# nuclear data and
# the astrophysical site of the r-process

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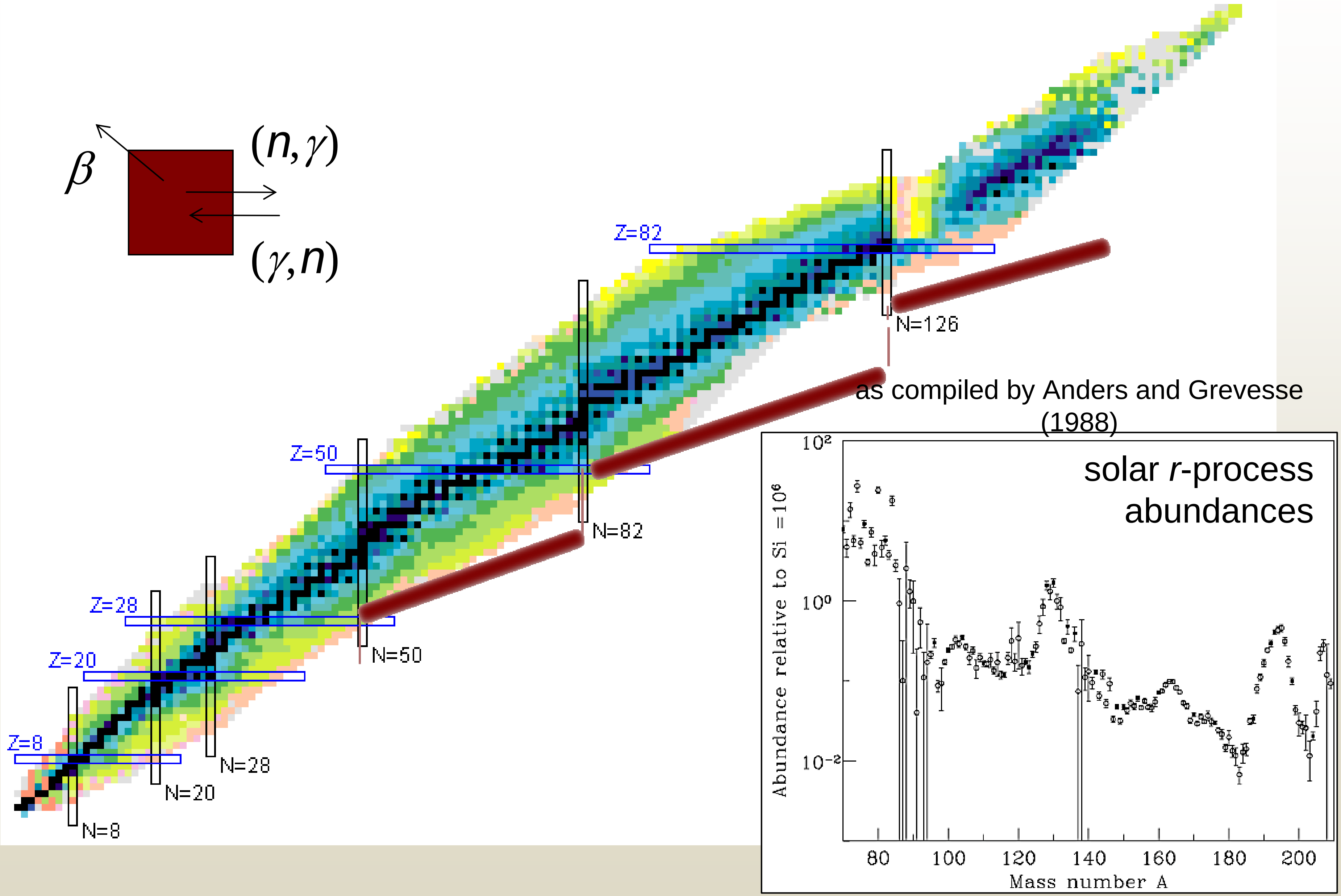
Union College/Notre Dame/JINA

International Workshop XLI
on Gross Properties of Nuclei and Nuclear Excitations
Hirschegg, Austria
26 January – 1 February 2013

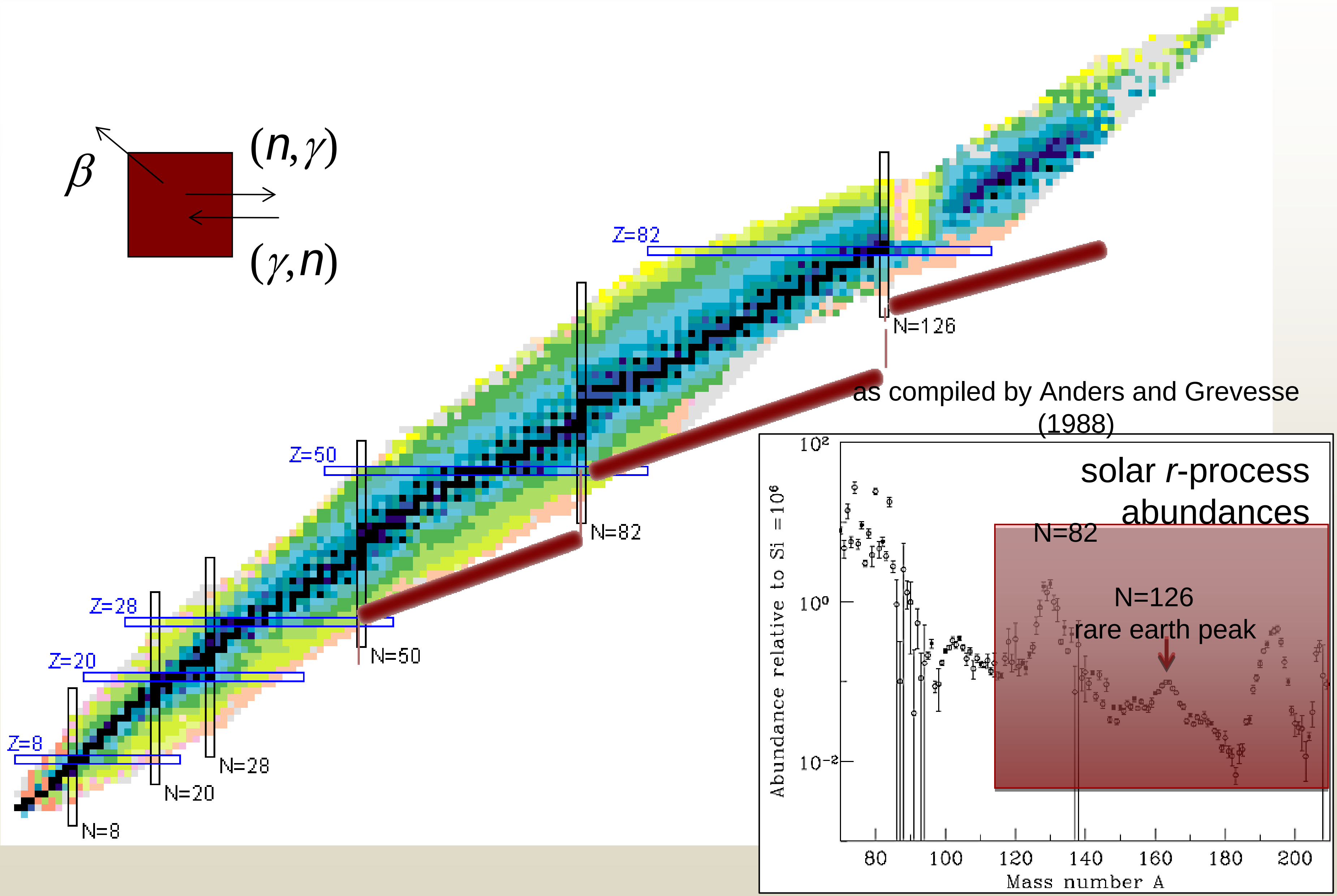
# rapid neutron capture nucleosynthesis



as compiled by Anders and Grevesse (1988)

solar *r*-process abundances

# rapid neutron capture nucleosynthesis



as compiled by Anders and Grevesse (1988)

solar *r*-process abundances

# r-process astrophysical site?

## compact object mergers

*e.g., Lattimer & Schramm (1974, 1976), Meyer (1989), Frieburghaus et al (1999), Goriely et al (2005), Surman et al (2005), Argast et al (2004), Wanajo & Ishimaru (2006), Oechslin et al (2007), Surman et al (2008), Nakamura et al (2011), Goriely et al (2012), Korobkin et al (2012), talk by A. Arcones*

## core collapse of massive stars

neutrino-driven wind *e.g., Meyer et al (1992), Woosley et al (1994), 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), Cardall & Fuller (1997), Otsuki et al (2000), Thompson et al (2001), Terasawa et al (2002), Liebendorfer et al (2005), Wanajo (2006), Arcones et al (2007), Huedepohl et al (2010), Fischer et al (2010), Roberts & Reddy (2012), talk by M. Hempel*

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

He shells in low metallicity SNe *e.g., Epstein et al (1988), Nadyozhin & Panov (2008), Banerjee et al (2011)*

neutron-rich jets *e.g., Cameron (2003), Nishimura et al (2006), Fujimoto et al (2008),*

# r-process astrophysical site?

## compact object mergers

low $Y_e$ (=1/(1+$n/p$))
low entropy
fission cycling

*e.g., Lattimer & Schramm (197 rieburghaus et al (1999), Goriely et al (2005), Surman et al (2005), ajo & Ishimaru (2006), Oechslin et al (2007), Surman et al (2008), Nakamura et al (2011), Goriely et al (2012), Korobkin et al (2012), talk by A. Arcones*

## core collapse of ma

$Y_e$ < 0.5
high entropy, fast dynamic timescale

neutrino-driven wind *e 4), Takahashi et al (1994), Witti et al (1994), Fuller eyer et al (1998), Qian & Woosley (1996), Hoffman et al (1997), Cardall & Fuller (1997), Otsuki et al (2000), Thompson et al (2001), Terasawa et al (2002), Liebendorfer et al (2005), Wanajo (2006), Arcones et al (2007), Huedepohl et al (2010), Fischer et al (2010), Roberts & Reddy (2012), talk by M. Hempel*

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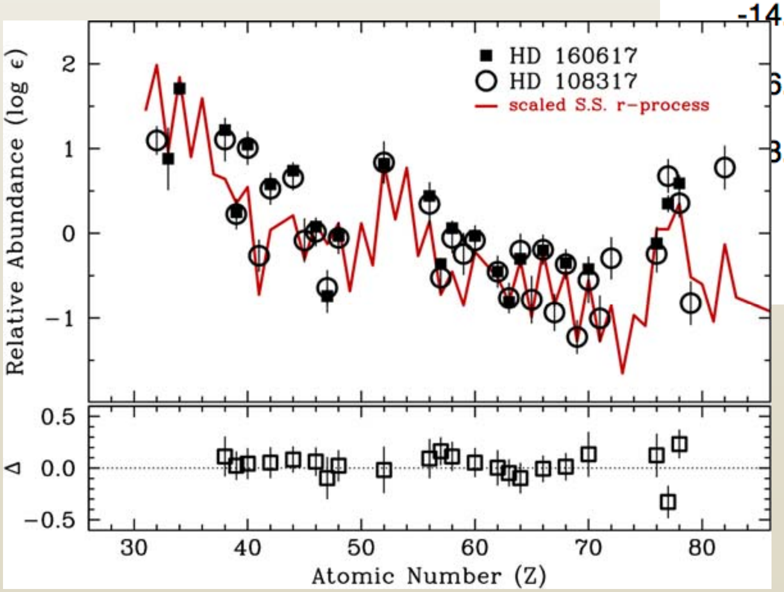
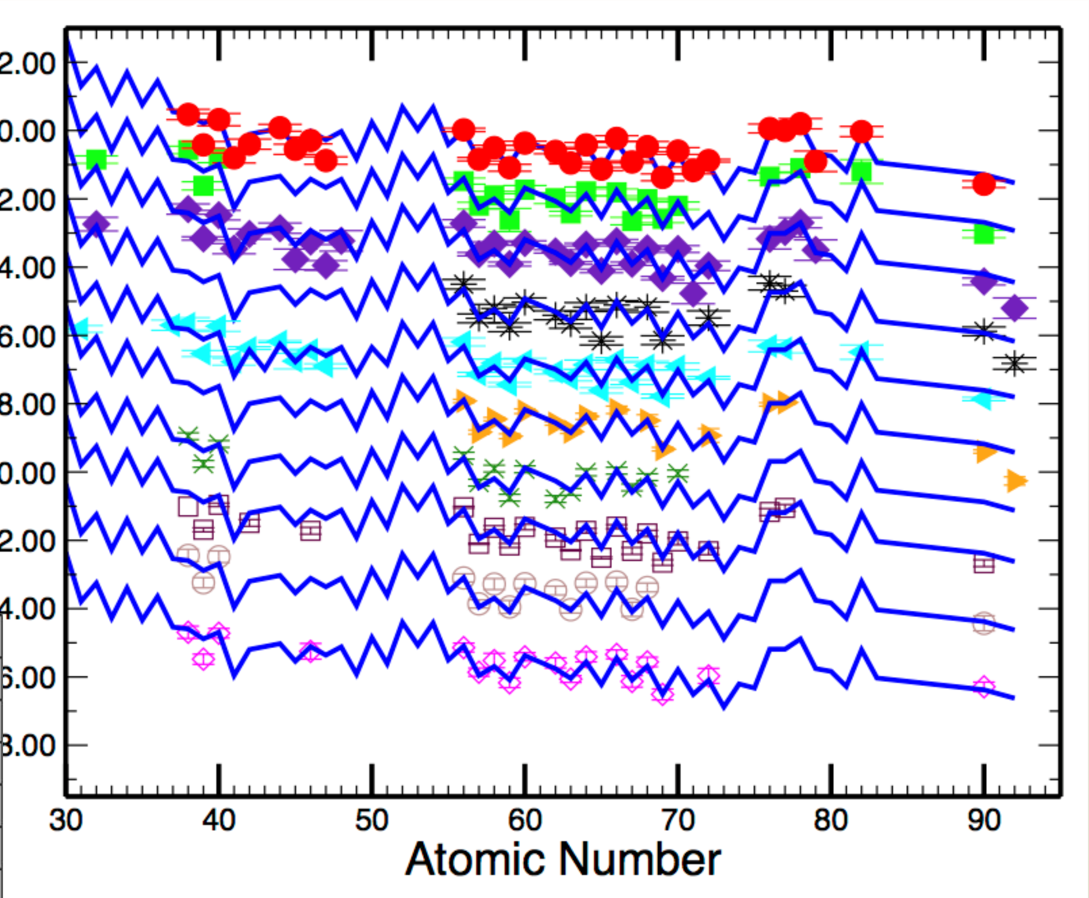
neutron-rich jets *e.g., Cameron (2003), Nishimura et al (2006), Fujimoto et al (2008),*

# observations of r-process elements

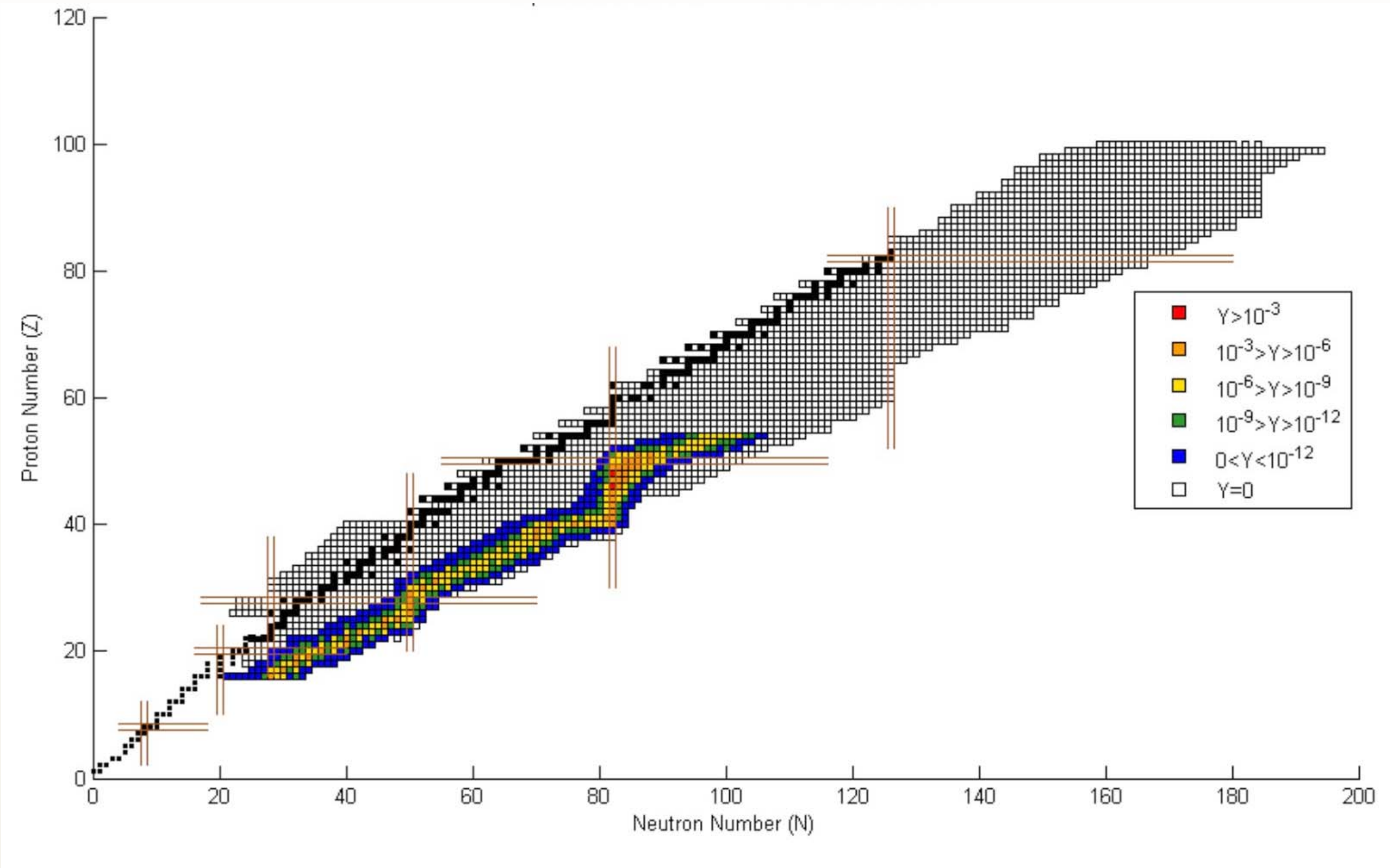
Cowan et al (2011)





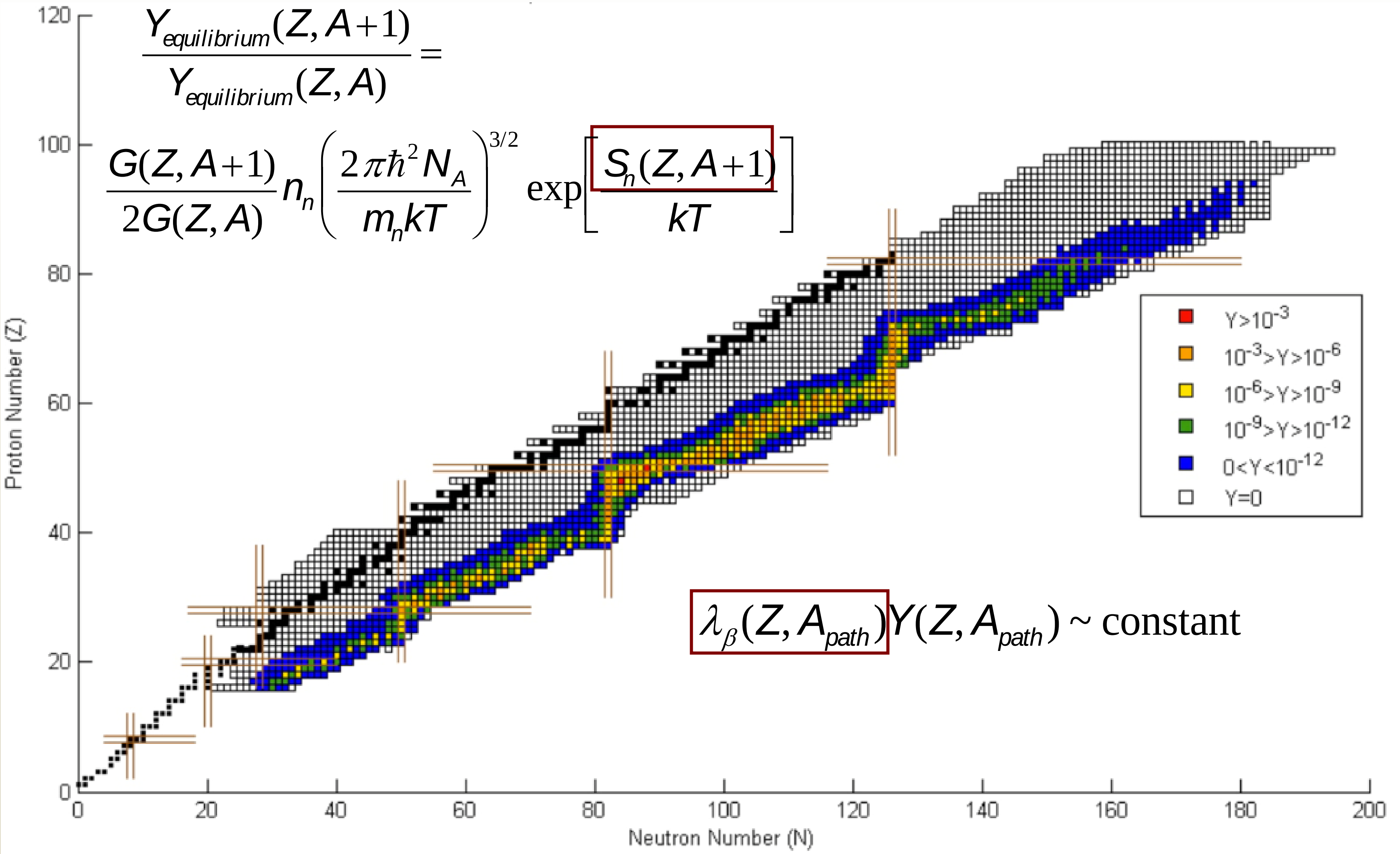
Roederer & Lawler (2012)

# rapid neutron capture nucleosynthesis



simulation by R Surman, initial seed distribution calculated with xnet (Hix and Thielemann 1999), movie by I Bentley

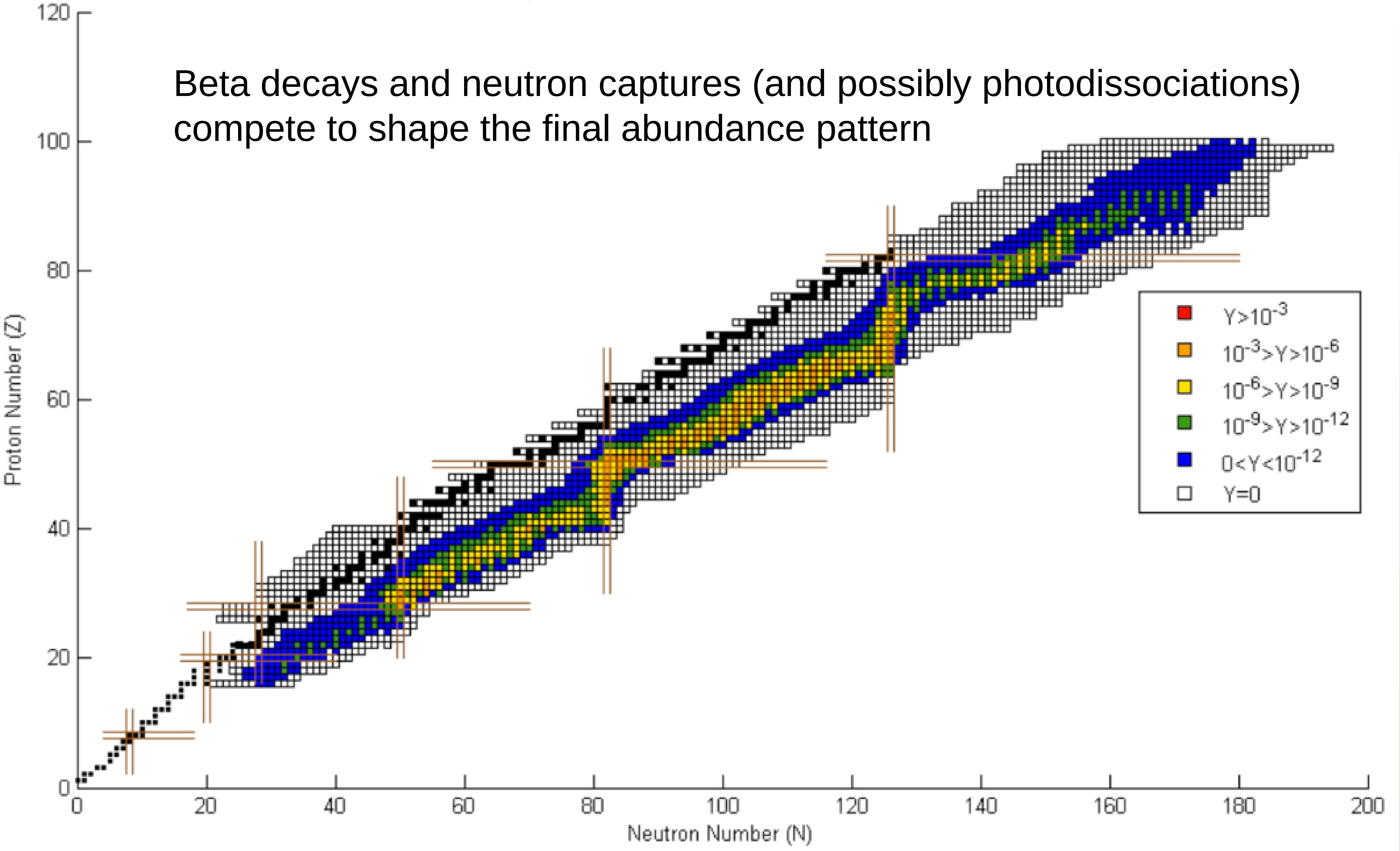
# classic/hot r-process: $(n,\gamma)$-$(\gamma,n)$ equilibrium



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

$$\boxed{\lambda_\beta(Z,A_{path})}\,Y(Z,A_{path}) \sim \text{constant}$$

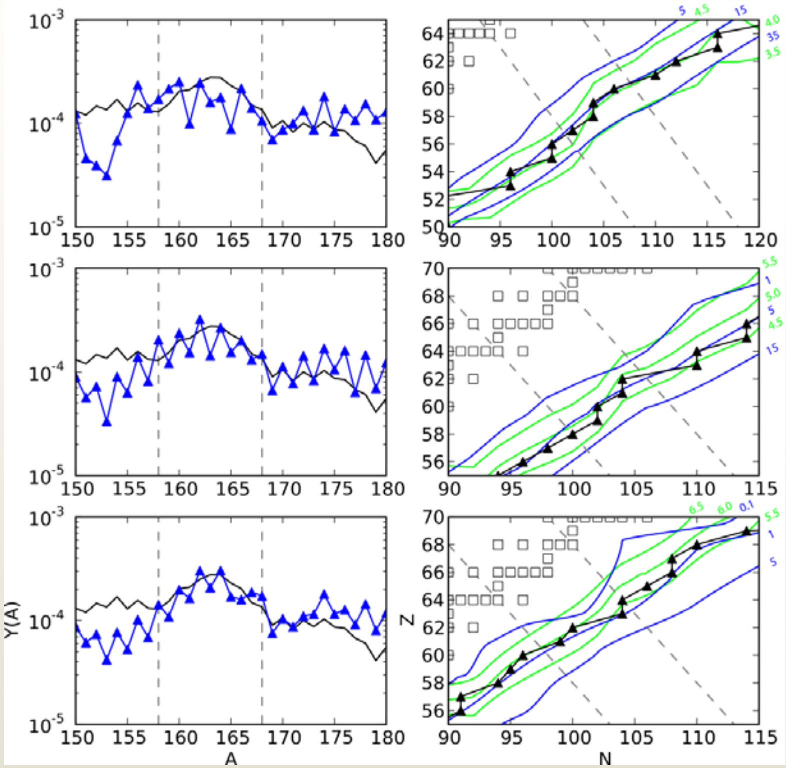
# freezeout from $(n,\gamma)$-$(\gamma,n)$ equilibrium



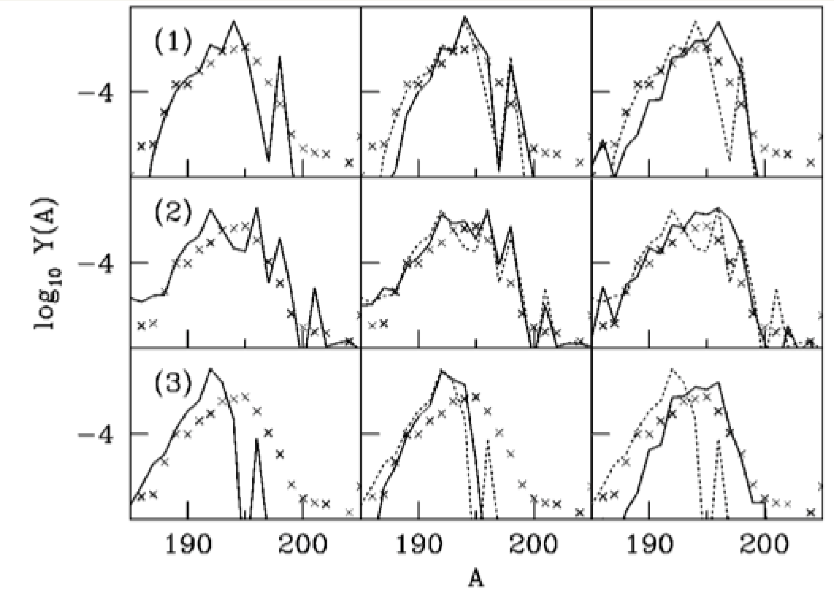
Beta decays and neutron captures (and possibly photodissociations) compete to shape the final abundance pattern

# freezeout from ($n,\gamma$)-($\gamma,n$) equilibrium

- rare earth peak forms
- main peaks can shift, spread, or narrow



Mumpower, McLaughlin, Surman (2012)

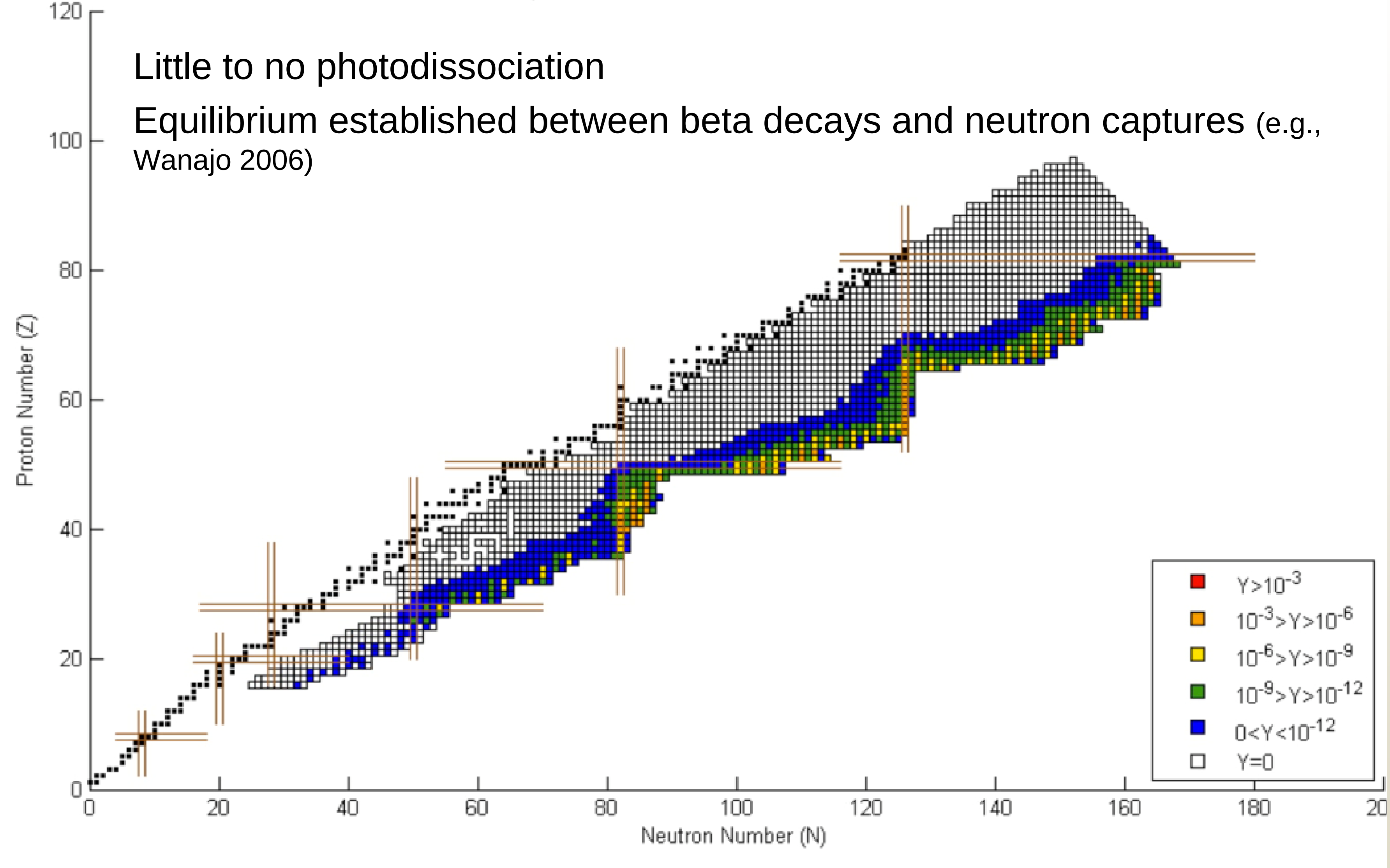


Surman & Engel (2001)

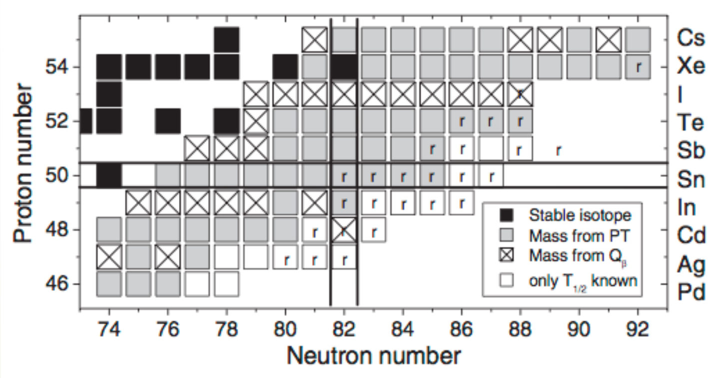
# ‘cold’ r-process

Little to no photodissociation

Equilibrium established between beta decays and neutron captures (e.g., Wanajo 2006)

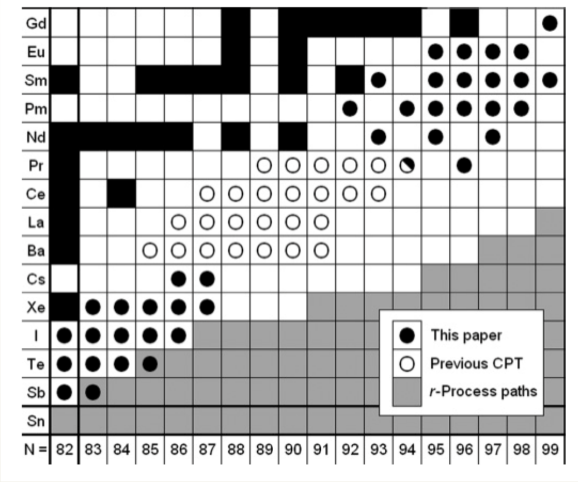


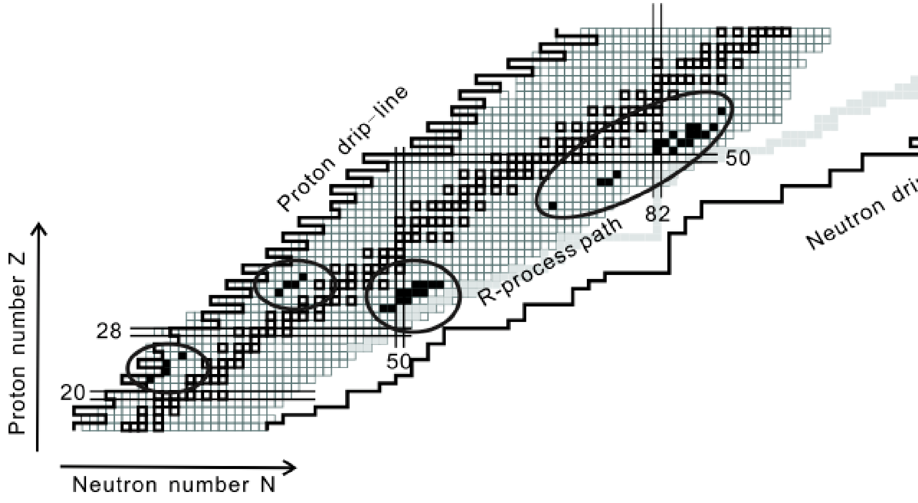
# experiments with neutron-rich nuclei: masses



Hakala et al (2012)
JYFLTRAP

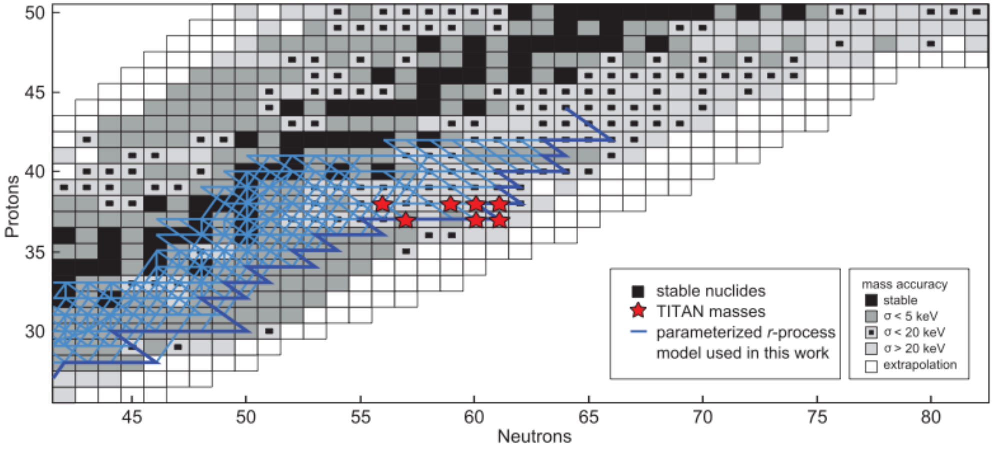
Van Schelt et al
(2012)
CPT



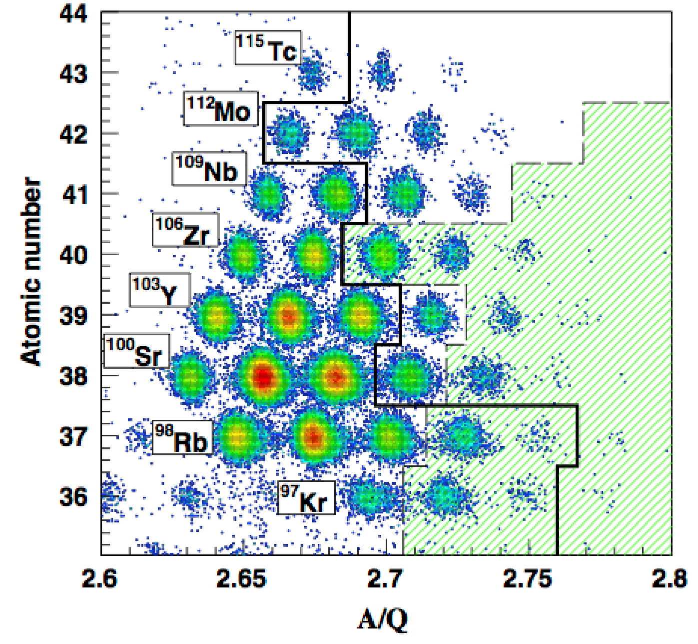


Sun et al (2009)
IMS-GSI

Simon et al (2012) TITAN



# experiments with neutron-rich nuclei: rates



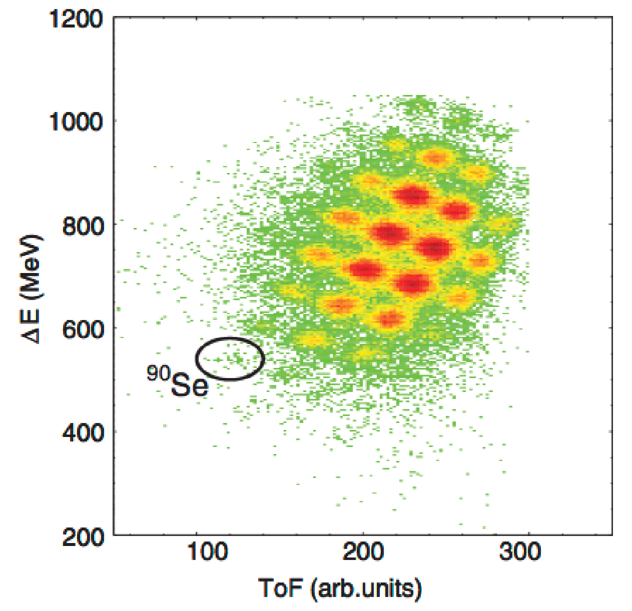
Nishimura et al (2012)
RIKEN

## beta decay rates

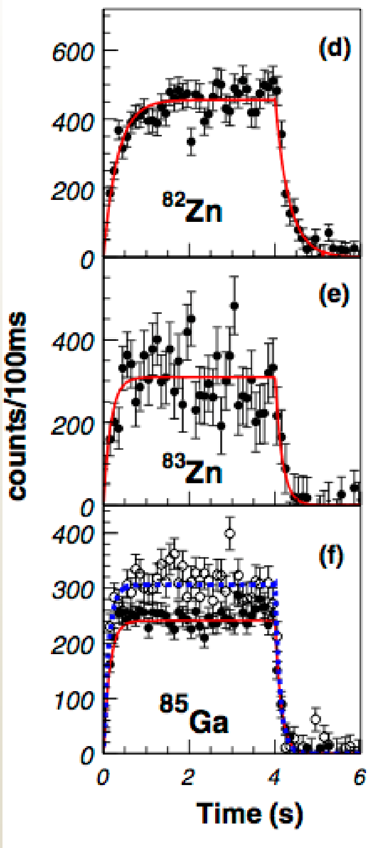
- HRIBF, NSCL, RIKEN

## direct reactions

- $^{131}$Sn(d,p) Kozub et al (2012)
- $^{132}$Sn(d,p) Jones et al (2011)



Quinn et al (2012)
NSCL



Madurga et al (2012)
HRIBF

# r-process sensitivity studies

Choose a baseline simulation

Vary one piece of nuclear data by a set amount, rerun the simulation, and compare the final abundance pattern to the baseline

Repeat for each nucleus in the network

neutron capture rates

Beun, Blackmon, Hix, McLaughlin, Smith, Surman, J. Phys. G (2008)
Surman, Beun, McLaughlin, Hix, PRC (2009)
Surman, Sinclair, Hix, Jones, Mumpower, McLaughlin, CGS-14 proceedings (2011)
Mumpower, McLaughlin, Surman, PRC (2012)

masses/neutron separation energies

Brett, Bentley, Paul, Aprahamian, Surman, EPJA (2012)

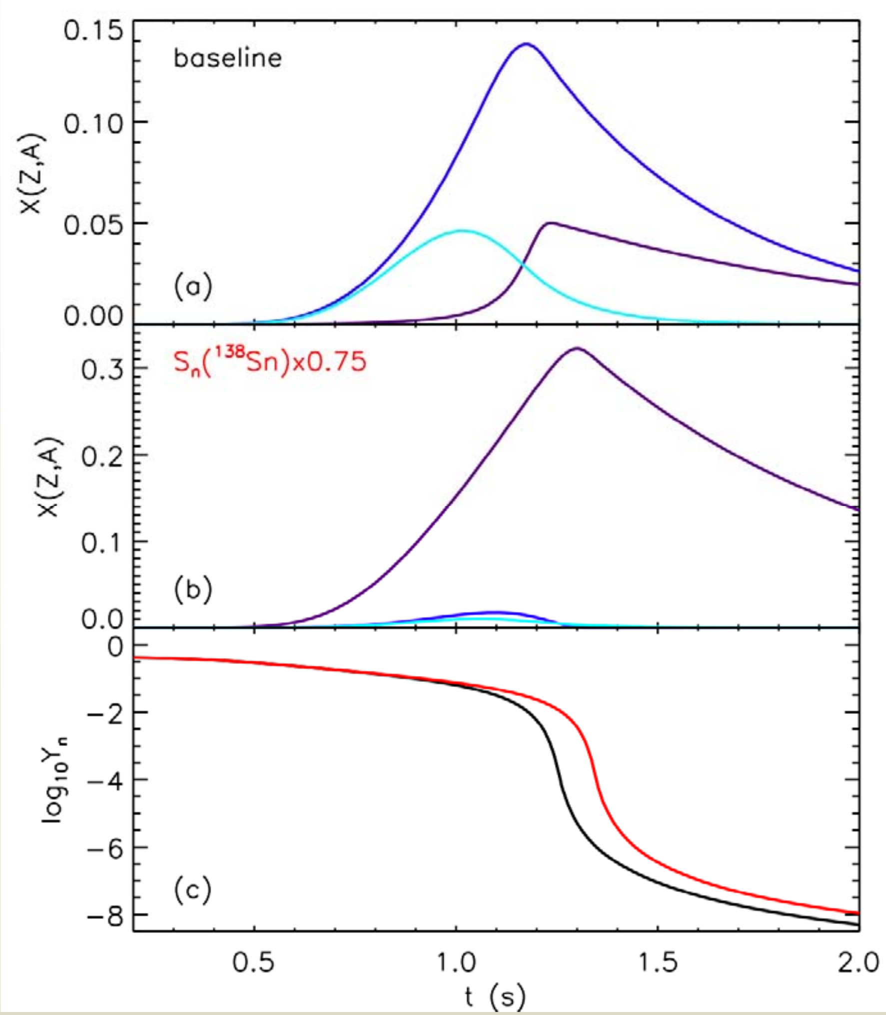
beta decay rates

Cass, Passucci, Surman, Aprahamian, NIC proceedings (2012)
Surman, Mumpower, Cass, Aprahamian, ICFN5 proceedings (2013)

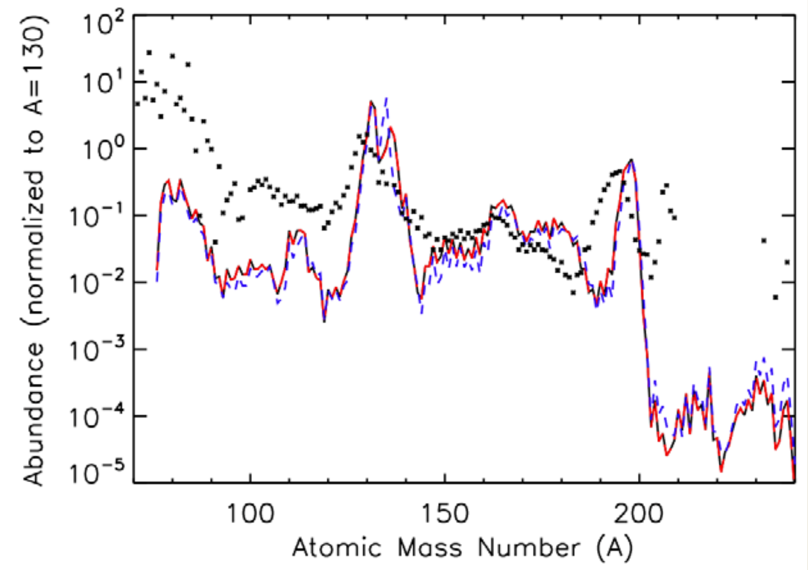
# the role of neutron separation energies in equilibrium

While (n,$\gamma$)-($\gamma$,n) equilibrium holds, the separation energies determine the abundances along an isotopic chain:

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



$^{136}$Sn —
$^{138}$Sn —
$^{140}$Sn —

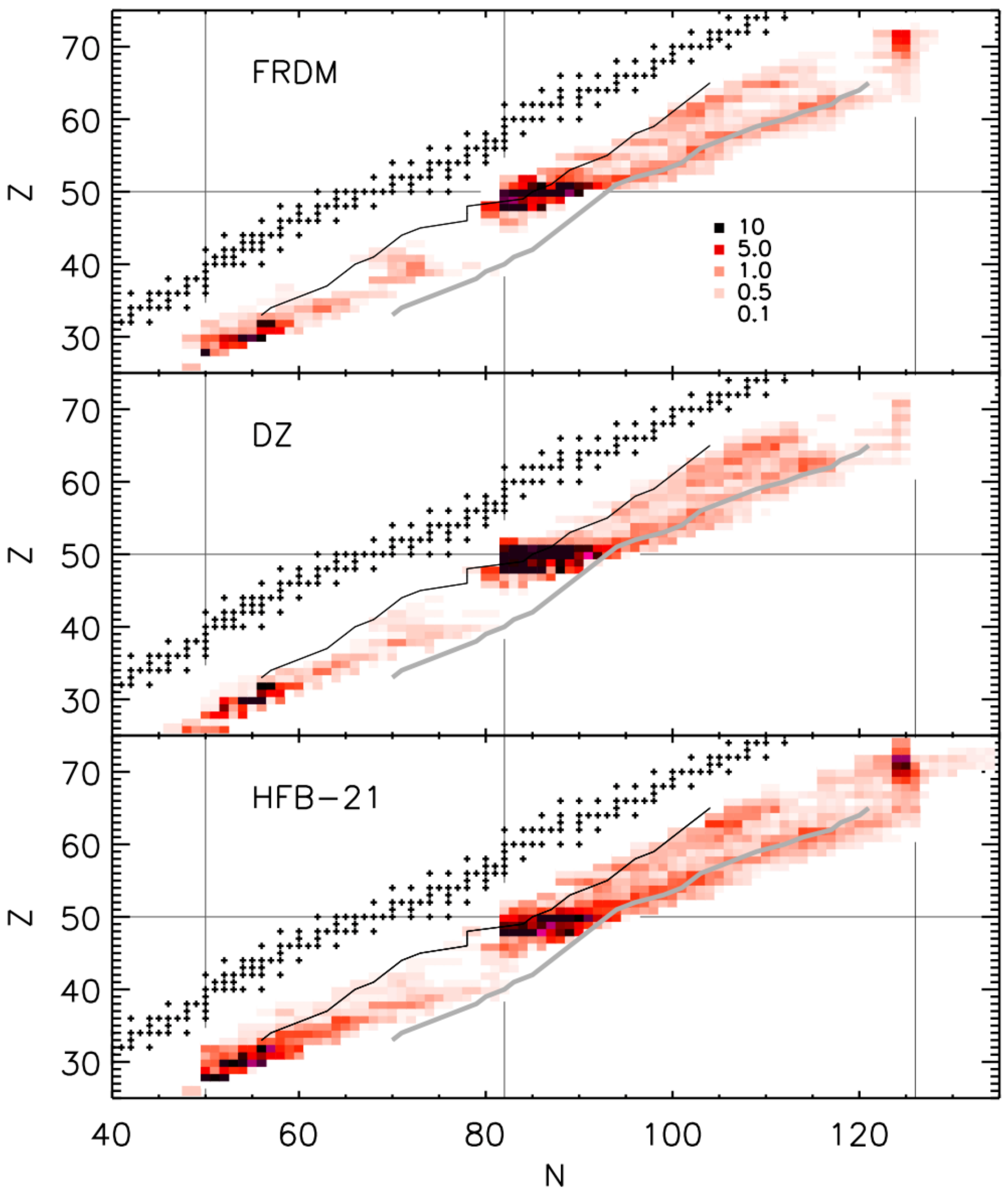


Brett et al (2012)

# binding energy sensitivity study

ΔBE = ±1 MeV
hot r-process example based on H (high frequency) r-process component in Qian et al (1998)

$$F = 100 \times \sum_{A} \left| X_{baseline}(A) - X(A) \right|$$



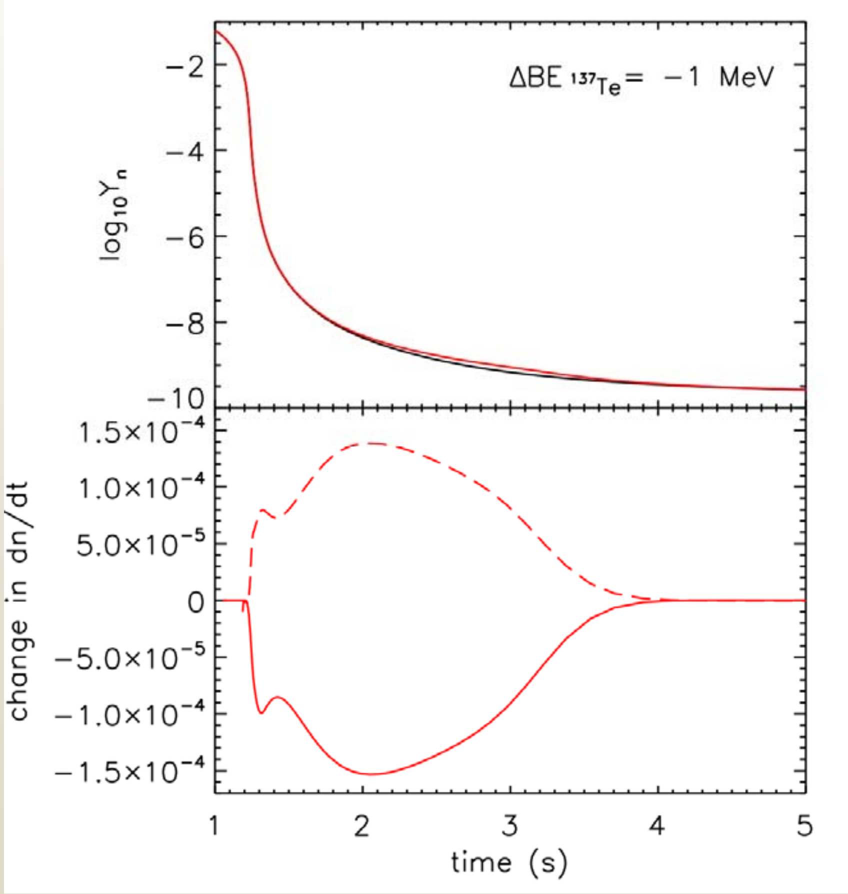
CARIBU
FRIB

R Surman et al ICFN5 (2012)

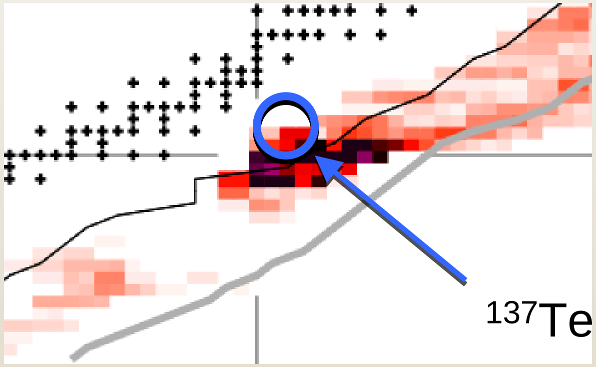
# the role of separation energies during freezeout

Separation energies appear explicitly in the expression for the photodissociation rates, which are calculated via detailed balance:

$$\lambda_\gamma(Z,A) \propto T^{3/2}\exp\left[-\frac{S_n(Z,A)}{kT}\right]\langle\sigma v\rangle_{(Z,A-1)}$$



Individual photodissociation rates become important as (n,γ)-(γ,n) equilibrium fails



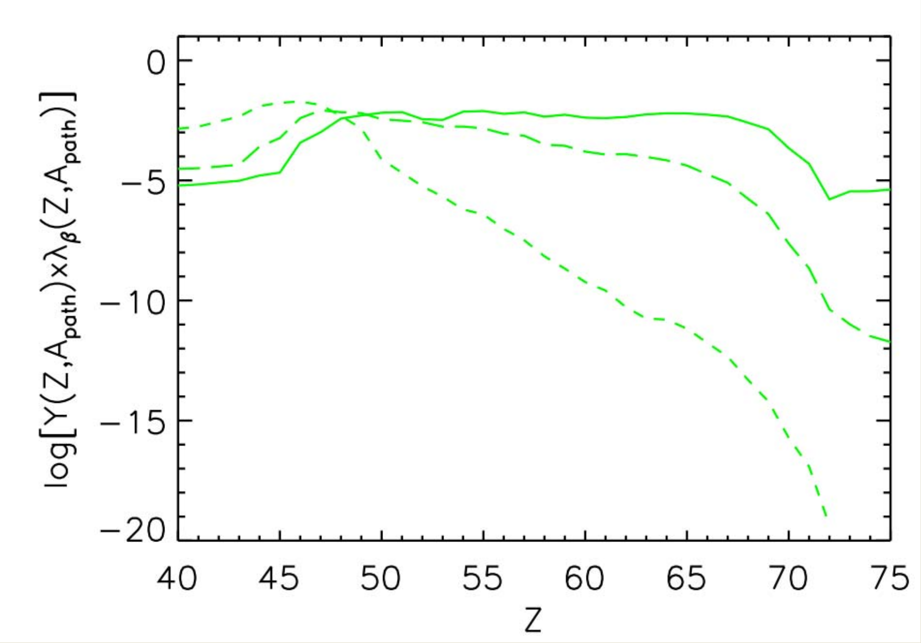
— A=130 region

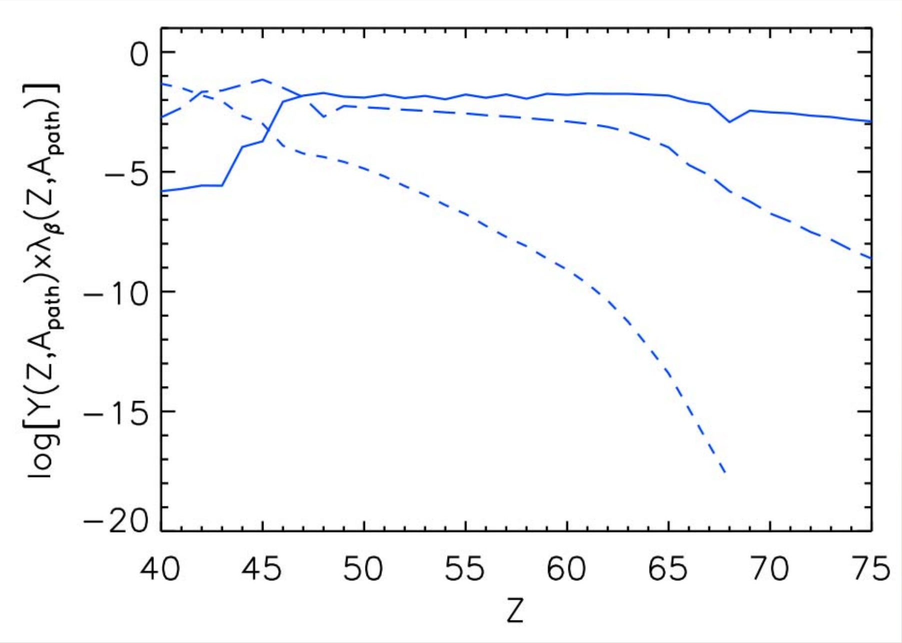
- - - elsewhere

# the role of beta decay rates in hot and cold r-processes

Steady beta flow:

$$\lambda_\beta(Z,A_{path})Y(Z,A_{path}) \sim \text{constant}$$



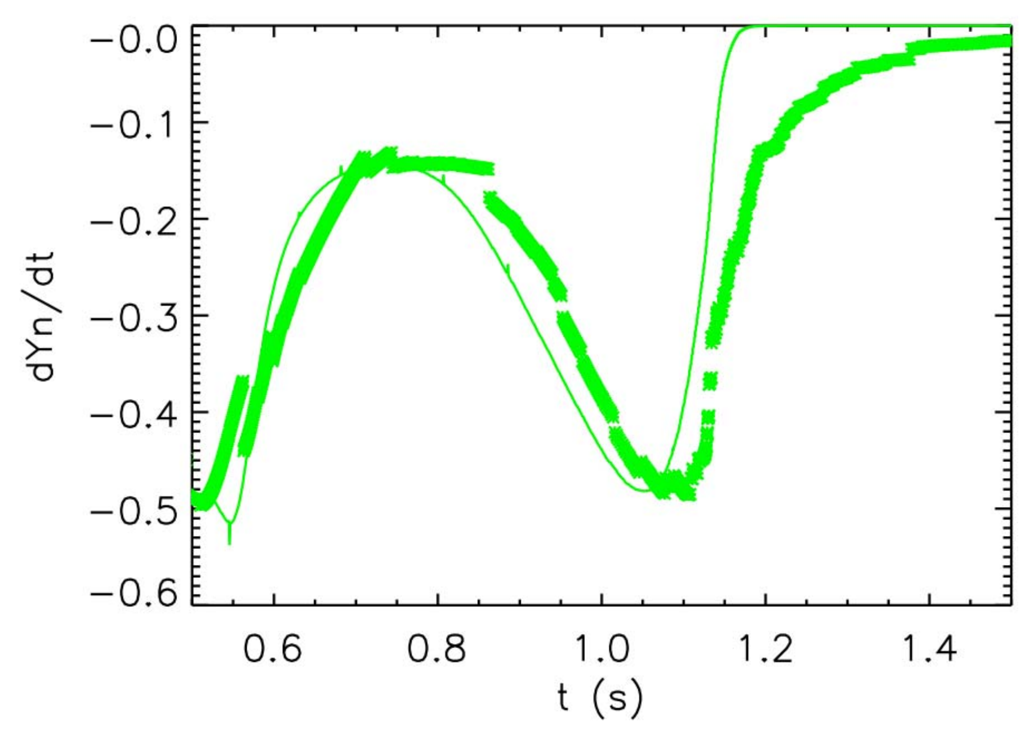


hot r-process example from Surman et al (2009)

cold r-process example parameterized as in Panov & Janka (2009)

Cass et al (2012)

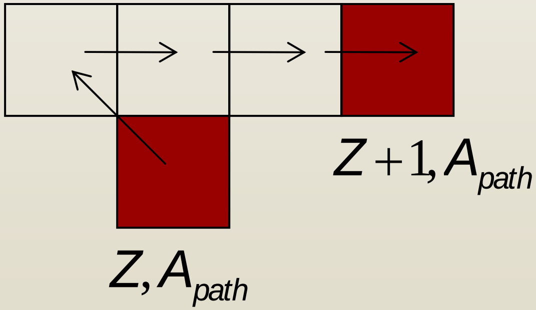
# the role of beta decay rates in hot and cold r-processes



— $\frac{dY_n}{dt}$

▬ $\sum_Z \lambda_\beta(Z, A_{path}) Y(Z, A_{path}) N'$

$N'$ neutron captures



$$\frac{dY_n}{dt} \approx \sum_Z \lambda_\beta(Z, A_{path}) Y(Z, A_{path}) N'$$

where $N'$ is the number of neutrons required to return to the path at $Z+1$ following decay

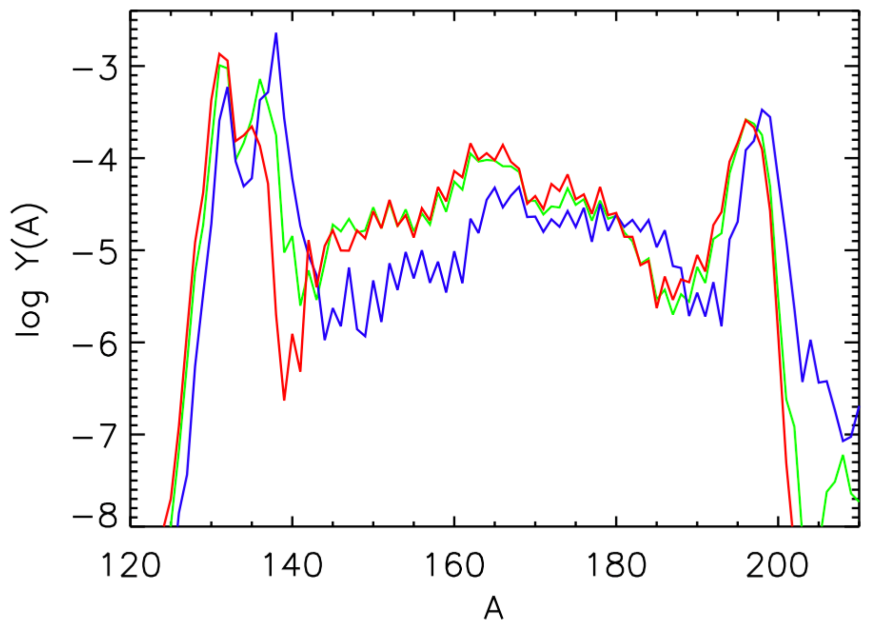
Cass et al (2012)

# beta decay rate example

baseline

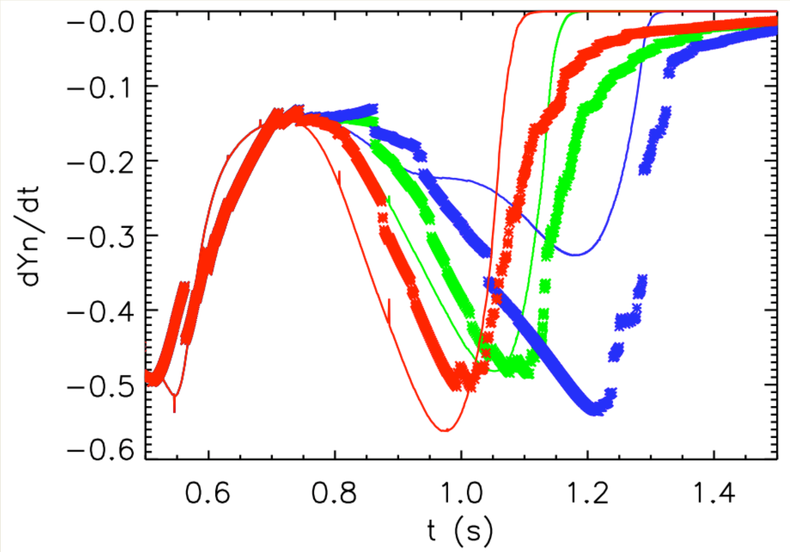
$\lambda_\beta(Z,A) \times 10$

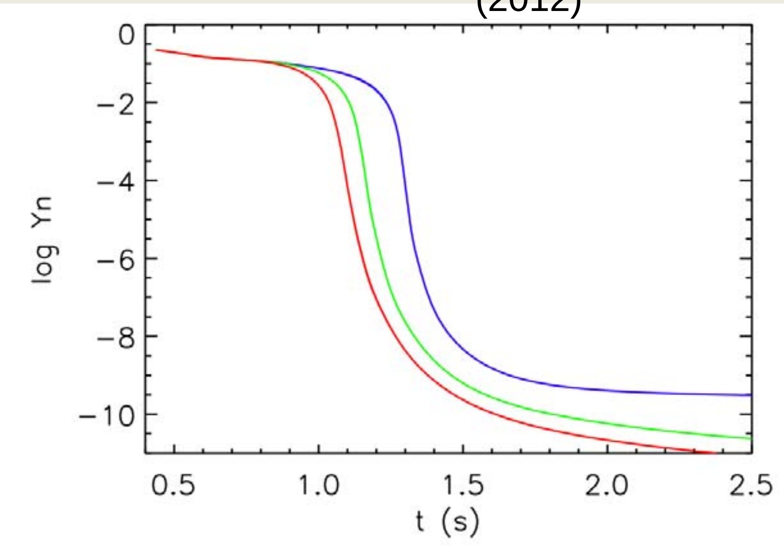
$\lambda_\beta(Z,A) \div 10$



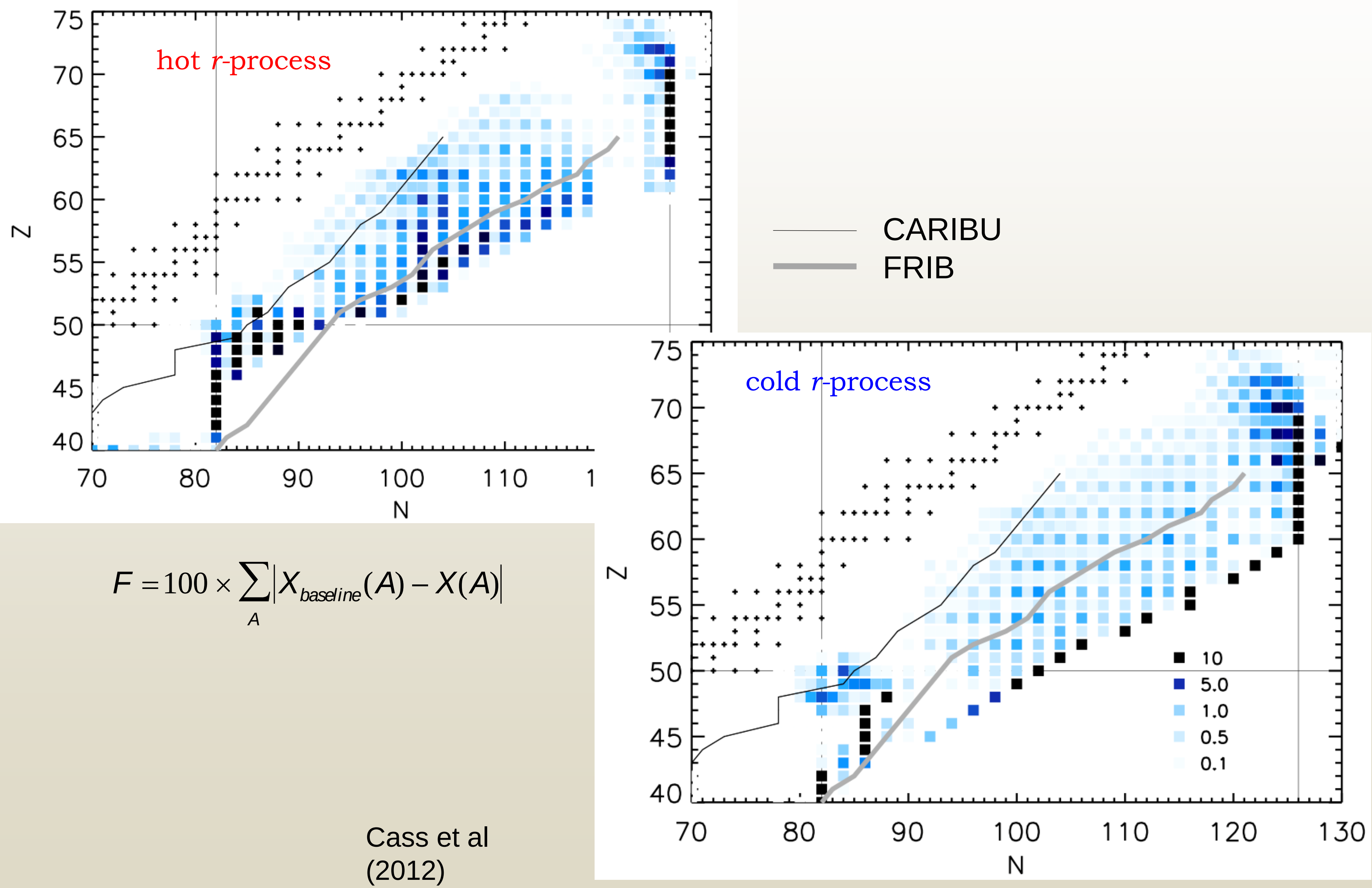
$^{140}$Sn

Cass et al (2012)





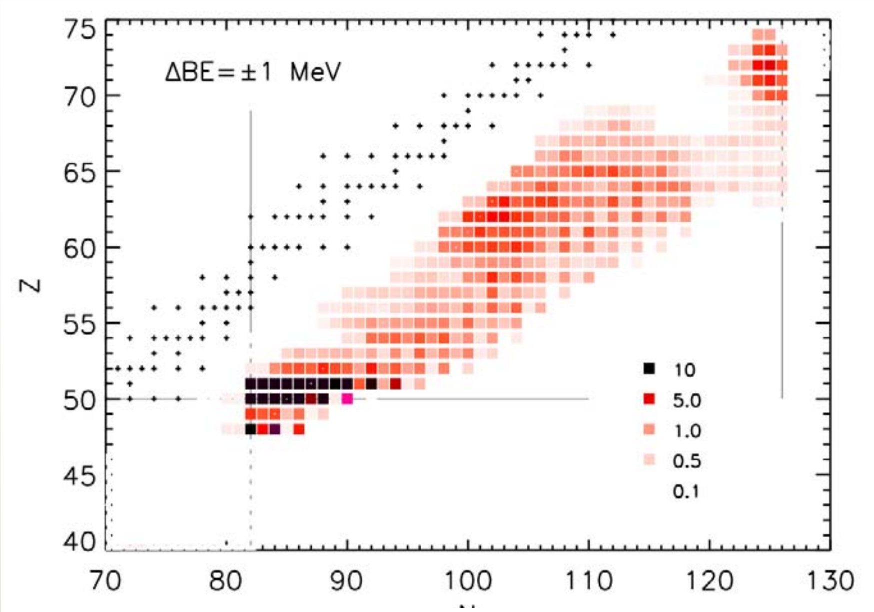
# beta decay sensitivities

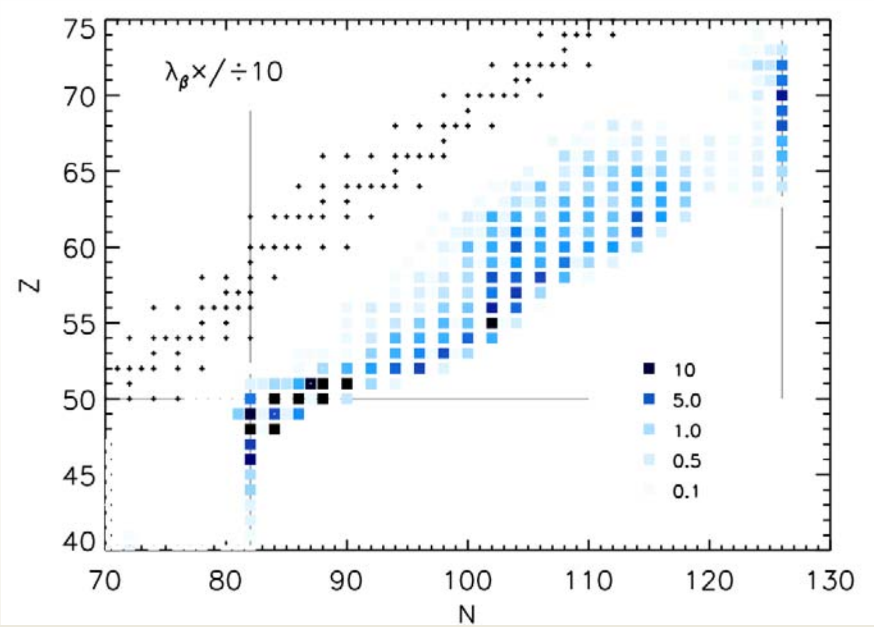


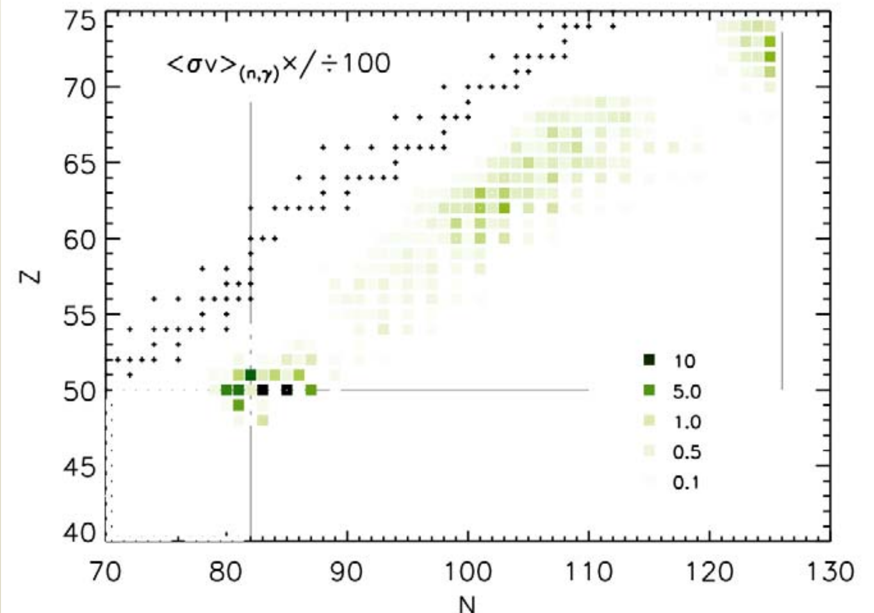
$$F = 100 \times \sum_{A} \left| X_{baseline}(A) - X(A) \right|$$

Cass et al
(2012)

# sensitivity study general trends: astrophysical conditions





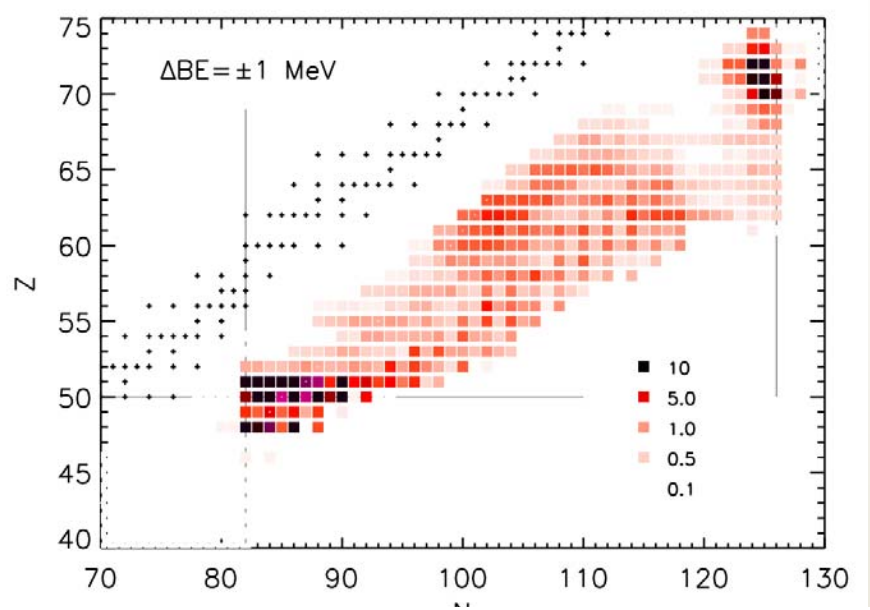


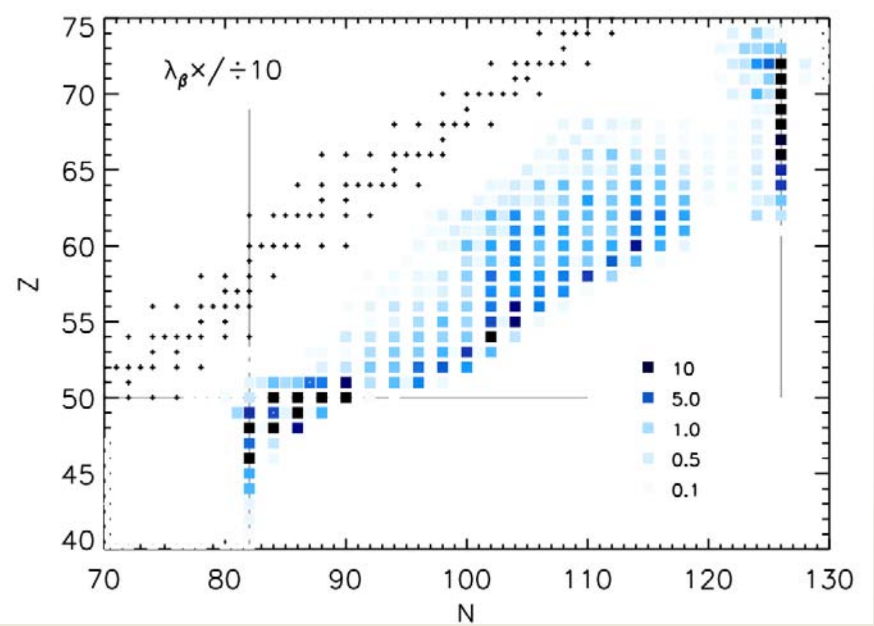
Wind parameterized as in Meyer (2002)

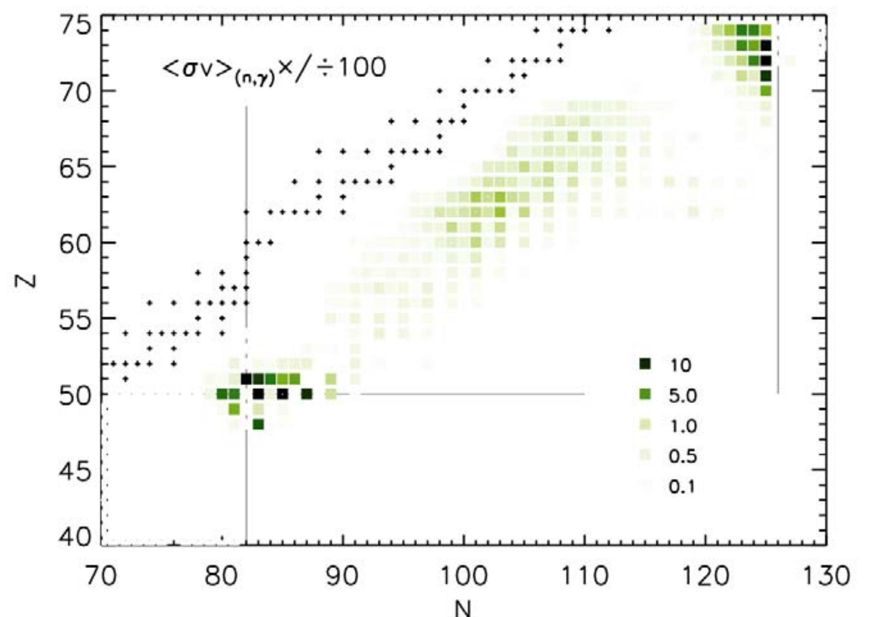
$s/k = 200$

$Y_e = 0.3$

# sensitivity study general trends: astrophysical conditions





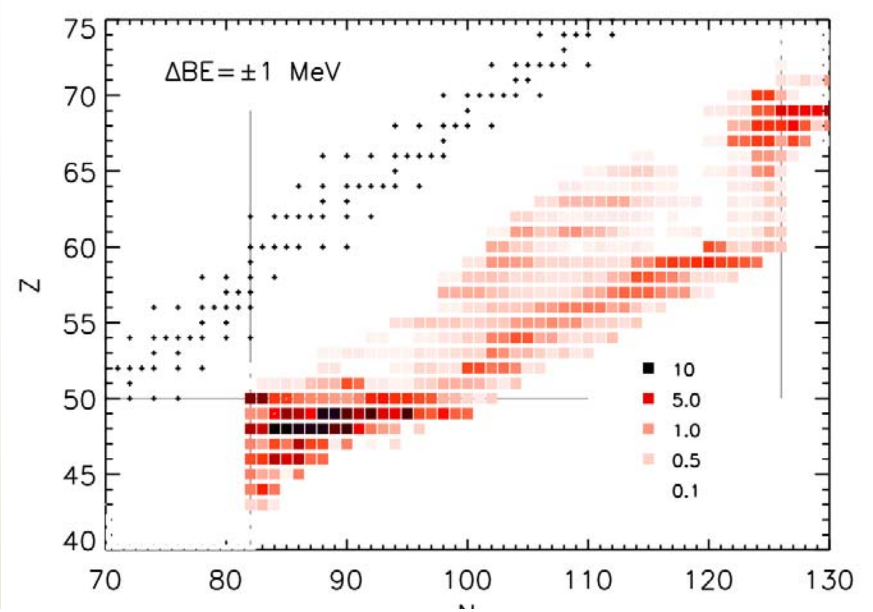


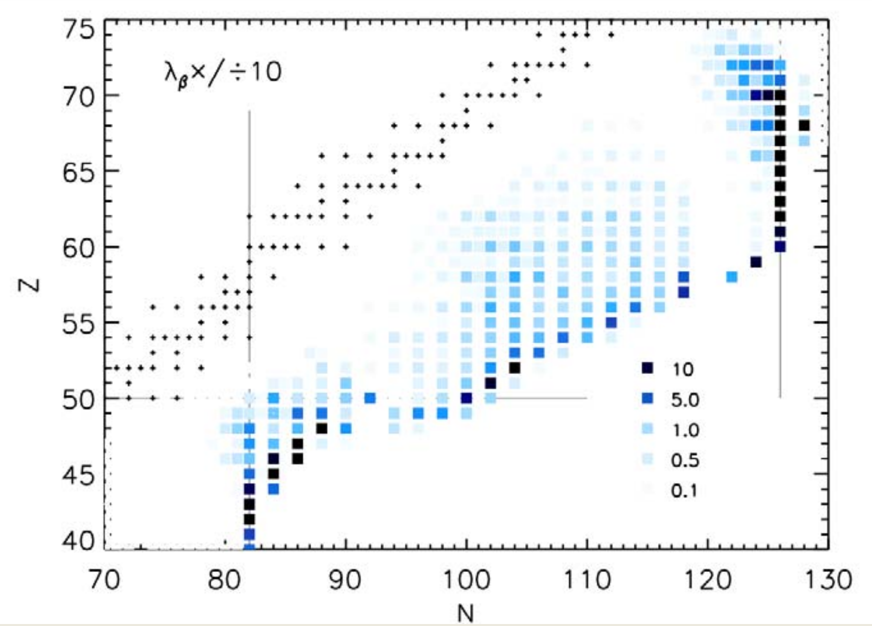
Wind parameterized as in Meyer (2002)

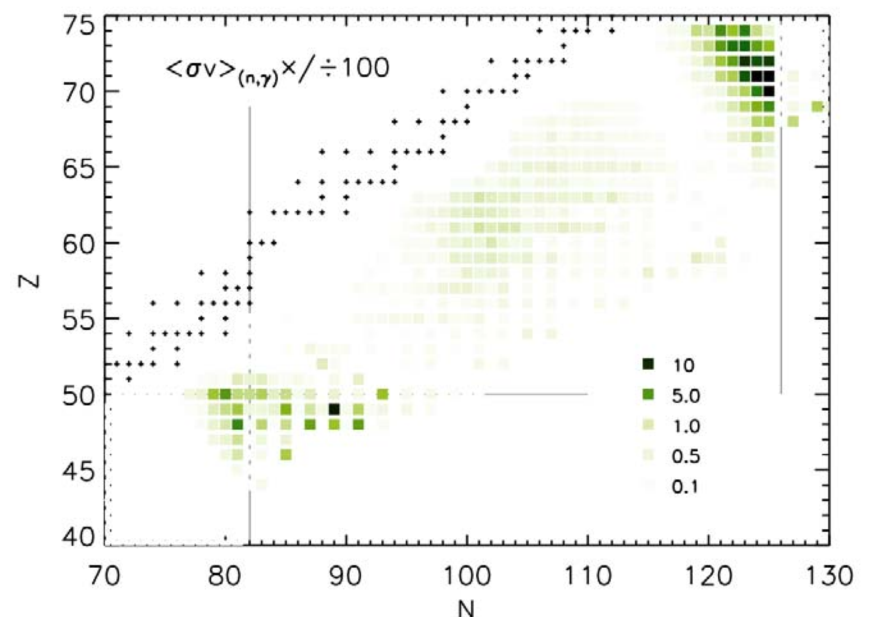
$s/k = 100$

$Y_e = 0.25$

# sensitivity study general trends: astrophysical conditions





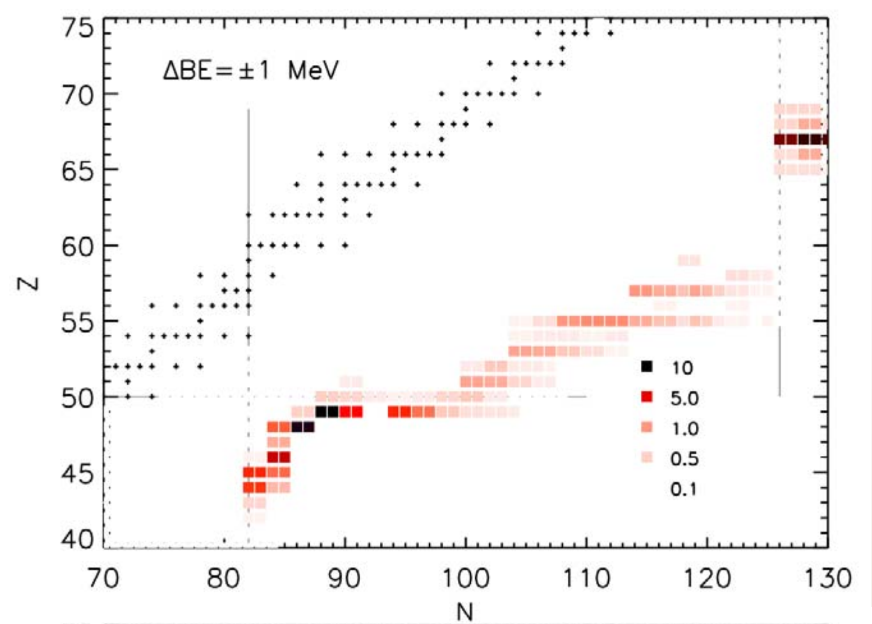


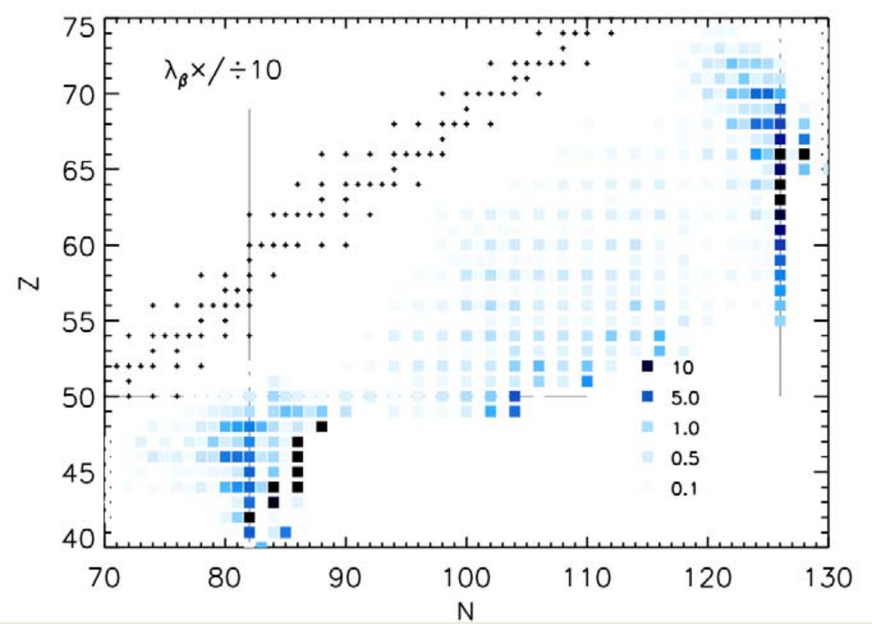
Wind parameterized as in Meyer (2002)

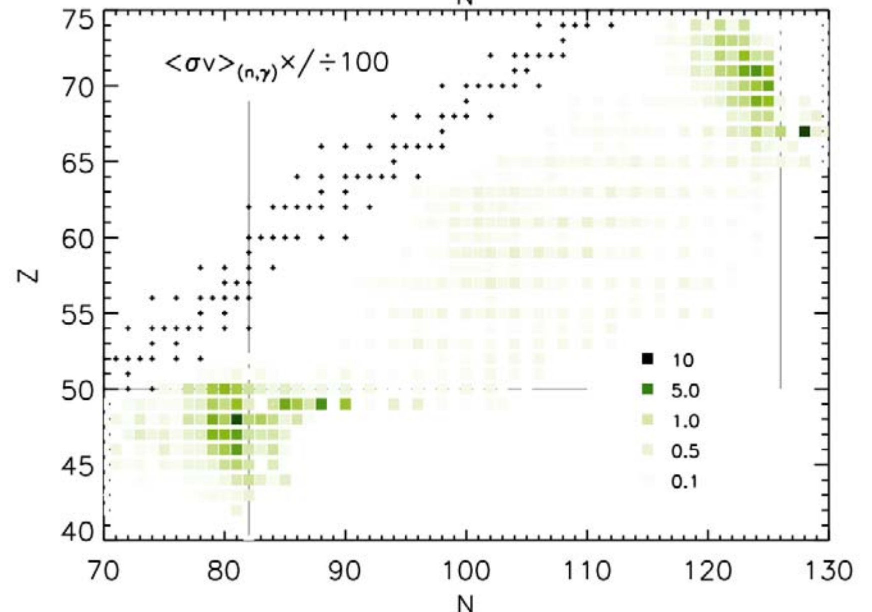
$s/k = 10$

$Y_e = 0.15$

# sensitivity study general trends: astrophysical conditions







Sample NS-NS merger trajectory from A. Bauswein and H-Th. Janka

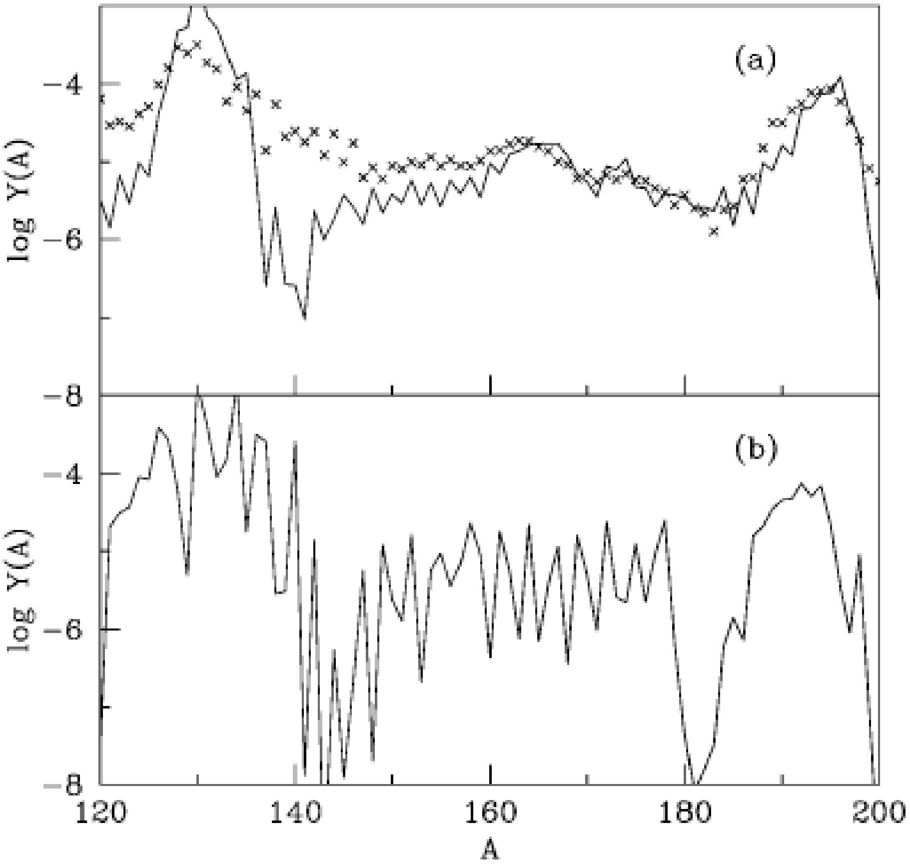
# nuclear data and the r-process site

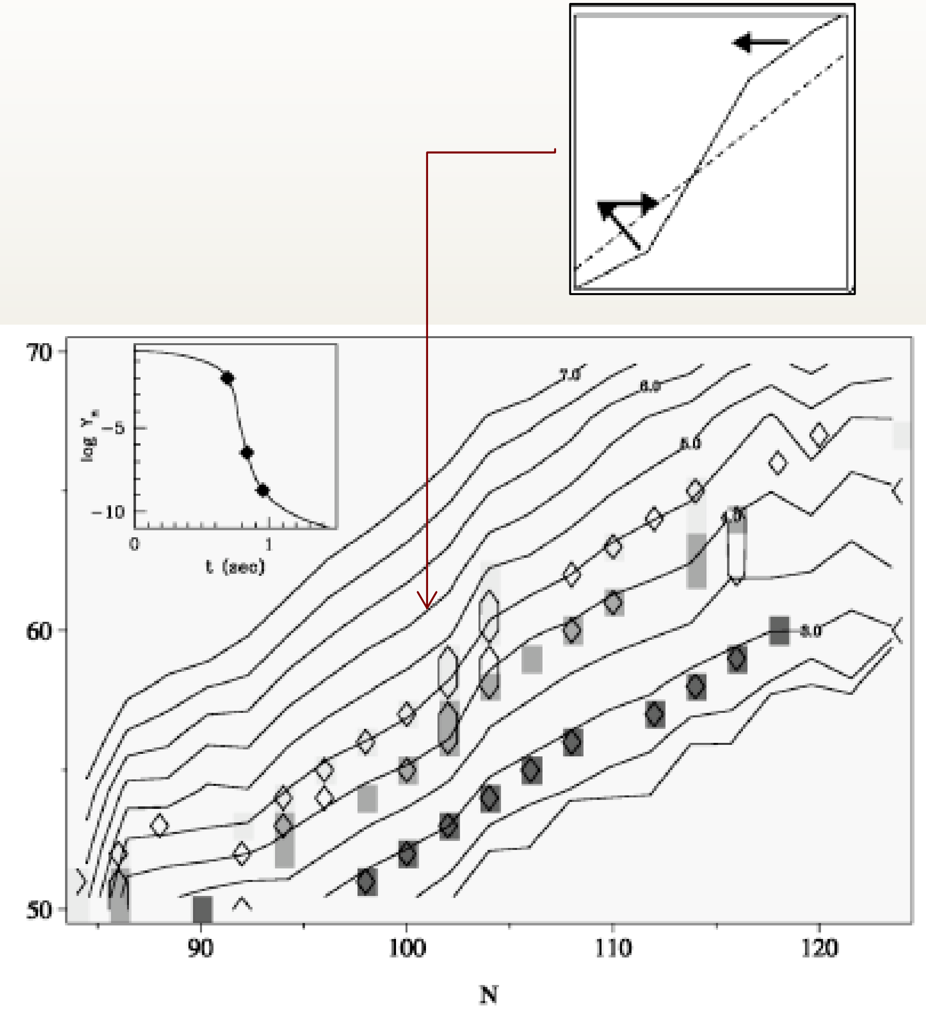
With the next generation of radioactive beam facilities + theoretical efforts to develop improved models, we will know the nuclear physics properties of nuclei populated in the late stages of the r-process

With the current and planned stellar surveys + follow-up spectroscopy, we will know the r-process abundance pattern (and all of its variations) in unprecedented detail

→ we can use these details to get at the hydrodynamic conditions that must have existed during the late stage of the r-process

# rare earth peak formation in a hot r-process

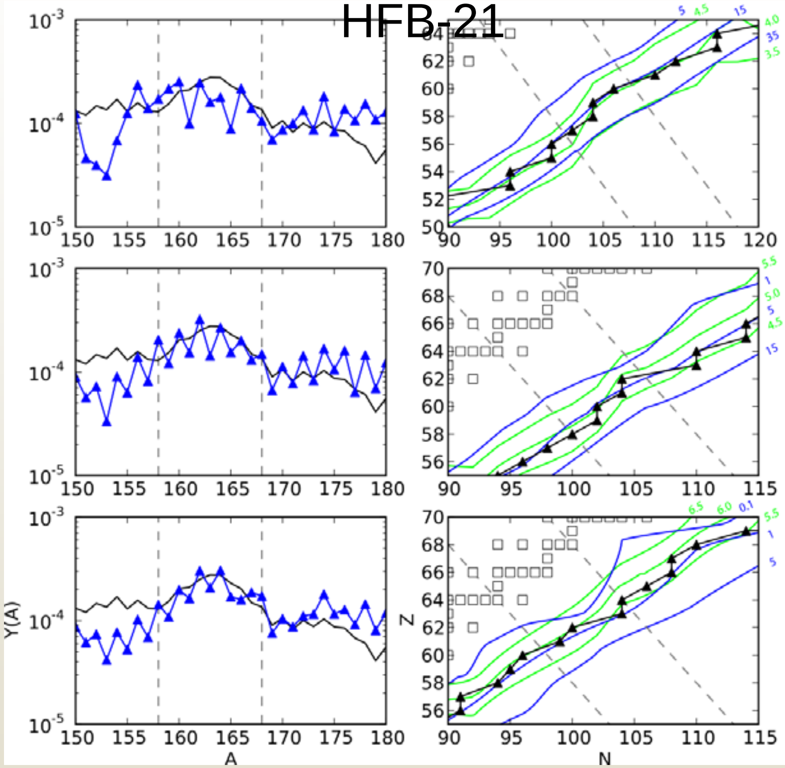


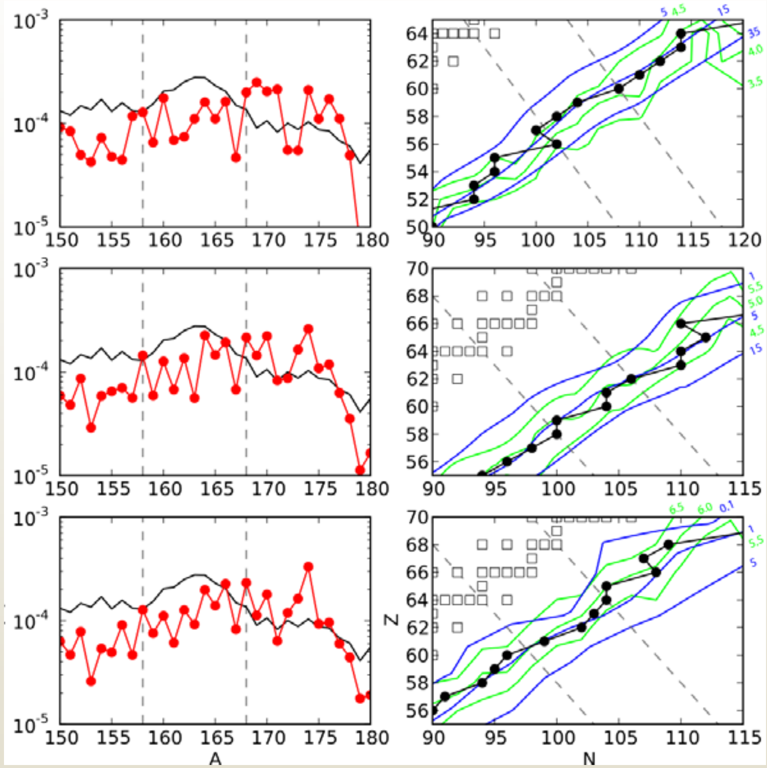


Surman, Engel, Bennett, Meyer
(1997)

# rare earth peak formation: dependence on nuclear data

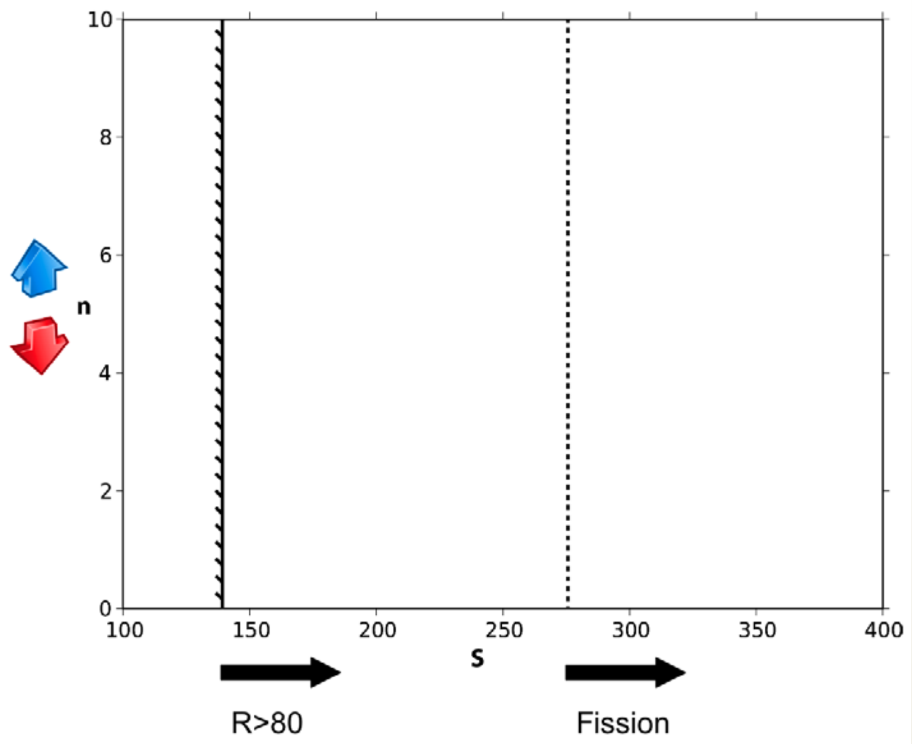
FRDM
HFB-21





Mumpower, McLaughlin, Surman (2012)

# using the rare earth peak to constrain the r-process site



Mumpower, McLaughlin, Surman (2012)

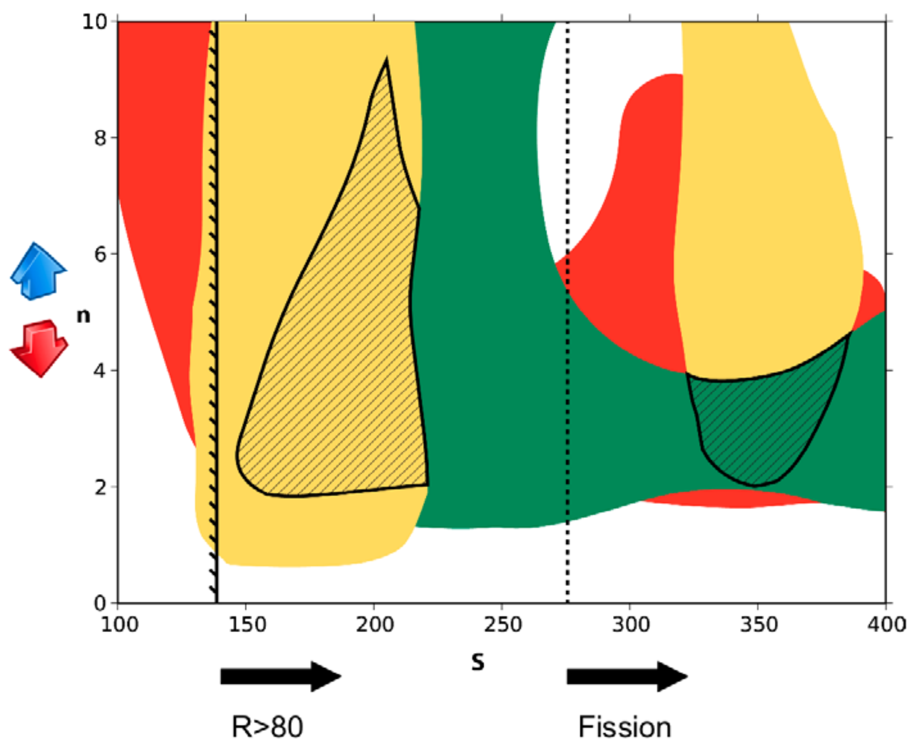
Parameterized wind based on Meyer (2002):

$$\rho(t) = \rho_1 e^{-3t/\tau} + \rho_2 \left( \frac{\Delta}{\Delta + t} \right)^n$$

with $\tau$=80 ms, $Y_e$=0.3, FRDM masses

Vary 50<$s/k$<400, 0<$n$<10

# using the rare earth peak to constrain the r-process site



🟥 match with rare earth region

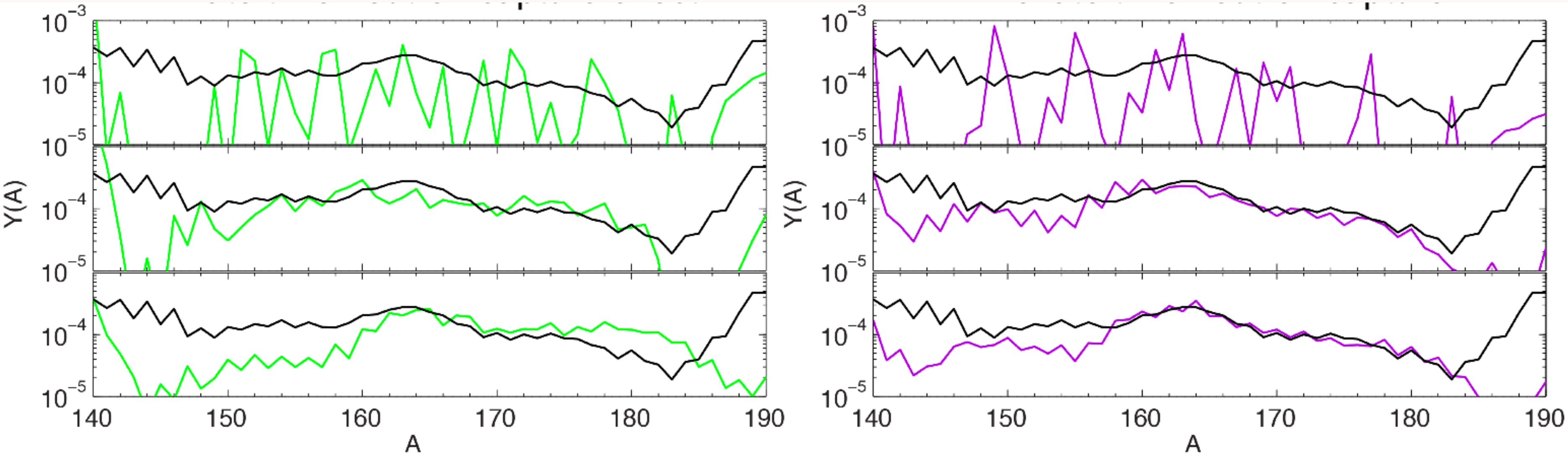
🟨 match with ratio of the A~195 main peak to rare earth peak

🟩 minimal late time neutron capture

Mumpower, McLaughlin, Surman (2012)

# late-time capture effect

e.g., Arcones & Martinez-Pinedo (2011), Mumpower, McLaughlin, Surman (2012)



strong

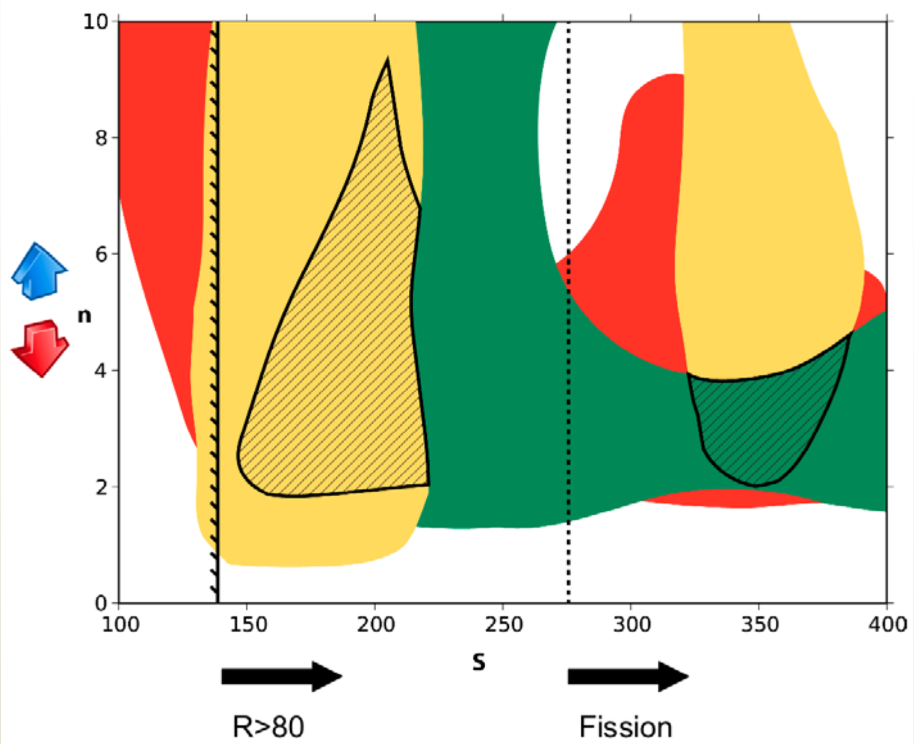
weak

poor match to solar

better match to

solar

# using the rare earth peak to constrain the r-process site



🟥 match with rare earth region

🟨 match with ratio of the A~195 main peak to rare earth peak

🟩 minimal late time neutron capture

Mumpower, McLaughlin, Surman (2012)

# summary

Our sensitivity studies have

identified the nuclei whose individual masses, beta decay rates, or neutron capture rates have the greatest impact on the r-process abundance pattern

elucidated the mechanisms by which this influence occurs (in equilibrium, during freezeout, in a cold r-process)

The greatest sensitivities (for masses and beta decay rates) do lie along the r-process path

However, nuclear properties of nuclei closer to stability, within the reach of experiment,

- set the final abundance pattern
- are important for r-processes in a broad range of astrophysical scenarios
- may help pin down the r-process astrophysical site