NIC XII - Satellite workshop on r-process nucleosynthesis

Sensitivities of the r-process to

…masses, β-decay rates, cross-sections

nuclear structure

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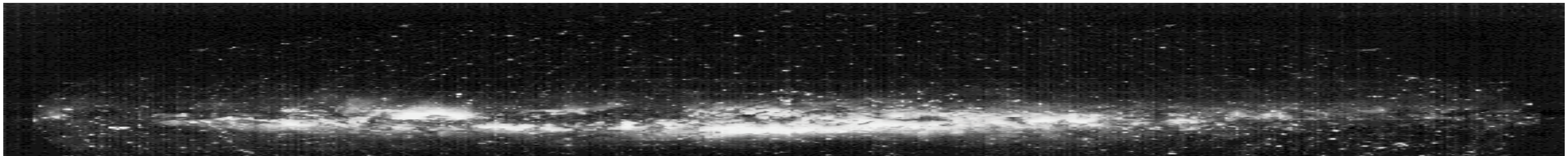
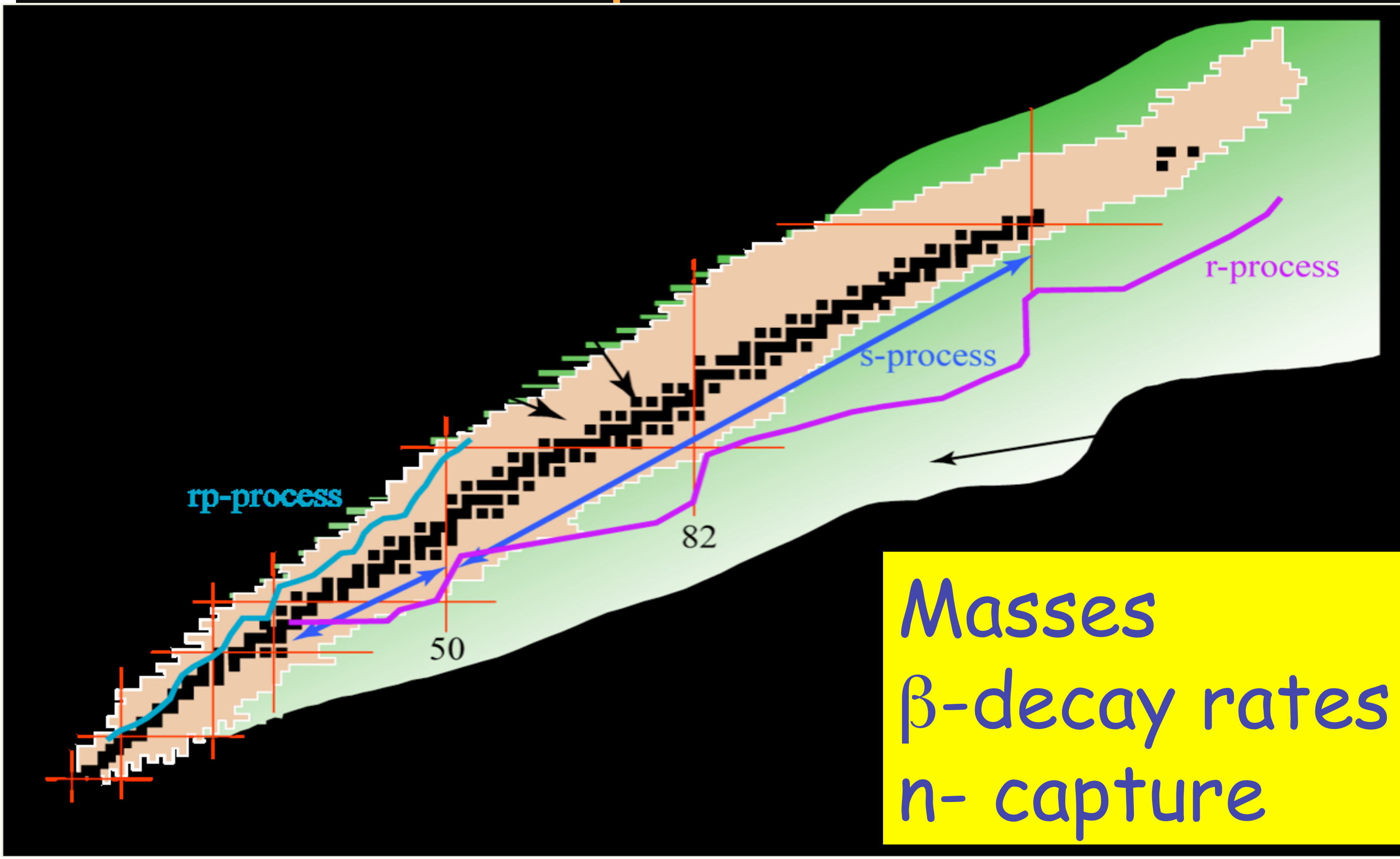
- Robustness of observational r-process patterns
- Uncertainties in astrophysical r-process sites
- What about the nuclear properties?
  r-process basic idea



r-process



Masses
β-decay rates
n- capture

Major Shells and evolution of shells…

Experimental & Theoretical Challenges

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Progress in Particle and Nuclear Physics 54 (2005) 535–613

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Review

Nuclear structure aspects in nuclear astrophysics

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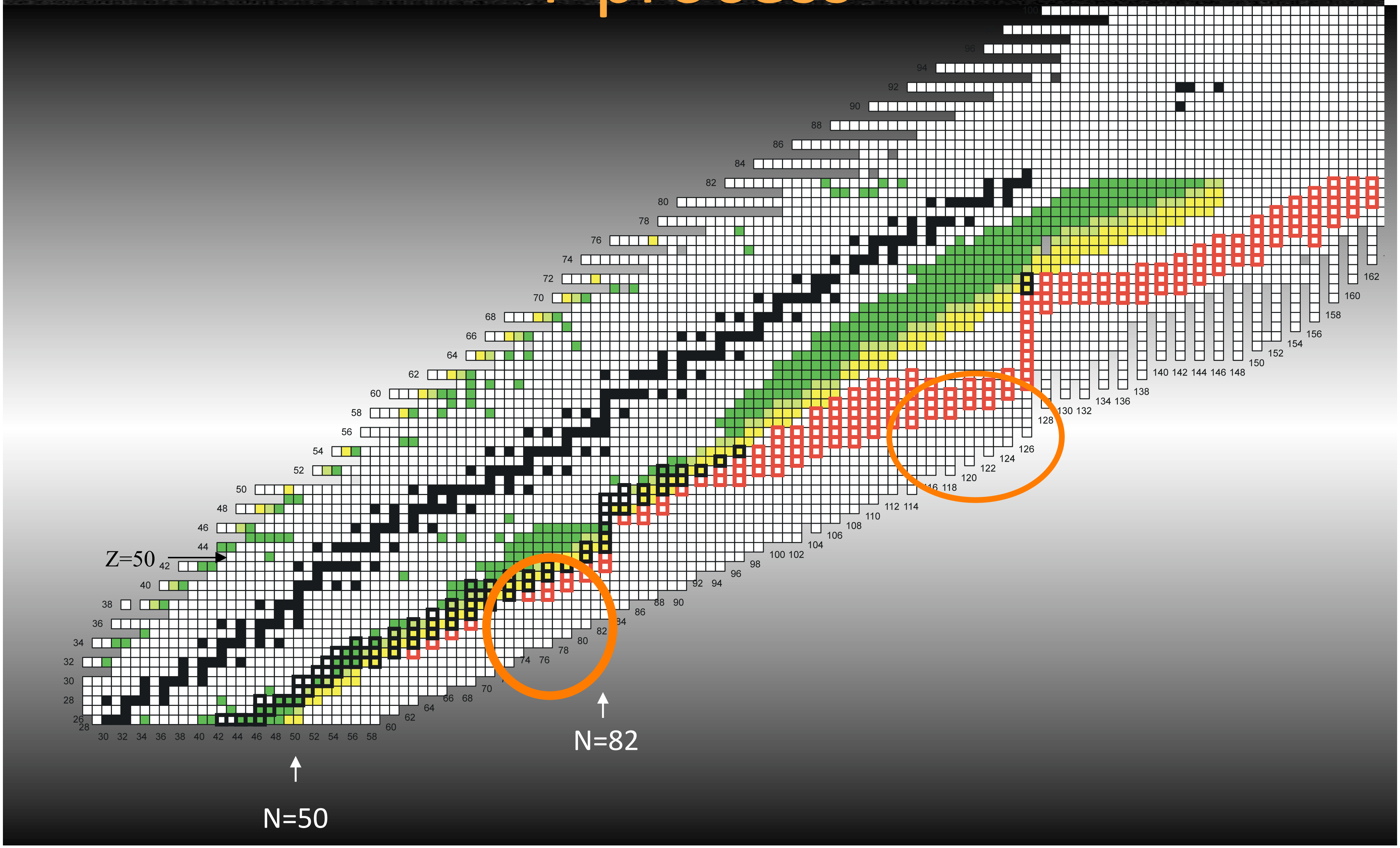
How do you decide which nuclei to measure???

H. Schatz

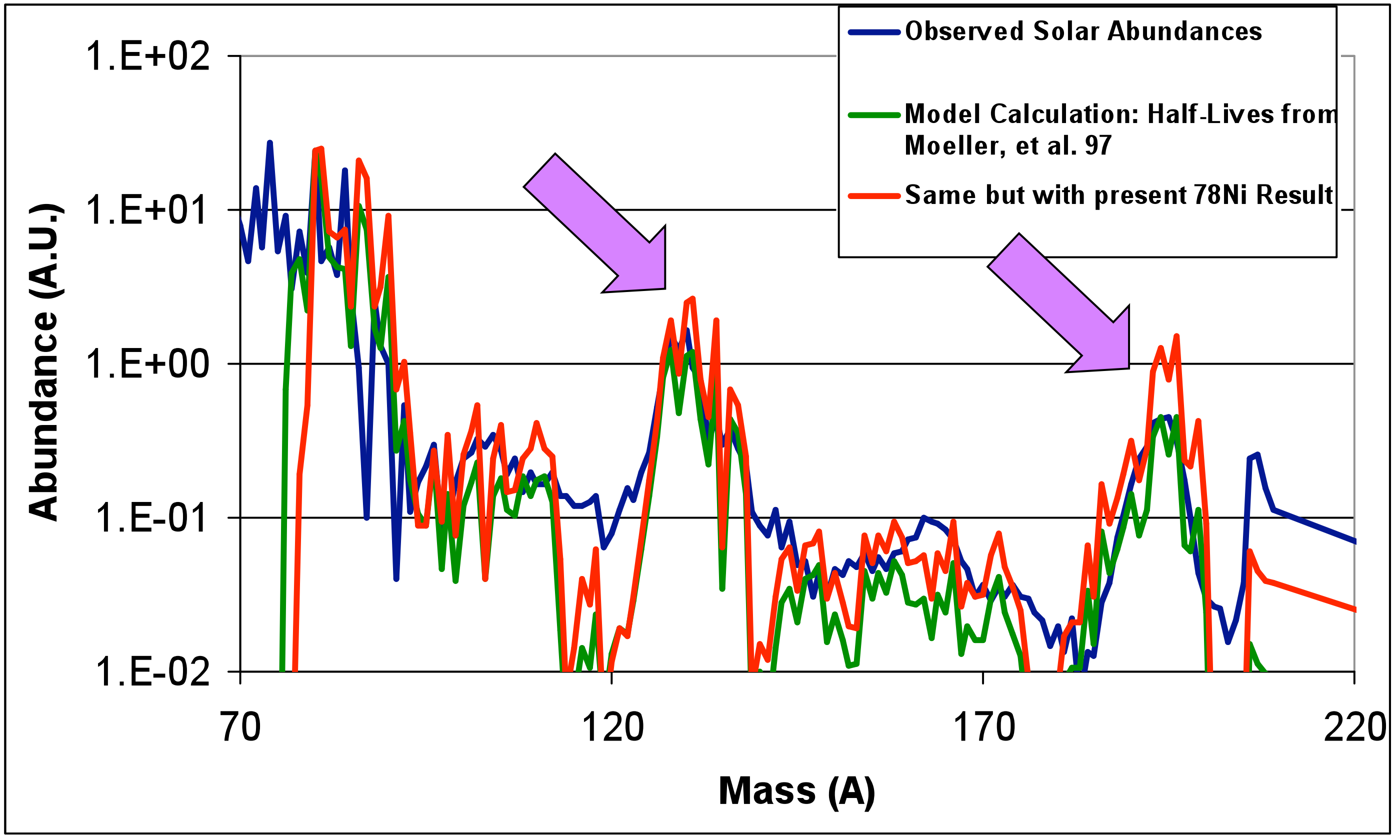
r-process



First experiment: r-process in the Ni region

Hosmer et al. PRL 94, 112501 (2005)

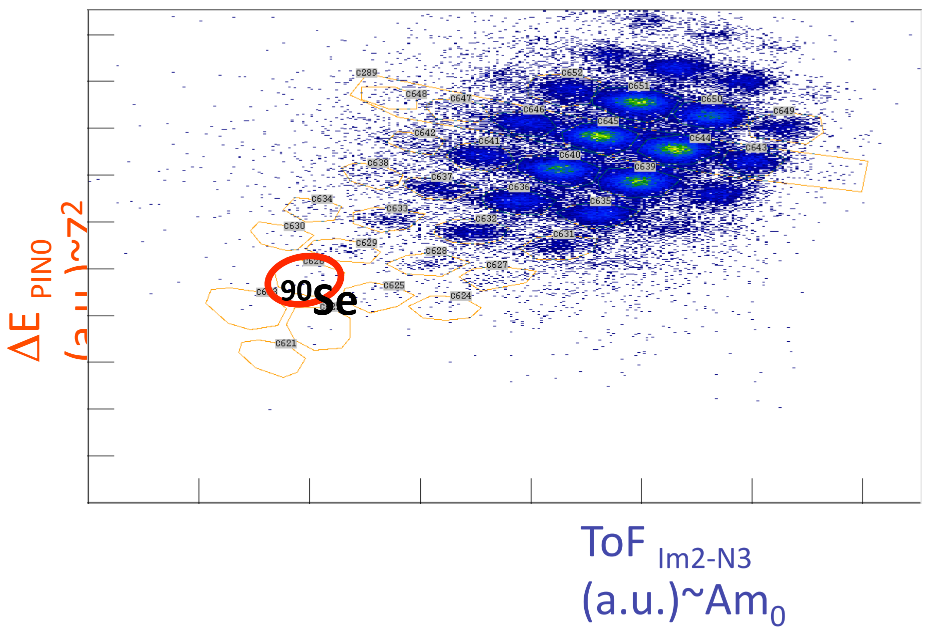
Impact of ^{78}Ni half-life on r-process models

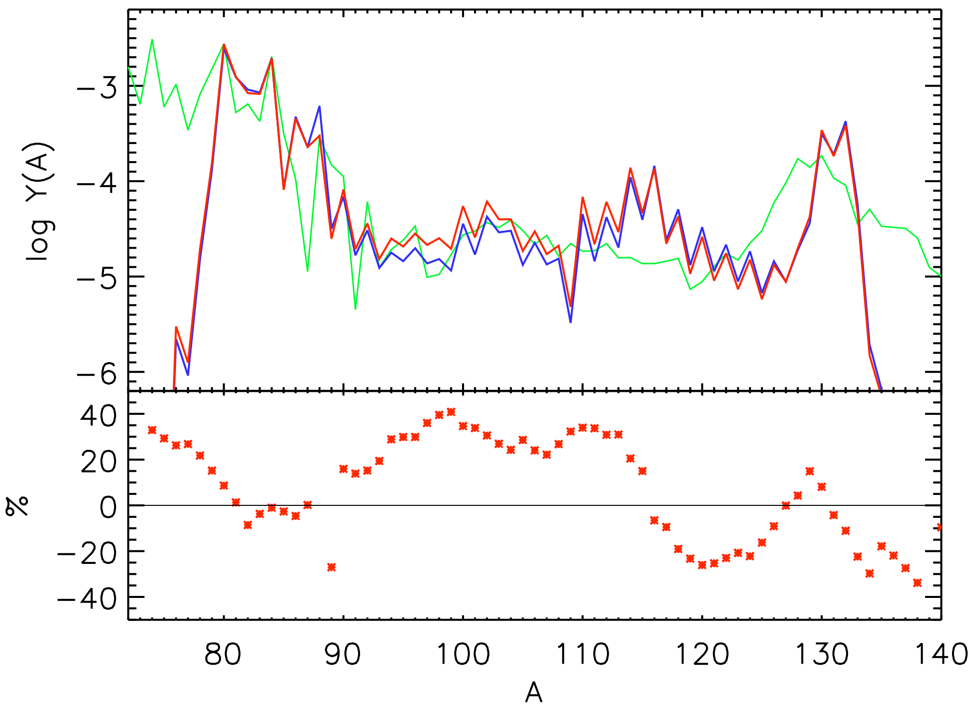


N=56 subshell with Z=34???

Quinn et al., Phys. Rev. C 85, 035807 (2012)

Fragmentation of 120 MeV/u ^{136}Xe beam





	Implantations		Maximum Likelihood Method (ms)
^{87}As	27	12	$1450(550)^{+3900}_{-1250}$
^{88}As	16	8	$200(10)^{+200}_{-90}$
^{88}Se	144	74	$650(35)^{+175}_{-140}$
^{89}Se	180	90	$345(25)^{+95}_{-80}$
^{90}Se	70	30	$195(10)^{+95}_{-65}$

r-process sensitivities…masses

More quantitative approach to choosing to measure nuclei that would have the greatest impact on

What?

Brad Meyer code modified by R. Surman

various **mass models**-

FRDM, Duflo-Zuker, ETFSIQ, HFB-21, F-spin

Method:

Adjusted the separation energy of each nucleus ± 25%

(>**3000 nuclei twice….**)

Calculated the max and fractional change from final abundances

What did we find?

Some consistent set of nuclei that are the most important to measure

So, What did we do?

Simulations….. Varied astrophysical conditions
varied seed nuclei
varied mass models

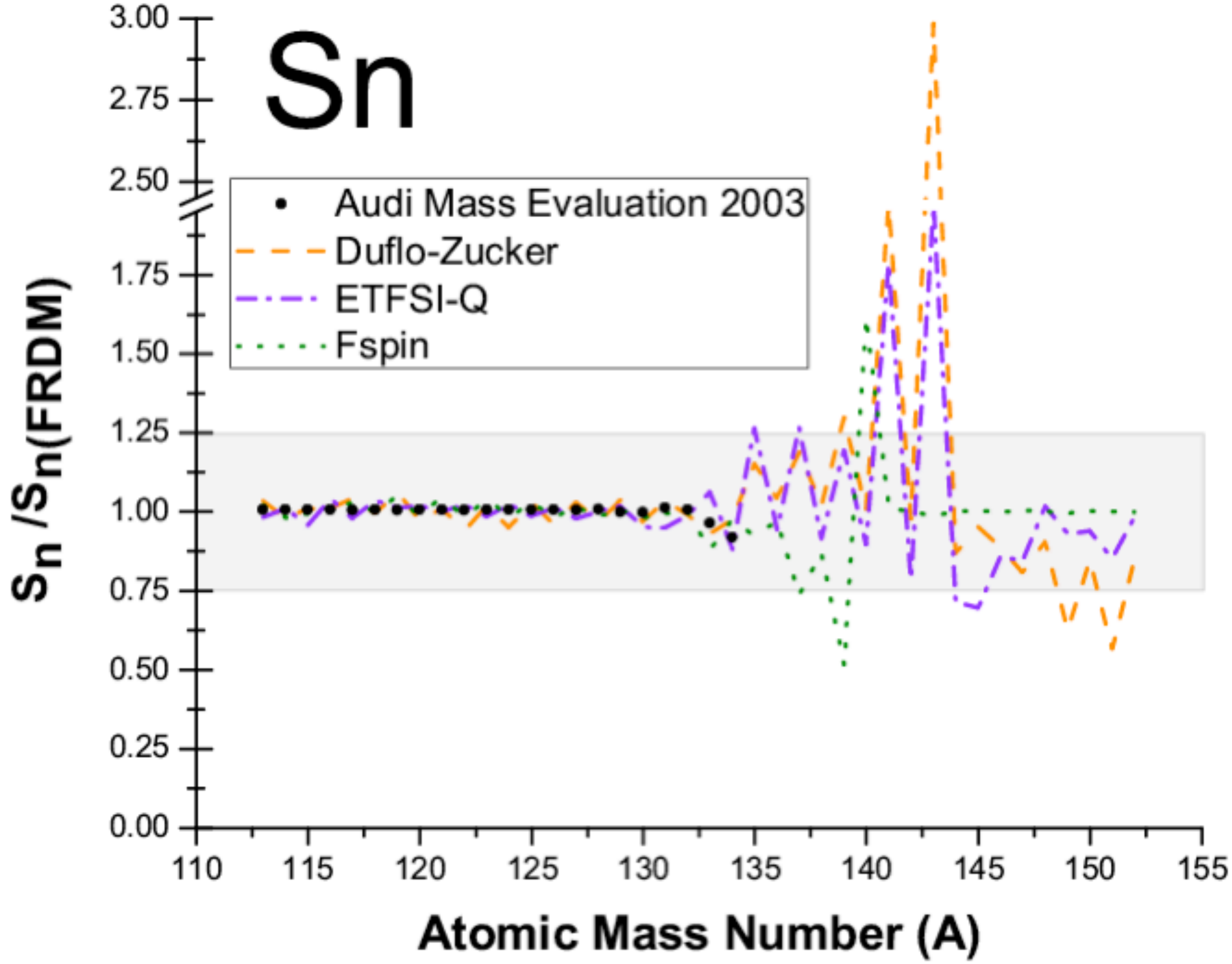
Input initial astrophysical conditions

- Temperature/density
- neutron/seed ratios
- Freeze-out times

Input nuclear physics

- masses
- n-capture rates
- beta decay half-lives
- (fission recycling, alpha recycling, neutrino interactions off)

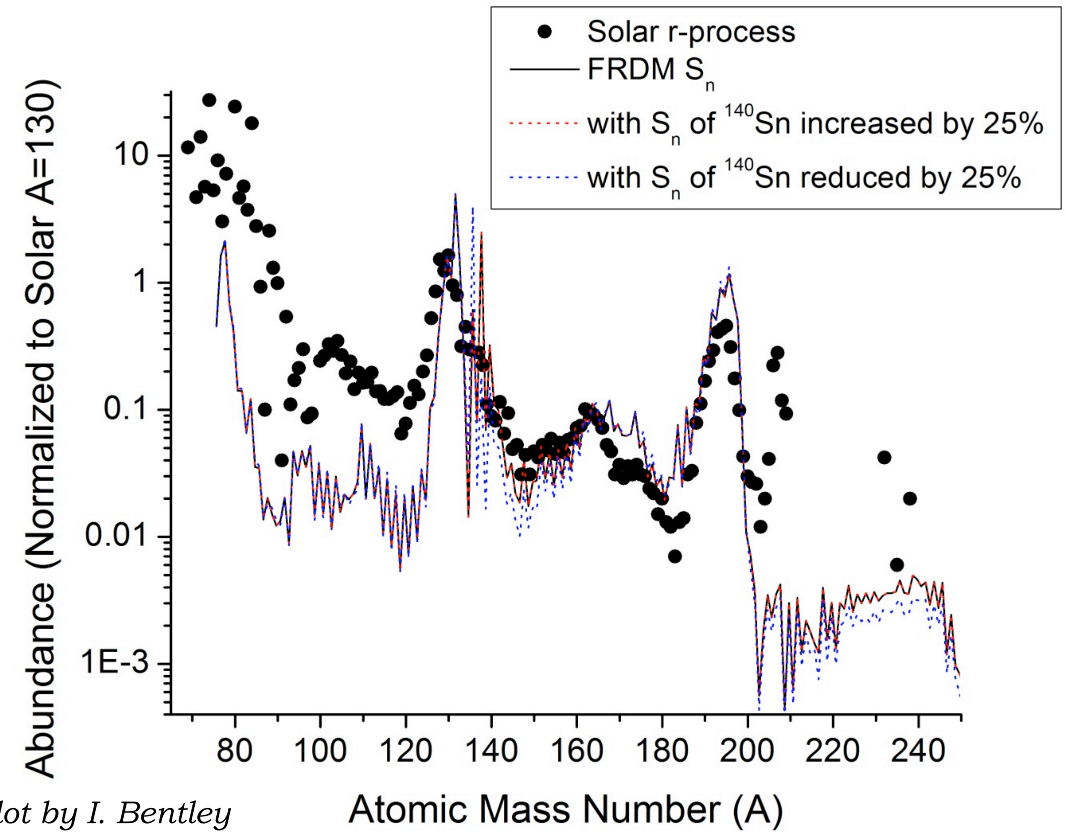
Why 25%



Sn
Audi Mass Evaluation 2003
Duflo-Zucker
ETFSI-Q
Fspin
3.00
2.75
2.50
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
110
115
120
125
130
135
140
145
150
155
Atomic Mass Number (A)
$S_n / S_n(FRDM)$

Neutron separation energy sensitivity study

S. Brett, I. Bentley, N. Paul, A. Aprahamian



plot by I. Bentley

Start with a baseline simulation

(here, the H-event conditions from Qian et al were used)

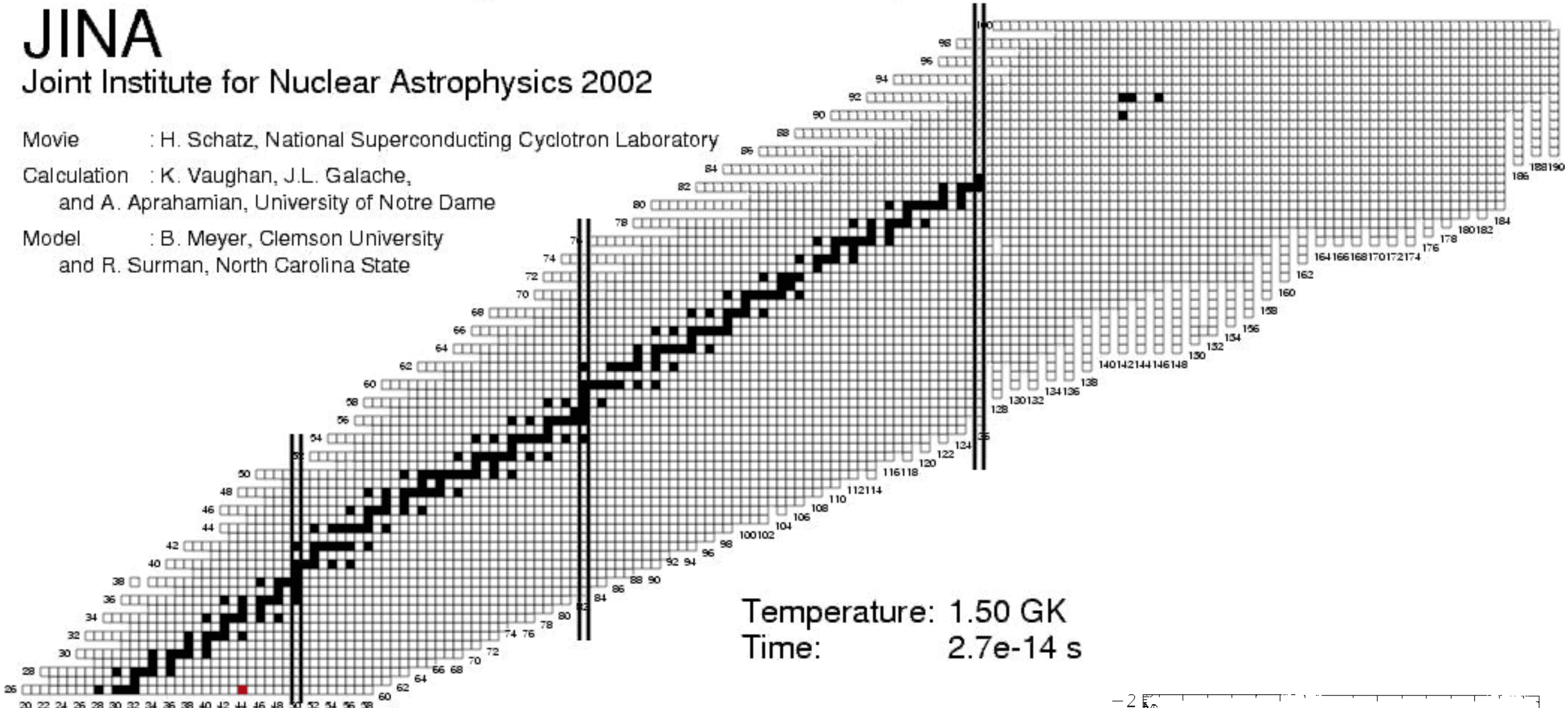
Vary one separation energy by 25% and rerun the simulation

Repeat >6000 times

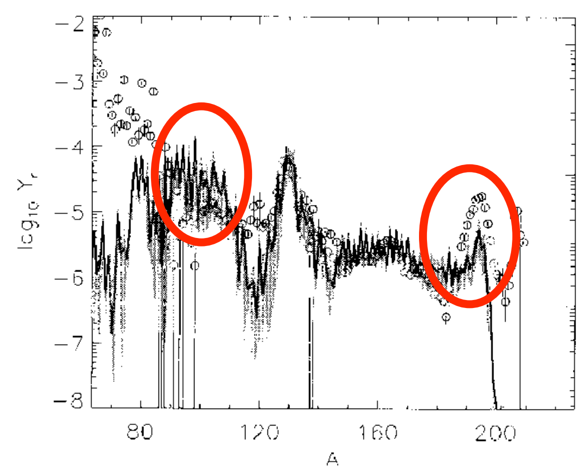
(twice for each heavy nucleus in the network)

$$\Delta Y_{S_n(Z_i, A_i)\pm 25\%} = \sum_A \left[Y_{baseline}(A) - Y_{S_n(Z_i, A_i)\pm 25\%}(A) \right]$$

Nucleosynthesis in the r-process



Closed shell nuclei have small S_n, enrichment around N=50, 82,126



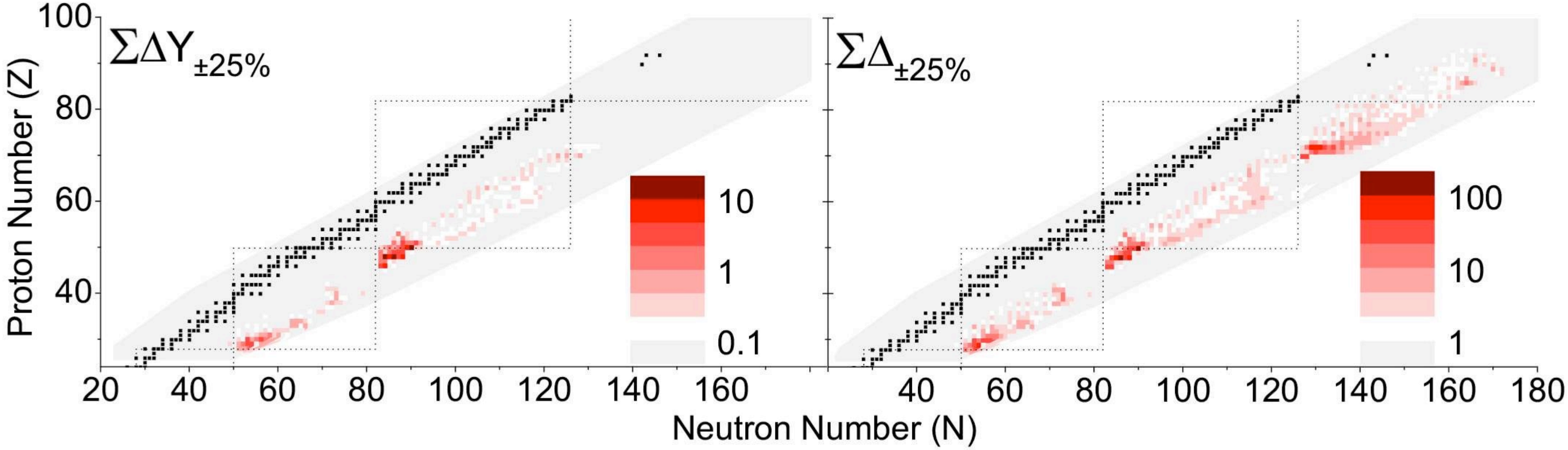
Input Parameters for the simulation were based on… Neutrino-less H-event from Qian et. al

Description	Value
Seed Nucleus	^{90}Se
$N_{neutron}/N_{seed}$	86
*Seed Nucleus	^{70}Fe
$^{*}N_{neutron}/N_{seed}$	67
Initial Density ($\rho_5 = 10^5 g/cm^3$)	0.0034
Initial Temperature ($T_9 = 10^9 K$)	1.5
Freeze-out Time	0.86s

$*\,^{90}Se$ was replaced with ^{70}Fe in order to allow for the dependence on the masses of nuclei between $70 \geq A \geq 90$ to be investigated. This was done in such a way that the electron fraction remains constant (Y_e=.19).

Evaluating the impact of the separation energy change
Two approaches

$$\Delta_{\pm 25\%}(N,Z) = \sum_A \frac{|Y(A) - Y(A, \pm\Delta S_n(N,Z))|}{Y(A)}.$$



$$\Delta Y_{\pm 25\%}(N,Z) = \sum_A |Y(A) - Y(A, \pm\Delta S_n(N,Z))|.$$

FRDM

Neutron separation energy sensitivity study

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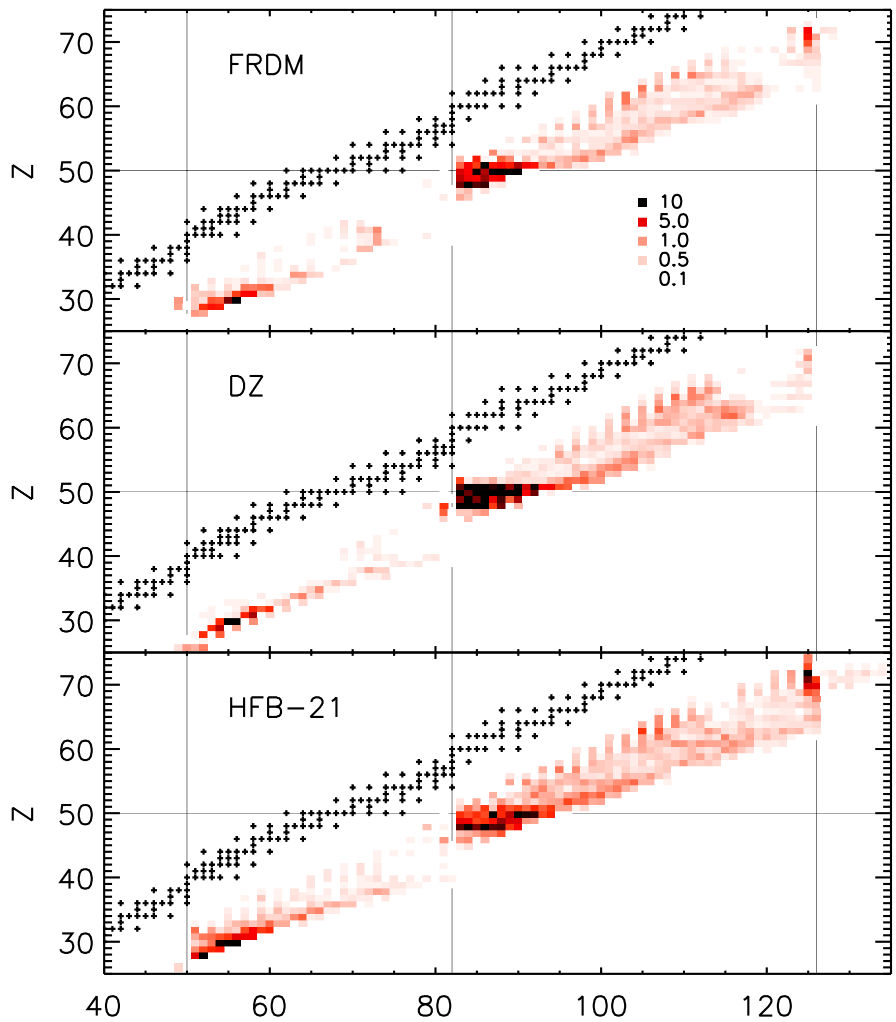
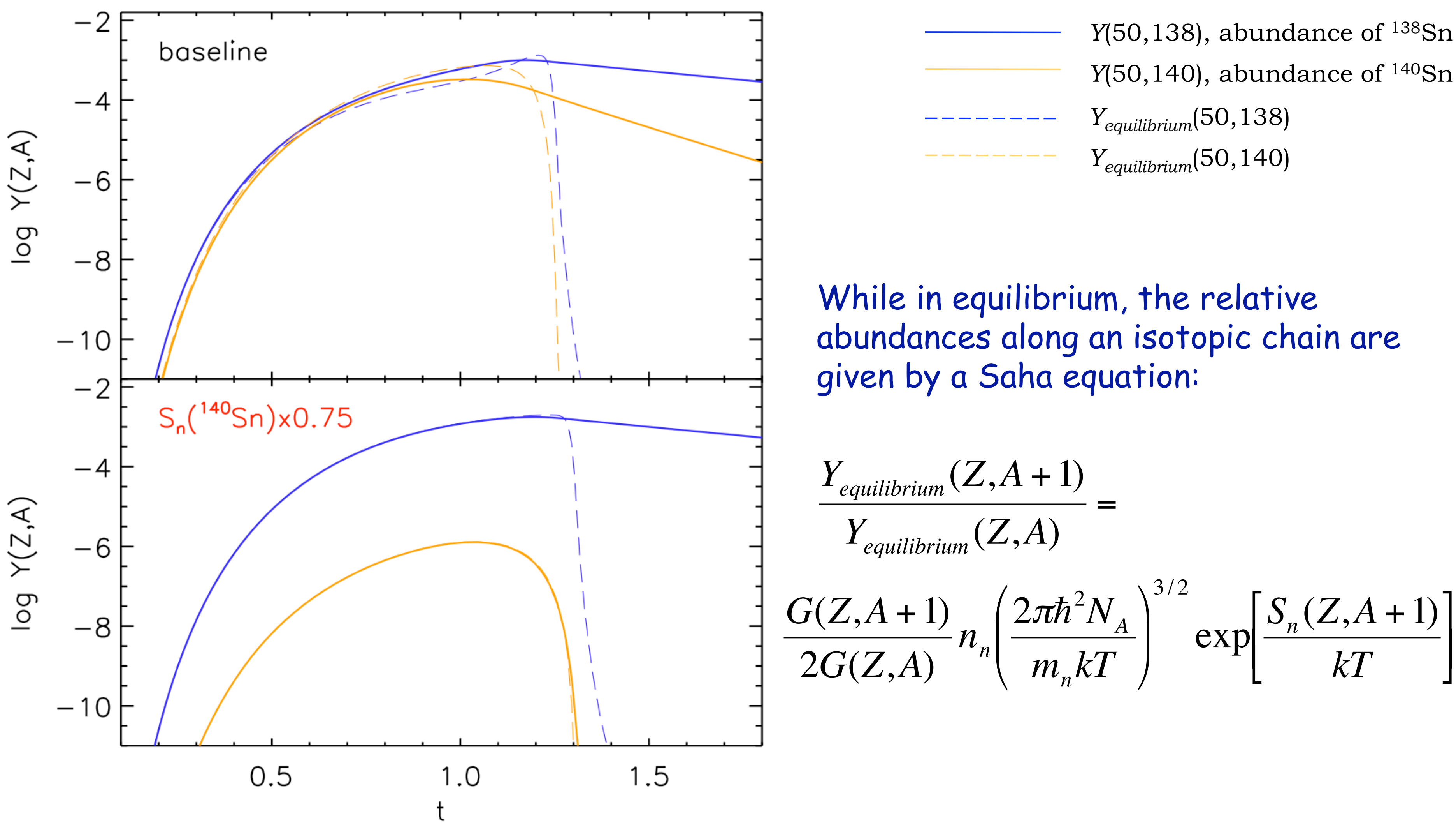


$$\Delta Y_{S_n(Z_i, A_i)\pm 25\%} = \sum_{A}^{N} \left[Y_{baseline}(A) - Y_{S_n(Z_i, A_i)\pm 25\%}(A) \right]$$

The role of neutron separation energies in a hot *r*-process



While in equilibrium, the relative abundances along an isotopic chain are given by a Saha equation:

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

ΔY for FRDM

Nucleus	ΔY
^{136}Cd	20.2
^{140}Sn	12.1
^{135}Cd	8.80
^{83}Cu	8.42
^{139}Sn	8.19
^{142}Sb	5.64
^{135}Sn	5.44
^{133}Cd	5.38
^{140}Sb	5.25
^{134}Cd	5.23
^{82}Cu	4.14
^{134}In	4.14
^{131}Pd	3.29
^{137}Sn	2.94
^{141}Sn	2.91
^{83}Zn	2.89
^{85}Zn	2.71
^{85}Cu	2.66
^{130}Pd	2.39
^{132}Pd	2.39

ΔY for ETFSI-Q

Nucleus	ΔY
^{140}Sn	20.1
^{136}Cd	19.0
^{142}Sn	17.3
^{137}Cd	15.3
^{79}Ni	12.5
^{80}Ni	12.0
^{135}Cd	11.5
^{134}Cd	11.5
^{138}Cd	8.57
^{132}Pd	7.66
^{130}Pd	7.34
^{132}In	7.33
^{129}Pd	5.12
^{139}Sn	4.63
^{131}Pd	4.37
^{138}In	3.98
^{139}In	3.95
^{86}Zn	3.21
^{141}Sn	2.92
^{85}Zn	2.86

ΔY for DZ

Nucleus	ΔY
^{80}Ni	13.6
^{79}Ni	9.96
^{138}Cd	7.08
^{137}Cd	5.49
^{83}Cu	4.27
^{131}Pd	3.54
^{82}Cu	3.36
^{132}Pd	3.12
^{136}Cd	3.00
^{130}Pd	2.97
^{86}Zn	2.84
^{129}Pd	1.88
^{85}Zn	1.81
^{134}Ag	1.49
^{142}Sn	1.42
^{135}Ag	1.39
^{135}Cd	1.36
^{133}Cd	1.10
^{141}Sn	1.08
^{144}Sn	1.07

ΔY for HFB21

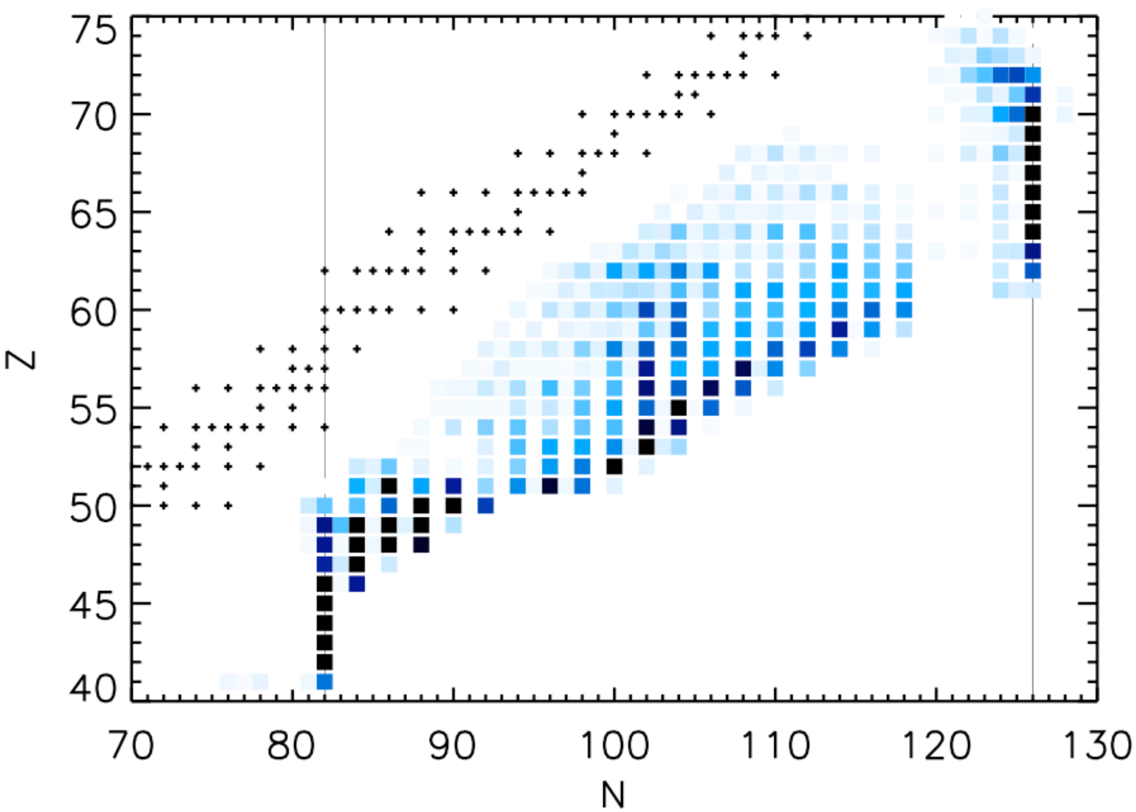
Nucleus	ΔY
^{136}Cd	22.7
^{137}Cd	10.8
^{138}Cd	10.4
^{135}Cd	6.97
^{140}Sn	5.97
^{130}Pd	5.46
^{83}Cu	5.23
^{142}Sn	4.66
^{134}Cd	4.57
^{141}Sn	4.21
^{86}Zn	3.82
^{133}Cd	3.52
^{132}Cd	3.04
^{137}Sn	2.86
^{82}Cu	2.63
^{138}In	2.47
^{139}In	2.23
^{129}Pd	1.95
^{131}Pd	1.81
^{131}Ag	1.69

r-process sensitivities…beta-decay rates

J. Cass, G. Passucci, R. Surman, A. Aprahamian

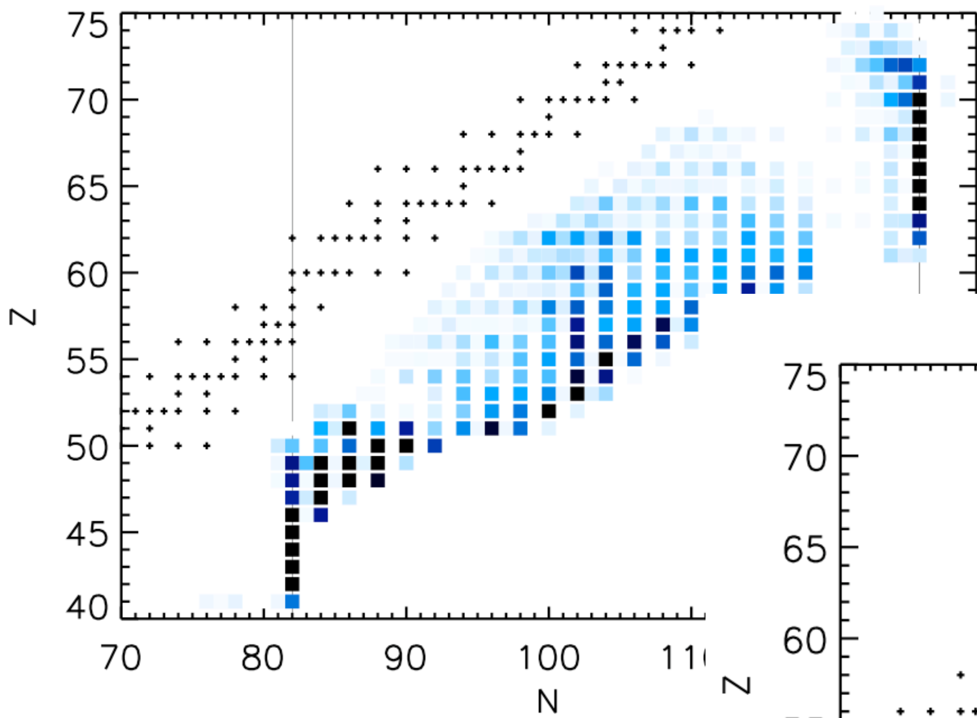
To start…

Vary one beta decay rate by an order of magnitude, rerun the simulation, and compare the final abundance pattern to the baseline

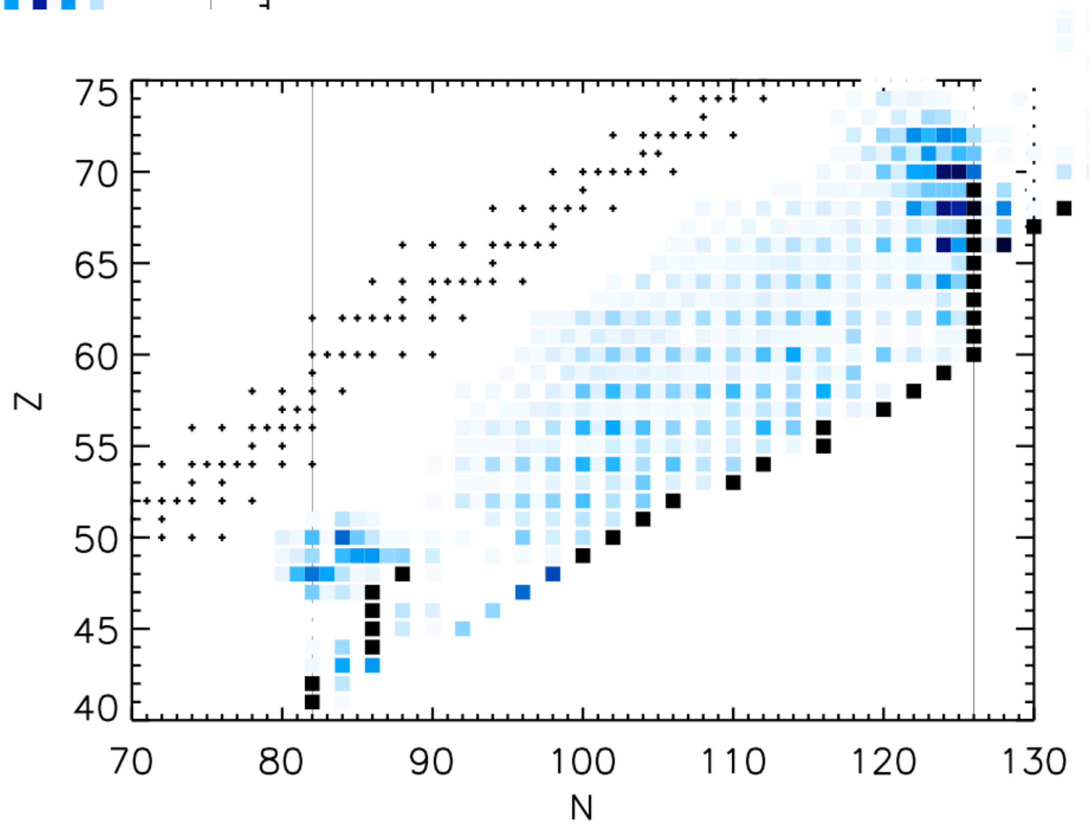


White to black = 0-10% change in the final abundance patterns

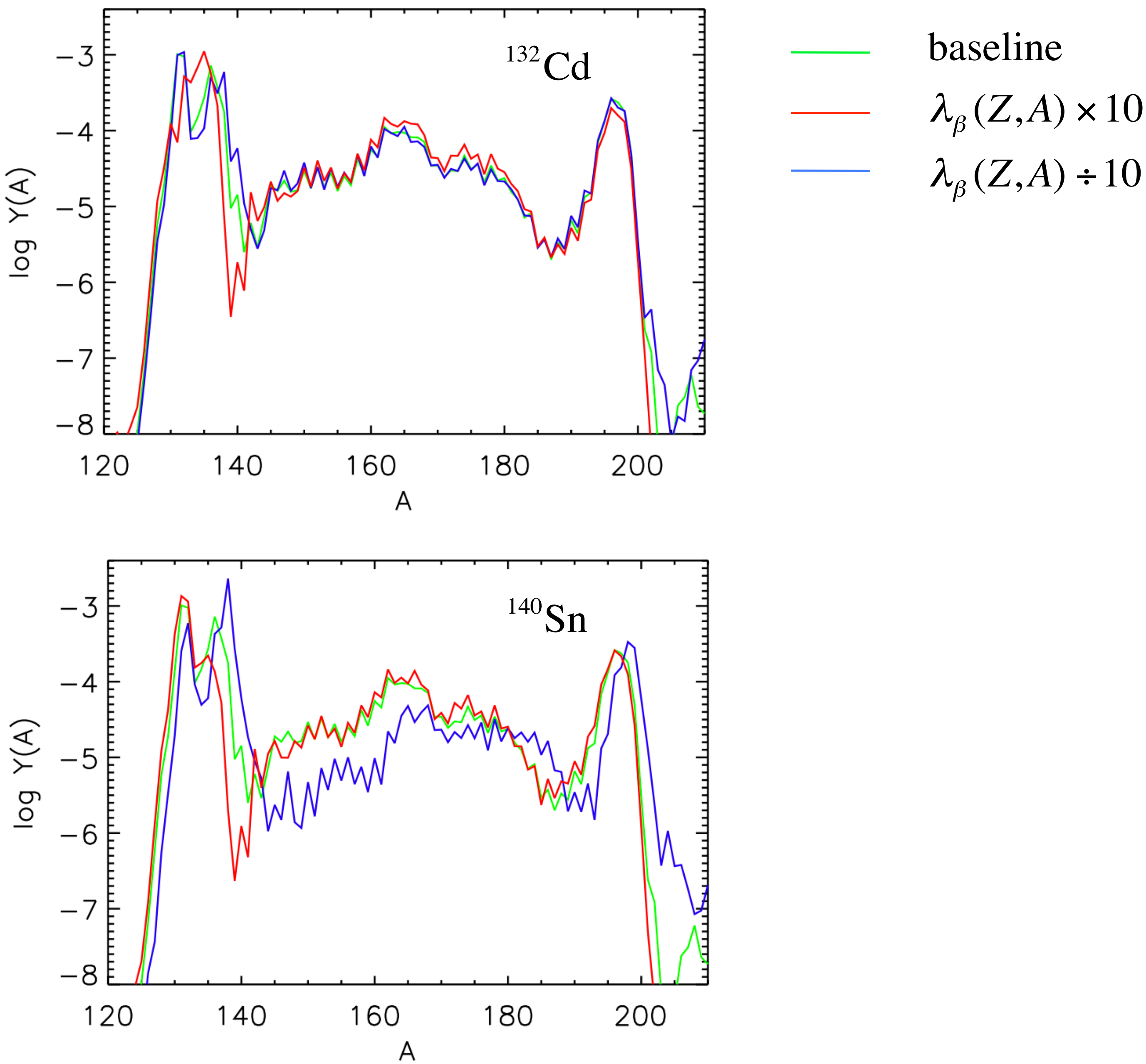
Beta decay rate sensitivity study



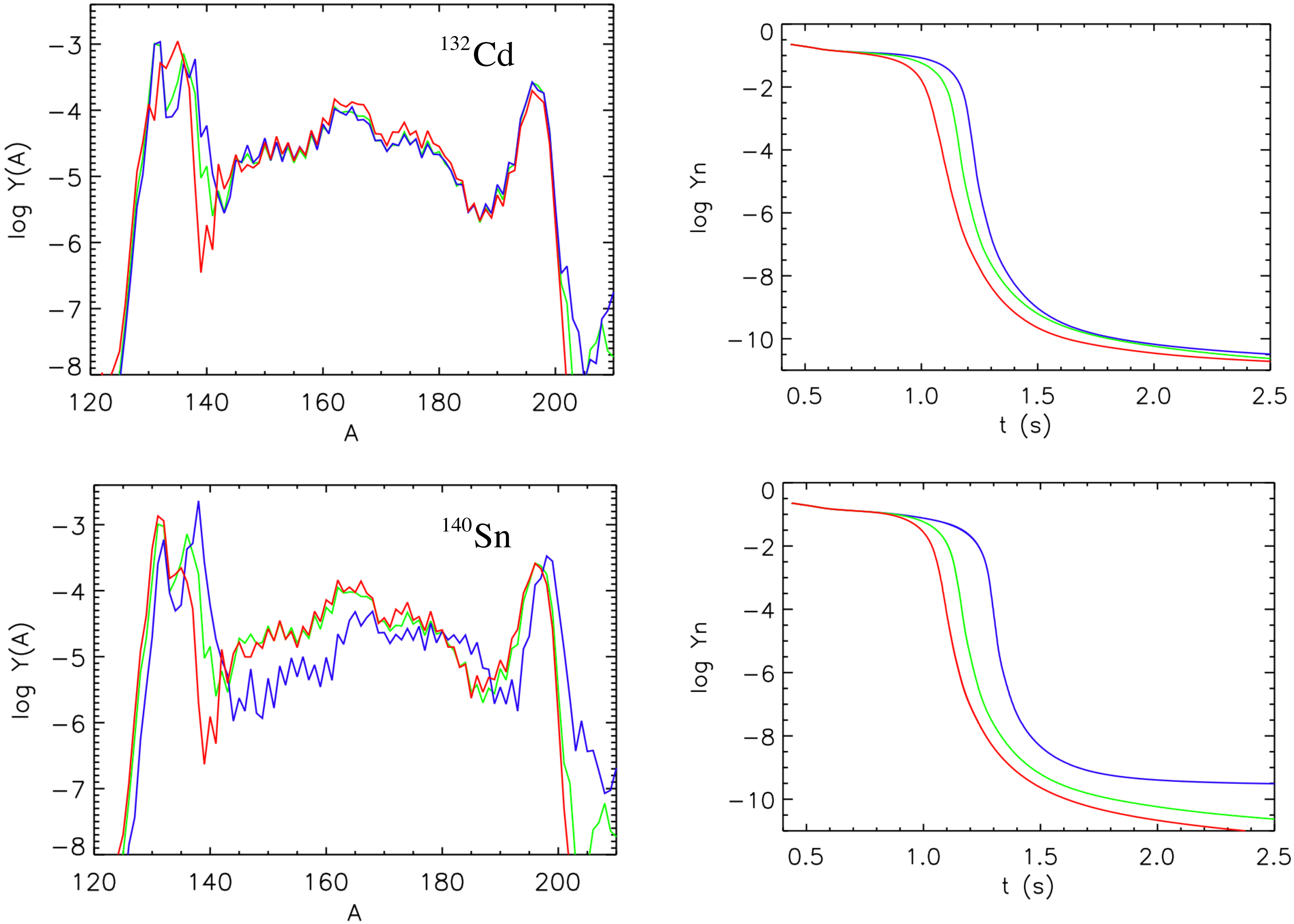
hot r-process



cold r-process



^{132}Cd
^{140}Sn
baseline
$\lambda_\beta(Z,A)\times 10$
$\lambda_\beta(Z,A)\div 10$
log Y(A)
A



132Cd
140Sn
log Y(A)
A
log Yn
t (s)

summary

We have carried out the first quantitative/ comprehensive sensitivity study of an r-process simulation to **masses**, **beta decay rates**, neutron capture cross sections.

- we varied mass models
- we varied decay rates
- consistent set of nuclei that we should measure

Sensitivity Study Masses

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Sensitivity Study β-decay rates

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Nuclear Structure sensitivities of the r-process