The Rare Earth Peak:
an overlooked r-process diagnostic

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INT 12-2a Core Collapse Supernovae:
Models and Observable Signals
Institute of Nuclear Theory
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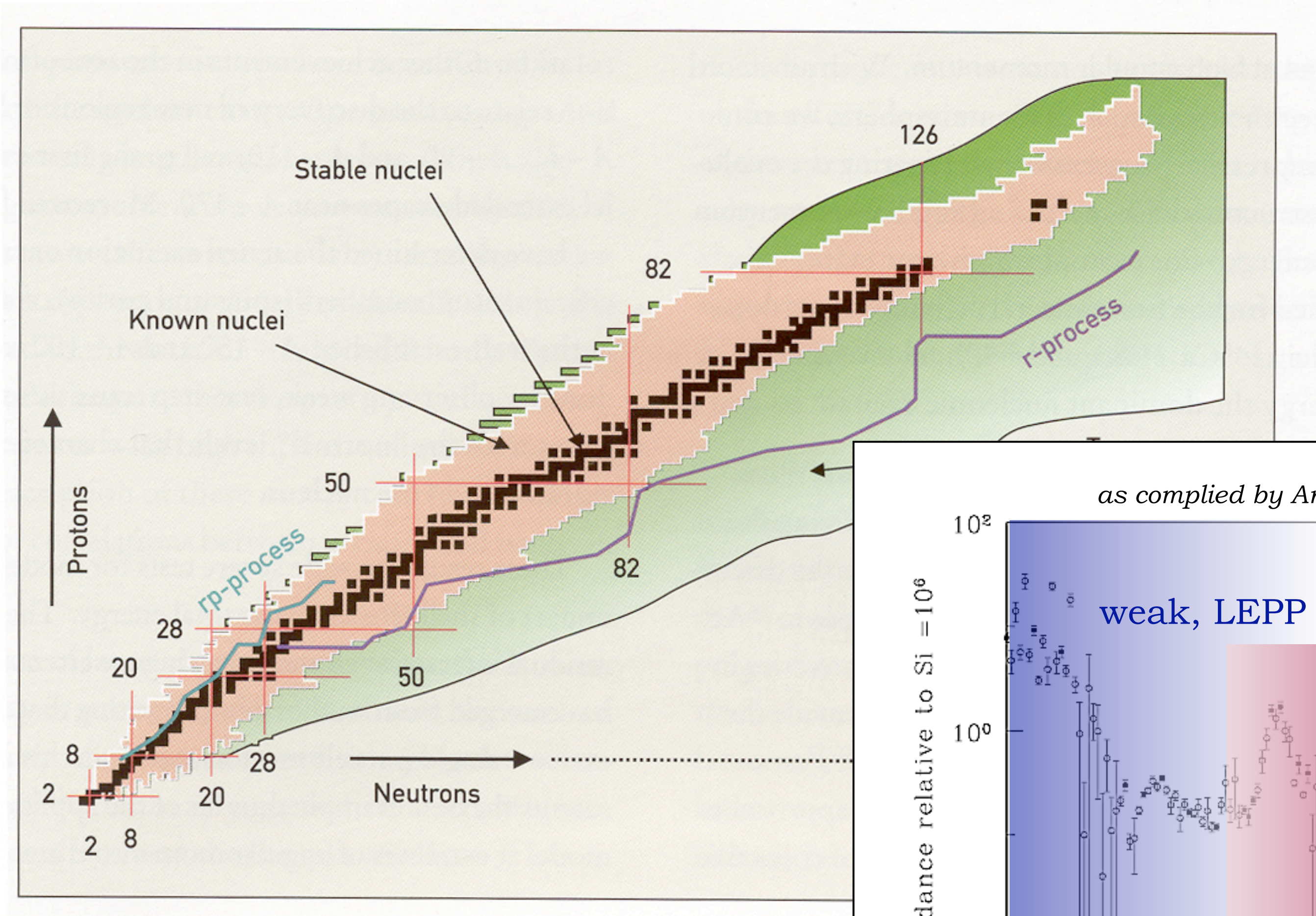
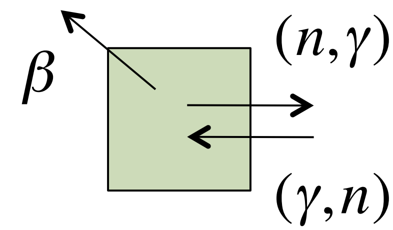
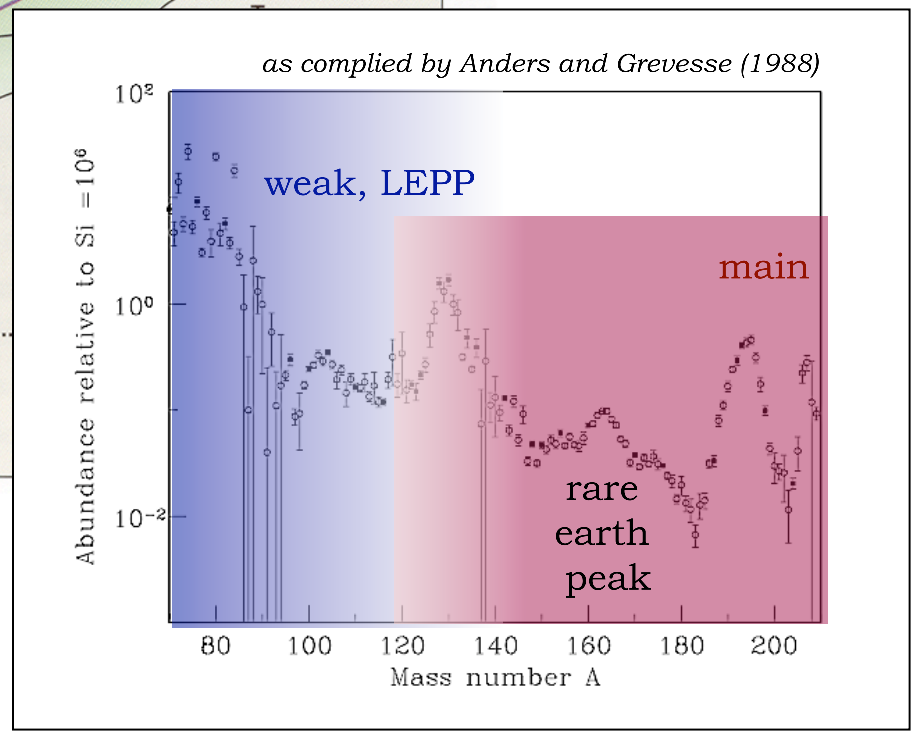
rapid neutron capture nucleosynthesis

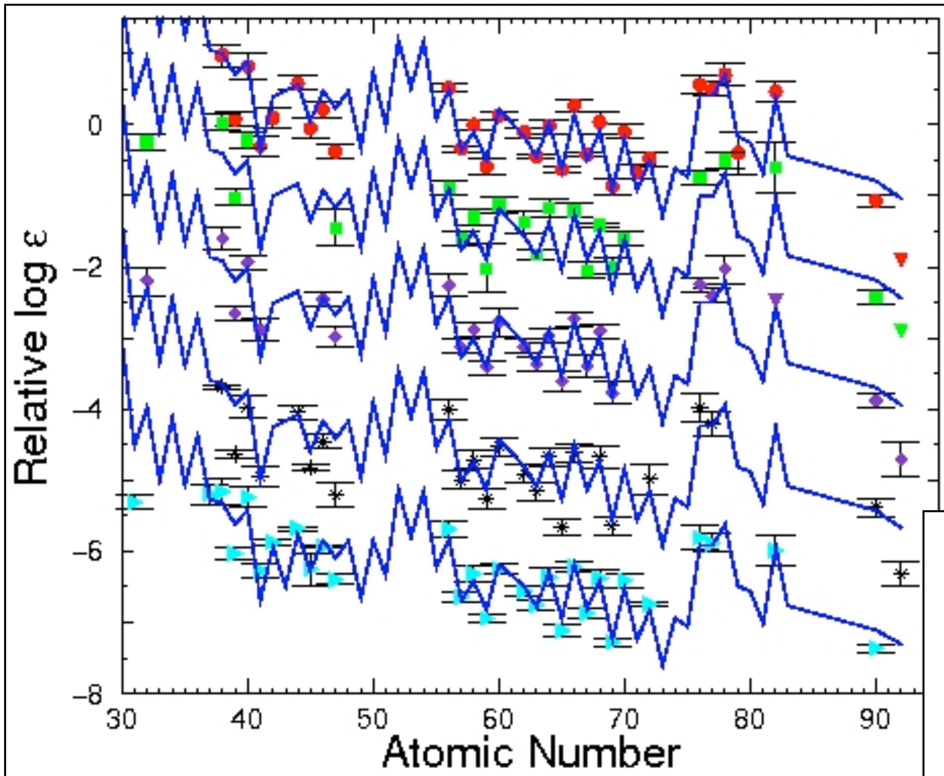






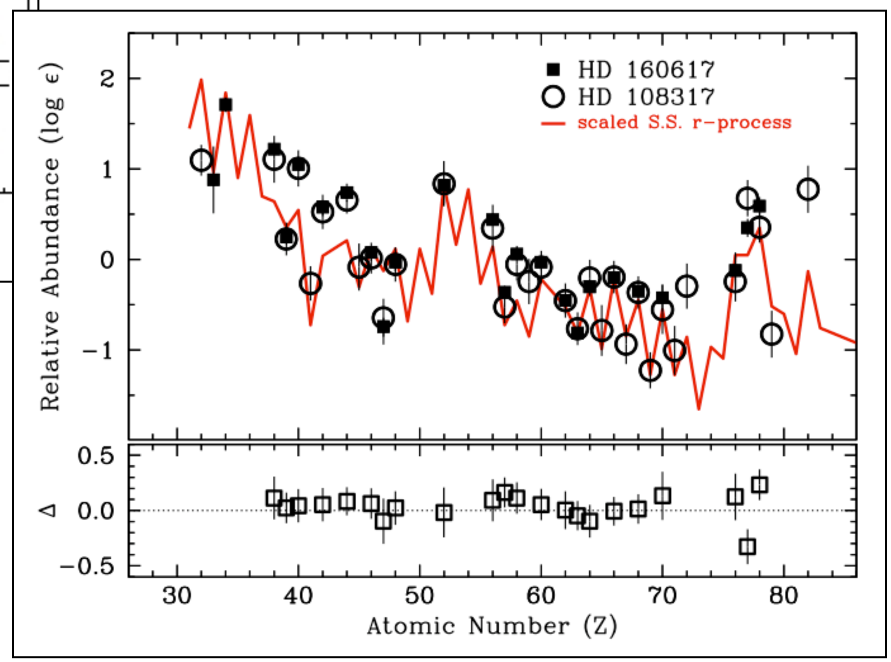
solar *r*-process
abundances

r-process nucleosynthesis: an observable signal of supernovae?



Cowan (2008)

Sample halo star *r*-process elemental abundances compared to solar



Roederer & Lawler (2012)

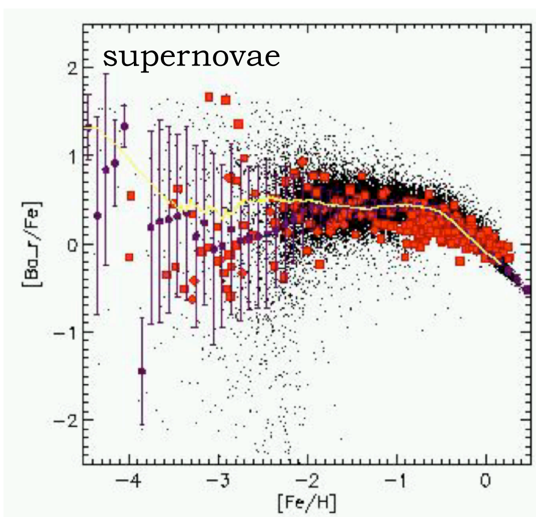
Several environments within NS-NS or BH-NS mergers have been found to be attractive *r*-process sites

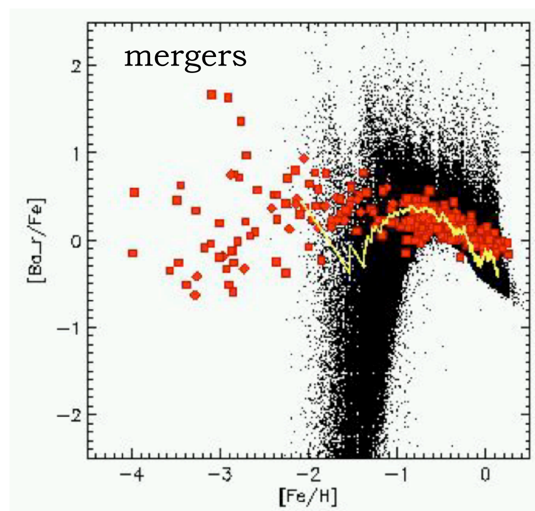
e.g., Lattimer & Schramm (1974, 1976), Meyer (1989), Frieburghaus et al (1999), Goriely et al (2005), Surman et al (2005), Oechslin et al (2007), Surman et al (2008), Nakamura et al (2011), Goriely et al (2012), Korobkin et al (2012)

…but the timescale for mergers to develop appears inconsistent with the data

e.g., Sneden et al (1996), Ryan et al (1996), Truran et al (2002), Argast et al (2004), Wanajo & Ishimaru (2006)

Argast et al (2004)





Some suggested supernova *r*-process sites:

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), etc., etc.*

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

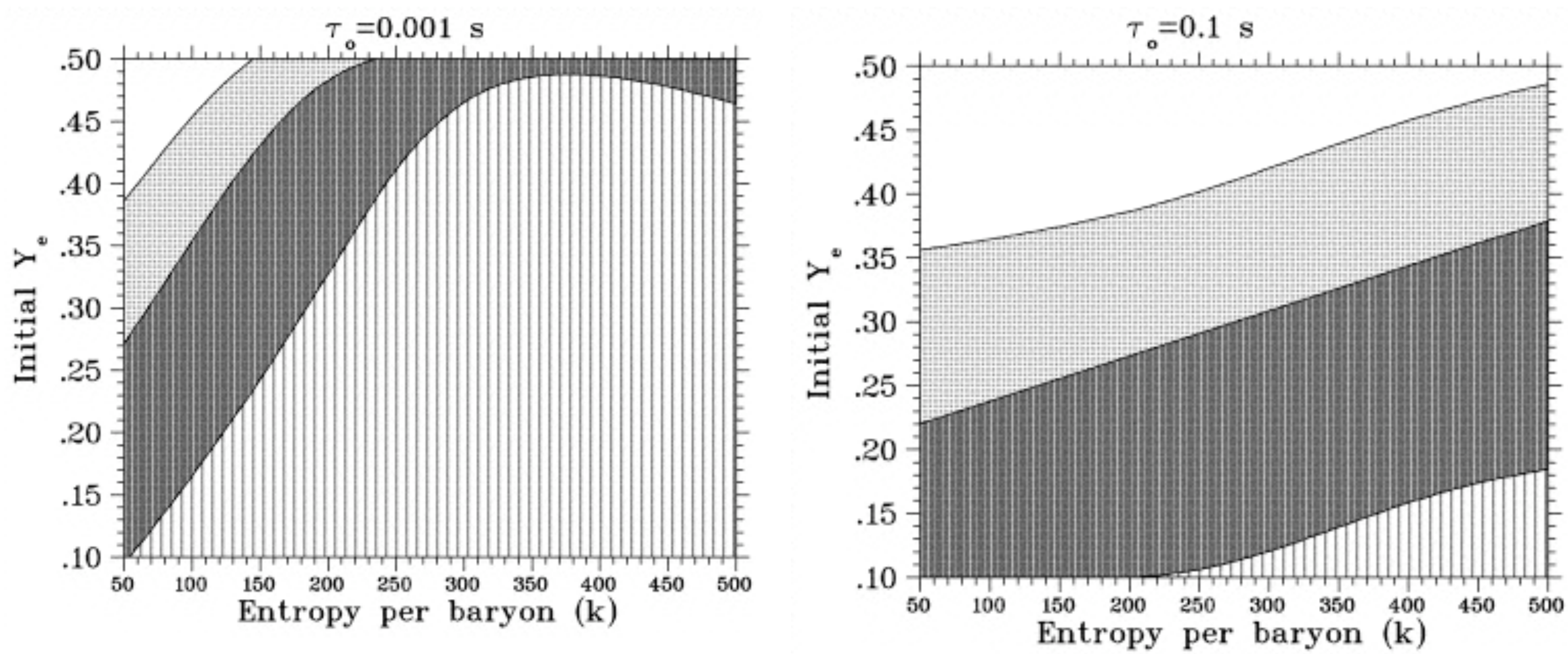
He shells in low metallicity SNe *e.g., Epstein et al (1988), Nadyozhin & Panov (2008), Banerjee et al (2011)*

neutron-rich jets *e.g., Cameron (2003), Nishimura et al (2006), Fujimoto et al (2008), Winterer et al (2012)*

Key quantities:

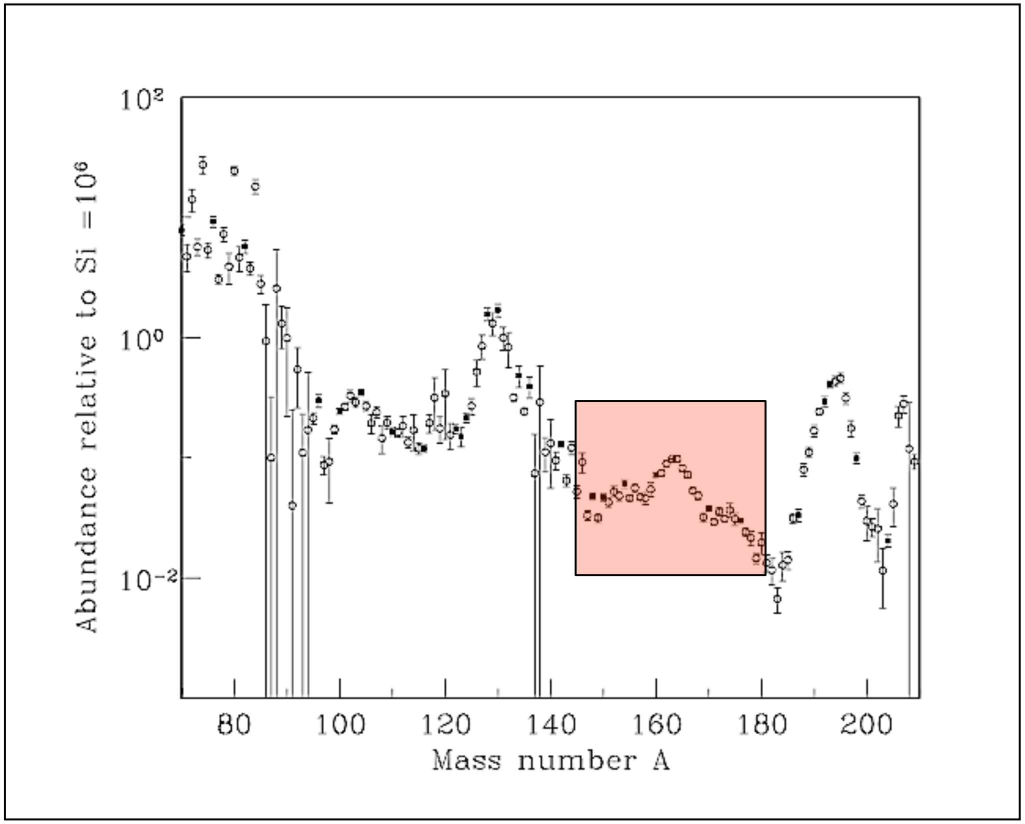
- electron fraction Y_e
- entropy s/k
- dynamic timescale τ

} neutron to seed ratio R

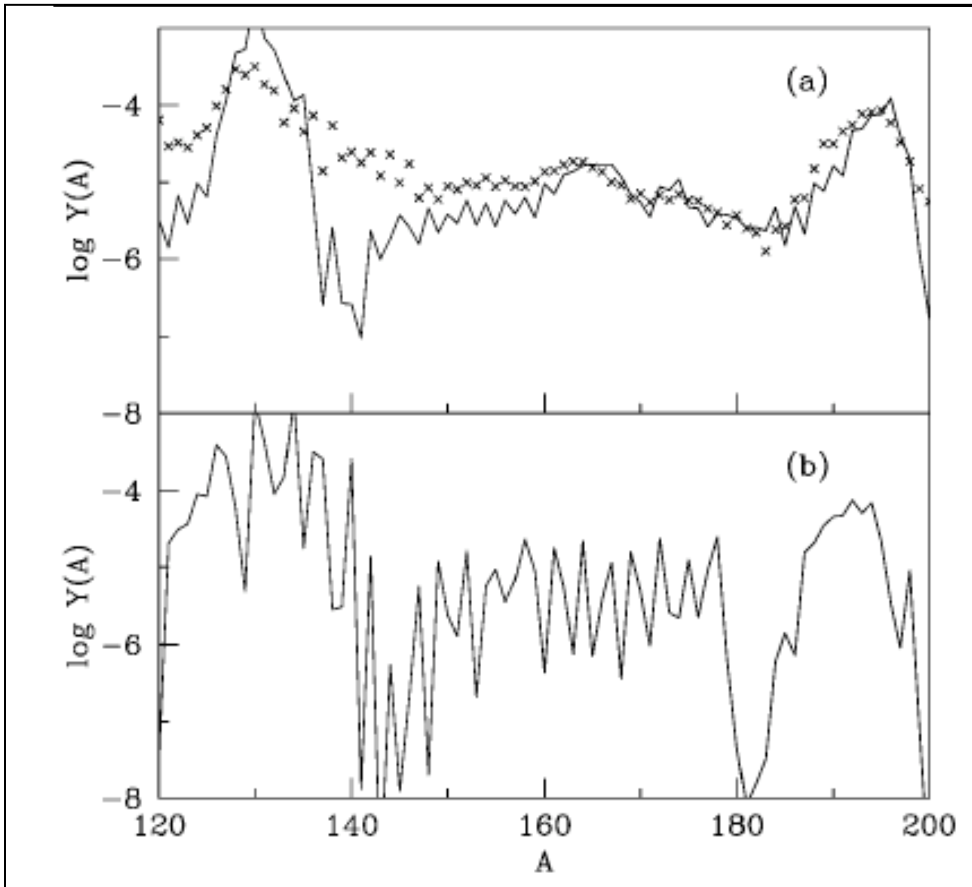


Meyer and Brown (1997)

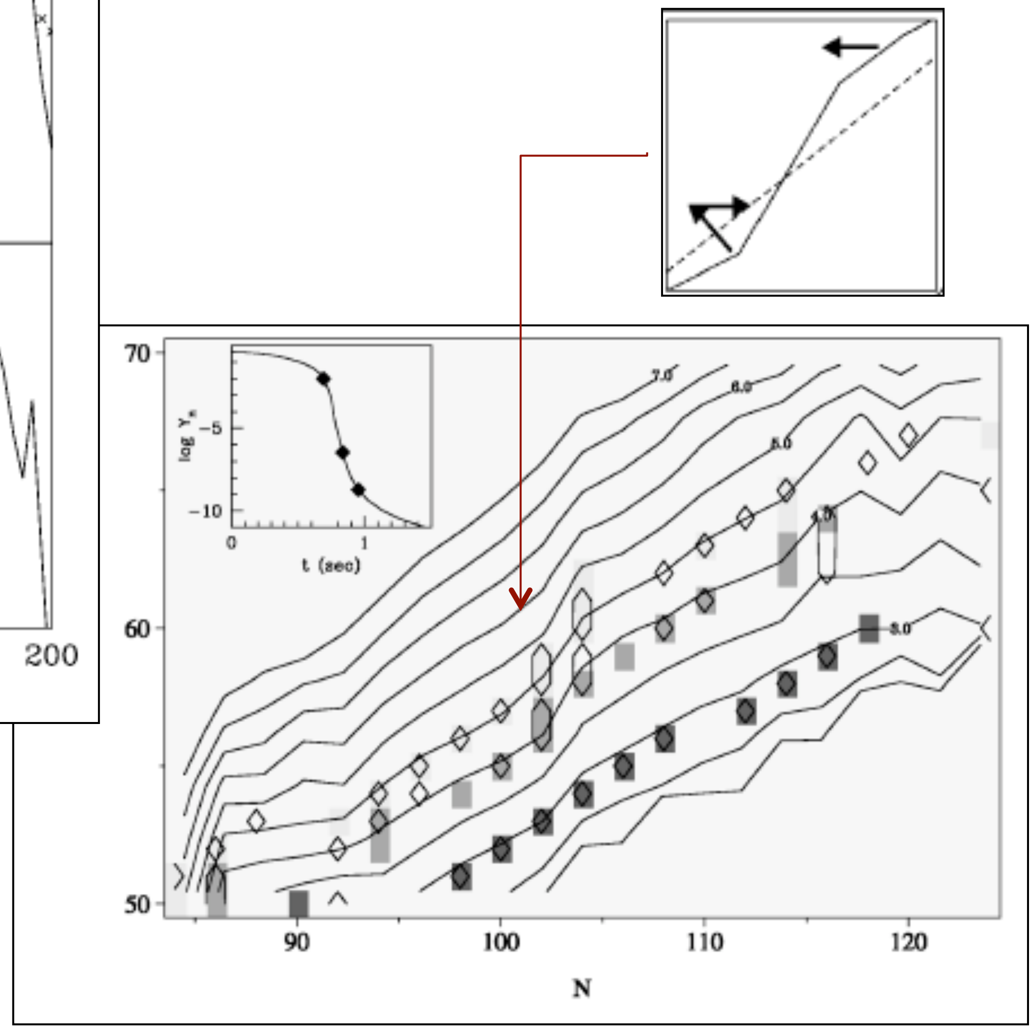
the rare earth peak



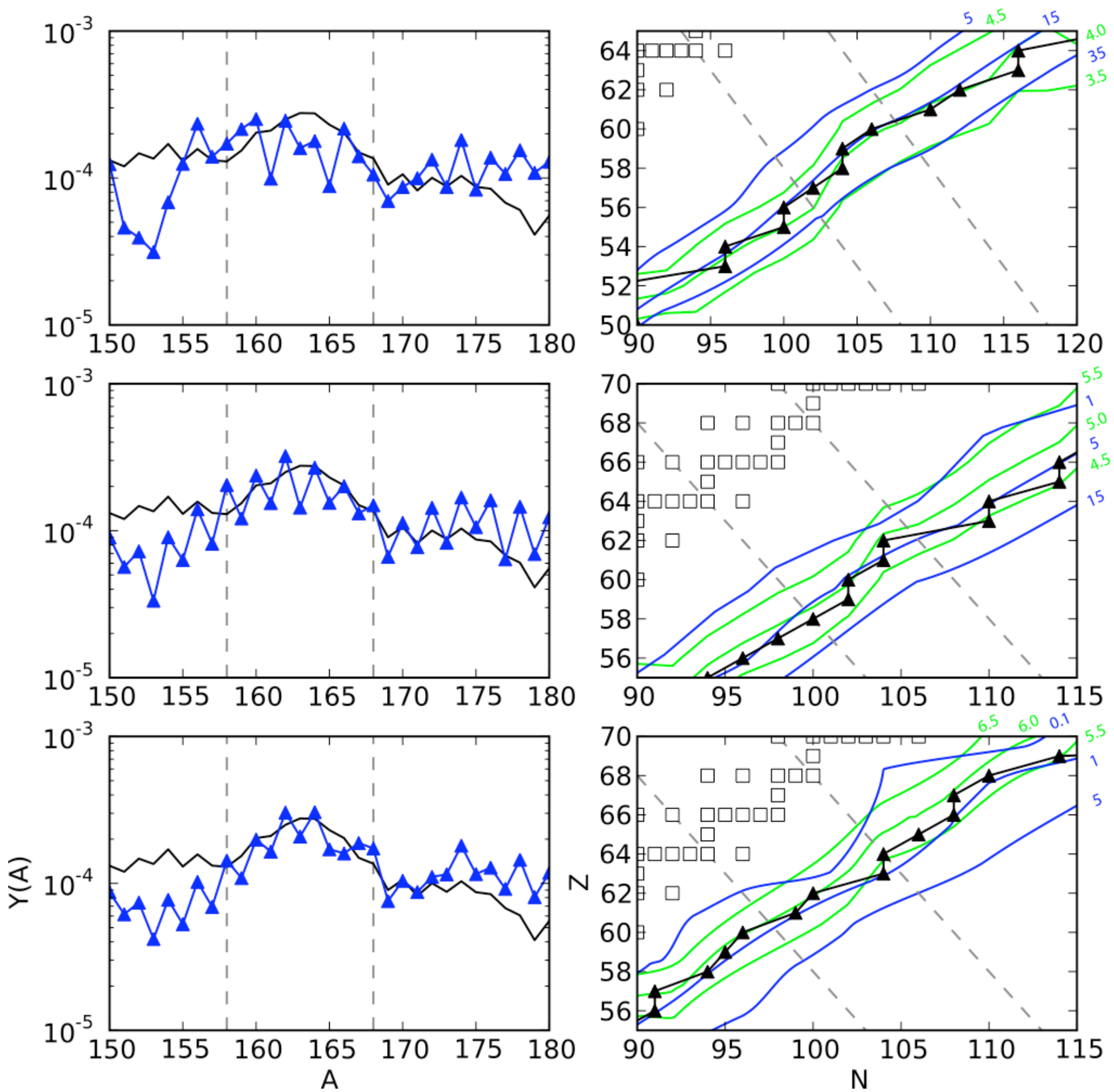
rare earth peak formation mechanism: hot *r*-process



Surman, Engel, Bennett, Meyer (1997)



rare earth peak formation mechanism: hot *r*-process

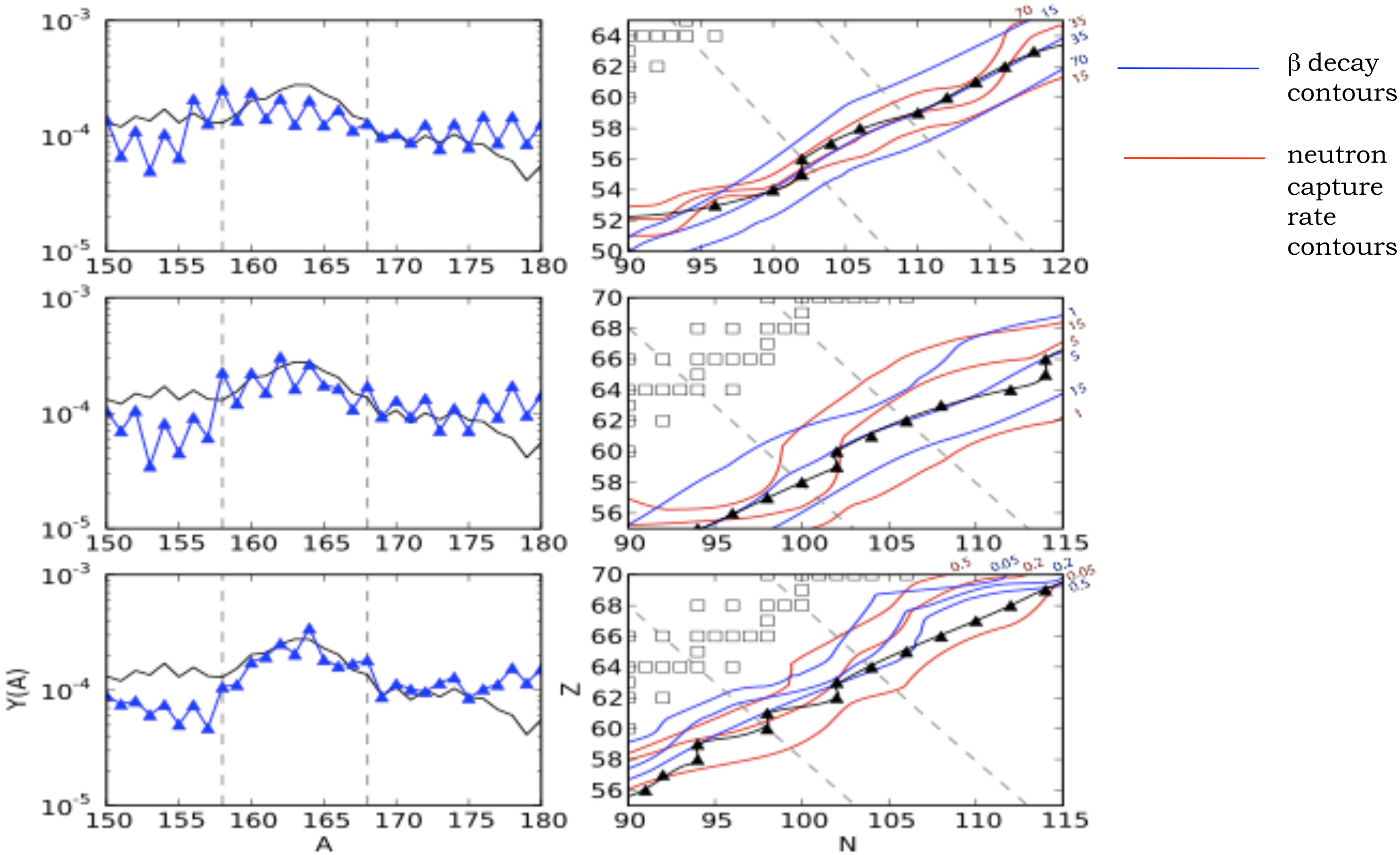


β decay contours

neutron separation energy contours

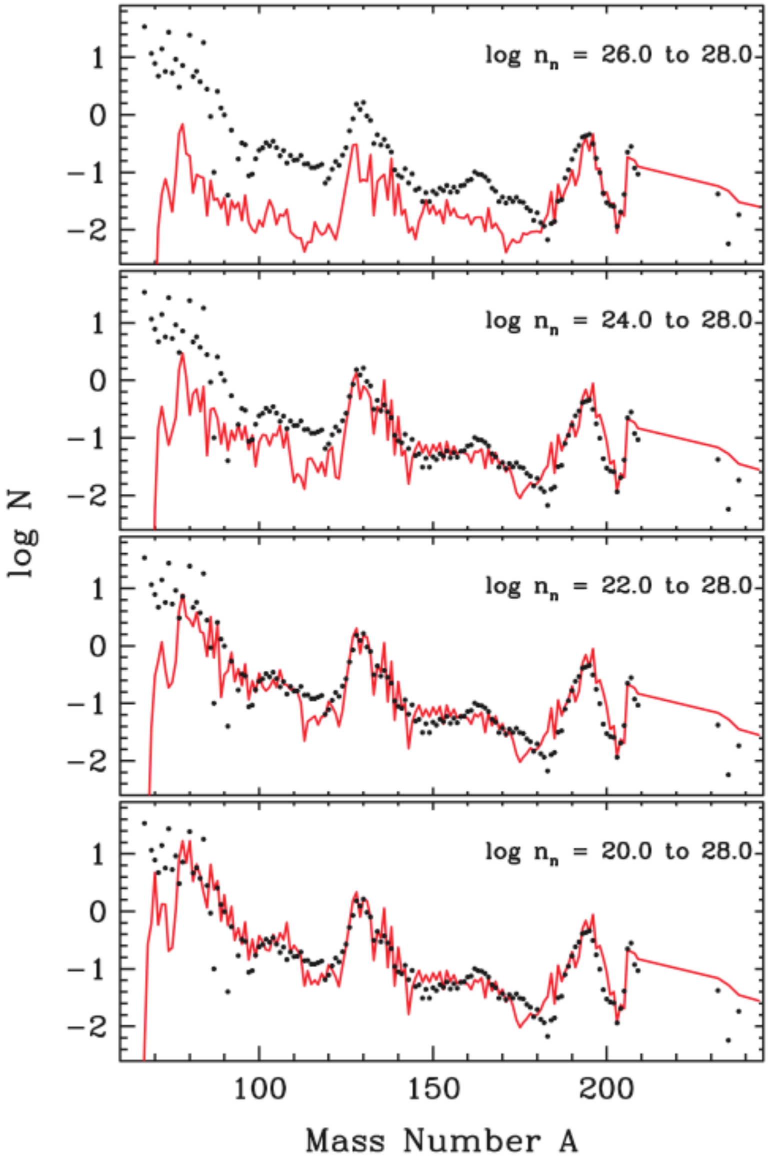
Mumpower, McLaughlin, and Surman, PRC (2012)

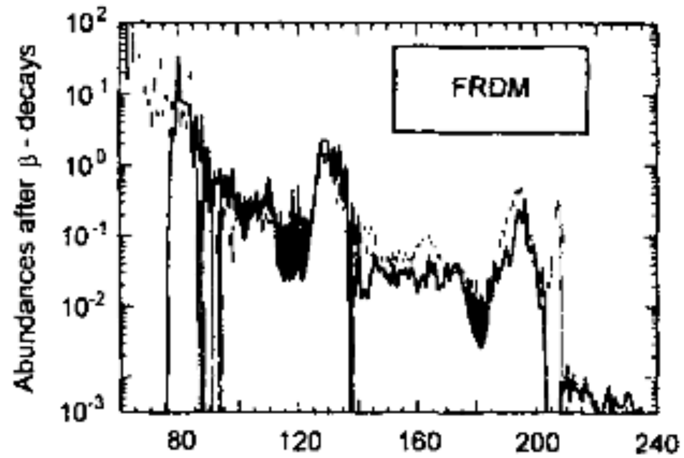
rare earth peak formation mechanism: cold *r*-process



Mumpower, McLaughlin, and Surman, PRC (2012)

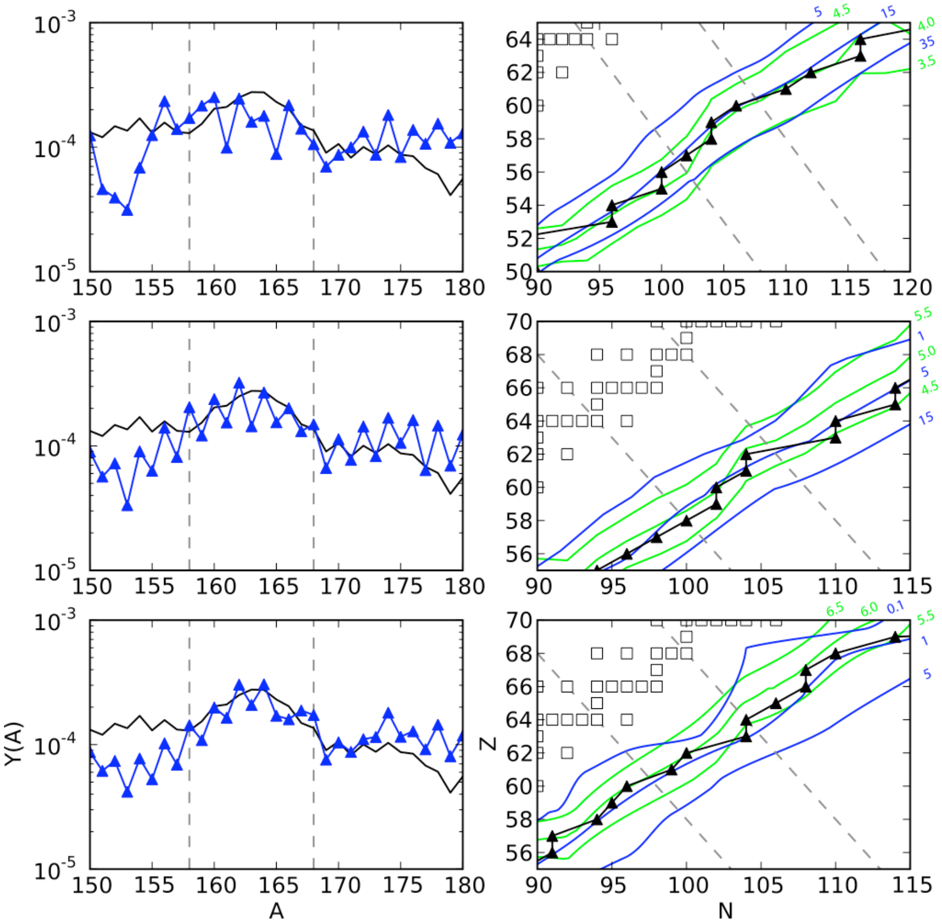
rare earth peak formation requirements: dynamics





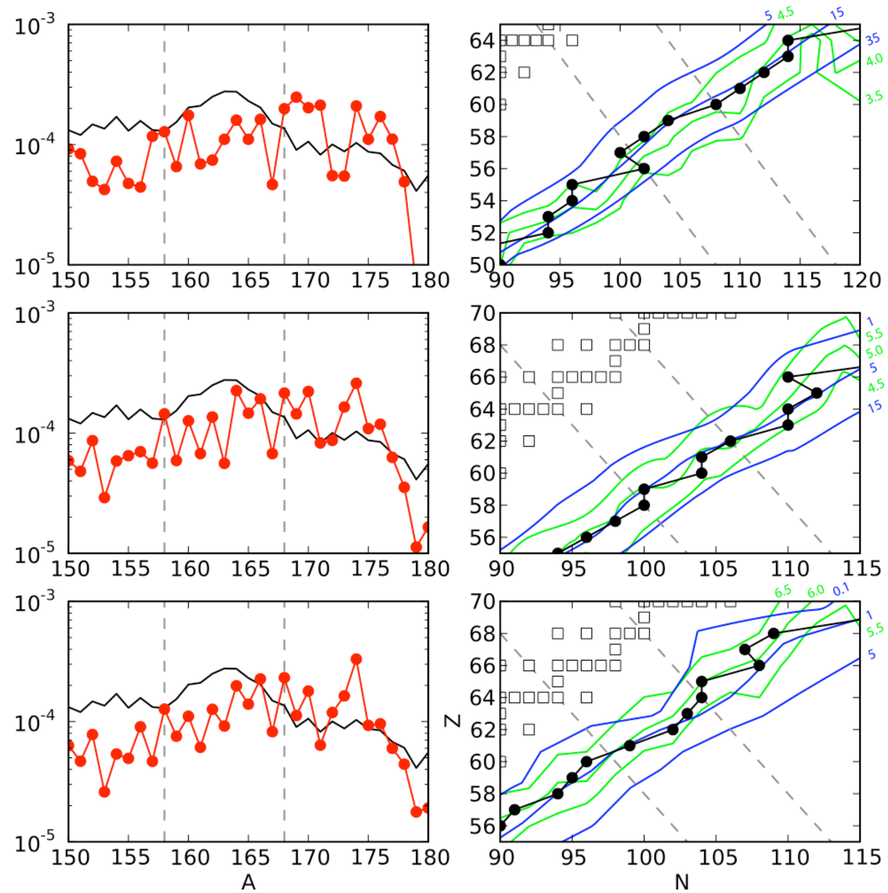
multiple components, instantaneous freezeout from (n,γ)-(γ,n) equilibrium, e.g. Kratz et al

rare earth peak formation requirements: nuclear data

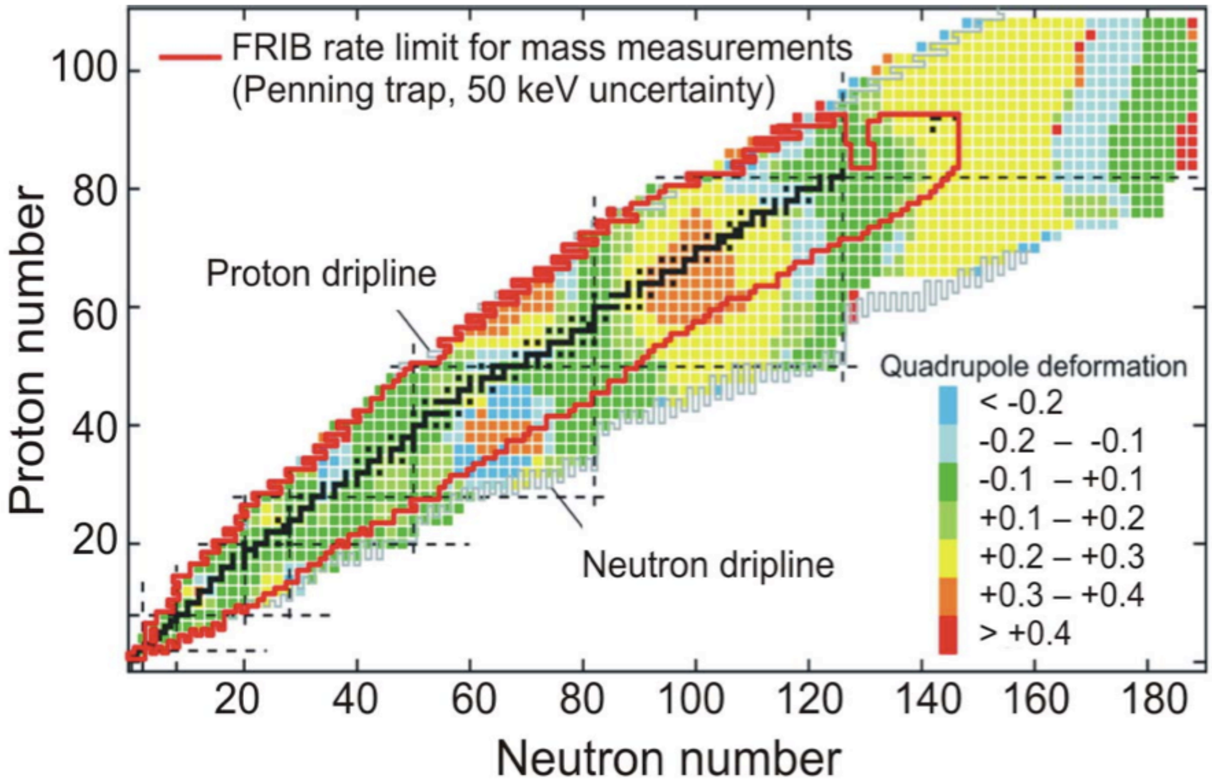


FRDM

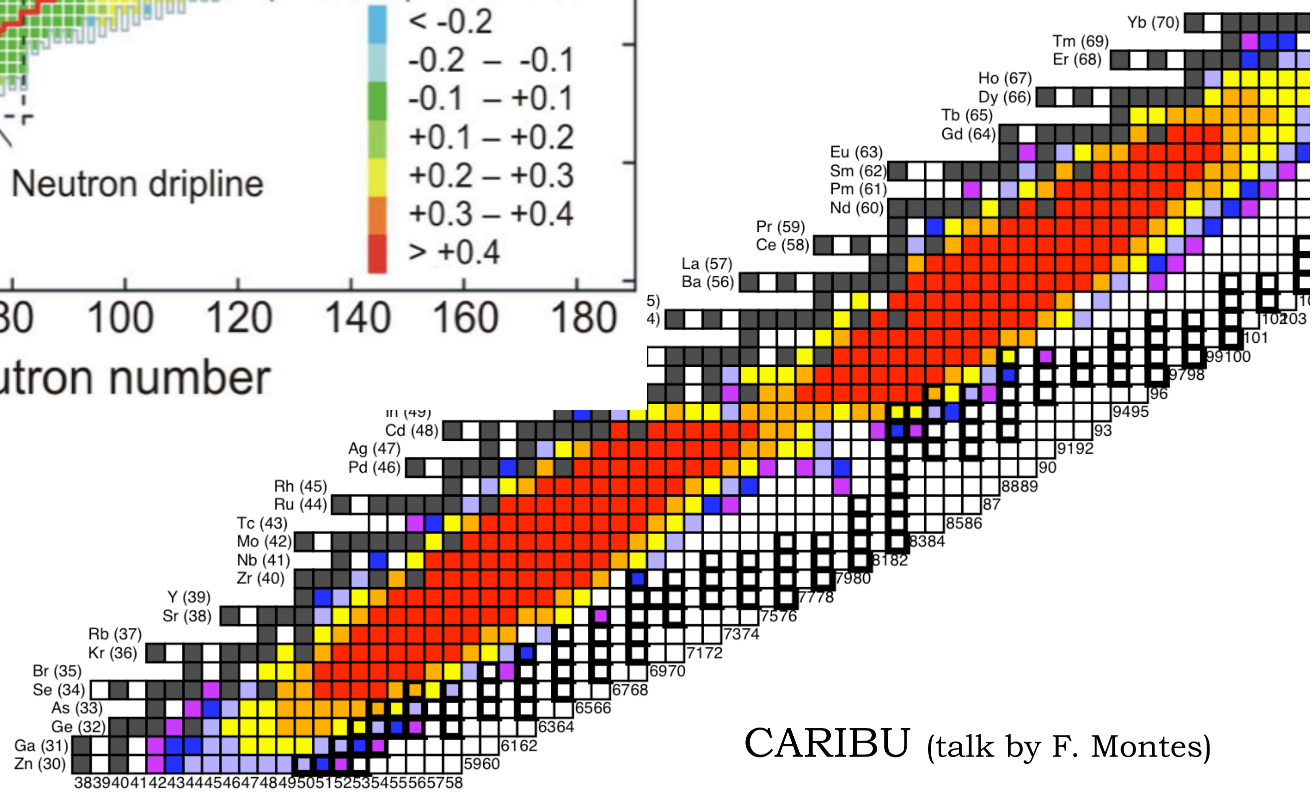
HFB-17



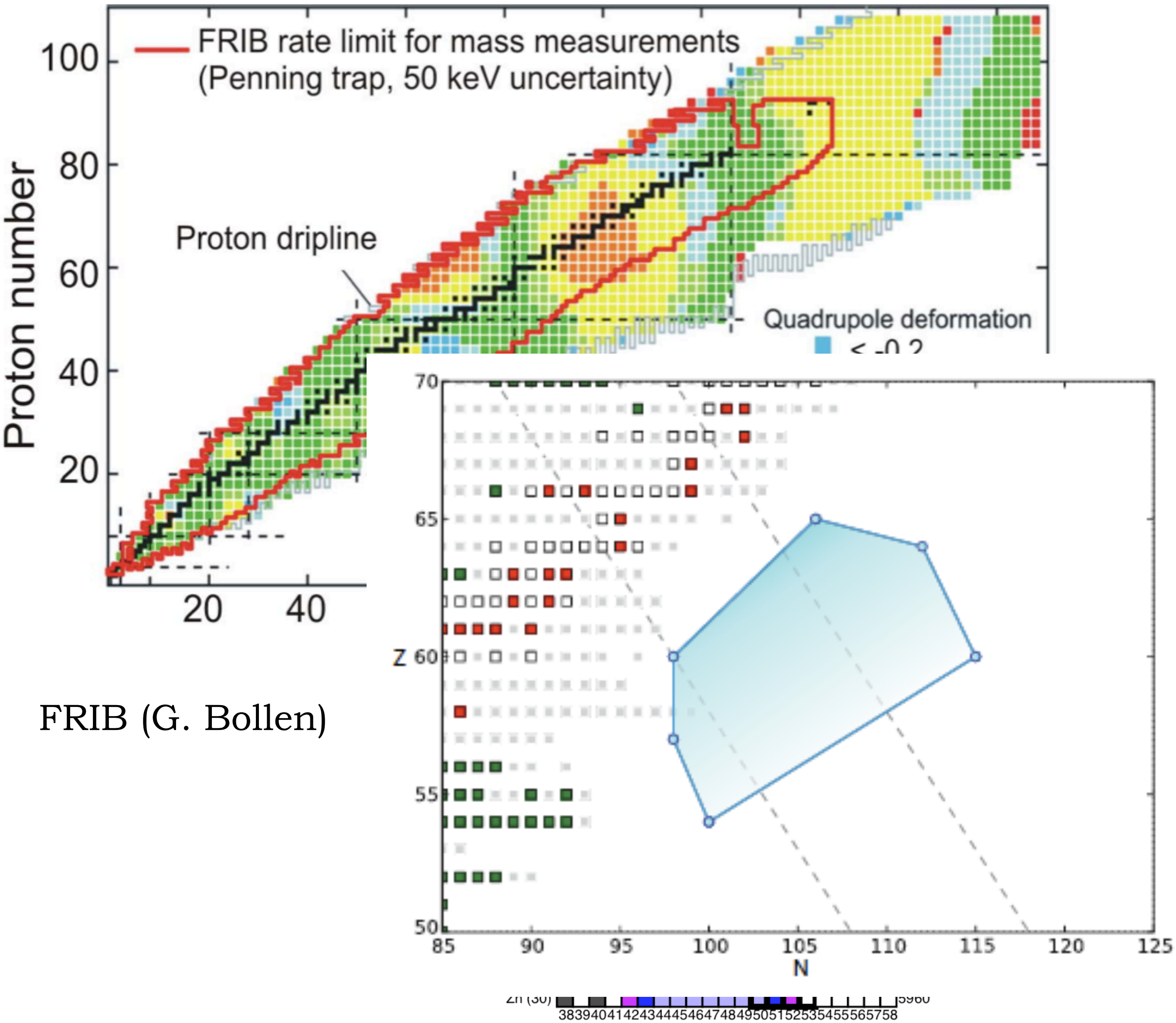
Mumpower, McLaughlin, and Surman, PRC (2012)



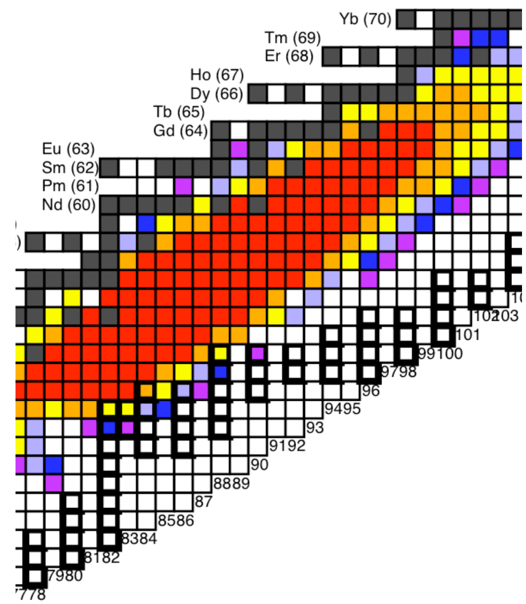
FRIB (talk by G. Bollen)



CARIBU (talk by F. Montes)

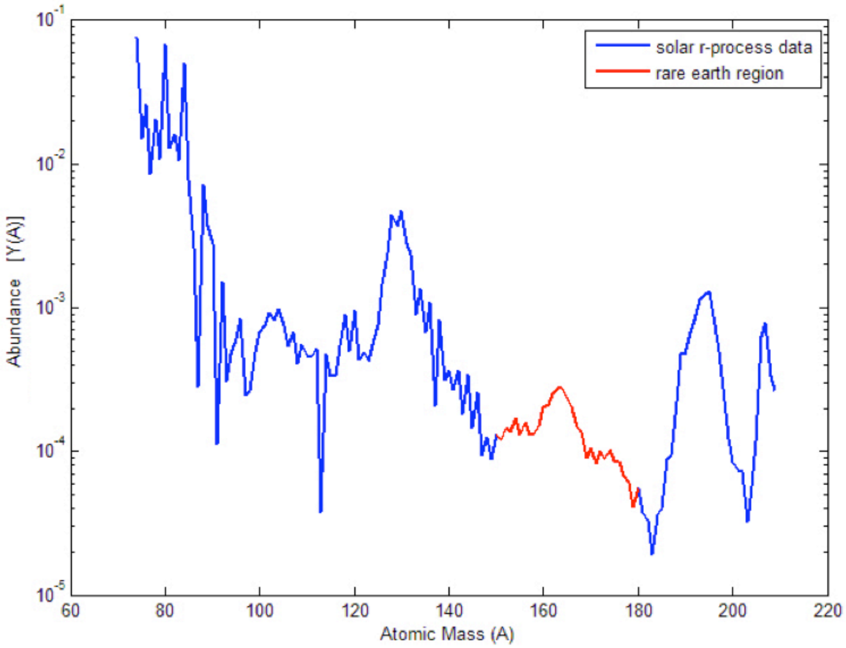


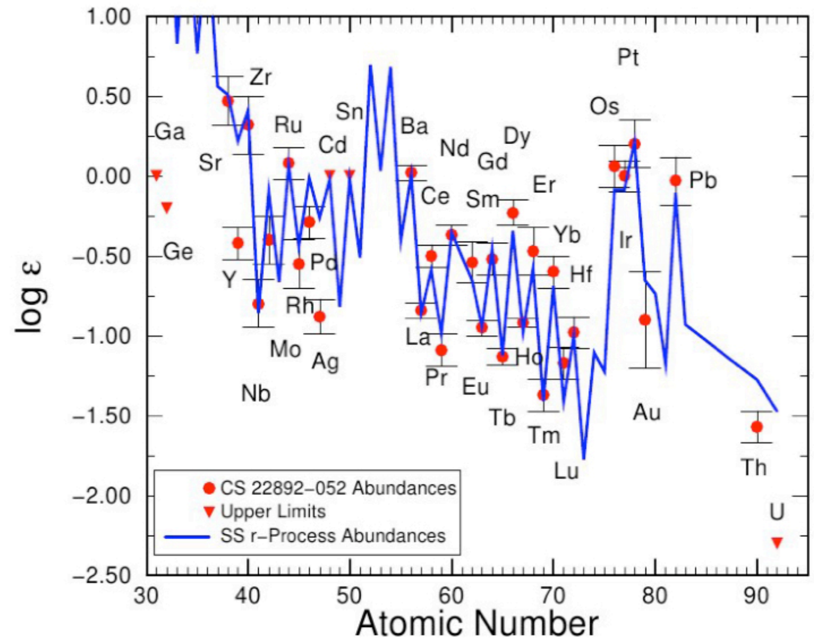
FRIB (G. Bollen)



CARIBU (F. Montes)

Can we use our understanding of rare earth peak formation to further constrain the *r*-process astrophysical site?





Mumpower, McLaughlin, Surman, ApJ (2012)

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

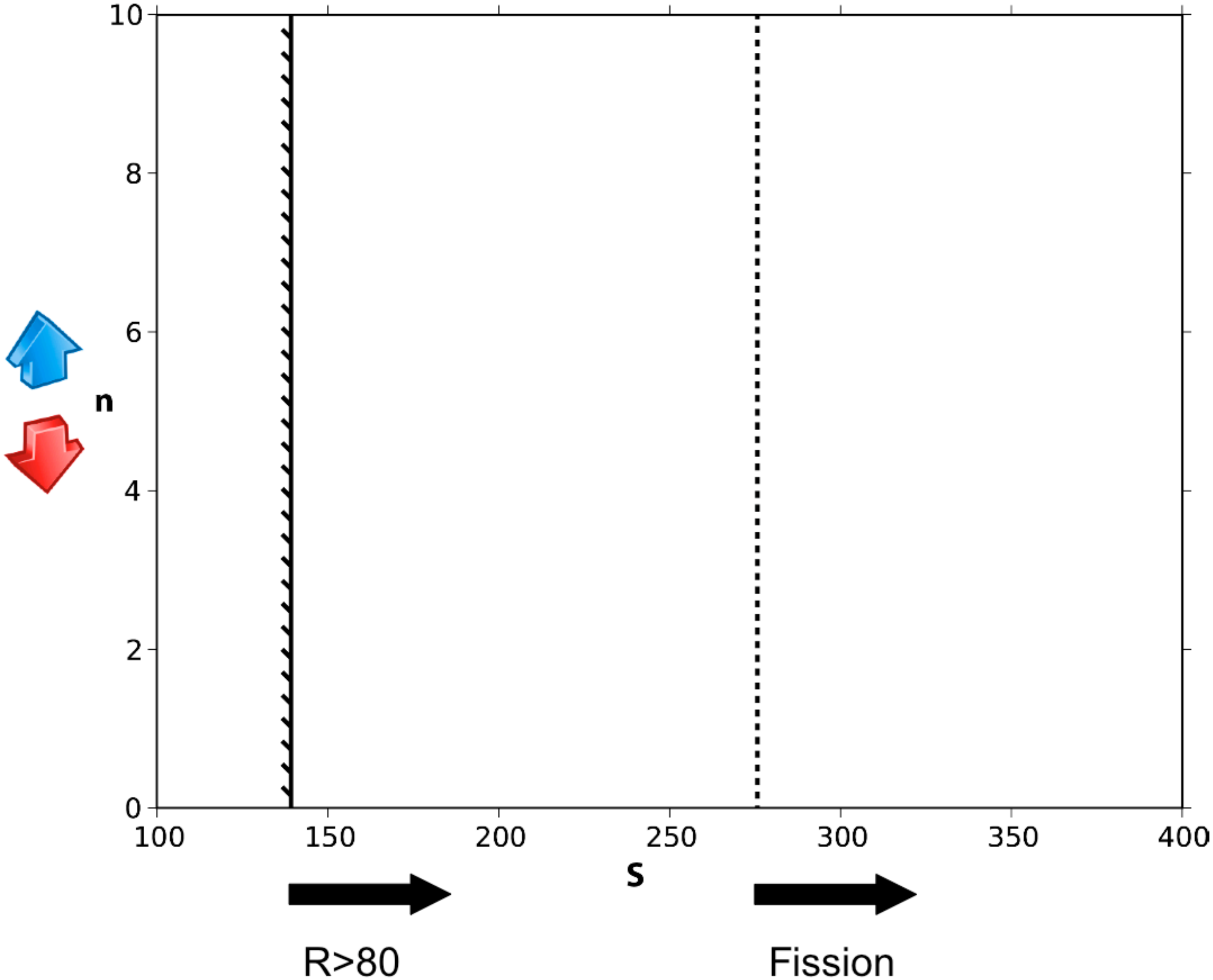
based on Meyer (2002), except power law *n* allowed to vary

1<*n*<5 : hot r-process

5<*n*<10: cold r-process

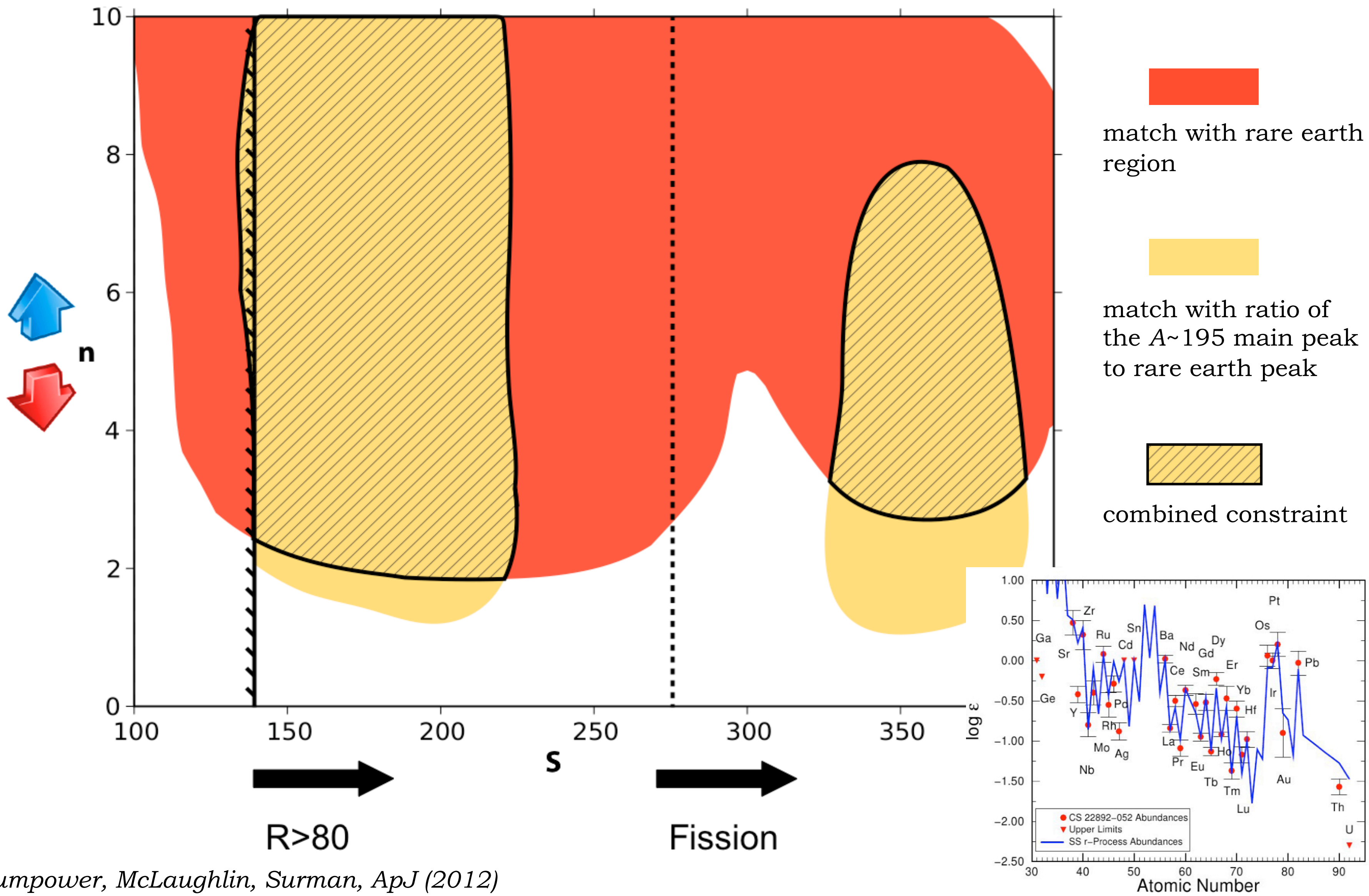
Set τ = 80 ms, Y_e = 0.30 or 0.40, nuclear model (FRDM)

Vary *s*/*k* ~ 50-400, *n* ~ 0-10



$Y_e = 0.30$

new constraint: compare rare earth elements to halo star



Mumpower, McLaughlin, Surman, ApJ (2012)

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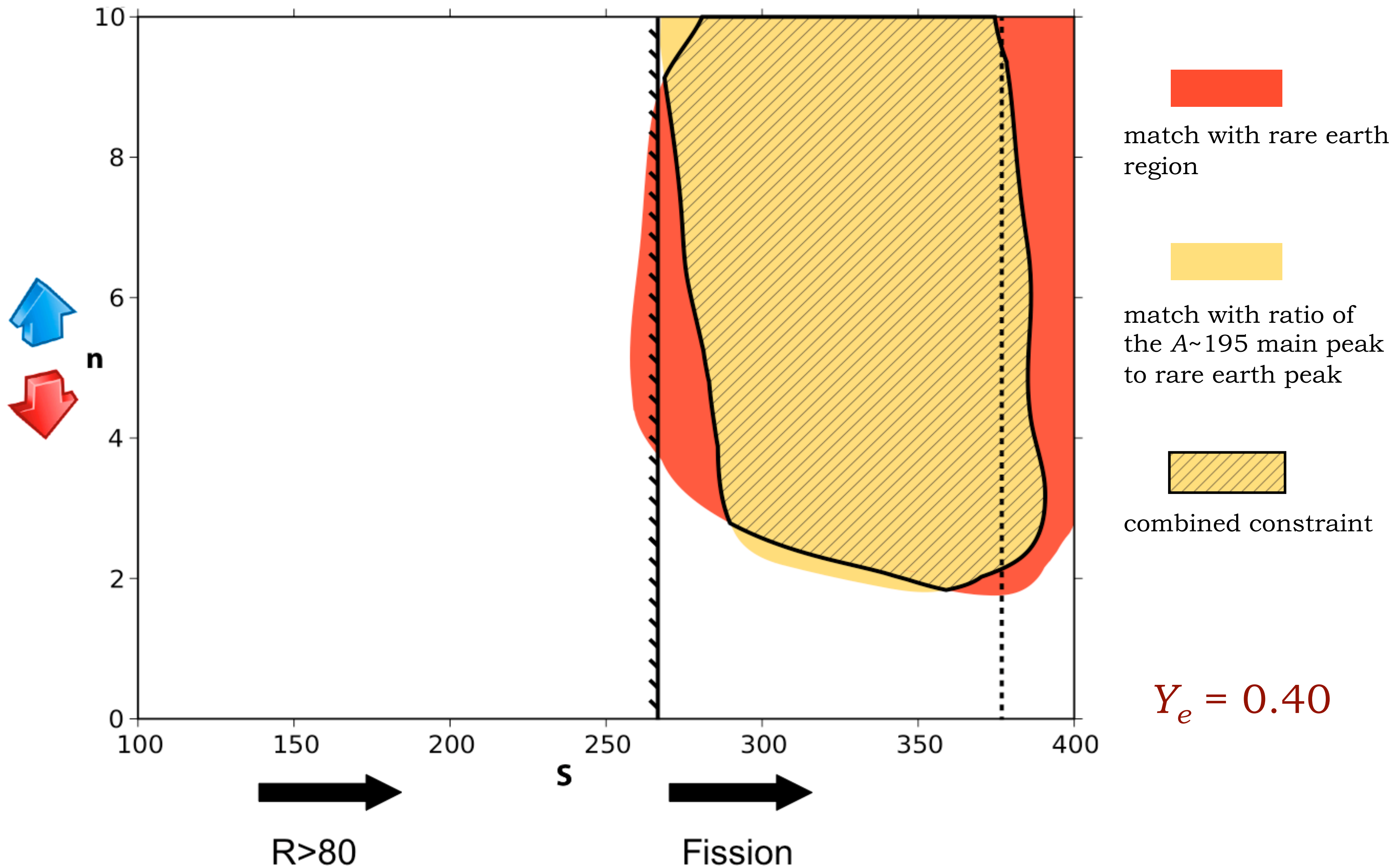
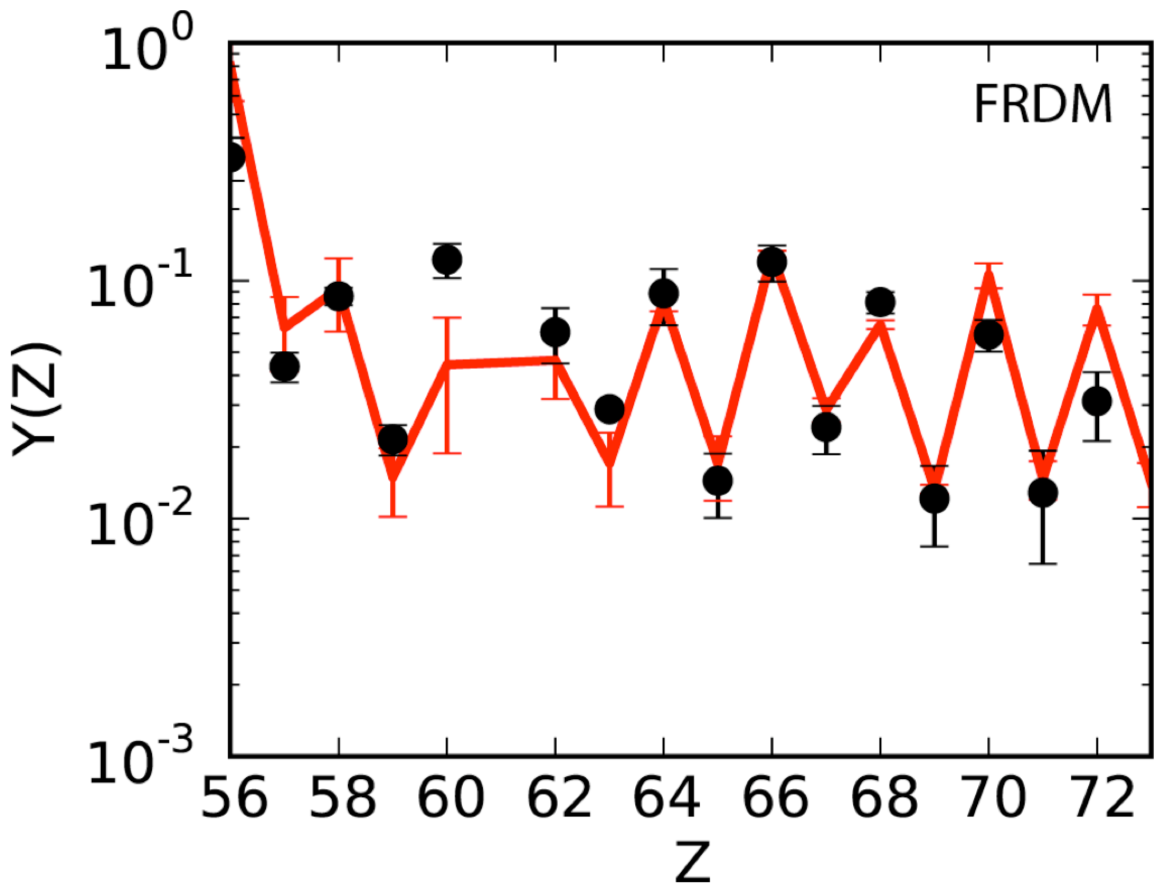


Mumpower, McLaughlin, Surman, ApJ (2012)

average abundance pattern compared to halo star data



Mumpower, McLaughlin, Surman, ApJ (2012)

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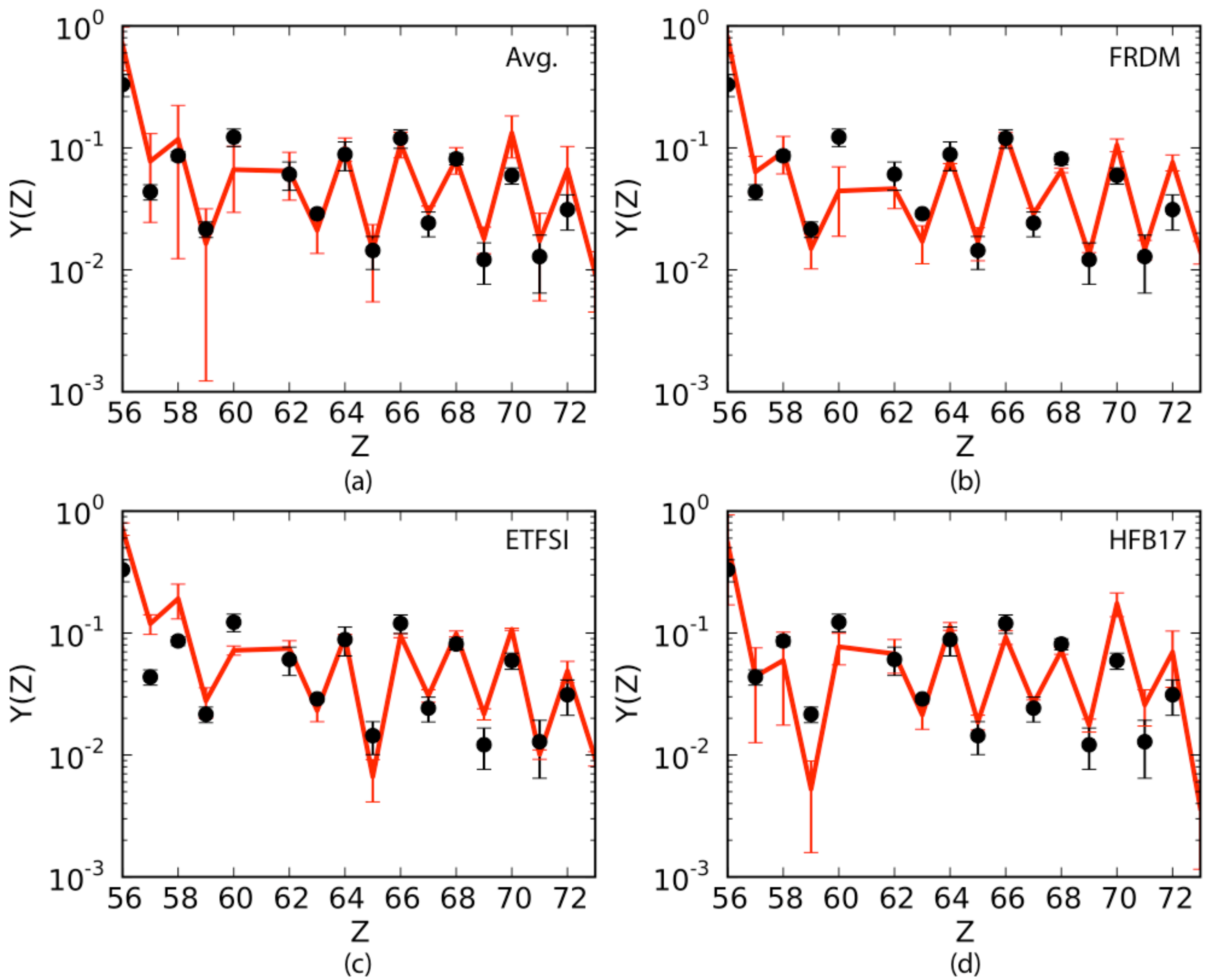
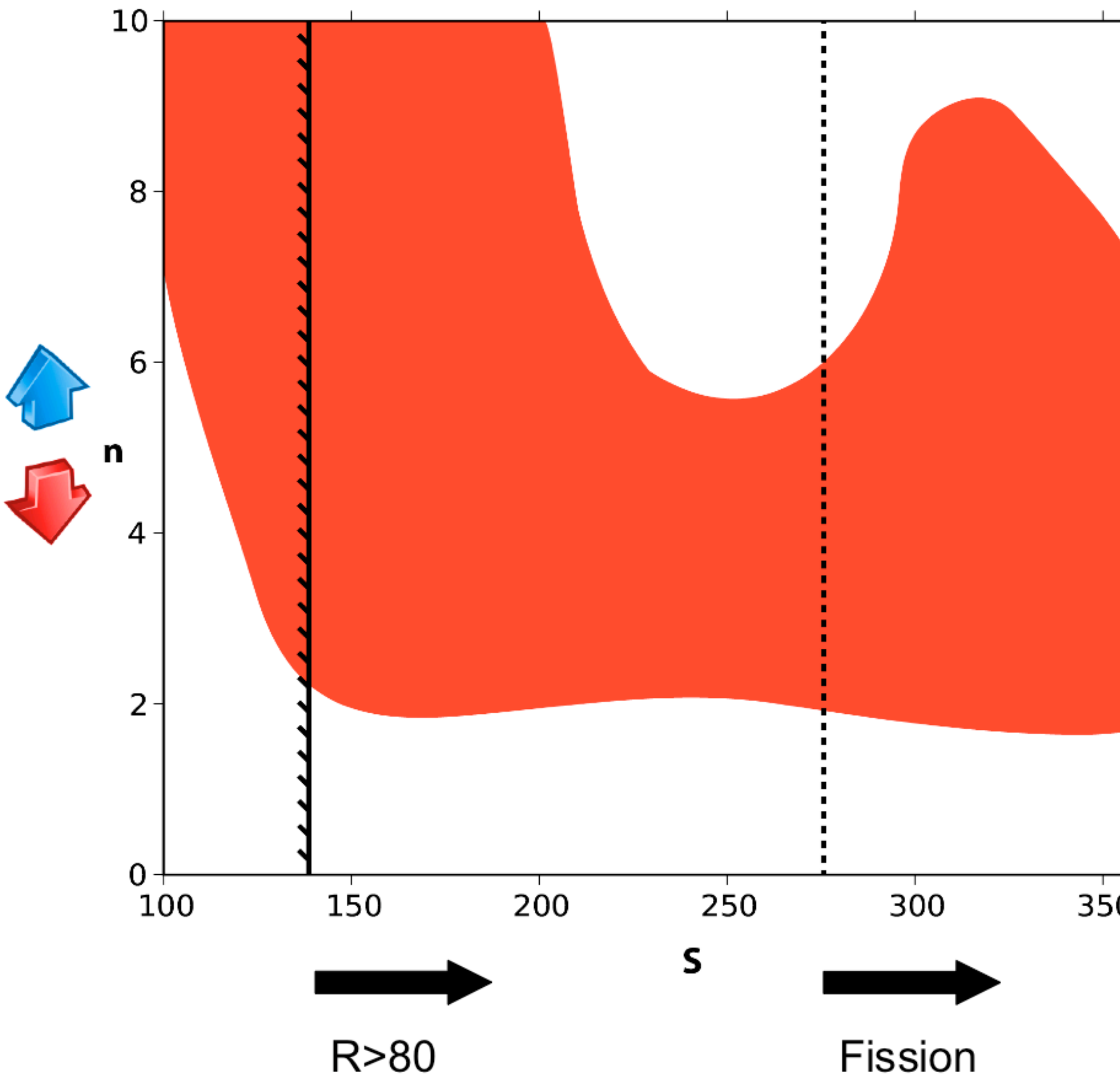
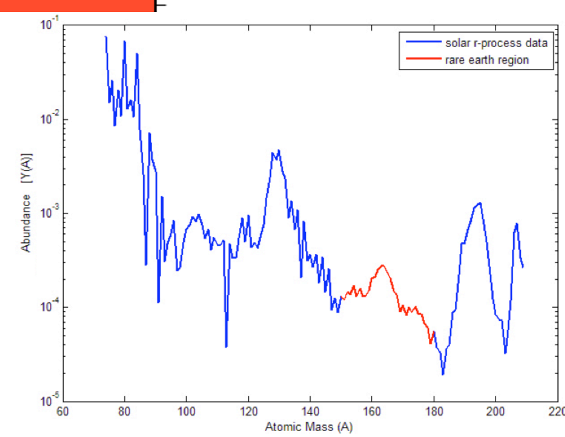


Mumpower, McLaughlin, Surman, ApJ (2012)

new constraint: compare rare earth region to solar pattern



Mumpower, McLaughlin, Surman, ApJ (2012)



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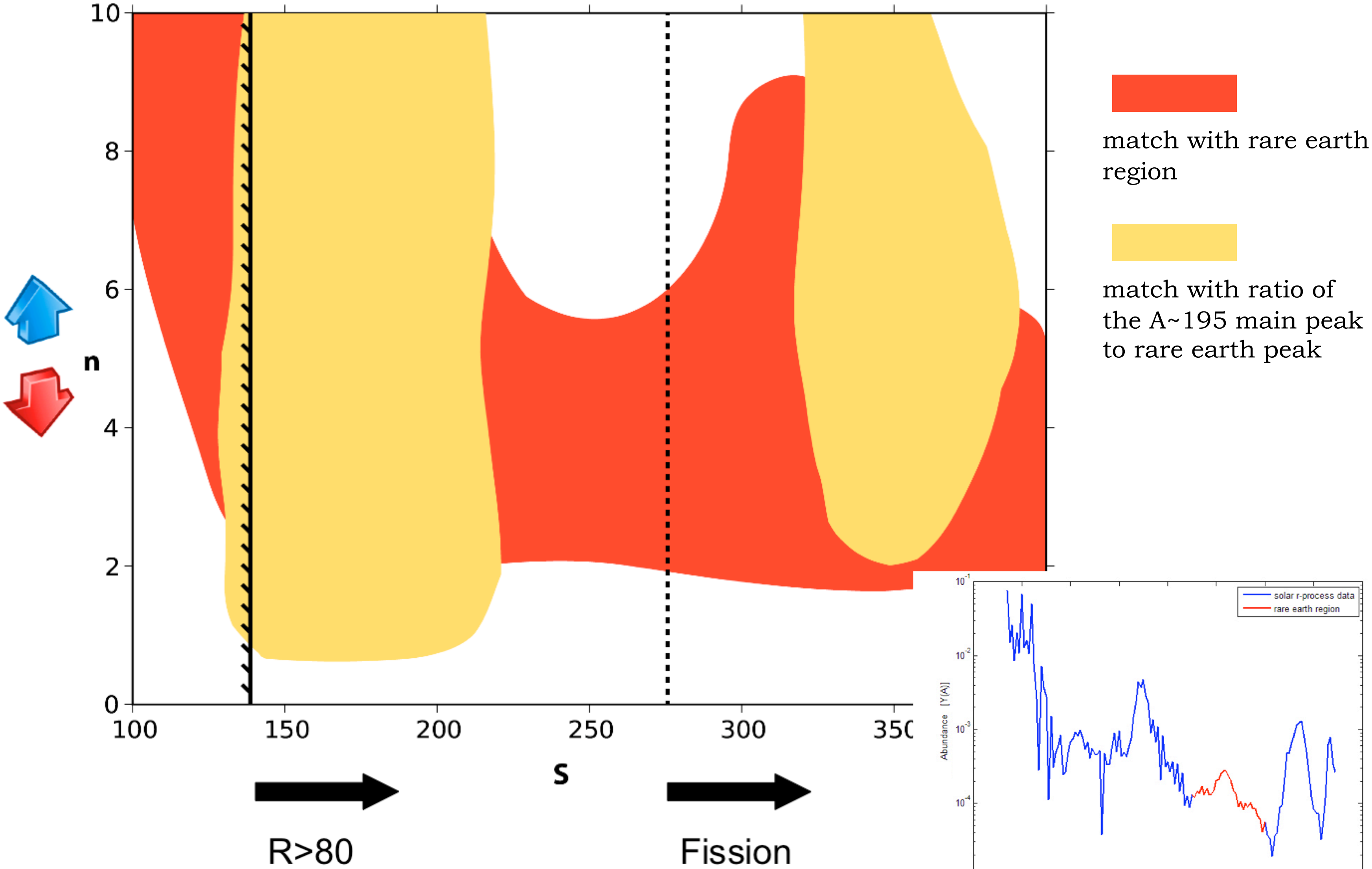
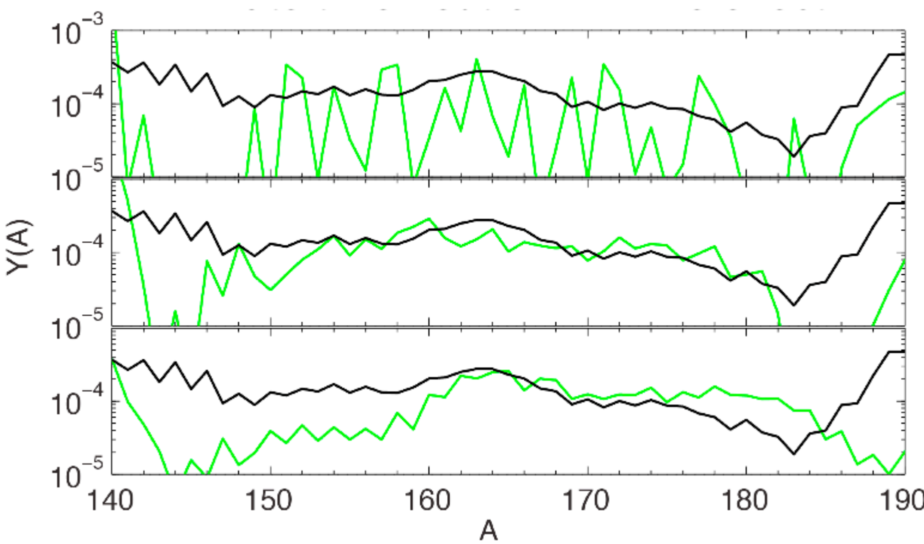
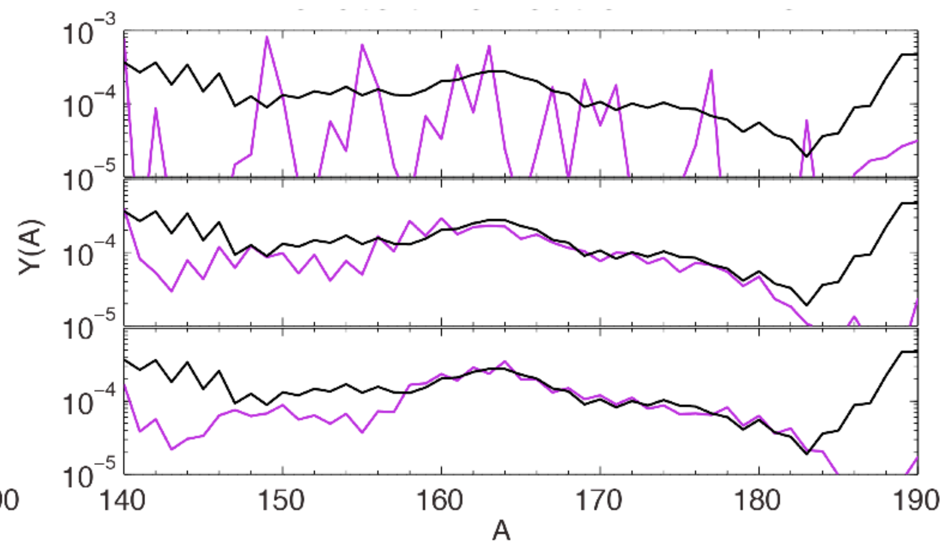


Mumpower, McLaughlin, Surman, ApJ (2012)

late-time neutron capture effect

Arcones & Martinez-Pinedo (2011),
Mumpower, McLaughlin, Surman PRC (2012)





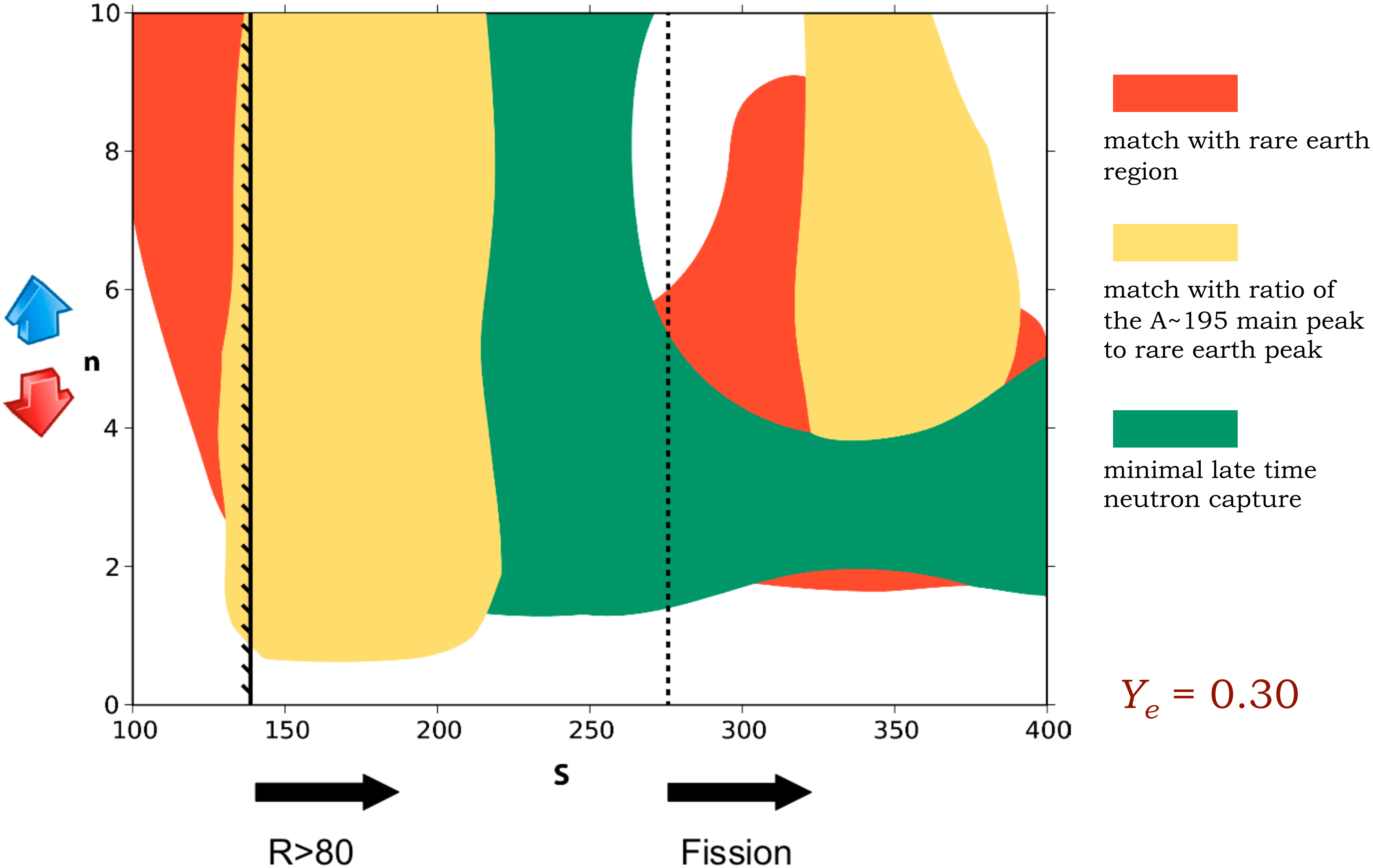
strong

poor match to solar

weak

better match to solar

new constraint: compare rare earth region to solar pattern



Mumpower, McLaughlin, Surman, ApJ (2012)

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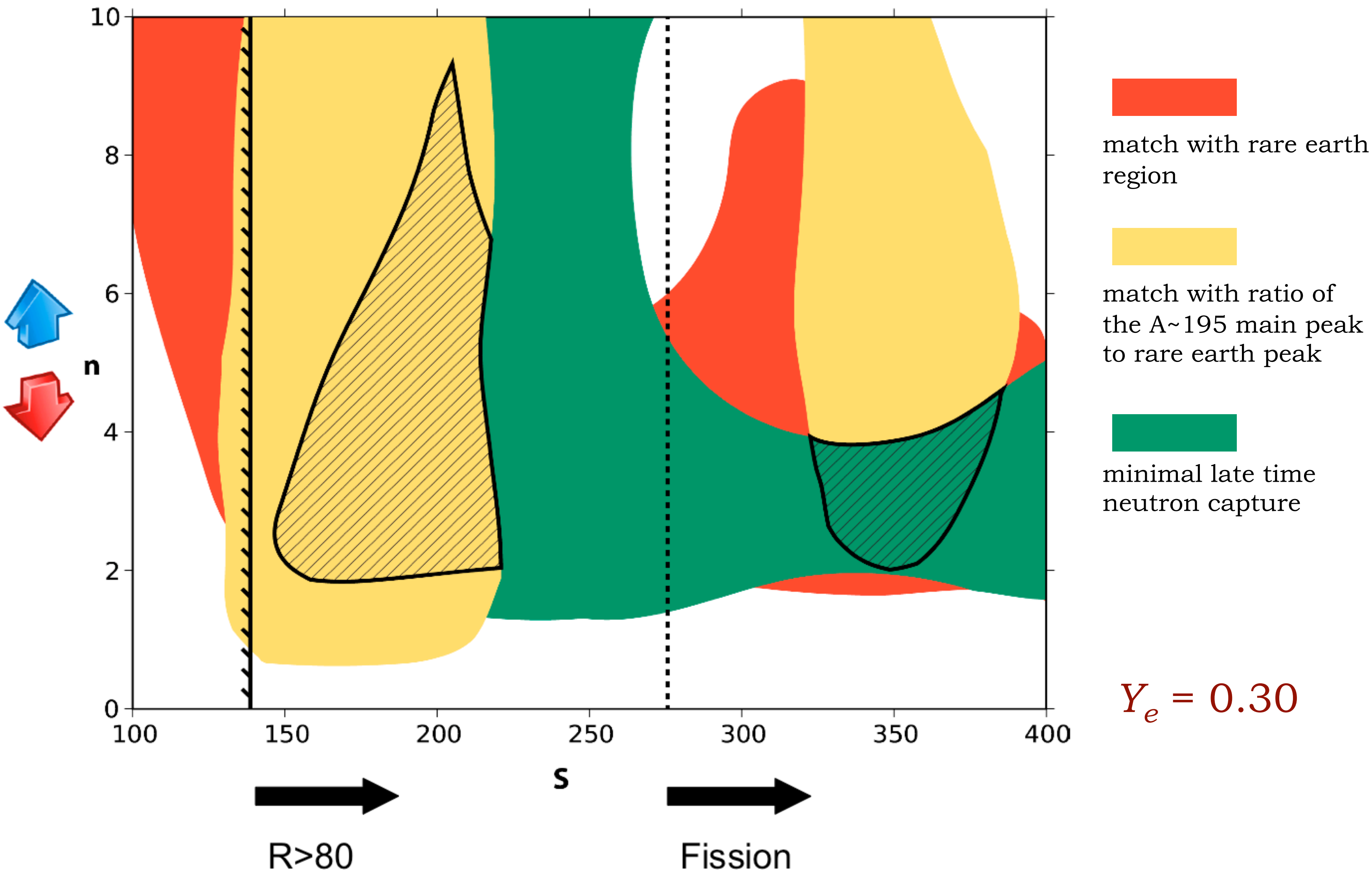

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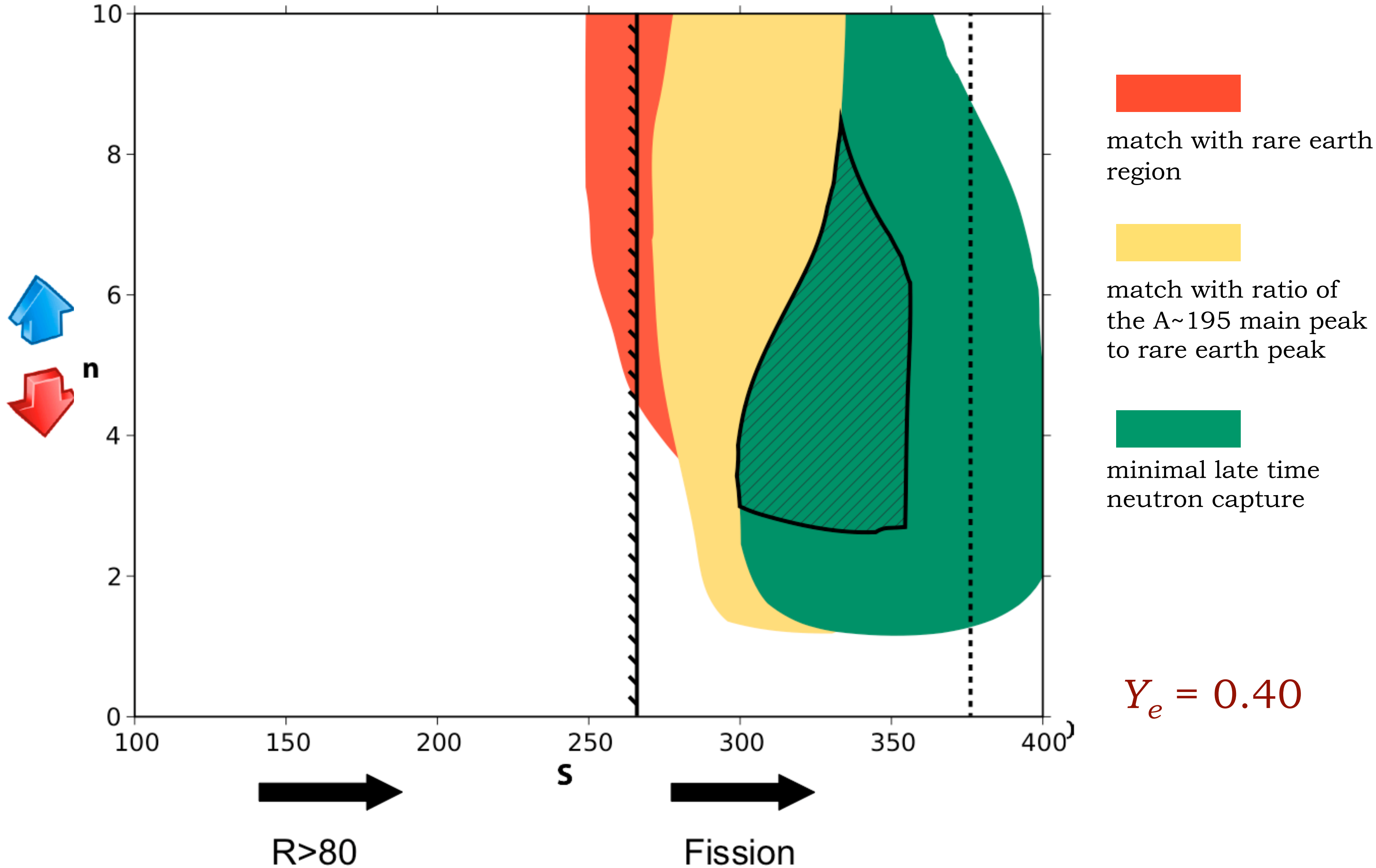
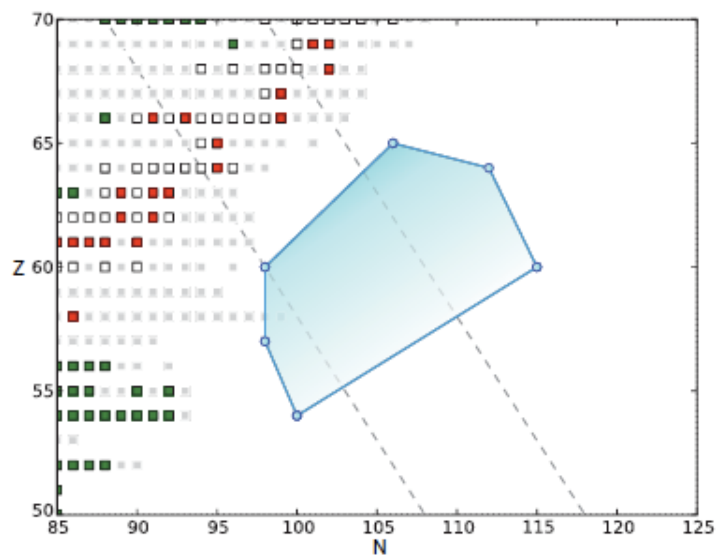


Mumpower, McLaughlin, Surman, ApJ (2012)

The rare earth peak offers unique insight into the nuclear physics and the astrophysics of the r-process. Its formation seems to require:

a deformation maximum in the rare earth region

the ‘right amount’ of neutron capture at late times in the r-process



Once the nuclear physics uncertainties are clarified by experiments at the next generation of radioactive beam facilities, the rare earth peak will become an even more powerful probe of the r-process astrophysical environment.