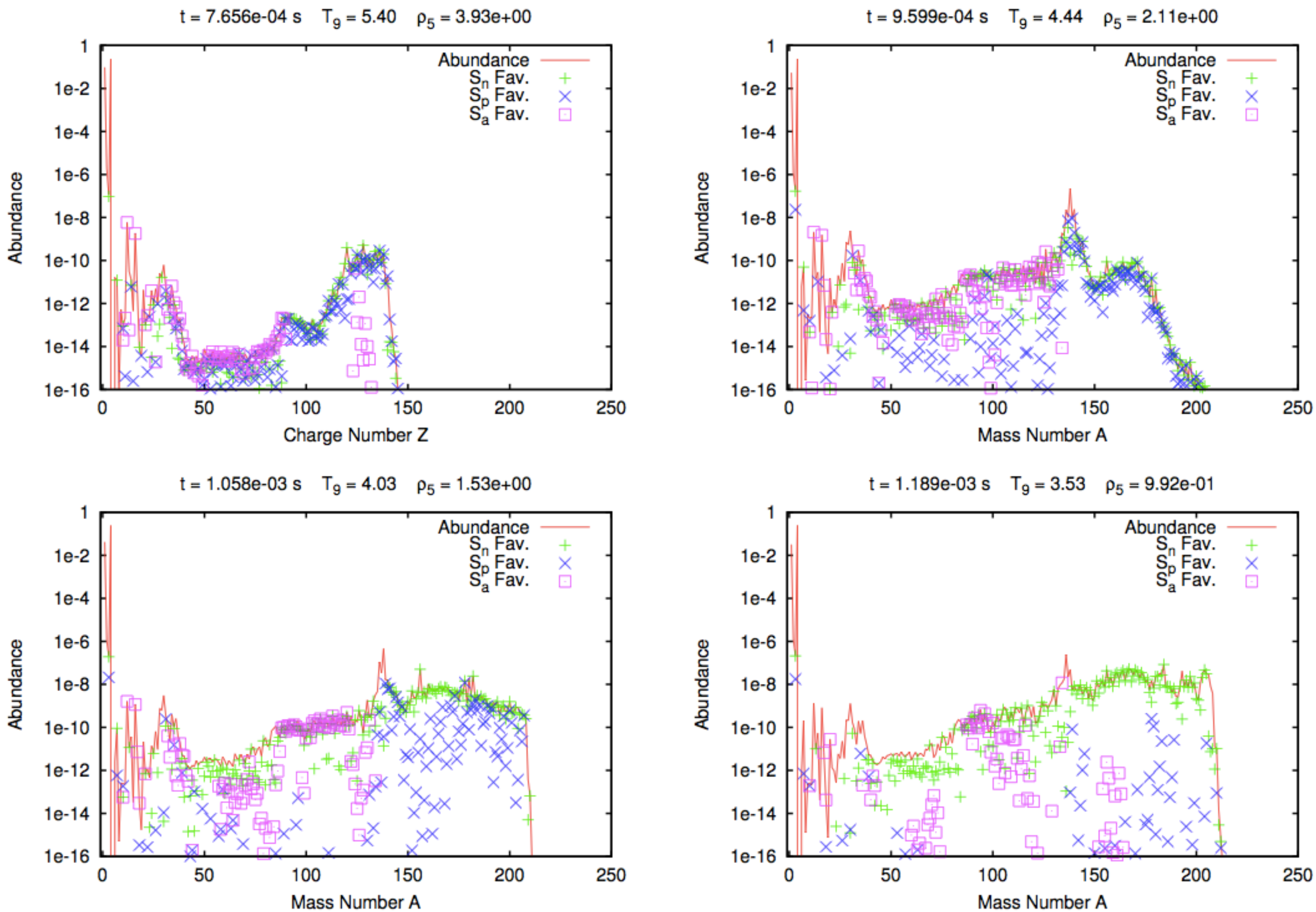


An Unsuccessful *r*-Process

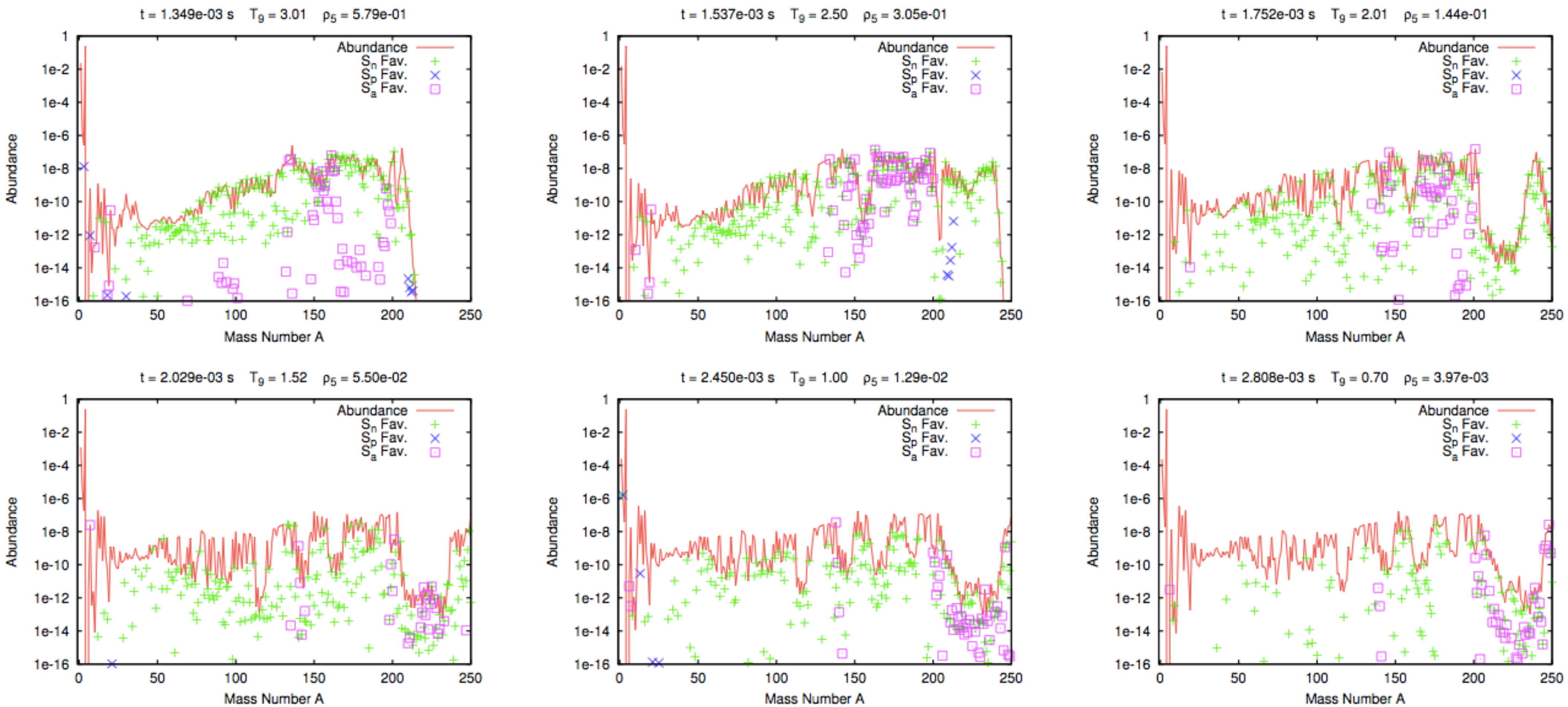
What can we learn from an UNSUCCESSFUL *r*-process?



Track the Evolution: I

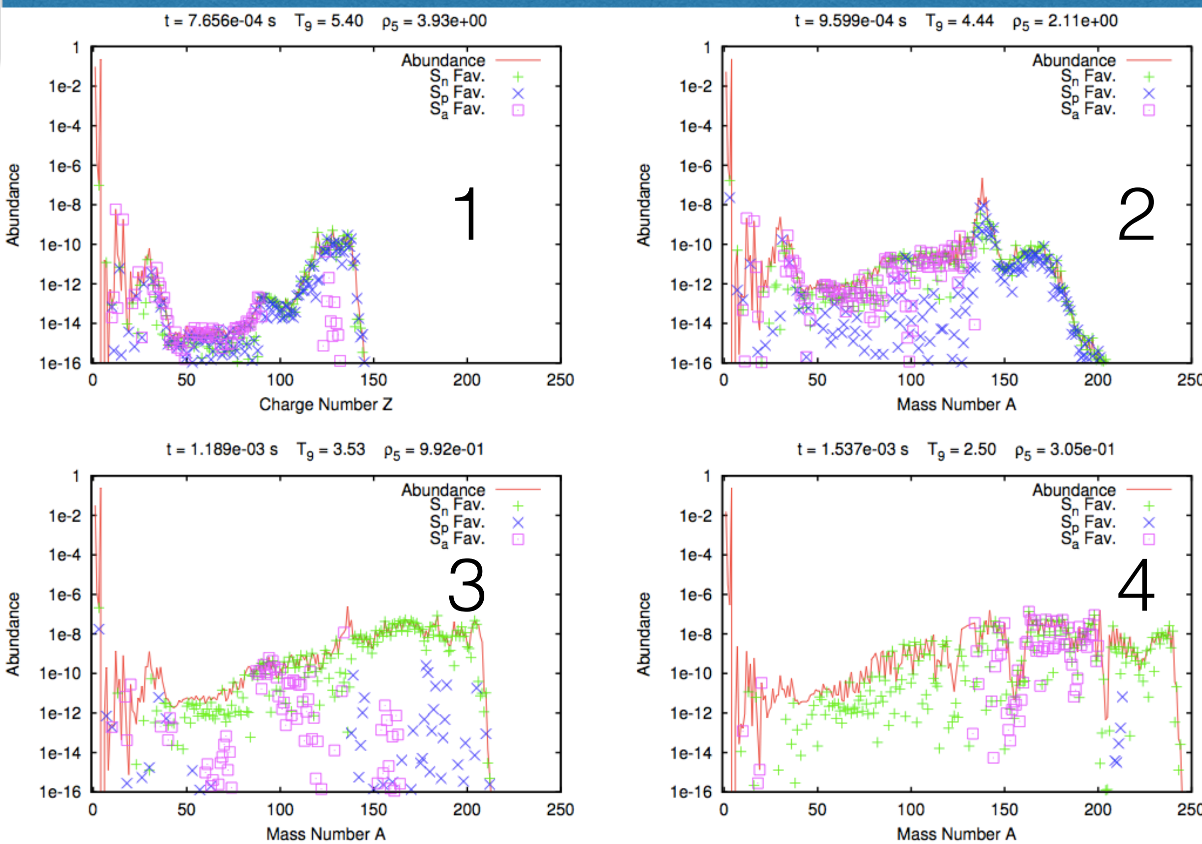


Track the Evolution: II



- Neutron reactions dominate the production of heavier nuclei.
- Alpha equilibria take over the nucleosynthesis but CANNOT make changes.

Reaction Rates

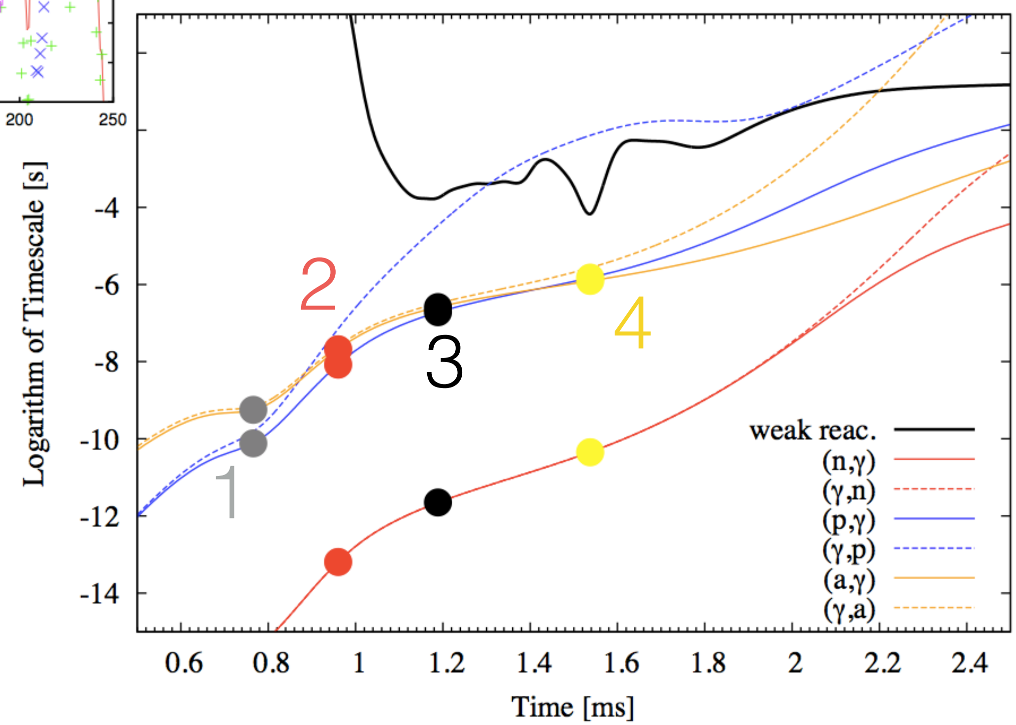


$$\tau_{\rm weak} = \left[\frac{1}{Y_h}\sum_{Z>2,A}\lambda_w(Z,A)Y(Z,A)\right]^{-1}$$

$$\tau_{(i,\gamma)} = \left[\frac{\rho Y_i}{Y_h}N_A\sum_{Z>2,A}\langle\sigma v\rangle_{(i,\gamma)}(Z,A)Y(Z,A)\right]$$

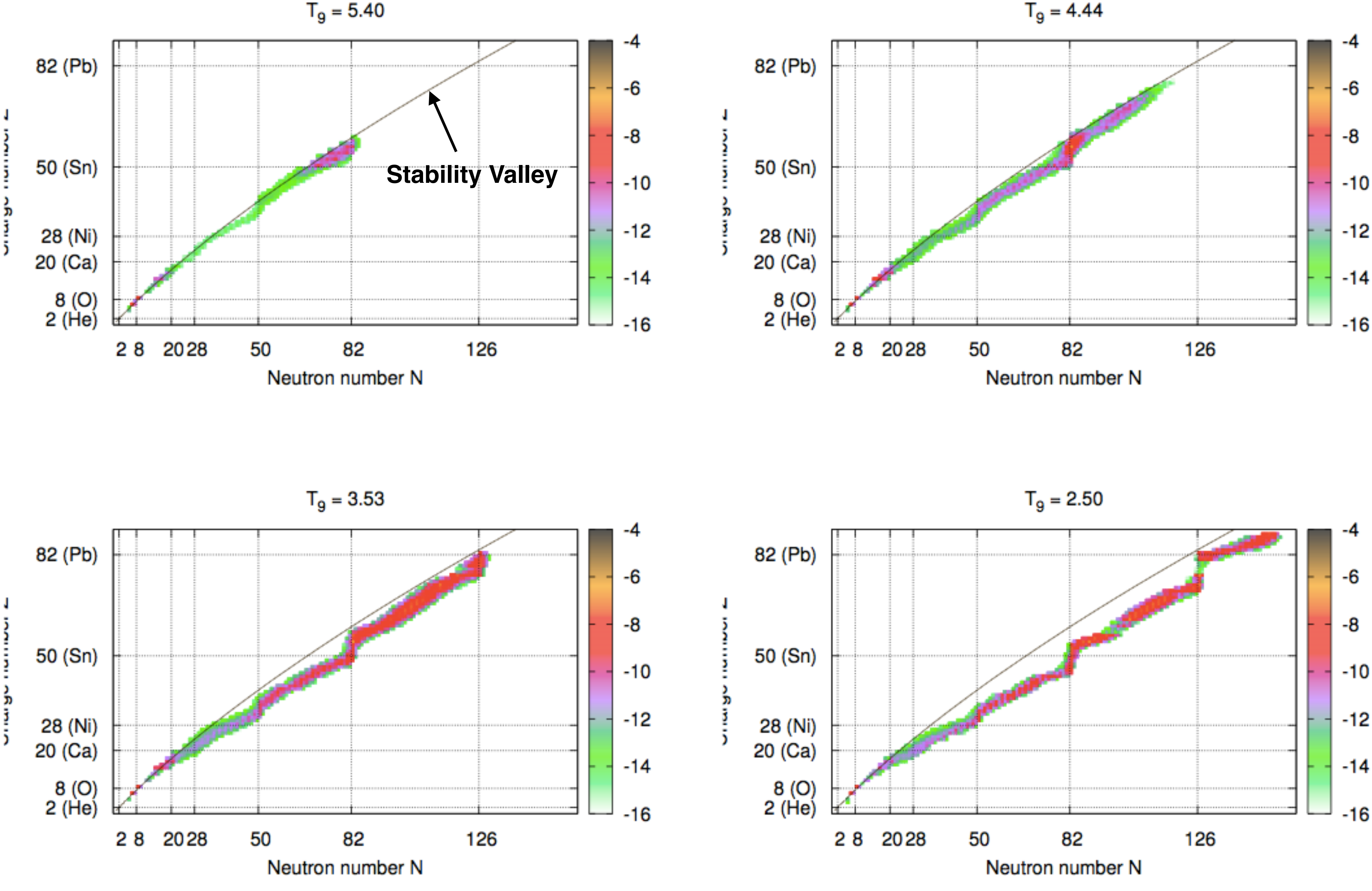
$$\tau_{(\gamma,i)} = \left[\frac{1}{Y_h}\sum_{Z>2,A}\lambda_{(\gamma,i)}(Z,A)Y(Z,A)\right]^{-1}$$

$$Y_n = \sum_{Z>2,A}Y(Z,A)$$

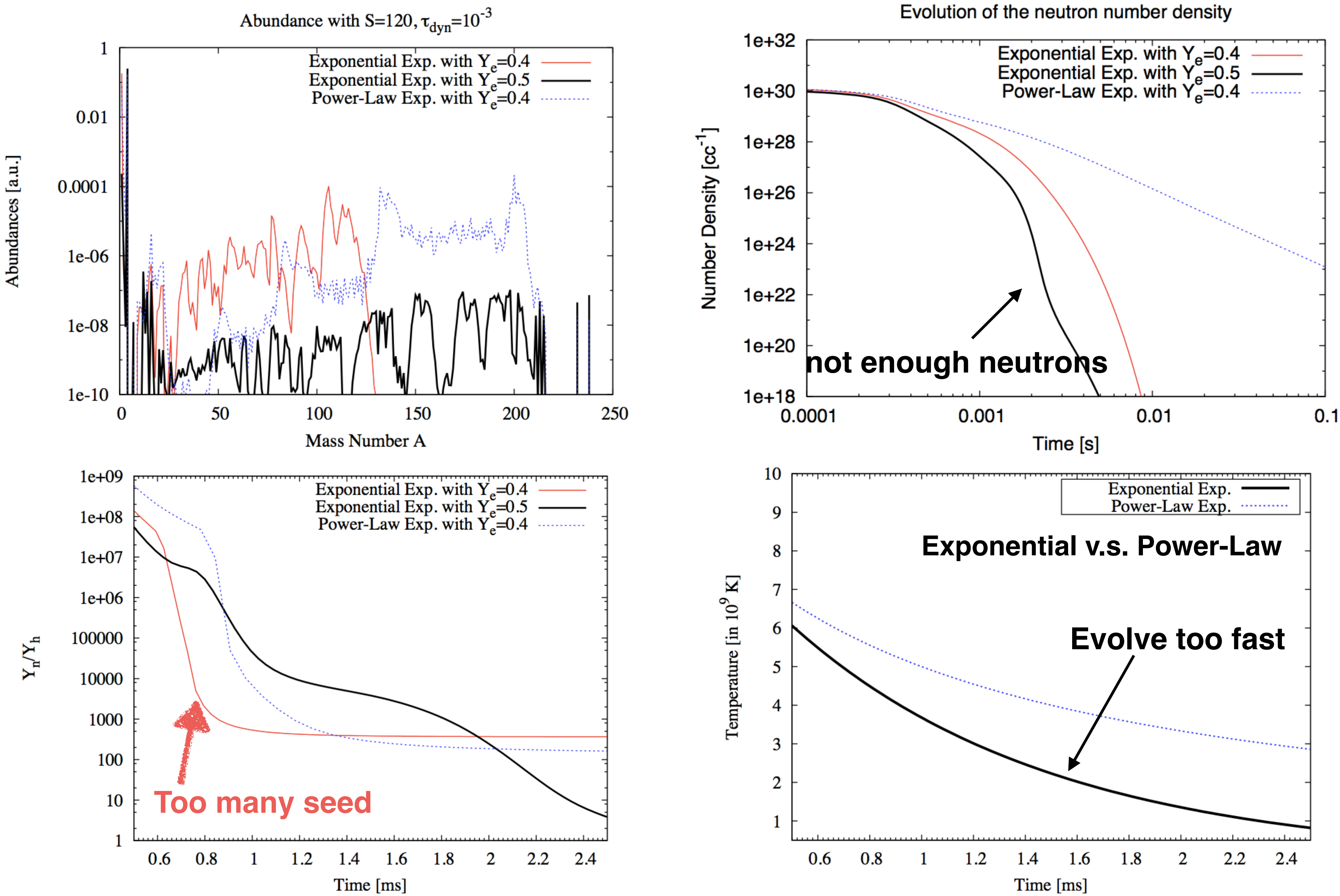


Neutron reactions are much faster !

Neutrons Capture?



How to be successful?



Summary

- Neutrons dominate the production of heavy nuclei.
- To make a complete *r*-process:
    1. High neutron-to-seed ratio
    2. Enough time for neutron flux
- Power-Law expansion is a better parametric approximation for long time evolution.