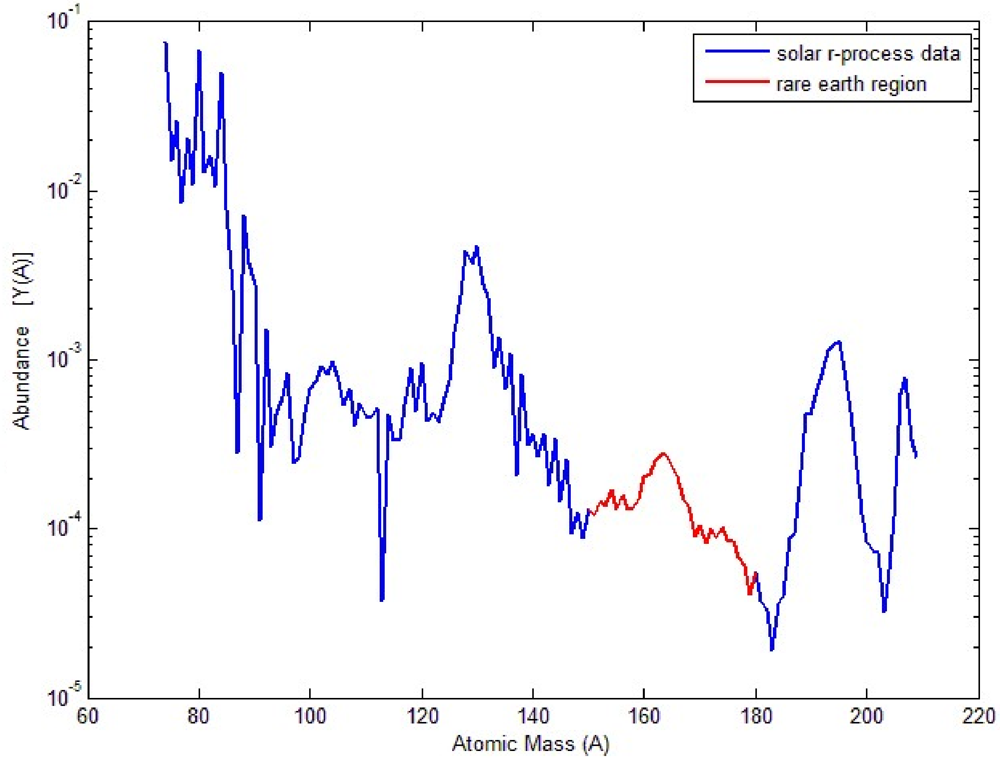
The Rare Earth Peak: An Overlooked *r*-Process Diagnostic



Matthew Mumpower

Gail McLaughlin, Rebecca Surman

Saturday August 4th 2012

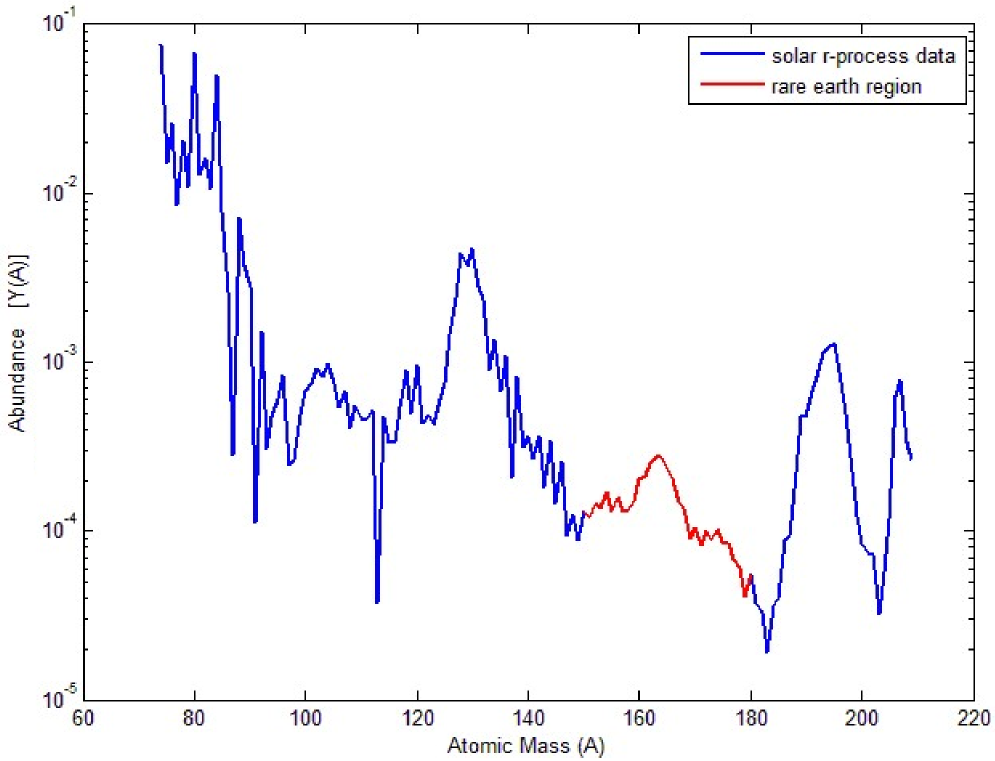
NIC XII *r*-Process Workshop

NCSU Astrophysics

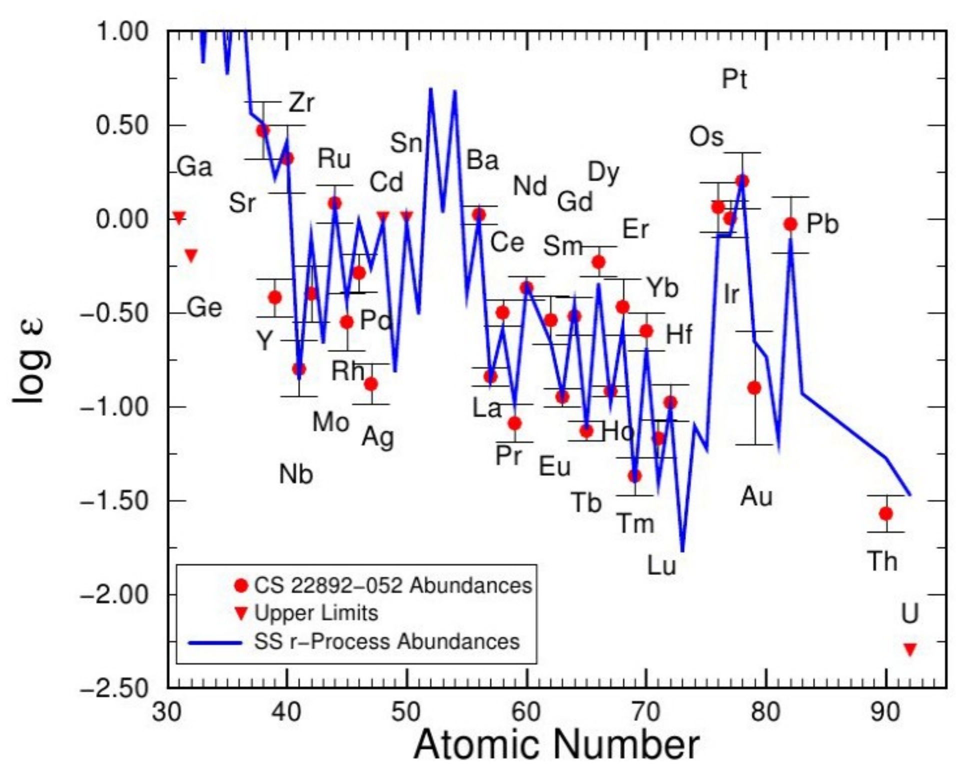
r-Process Data

Solar r-process residuals (meteoritic data)

Halo stars (observational data)



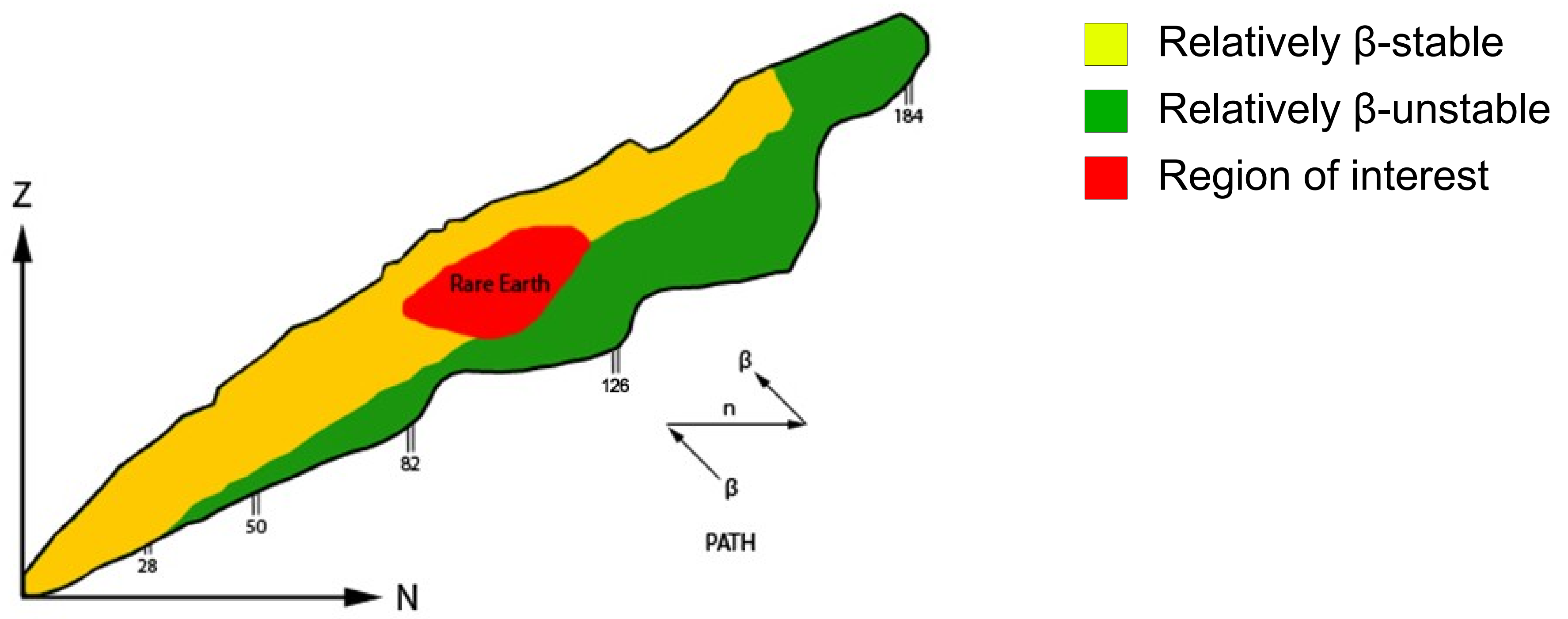
Isotopic abundances



Elemental abundances

Importance Of The Rare Earth Region

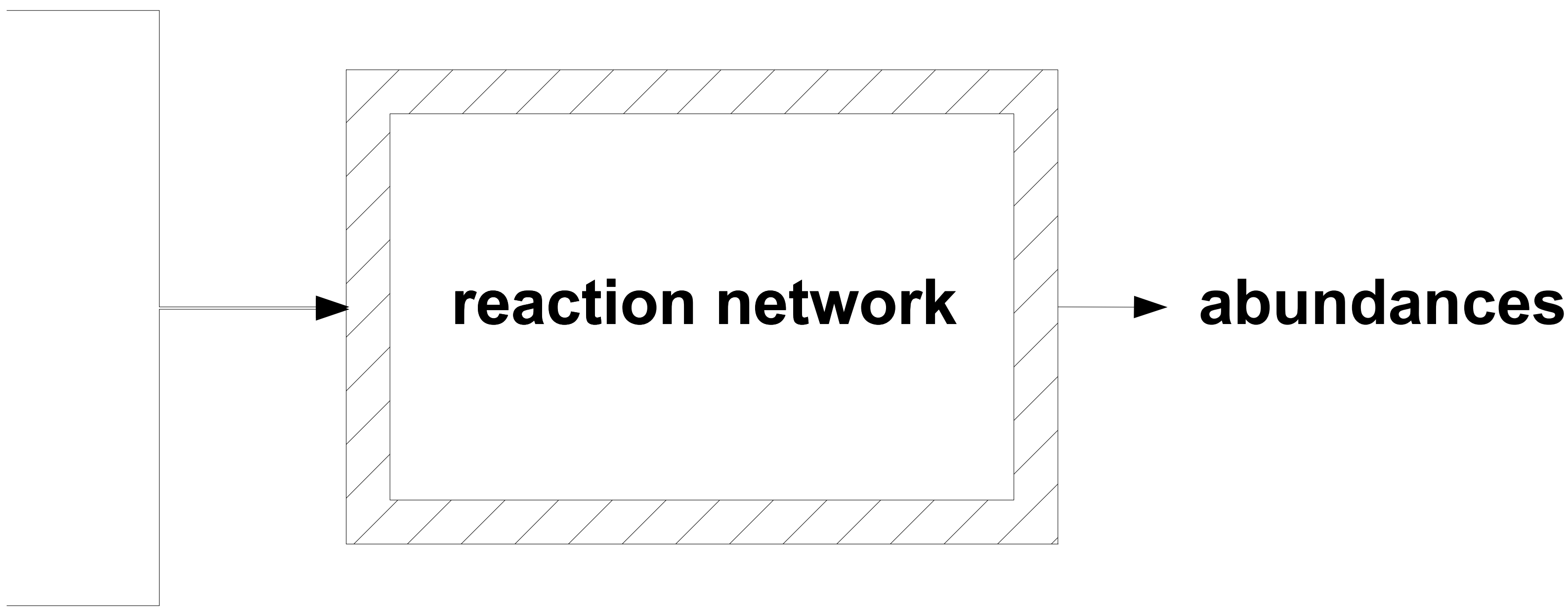
- Peak forms away from closed shells
- Thus, by a different mechanism than A=130, A=195 peaks
- Region forms at late times (low R) during the *r*-process
- Thus, sensitive to **nuclear physics inputs**
- And, **thermodynamic conditions**



A Simple *r*-Process Calculation

nuclear physics inputs

(Sn, β-rates, n-cap rates, …)



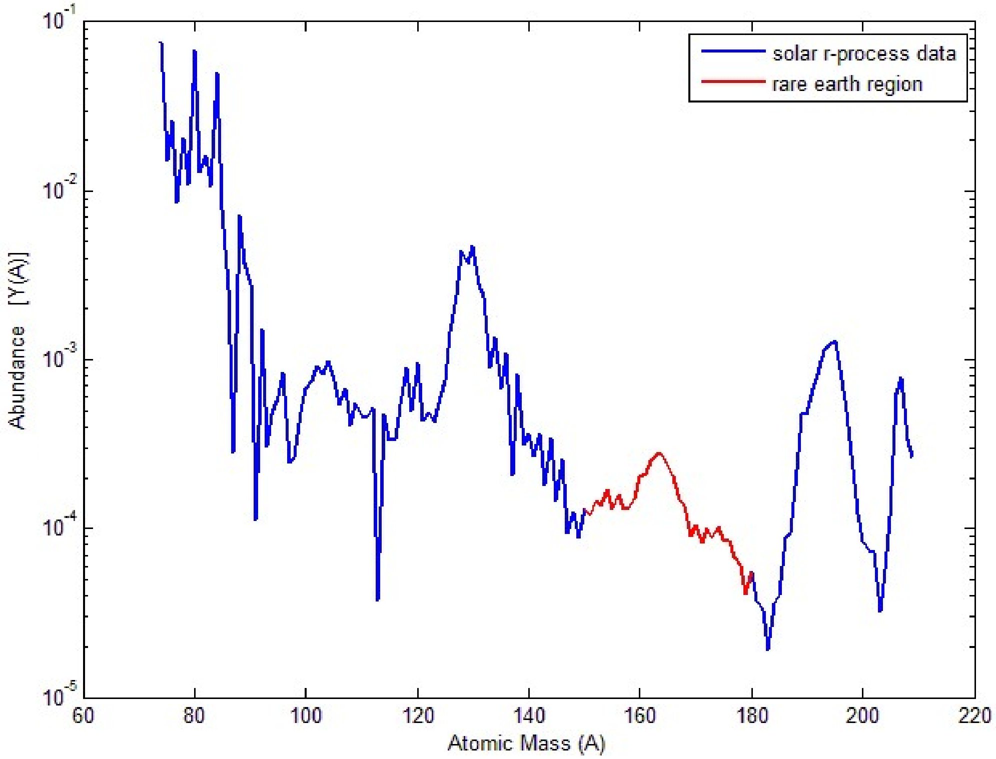
Environment conditions

(temperature, density, ...)

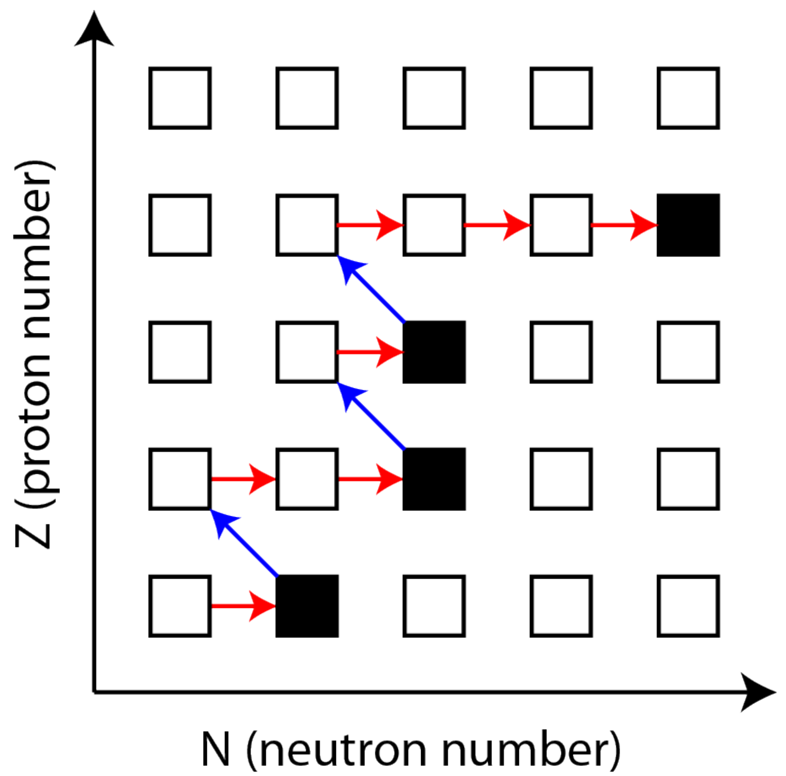
The r-Process Path

"Set of most abundant isotopes"

1. Understand nuclear flow
2. Relevant nuclear physics sets the path
3. Another way of looking at abundances

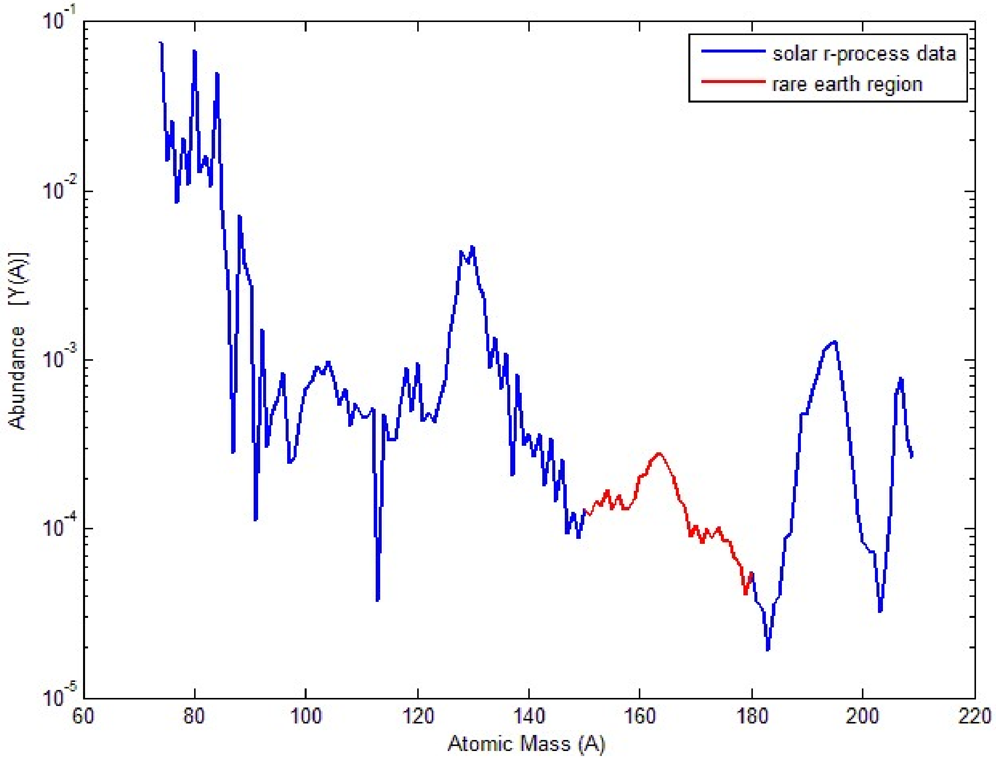


Z + N = A

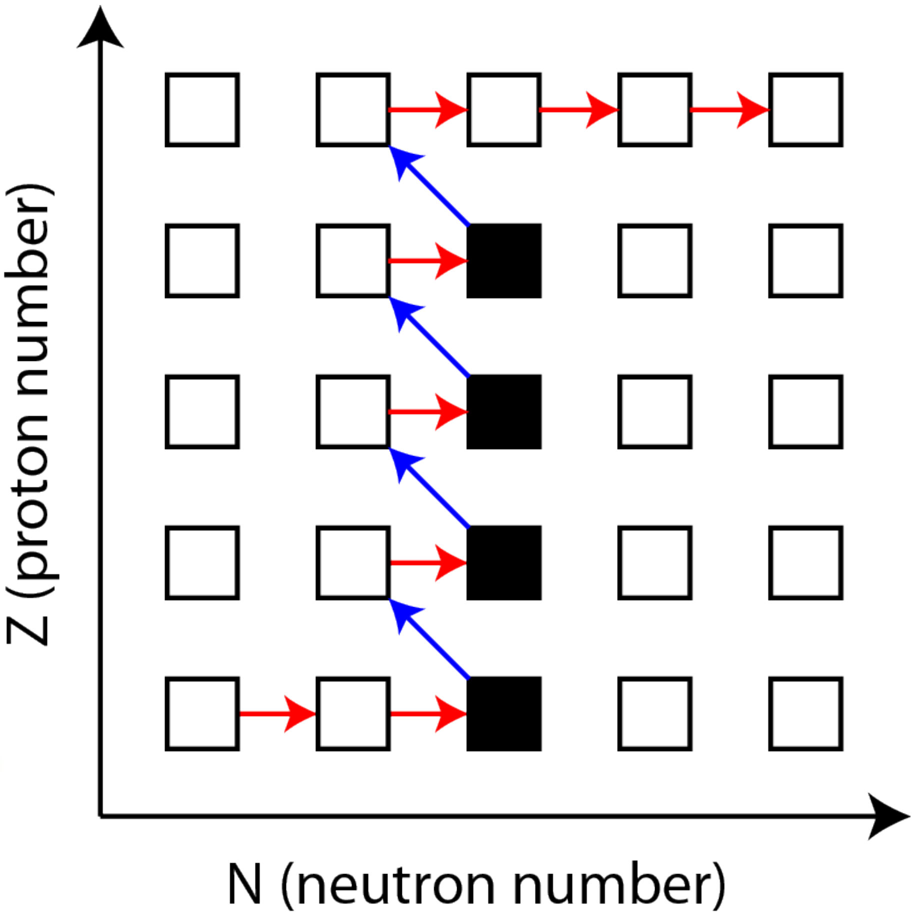


Understanding Solar Abundance Features

How do the “peaks” form? (A=80, A=130, A=195)



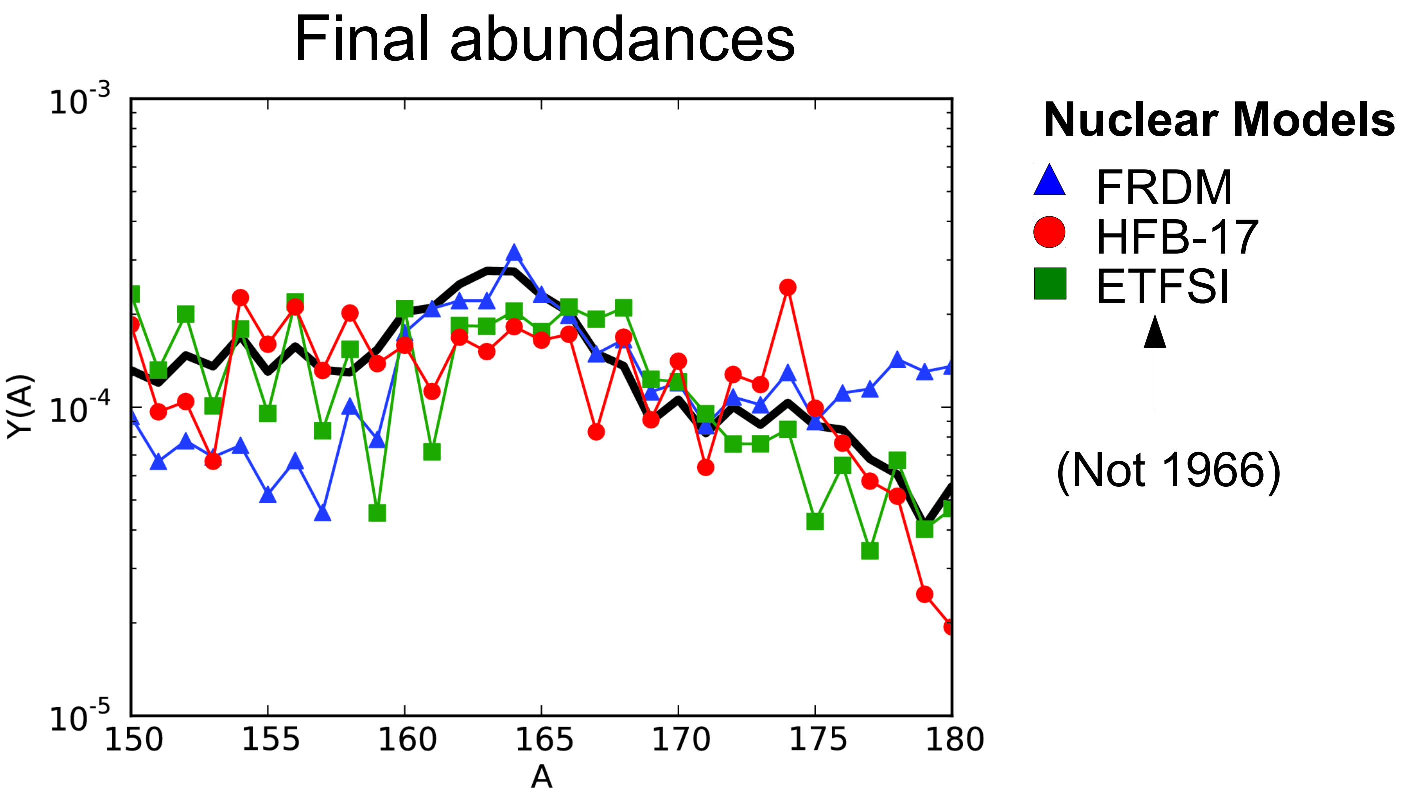
Isotopic abundances



What about the Rare Earth Peak? (A~160)

Rare Earth Peak Formation

Some example calculations...



How Does The Rare Earth Peak Form?
By Two Different Mechanisms

<u>Hot Evolution</u>

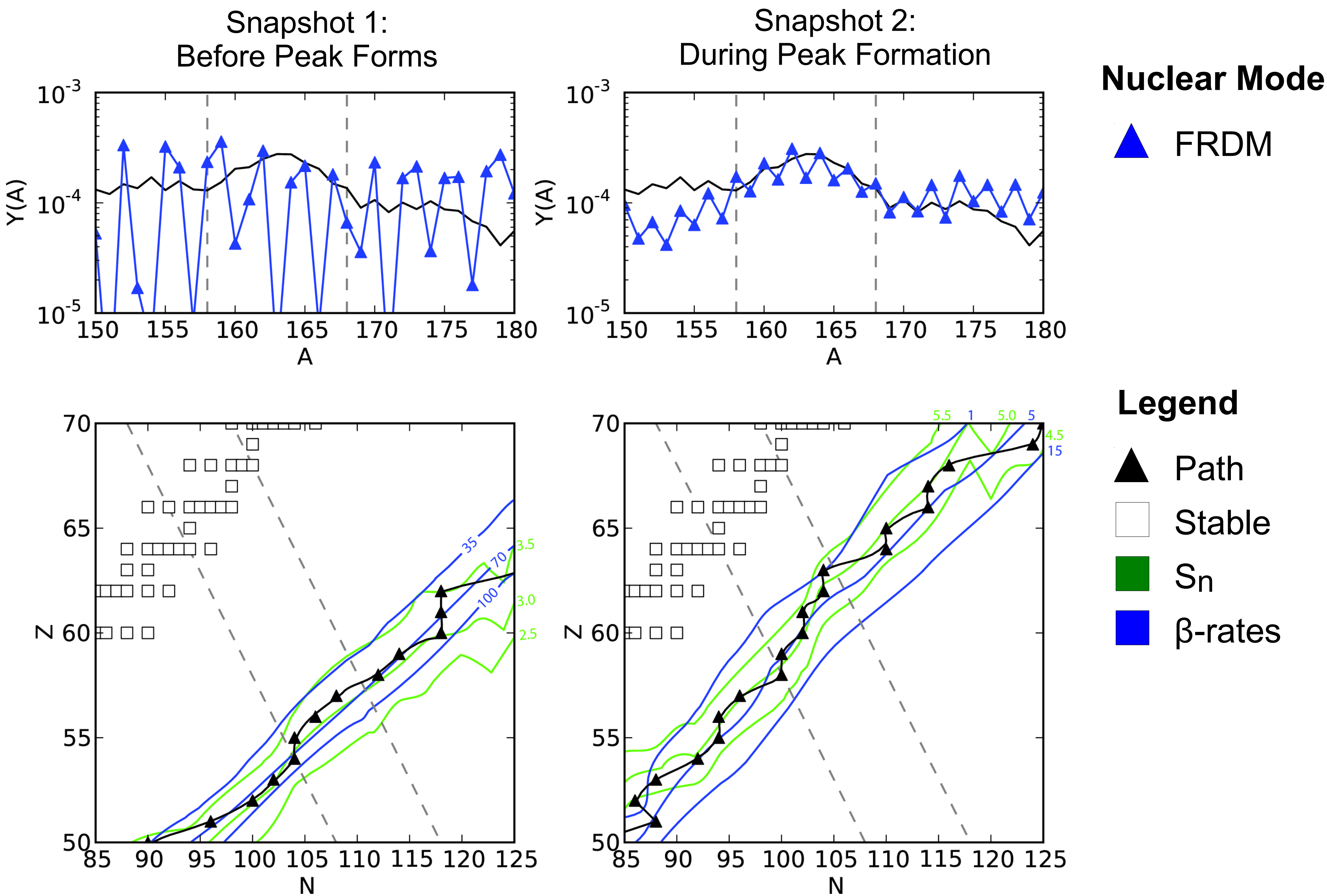
- T~1GK $(Z, N) + n \text{✘}\!\leftrightarrow (Z, N+1) + \gamma$
- T and ρ decline relatively slowly
- Reaction Channels:
  Neutron capture*
  Photo-dissociation*
  β-decay
- Peak forms by “funneling” mechanism

<u>Cold Evolution</u>

- T<1GK $(Z, N) + n \text{✘}\!\leftrightarrow (Z, N+1) + \gamma$
- T and ρ decline relatively quickly
- Reaction Channels:
  Neutron capture*
  β-decay*
  β-delayed neutron emission
- Peak forms by “trapping” mechanism

Rare Earth Peak Formation

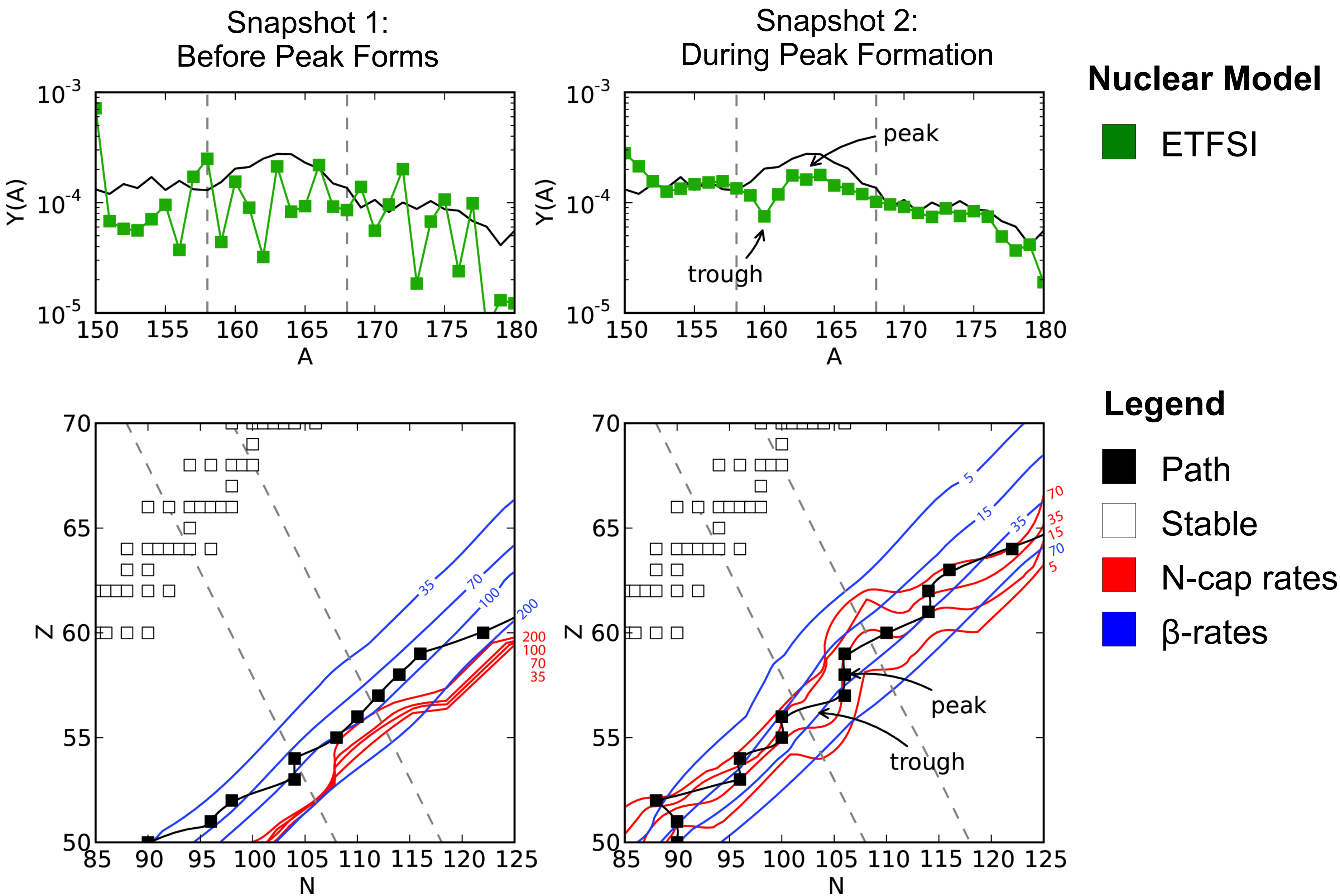
Hot Evolution - Funneling



Mechanism discovered by Surman + Engel (1997)

Rare Earth Peak Formation

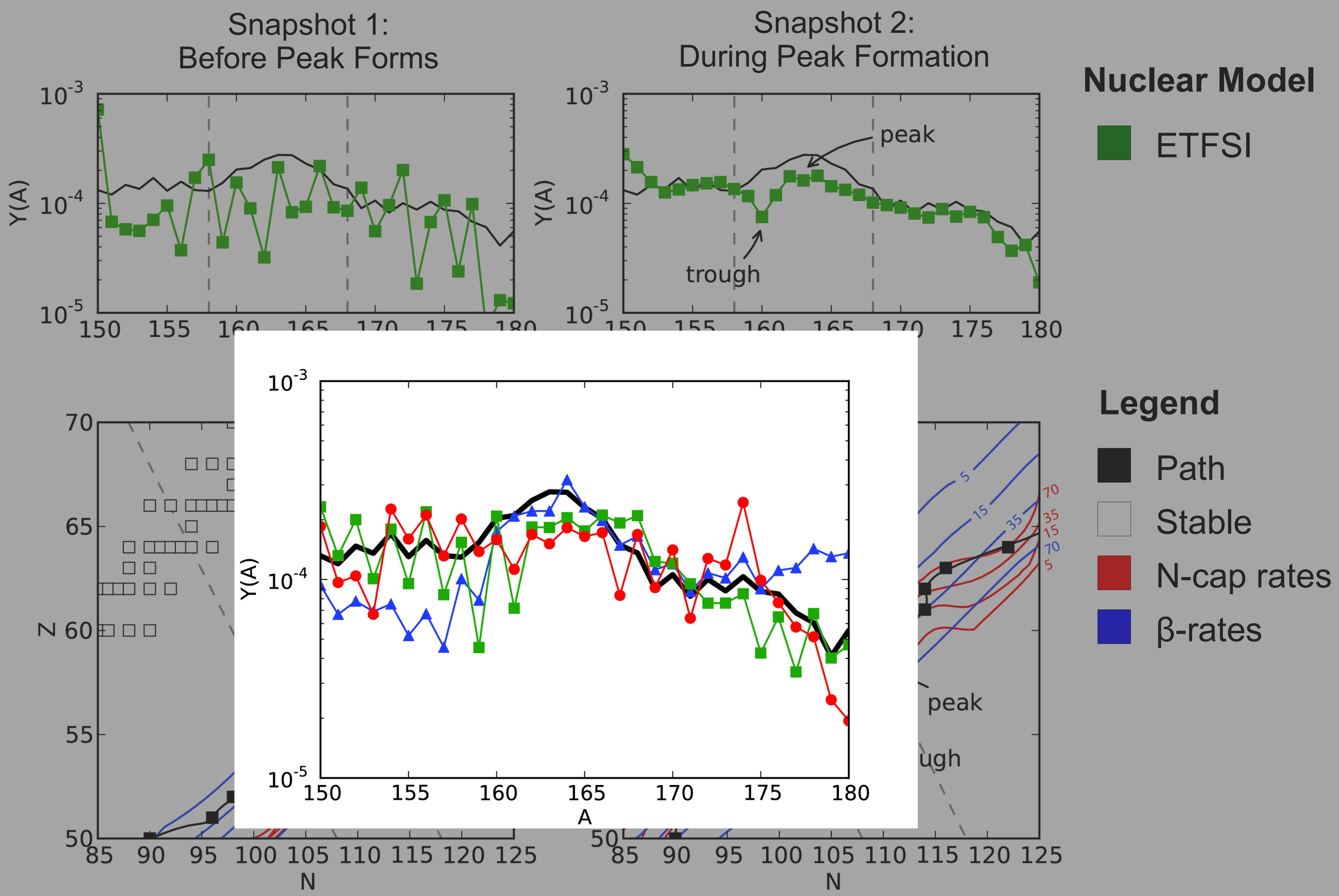
Cold Evolution - Trapping



Mumpower et al. (2012)

Rare Earth Peak Formation

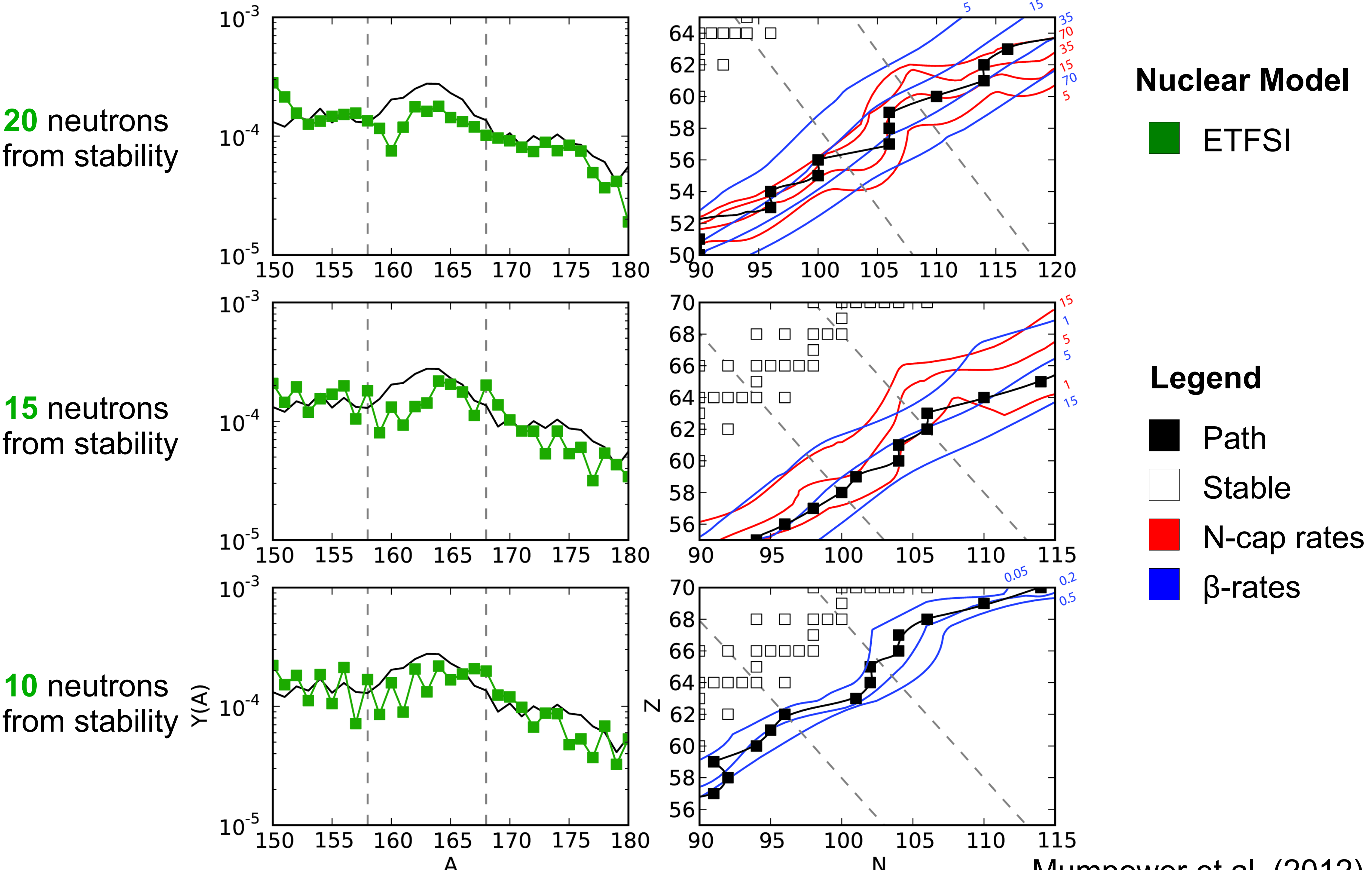
Cold Evolution - Trapping



Mumpower et al. (2012)

Peak Formation – Fails

Due To Neutron Captures Closer To Stability



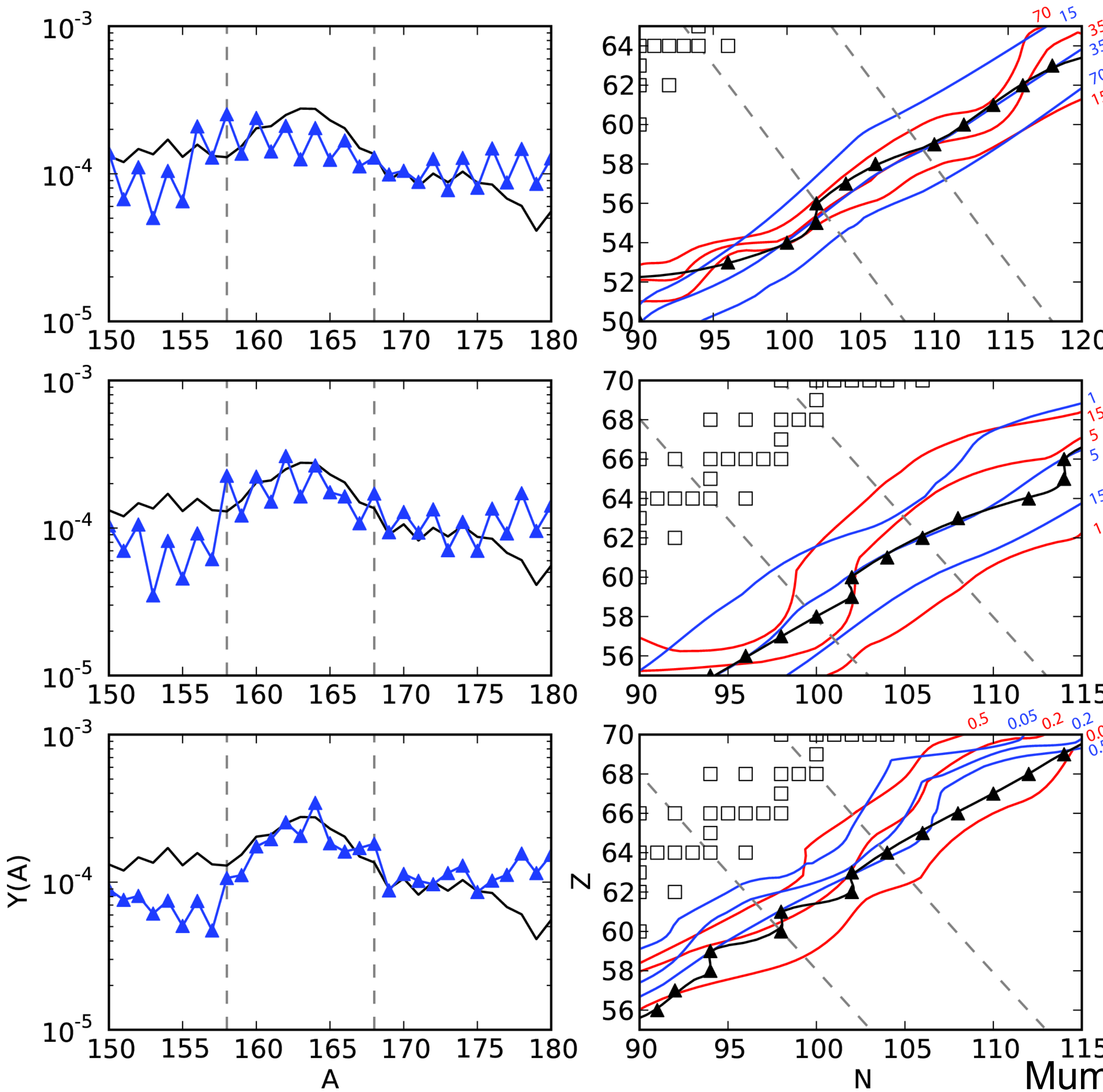
Mumpower et al. (2012)

Successful Rare Earth Peak Formation

20 neutrons from stability

15 neutrons from stability

10 neutrons from stability



Nuclear Model

▲ FRDM

Legend

■ Path

□ Stable

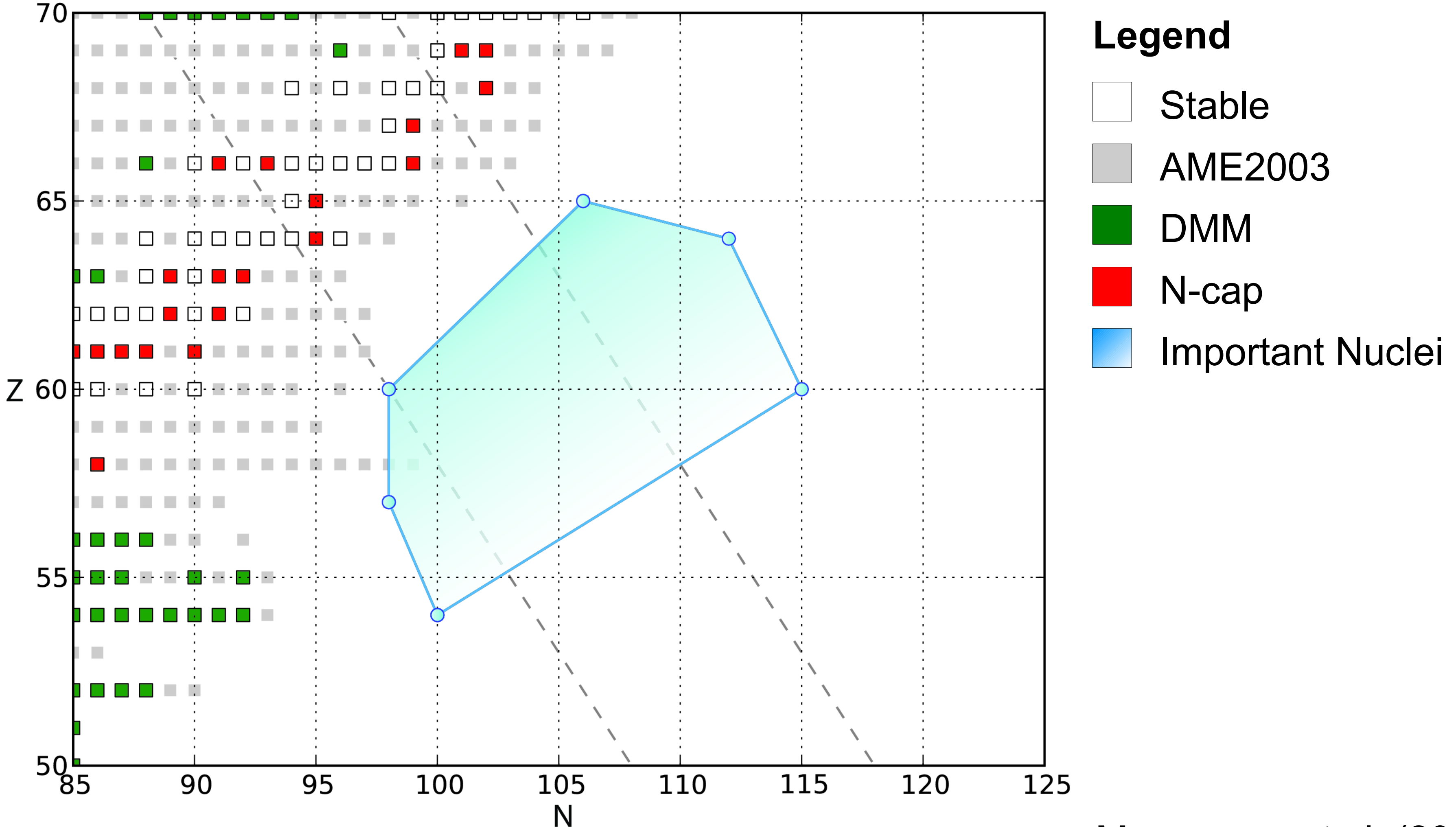
■ N-cap rates

■ β-rates

Mumpower et al. (2012)

Nuclei Important For Peak Formation?

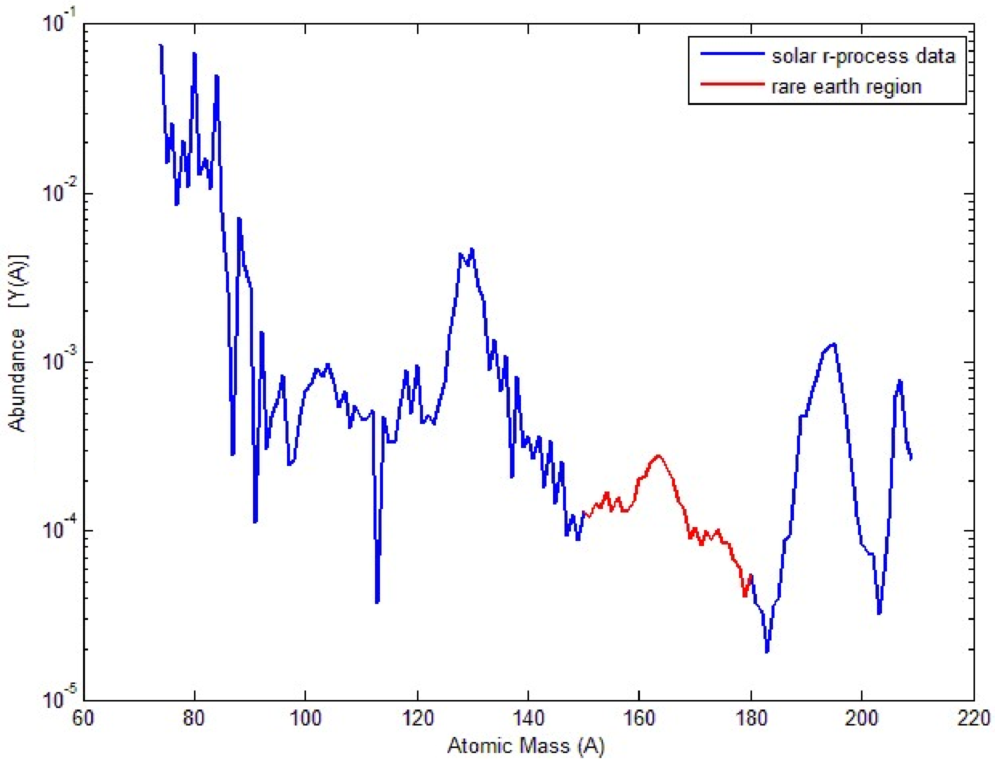
Those nuclei 10-15 neutrons from stability...



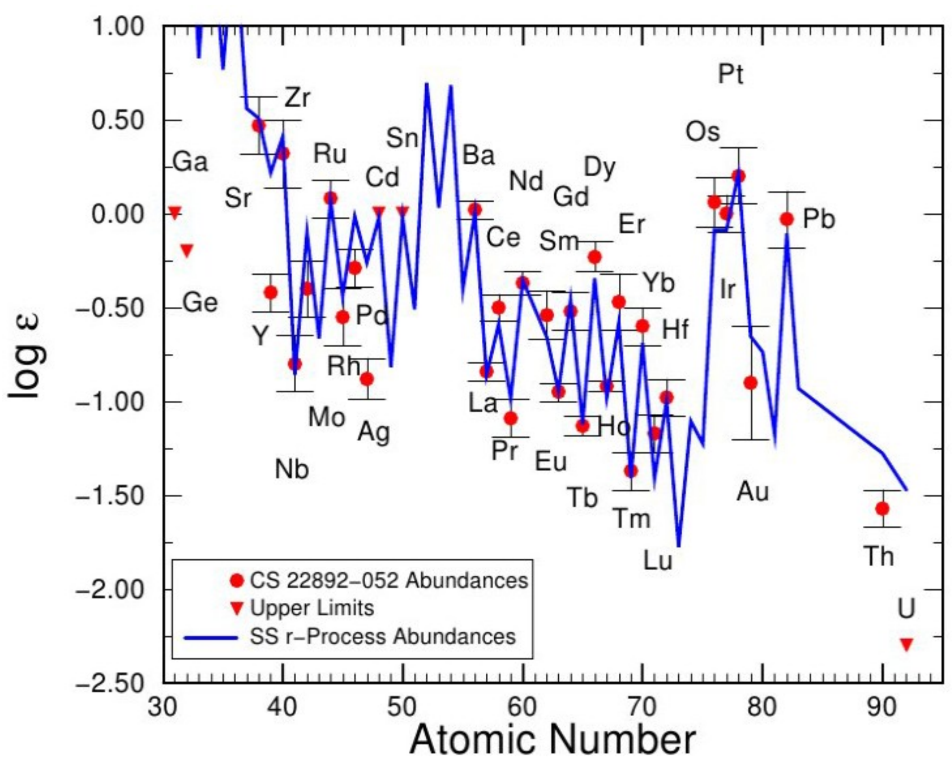
Mumpower et al. (2012)

A New Way To Constrain r-Process Conditions

- Use successful rare earth peak formation to constrain conditions favorable for the r-process
- Perform many simulations each with differing conditions
- Compare final pattern to both solar and halo star data



Isotopic abundances



Elemental abundances

Density Parameterization

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

early-time late-time

- Similar to ν-driven wind parameterization by Meyer (2002) with...
- $3\tau = \tau_{dyn}$ and $\rho(0)=\rho_1+\rho_2$ and $\Delta(\tau)$
- n = late time power law
- n = 1-5 (hot)
- n > 5 (cold)
- Separate the early time behavior (neutron-to-seed ratio) from late time behavior (rare earth peak formation)

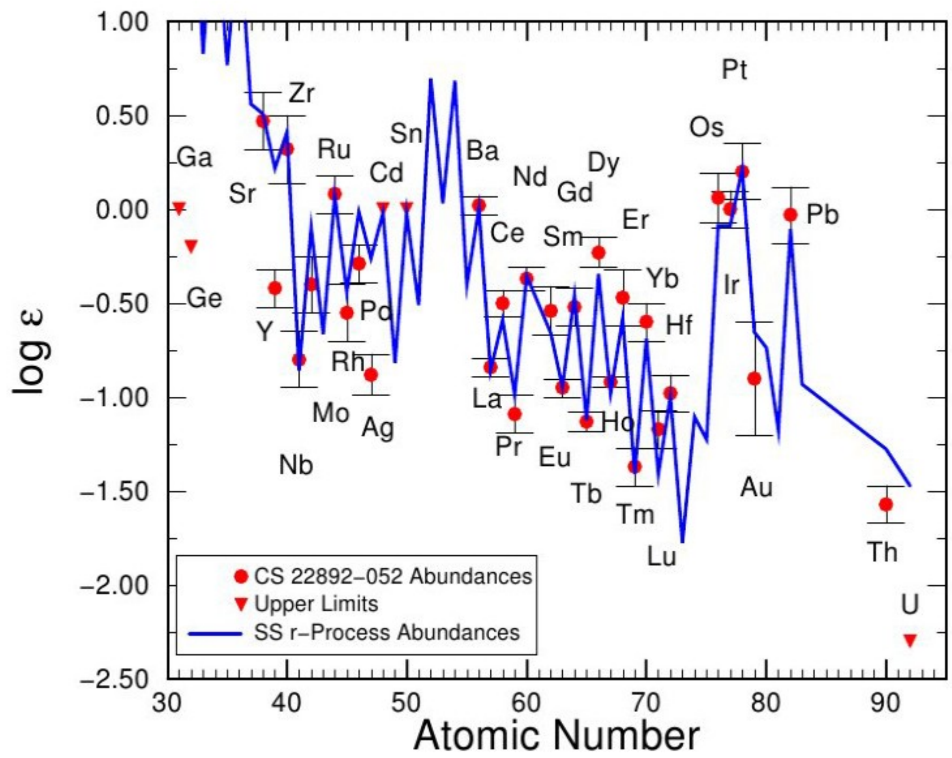
Comparing Simulations To Data

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

early-time   late-time

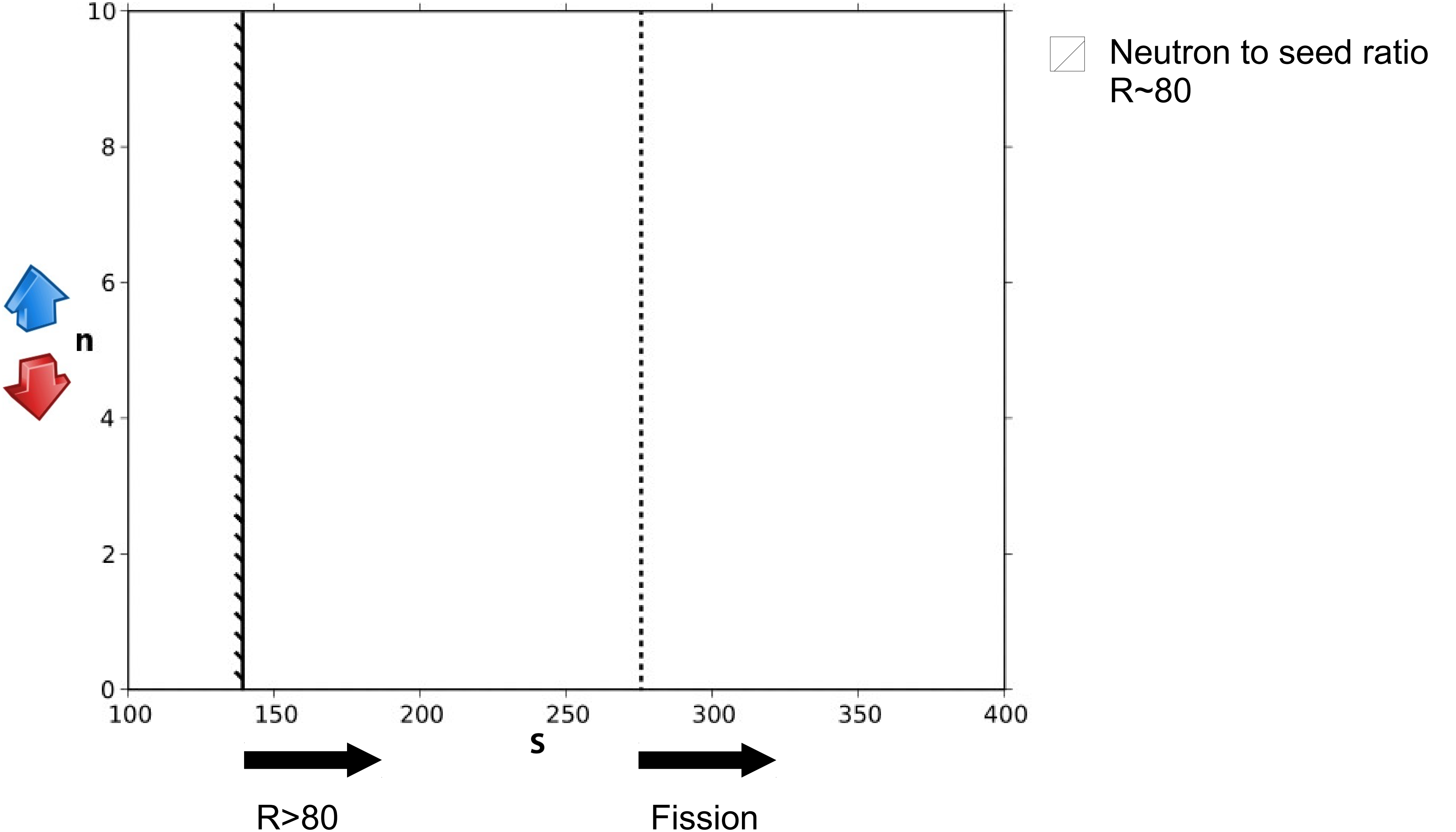
Fix:

- τ ~80ms
- Ye = 0.30
- nuclear model (FRDM)
- **Allow other parameters to vary:**
- S ~ 50 to 400
- n ~ 0 to 10



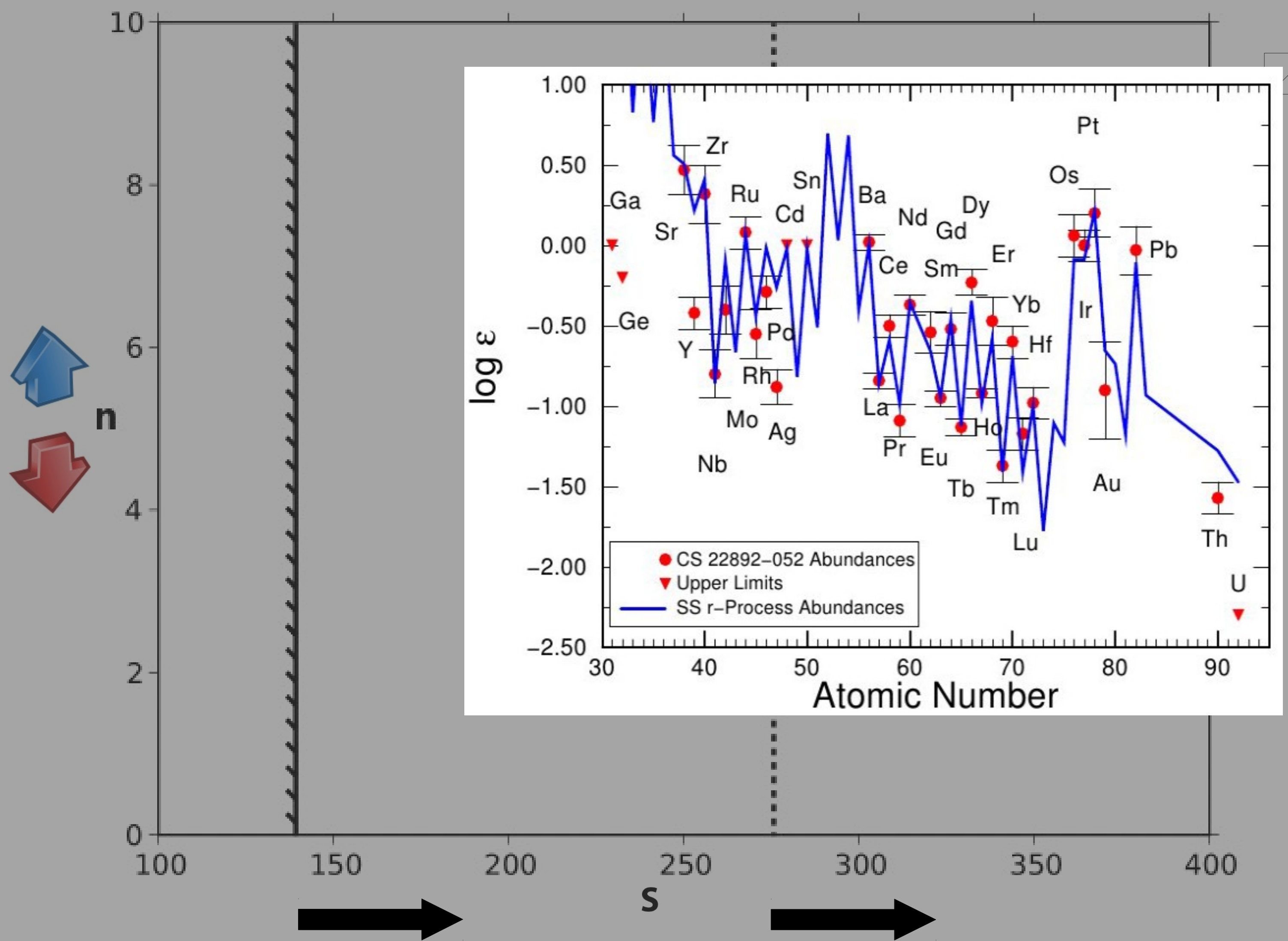
Elemental abundances

Old Constraint: Neutron To Seed Ratio



Mumpower et al. (2012)

Comparing Simulations To Halo Star Data



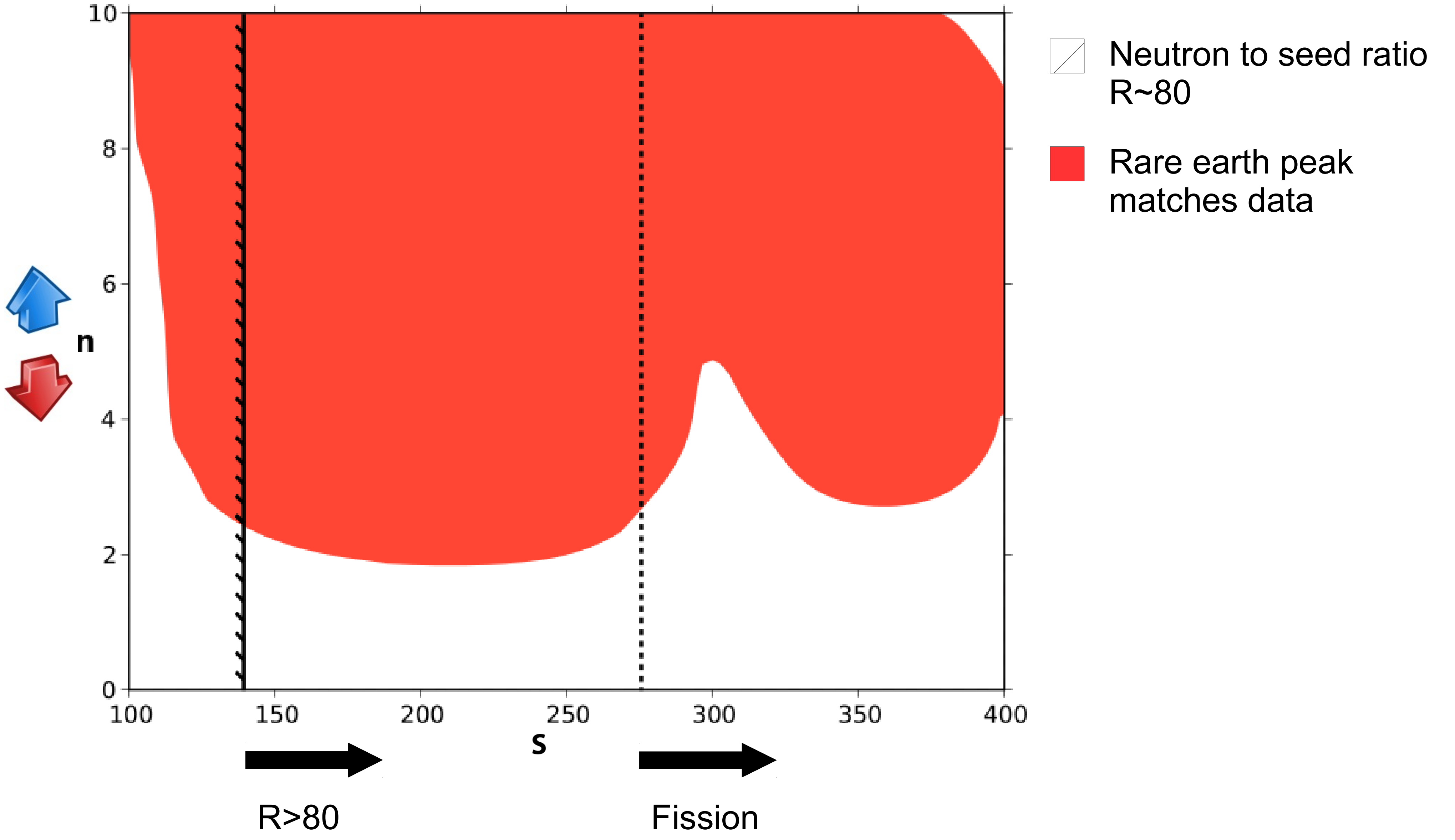
Neutron to seed ratio
R~80

R>80

Fission

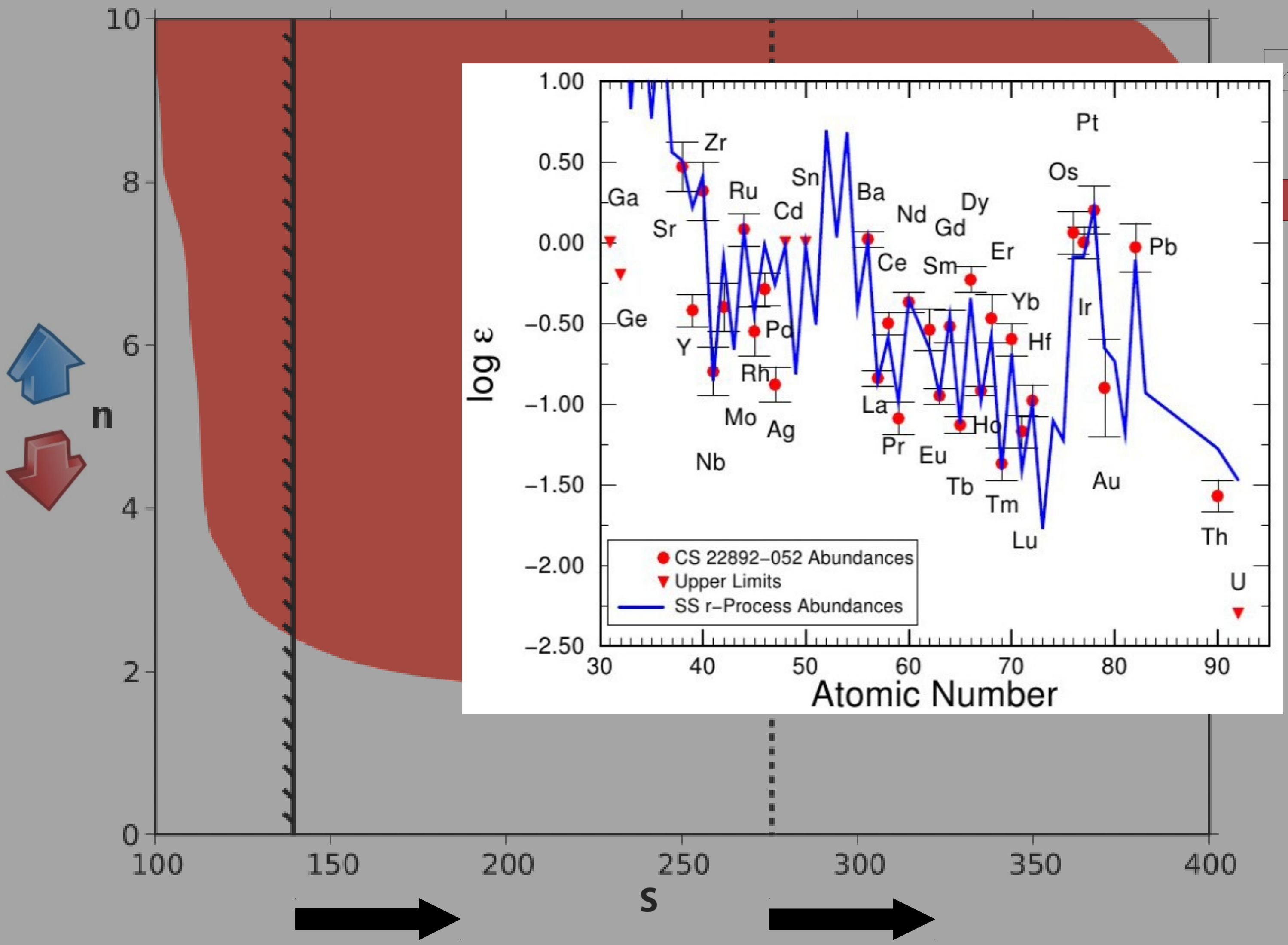
Mumpower et al. (2012)

New Constraint: Rare Earth Peak Forms



Mumpower et al. (2012)

Constraint: Ratio A=195 Peak to REP



R>80

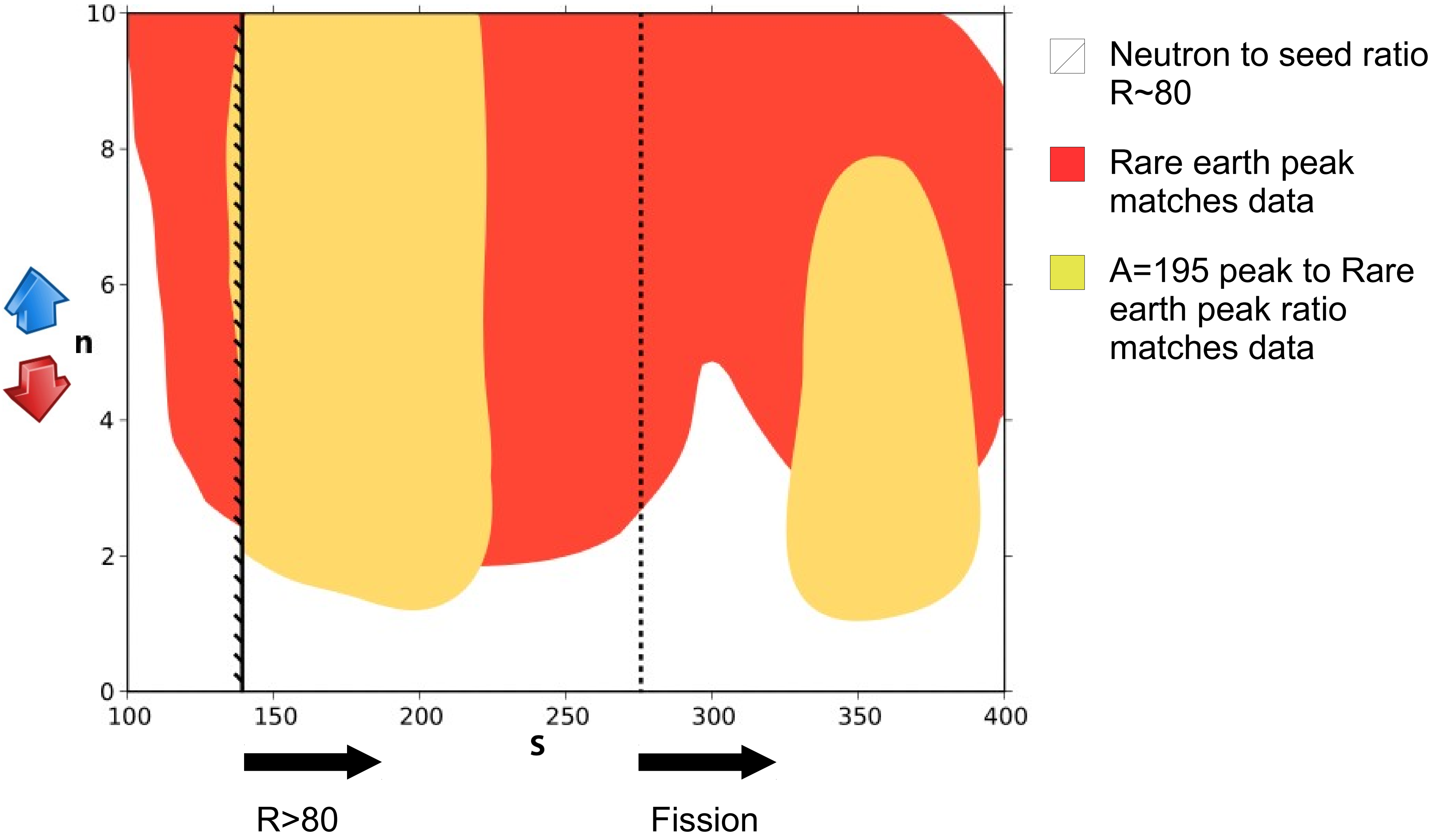
Fission

Neutron to seed ratio R~80

Rare earth peak matches data

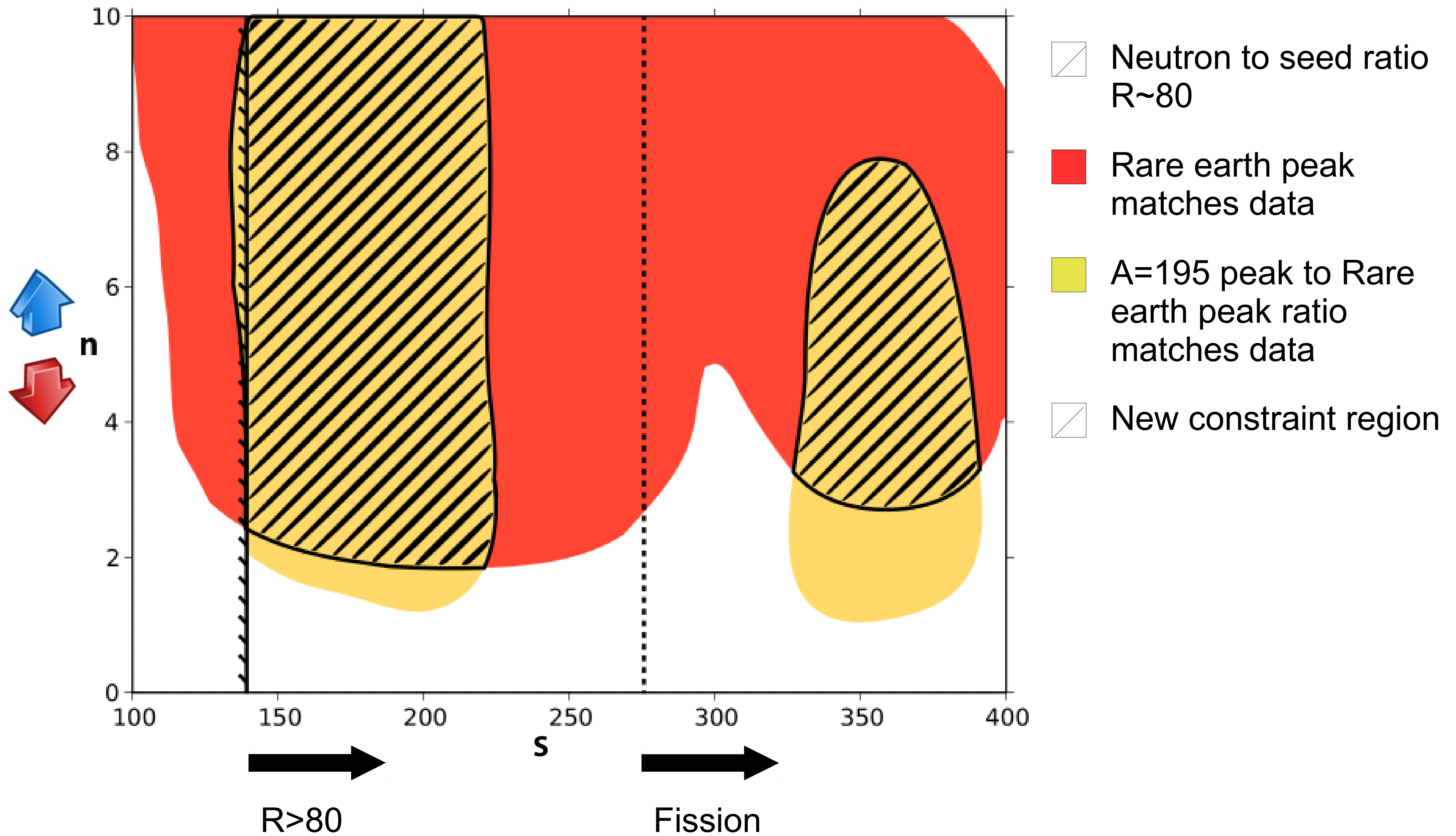
Mumpower et al. (2012)

2^{nd} Constraint: Ratio A=195 Peak to REP



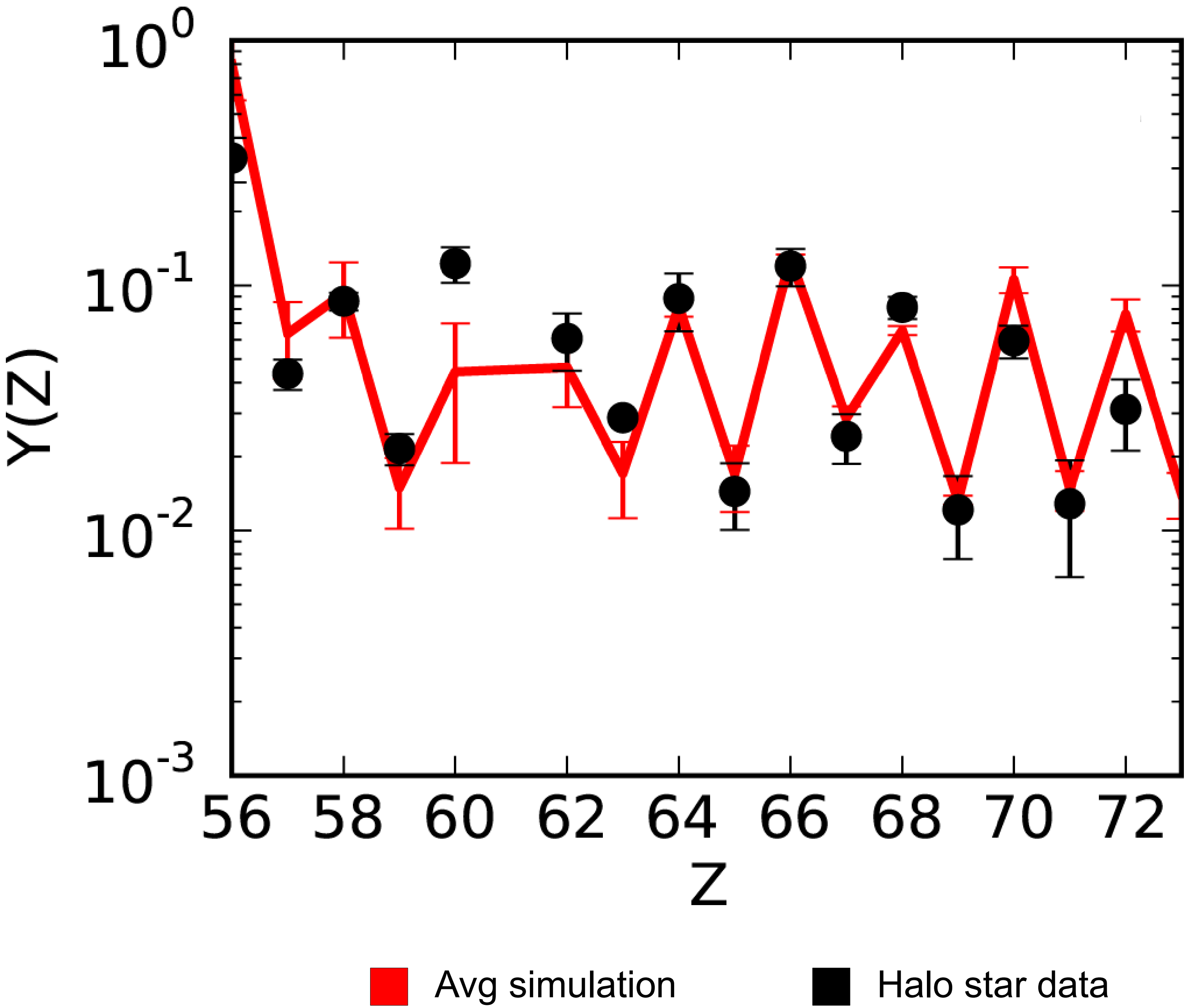
Mumpower et al. (2012)

Result: New (Smaller) Constraint Region



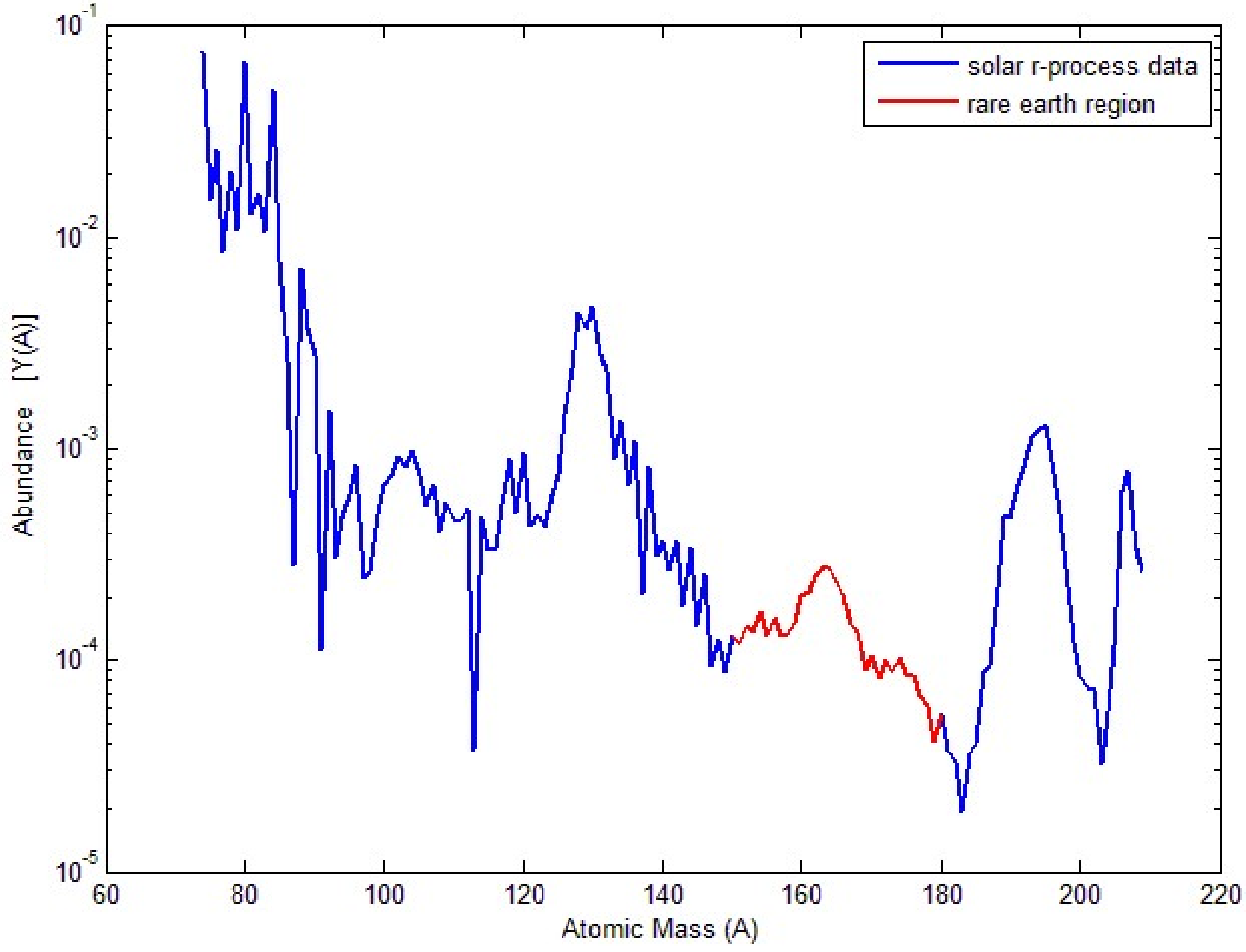
Mumpower et al. (2012)

New Constraints Do Remarkably Well

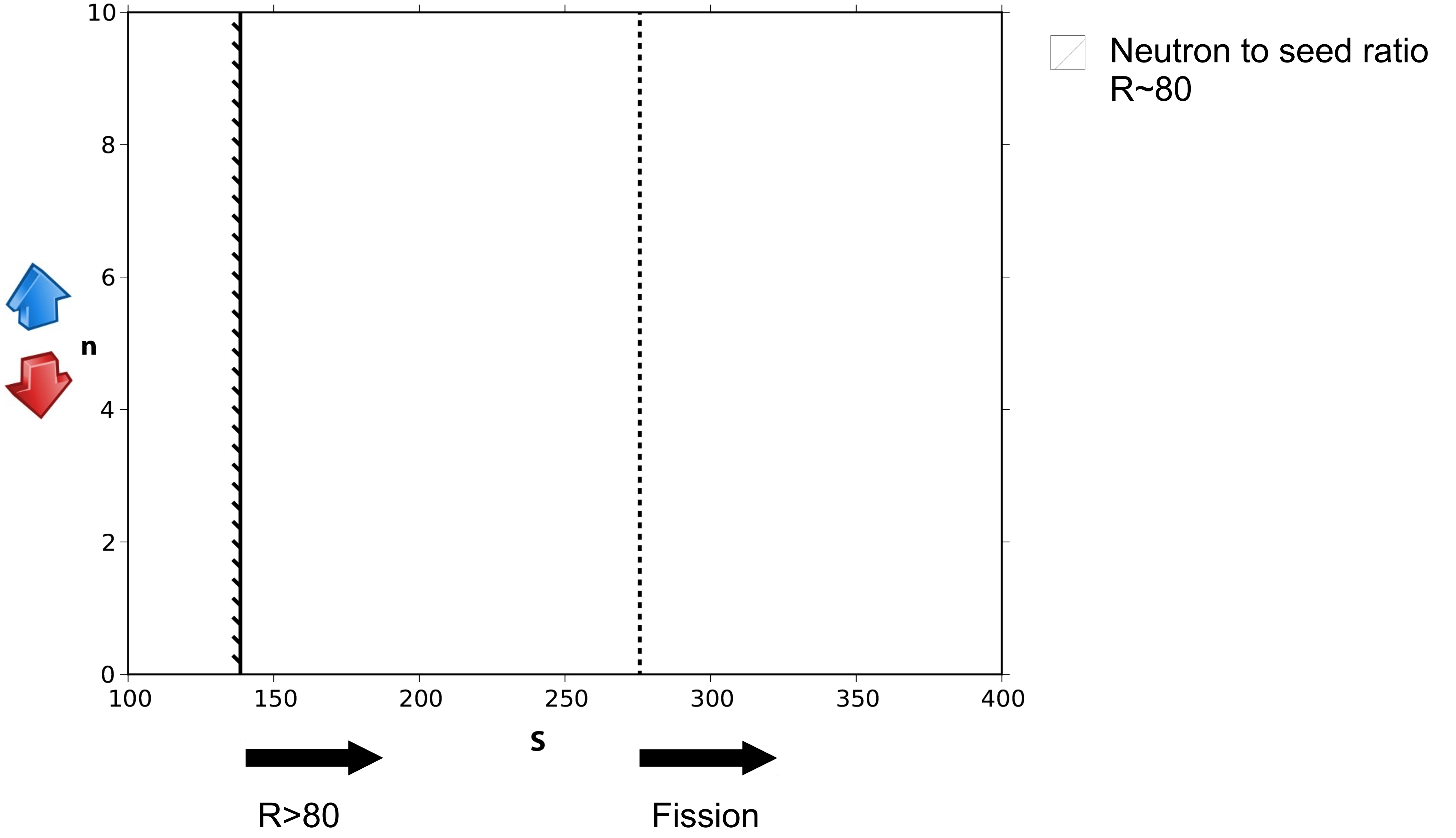


Mumpower et al. (2012)

Comparing Simulations To Solar Data



Old Constraint: Neutron To Seed Ratio



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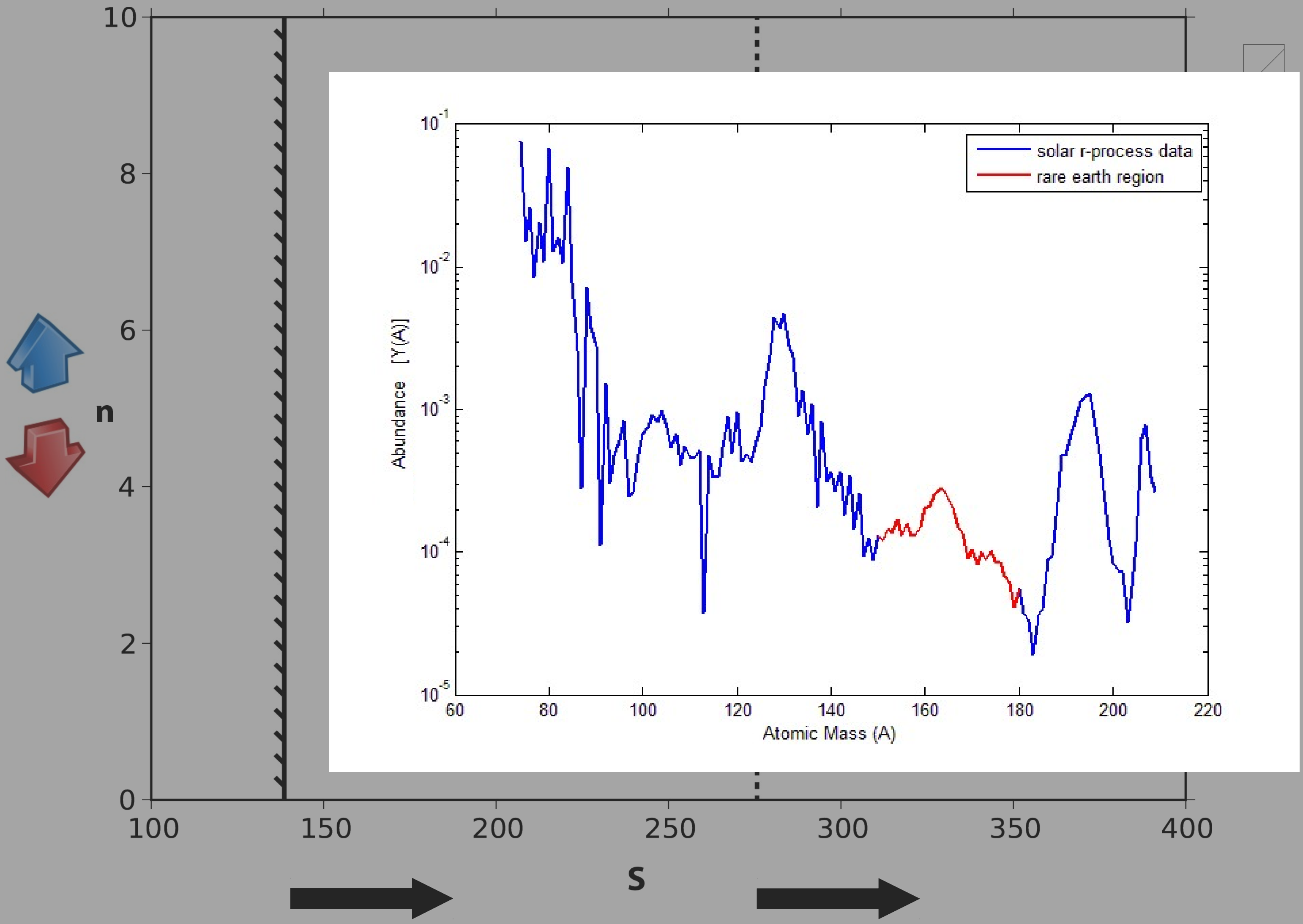


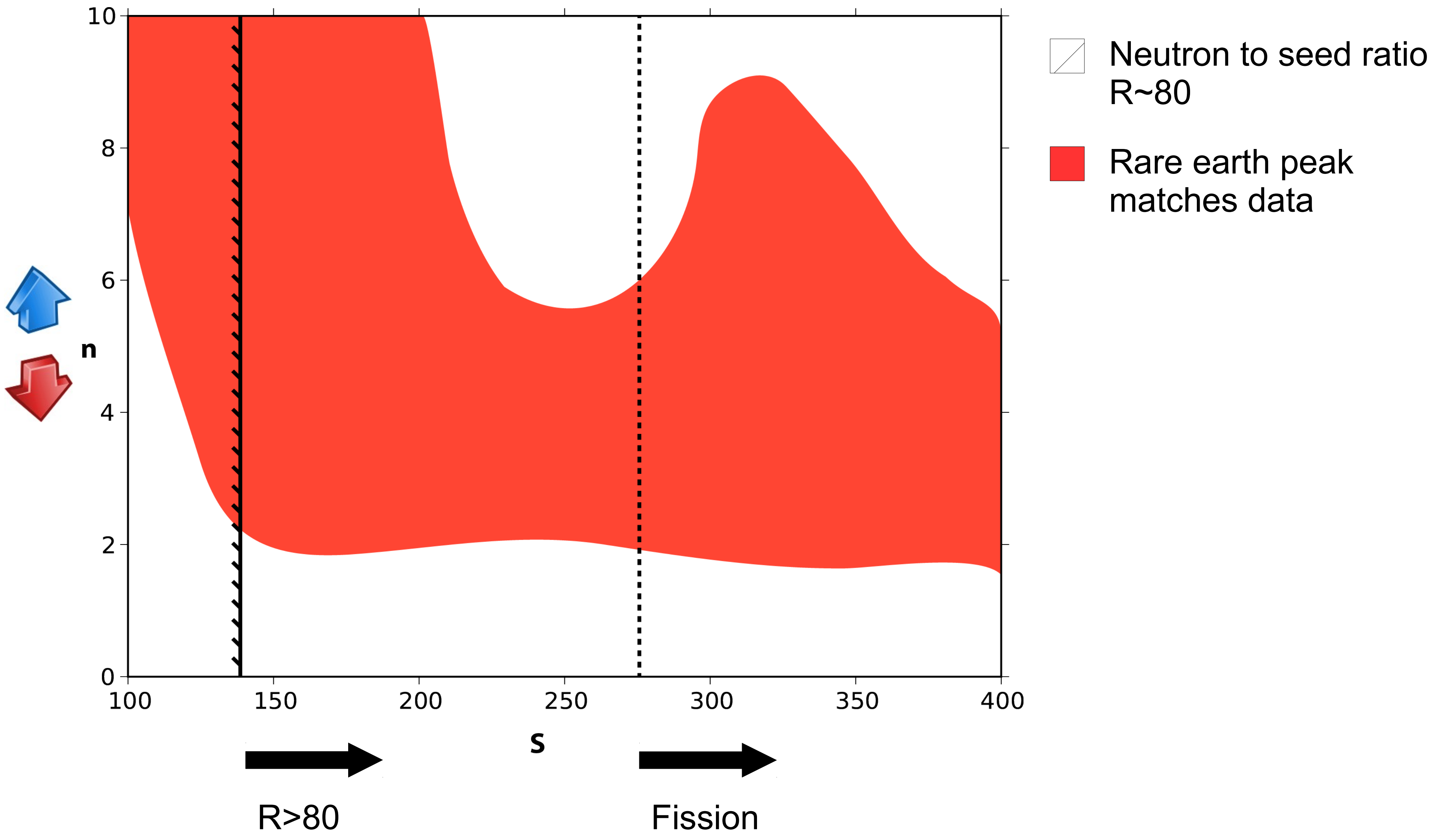
Neutron to seed ratio
R~80

R>80

Fission

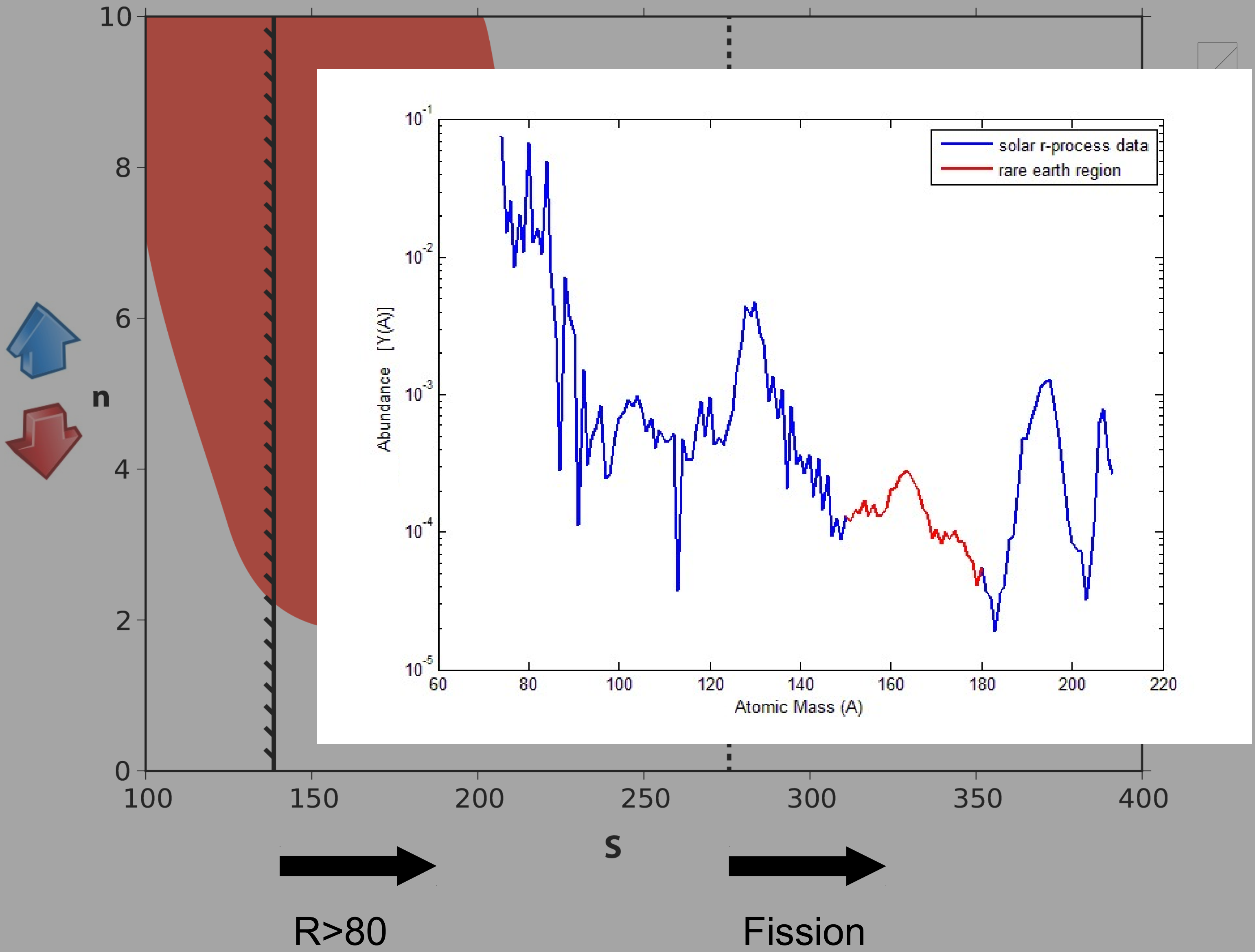
Mumpower et al. (2012)

New Constraint: Rare Earth Peak Forms



Mumpower et al. (2012)

Comparing Simulations To Solar Data

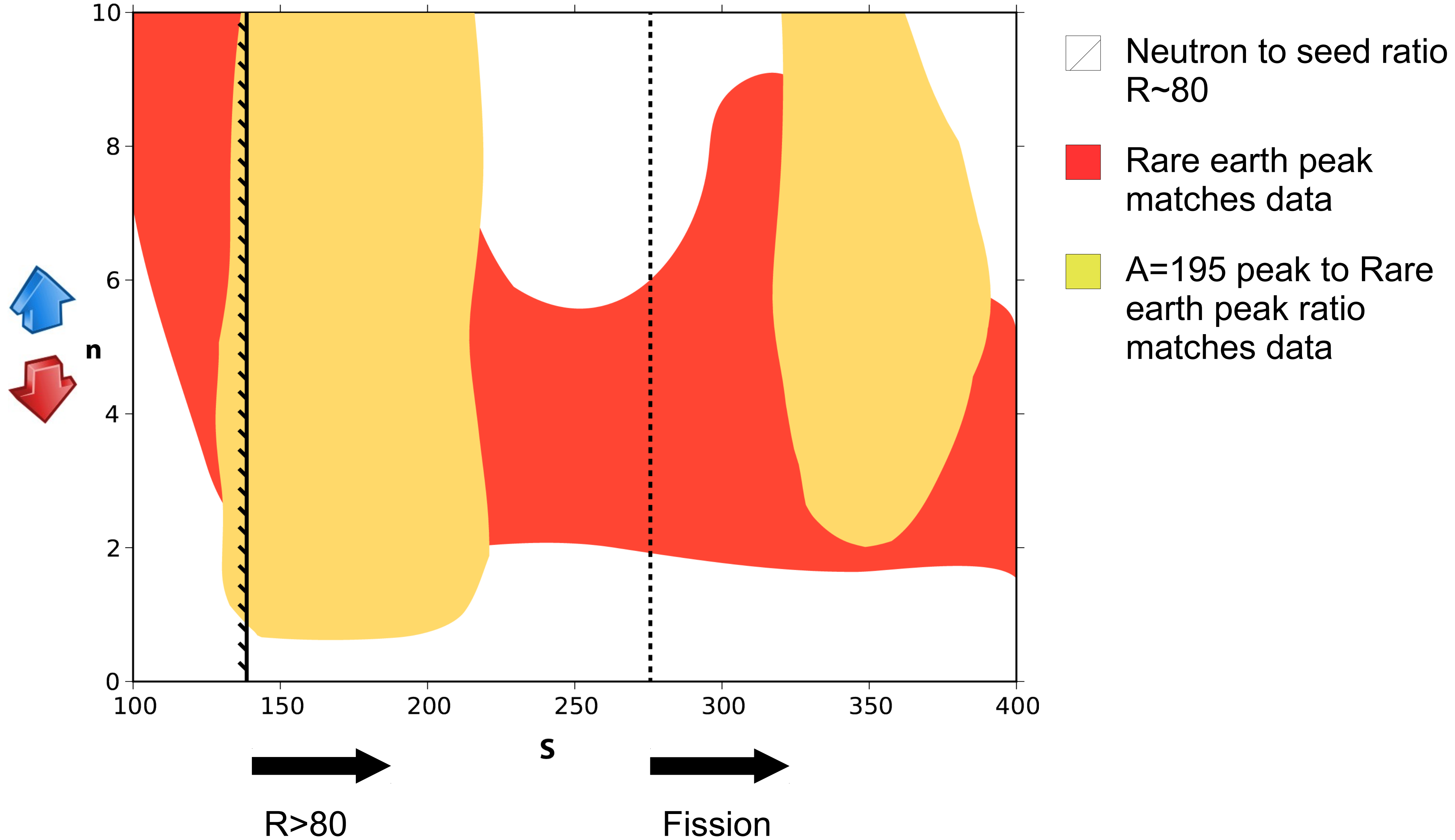


Neutron to seed ratio R~80

Rare earth peak matches data

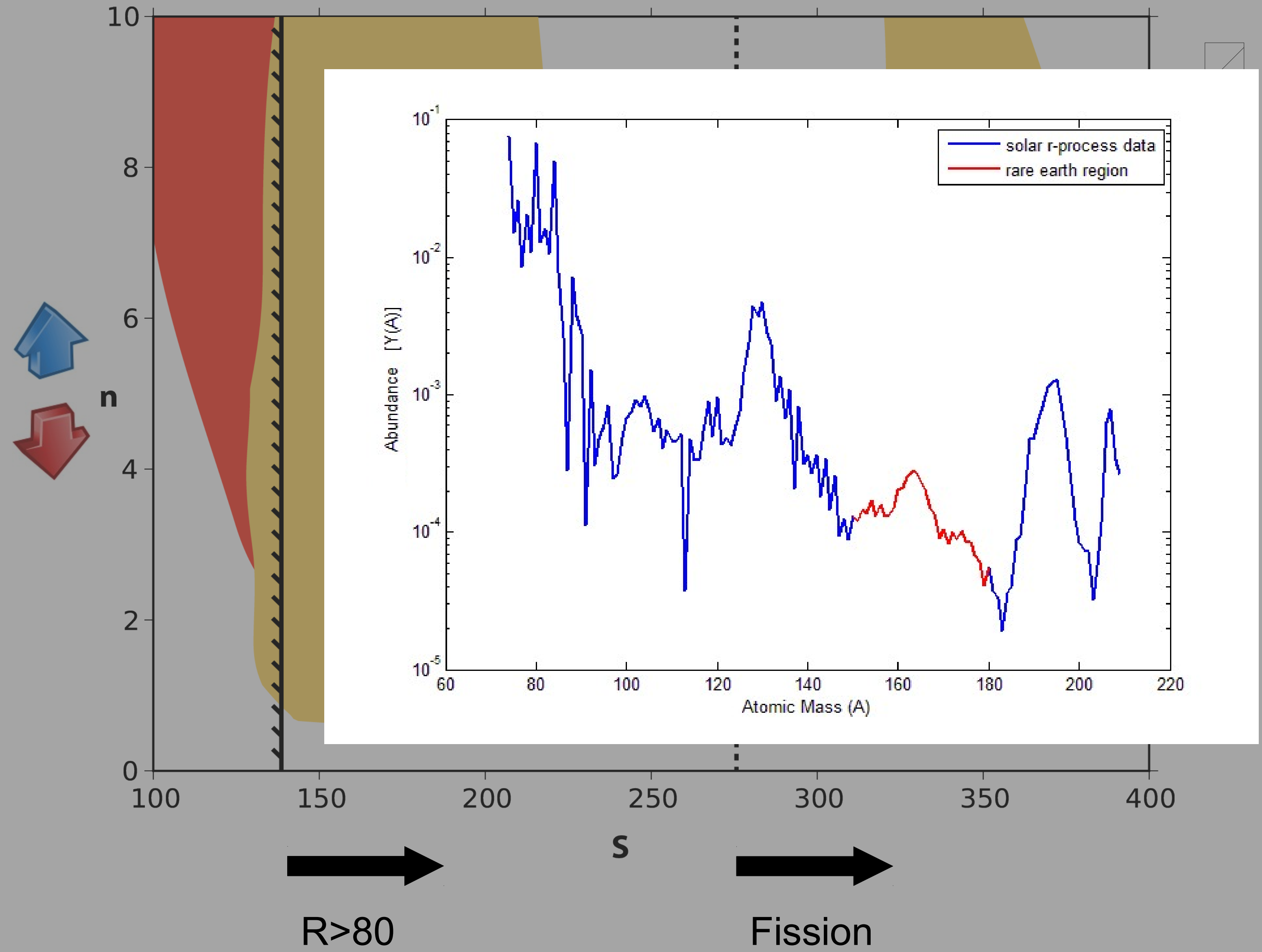
Mumpower et al. (2012)

2nd Constraint: Ratio A=195 Peak to REP



Mumpower et al. (2012)

Comparing Simulations To Solar Data



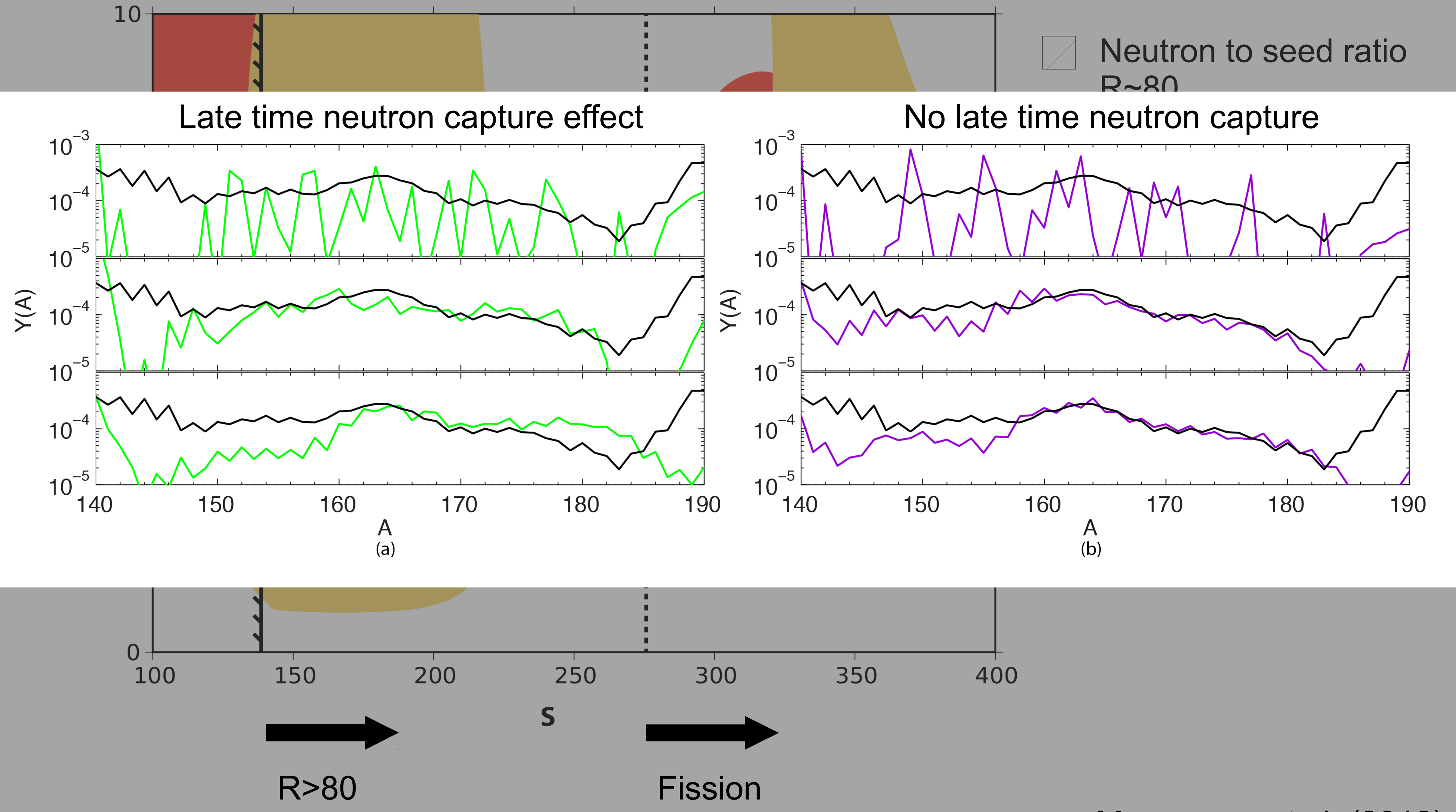
Neutron to seed ratio R~80

Rare earth peak matches data

A=195 peak to Rare earth peak ratio matches data

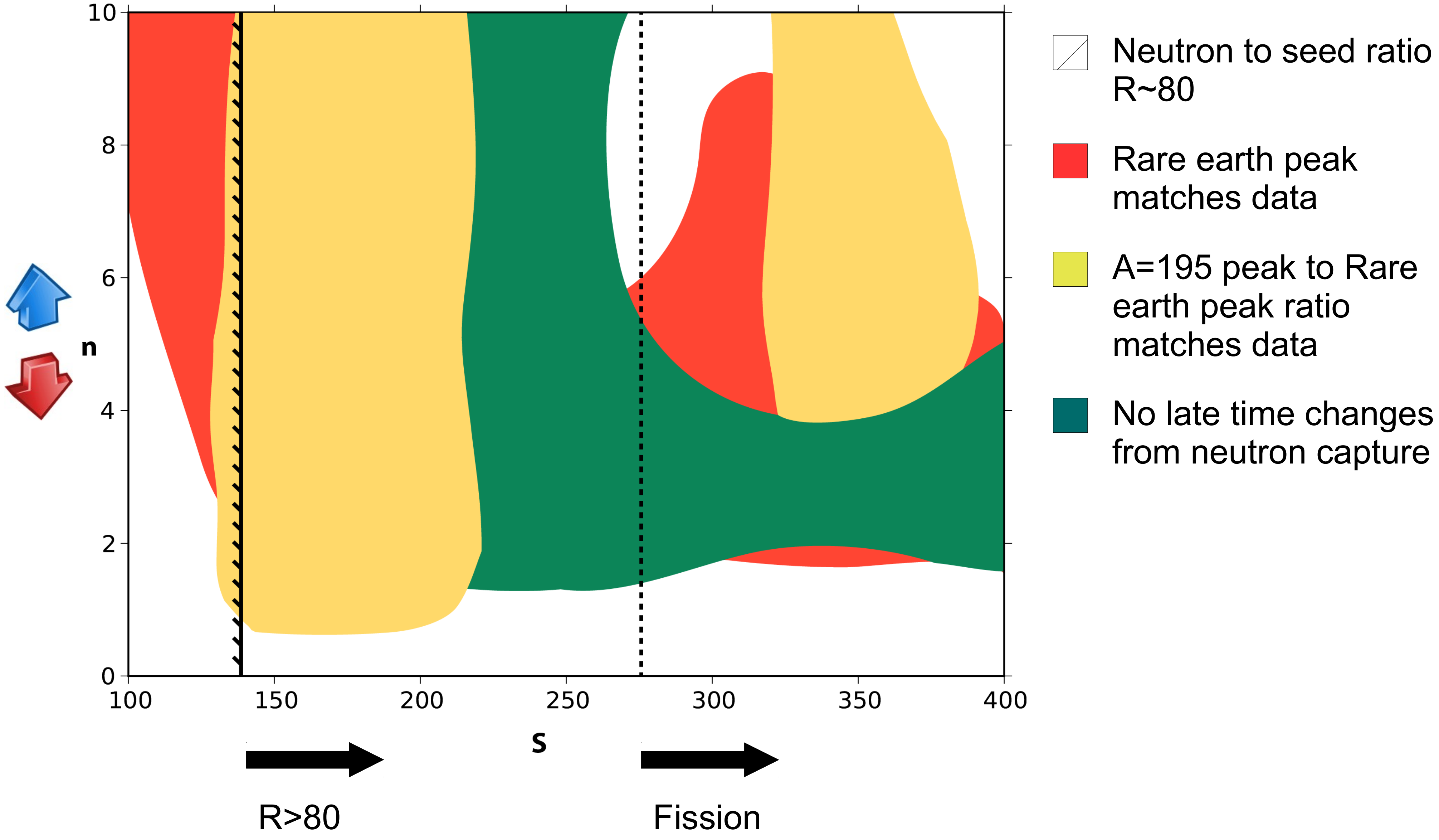
Mumpower et al. (2012)

Late Time Neutron Capture Effect



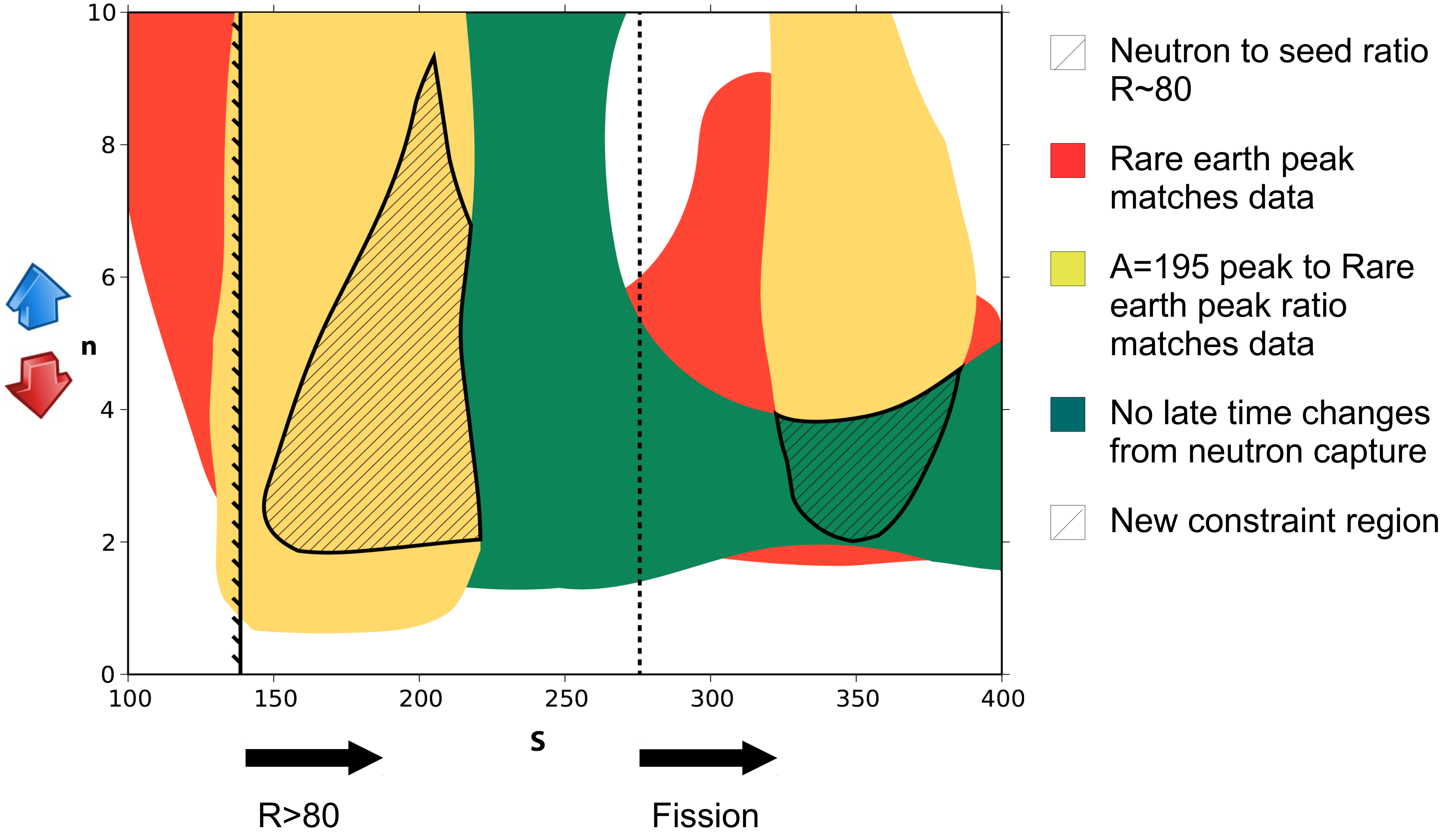
Mumpower et al. (2012)

3rd Constraint: Limit Late Time Neutron Capture



Mumpower et al. (2012)

Result: New (Smaller) Constraint Regions



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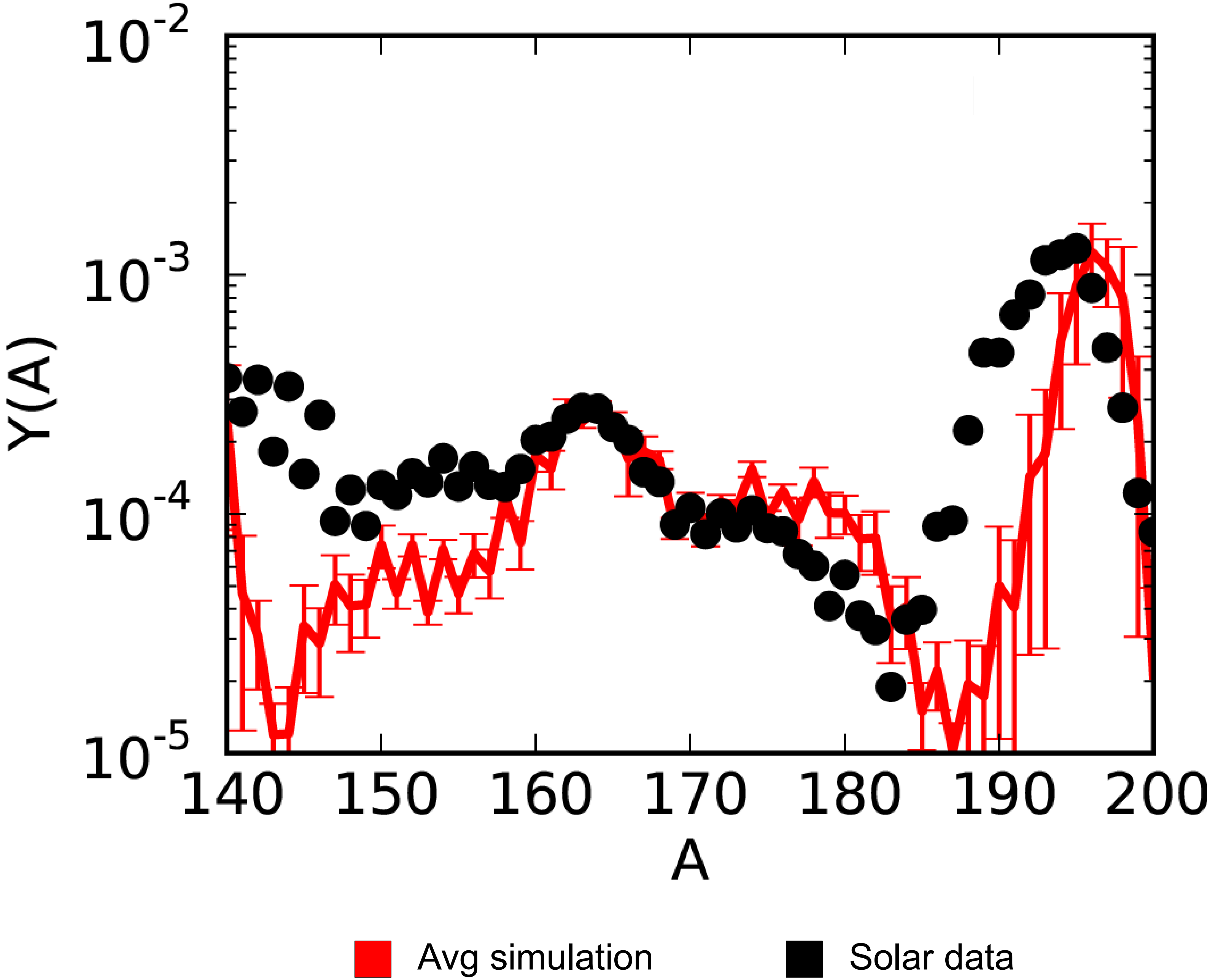
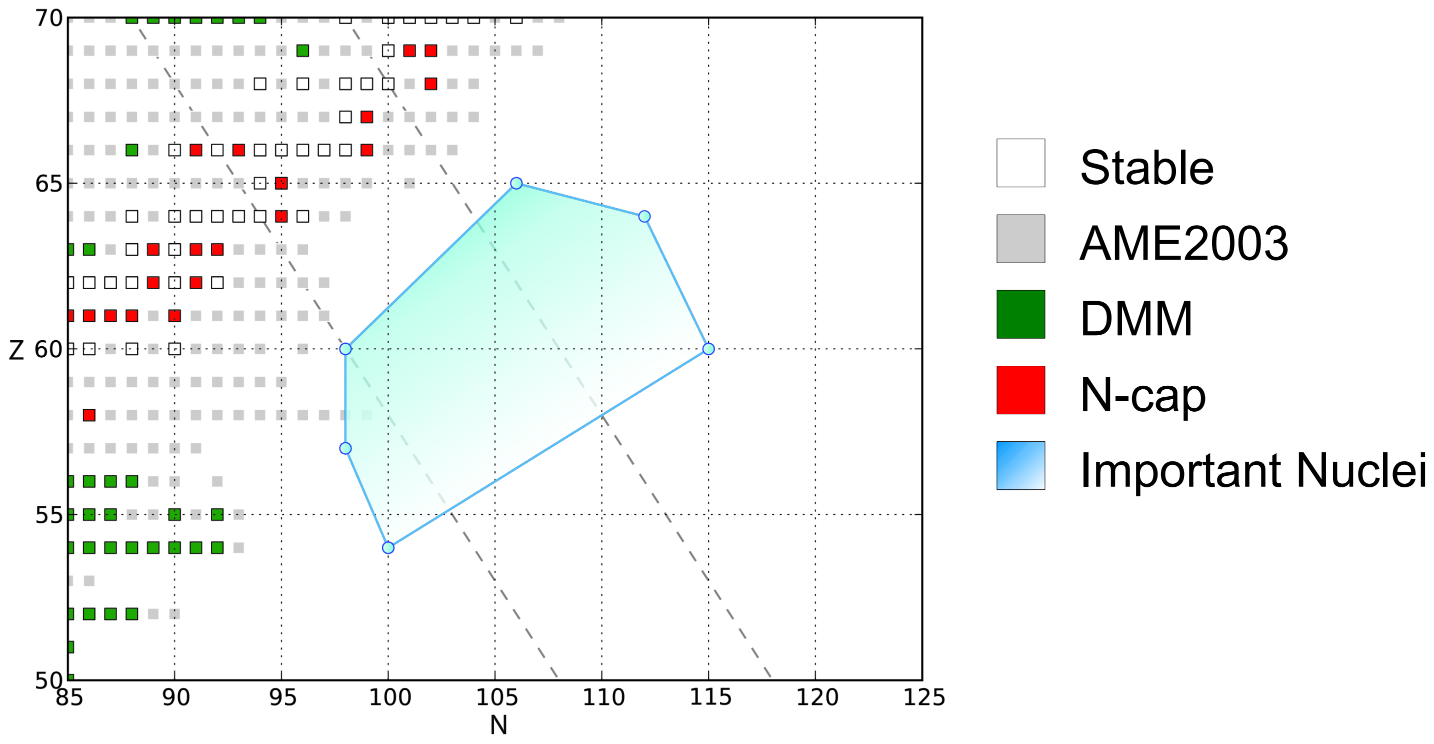


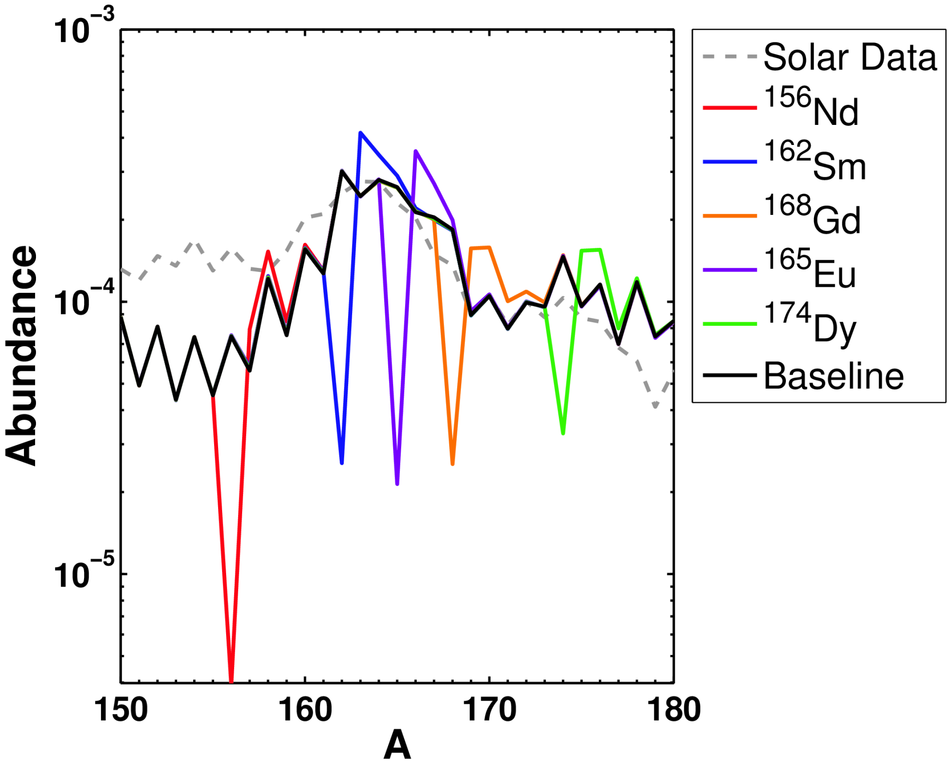
Mumpower et al. (2012)

Neutron Capture Rate Uncertainties

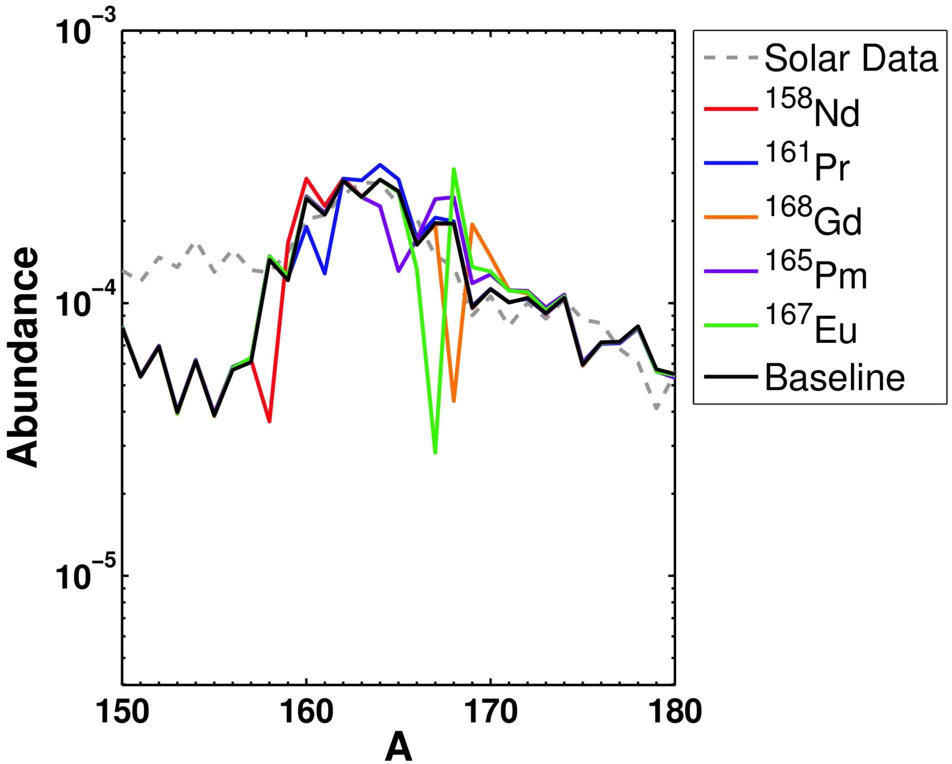
- “Sensitivity study” - how do abundances change with change in an individual rate?
- Baseline simulation – fix conditions & rates remain changed
- Rate change simulation – single rate is changed, all else fixed
- Does the rate change produce a change in the final abundances?



How Neutron Capture Rates Change Final Rare Earth Abundances – Local Changes Only



Hot Evolution



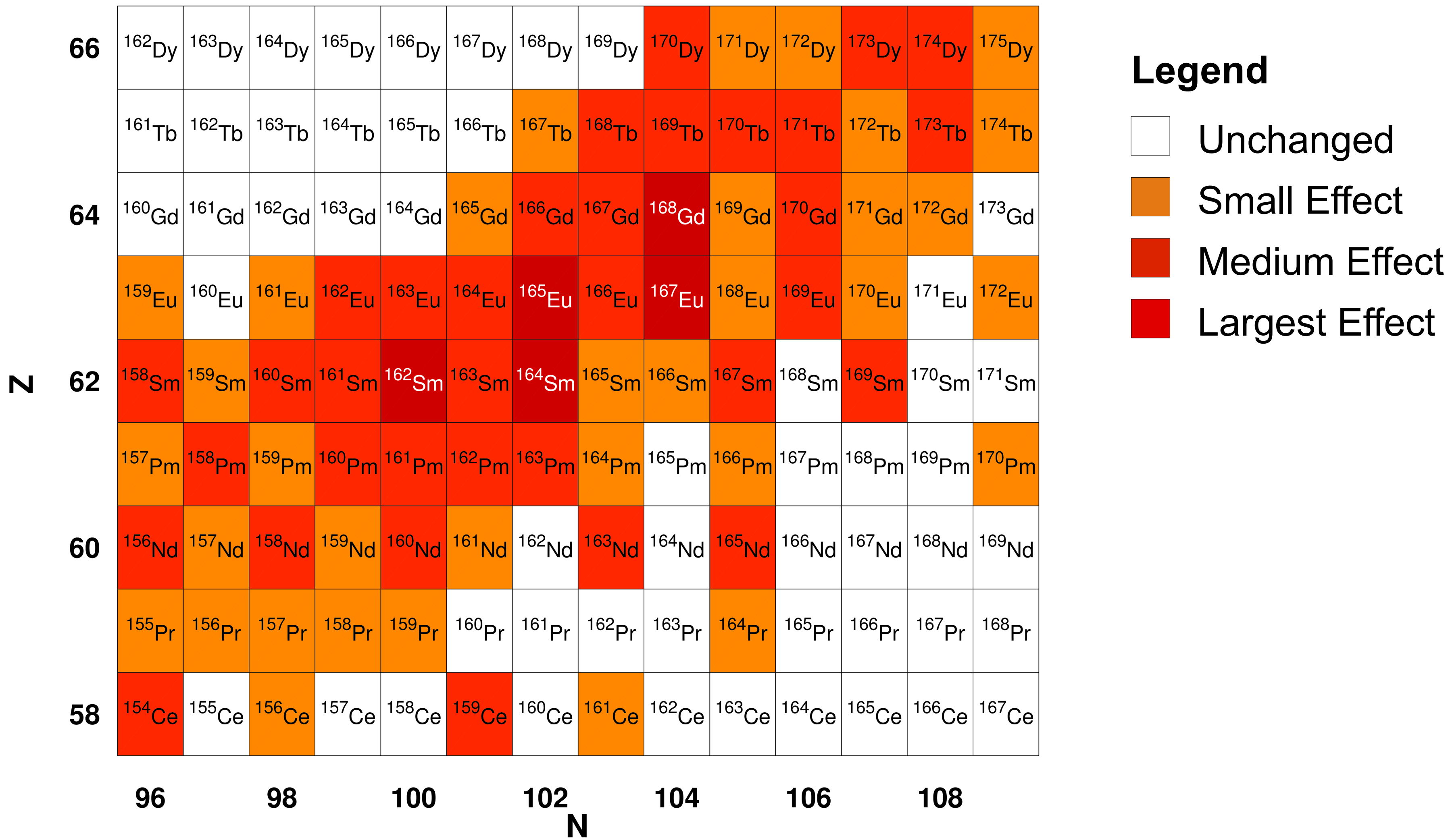
Cold Evolution

Each neutron capture rate changed by a factor of 10

Mumpower et al. (2012)

Important Neutron Capture Rates

Hot Evolution

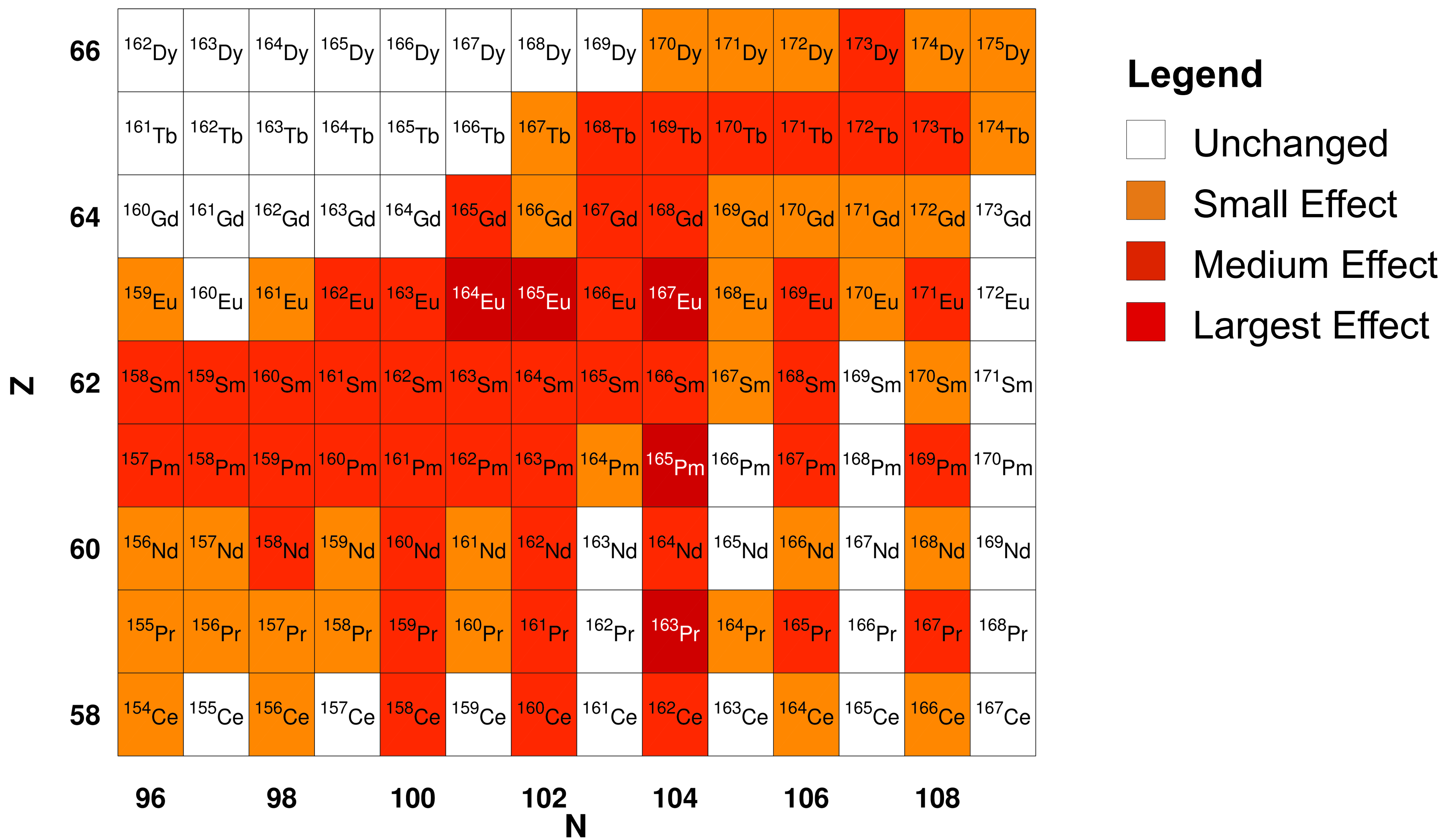


Each neutron capture rate changed by a factor of 10

Mumpower et al. (2012)

Important Neutron Capture Rates

Cold Evolution



Each neutron capture rate changed by a factor of 10

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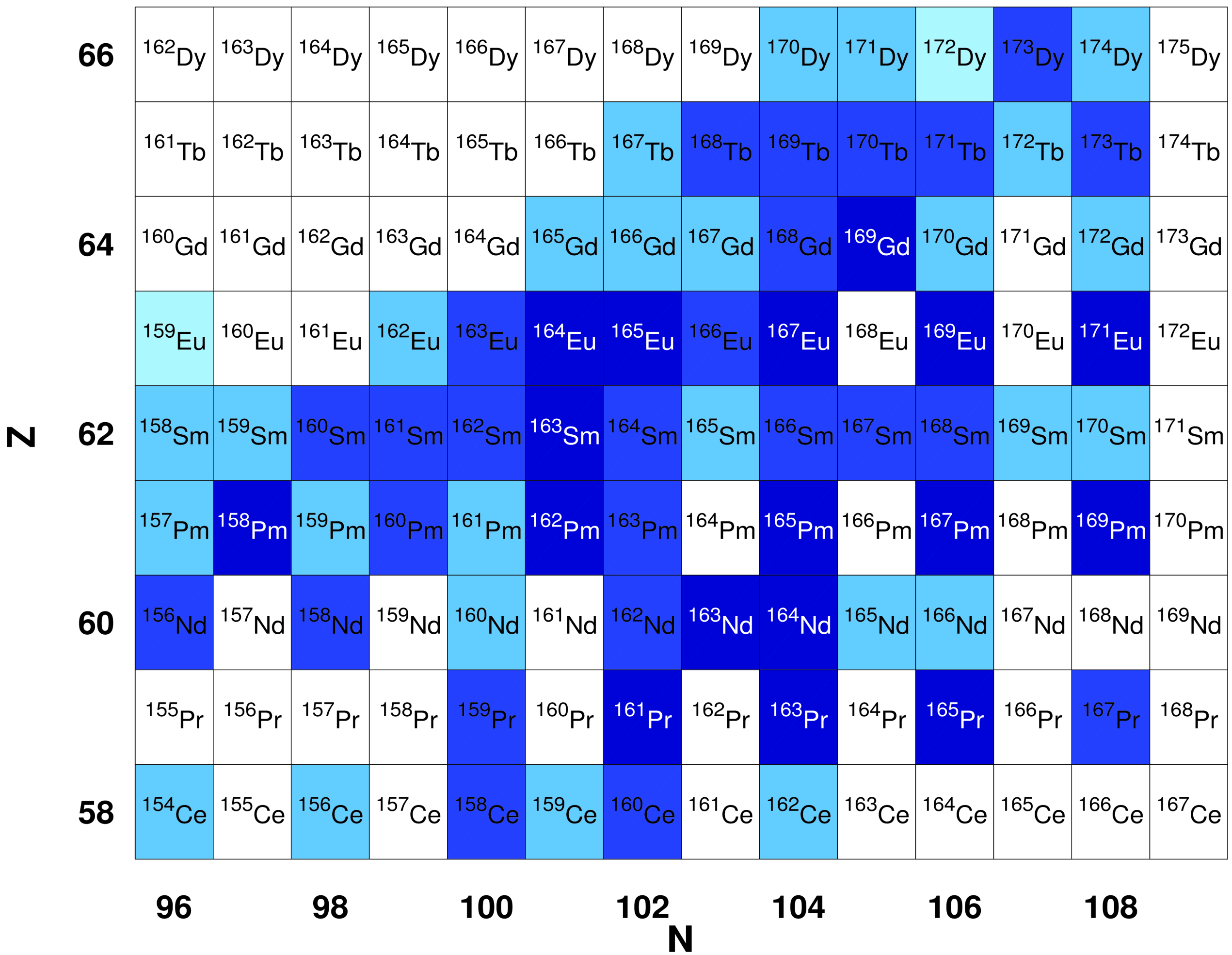
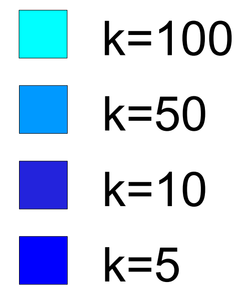
The Most Influential Rare Earth Neutron Capture Rates



Capture Rate Changed By Factor Of



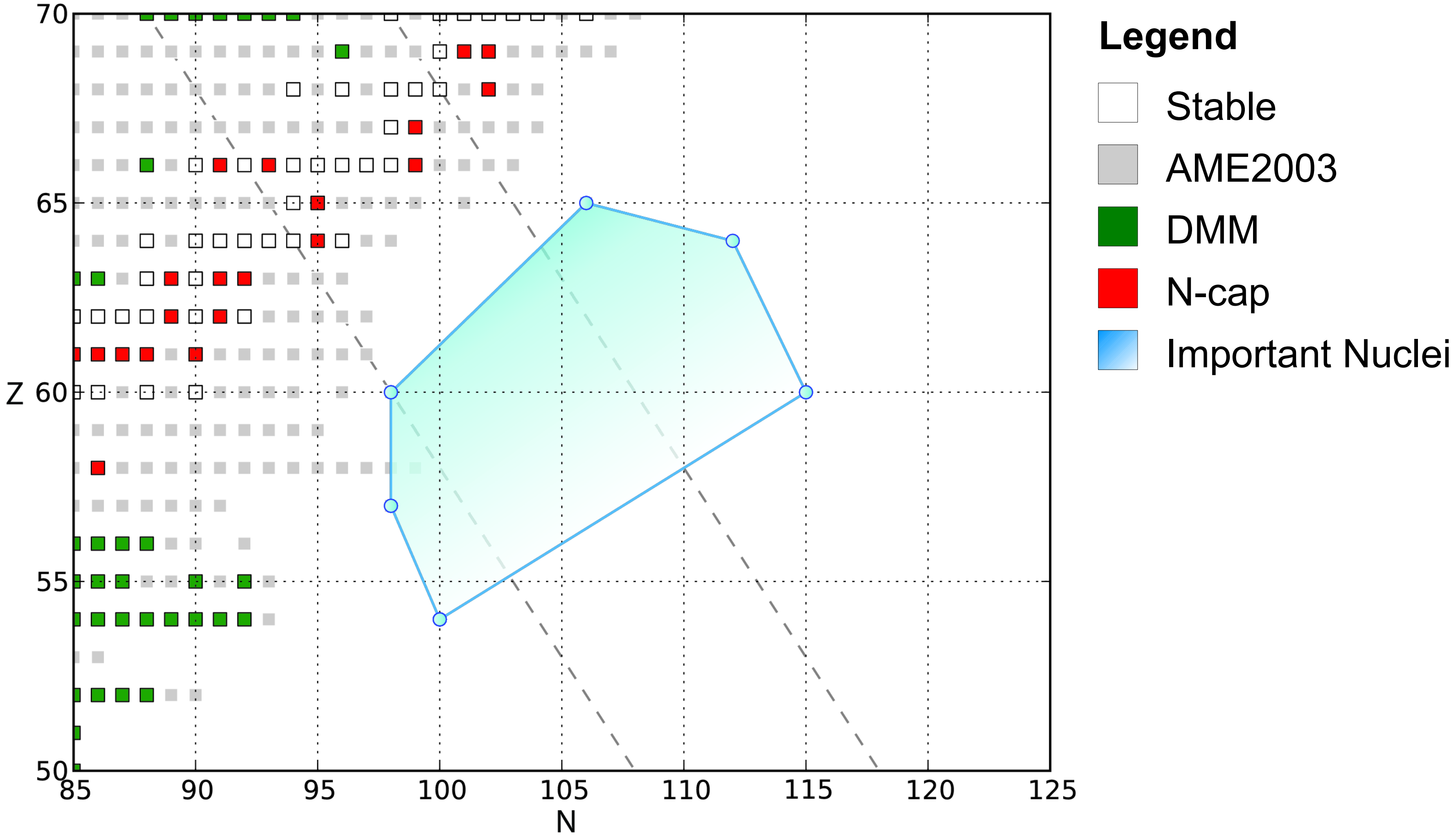
Changes final abundances by 200% locally (A ~ 2 to 4 units)

Considering a range of conditions and nuclear models

Mumpower et al. (2012)

Which Nuclei In The Rare Earth Peak Are Important?

Those nuclei 10-15 neutrons from stability



Mumpower et al. (2012)

The Rare Earth Peak:
An Overlooked *r*-Process Diagnostic

- Formation: delicate, out of equilibrium; sensitive to **thermodynamic conditions** (Neutron separation energies vs Neutron capture rates)

- Understanding neutron capture (at low R) is critical:

  Form / dissolve peak, late time neutron capture effect, uncertainties

- Successful formation → New insights into freeze-out conditions

- Important nuclei 10-15 neutrons from stability