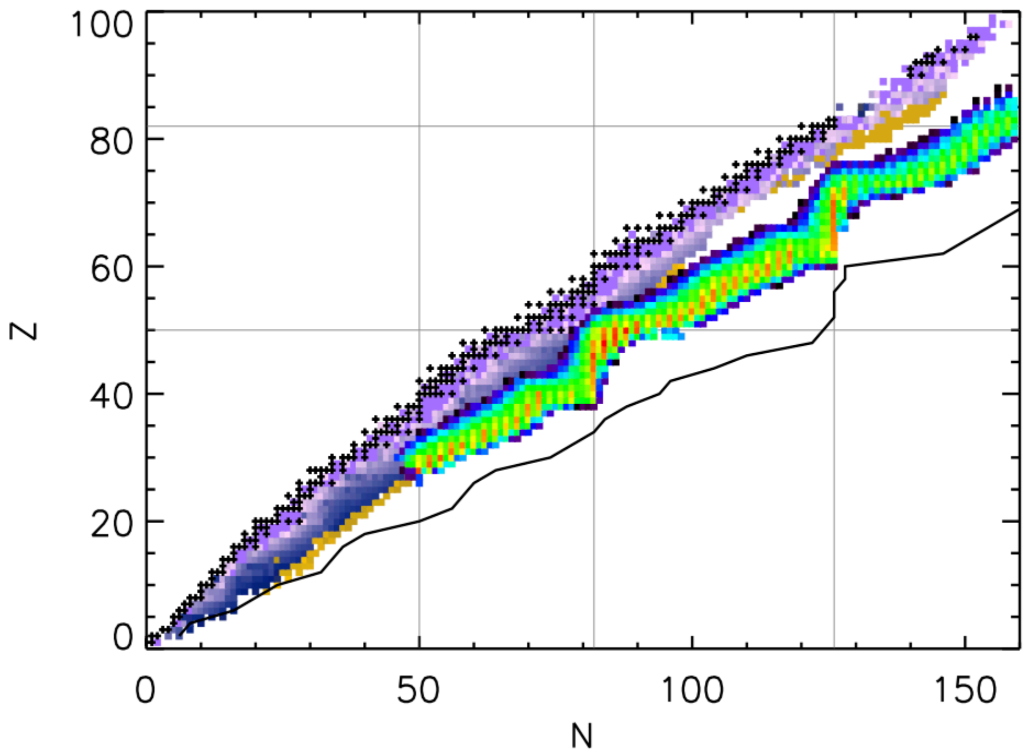
nuclear reaction rate needs for heavy element nucleosynthesis



Rebecca Surman
University of Notre Dame

INT 15-58W
Reactions and Structure of Exotic Nuclei
4 March 2015

UNIVERSITY OF NOTRE DAME College of Science

J I N A

solar system abundances

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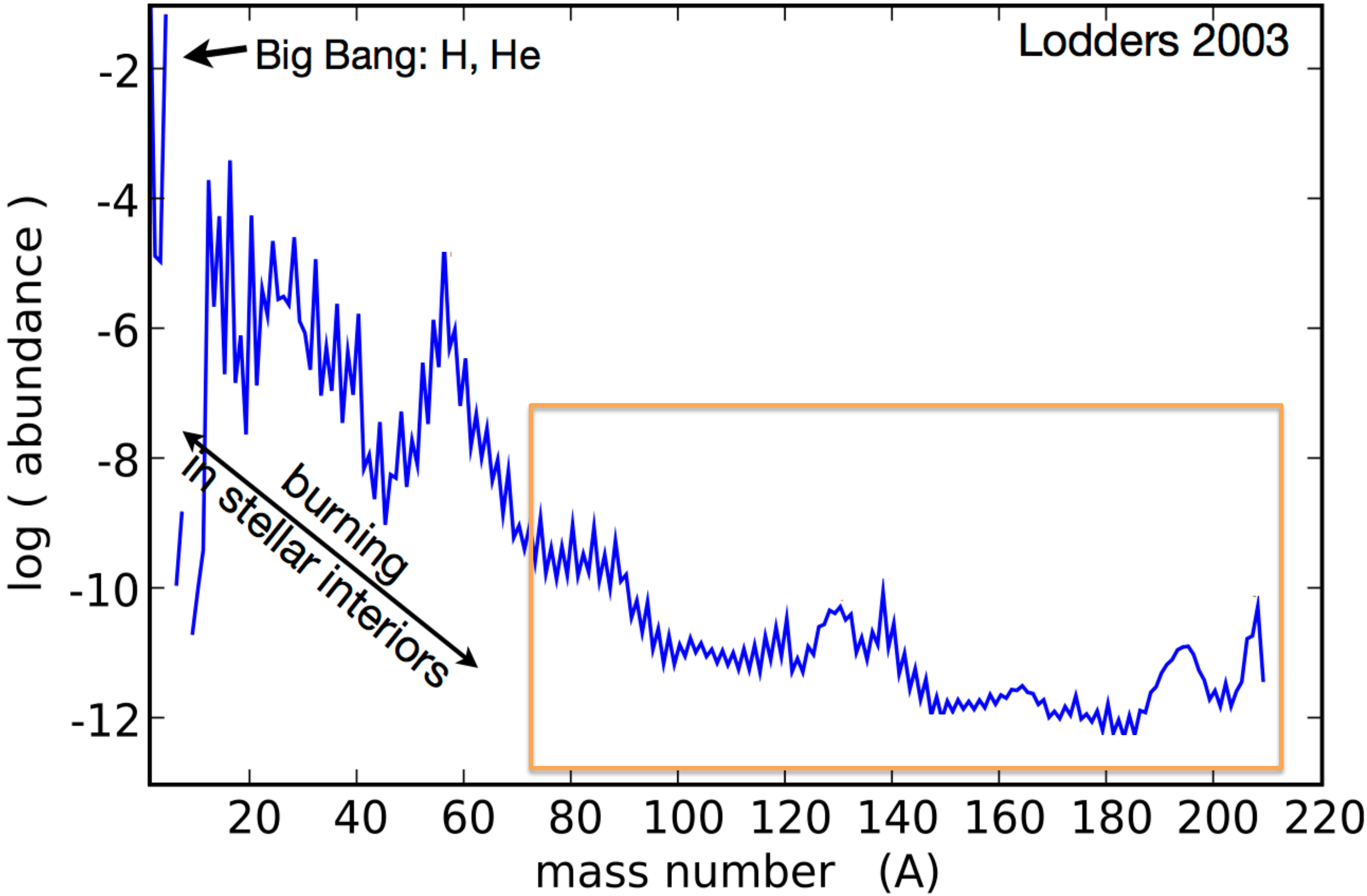

plot courtesy A. Arcones

r-process nucleosynthesis

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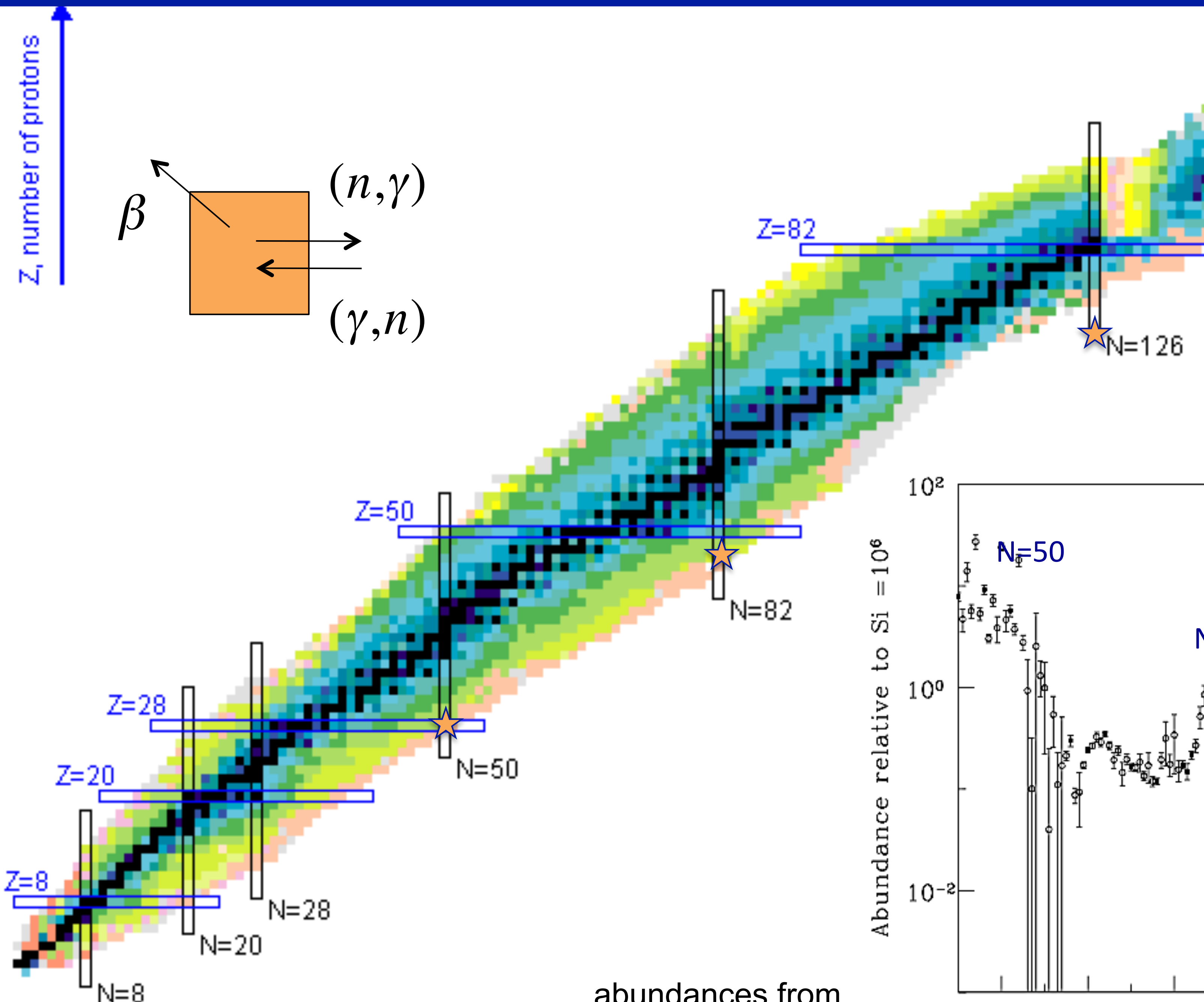

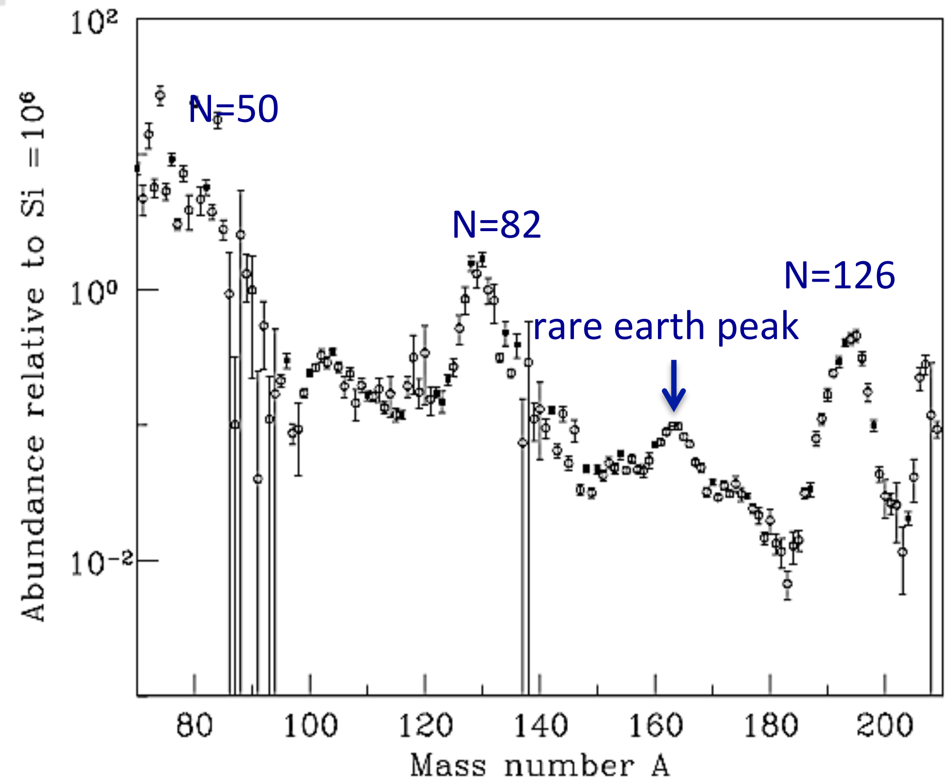

abundances from
Anders and Grevesse (1988)

r-process nucleosynthesis: (n,γ)-(γ,n) equilibrium

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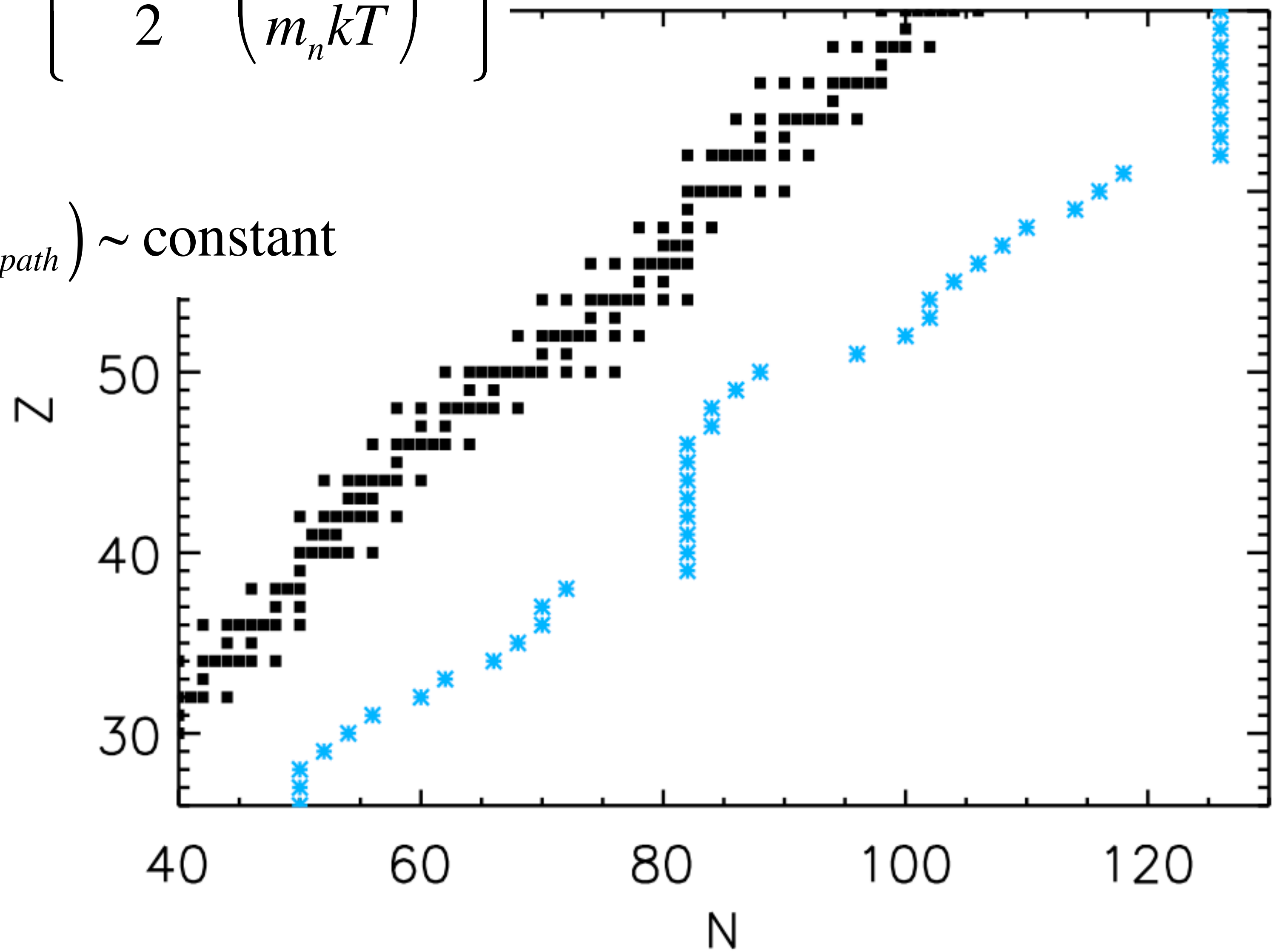
equilibrium path:

$$S_n\left(Z,A_{path}\right) \sim -kT\ln\left\{\frac{\rho N_A Y_n}{2}\left(\frac{2\pi\hbar^2}{m_n kT}\right)^{3/2}\right\}$$

steady beta flow:

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



r-process nucleosynthesis: (n,γ)-(γ,n) equilibrium

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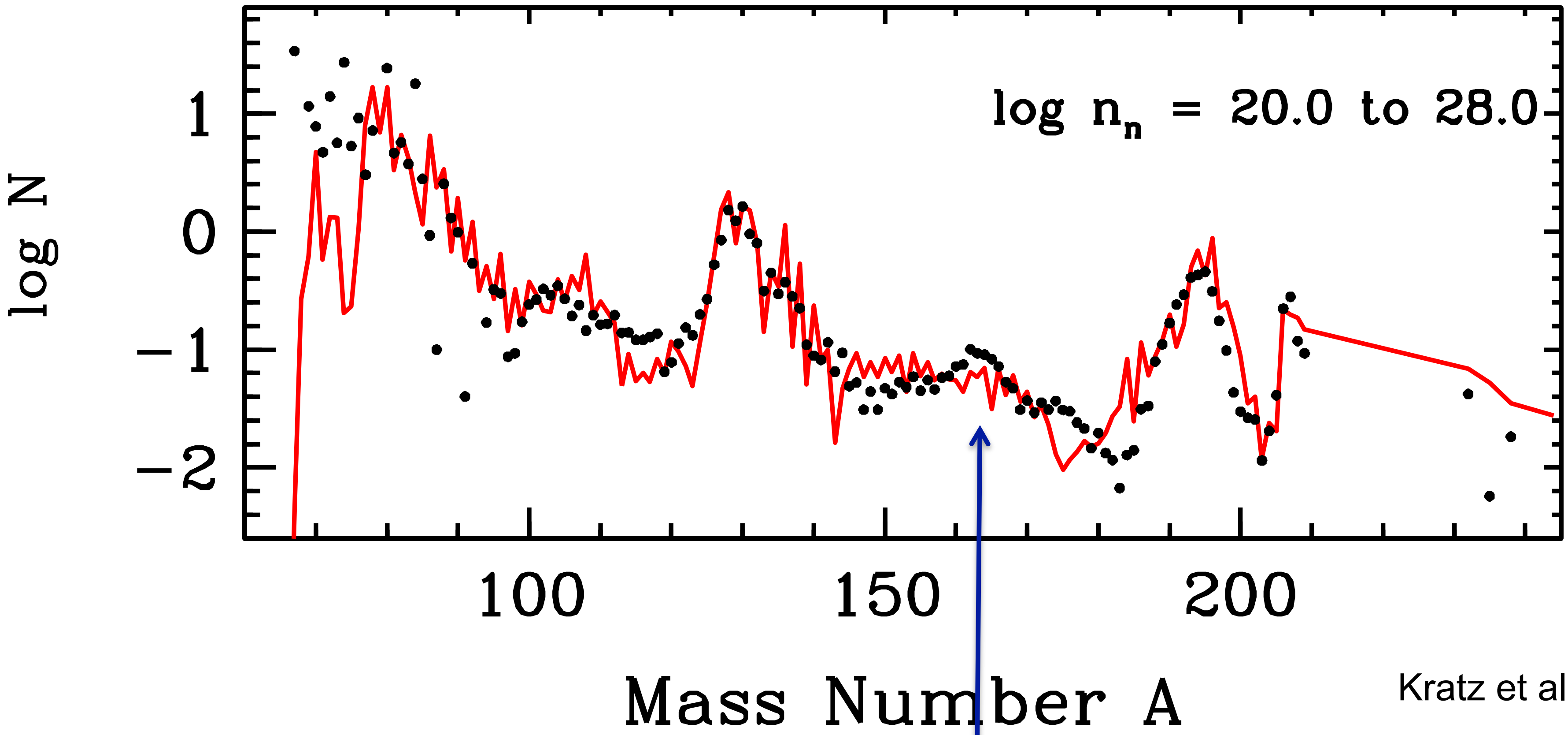
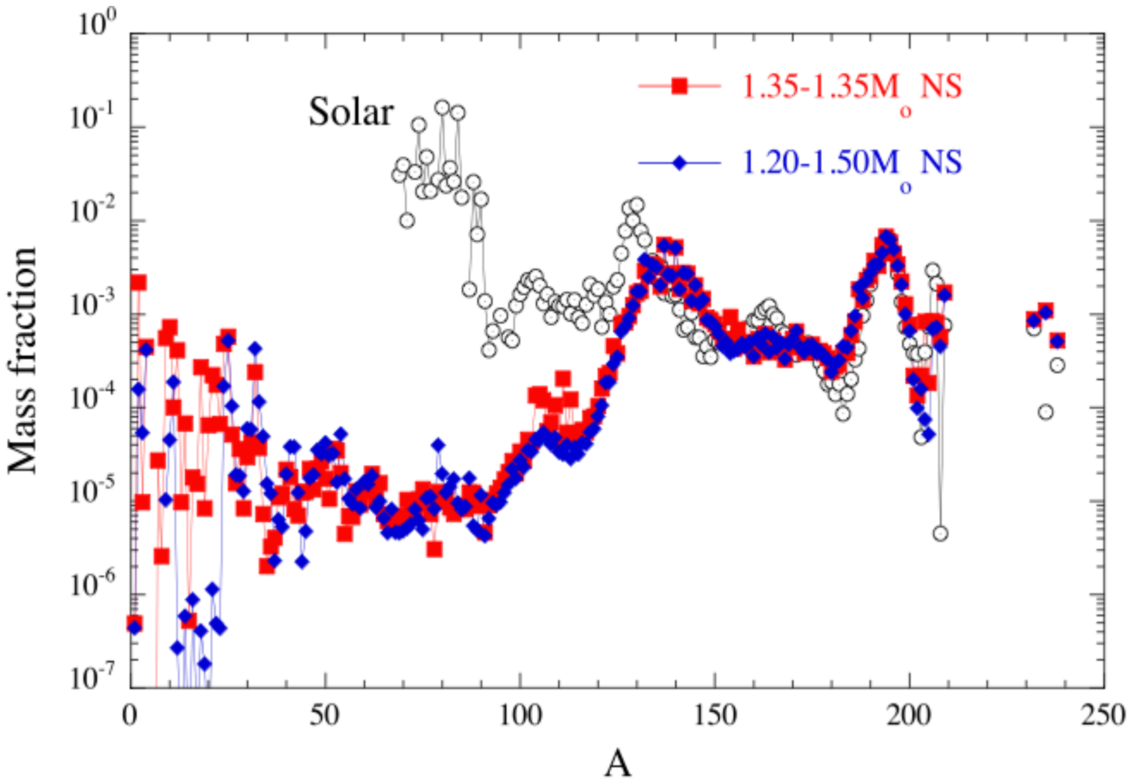


Kratz et al (2007)

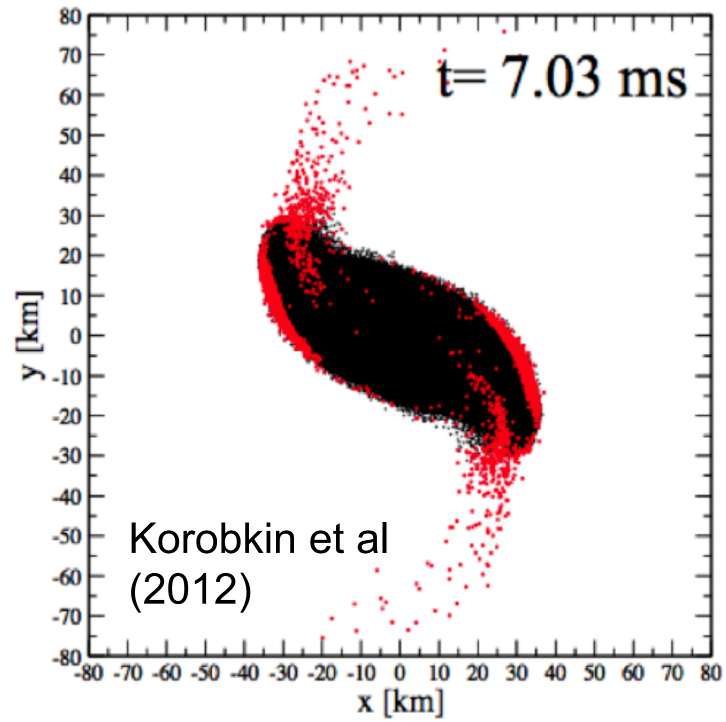
can fit most abundance pattern features
except for the rare earth peak

r-process astrophysical site: compact object mergers?



Goriely et al (2012)

neutron star-neutron star or black hole-neutron star mergers



Korobkin et al (2012)

cold/mildly heated prompt ejecta

e.g., Lattimer & Schramm (1974, 1976), Meyer (1989), Frieburghaus et al (1999), Goriely et al (2005), Argast et al (2004), Wanajo & Ishimaru (2006), Oechslin et al (2007), Nakamura et al (2011), Goriely et al (2012), Korobkin et al (2012), Rosswog el at (2013), Wanajo et al (2014), Just et al (2014), etc., etc.

observations of *r*-process elements

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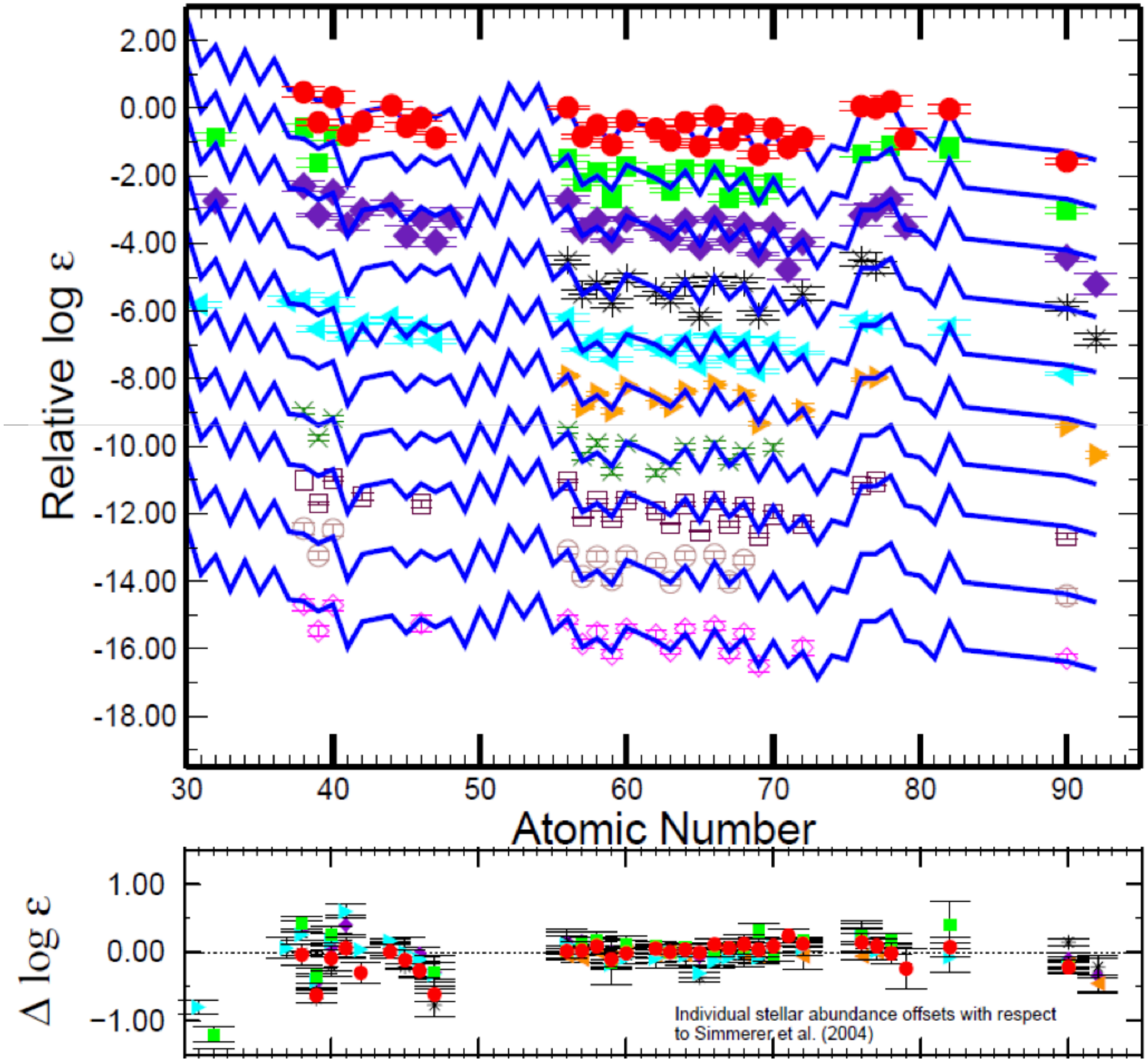
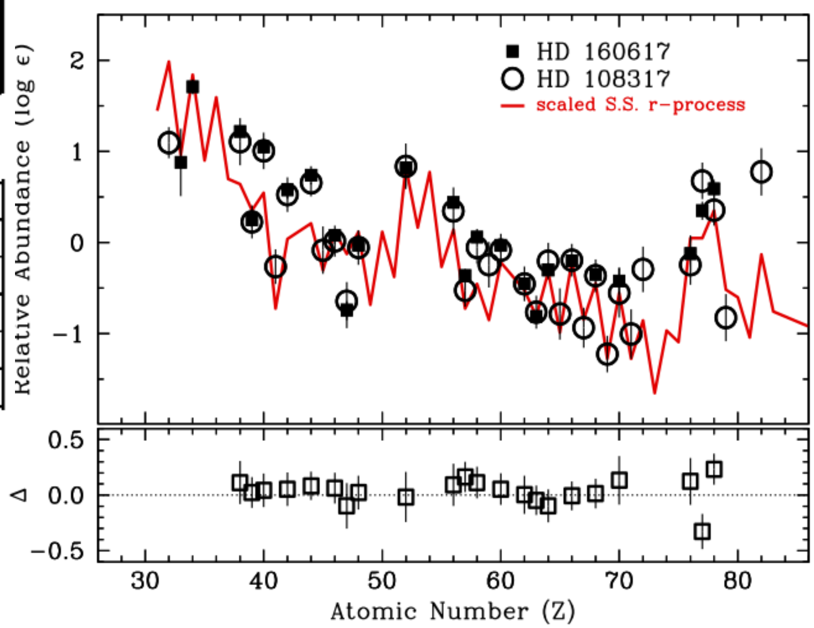


Roederer & Lawler (2012)

Cowan et al (2011)



r-process astrophysical site: core-collapse supernovae?

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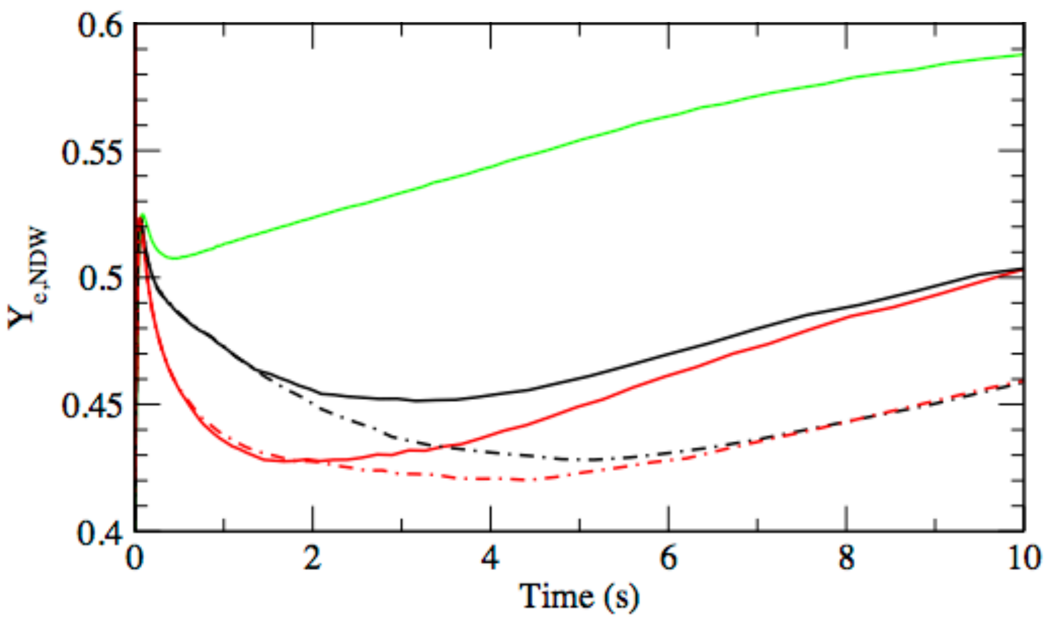
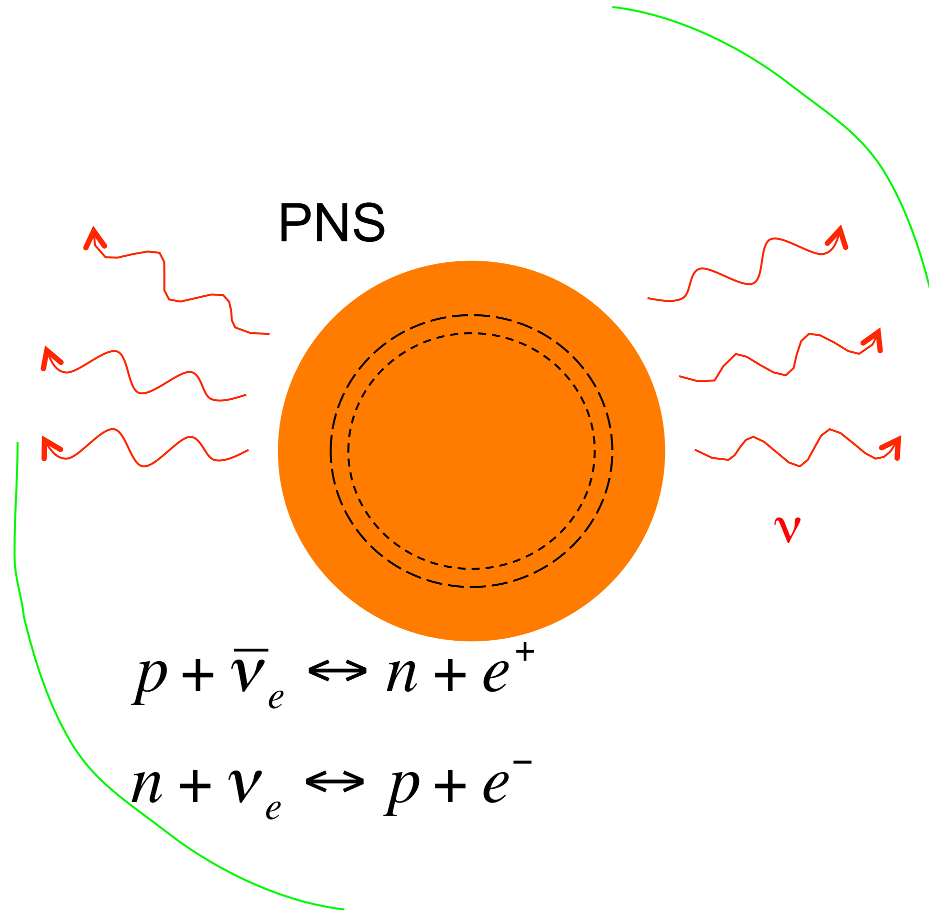


Roberts, Reddy & Shen (2012)



$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$n + \nu_e \leftrightarrow p + e^-$$

supernova 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), Horowitz et al (2012), Wanajo (2013), Martinez-Pinedo et al (2014)

sensitivity to seed assembly reaction rates

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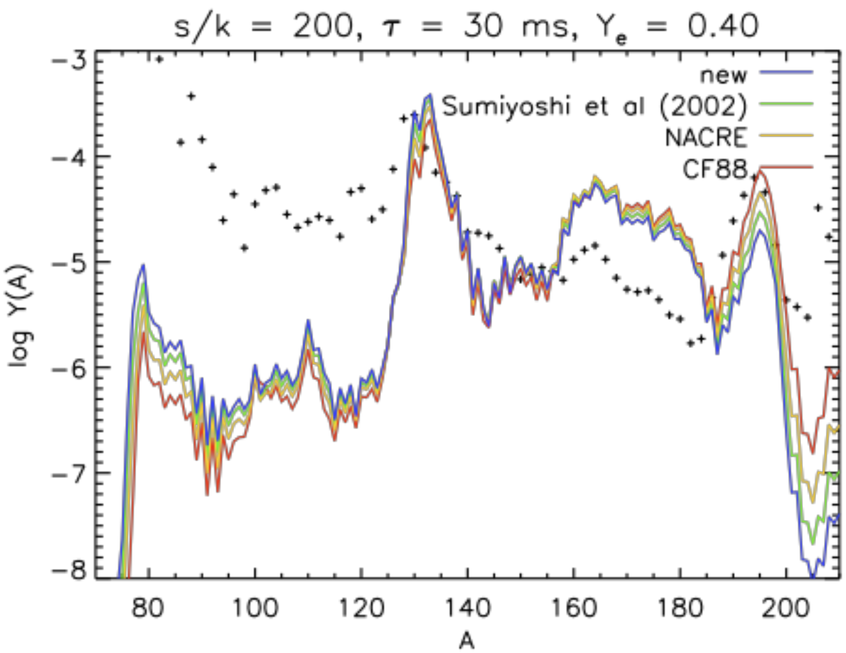
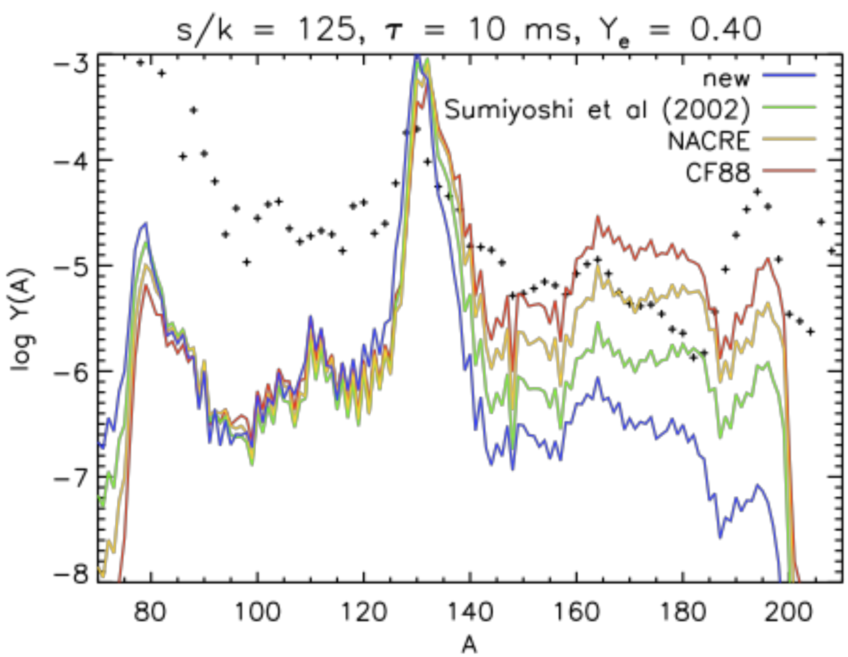
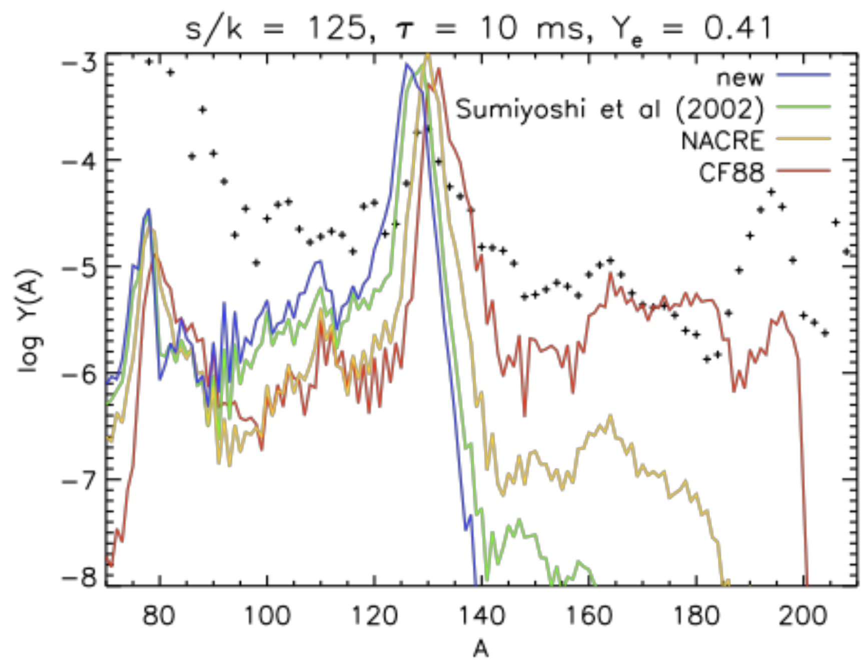


$\alpha\alpha n$ reaction rate sensitivity

new rate determined by Arnold et al (2012)





r-process astrophysical site: abundance pattern signatures

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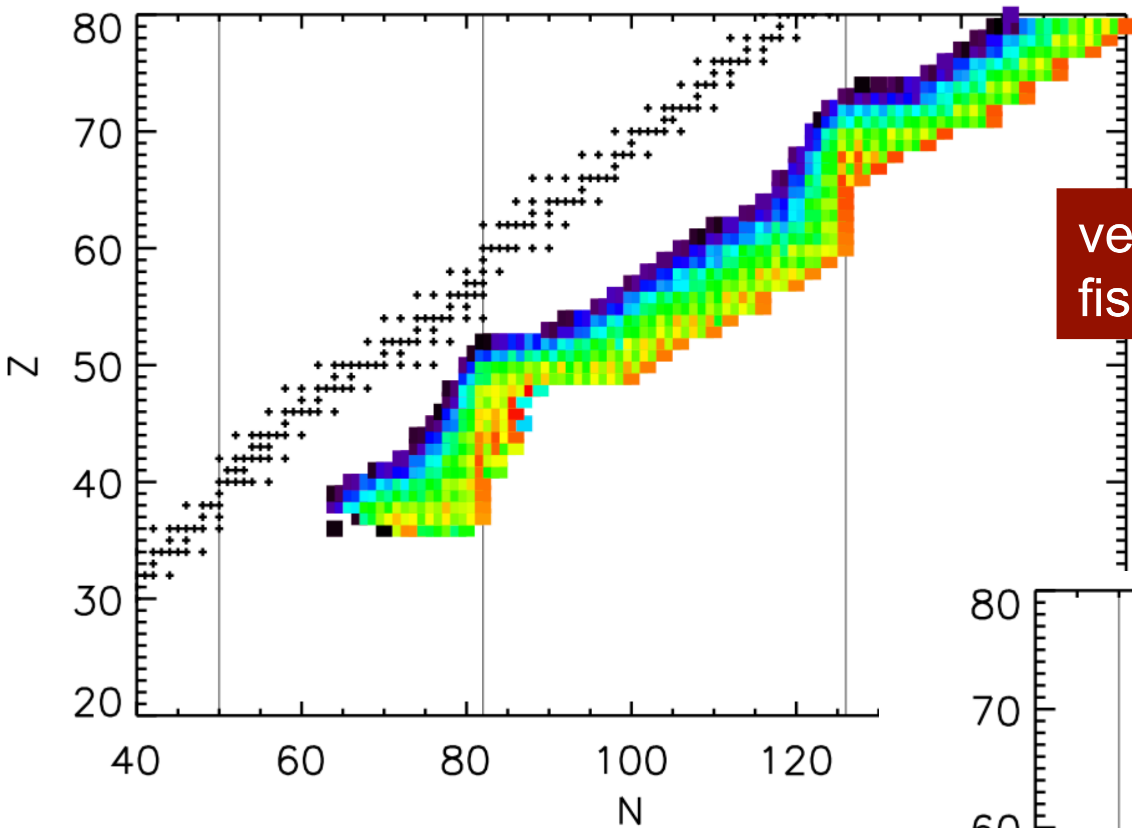
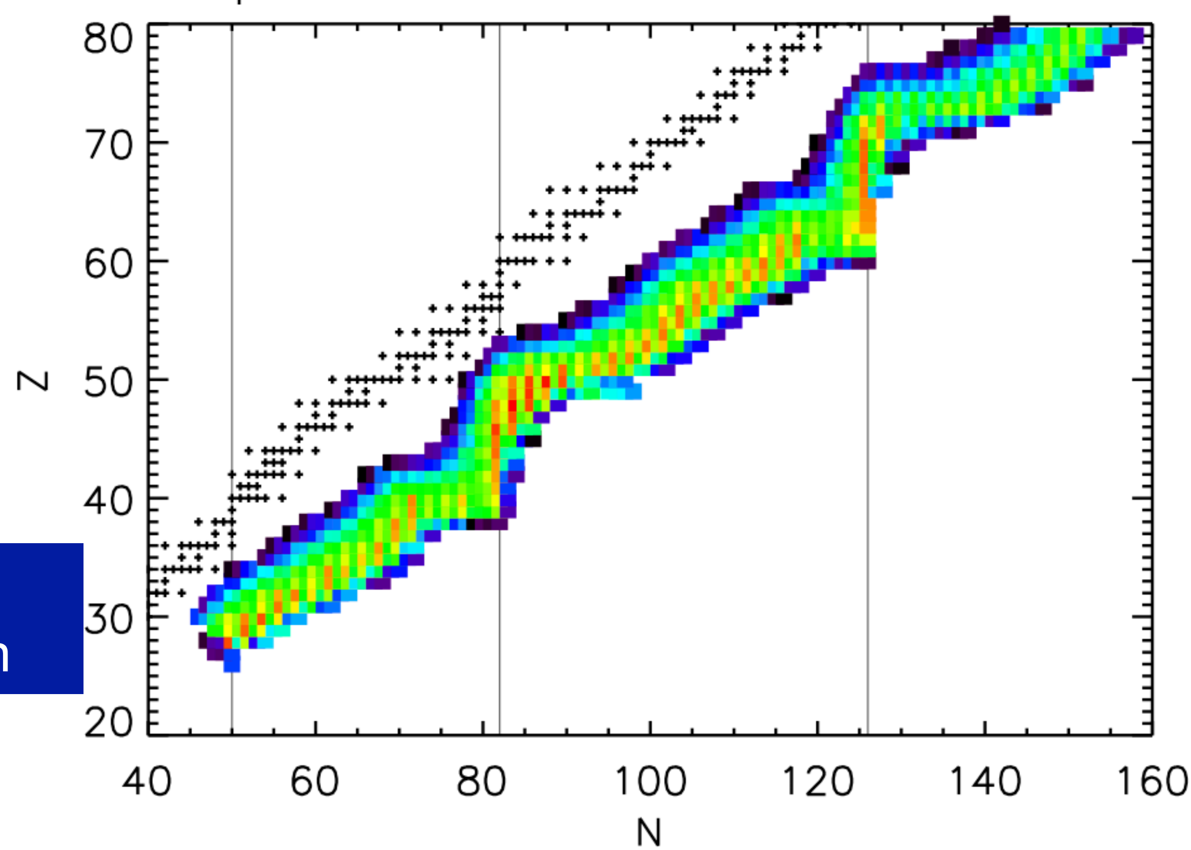


very neutron rich
fission cycling

barely neutron rich
limit seed production



r-process astrophysical site: abundance pattern signatures

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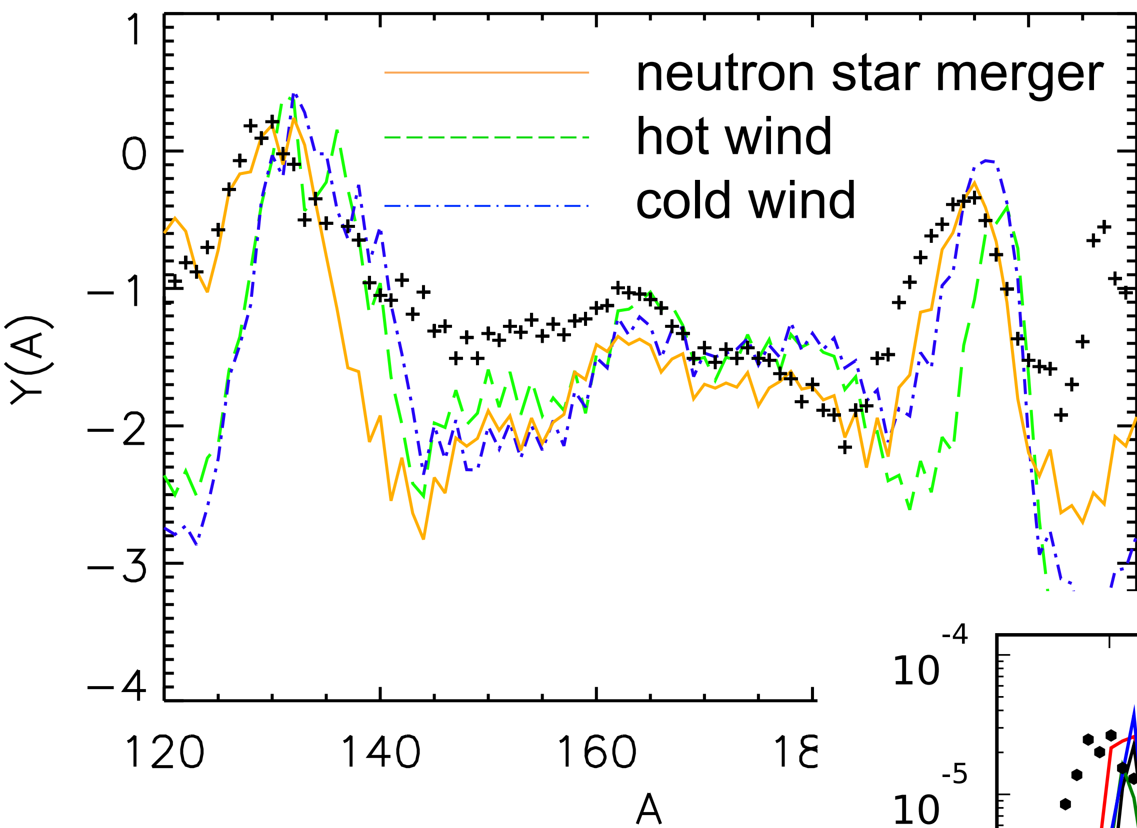
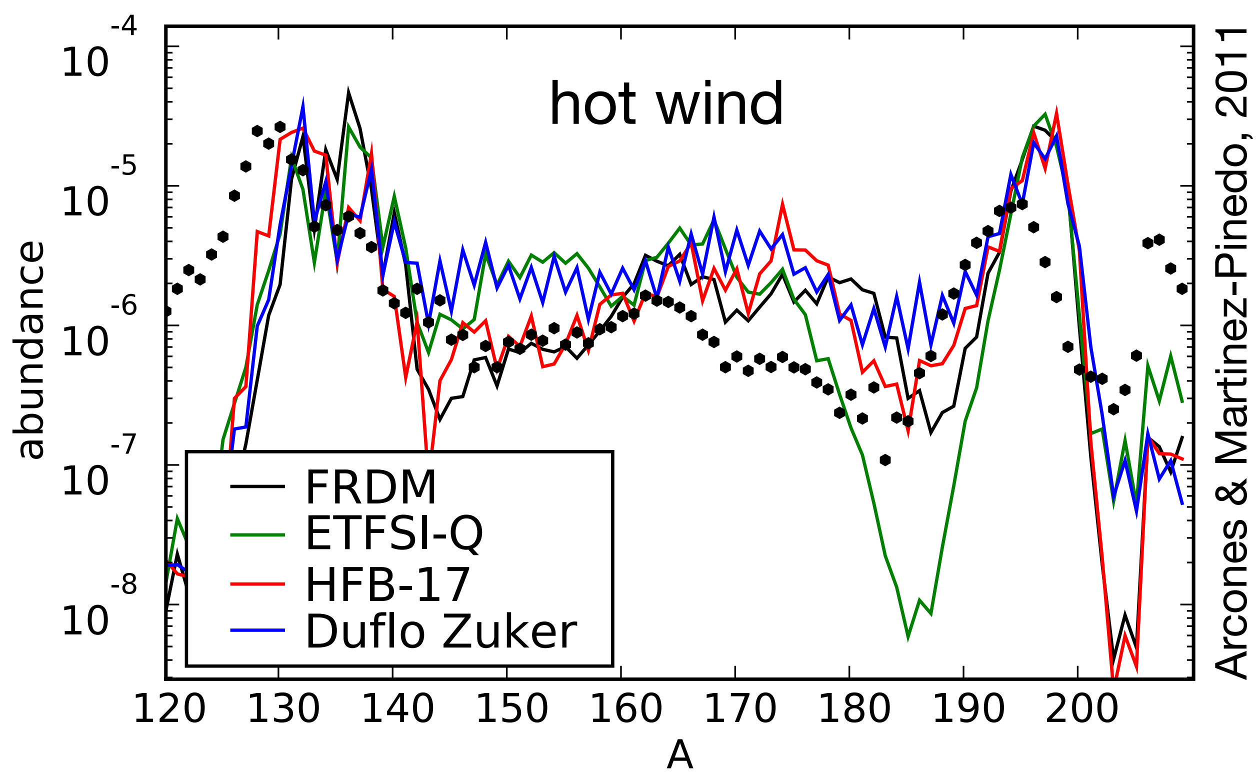


Mumpower, Cass, Passucci, Surman, Aprahamian (2014)



r-process nuclear data needs

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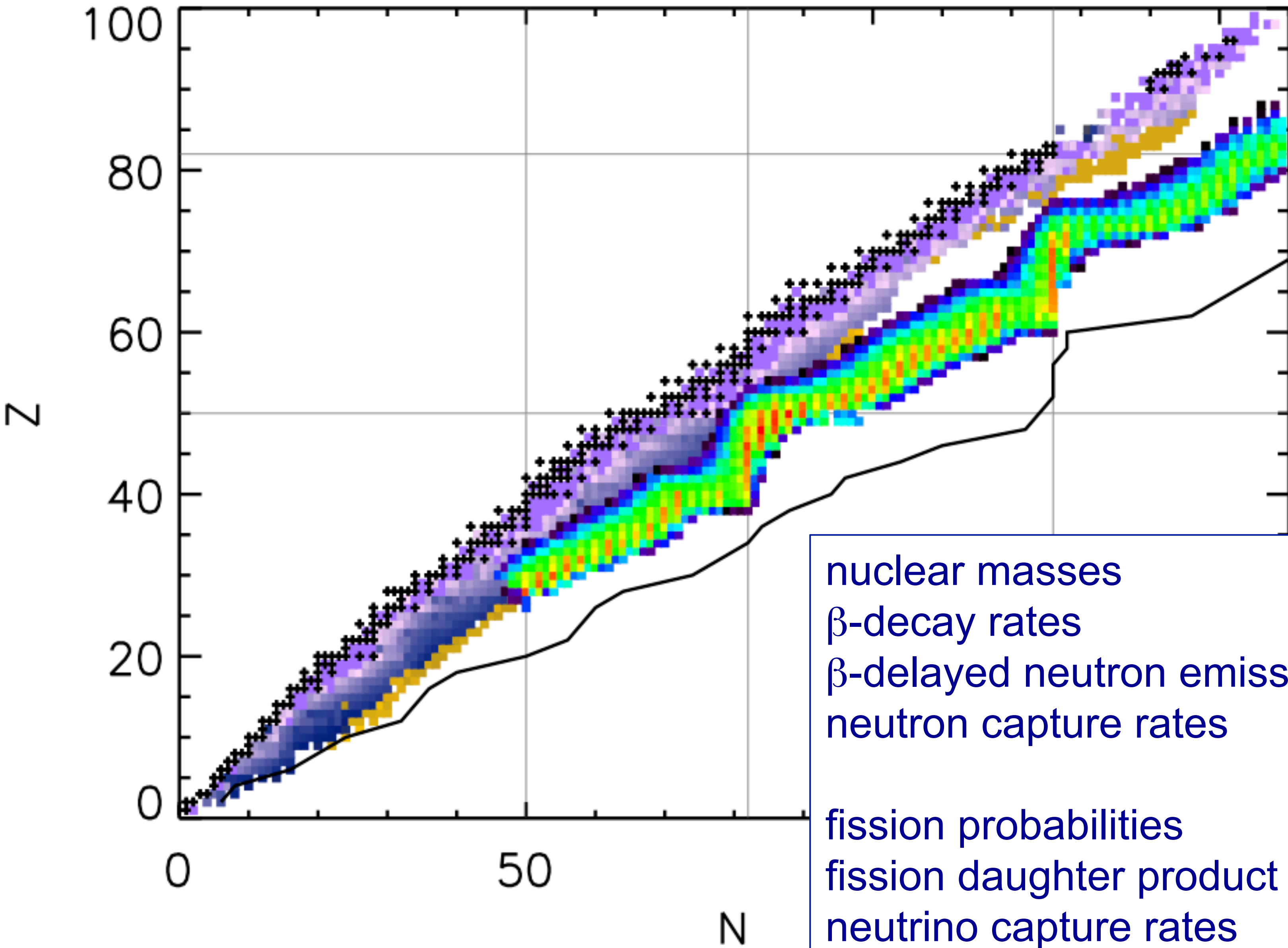

nuclear masses
β-decay rates
β-delayed neutron emission probabilities
neutron capture rates

fission probabilities
fission daughter product distributions
neutrino capture rates

r-process nuclear data needs

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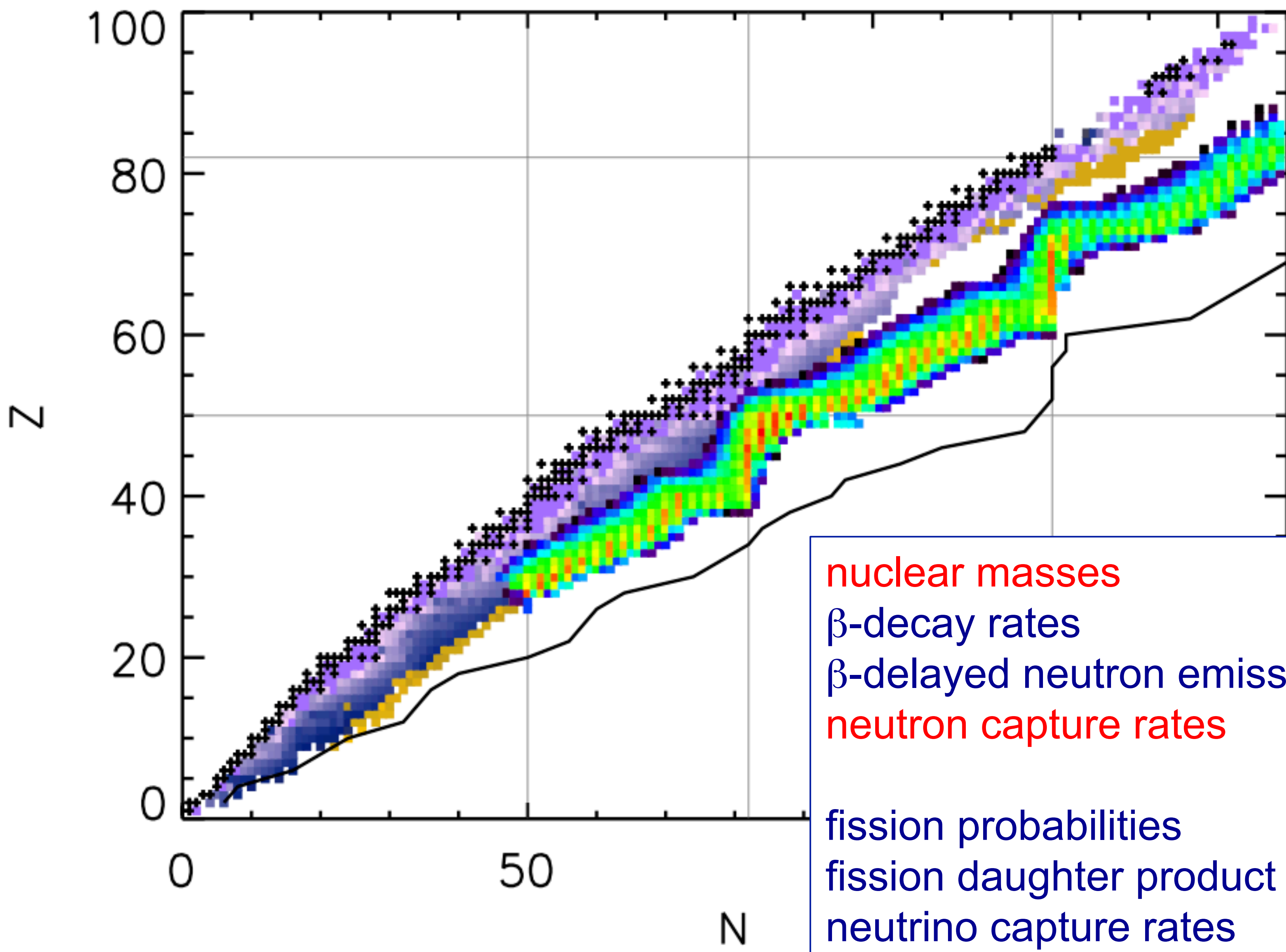

nuclear masses
β-decay rates
β-delayed neutron emission probabilities
neutron capture rates

fission probabilities
fission daughter product distributions
neutrino capture rates

nuclear mass uncertainties

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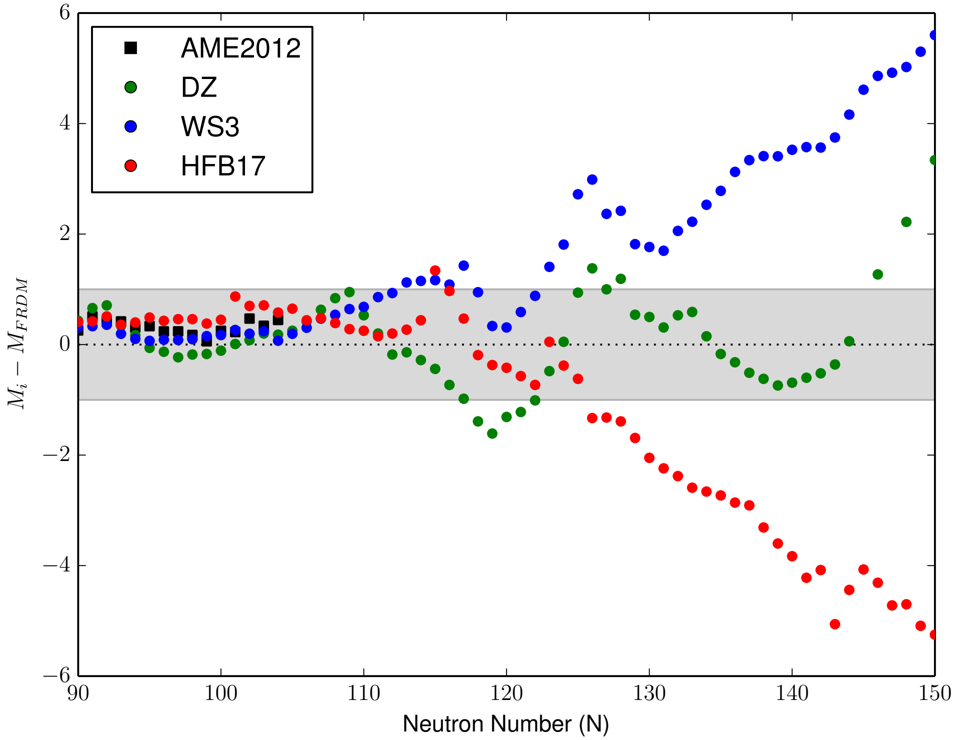
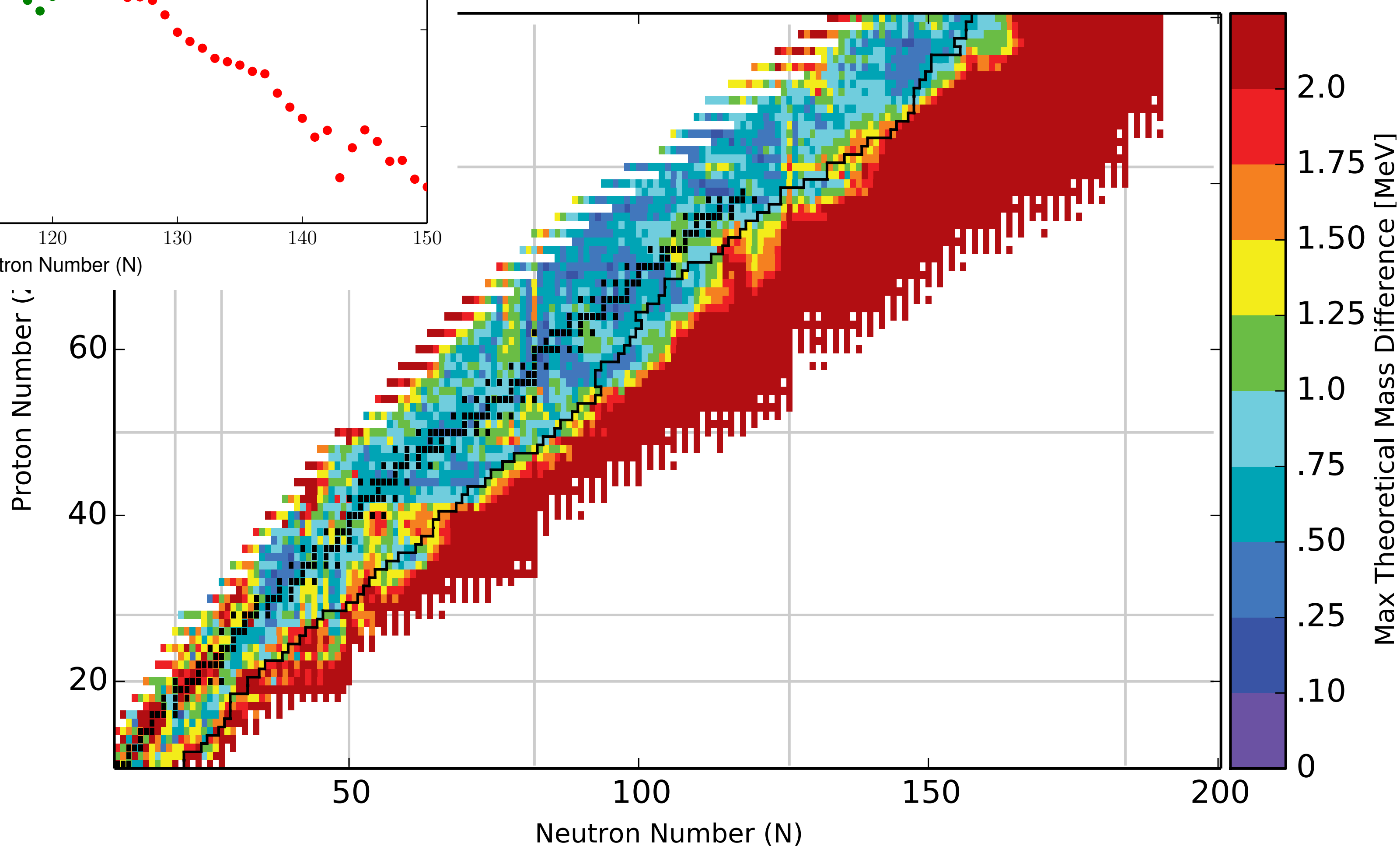


Mumpower, Surman, Fang, Beard, Aprahamian (2015)



nuclear mass uncertainties and *r*-process simulations

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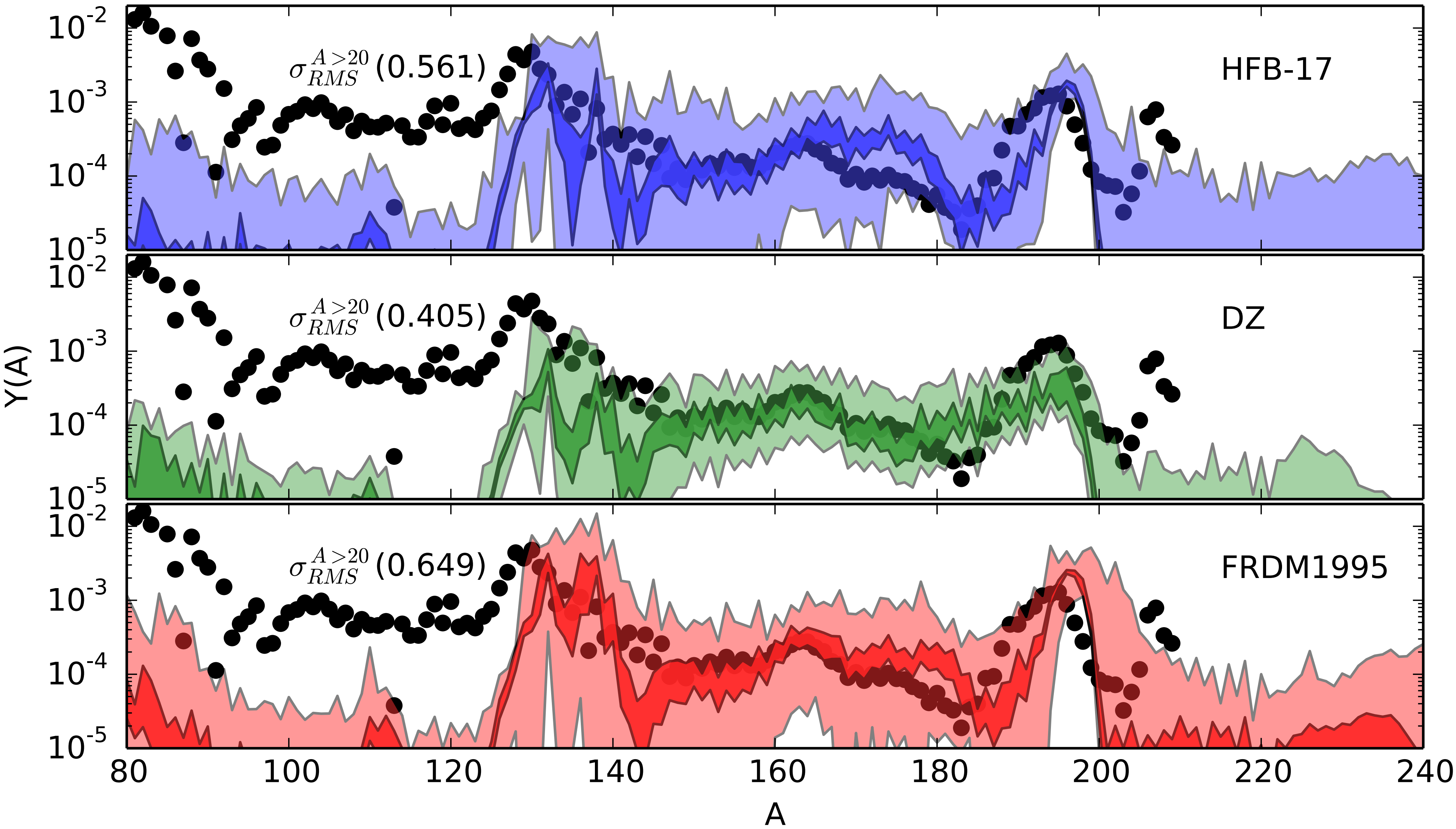

Mumpower, Surman, Aprahamian (2015)

key nuclear masses for the *r* process

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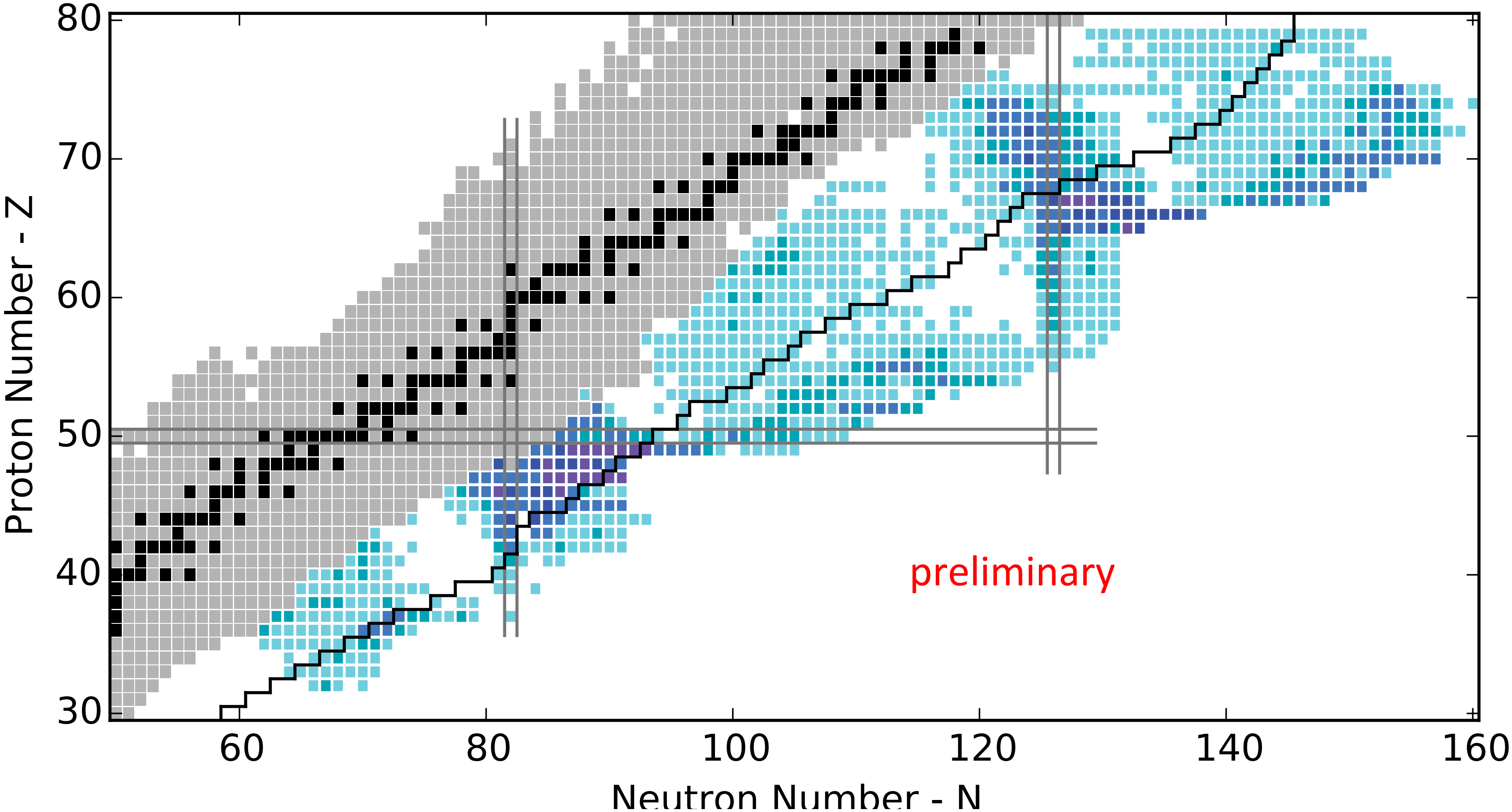

Mumpower, Surman, Möller, Fang, Beard, Aprahamian, in preparation

neutron capture

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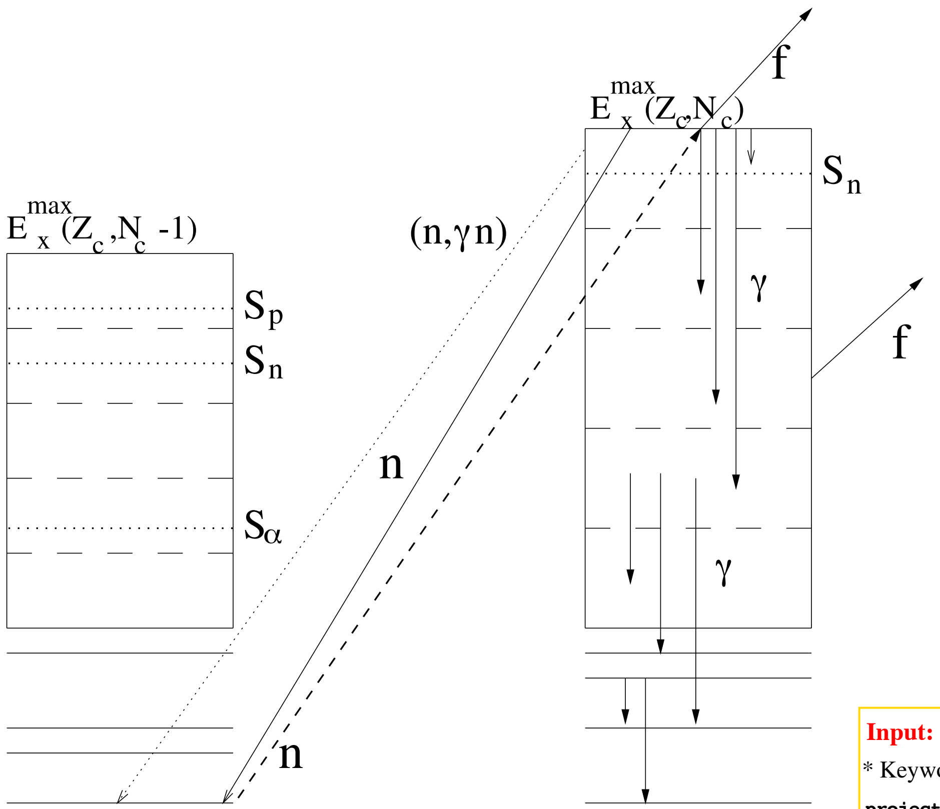
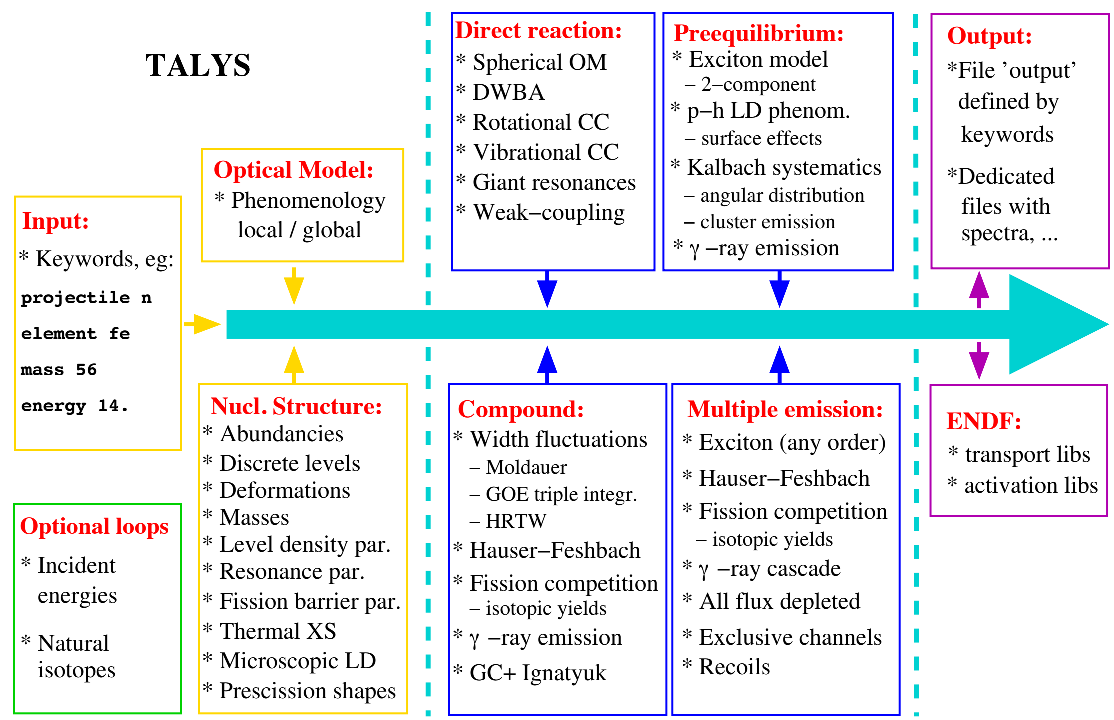


TALYS



Inputs for each nuclide:
- separation energies
- optical model parameters
- level densities
- gamma strength functions
- etc.

neutron capture rate uncertainties

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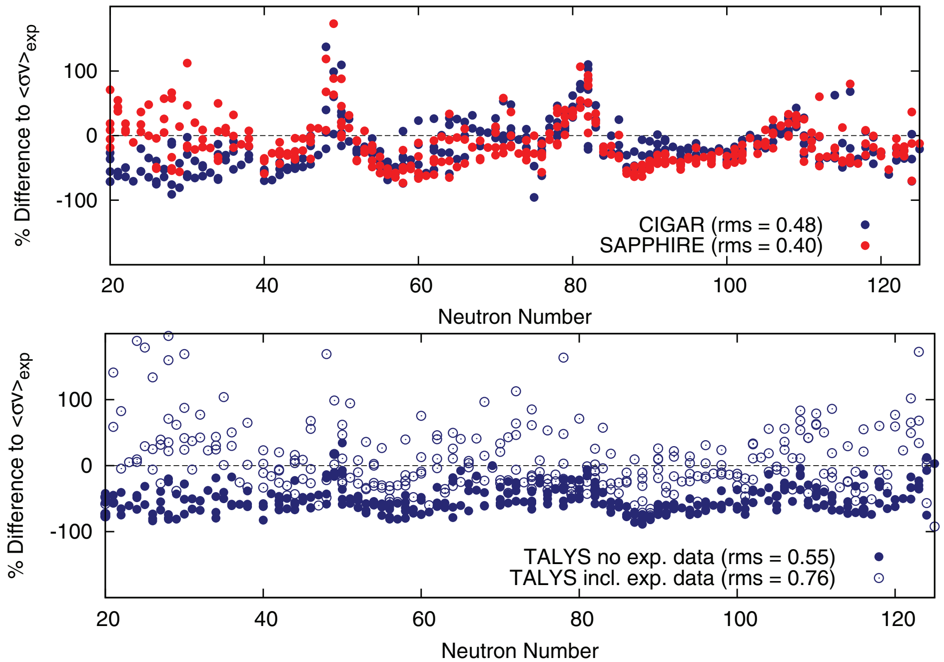
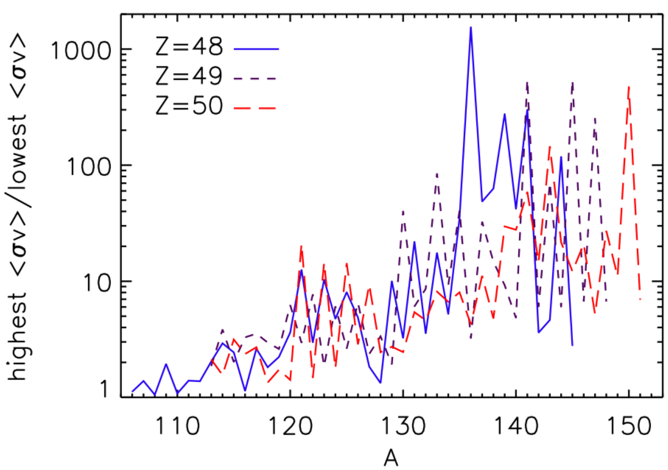
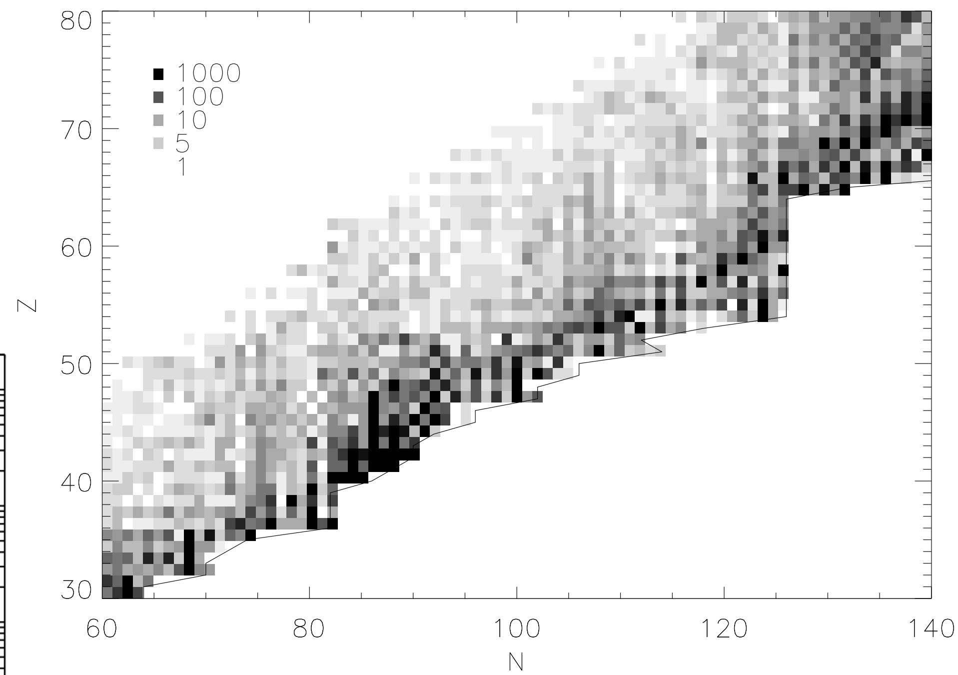


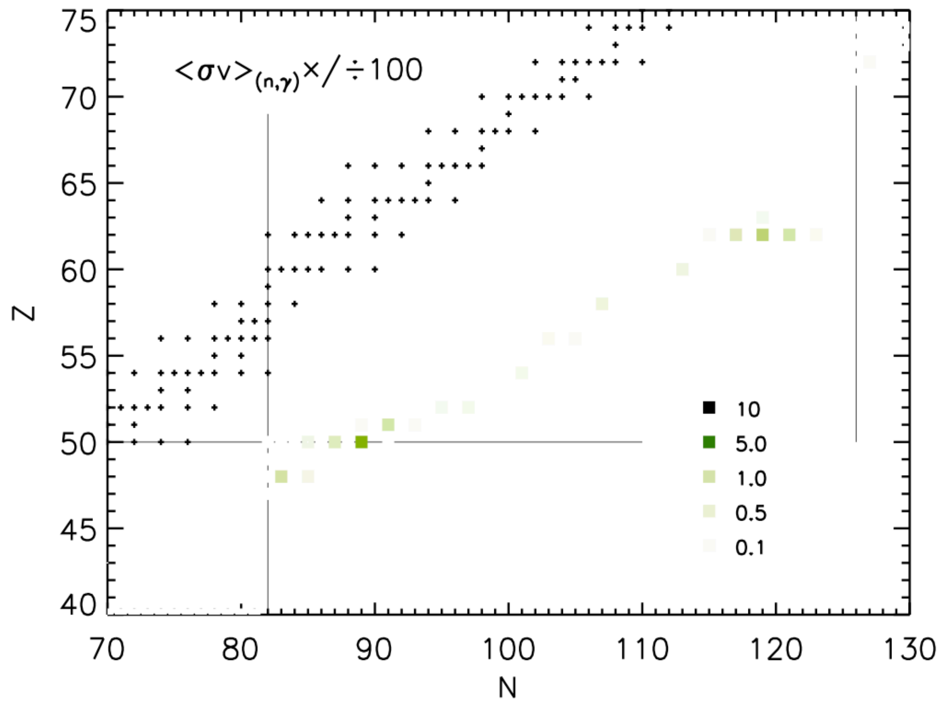
Beard, Uberseder, Crowter, Wiescher (2014)





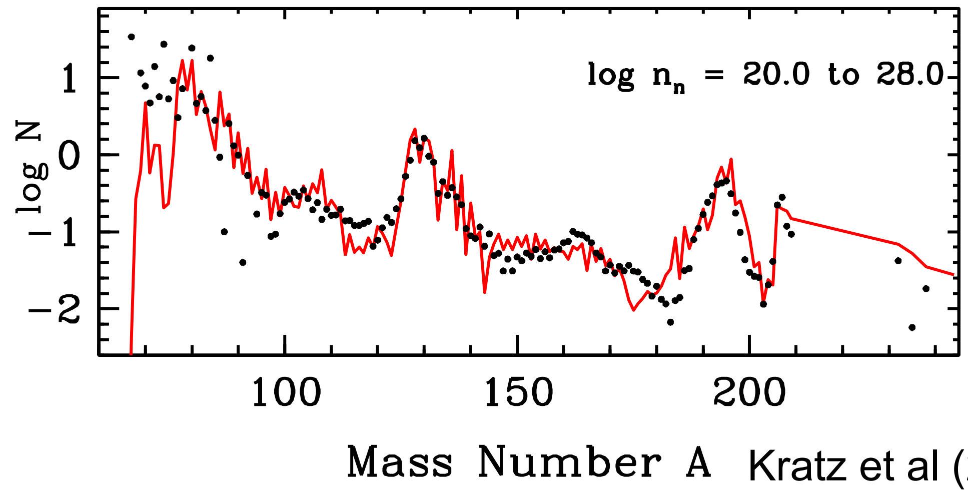
Surman and Engel (2001)

r-process neutron capture rate sensitivities



Surman et al (2013)

hot wind *r*-process simulation,
(*n*,*γ*)-(*γ*,*n*) equilibrium only



Kratz et al (2007)

r-process neutron capture rate sensitivities

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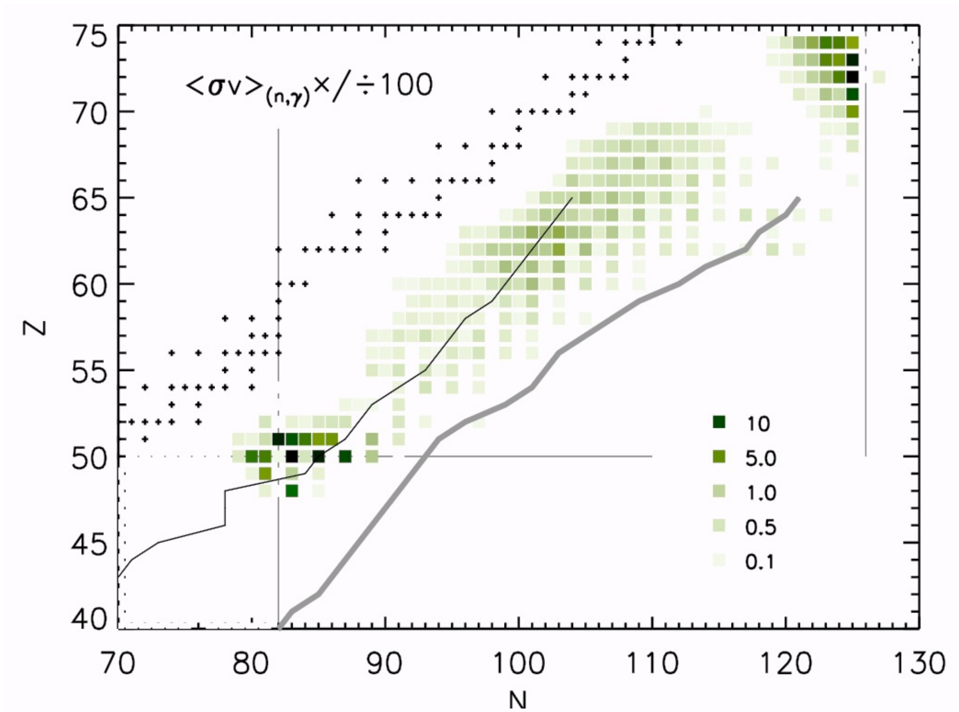
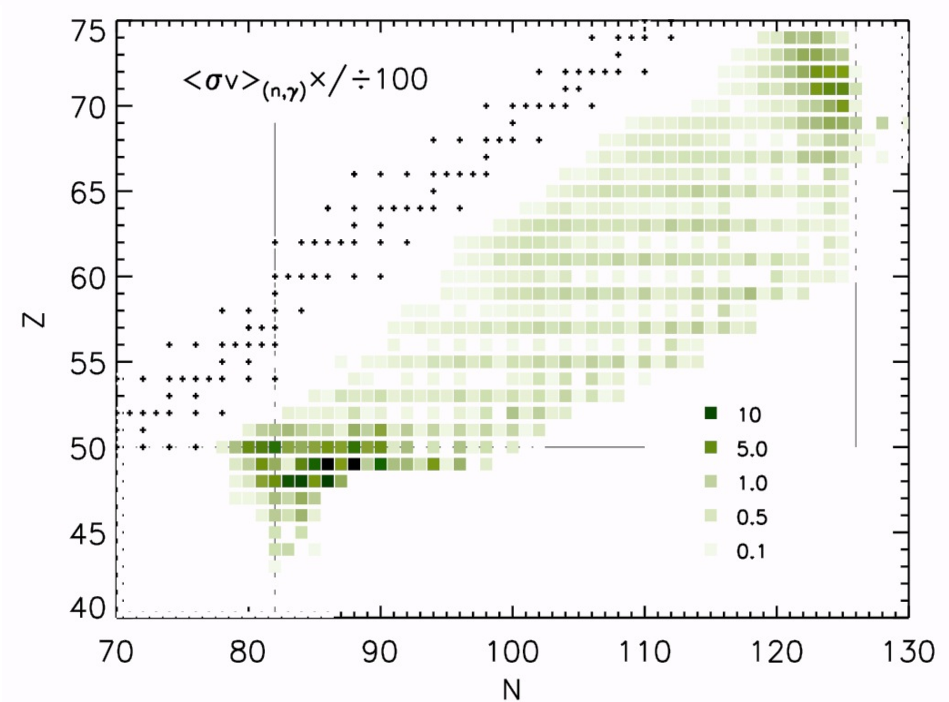


hot wind *r*-process simulation, including freezeout from equilibrium

initial estimate for CARIBU

anticipated FRIB reach



cold wind *r*-process simulation

Surman et al (2013)

neutron capture rate experimental prospects

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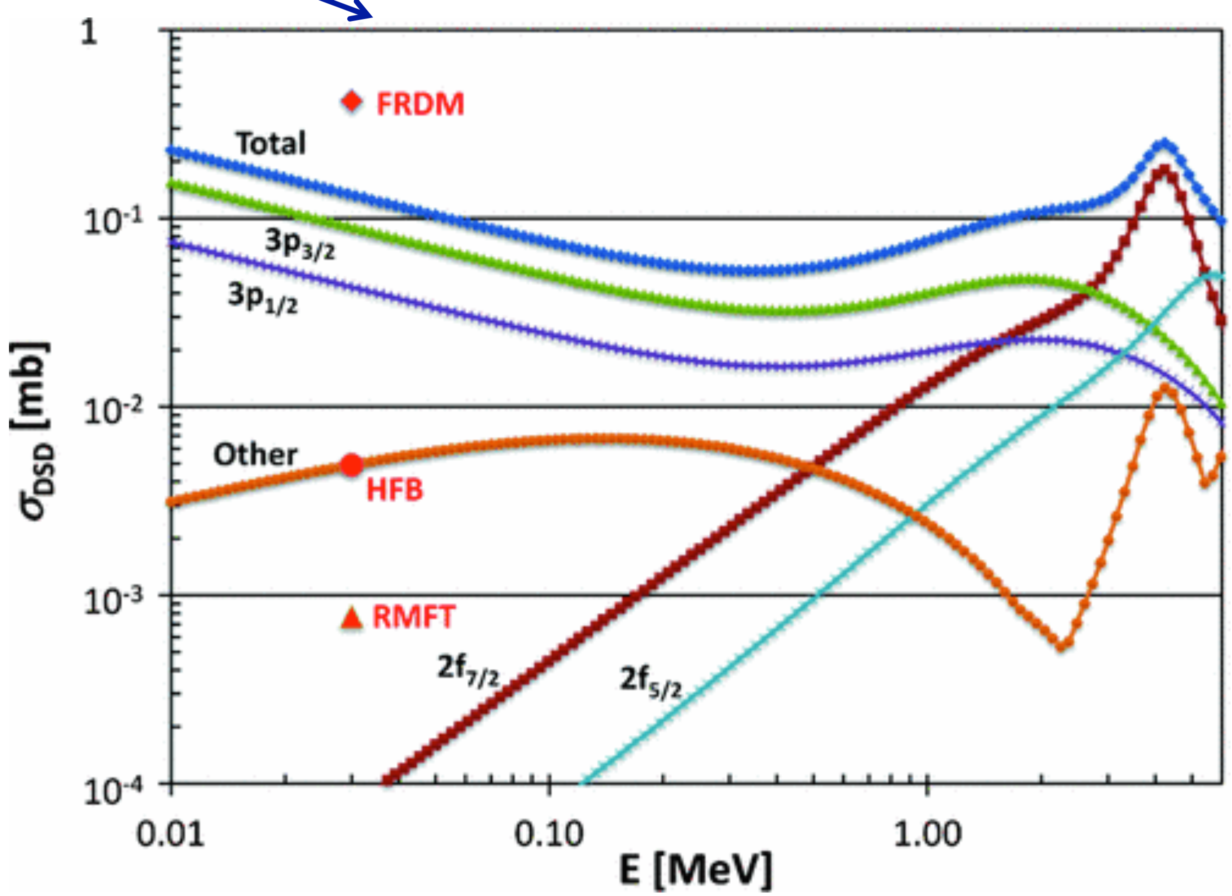
transfer reactions:

^{95}Mo(*d,p*) Ratkiewicz et al, in preparation – study use of *(d,p)* as a surrogate for *(n,γ)*

^{128}Sn(*d,p*), ^{126}Sn(*d,p*) Manning et al, in preparation

^{130}Sn(*d,p*) Kozub et al (2012)

^{132}Sn(*d,p*) Jones et al (2011)



neutron capture rate experimental prospects

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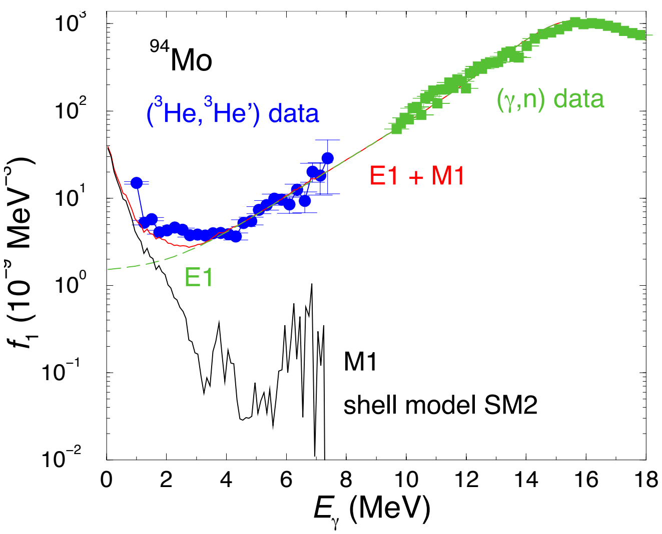
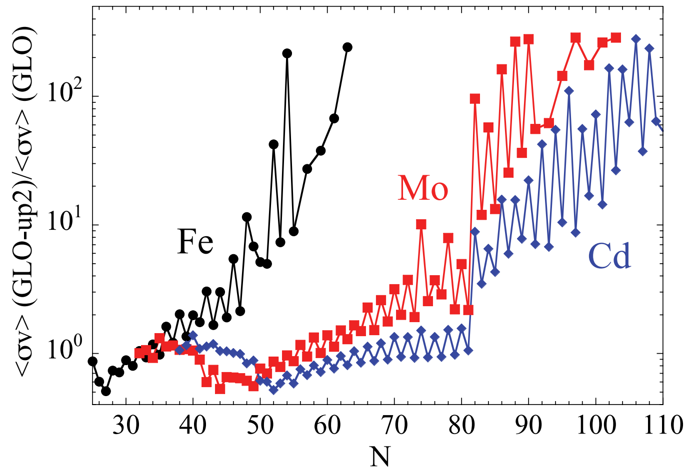
γSF approaches:

Ex: $^{93-98}$Mo Guttormsen et al (2005)



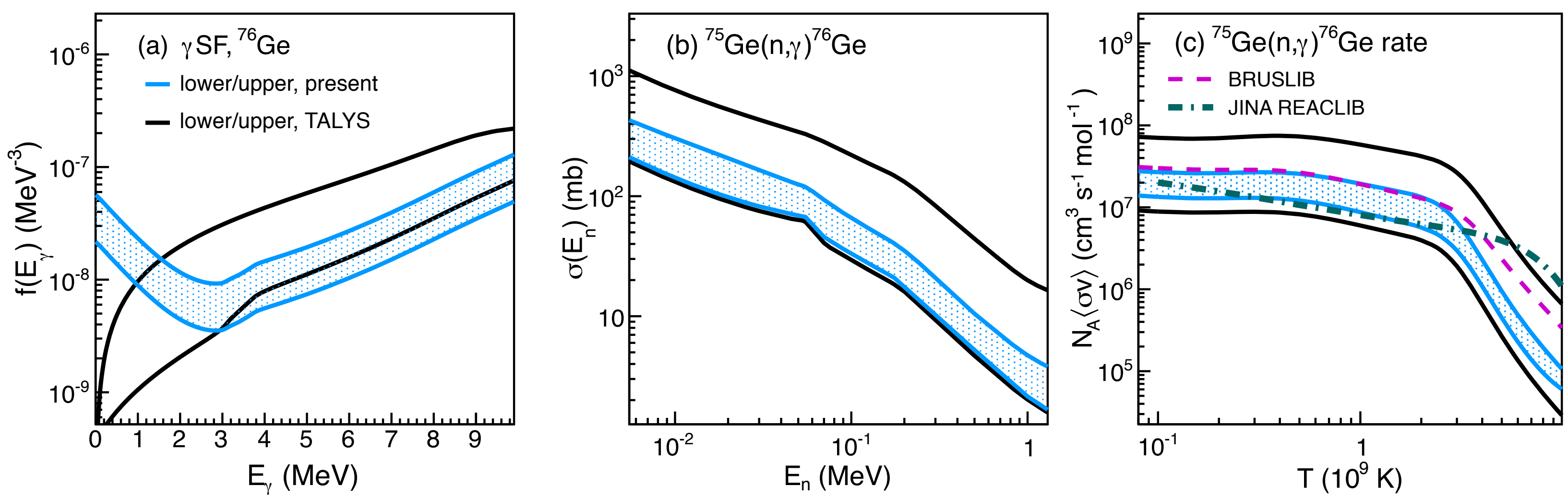


Larsen and Goriely (2010)

β-Oslo method:

Spyrou et al (2014)

Frauendorf et al (2014)



neutron capture rates and *r*-process simulations

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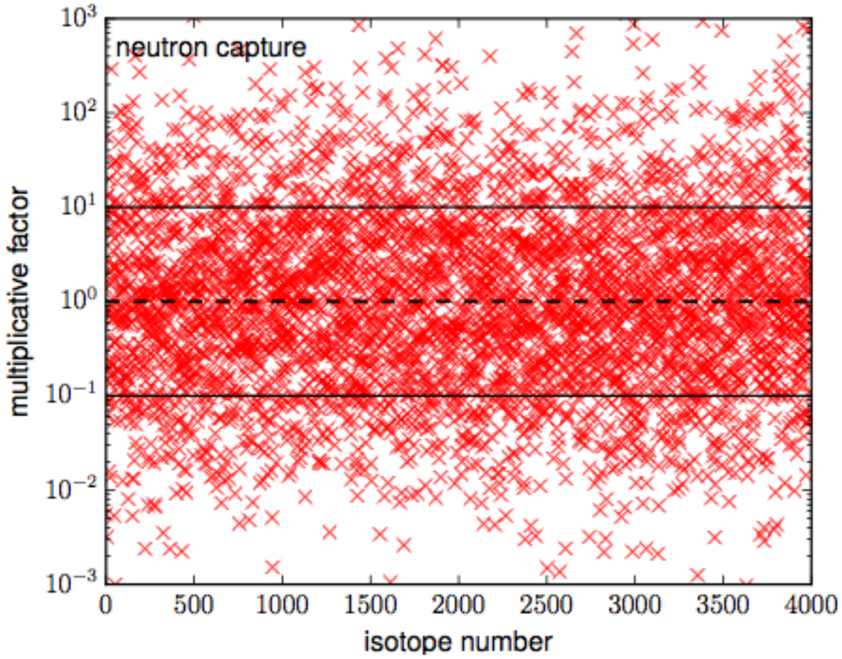
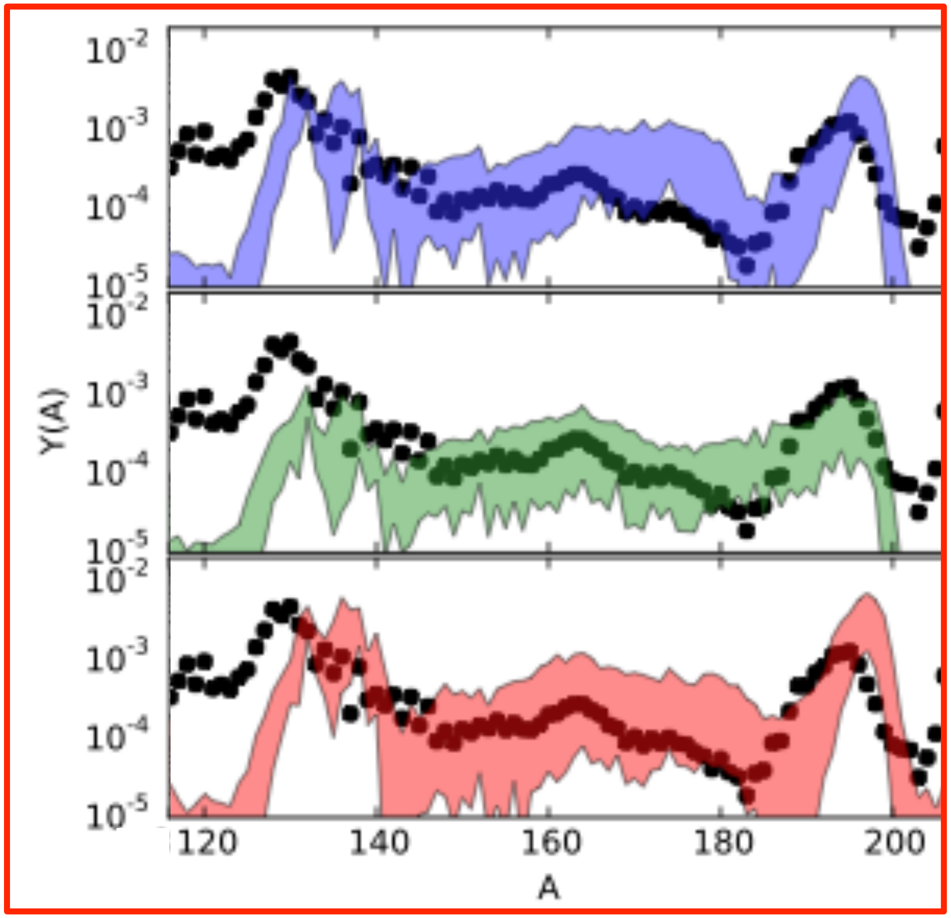


neutron capture rate variations

Mumpower, Surman, Aprahamian (2015)



nuclear data and the rare earth peak

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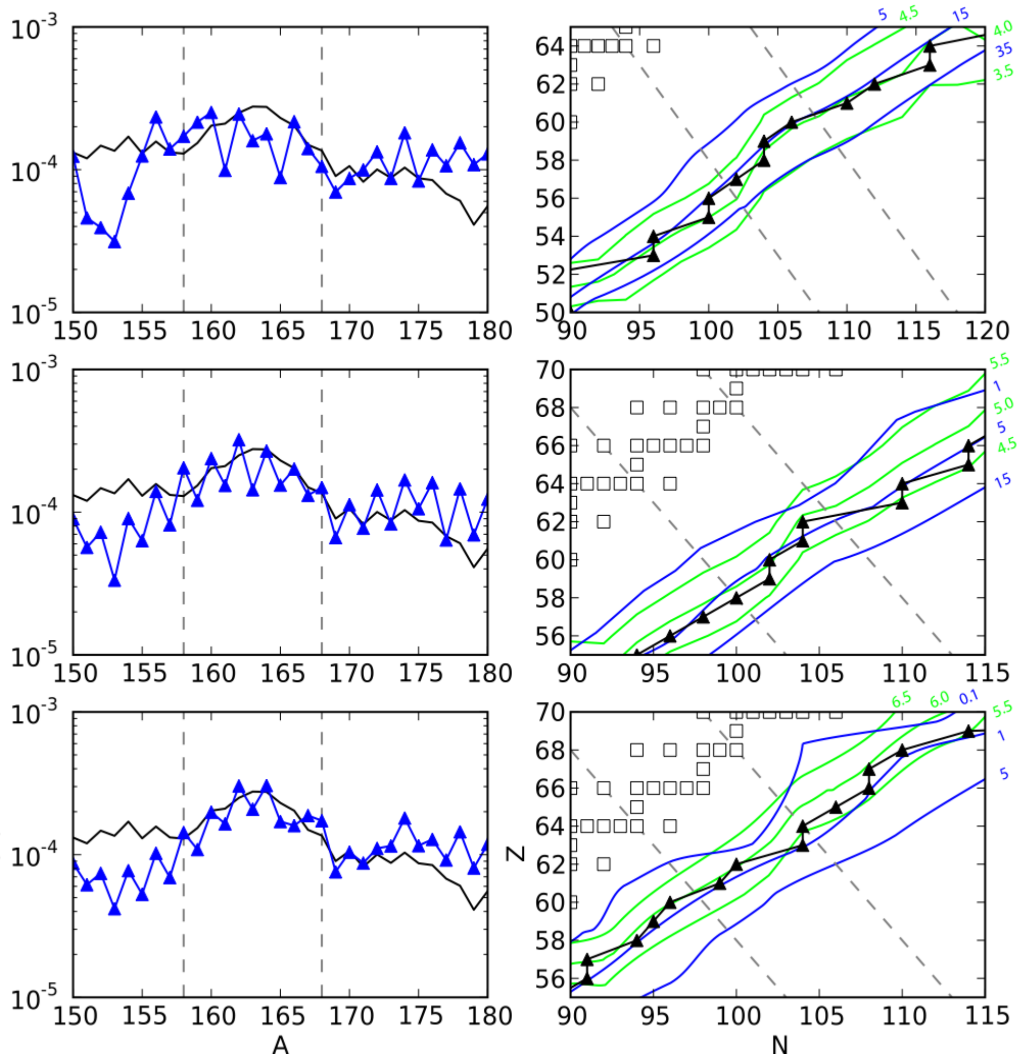


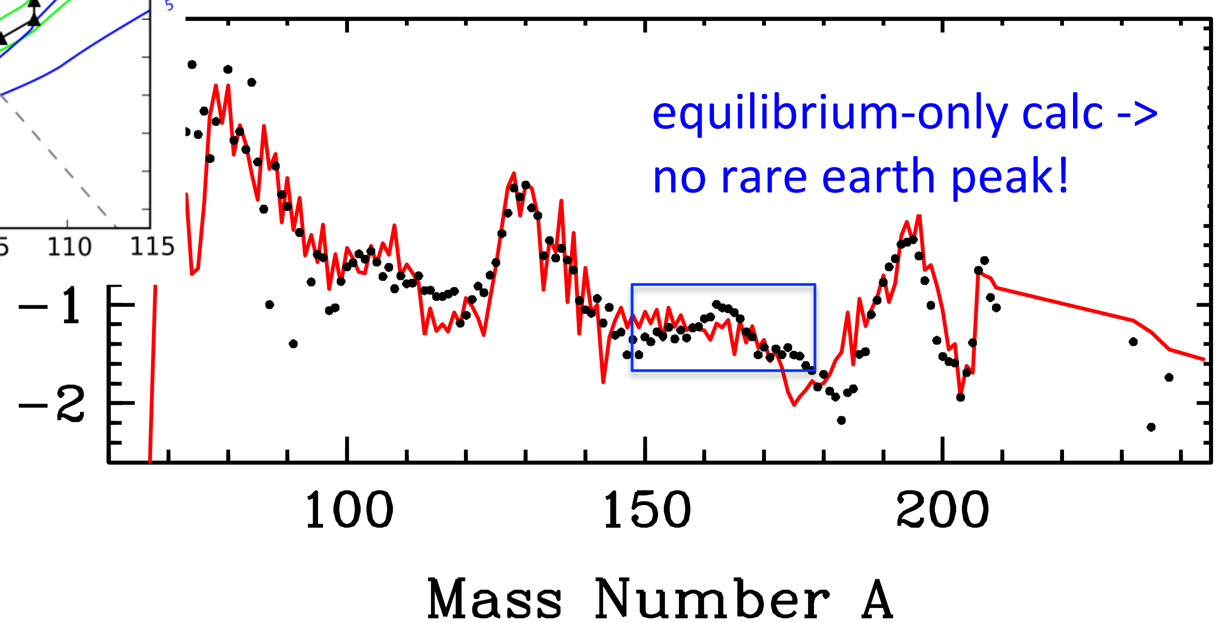
Mumpower, McLaughlin, and Surman, PRC (2012)

FRDM

β decay contours

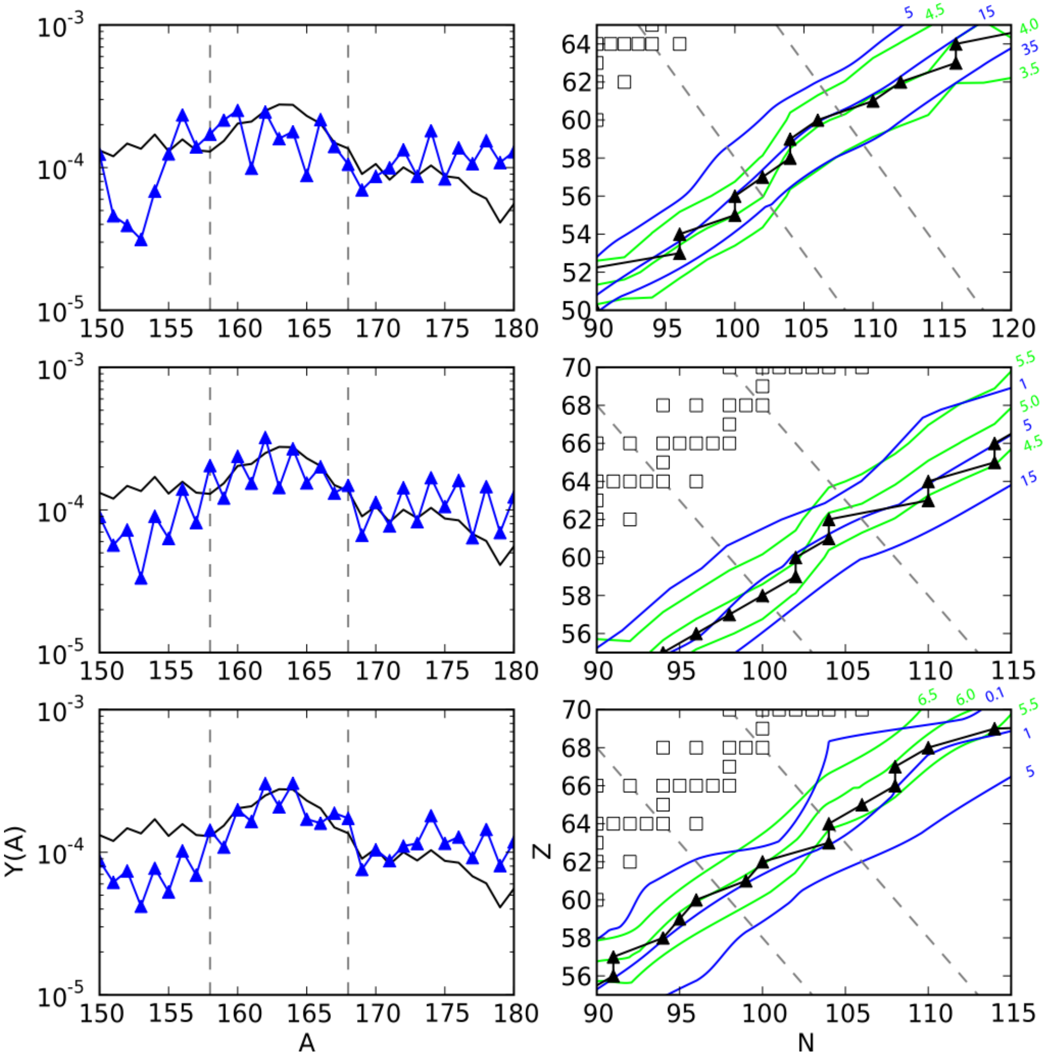
neutron separation energy contours

Kratz et al (2007)



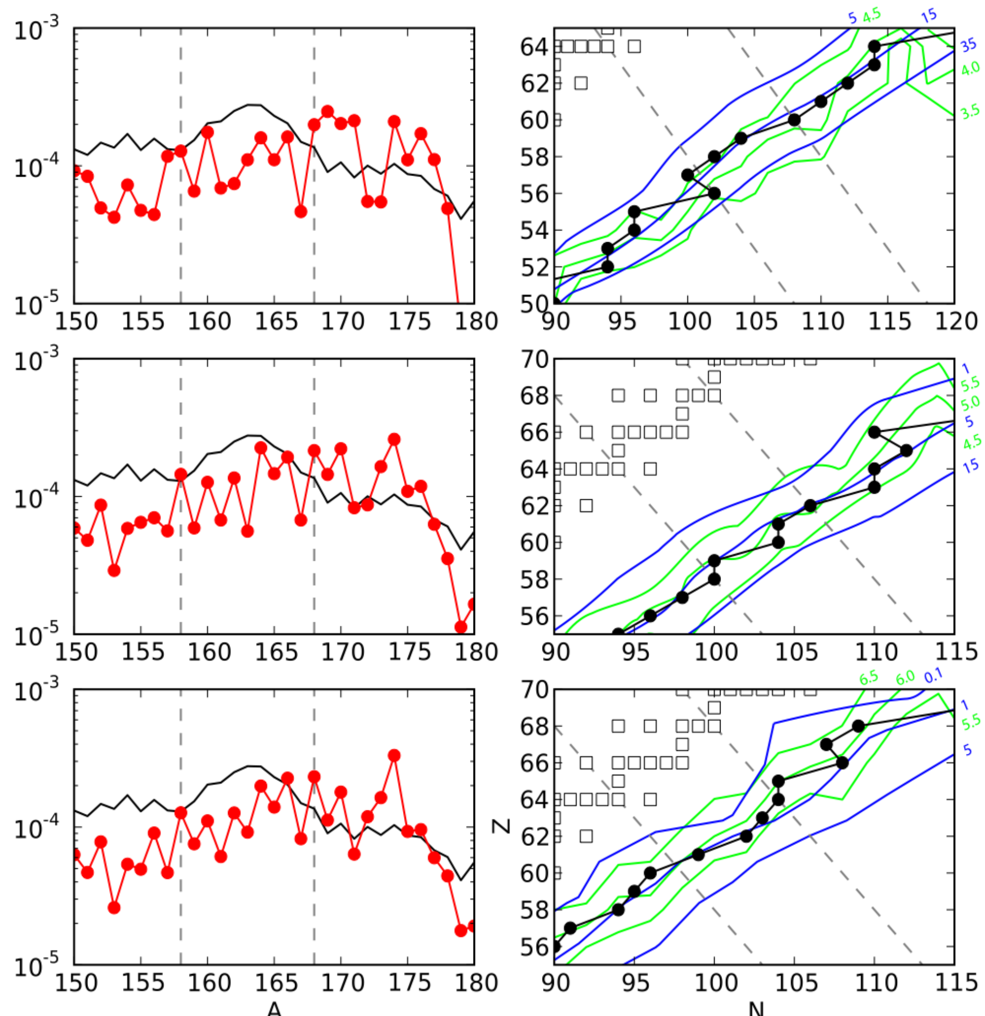
nuclear data and the rare earth peak

Mumpower, McLaughlin, and Surman, PRC (2012)



FRDM

HFB-17



β decay contours

neutron separation energy contours

no REP formation

nuclear data and the rare earth peak

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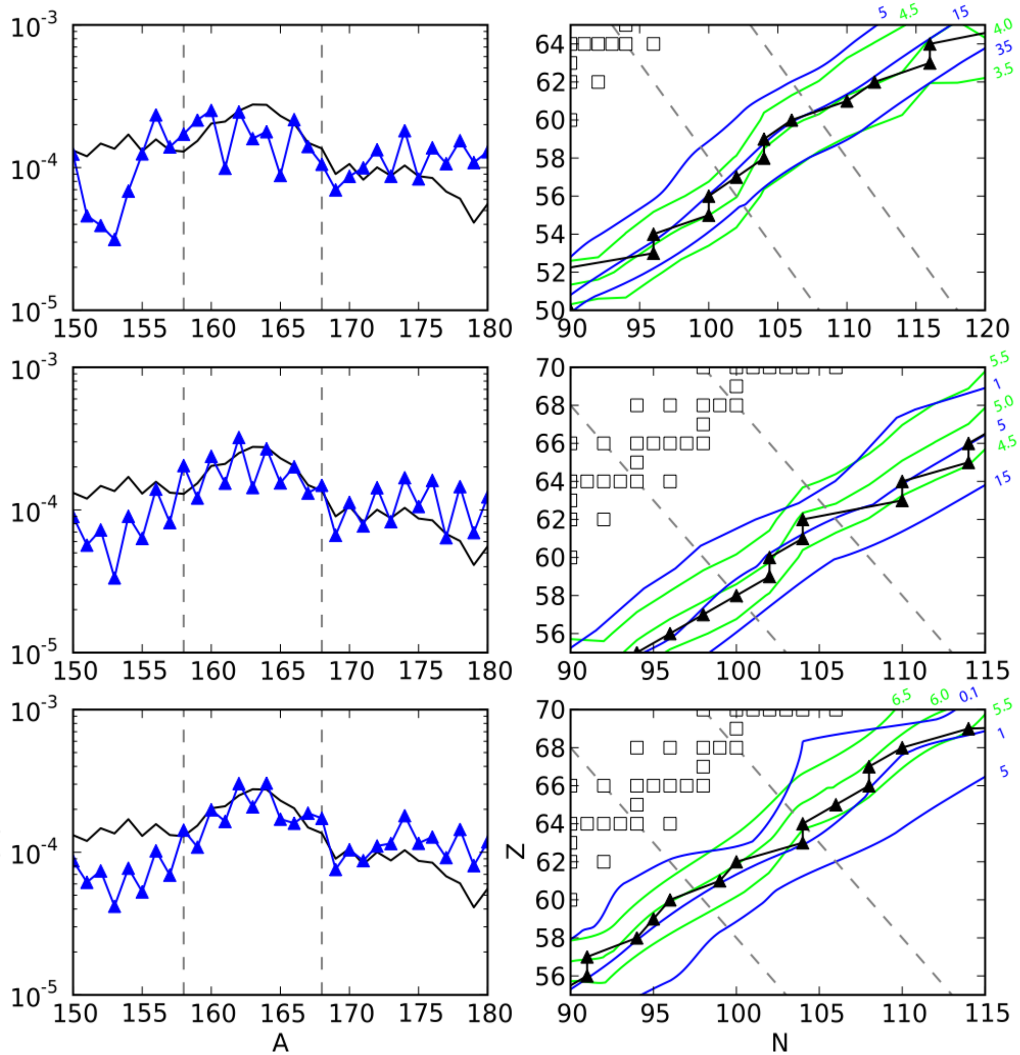


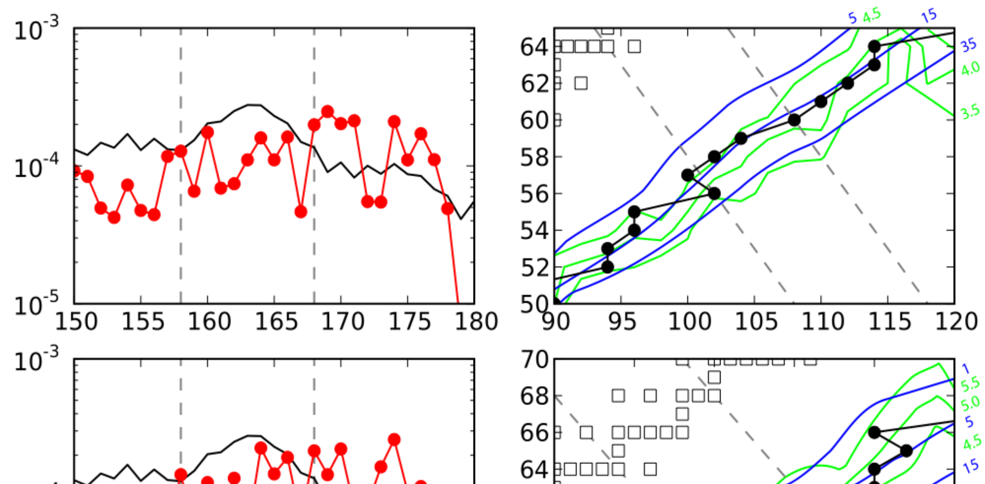
FRDM

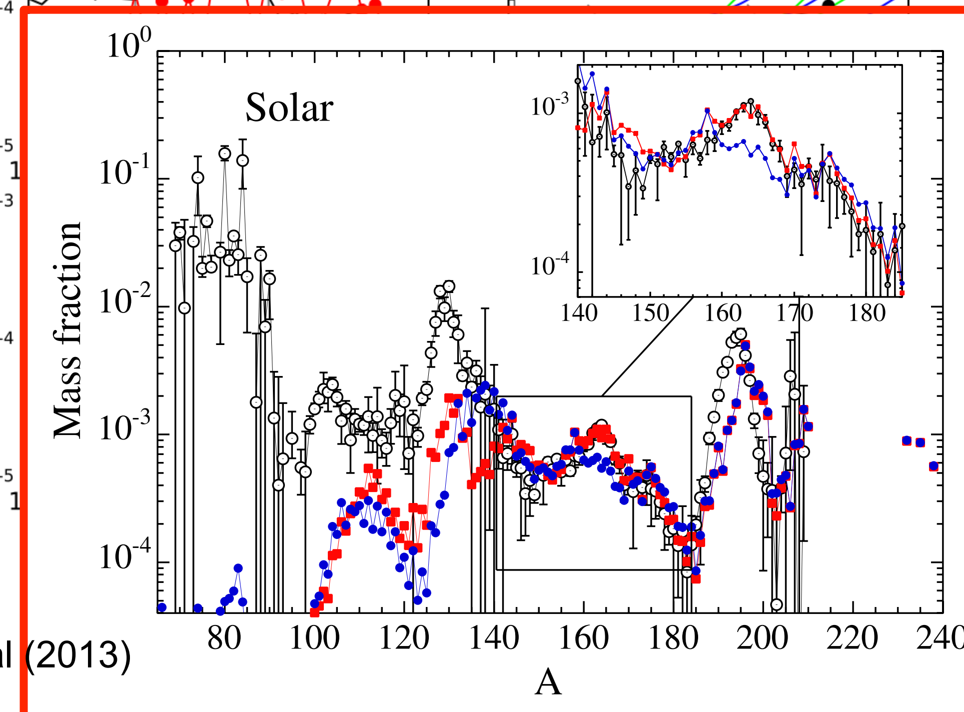
β decay contours

neutron separation energy contours

Mumpower, McLaughlin, and Surman, PRC (2012)

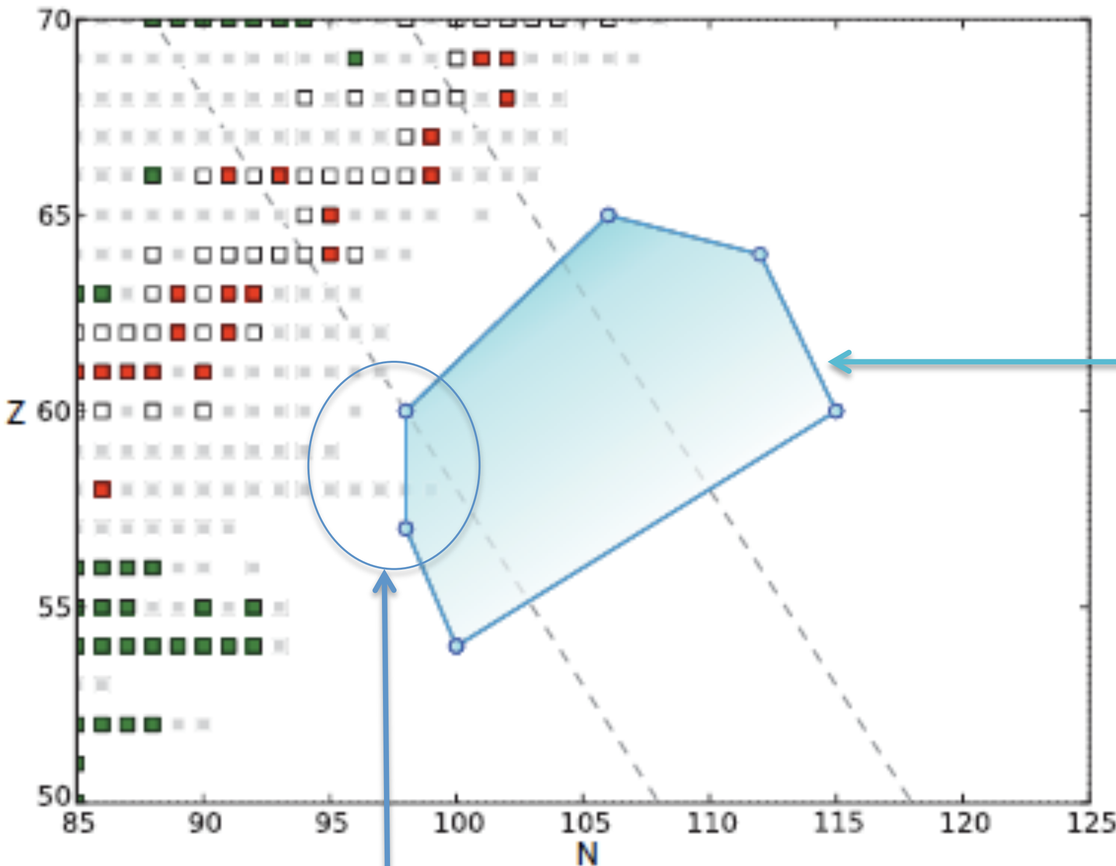
HFB-17





Goriely et al (2013)

nuclear data and the rare earth peak



Region of interest identified in Mumpower, McLaughlin, Surman (2012)

new measurements of halflives at RIKEN, Wu et al, in preparation

nuclear data and the rare earth peak

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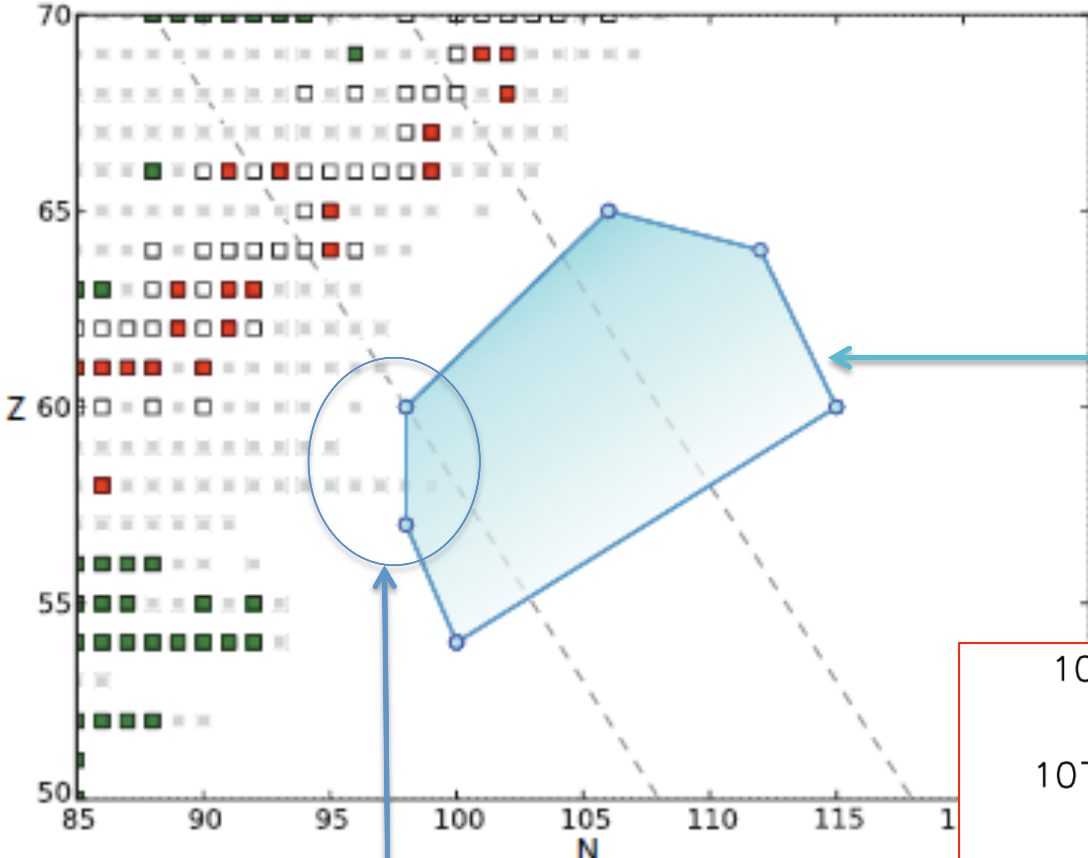

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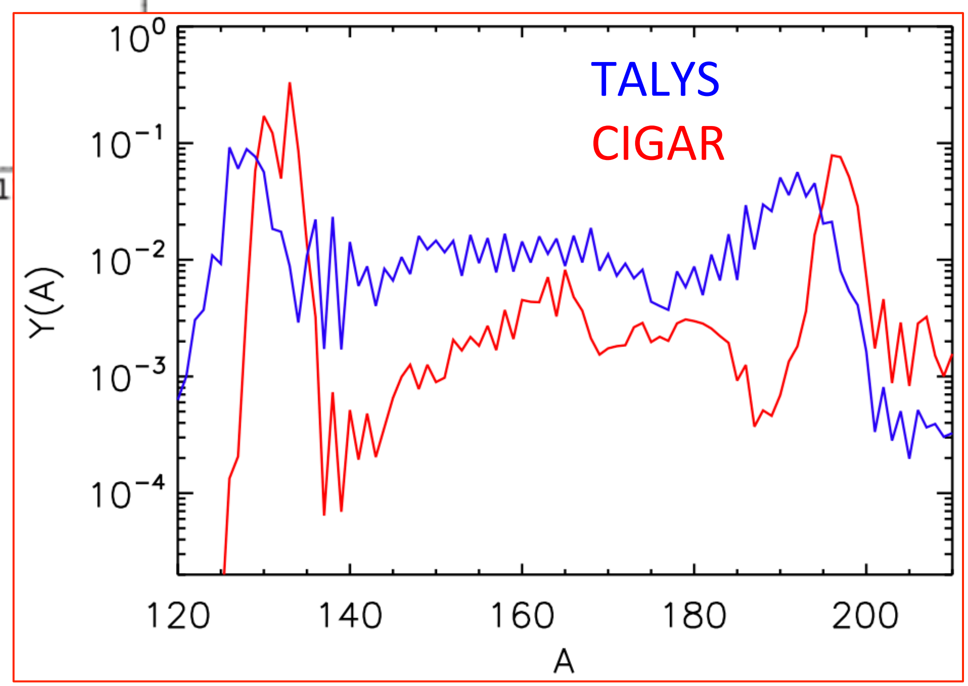
Wu et al, in preparation



summary

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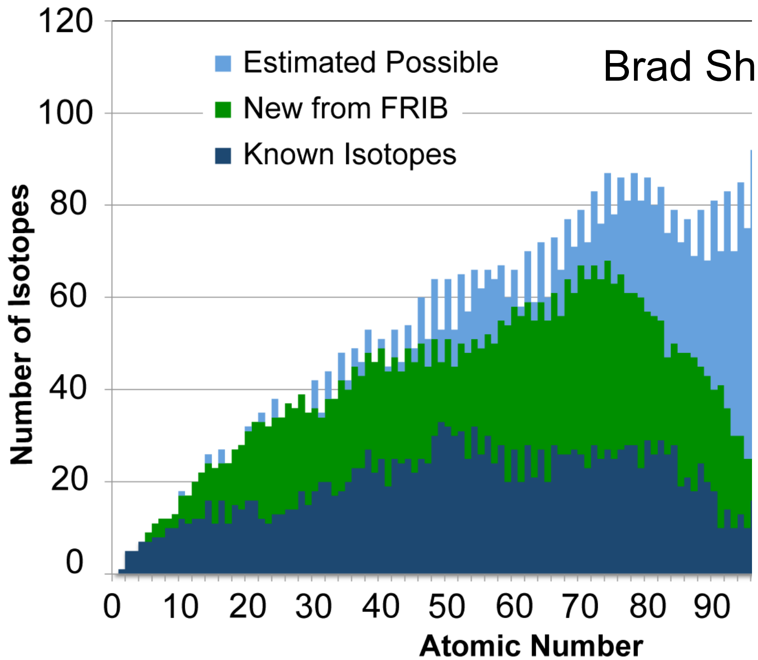
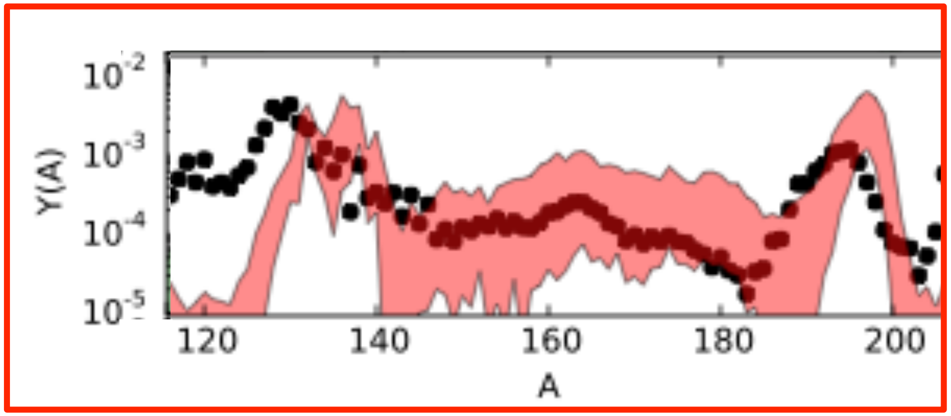
The site of the *r* process remains one of the greatest mysteries of nuclear astrophysics.

The capability of current and next generation radioactive beam facilities to reach extremely neutron-rich nuclei for the first time will open up a promising new approach to this mystery: exploiting the details of the *r*-process pattern to constrain astrophysical conditions

Fresh theoretical efforts are crucial in order to achieve the necessary reductions in neutron capture rate uncertainties



Brad Sherrill



Mumpower et al (2014)