Neutron capture and *r*-process nucleosynthesis

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r-process nucleosynthesis: open questions

Astrophysics

What is the astrophysical site of the *r* process?

Some possibilities:

supernovae *e.g., Meyer et al (1992), Woosley et al (1994), Takahashi et al (1994), Arcones et al (2007), Hudepohl et al (2010)*

shocked surface layers of O-Ne-Mg cores *e.g., Wanajo et al (2003), Ning et al (2007), Hoffman et al (2008)*

neutron star mergers *e.g., Lattimer et al (1974), Meyer (1989), Frieburghaus et al (1999), Rosswog et al (2001), Goriely (2004)*

gamma-ray bursts *e.g., Surman et al (2005), Metzger et al (2008), Wanajo & Janka (2010)*

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

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Nuclear Physics

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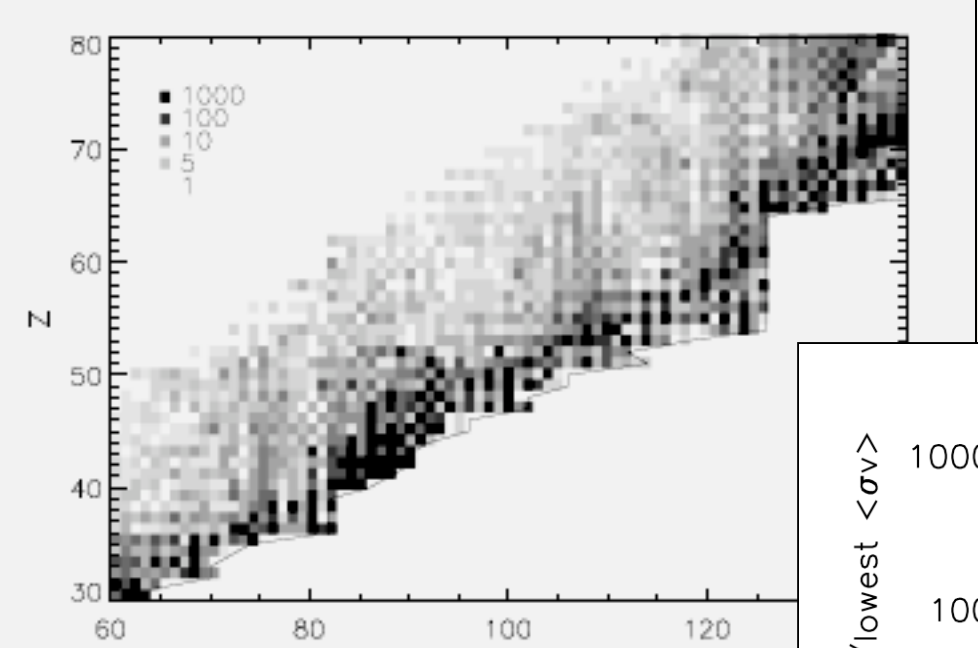
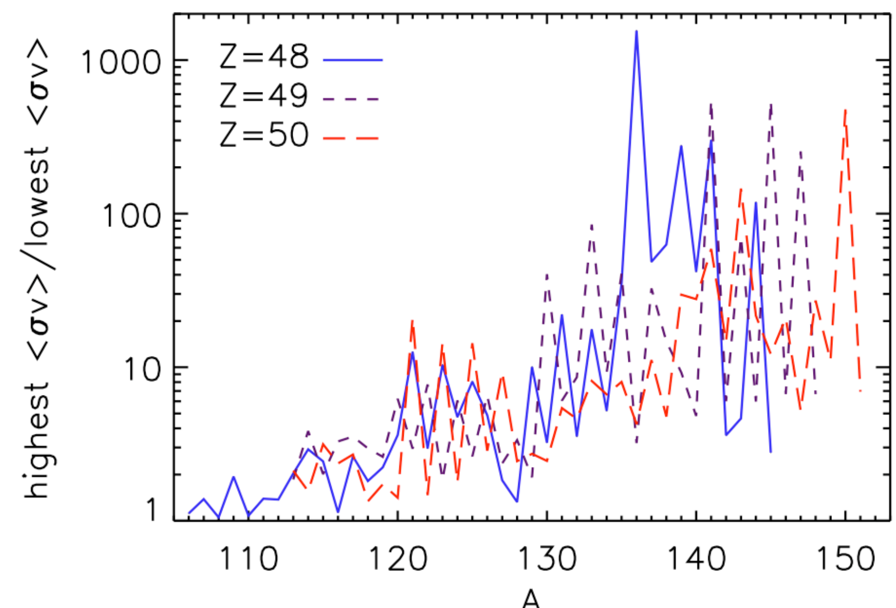
theoretical neutron capture cross sections



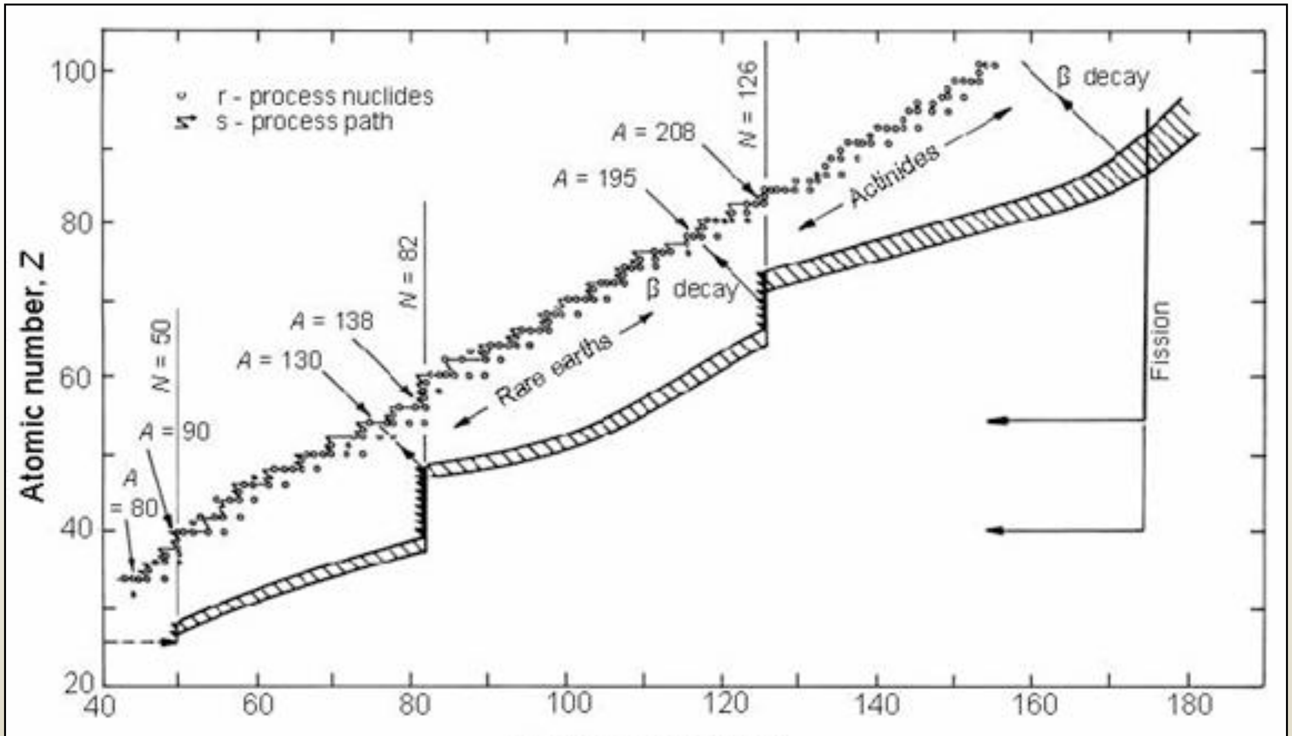
from Surman & Engel (2001)

$$\frac{\langle \sigma v \rangle_{high}}{\langle \sigma v \rangle_{low}}$$



from Surman et al (2009)

‘waiting point’ approximation



from Seeger et al (1965)

r-process abundances built up in (n,γ)-(γ,n) equilibrium

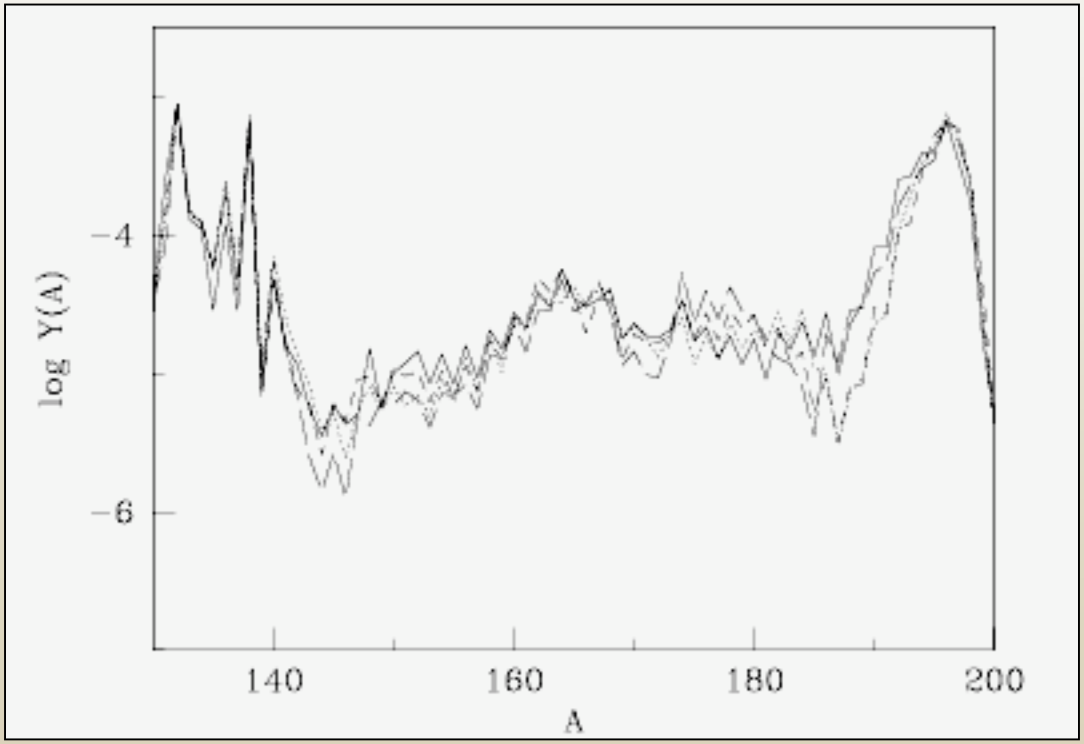
$$\lambda_\gamma \propto T^{3/2} \exp\left(-\frac{S_n}{kT}\right) \langle \sigma v \rangle_{Z,A}$$

neutron capture rates - do they matter?

⇒ can influence time until onset of freezeout

e.g., Goriely (1997,8), Farouqi et al (2006), Rauscher (2005)

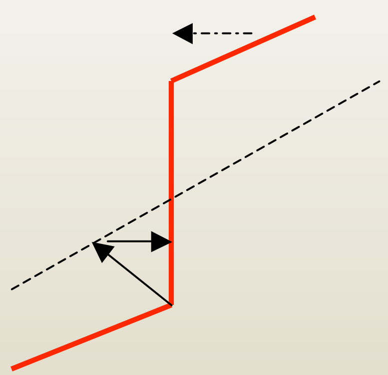
⇒ can shape the details of the abundance distribution at late times *e.g., Surman et al (1998), Surman & Engel (2001)*

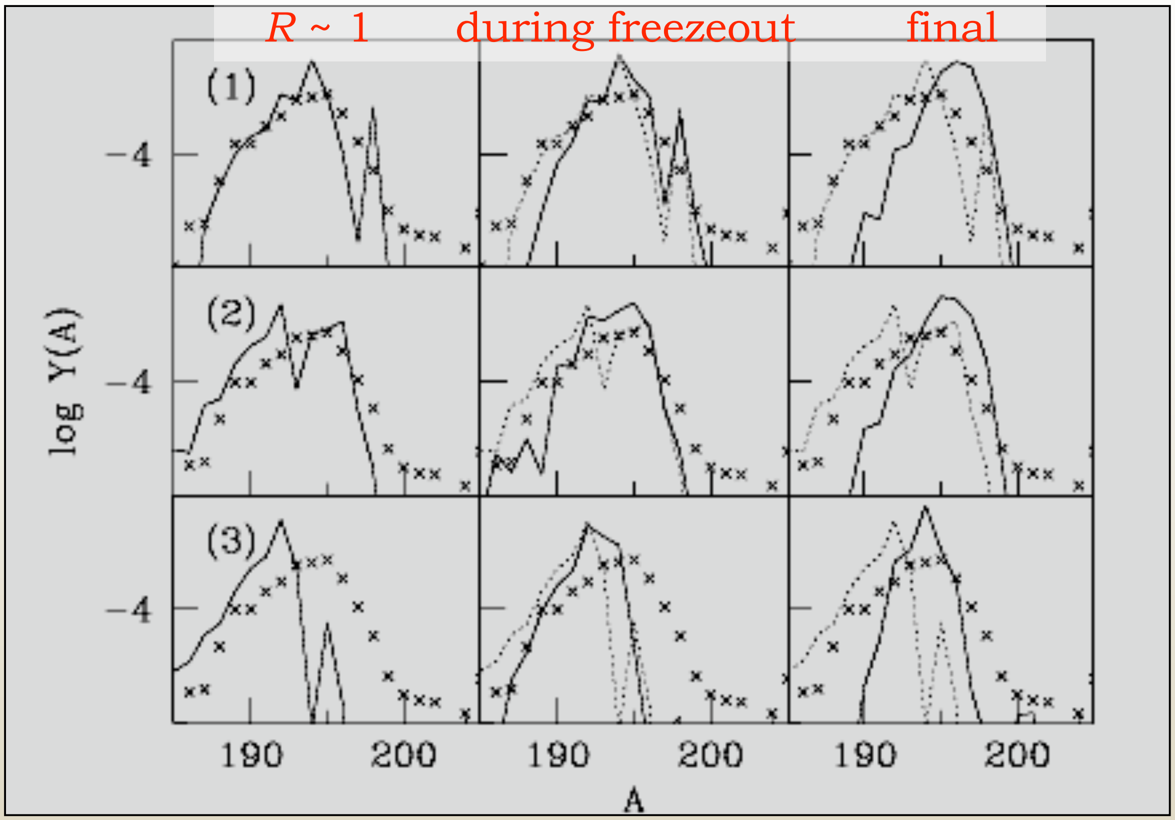


Surman & Engel (2001)

peak shaping during freezeout from equilibrium

'funneling' effect narrows and shifts peaks



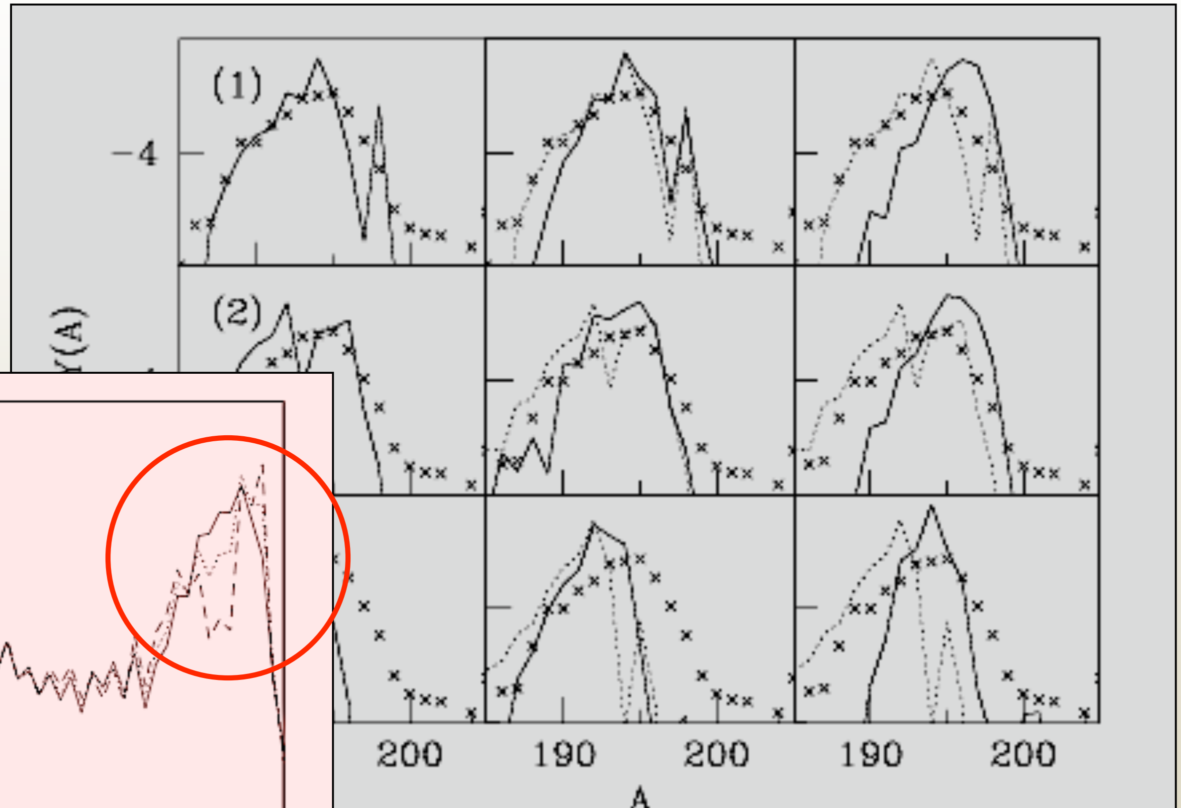


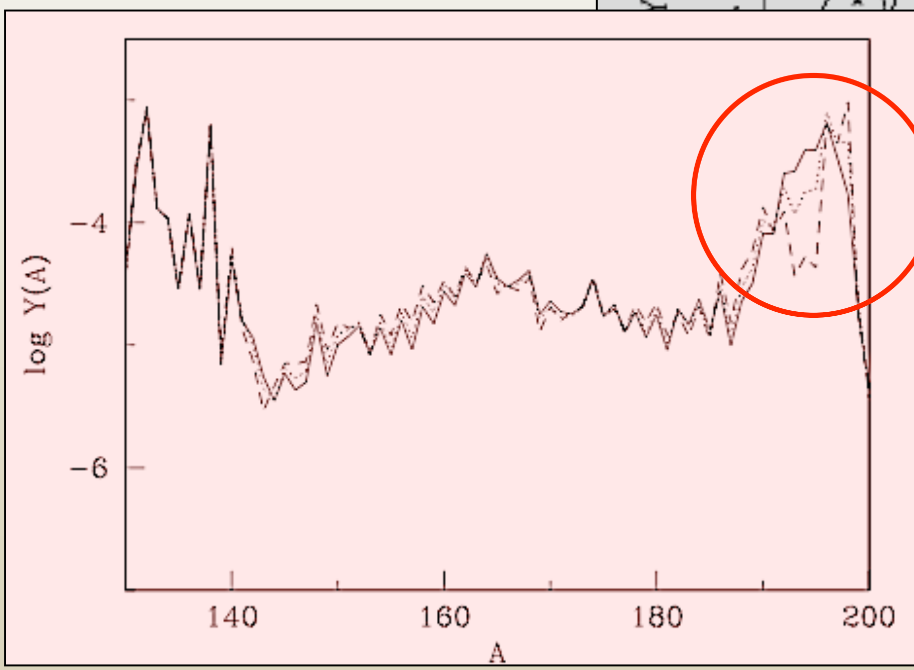
Surman & Engel (2001)

competes with spreading from beta-delayed neutron emission

peak shaping during freezeout from equilibrium

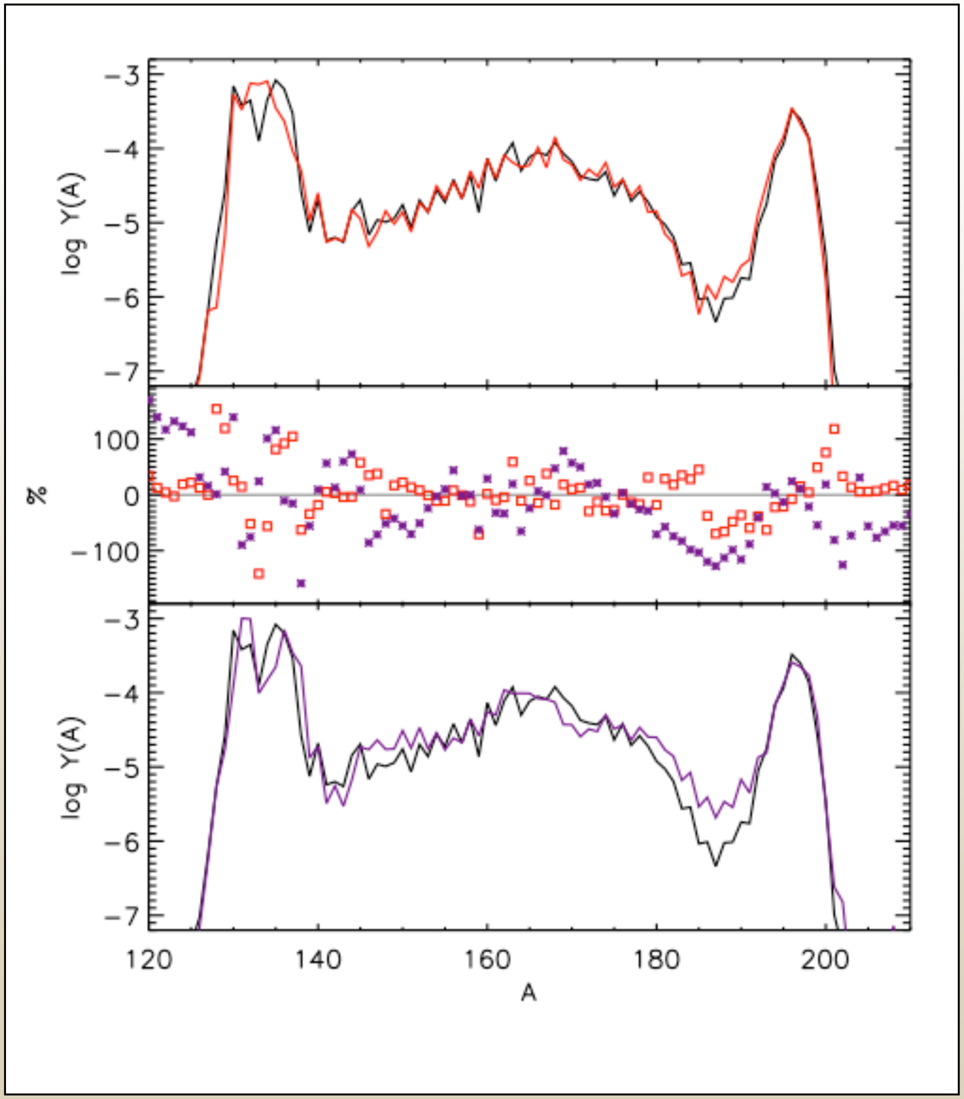
changes to capture rates modify this mechanism





Surman & Engel (2001)

mass model/capture rate comparison



Neutron capture rate variation

Mass model variation

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

influence of *individual* rates?

our sensitivity analysis:

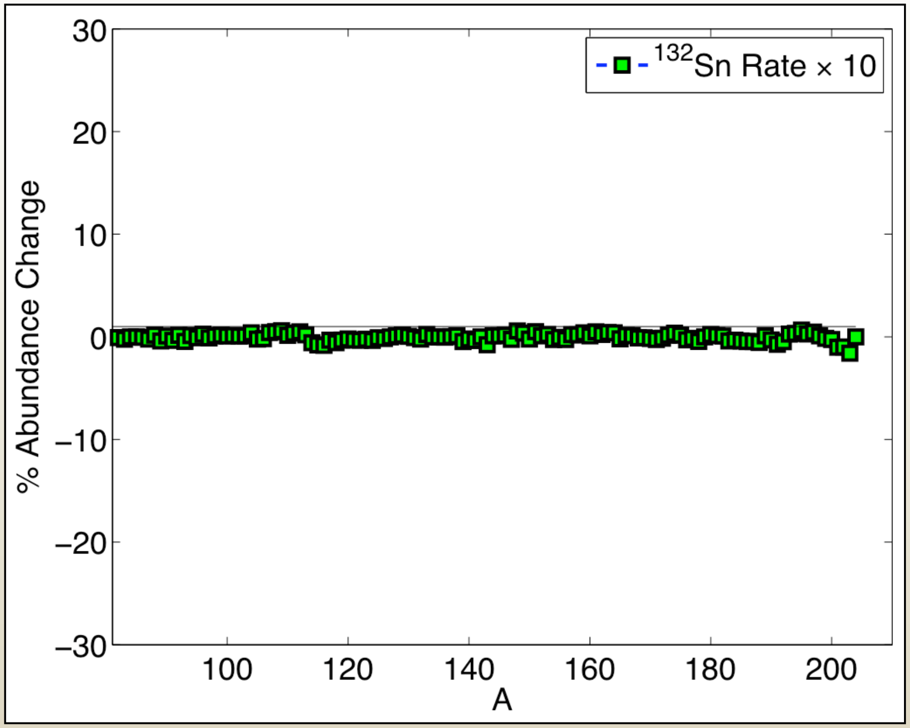
• choose a baseline simulation that well reproduces the appropriate section of the solar *r*-process abundance pattern

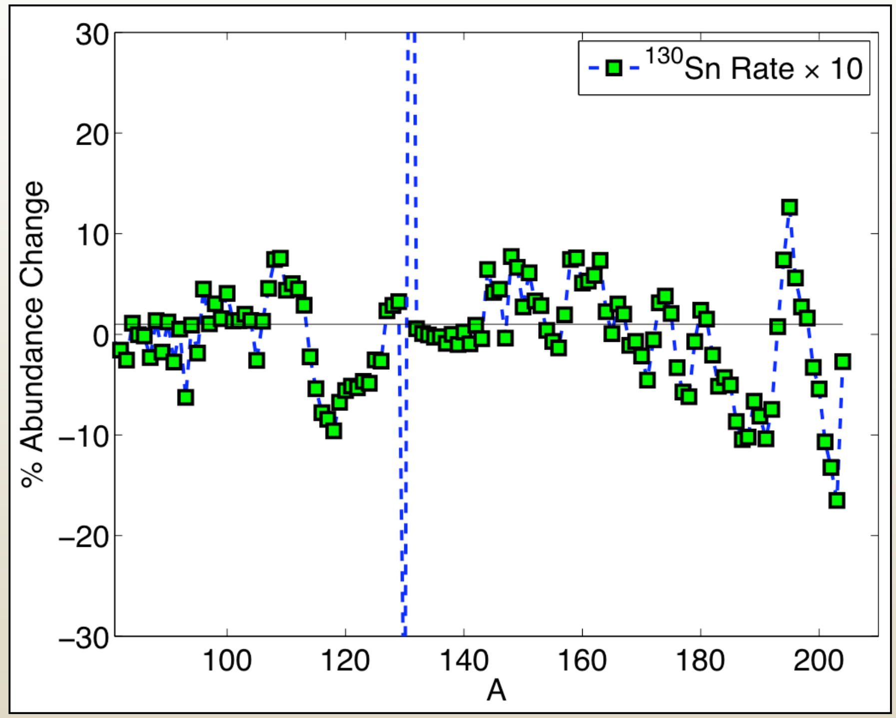
• modify a neutron capture rate in that region by a factor *k*

• rerun simulation and compare to baseline

• repeat for each nucleus in the region of interest for *k* = 10, 50, 100, 1000

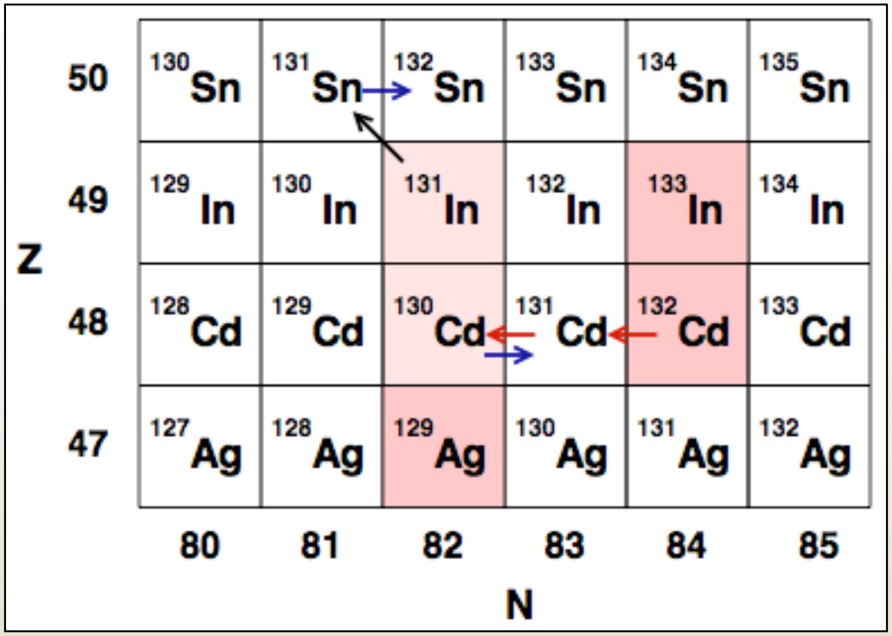
influence of individual rates of ^{132}Sn and ^{130}Sn





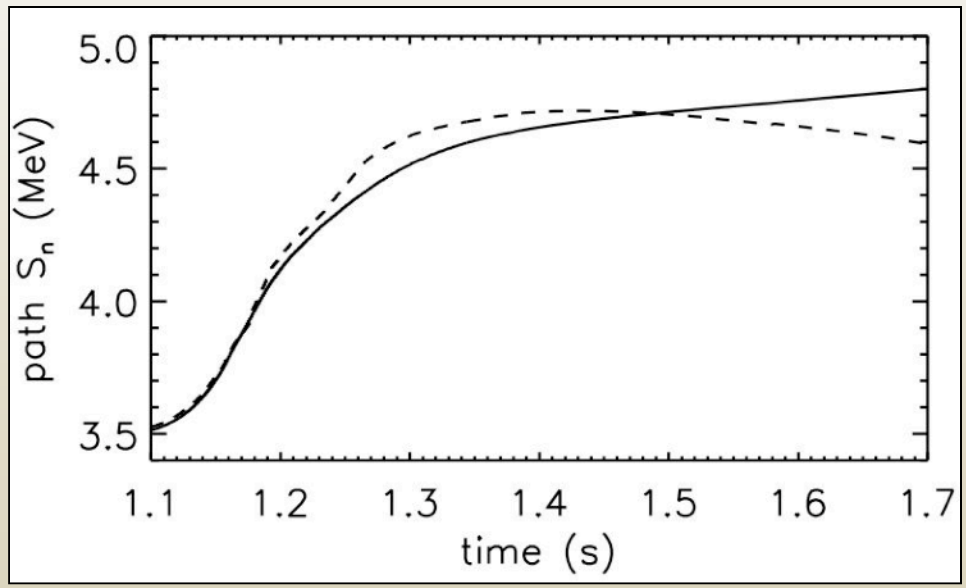
Beun, et al (2008)

nonequilibrium effects of capture rates



equilibrium path S_n - - - - - - - -

actual path S_n ————



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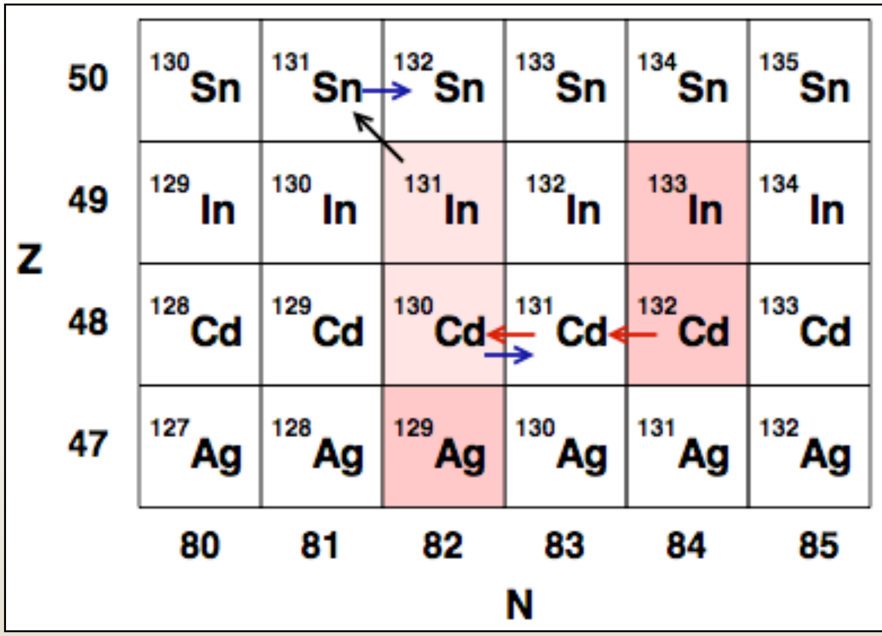
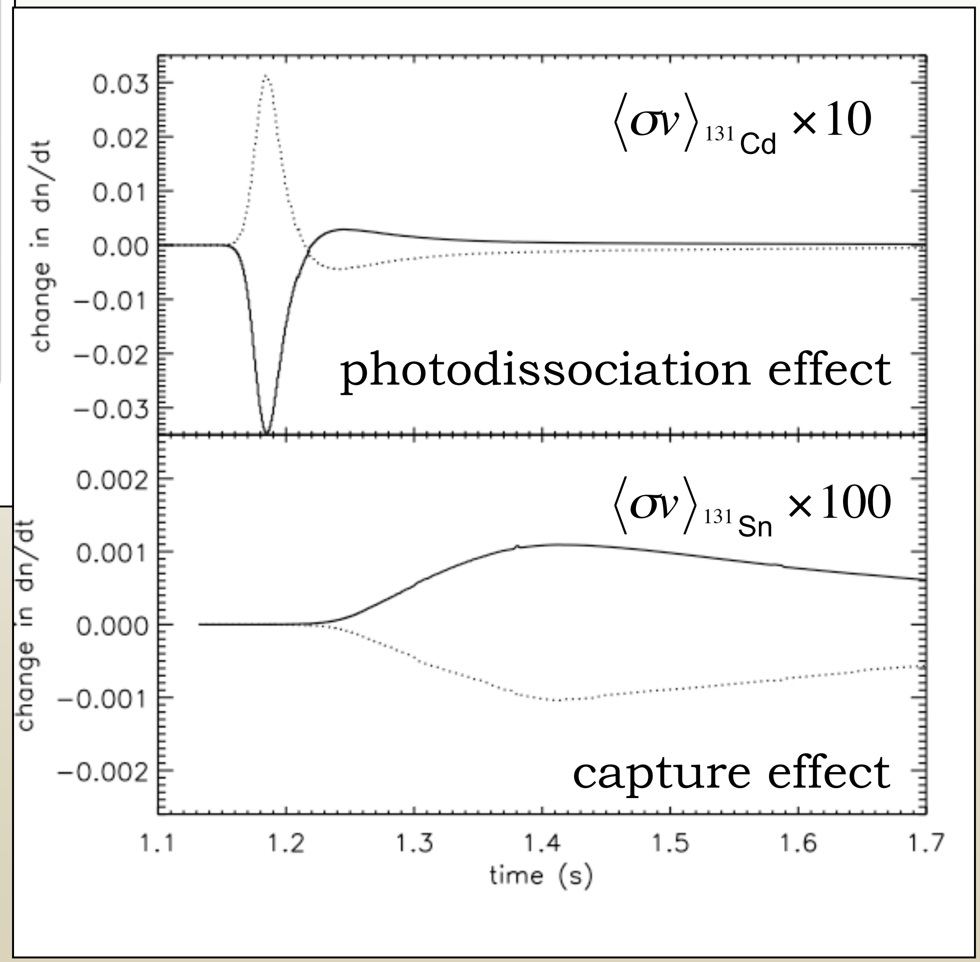
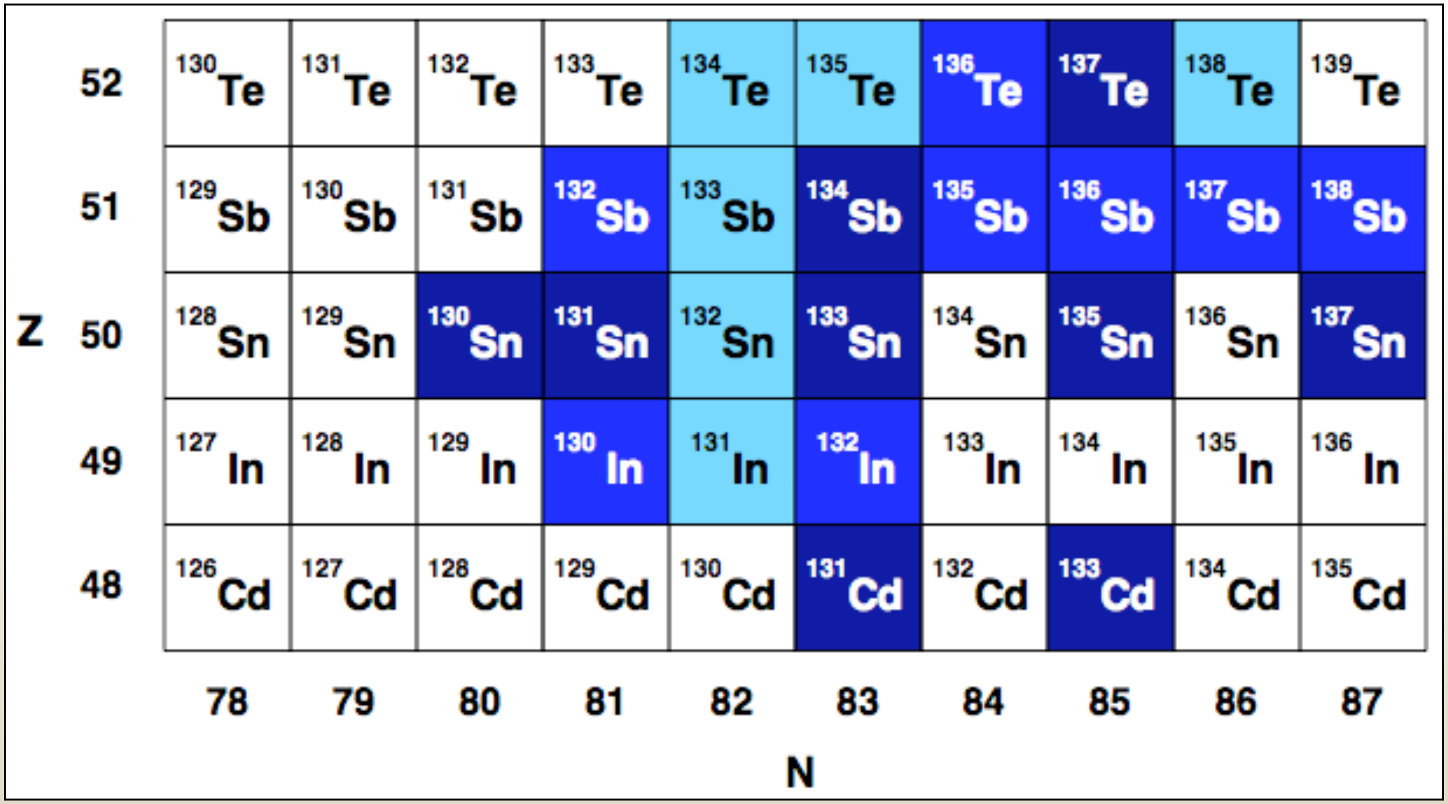




130 peak
rare earth region + 195 peak

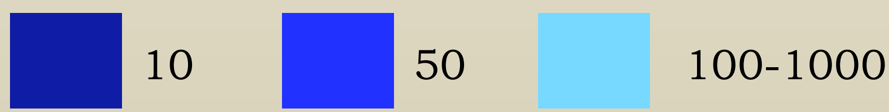
Surman, Beun, McLaughlin, and Hix, PRC, 79, 045809 (2009)

influential neutron capture rates: *A*~130 region

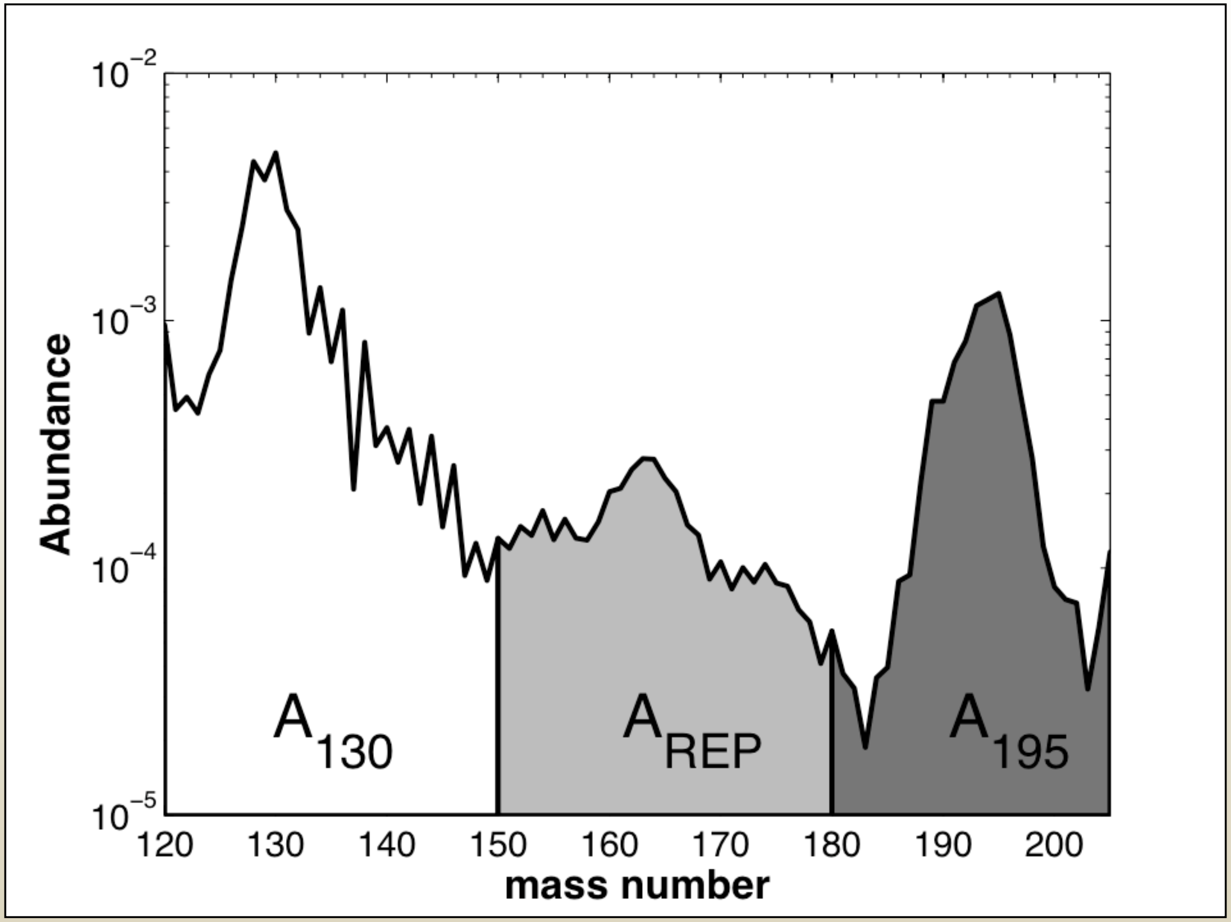


Surman, Beun, McLaughlin, and Hix, PRC, 79, 045809 (2009)

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

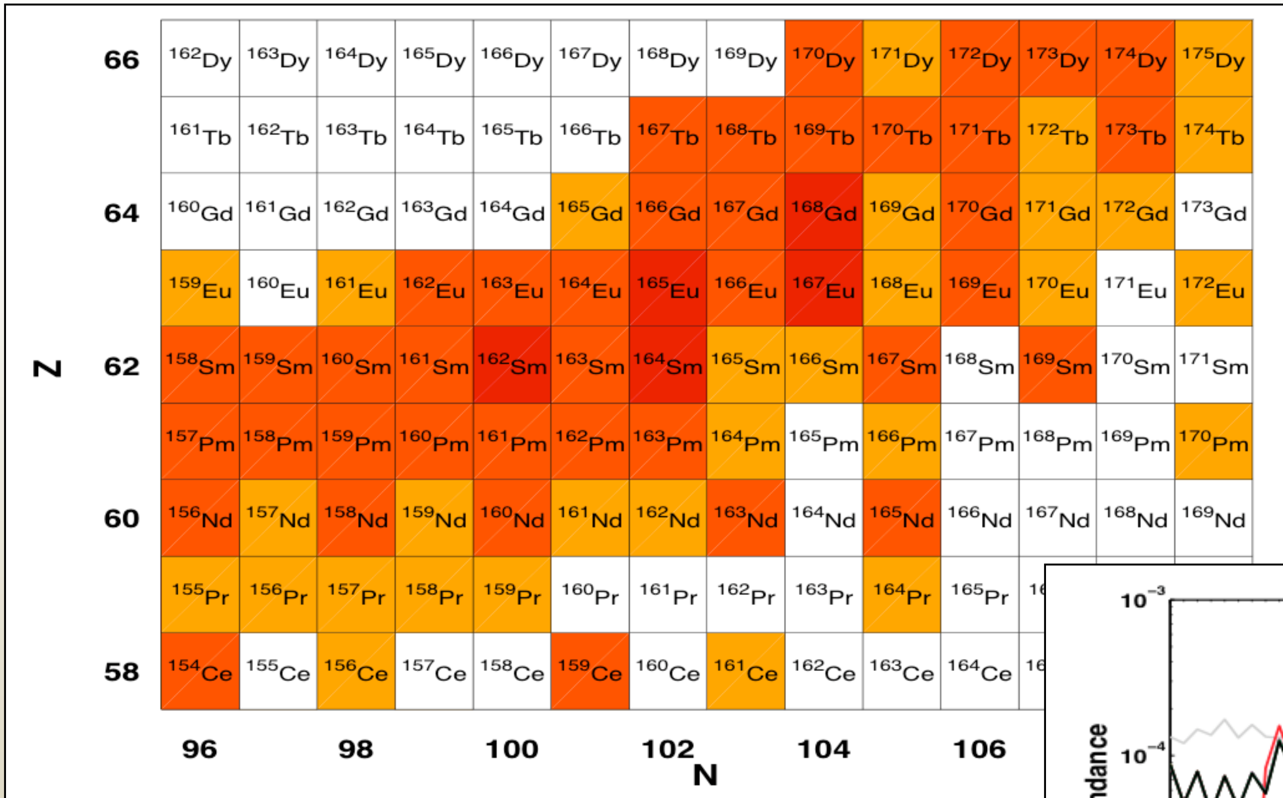


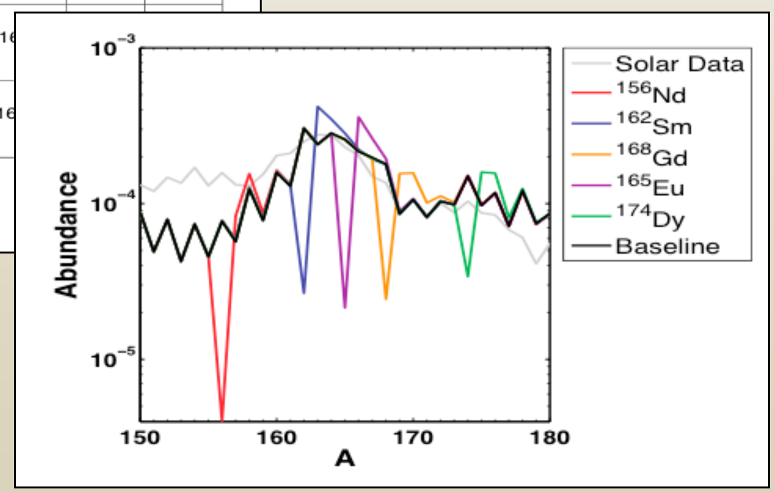
neutron capture in the rare earth region



Mumpower et al (in preparation)

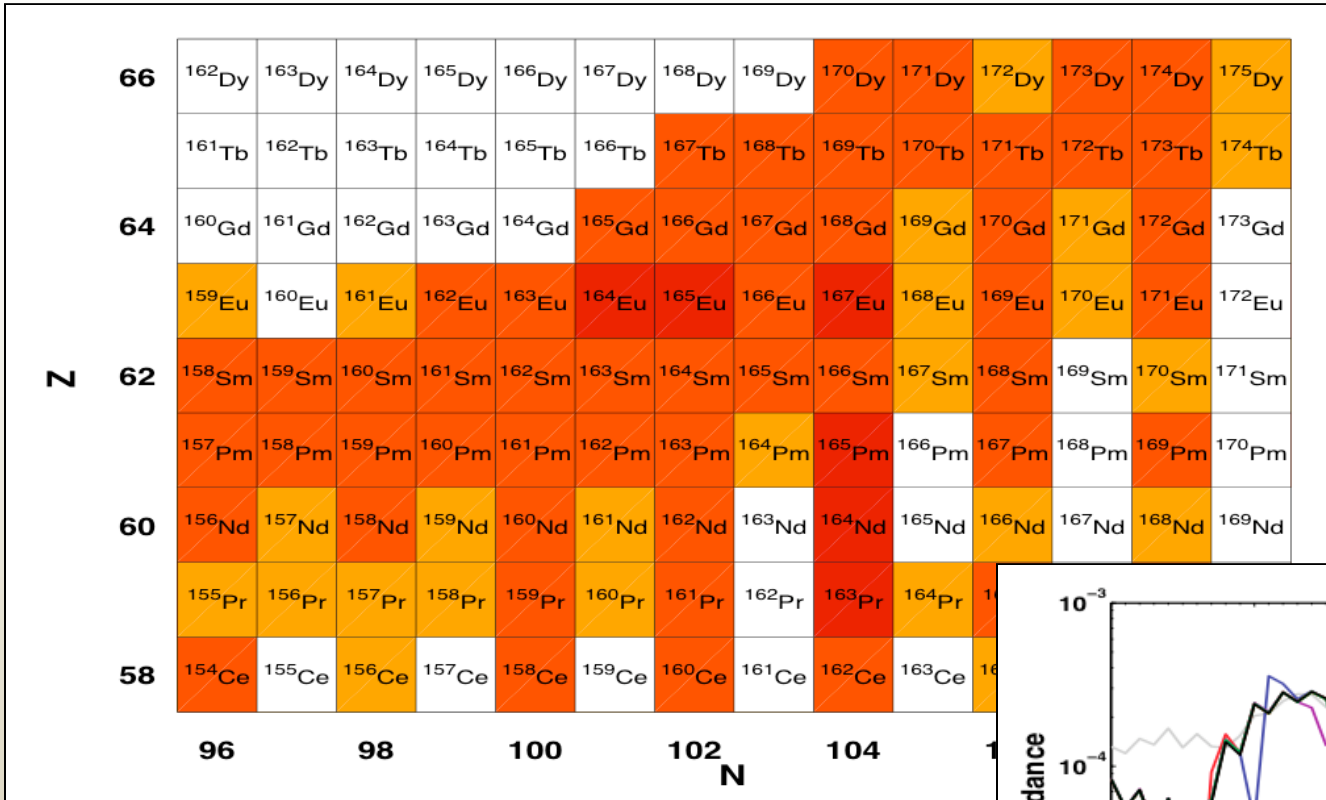
rare earth region: classical trajectory

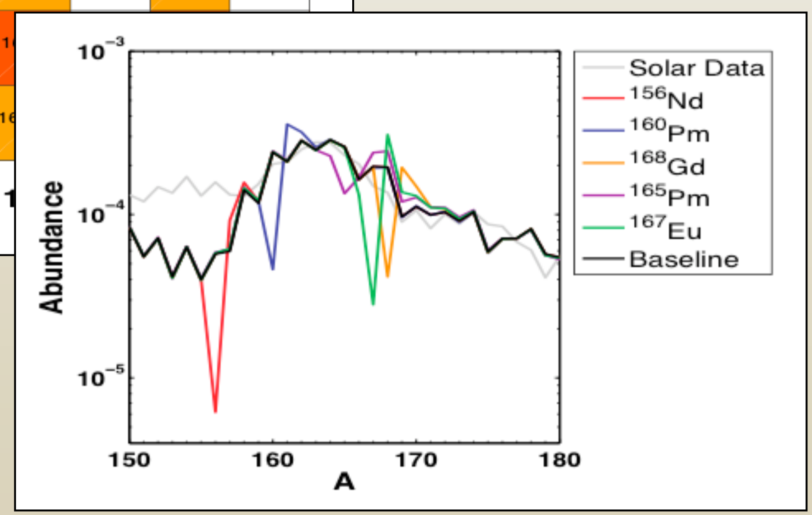




Mumpower et al (in preparation)

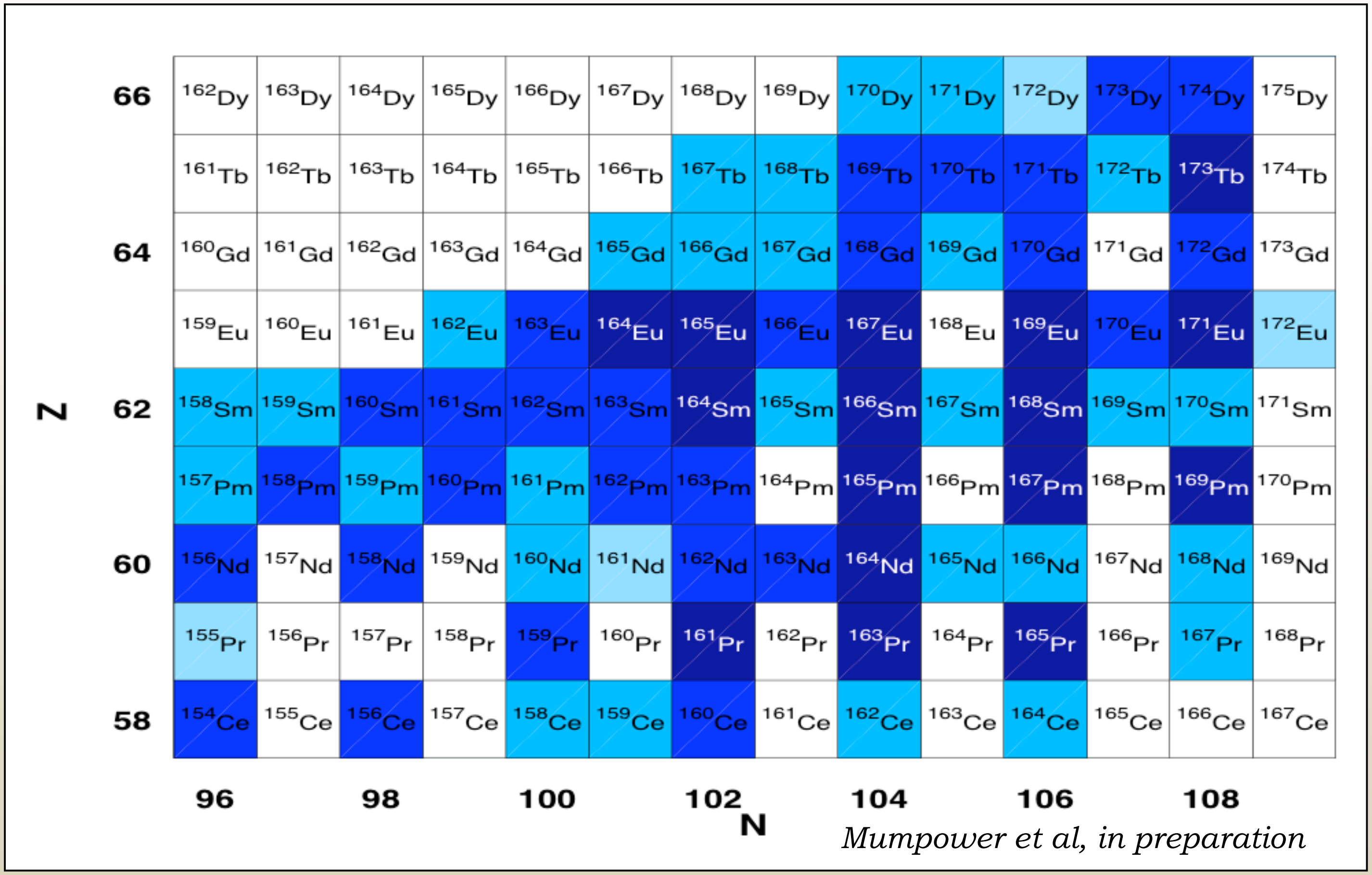
rare earth region: cold *r*-process





Mumpower et al (in preparation)

influential neutron capture rates: rare earth region

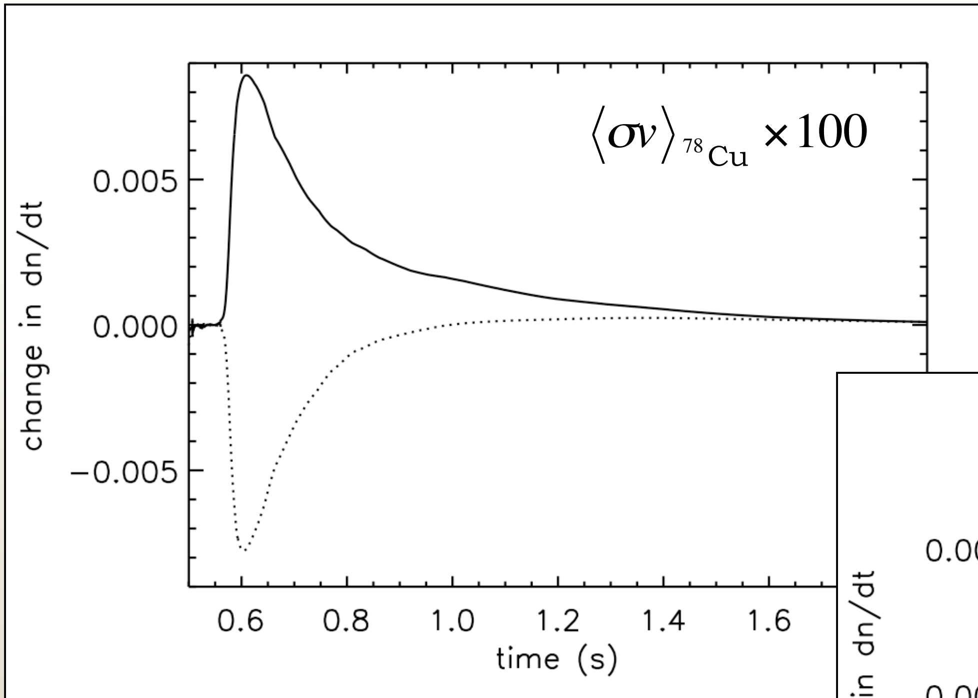


F > 200 for rate changes of factors of:

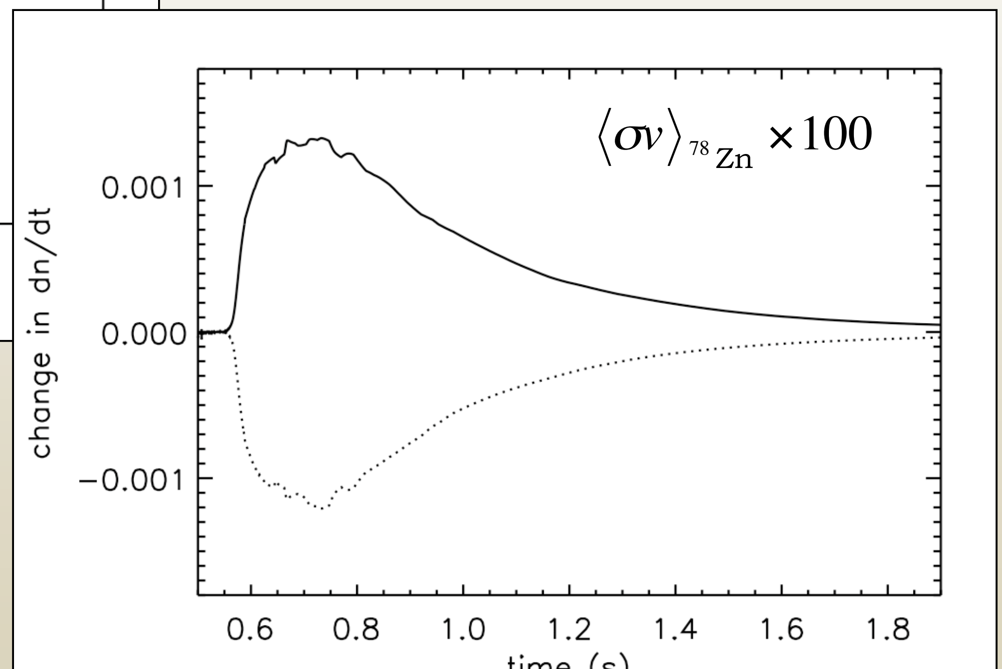
- 5
- 10
- 50
- 100

$$F = 100 \times \sum_A \frac{|Y(A) - Y_{baseline}(A)|}{Y_{baseline}(A)}$$

neutron capture in the A ~ 80 region



80 peak
above 80 peak



Surman et al, in preparation (2010)

- capture mechanism similar to A ~ 130 region
- most important rates are for nuclei just to the left of closed shell

summary

The necessity of nuclear masses and beta decay rates for the *r* process has long been recognized.

Neutron capture rates are also important, as they play a key role in shaping the final *r*-process abundance pattern in both hot and cold *r*-process scenarios.