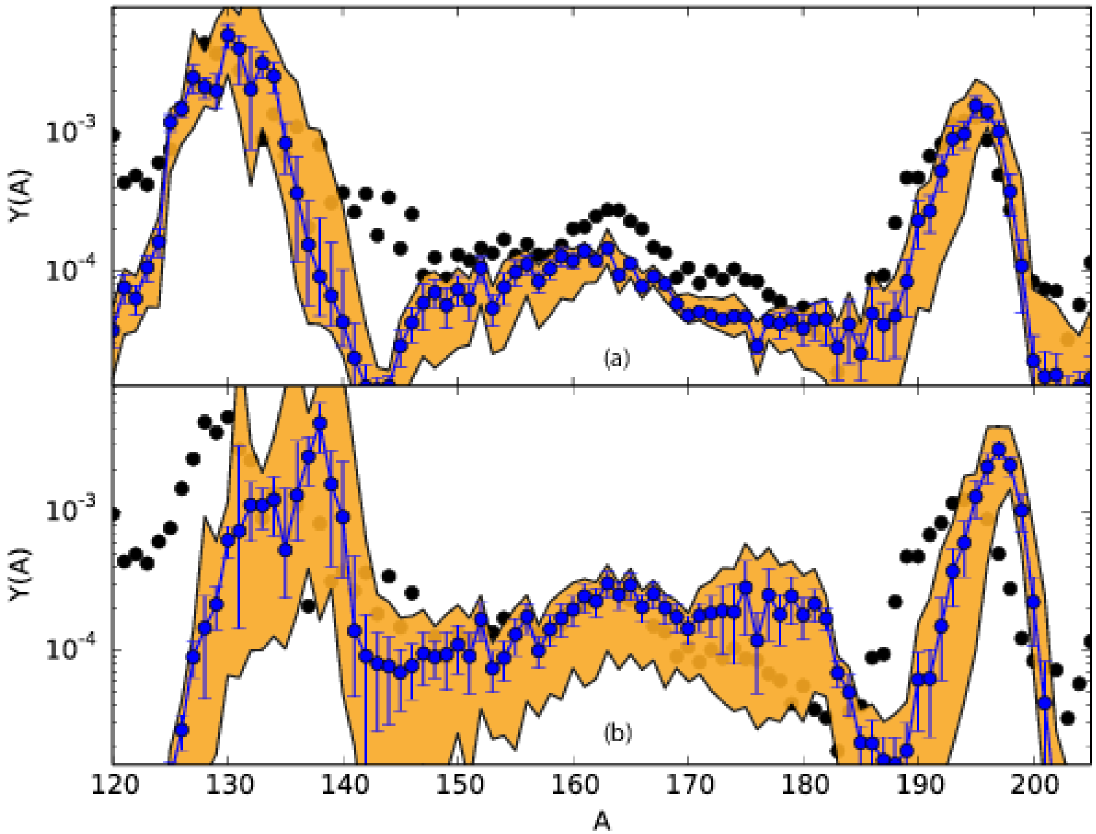
The impact of nuclear physics inputs on the freeze-out phase of the *r*-process



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UNIVERSITY OF NOTRE DAME

Friday August 8th 2014

INT Workshop

JINA

The Importance of the Freeze-out Phase

- Freeze-out is the last phase of the r-process when nuclides decay back to stability.

- Individual rates and beta-delayed neutron emission probabilities (P_n values) are critical because most nuclei are out of equilibrium with their neighbors.

- During freeze-out the interplay between these reaction channels help to shape the final abundance distributions we observe in nature (this includes the rare earth peak for instance).

- Thus, in order to accurately predict *r*-process outcomes it is imperative to understand how these nuclear properties evolve with neutron excess.

- To strengthen our understanding we need to improve our models based off new measurements.

The *r*-Process

"rapid" neutron capture (as compared to beta decay)

Far from stable isotopes → nuclides participating are short lived

→ little to no experimental data

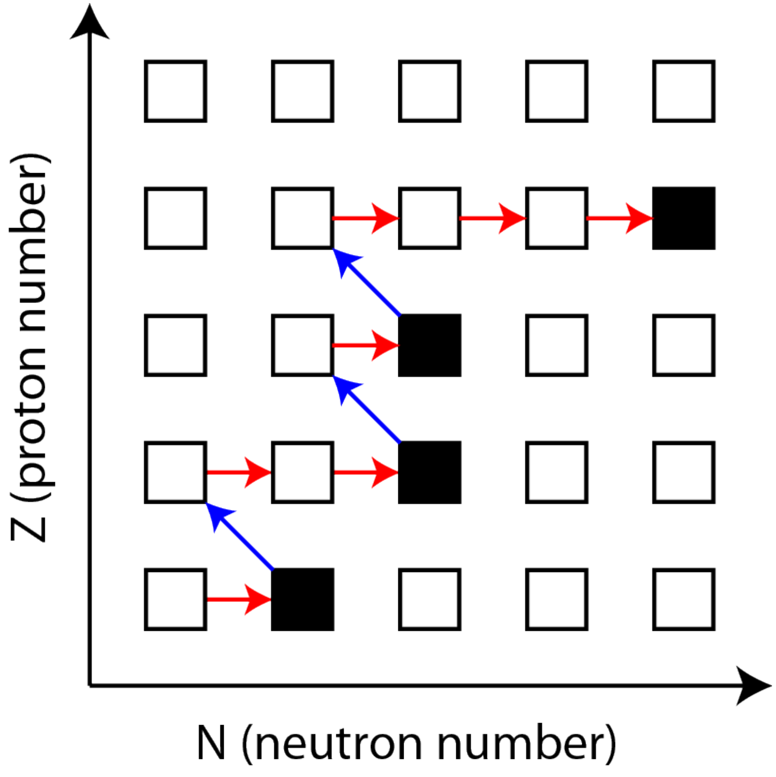
e.g. Uranium Z=92, N=146 → need lots of neutrons

Neutron Capture / Photo-dissociation

$$(Z, N) + n \leftrightarrow (Z, N+1) + \gamma$$

Beta Decay

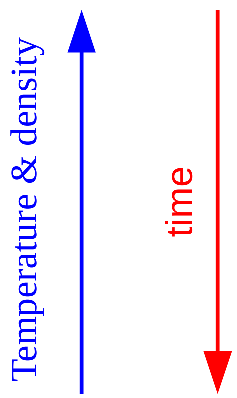
$$(Z, N) \rightarrow (Z+1, N-1) + e^- + \overline{\nu}_e$$



Freeze-out Nuclear Physics Inputs

Ingredient	Uncertainty	Abundance Impact
Masses / Q-values	Large towards dripline	Local & global
β-decay rates	Intermediate?	Local & global
Neutron capture rates	Large	Local & global
Alpha decay rates	Intermediate?	Local
β-delayed n-emission prob.	Intermediate?	Global
Fission barrier heights	Large	Local
Fission rates	Large	Local
Fission yields	Large	Global

Stages Of The *r*-Process



Nuclear Statistical Equilibrium (NSE)

Alpha recombination

$(n,\gamma) \leftrightarrow (\gamma,n)$ equilibrium & Quasi-equilibrium (QSE)

Freeze-out

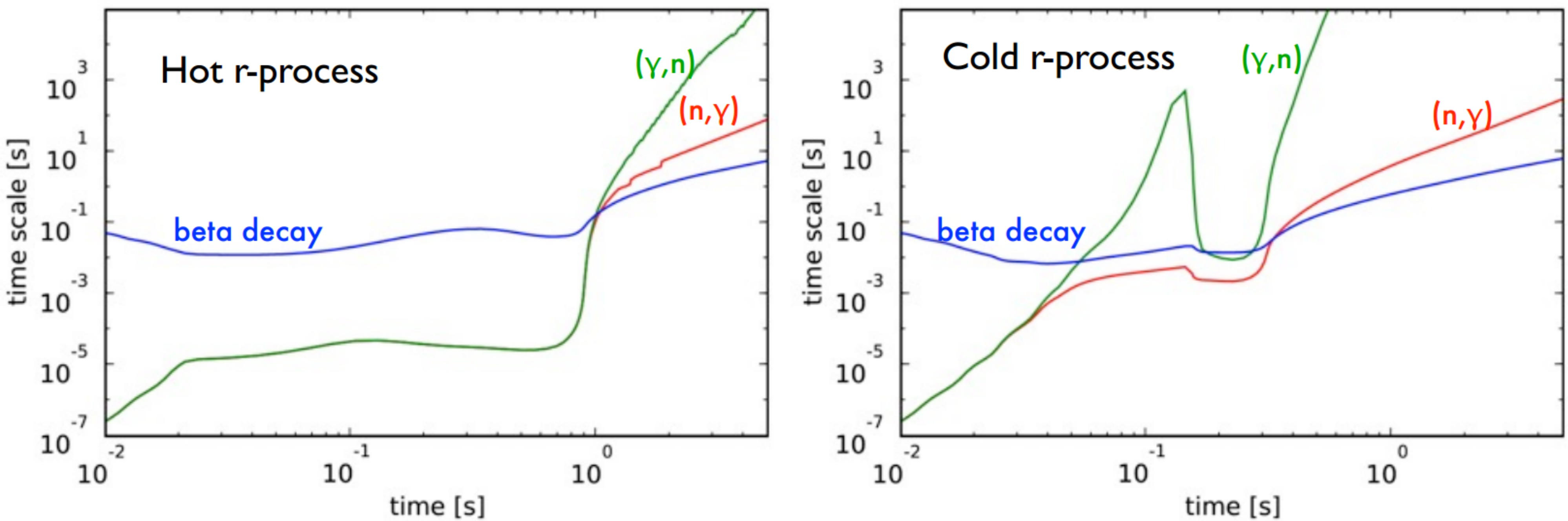
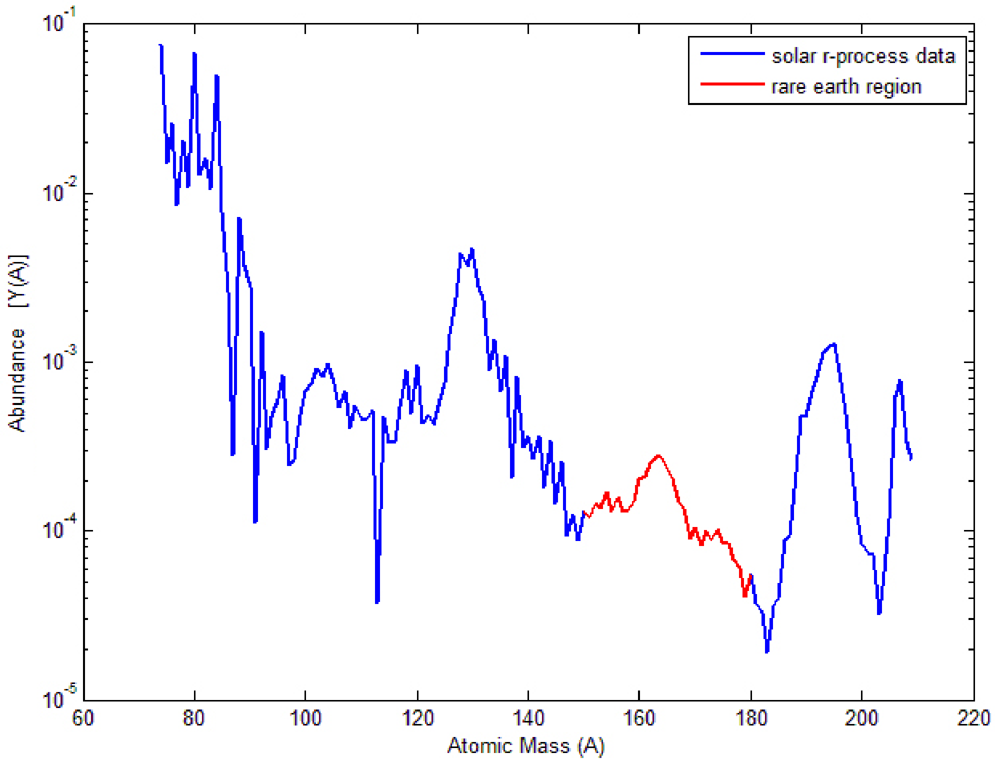


Figure from A. Arcones (2011)

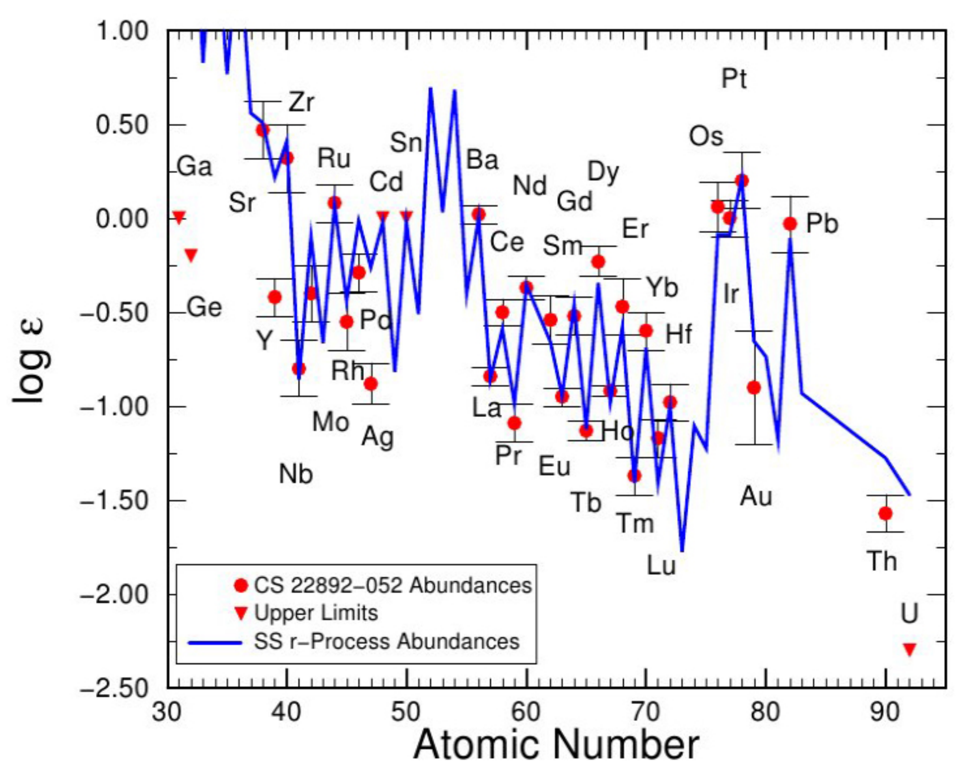
r-Process Data

Solar r-process residuals (meteoritic data)

Halo stars (observational data)



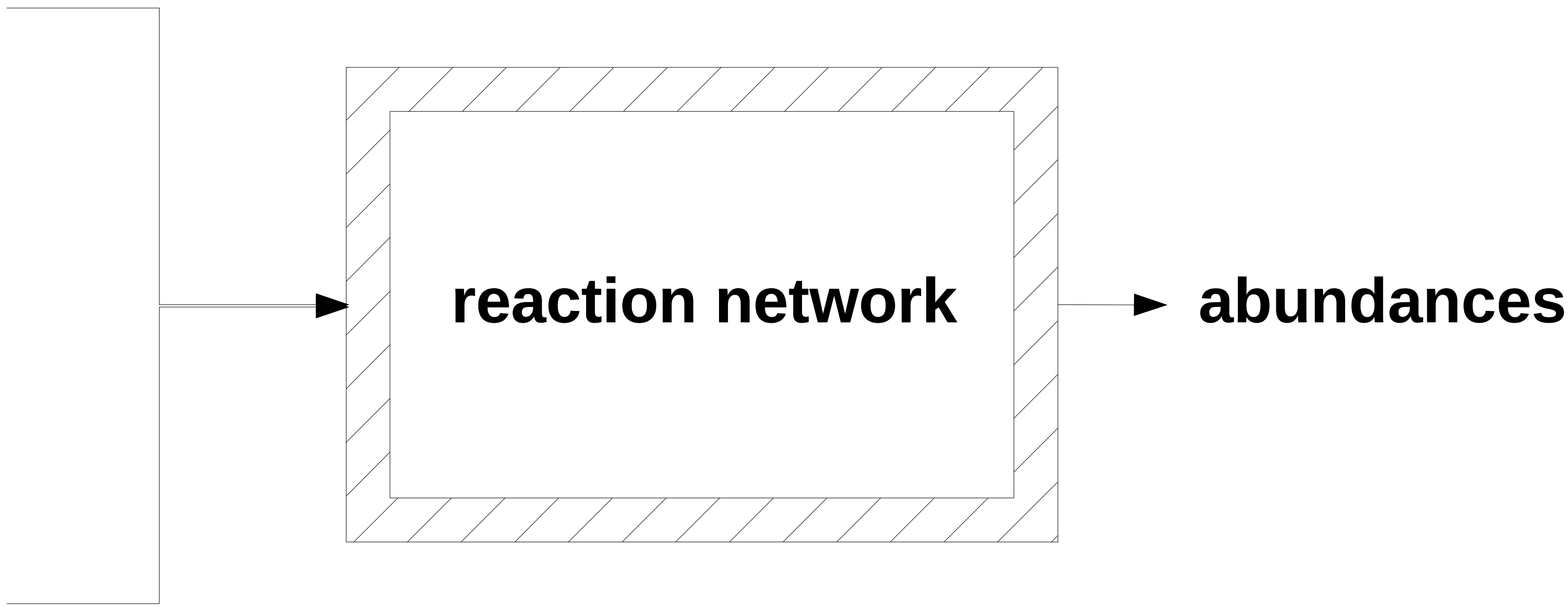
Isotopic abundances



Elemental abundances

r-Process Calculations Need

nuclear physics inputs
(Sn, β-rates, n-cap rates, …)

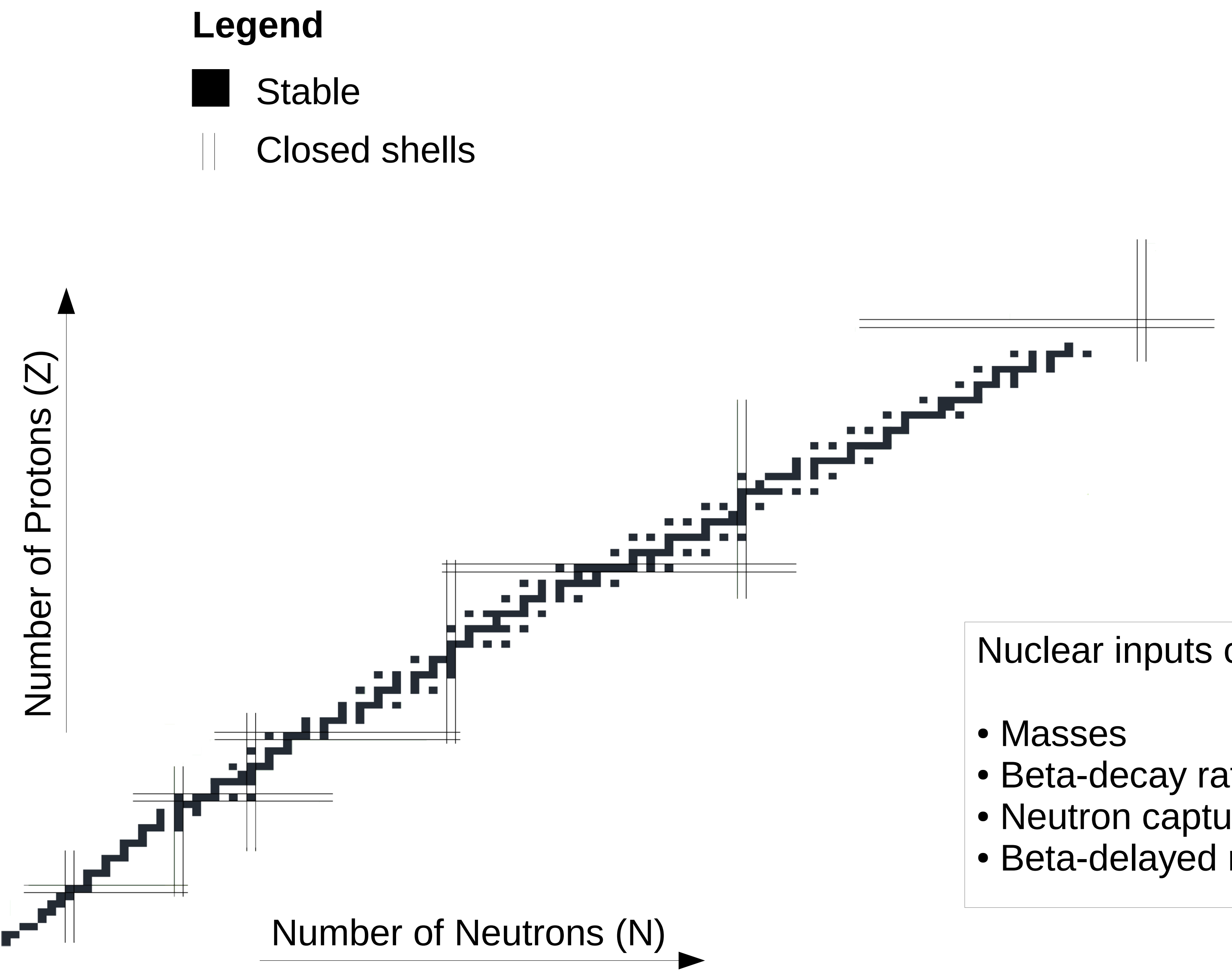


Environment conditions

(temperature, density, ...)

Nuclear Data

The Nuclear Chart

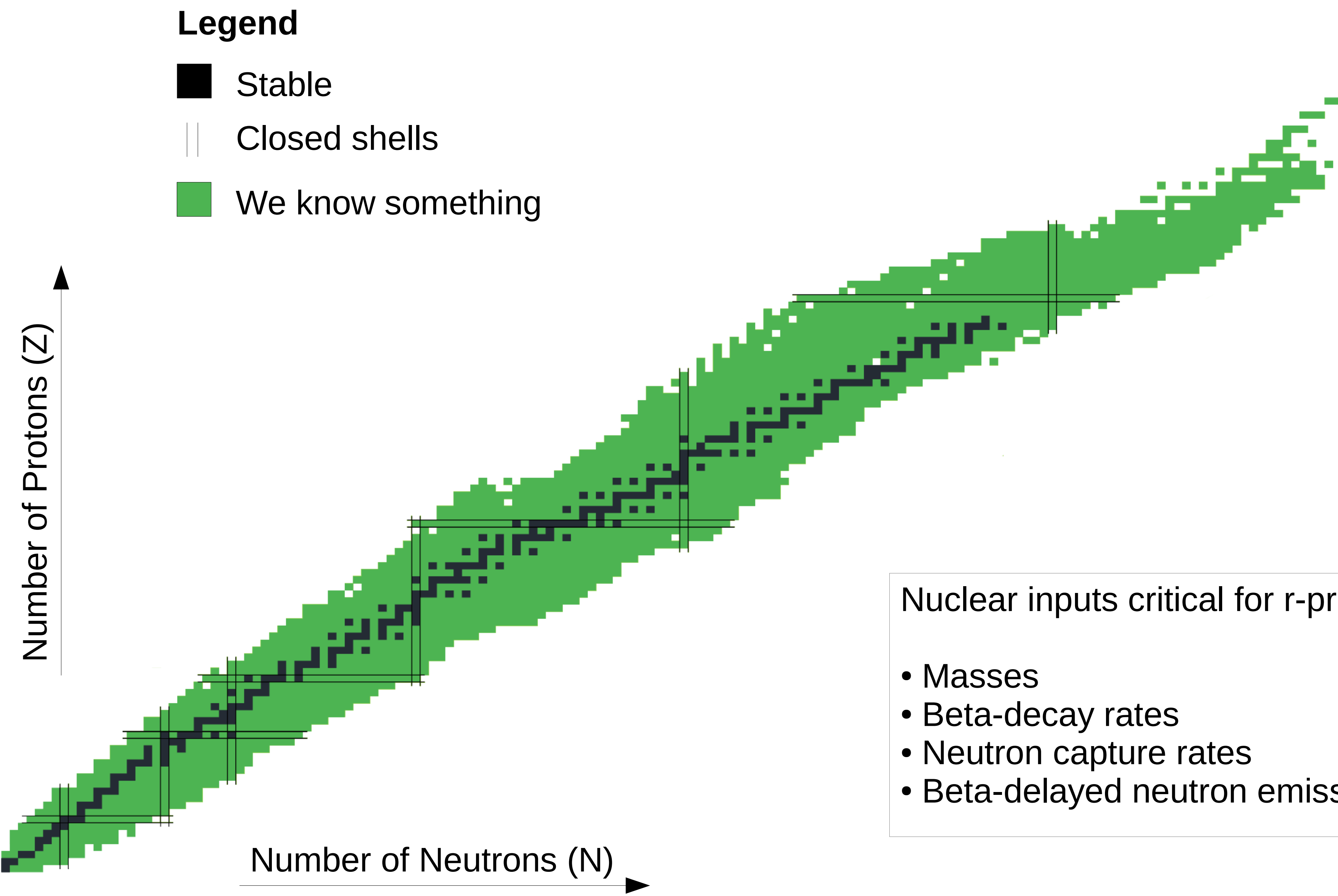


Nuclear inputs critical for r-process

- Masses
- Beta-decay rates
- Neutron capture rates
- Beta-delayed neutron emission

Nuclear Data

What Do We Know?

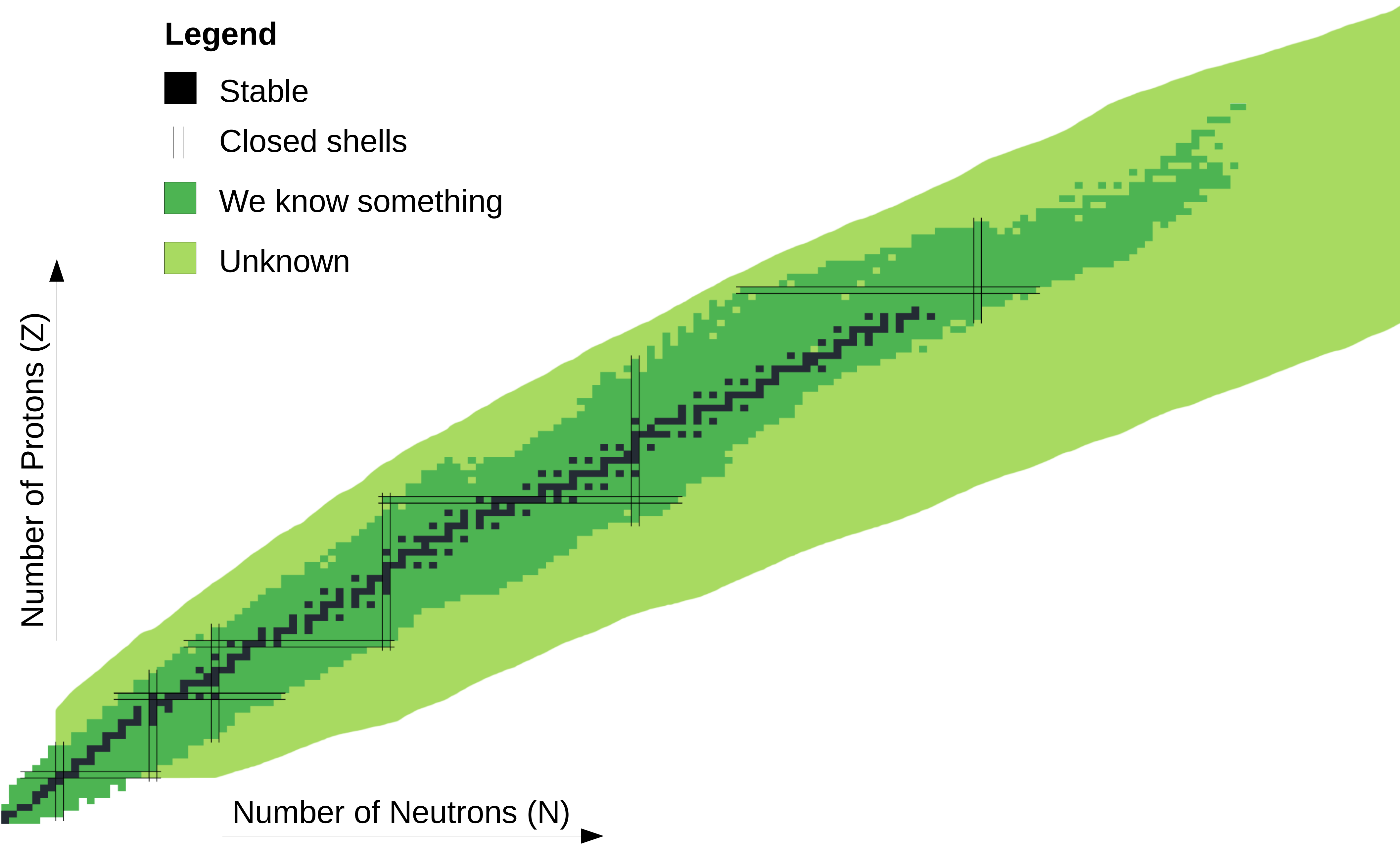


Nuclear inputs critical for r-process

- Masses
- Beta-decay rates
- Neutron capture rates
- Beta-delayed neutron emission

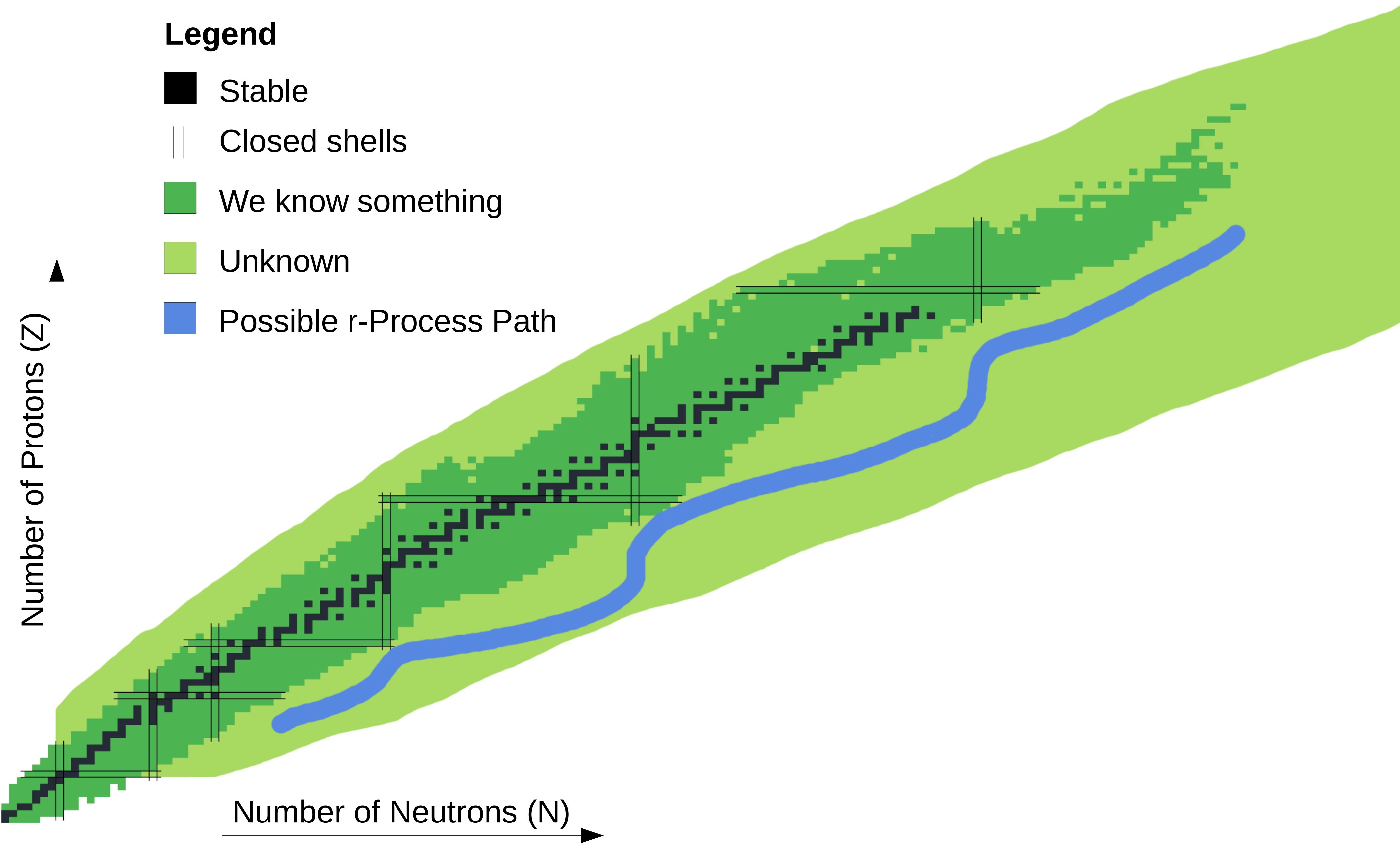
Nuclear Data

What We Don't Know



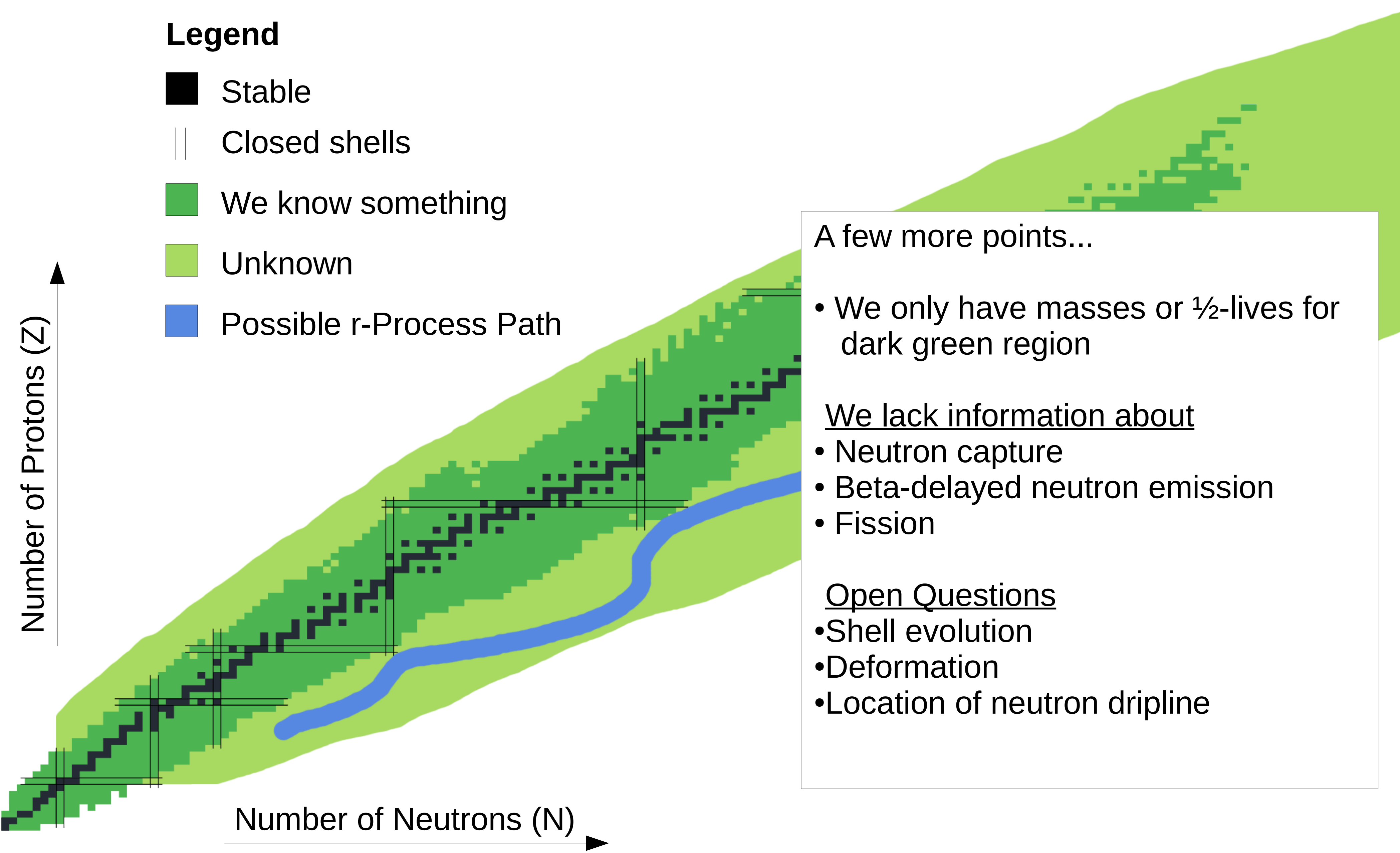
Nuclear Data

Possible r-Process Path



Nuclear Data

Possible r-Process Path



A few more points...

- We only have masses or ½-lives for dark green region

<u>We lack information about</u>

- Neutron capture
- Beta-delayed neutron emission
- Fission

<u>Open Questions</u>

- Shell evolution
- Deformation
- Location of neutron dripline

Sensitivity Studies Tell Us What Is Important

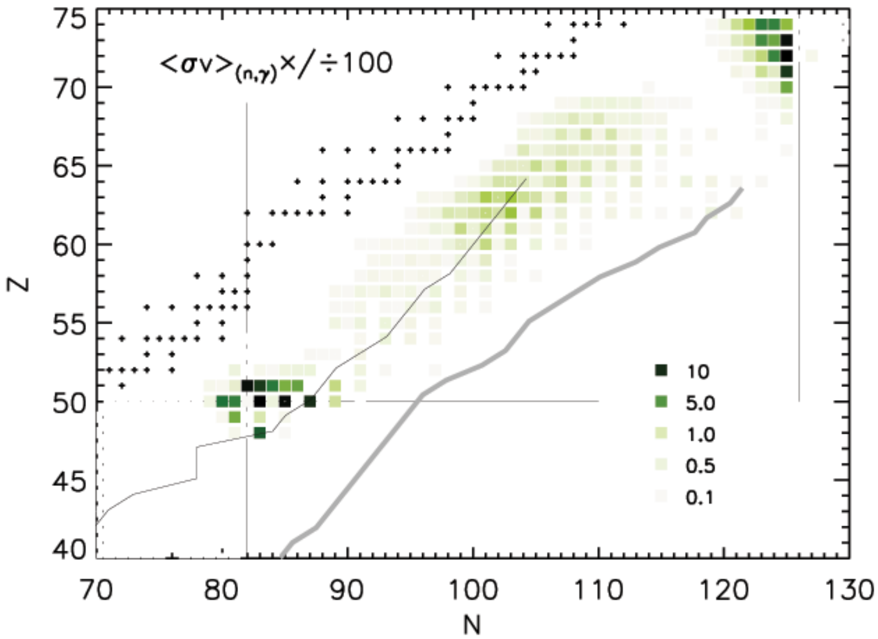
- How do abundances change with change in nuclear inputs?
- Baseline simulation – fix conditions & nuclear physics models
- Modified simulation – single nuclear physics input is changed
- Measure change by comparing differences in final composition:

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

where $$X(A) = AY(A)$$ Mass fraction (X) ↔ abundance (Y)

$$\sum_A X(A) = 1$$ Mass conservation

Hot Wind Sensitivity Study Results



Neutron Capture Rates

Mumpower et al PRC (2012)
Surman, Mumpower et al CGS-14 (2013)
Surman, Mumpower et al AIP Stardust (2014)

Individual rates determine:

How material moves to stability

Where remaining free neutrons are captured

The details of the final abundances

Important during freeze-out

once (n,γ)↔(γ,n) breaks

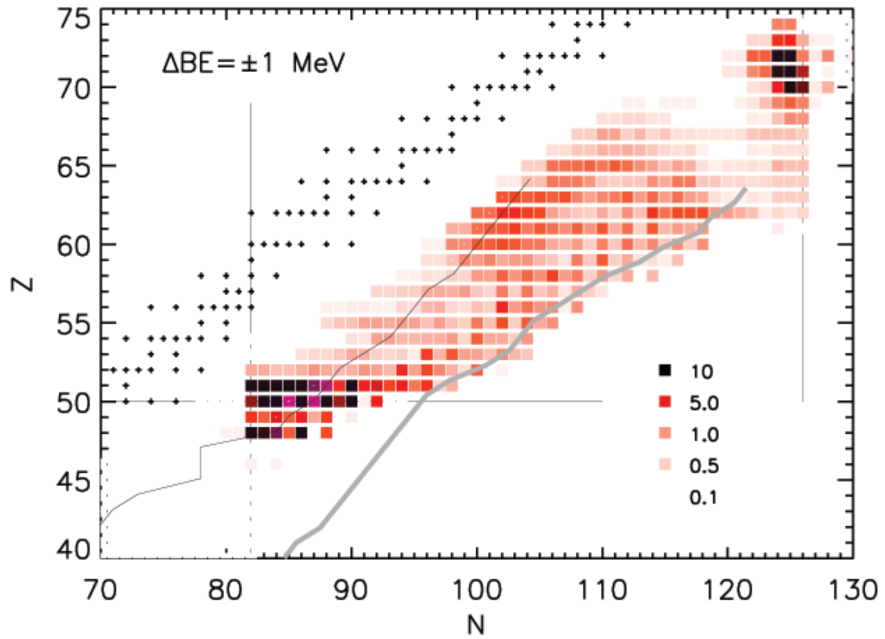
Accessibility Limits — CARIBU — Predicted FRIB

Hot Wind Sensitivity Study Results

Binding / Separation Energy

Brett et al. EPJA (2013)

Aprahamian et al. AIP Stardust (2014)



Contributes to calculation of (γ,n)-rate (detailed balance)

Mass surface defines the path during equilibrium

Kinks in mass surface can cause features in final abundances

Important during

(n,γ)↔(γ,n) equilibrium
&
freeze-out

Accessibility Limits — CARIBU — Predicted FRIB

Hot Wind Sensitivity Study Results

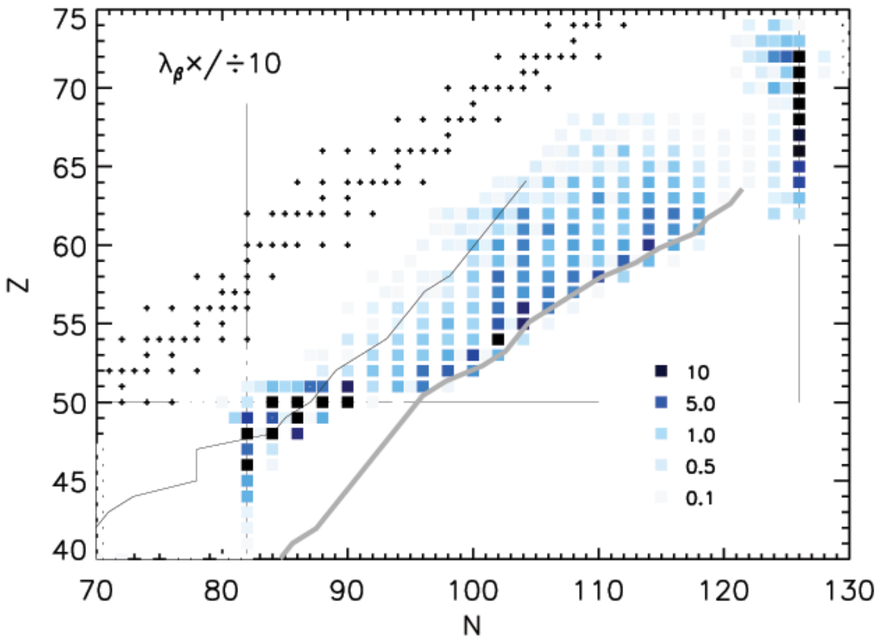
Beta-decay Rates

Surman, Mumpower, et al. ICFN5 (2013)

Mumpower et al. AIP Stardust(2014)

Important during

all stages of the r-process



Sets timescale for heavy element production

Slow rates (waiting points) build up material

Rates are particularly important at closed shells (A=130 / A=190) and rare earth peak (A~160 or N~104)

Accessibility Limits — CARIBU — Predicted FRIB

Hot Wind Sensitivity Study Results

Beta-delayed Neutron Emission

Mumpower & Surman (in prep)

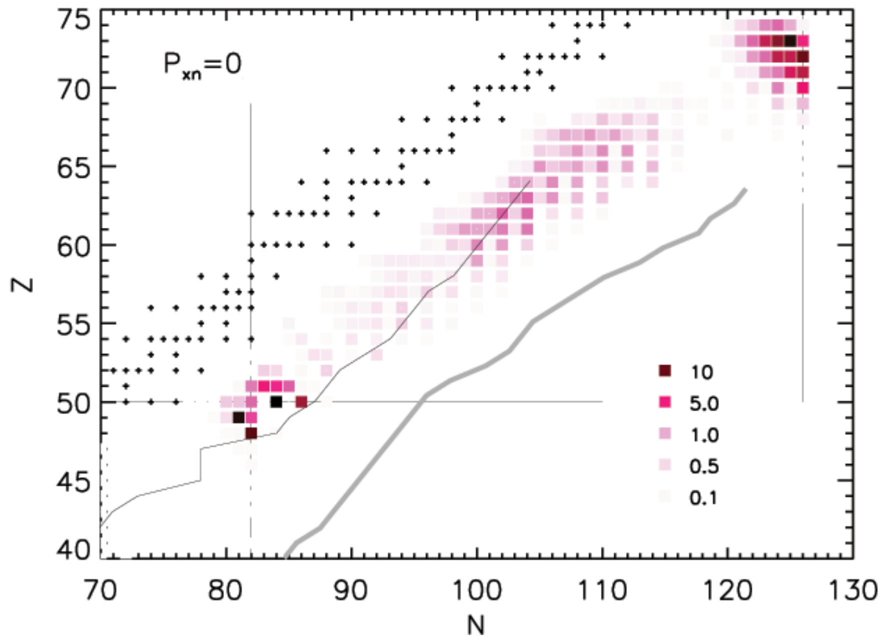
Important primarily during

freeze-out

Provides additional neutrons for capture during freeze-out

Along with neutron capture it determines the fine details of the abundance patterns (smoothing?)

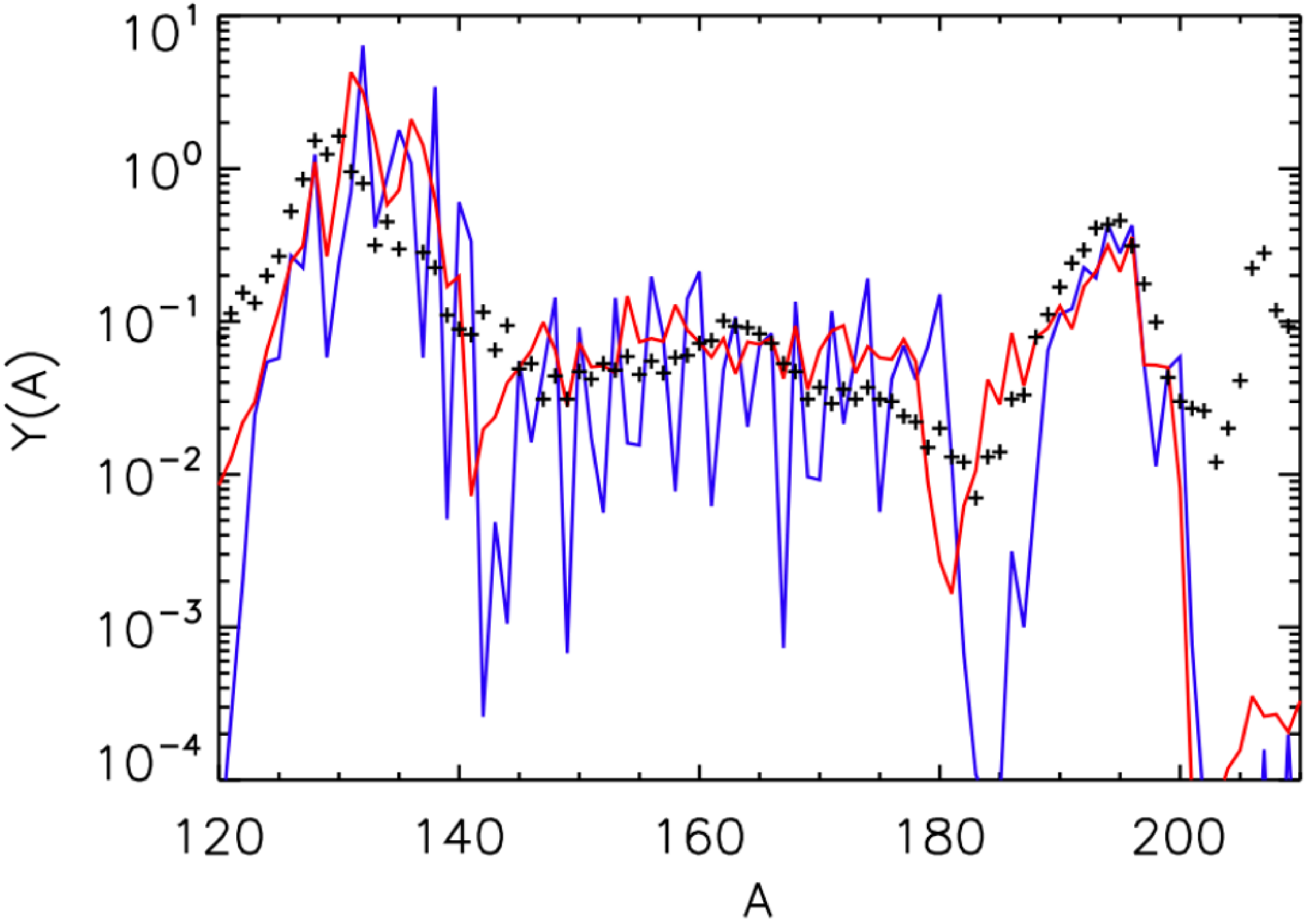
Rates are particularly important at closed shells (A=130 / A=190) and rare earth region (A~160)



Accessibility Limits — CARIBU — Predicted FRIB

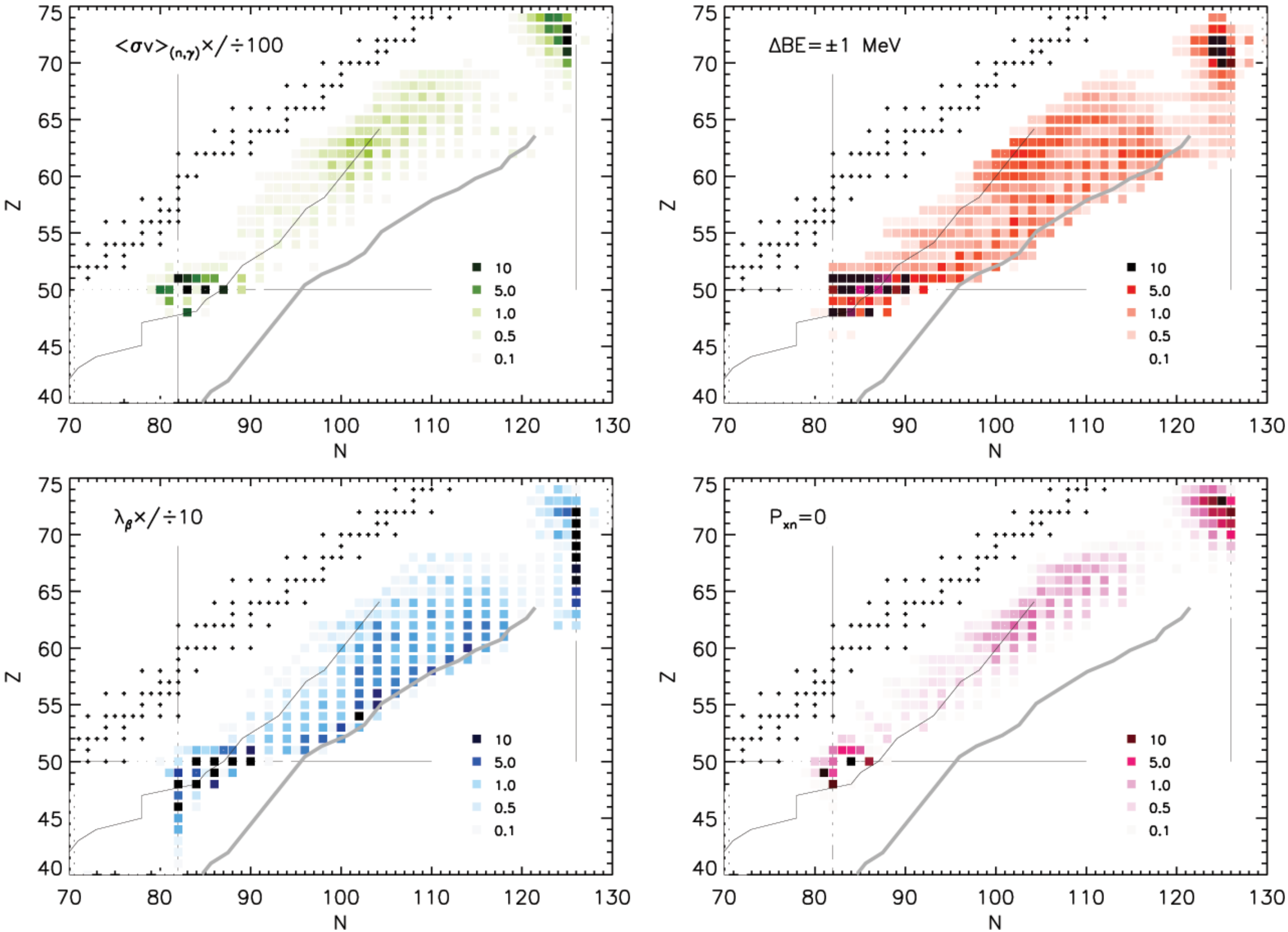
Beta-delayed Neutron Emission Probabilities

Turned on vs Turned off



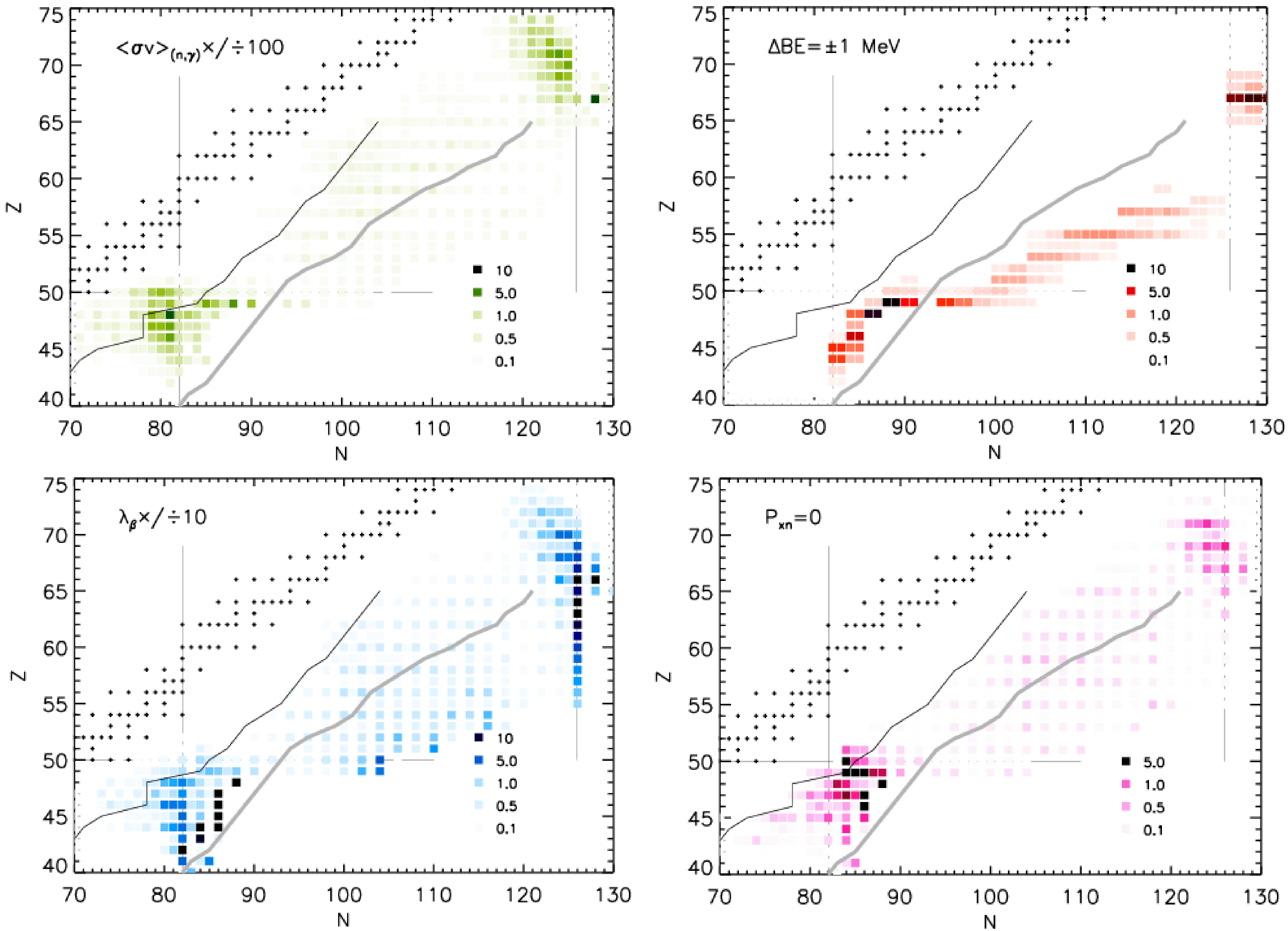
Mumpower & Surman in prep.

Wind r-Process Sensitivity Study Results



Accessibility Limits CARIBU Predicted FRIB

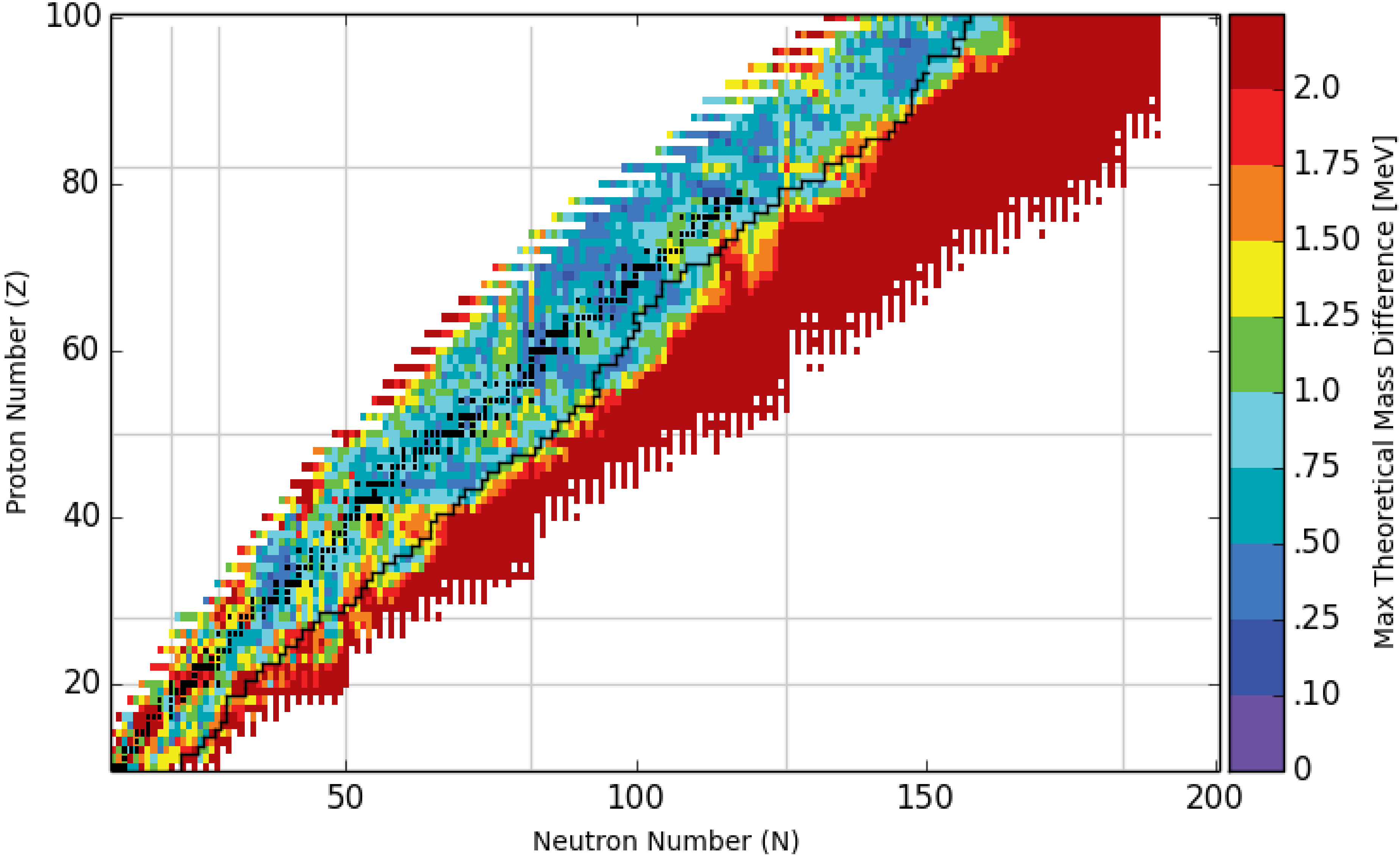
NSM Sensitivity Study Results



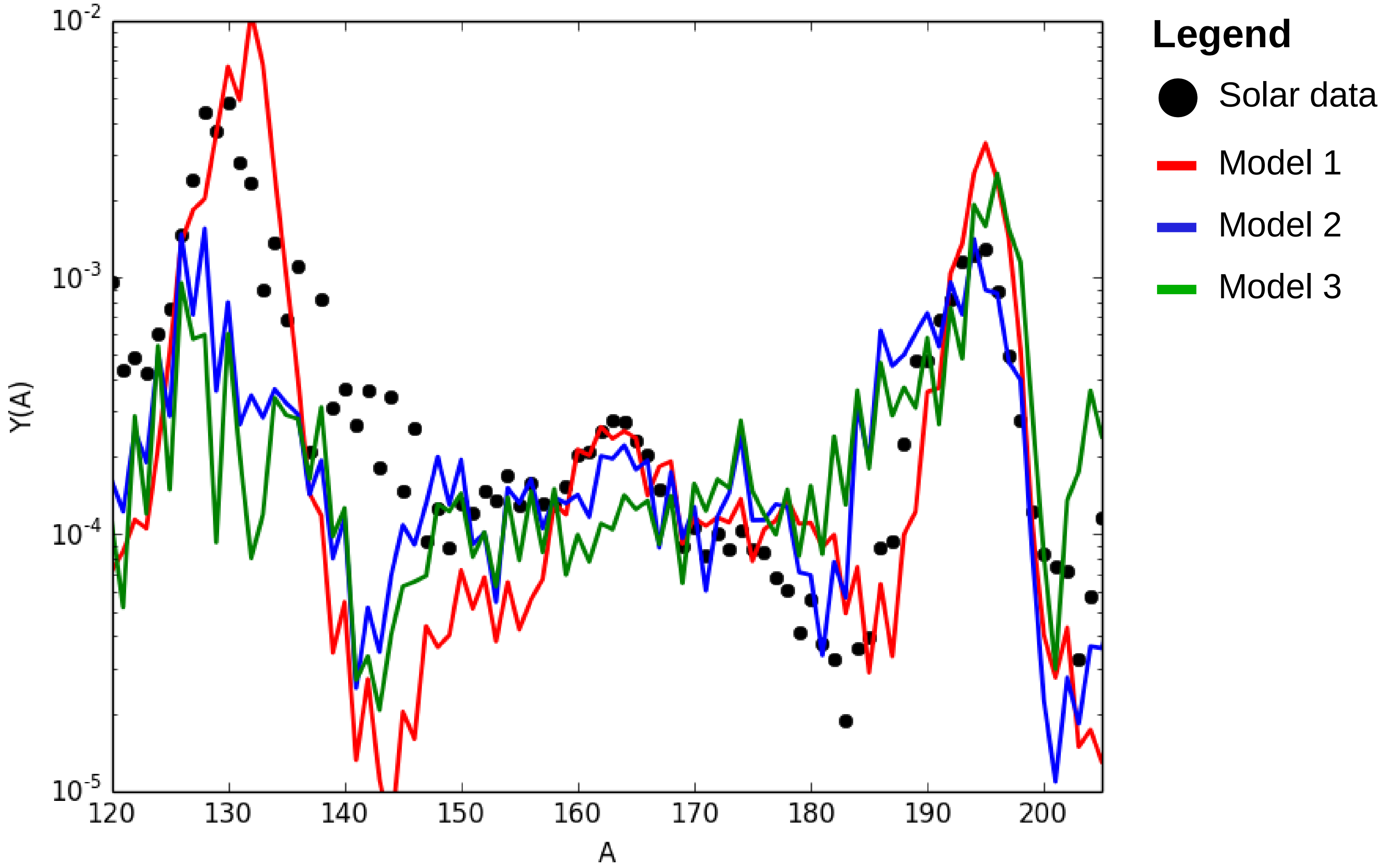
Accessibility Limits CARIBU Predicted FRIB

Differences in Mass Model Predictions

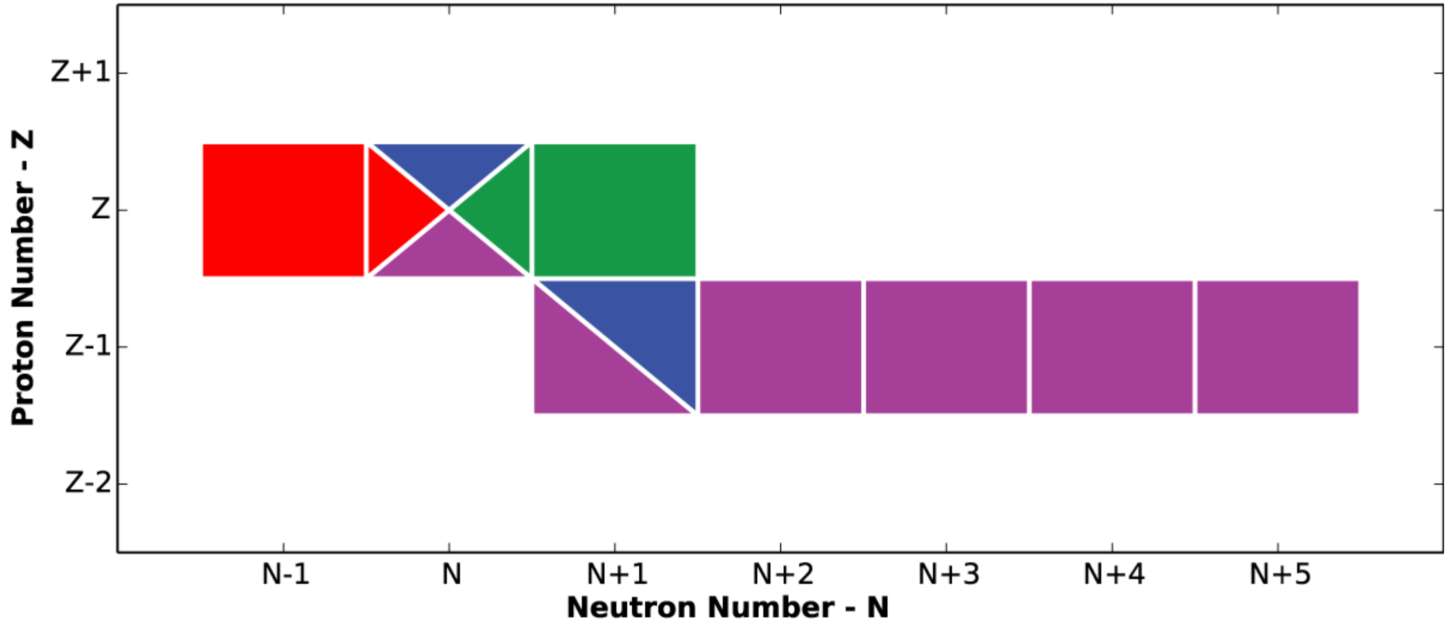
Across The Chart of Nuclides



Impact On *r*-process Abundances



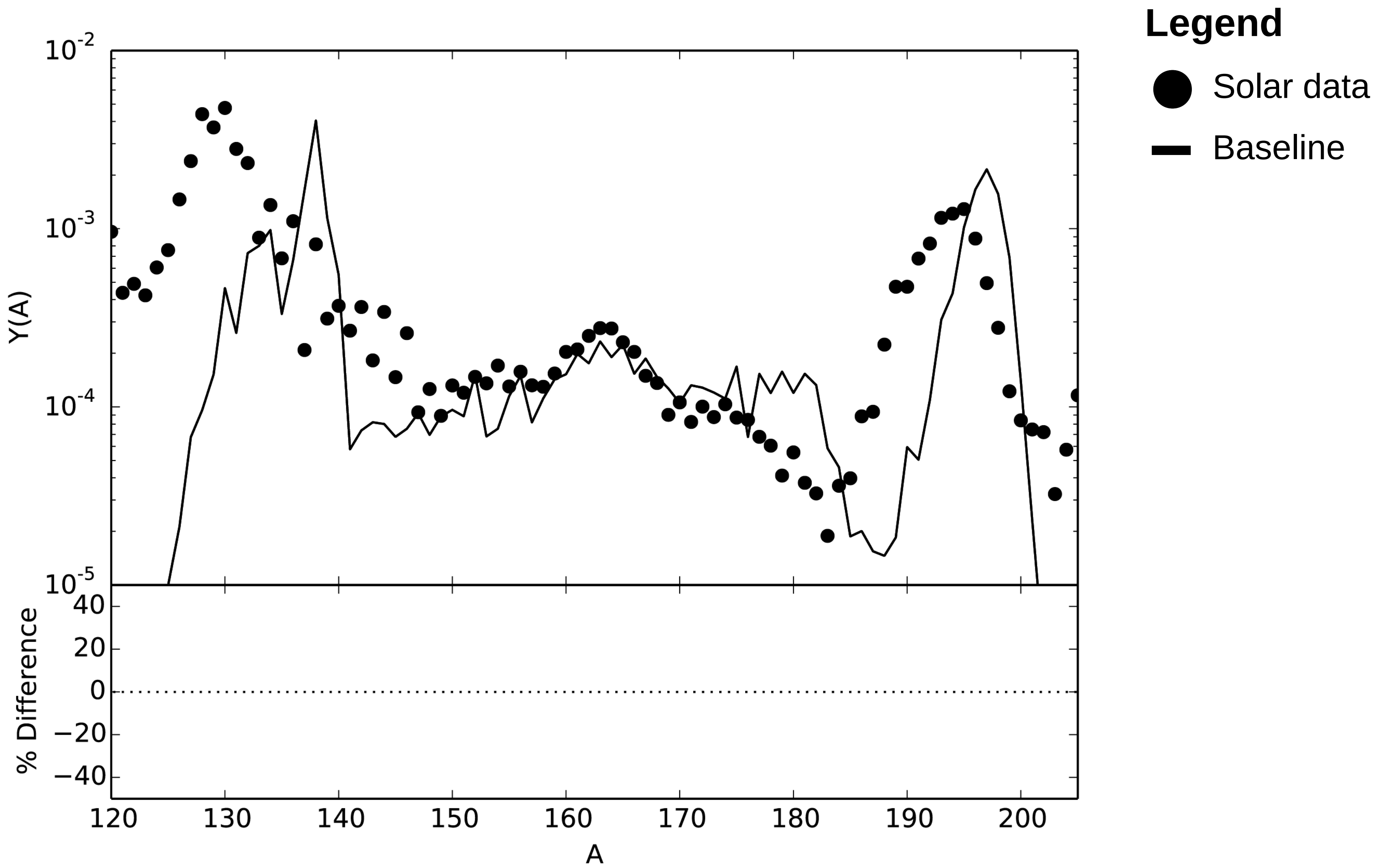
Towards A Mass Sensitivity Study



How do mass uncertainties change final abundances?

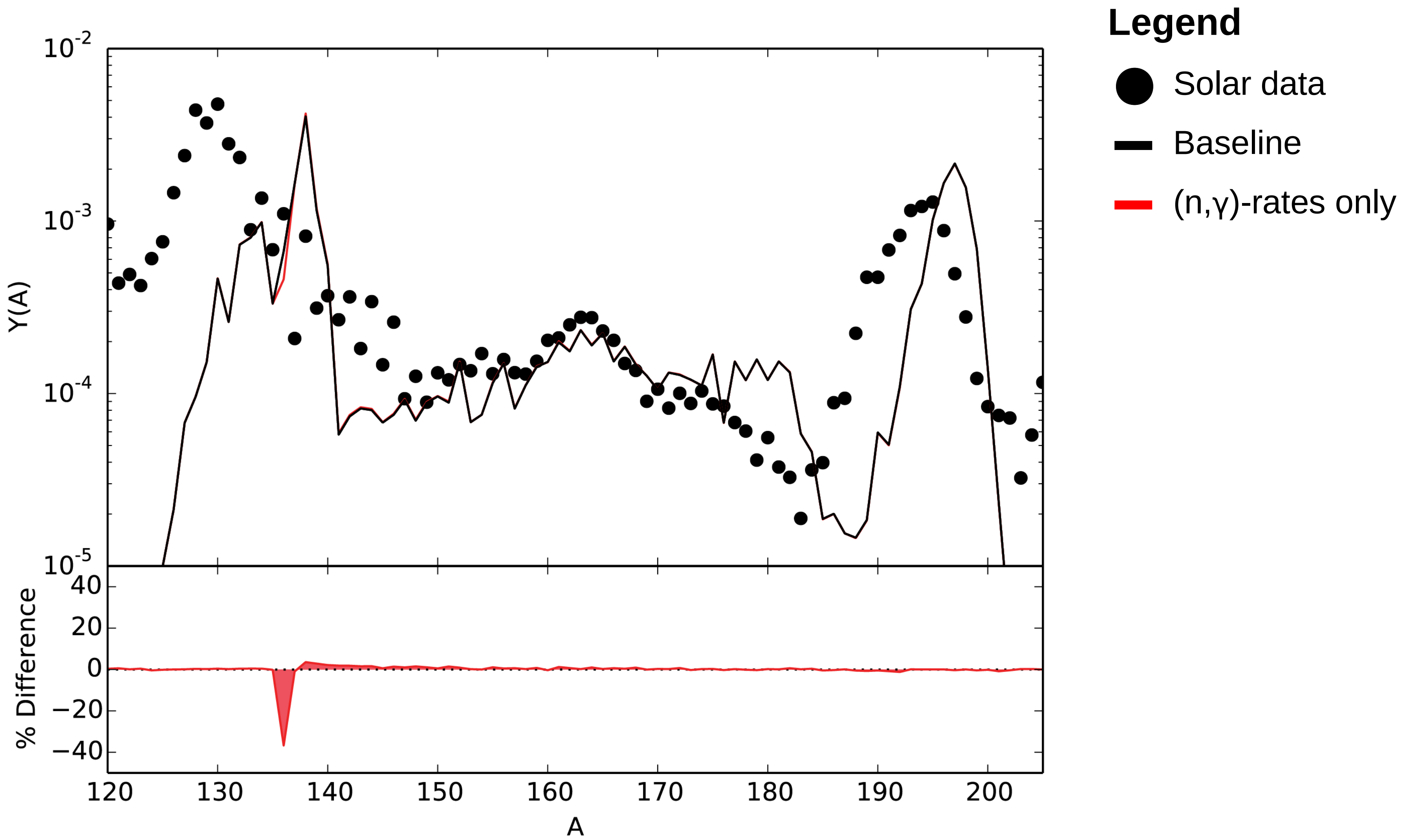
- Neutron separation energies (Z,A) (Z,A+1)
- Neutron capture rates (Z,A) (Z,A-1)
- Beta-decay rates (Z,A) (Z-1,A)
- Beta-delayed n-emission probabilities (Z,A) (Z-1,A) → (Z-1,A+3)

Result: ^{140}Sn (Z=50) +0.5MeV



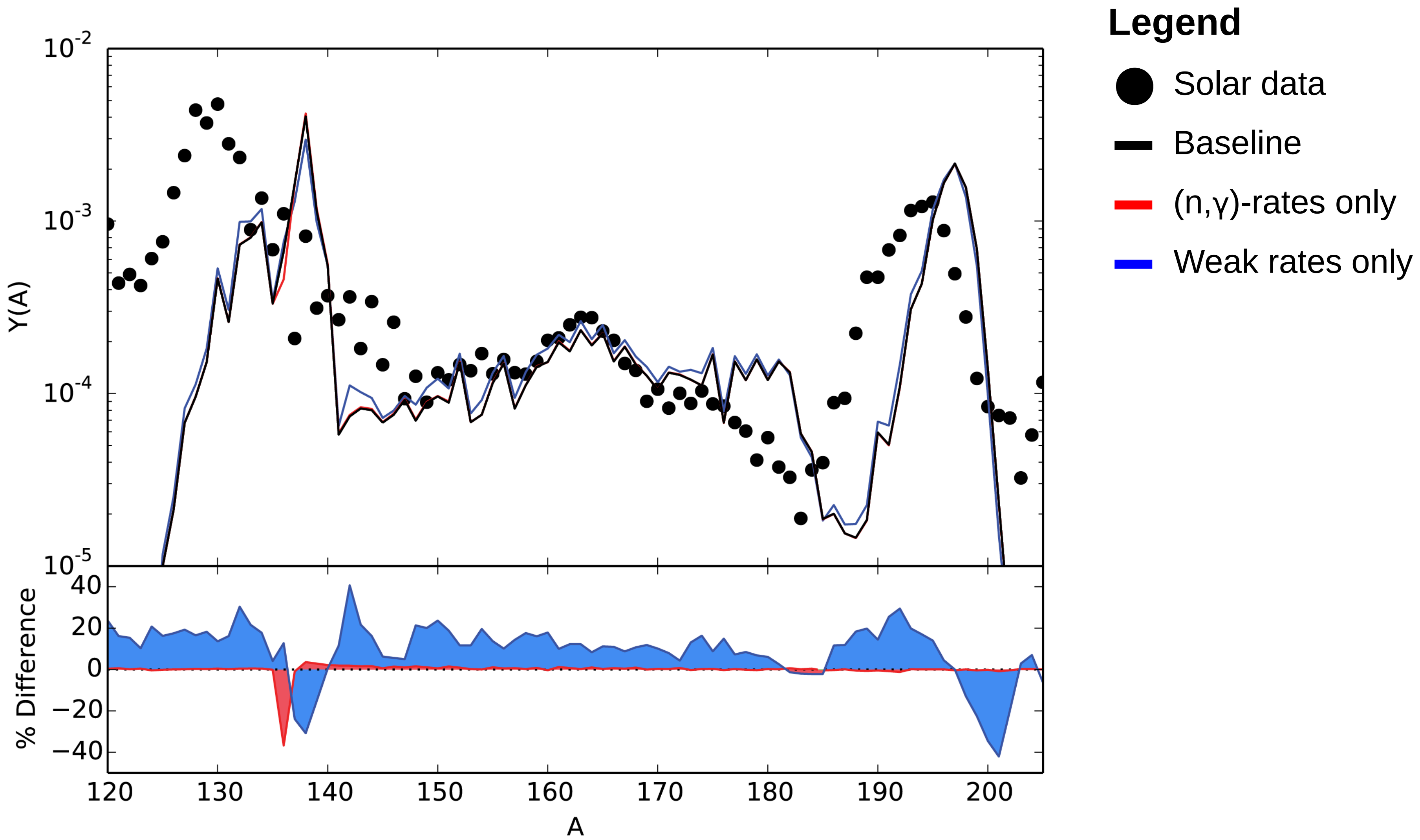
Mumpower et al. (in prep)

^{140}Sn (Z=50) neutron capture rates only



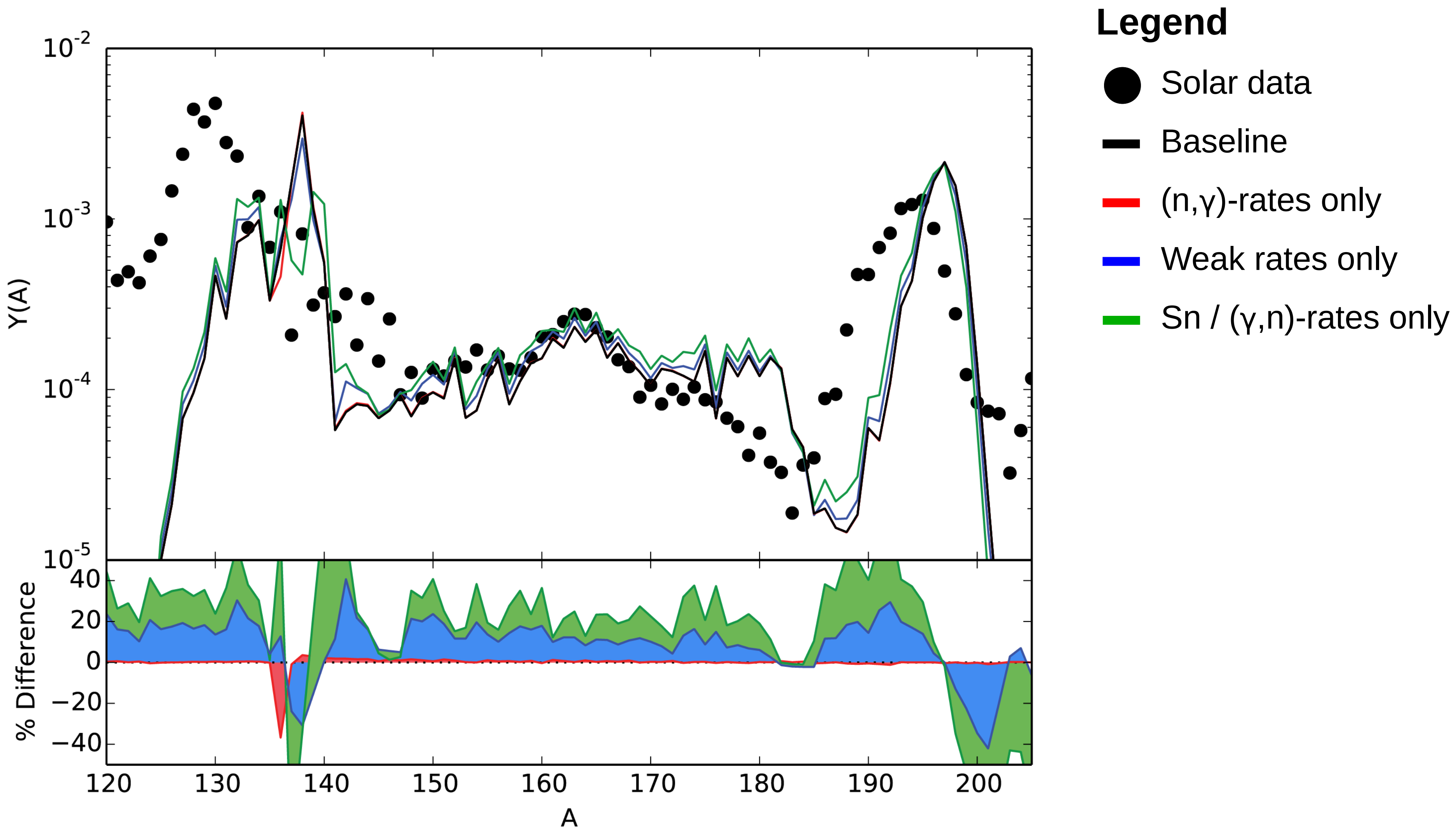
Mumpower et al. (in prep)

^{140}Sn (Z=50) beta-decay only



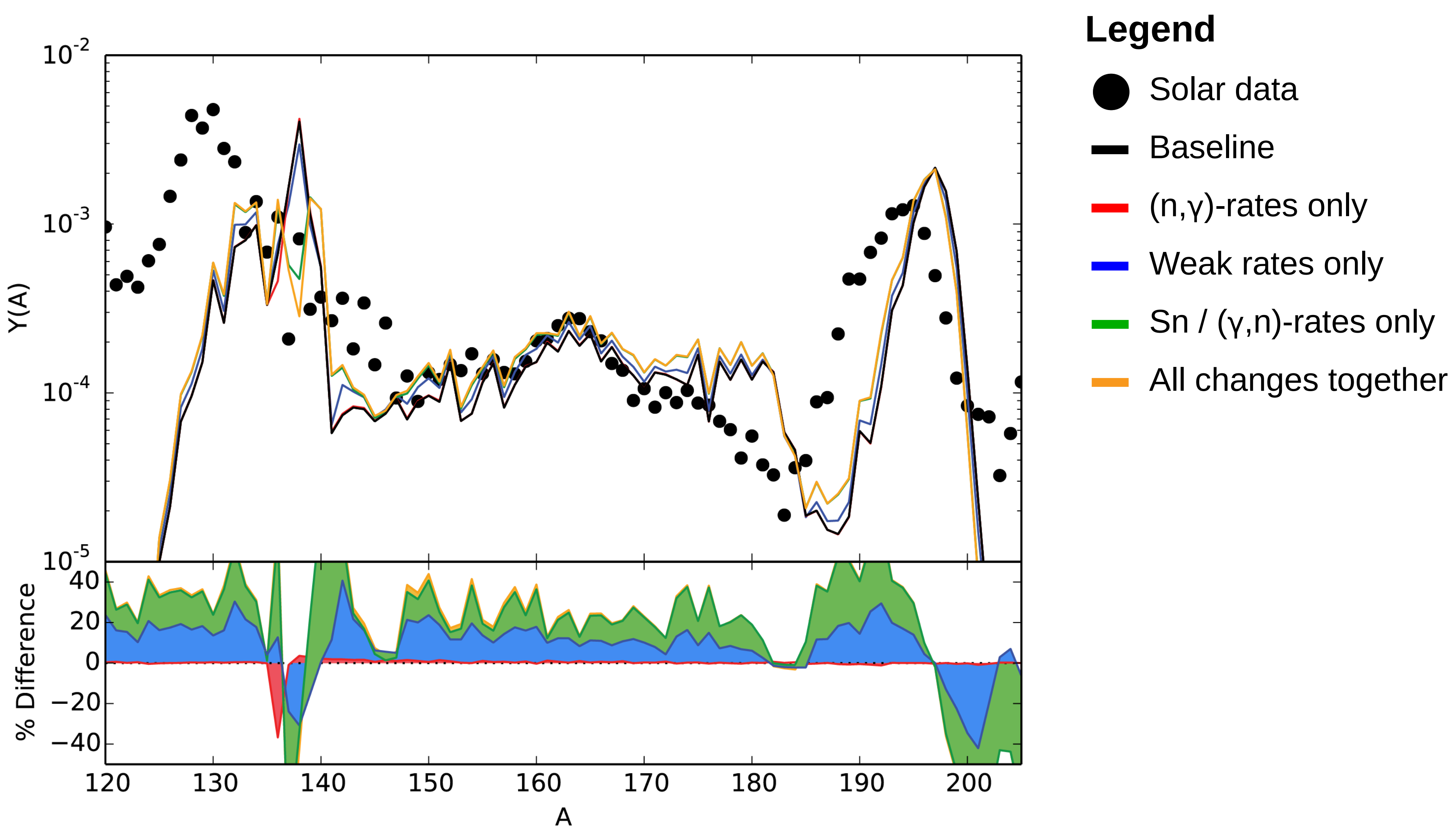
Mumpower et al. (in prep)

^{140}Sn (Z=50) photodissociation rates



Mumpower et al. (in prep)

^{140}Sn (Z=50) All changes together

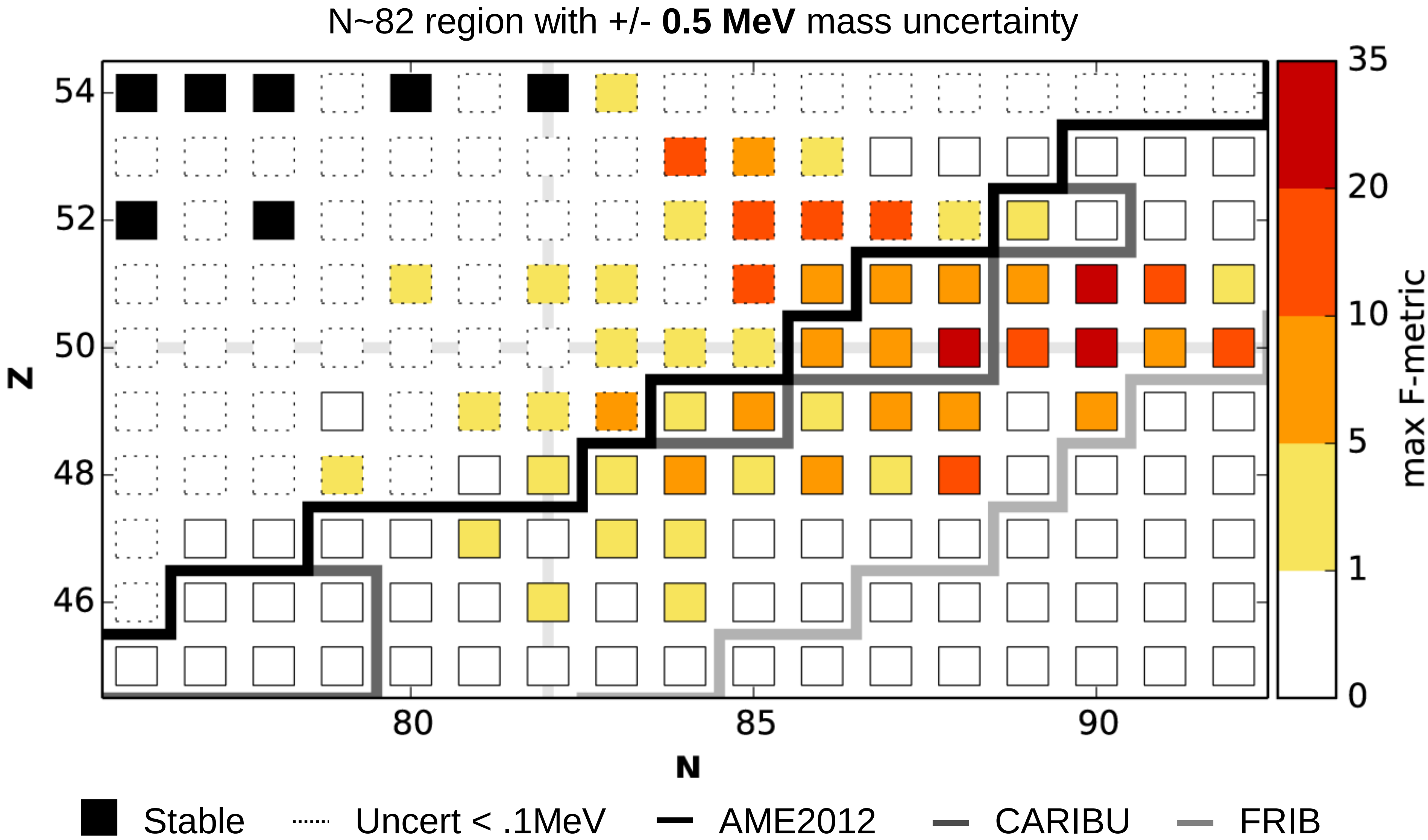


Over an order of magnitude change in the abundance for +**0.5MeV** change in mass of 140-Sn

Mumpower et al. (in prep)

Results of Our Mass Sensitivity Study

Wind *r*-Process

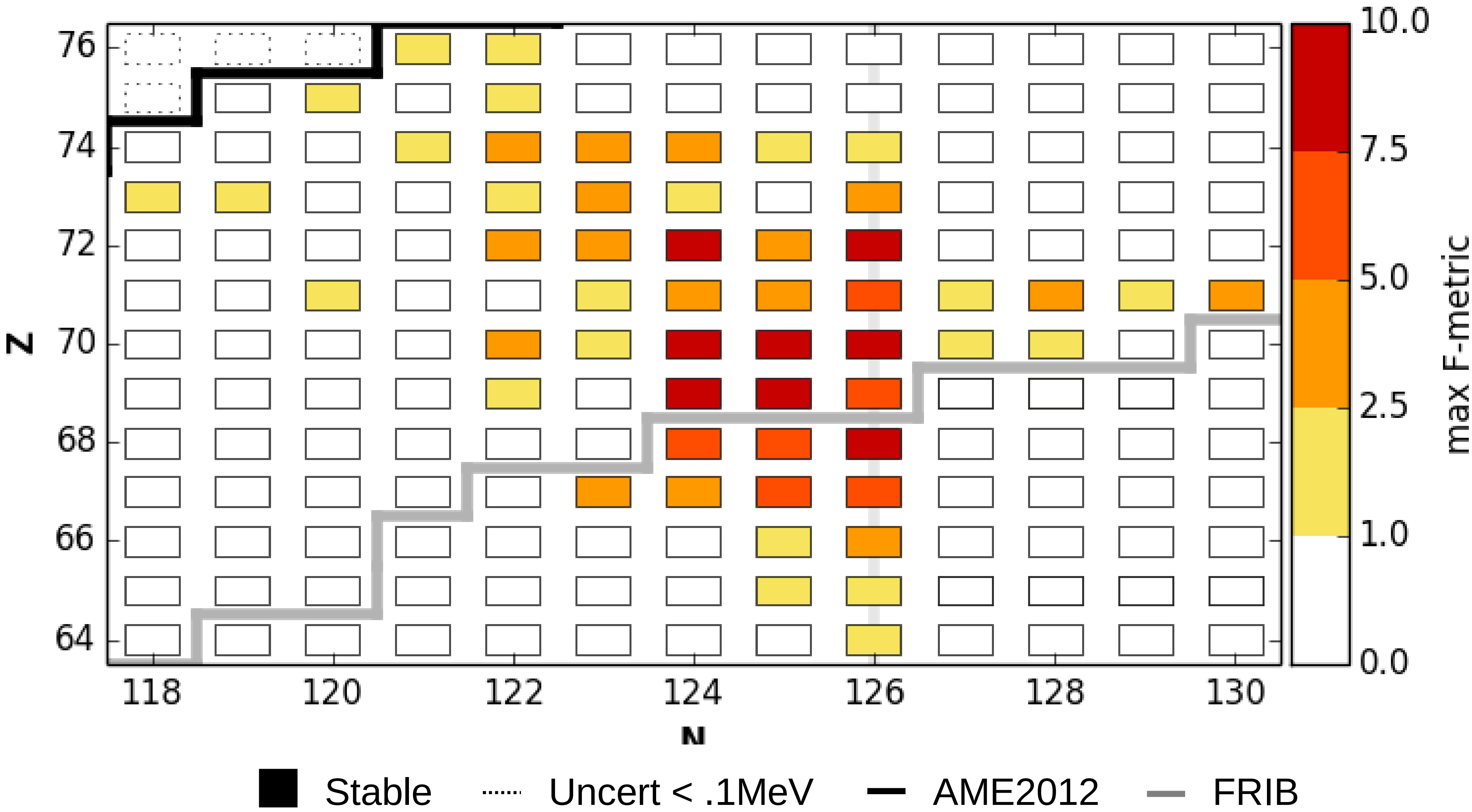


Mumpower et al. (in prep)

Results of Our Mass Sensitivity Study

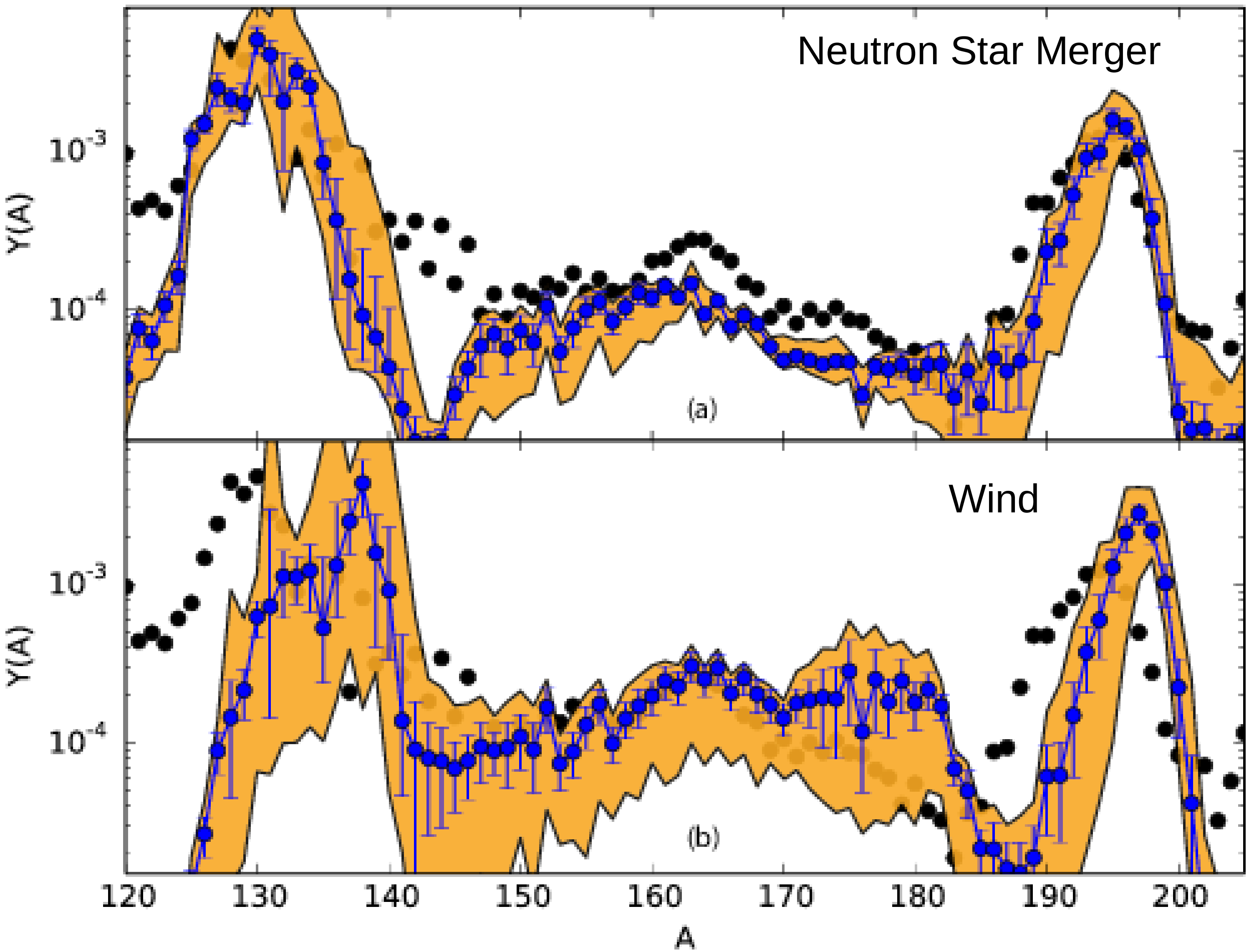
Wind *r*-Process

N~126 region with +/- **1.0 MeV** mass uncertainty



Mumpower et al. (in prep)

Estimated Final Abundances With Uncertainties

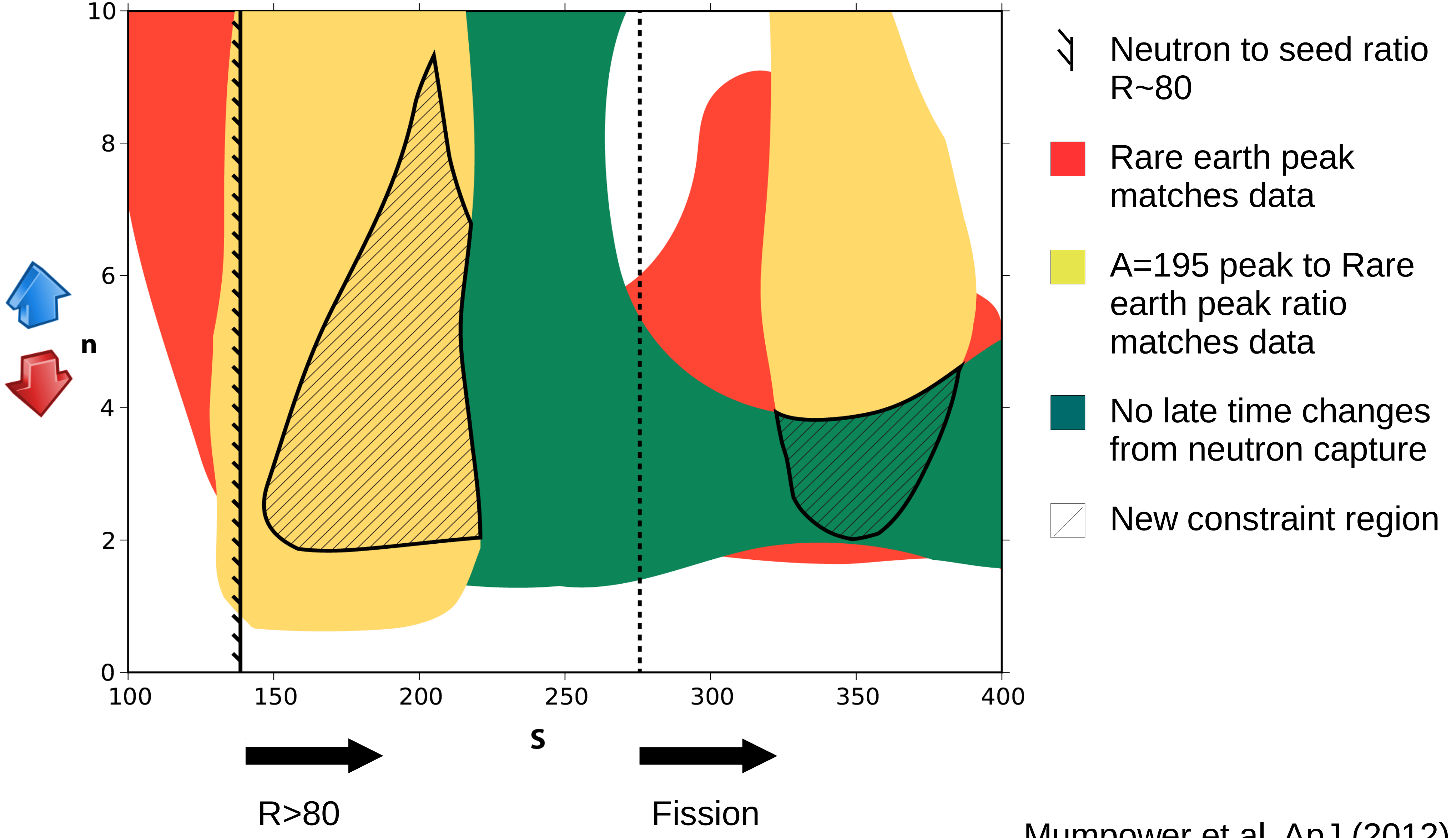


Variations in masses of N~82 and N~126 nuclei of +/- 1 MeV

Mumpower et al. (in prep)

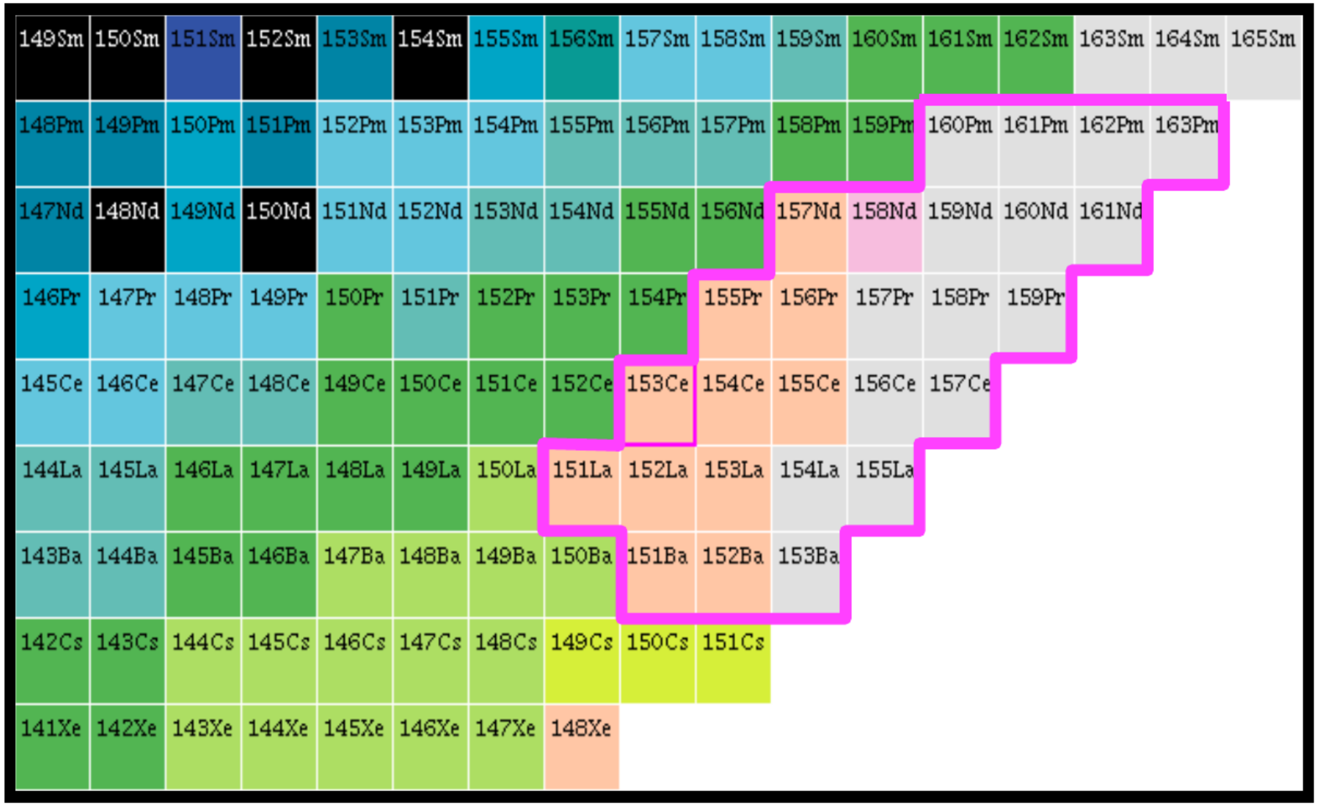
Why Are New Measurements Important?

Can be used to constrain r-process site e.g. rare earth peak



Mumpower et al. ApJ (2012)

Insight From New Measurements



In total over **40** new beta-decay half-lives measured @ RIKEN!

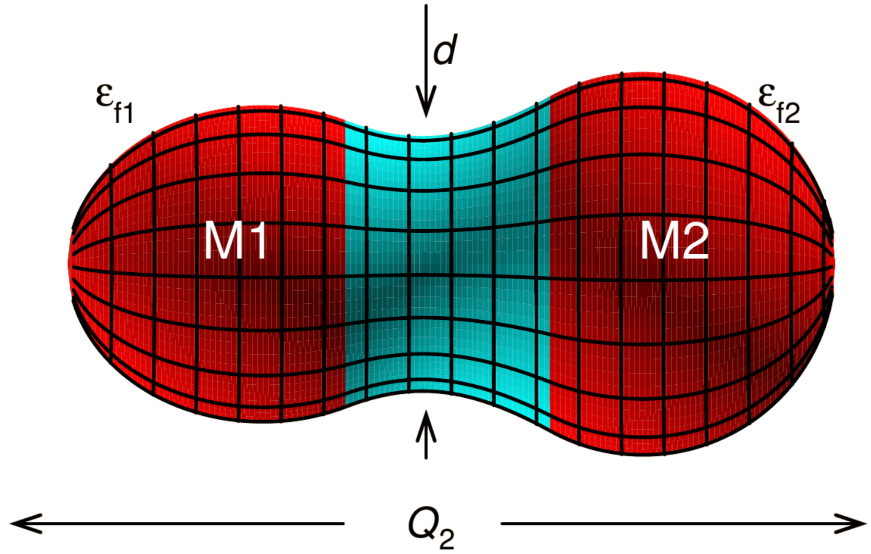
Preliminary hints at deformed sub-shell closure around N~100

Jin Wu et al. in preparation (2014)

Summary & Outlook

- *Individual* nuclear physics inputs can be critical for calculations of *r*-process nucleosynthesis.
- Masses impact Q-values and calculations of half-lives, reaction rates and the properties of fission.
- We don't need to measure 'everything' but we do need to understand how trends evolve with neutron excess.
- Improved nuclear models will help to strengthen our knowledge of freeze-out and narrow down the uncertainty in the site(s) of the *r* process.

Fission Model



Grid Size	Parameter	Definition
45	Q_2	Elongation (fission direction)
35	α_g	(M1-M2)/(M1+M2) Mass asymmetry
15	ε_{f1}	Left fragment deformation
15	ε_{f2}	Right fragment deformation
15	d	Neck
Total		5,009,235 grid points

Figure by Peter Moller

Fission Barrier Height Calculations

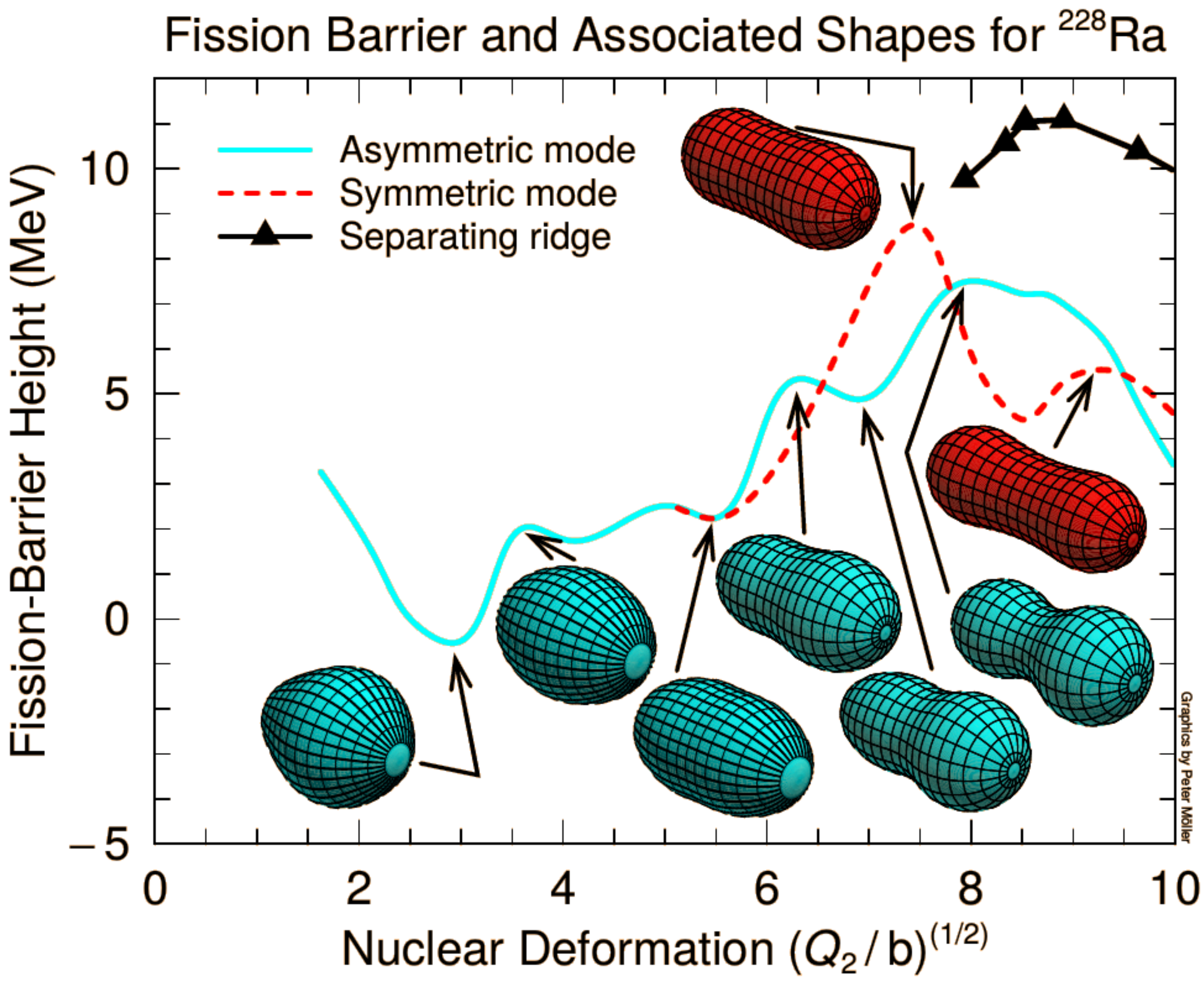
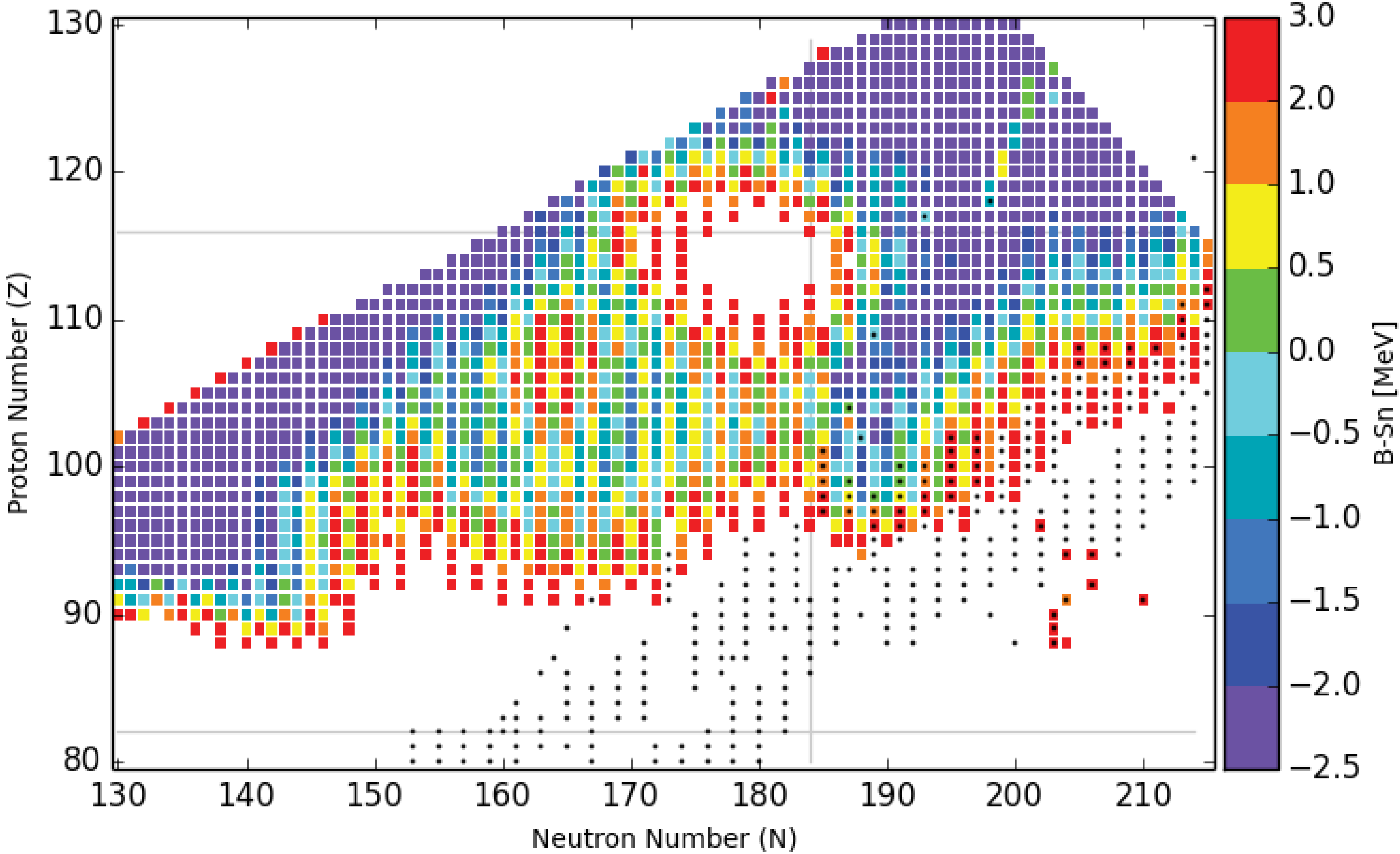


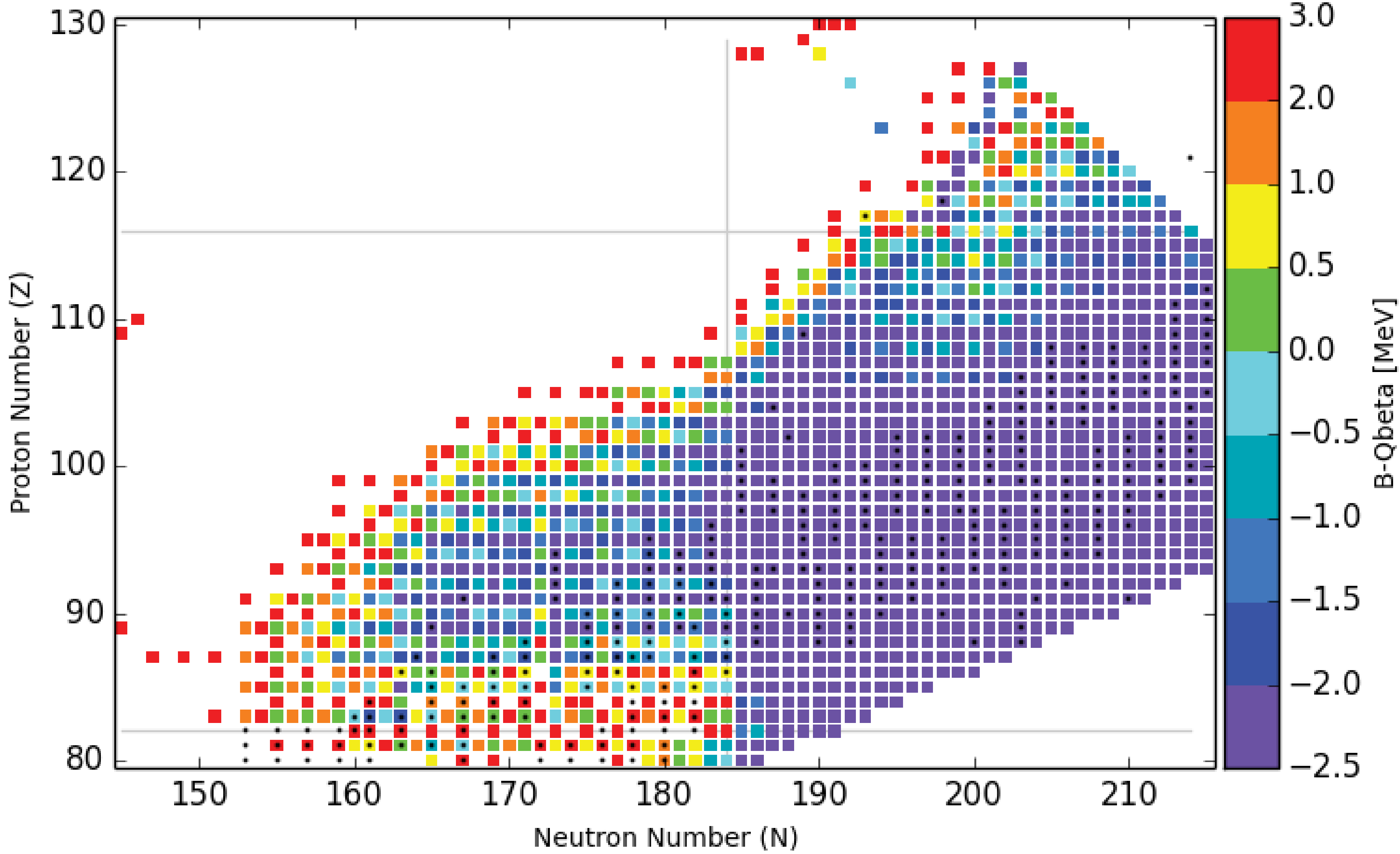
Figure by Peter Moller

New Fission Barrier Heights



Moller, … , Mumpower submitted (2014)

New Fission Barrier Heights



Moller, … , Mumpower submitted (2014)