Nuclear data and *r*-process nucleosynthesis

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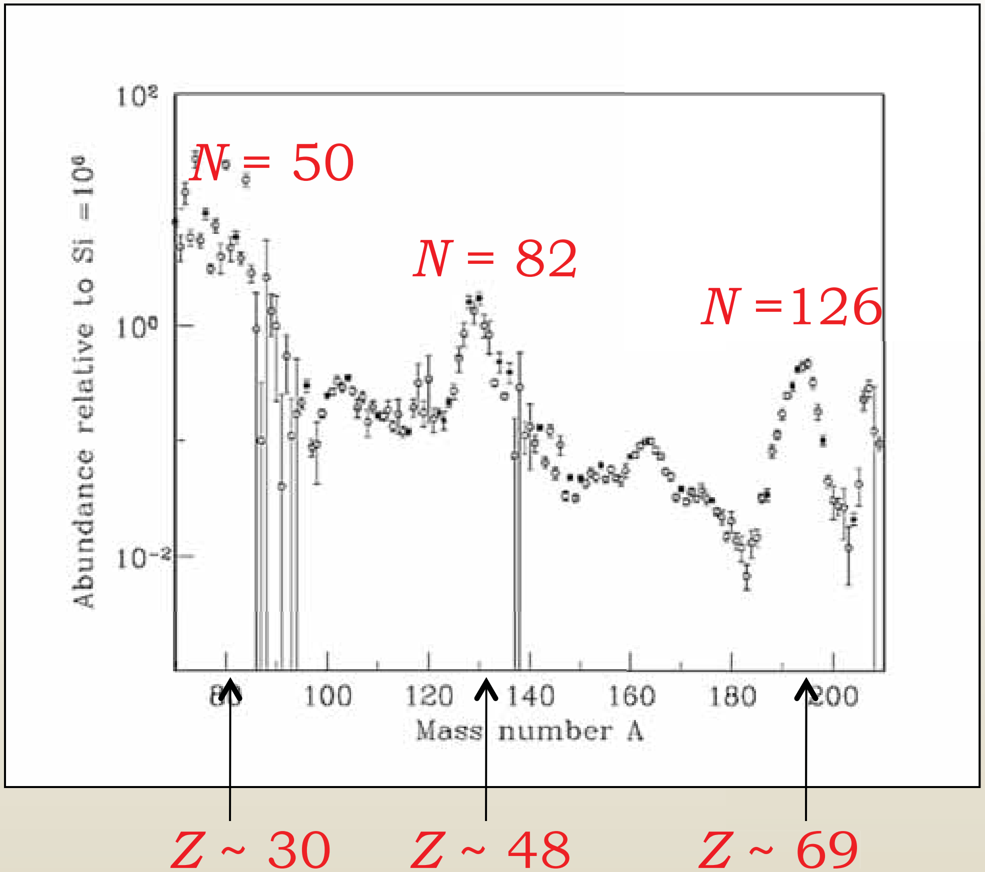
Workshop on Decay Spectroscopy at CARIBU:
Advanced Fuel Cycle Applications, Nuclear Structure, and Astrophysics

Argonne National Laboratory

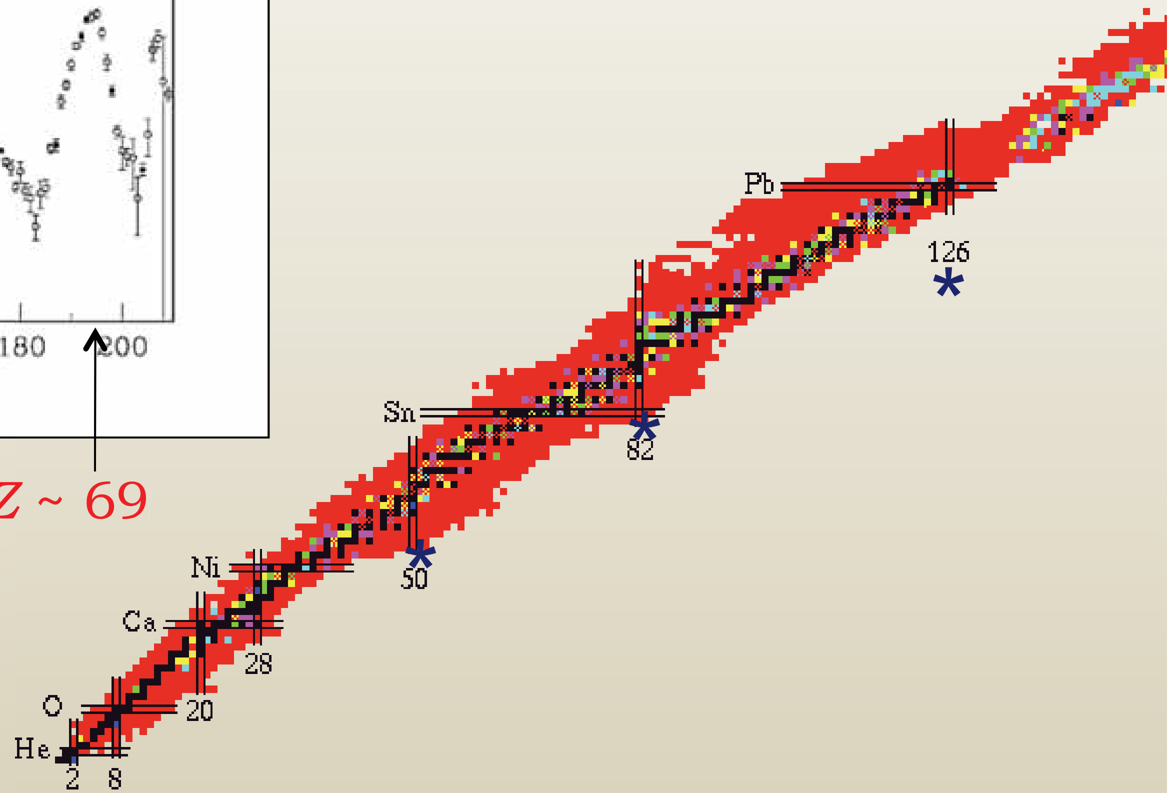
14 April 2011

rapid neutron capture nucleosynthesis

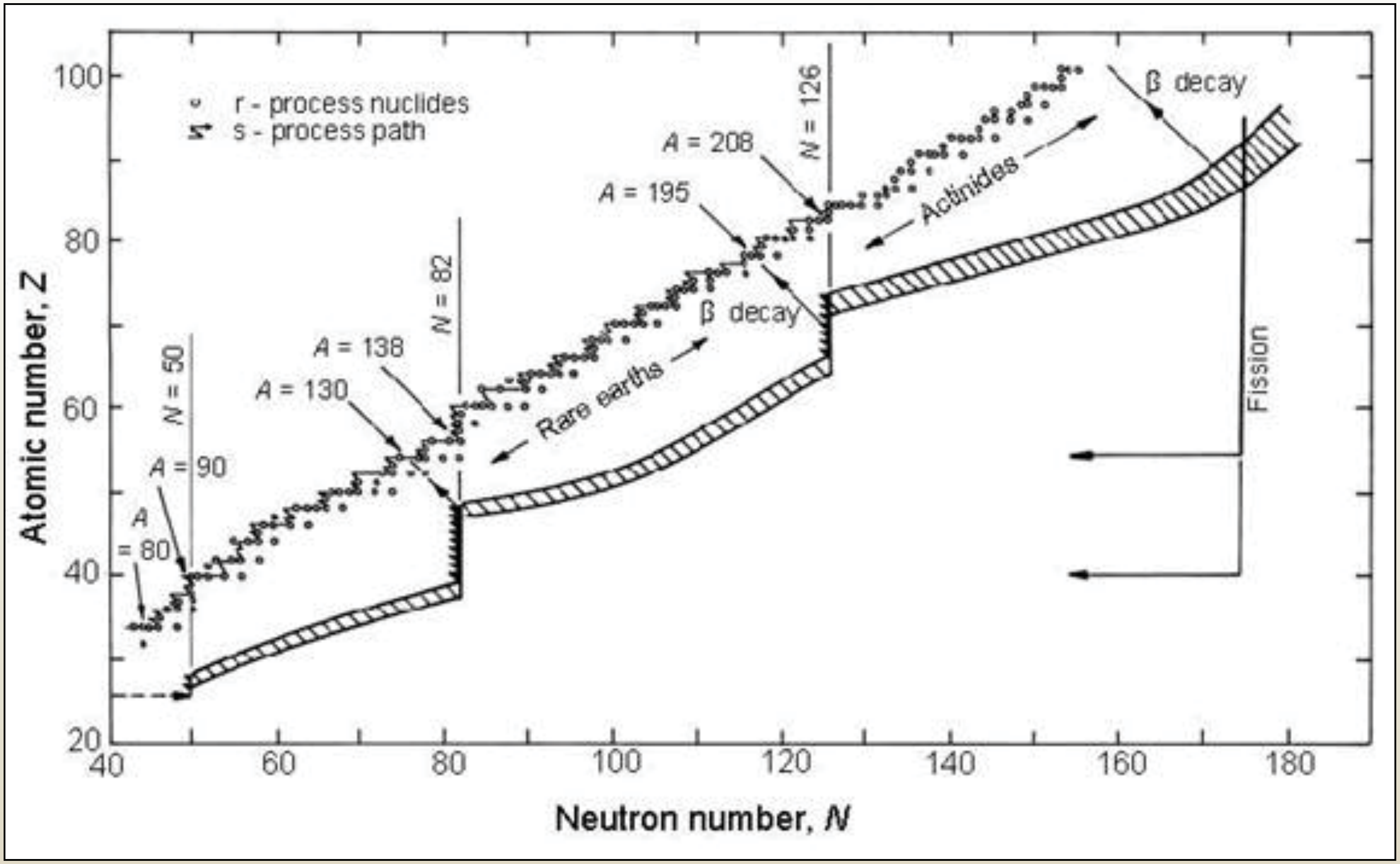


solar r-process abundances

as complied by Anders and Grevesse (1988)



classic picture of the *r* process



from Seeger et al (1965)

Astrophysics

What is the astrophysical site (or sites) of the *r* process?

Some possibilities:

supernovae *e.g., Meyer et al (1992), Woosley et al (1994), Takahashi et al (1994)*

neutron star mergers *e.g., Meyer (1989), Frieburghaus et al (1999), Rosswog et al (2001)*

shocked surface layers of O-Ne-Mg cores *e.g., Wanajo et al (2003), Ning et al (2007)*

gamma-ray bursts *e.g., Surman et al (2005)*

Nuclear Physics

What are the nuclear properties of neutron-rich nuclei far from stability?

We need:

masses

beta decay rates

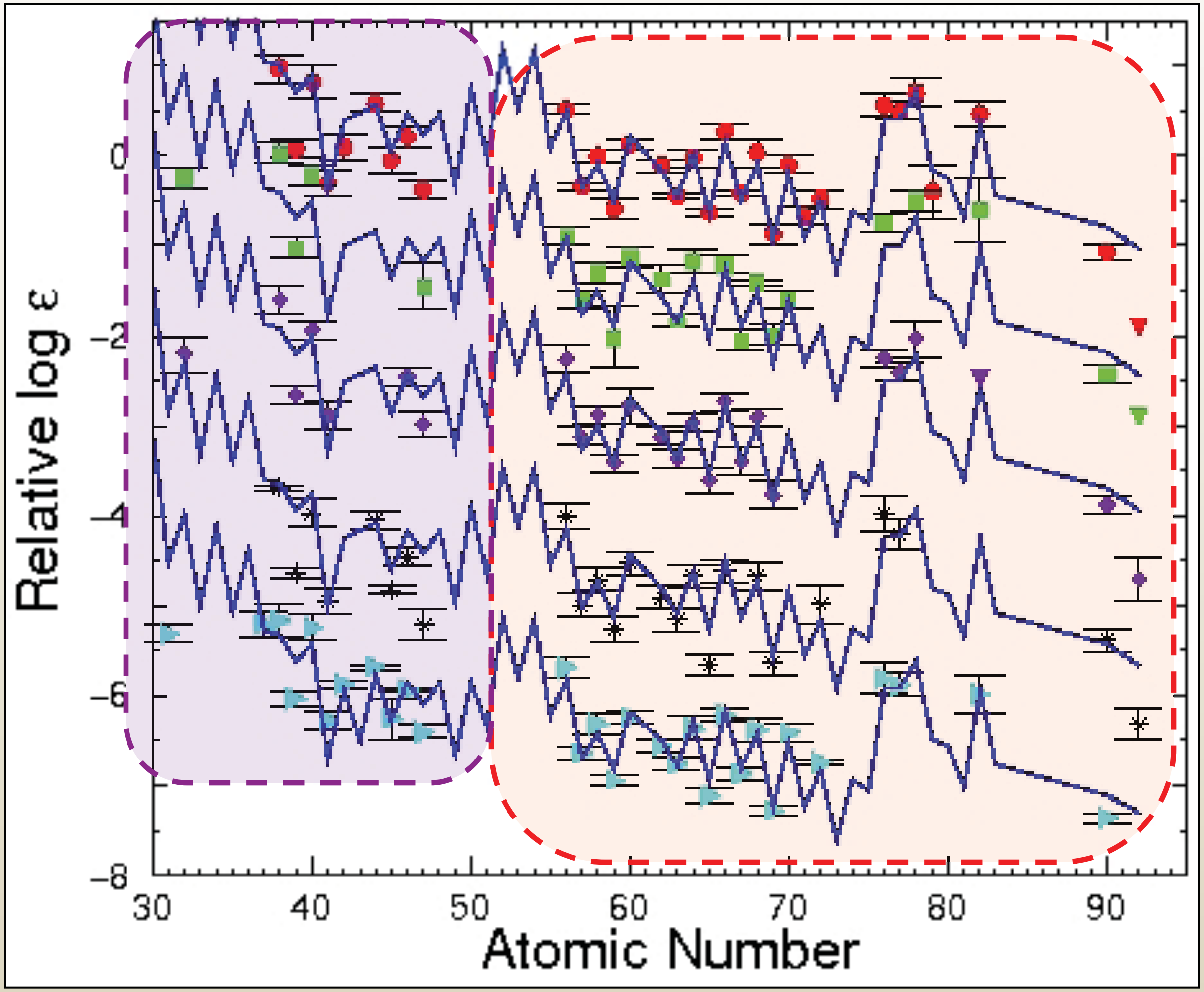
neutron capture rates

neutrino interaction rates

fission probabilities and daughter product distributions

halo star observations of *r*-process nuclei

Weak
r process,
LEPP



Main
r process

⇒ site within core-collapse supernovae?

Cowan et al (2006)

a supernova neutrino-driven wind *r* process?

Initial studies were very promising....

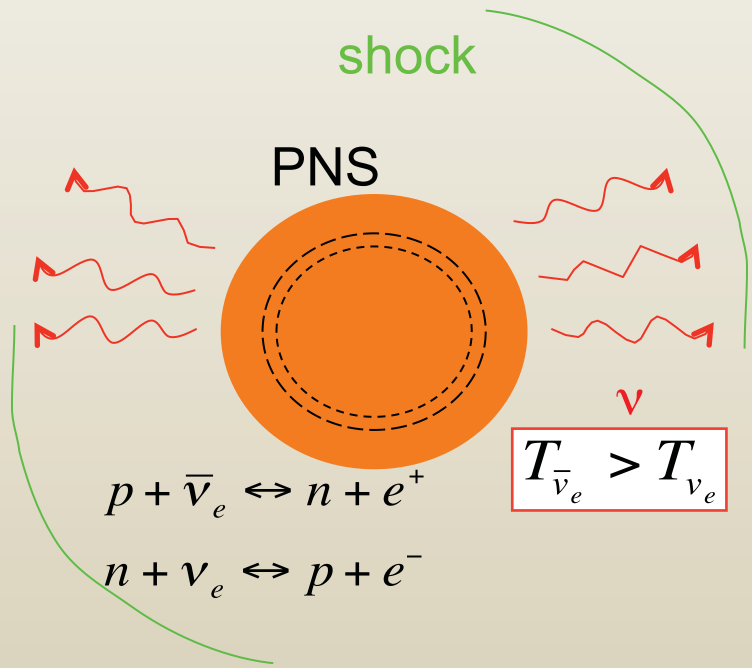
e.g., Meyer et al (1992), Woosley et al (1994)

...but it was found to be more difficult to produce the requisite conditions than first thought

e.g., Takahashi et al (1994), Witti et al (1994), Fuller & Meyer (1995), McLaughlin et al (1996), Meyer et al (1998), Qian & Woosley (1996), Hoffman et al (1997), Otsuki et al (2000), Thompson et al (2001), Terasawa et al (2002), Liebendorfer et al (2005), Wanajo (2006), Arcones et al (2007), etc., etc.

The most recent calculations of proto-neutron star evolution predict no robustly neutron-rich outflows

Huedepohl et al (2010), Fischer et al (2010)



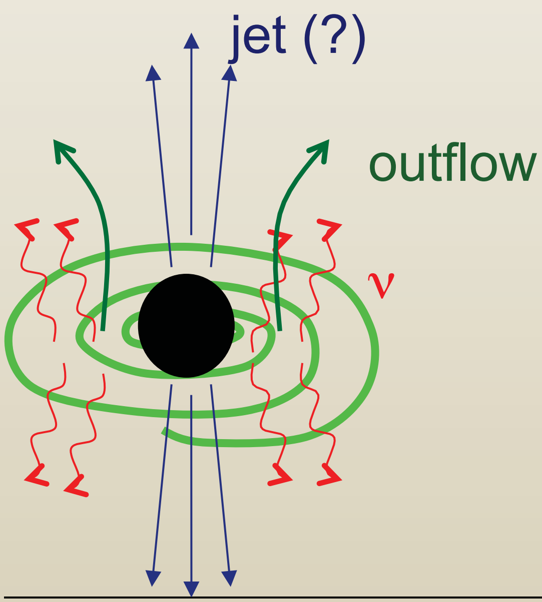
compact object mergers as an *r*-process site

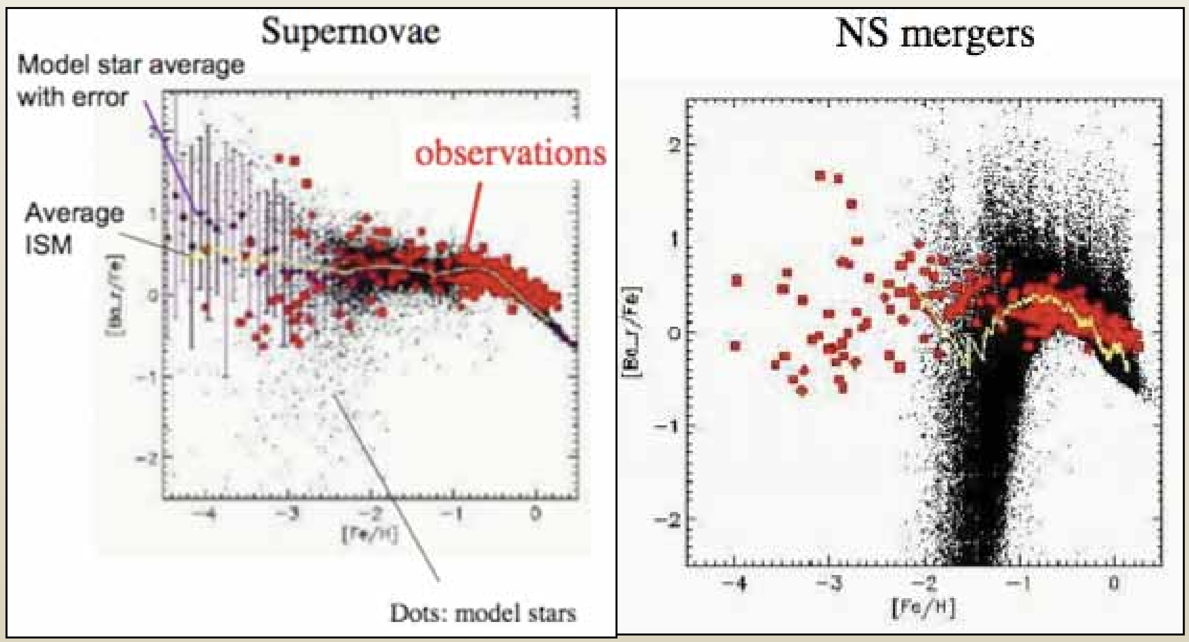
Several environments within NS-NS or BH-NS mergers have been found to be attractive *r*-process sites

e.g., Lattimer & Schramm (1974, 1976), Meyer (1989), Frieburghaus et al (1999), Goriely et al (2005), Oechslin et al (2007) , Surman et al (2008)

…but the timescale for mergers to develop is inconsistent with the data

e.g., Sneden et al (1996), Ryan et al (1996), Truran et al (2002), Argast et al (2004), Wanajo & Ishimaru (2006)





r-process nucleosynthesis: open questions

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How does the *r* process proceed?

(n,γ)-(γ,n) equilibrium, instantaneous freezeout
(i.e., Kratz)

↕

no (n,γ)-(γ,n) equilibrium, cold *r* process
(i.e., Wanajo)

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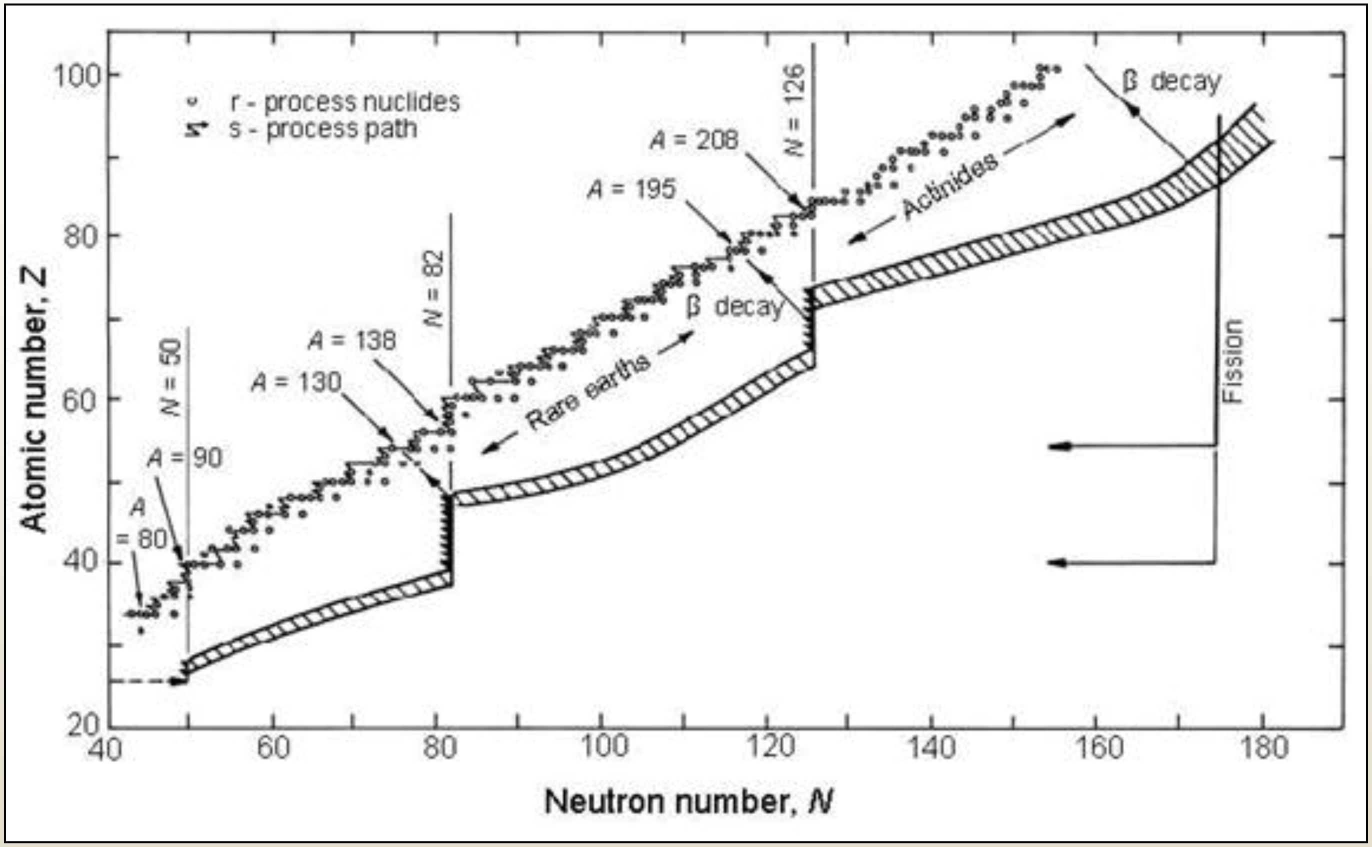
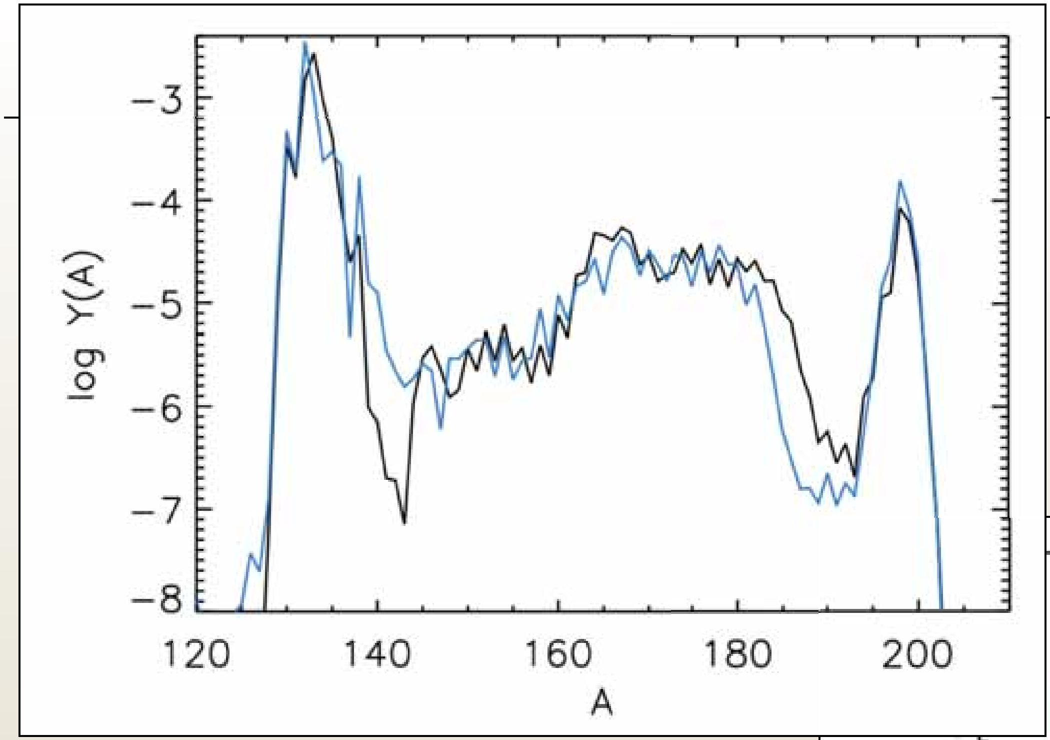
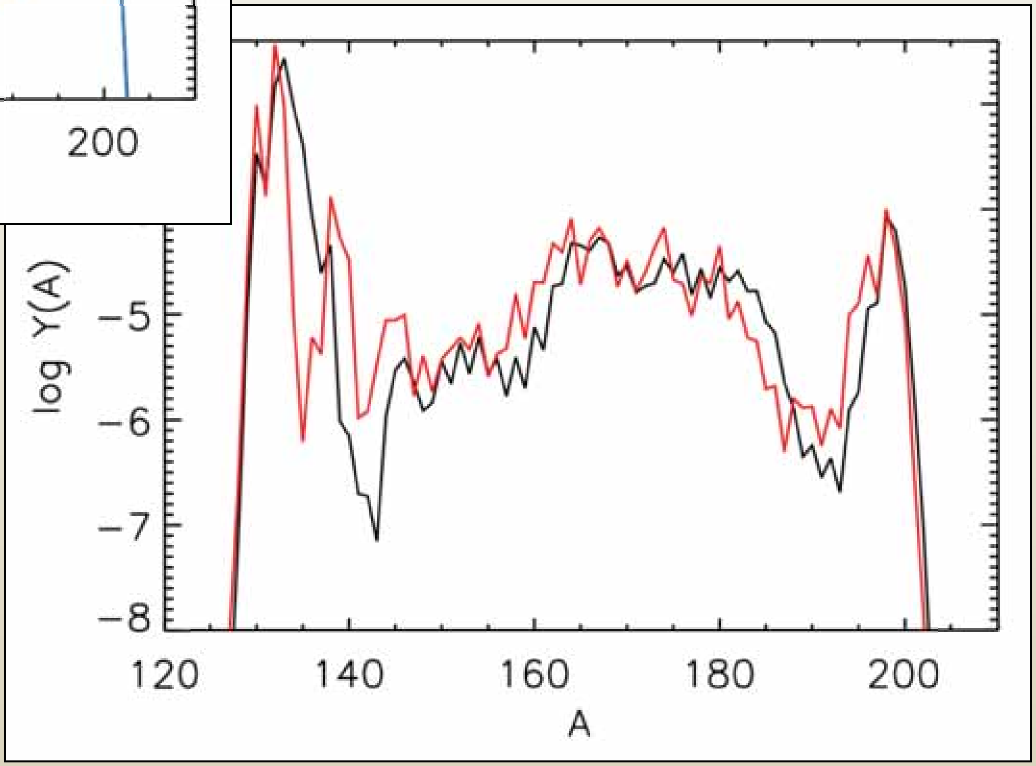


from Seeger et al (1965)

$$(n,\gamma)-(\gamma,n)\ \text{equilibrium}: \qquad S_n(Z,A_{path}) \sim -kT\ln\left\{\frac{n_n}{2}\left(\frac{2\pi\hbar^2}{m_n kT}\right)^{3/2}\right\}$$

nuclear masses





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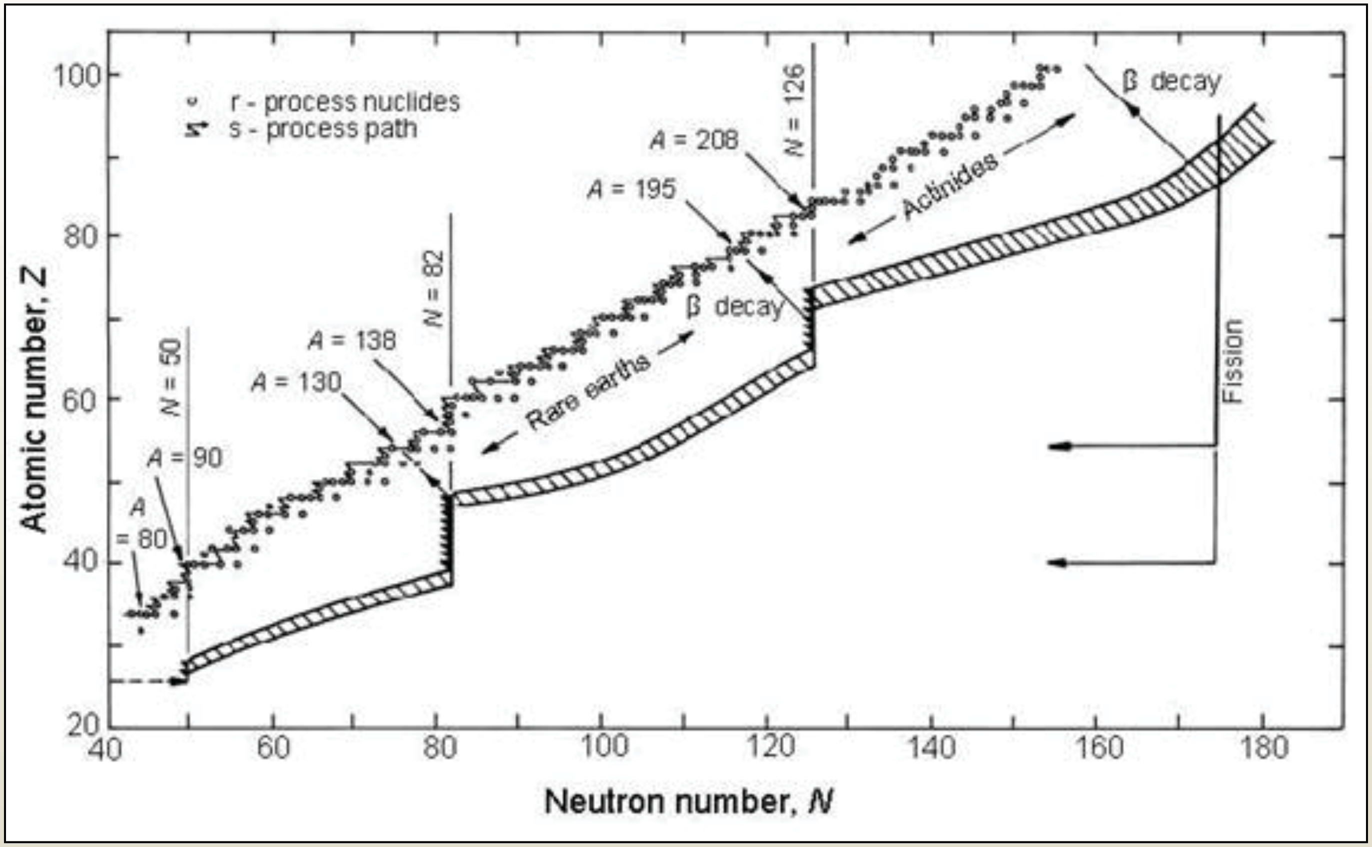
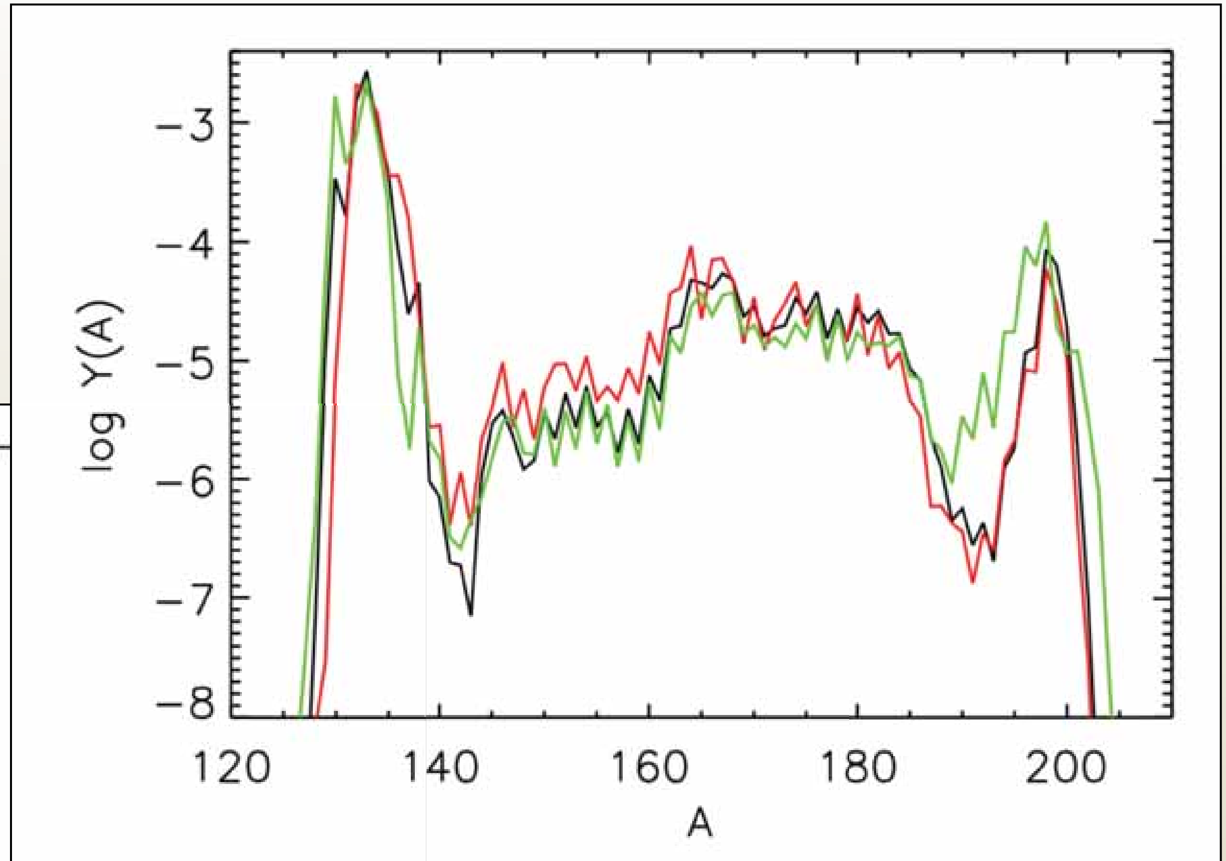


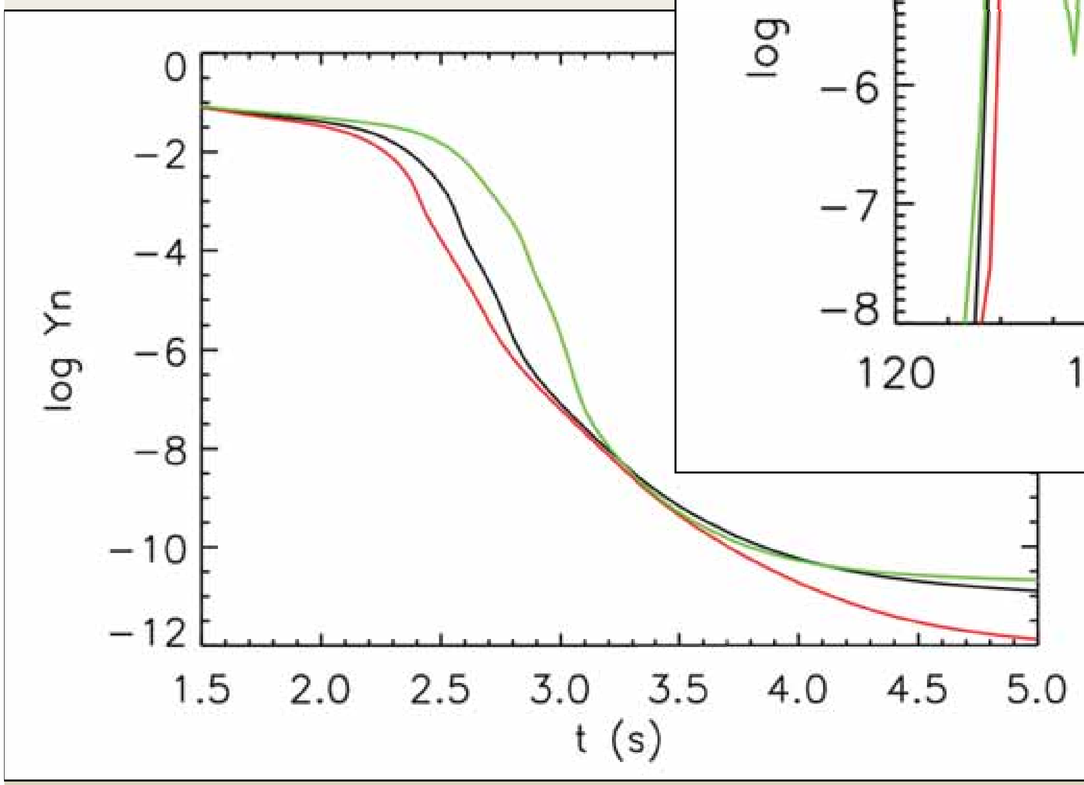
from Seeger et al (1965)

steady beta flow : $\lambda_\beta(Z,A_{path})Y(Z,A_{path}) \approx \text{constant}$

beta decay rates

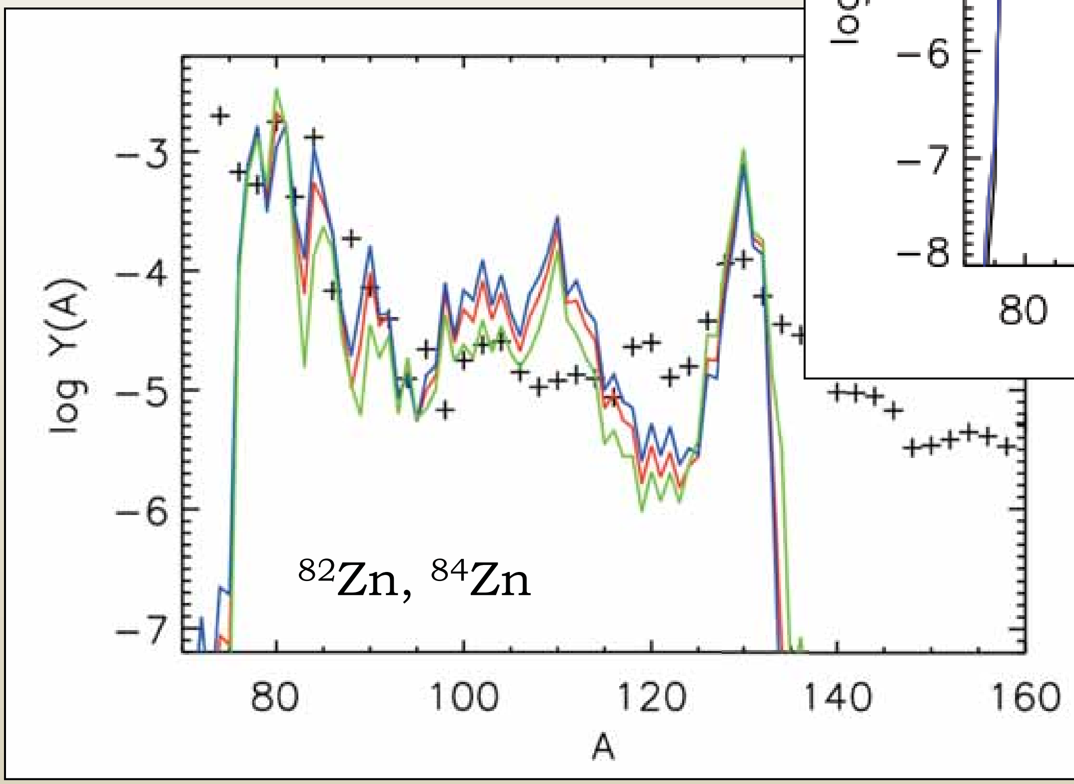
Moller et al {1997)
Moller et al (2003)
+ experimental

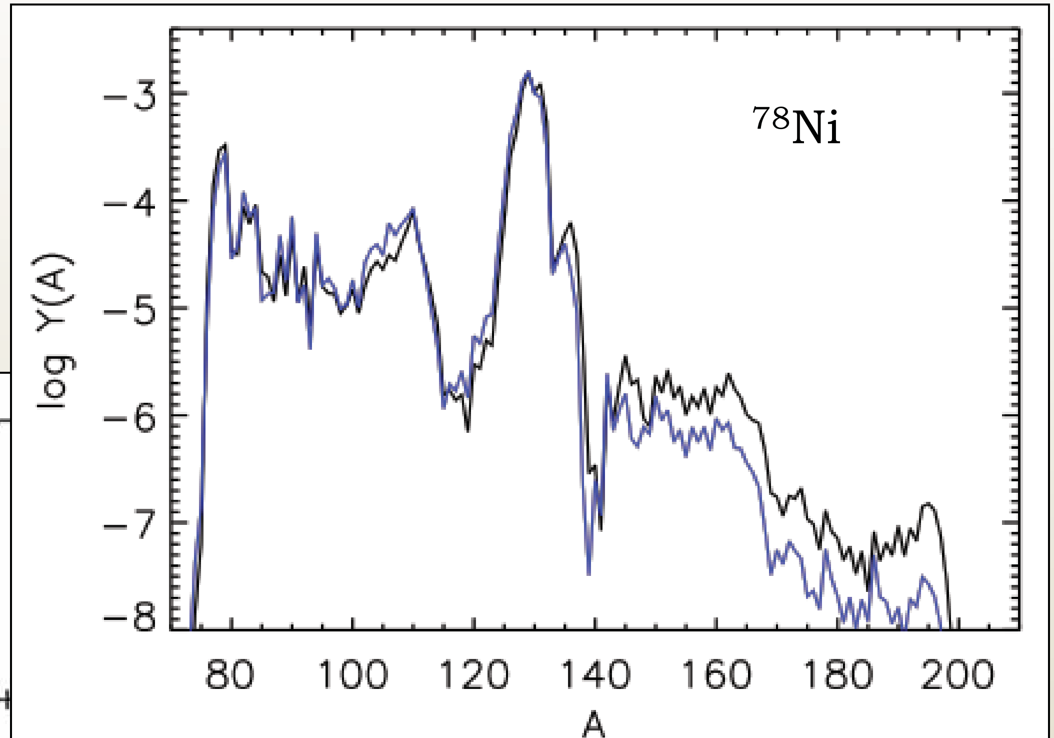




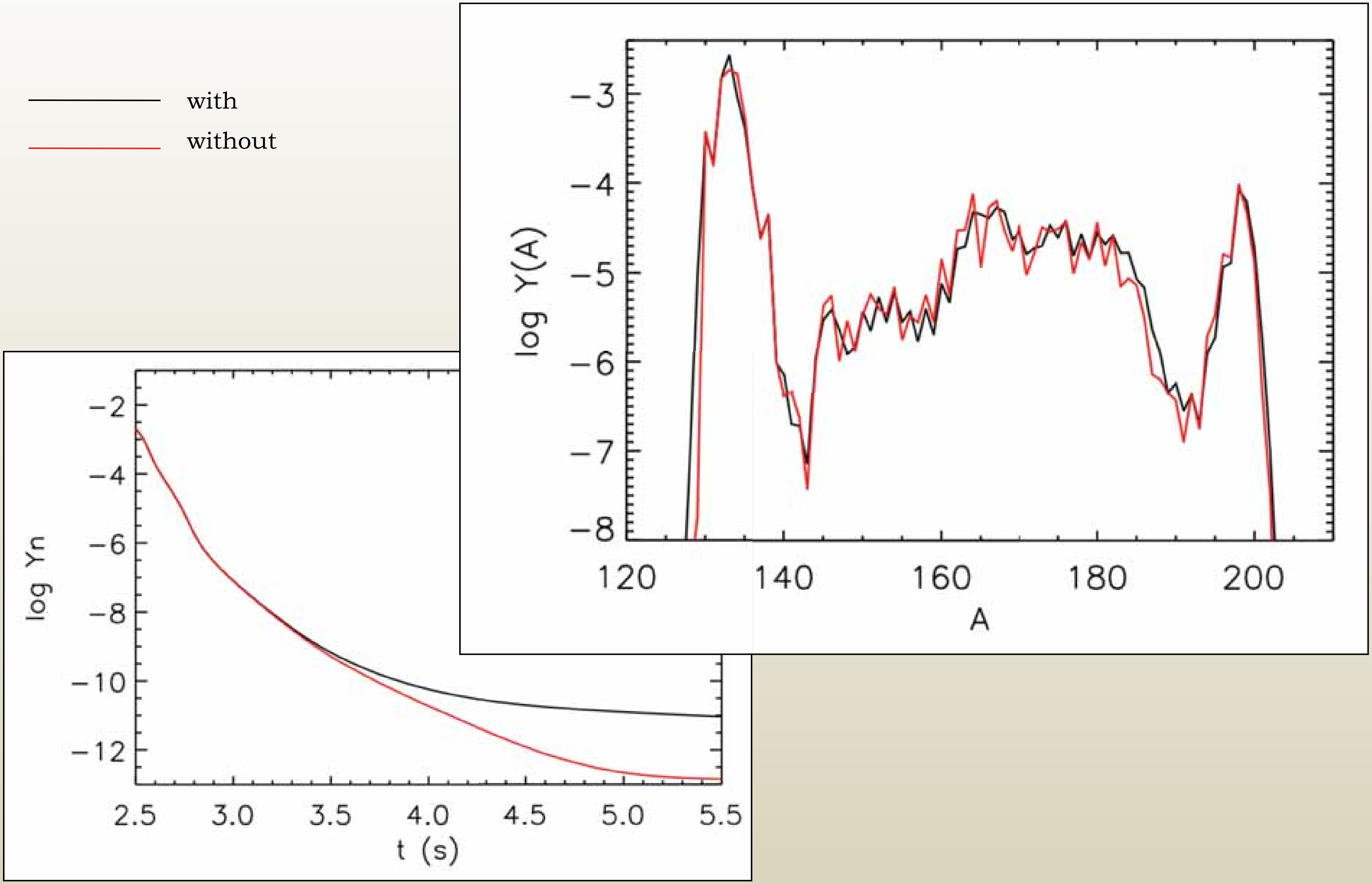
individual beta decay rates

Weak *r*-process trajectories with one or two beta decay rates modified

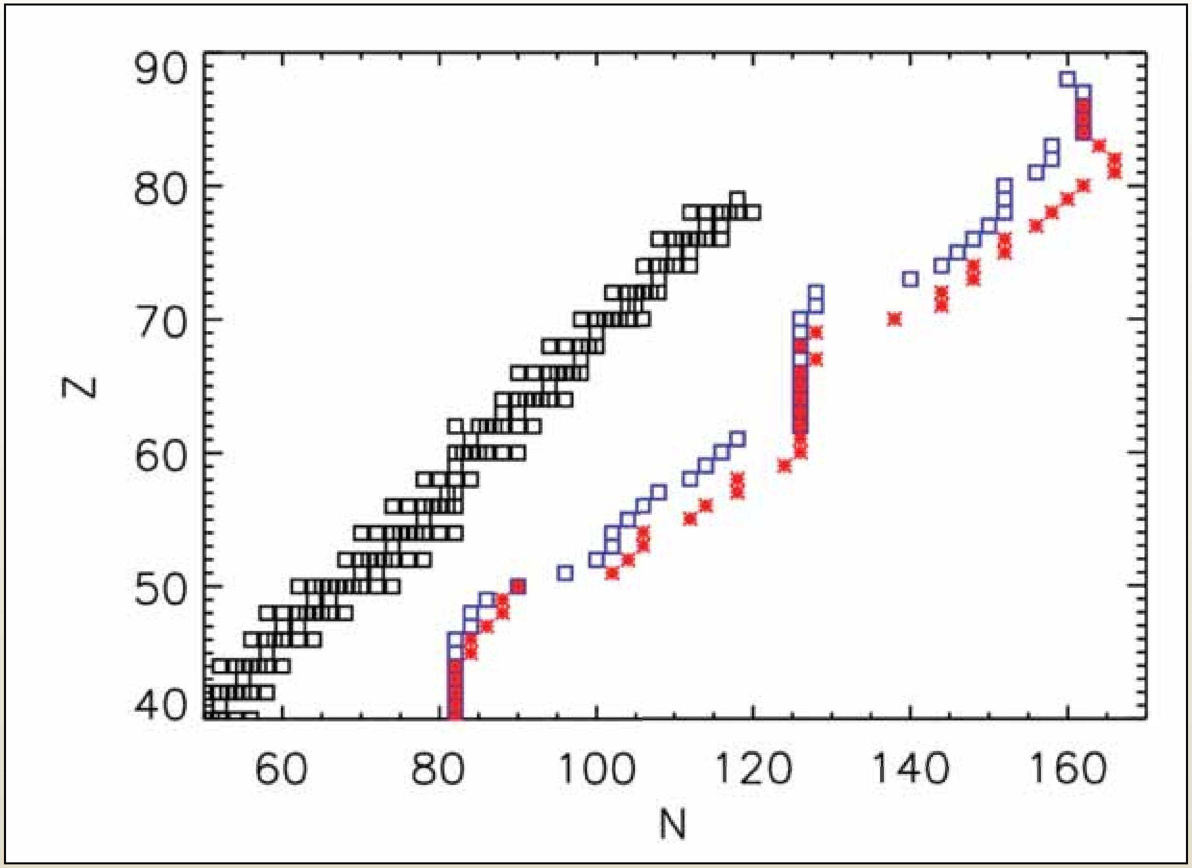




beta-delayed neutron emission

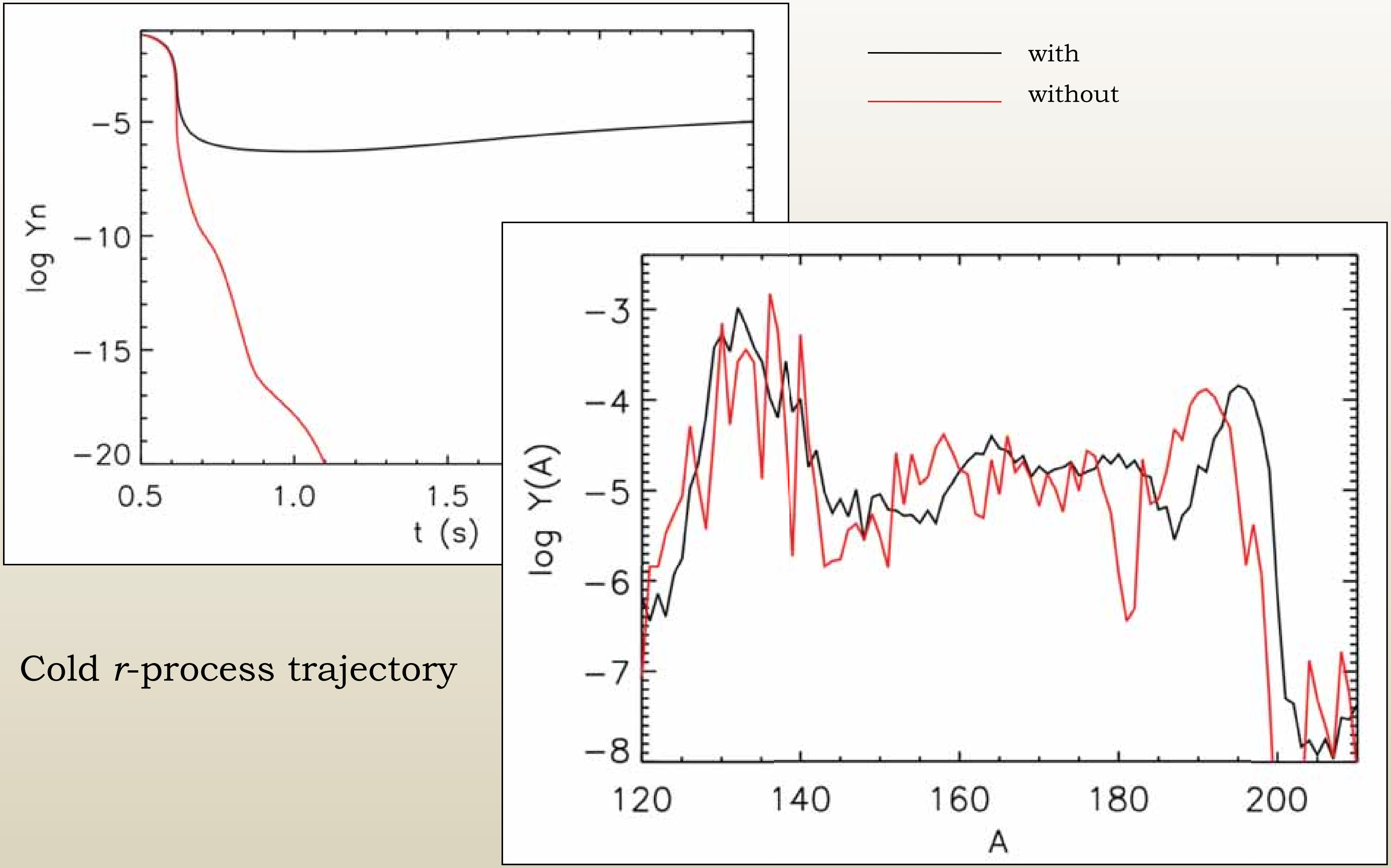


beta-delayed neutron emission and a cold *r* process



classical *r*-process path
cold *r*-process path

beta-delayed neutron emission



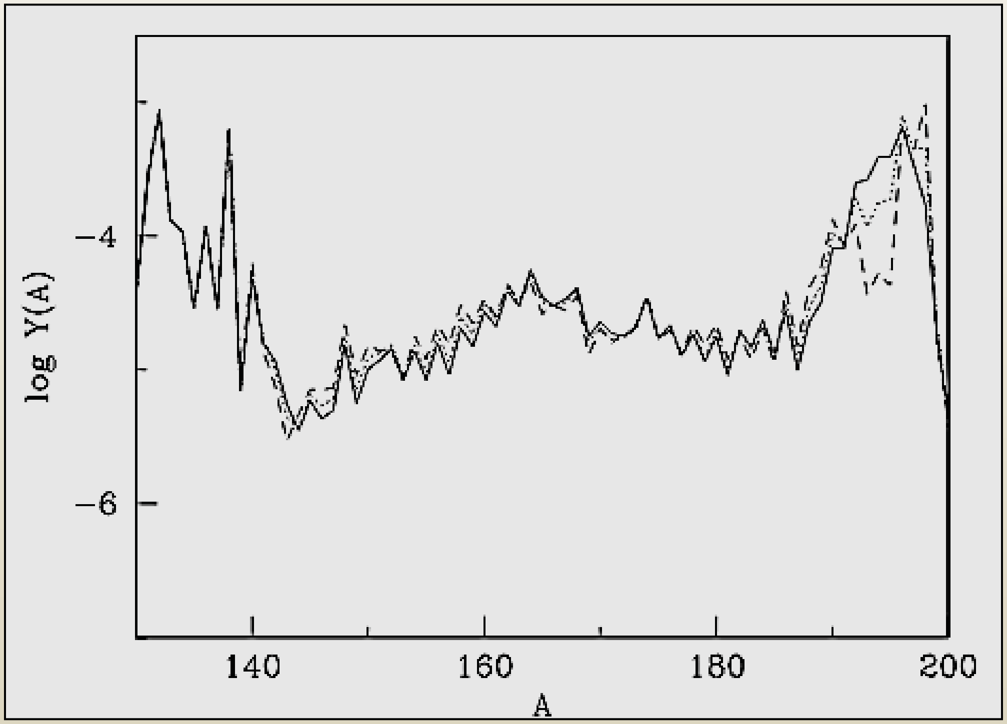
Cold *r*-process trajectory

⇒ can influence time until onset of freezeout

e.g., Goriely (1997,8), Farouqi et al, Rauscher (2005)

⇒ can shape local details of the abundance distribution

e.g., Surman et al (1998), Surman & Engel (2001)



Surman & Engel (2001)

neutron capture rates

⇒ can influence time until onset of freezeout

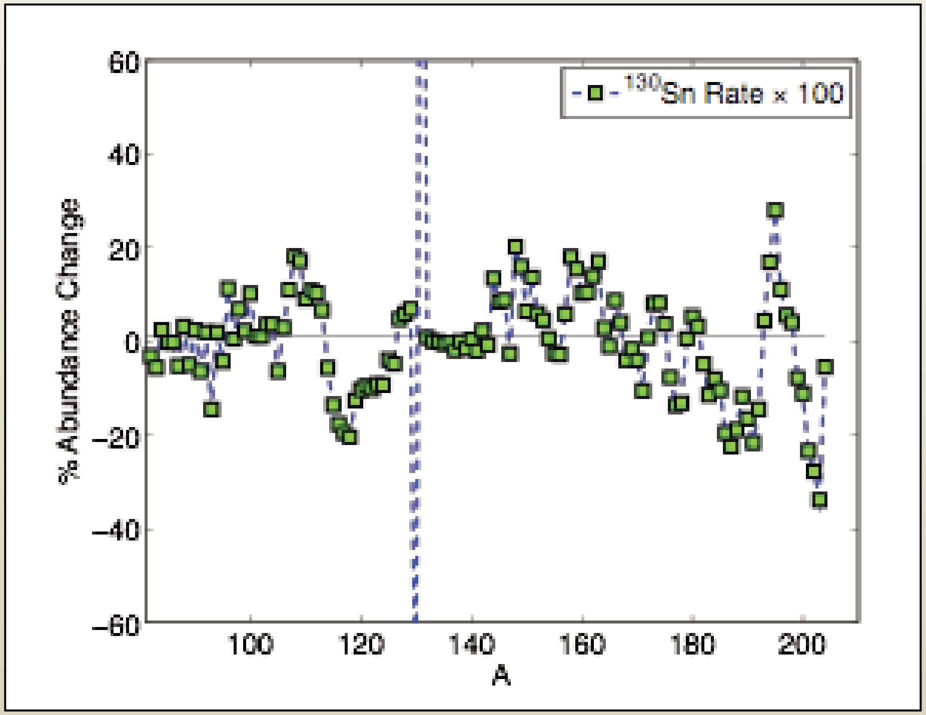
e.g., Goriely (1997,8), Farouqi et al, Rauscher (2005)

⇒ can shape local details of the abundance distribution

e.g., Surman et al (1998), Surman & Engel (2001)

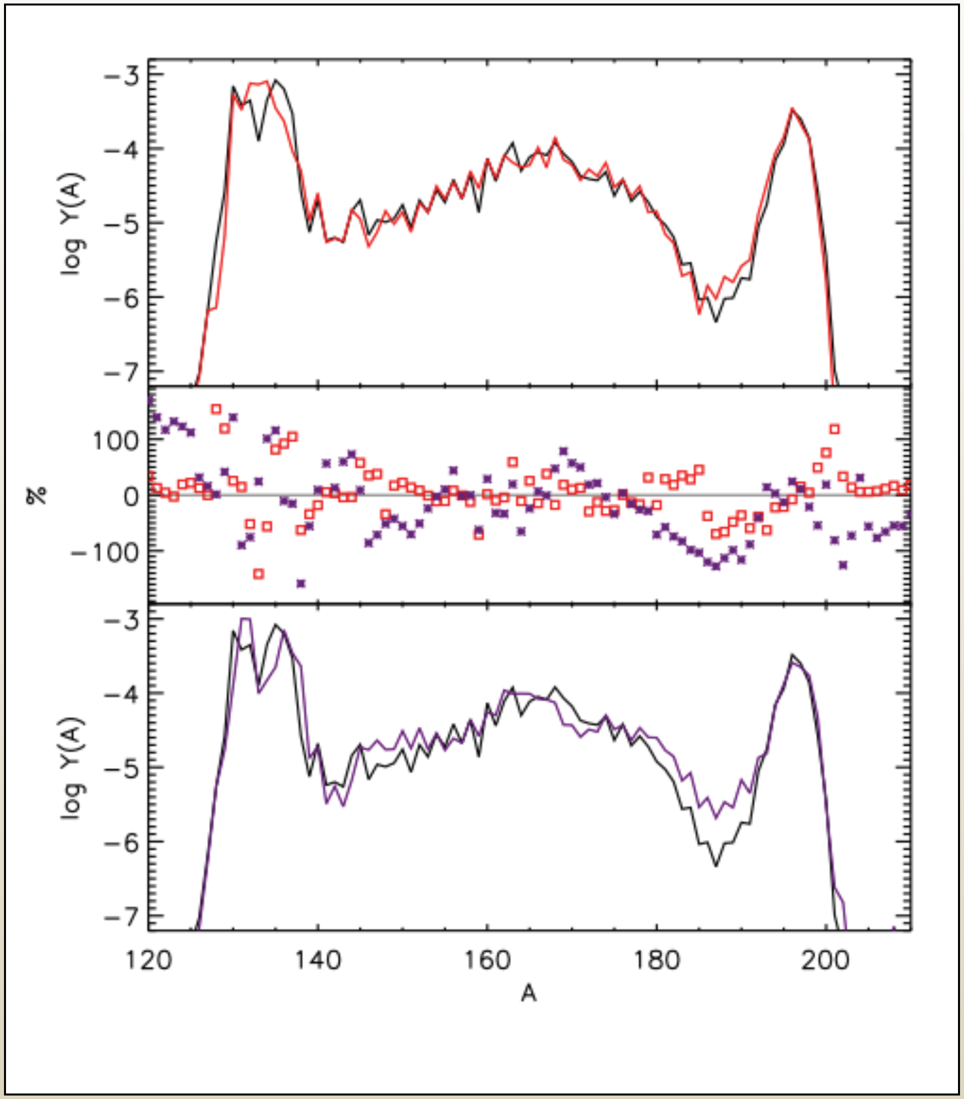
⇒ can influence the overall abundance pattern

e.g., Beun et al (2009), Surman et al (2009)



Beun, Blackmon, Hix, McLaughlin, Smith, and Surman, J Phys G, 36, 020201 (2009)

neutron capture rate/mass model variations

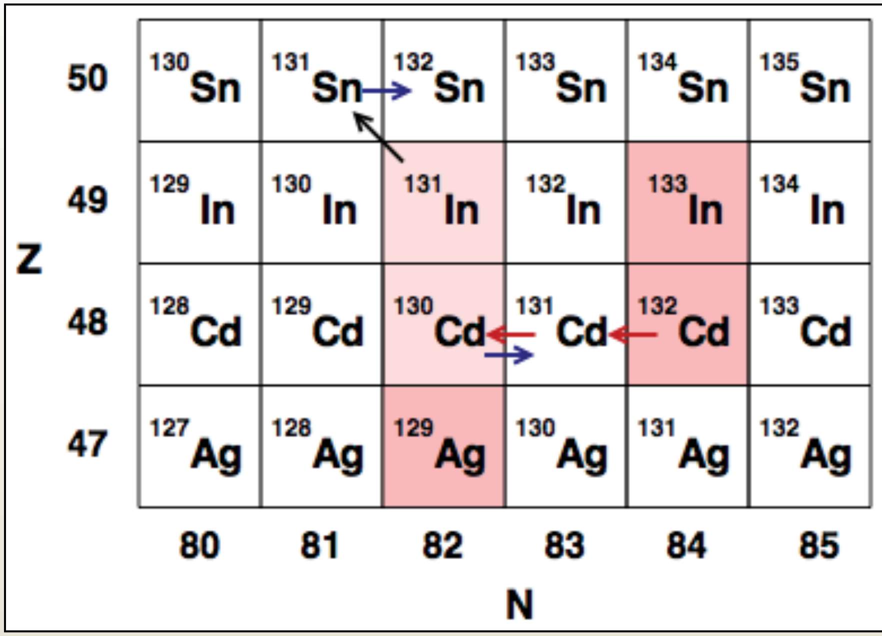


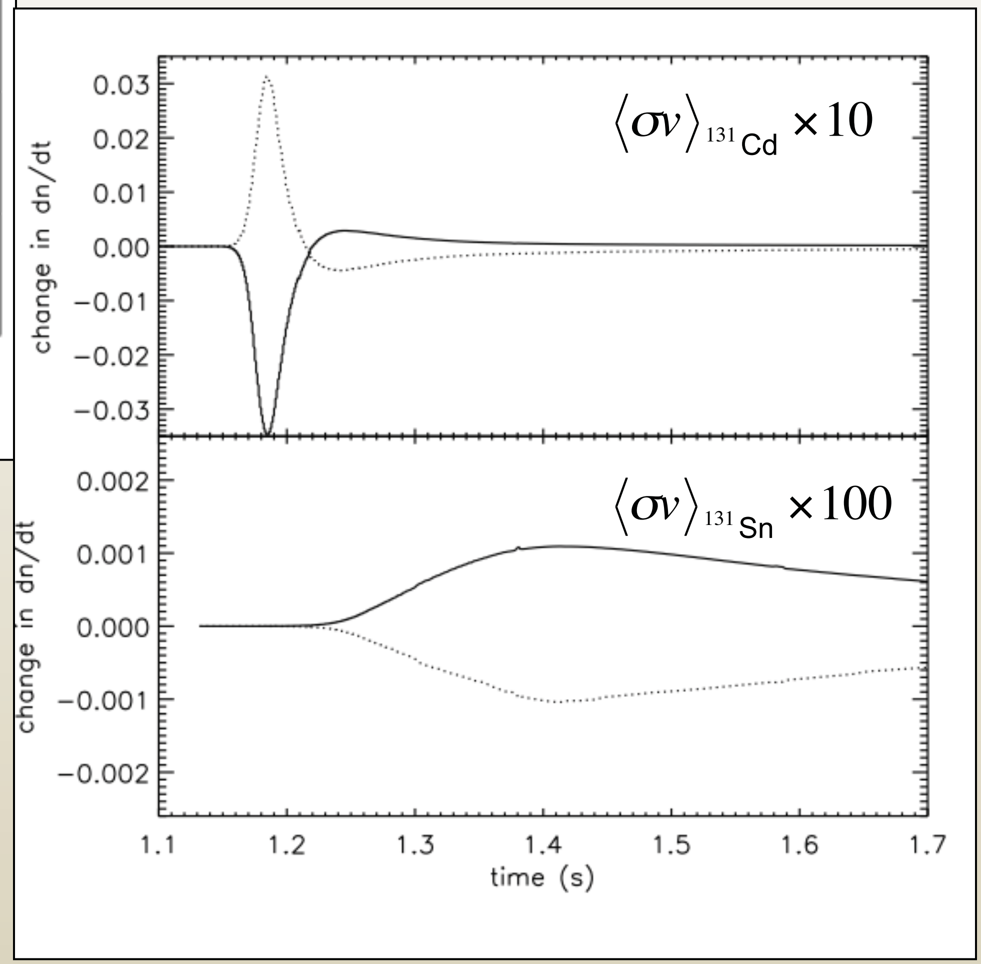
Neutron capture rate variation

Mass model variation

Surman, Beun, McLaughlin, and Hix, PRC, 79, 045809 (2009)

nonequilibrium effects of neutron capture rates



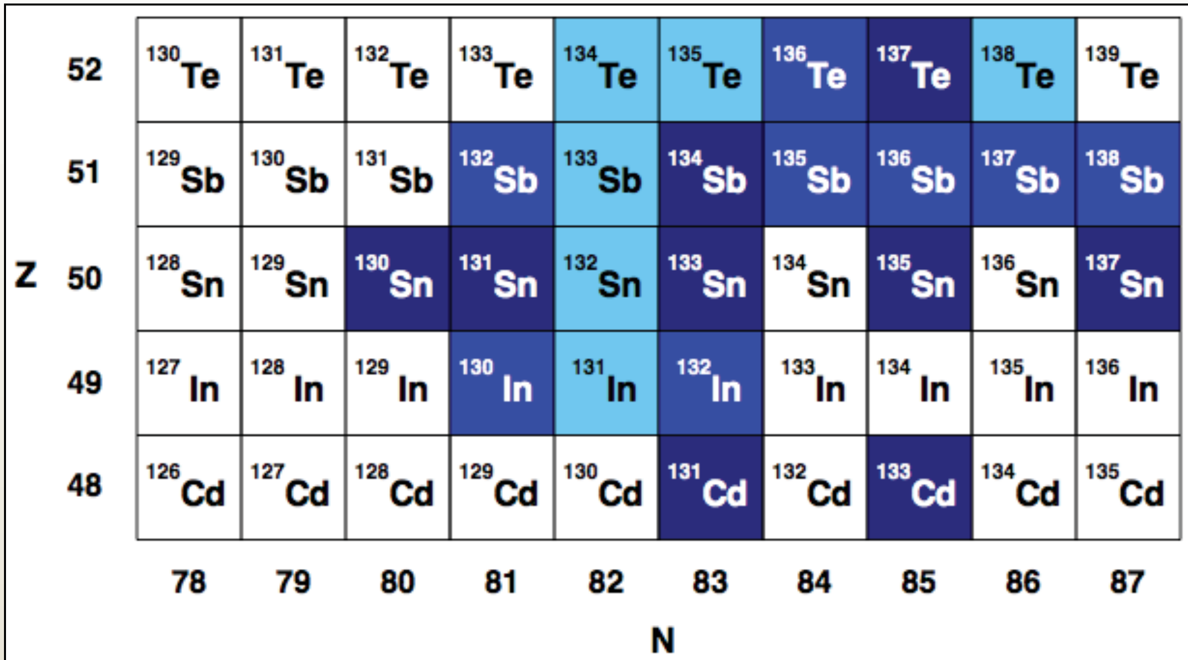


130 peak

rare earth region + 195 peak

Surman, Beun, McLaughlin, and Hix, PRC, 79, 045809 (2009)

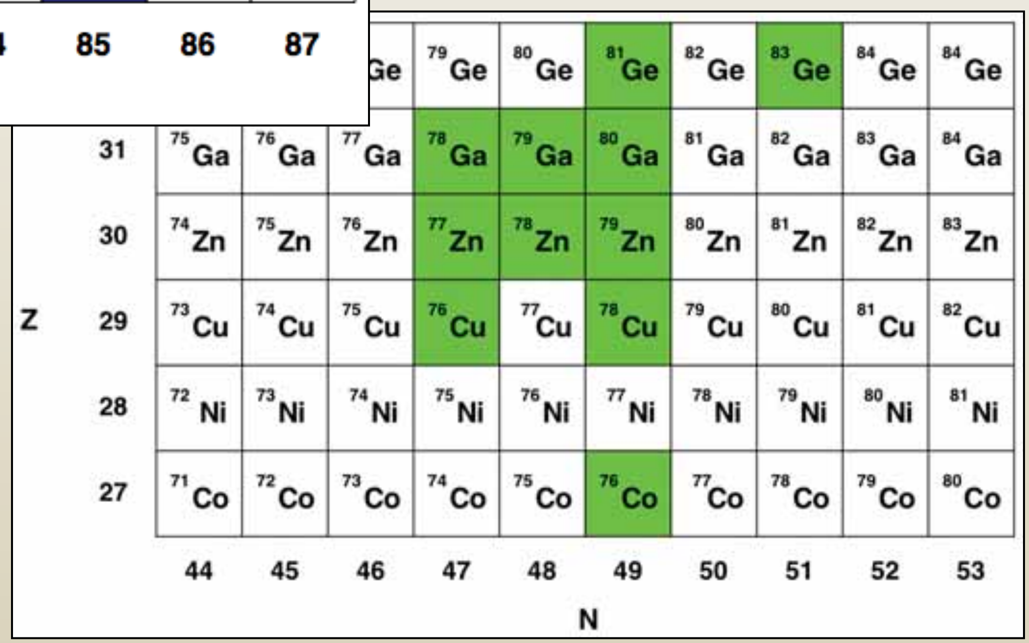
influential capture rates: A~130, A~80 regions



Capture rates that affect a 5-40% change in the global *r*-process abundance pattern for increases to the rate by a factor of:

10 | 50 | 100-1000

Surman, Beun, McLaughlin, and Hix, PRC, 79, 045809 (2009)

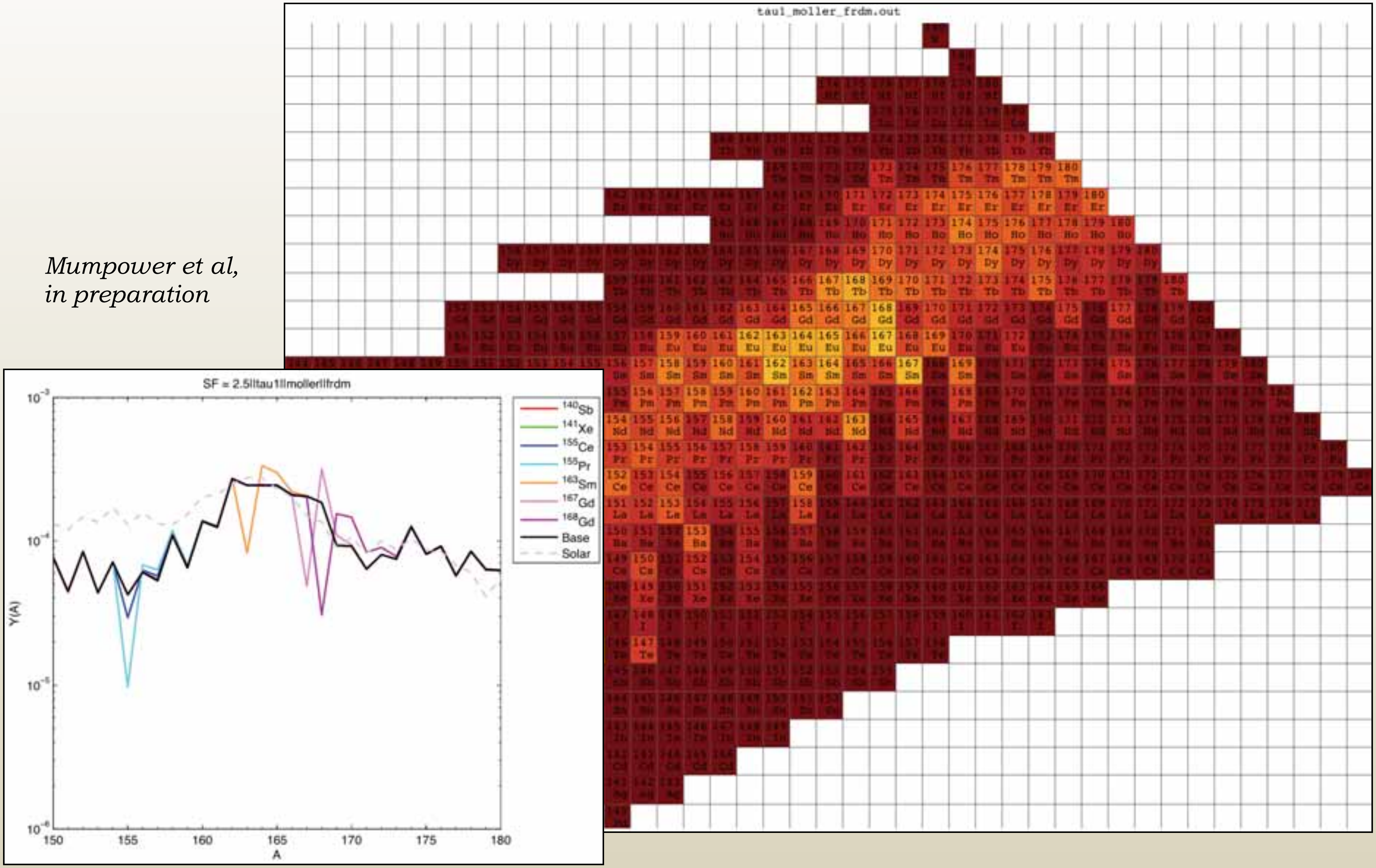


Capture rates that affect a 5-20% change in the weak *r*-process abundance pattern for increases to the rate by a factor of 100.

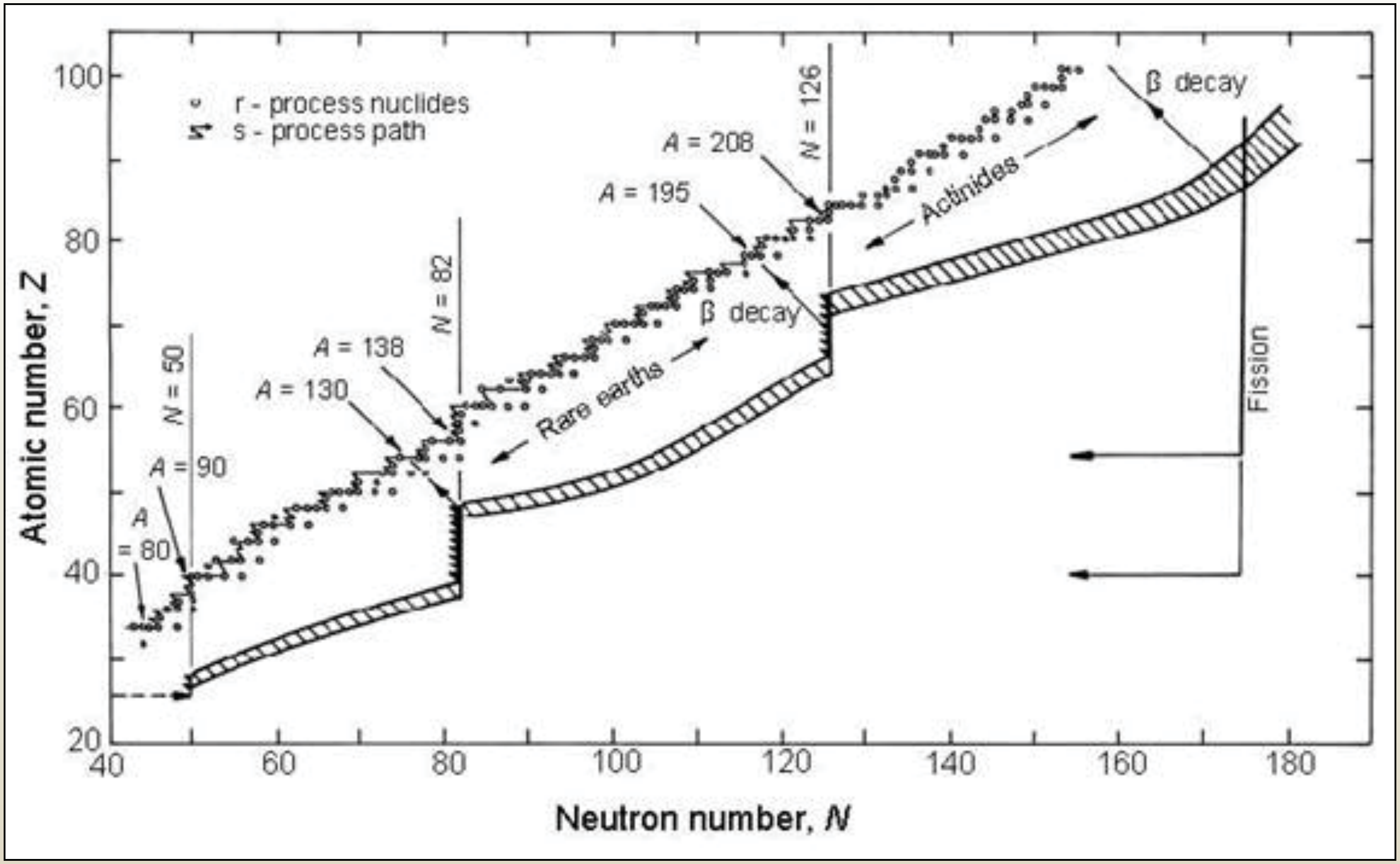
Surman et al, in preparation

influential neutron capture rates: rare earth region

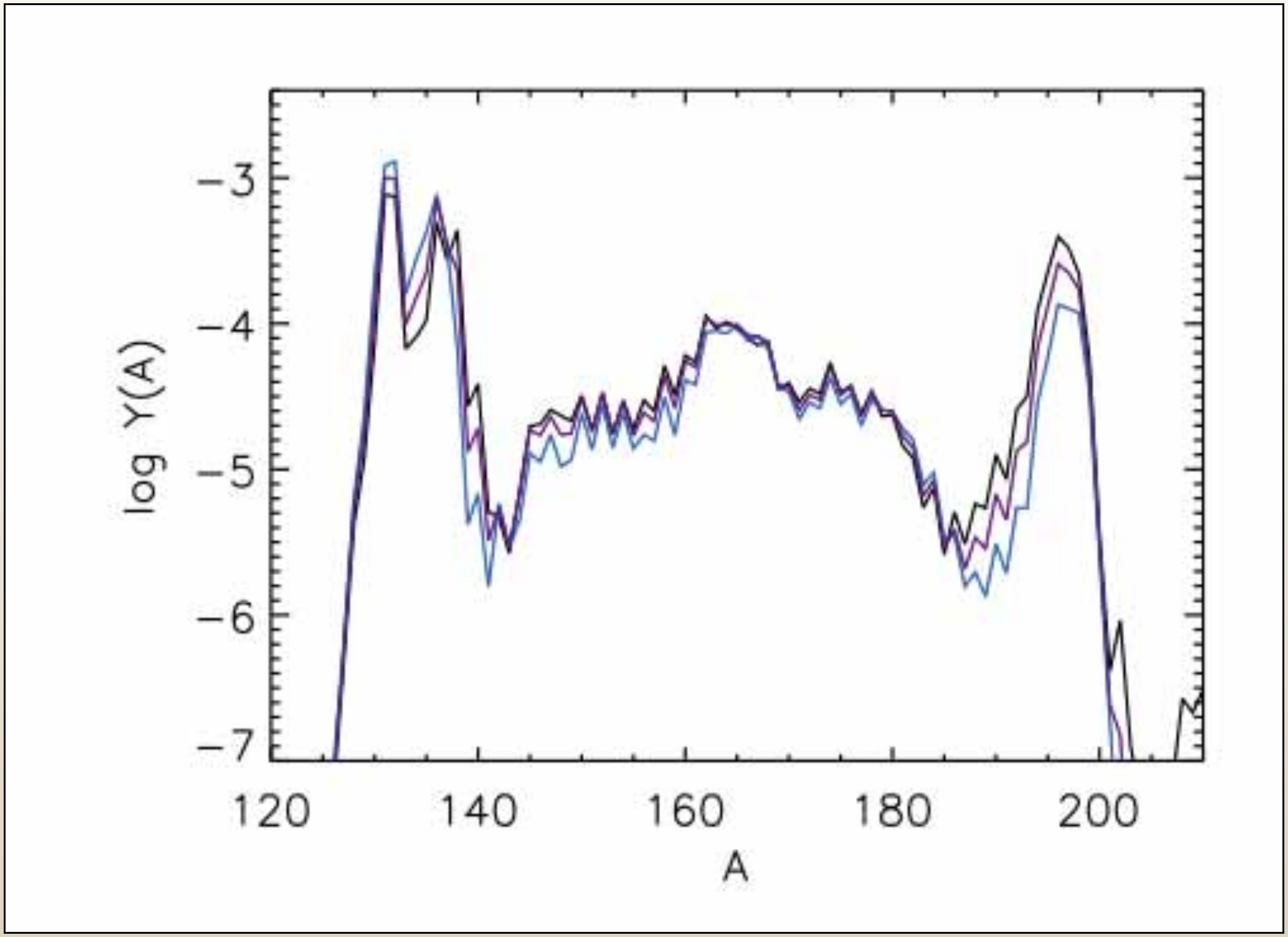
Mumpower et al,
in preparation



fission probabilities and daughter products



How is a consistent pattern achieved?



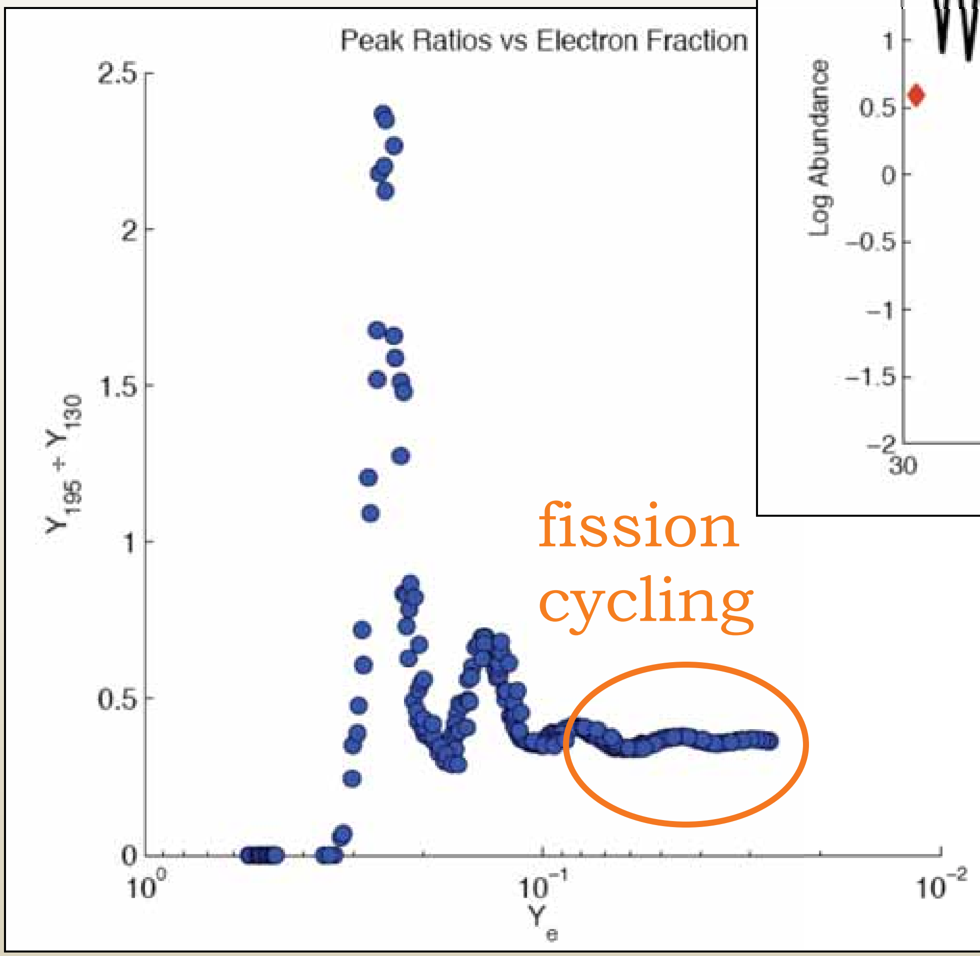
$Y_e = 0.25$

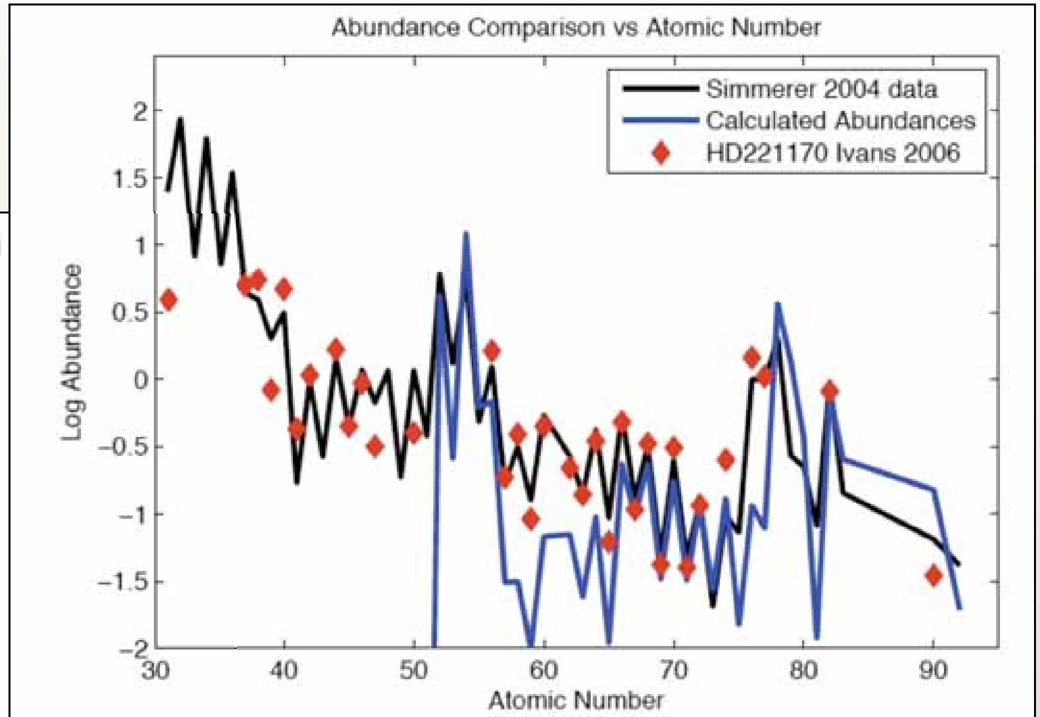
$Y_e = 0.26$

$Y_e = 0.27$

$$Y_e = \frac{1}{1 + n/p}$$

fission cycling and a consistent *r*-process pattern





Beun, McLaughlin, Surman, & Hix, PRC 77, 035804 (2008)

We still don't know where the *r* process takes place

⇒ but once astrophysical uncertainties are reduced, understanding the nuclear physics of neutron-rich nuclei will be crucial to make detailed comparisons between simulations and observations

We need:

nuclear masses

beta decay rates

As discussed by F. Montes

beta-delayed neutron emission probabilities

neutron capture rates

Particularly of nuclei on the beta-decay chains of the closed shell nuclei, and of nuclei in the rare earth region

fission probabilities and daughter product distributions