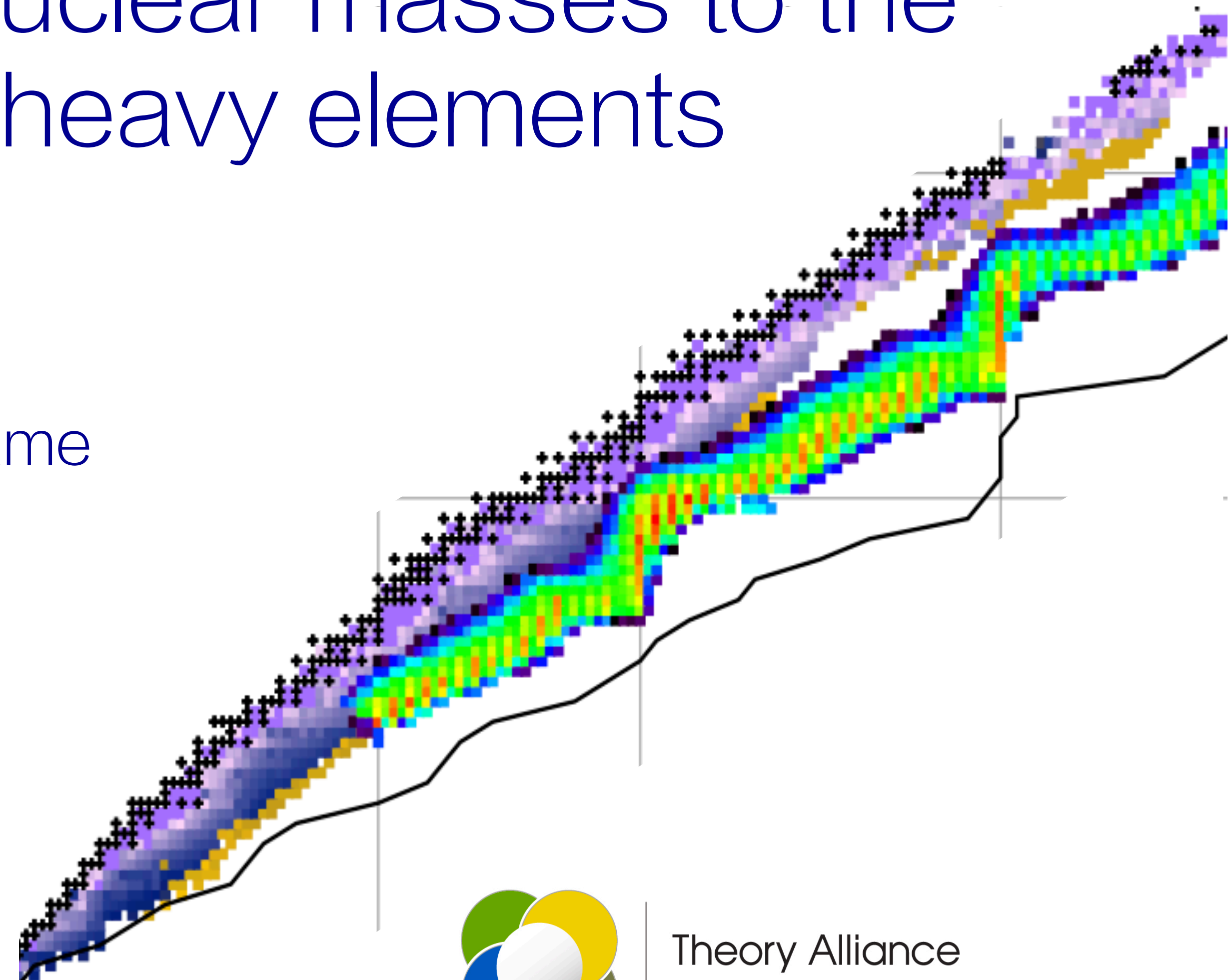
Connecting nuclear masses to the origins of the heavy elements

Rebecca Surman
University of Notre Dame

INT-16-2a
Bayesian Methods
in Nuclear Physics
5 July 2016



Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

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JINA-CEE

outline

- introduction to *r*–process nucleosynthesis
- nuclear mass uncertainties and *r*–process simulations
- reverse–engineering nuclear mass features using the *r*–process abundance pattern

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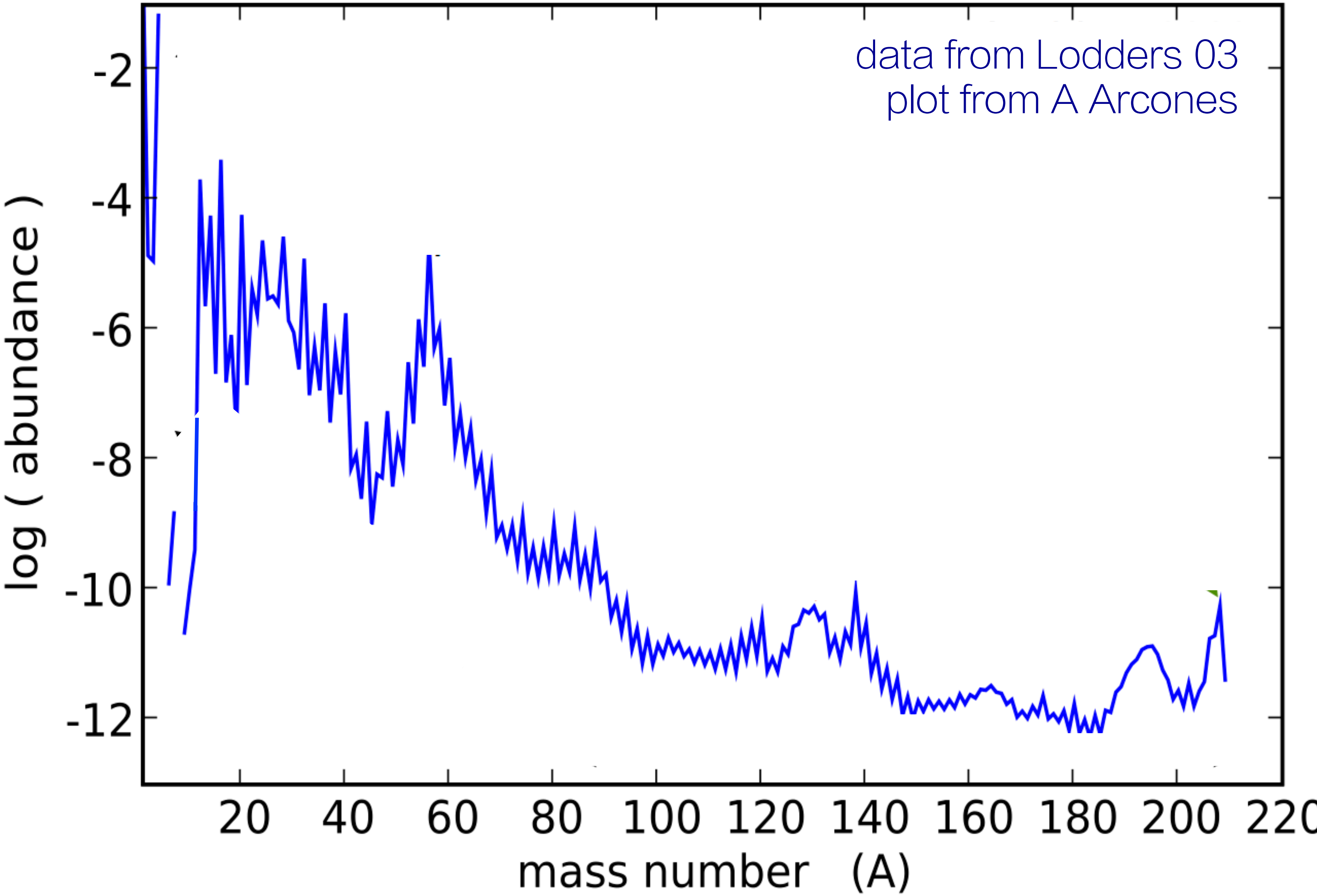
solar system abundances



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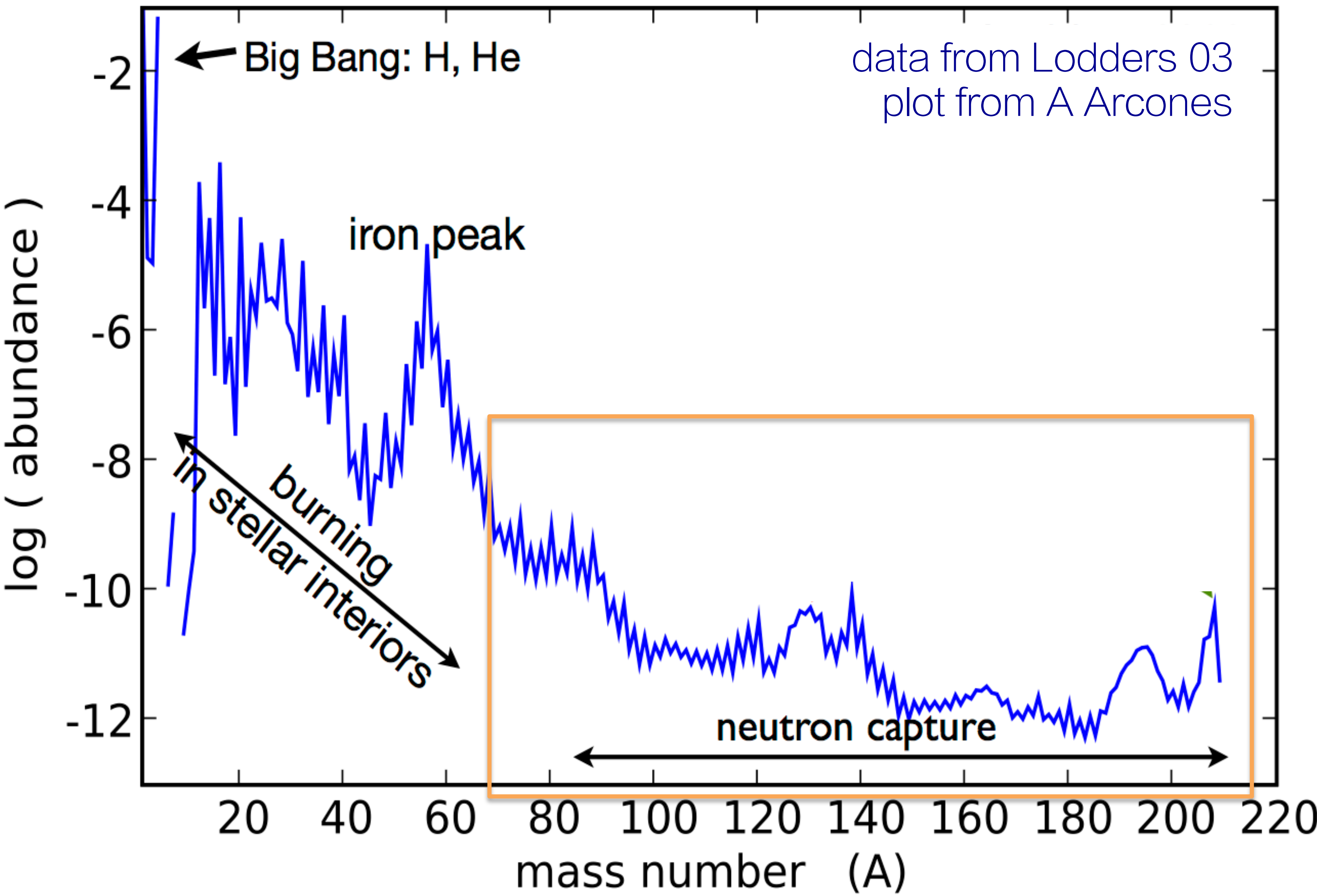
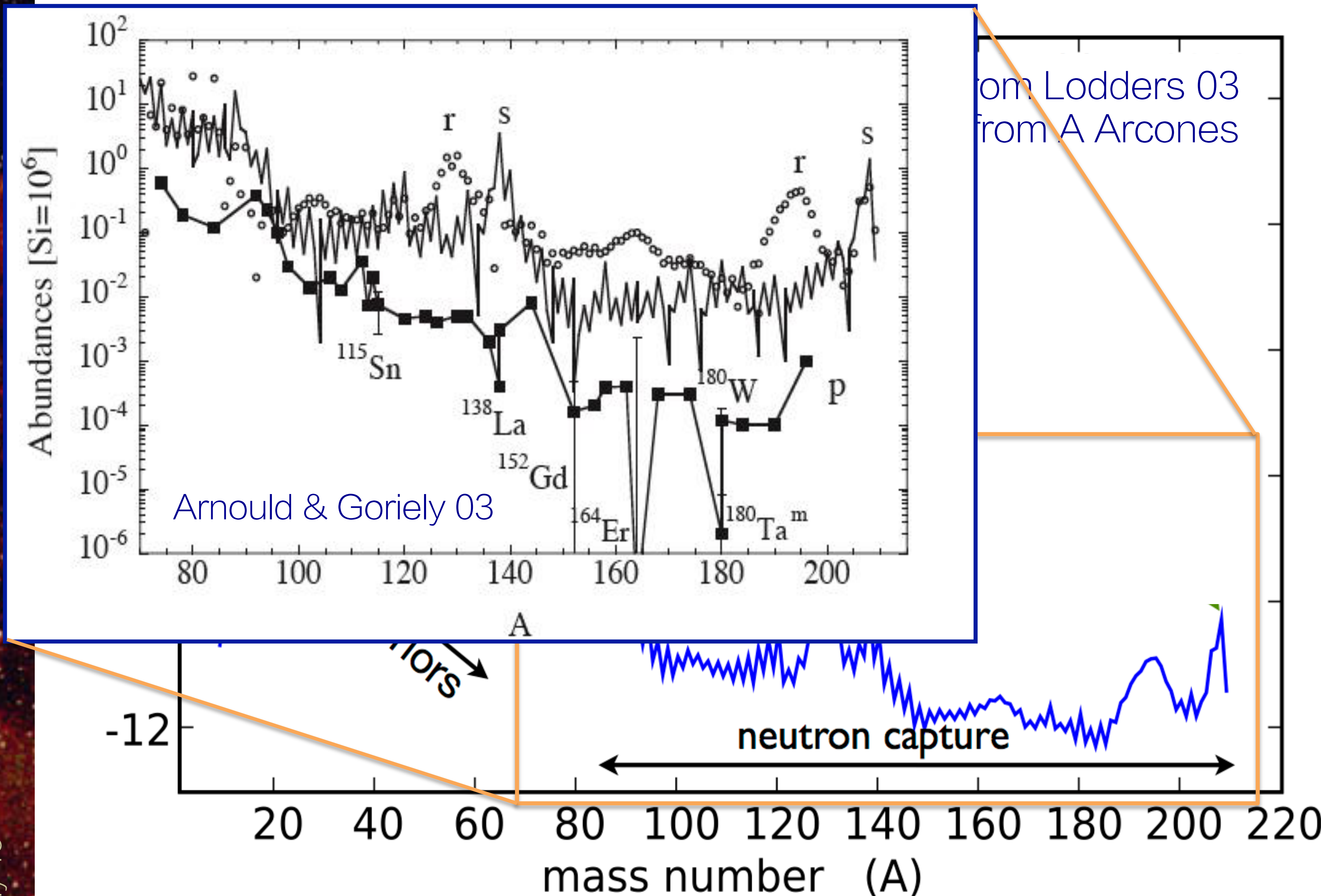
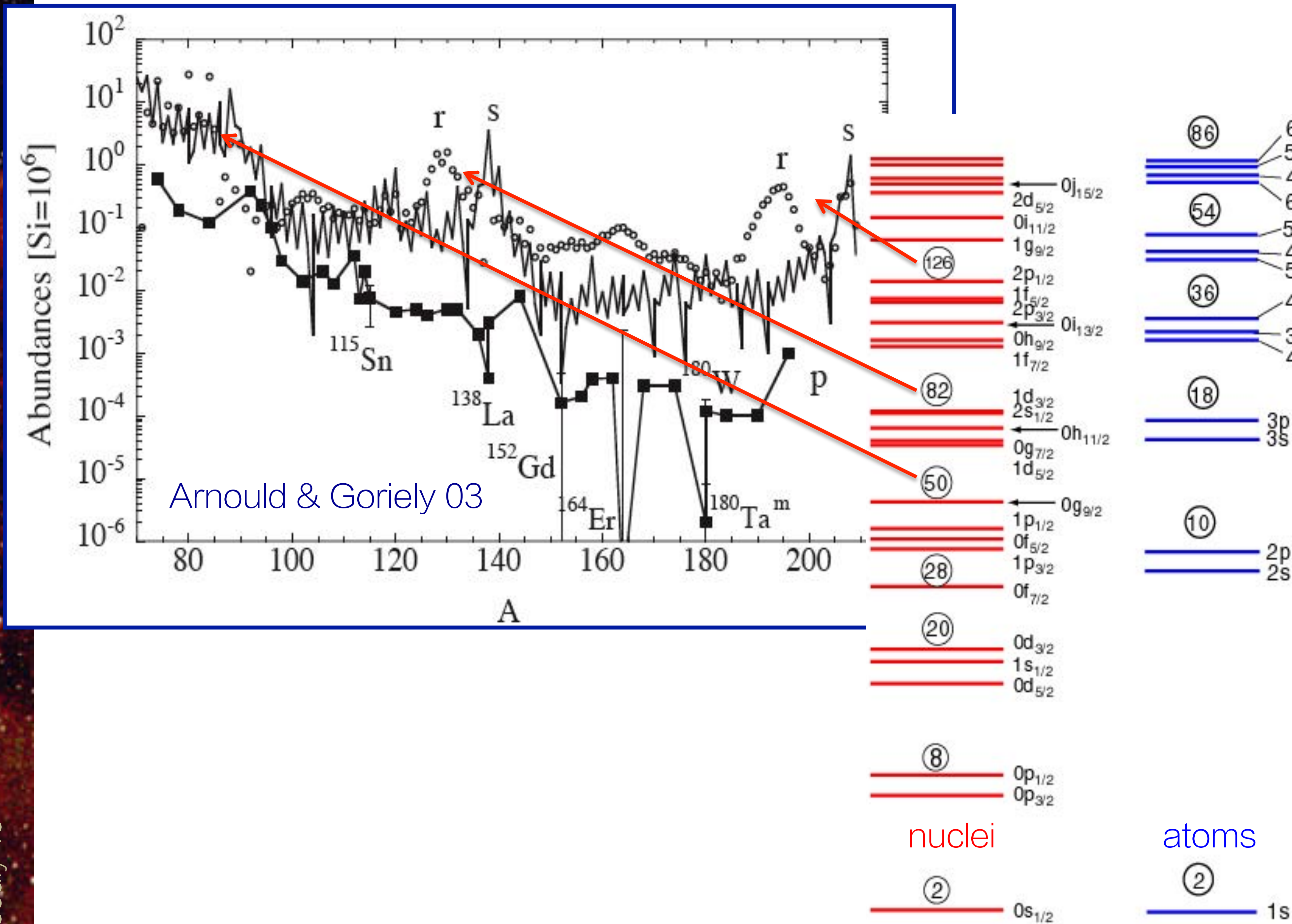
solar system abundances

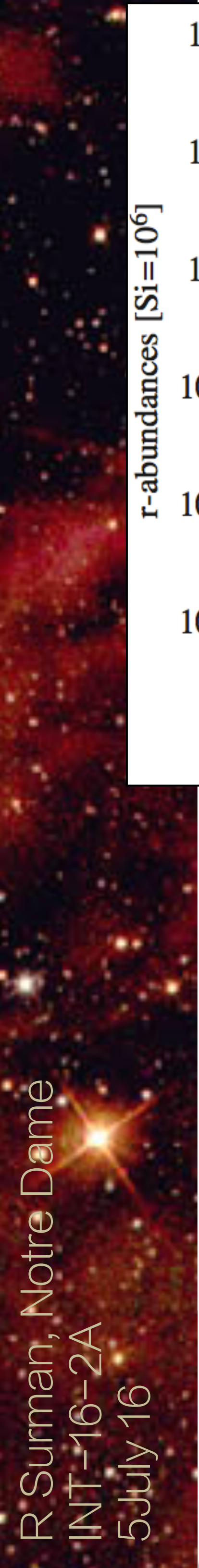


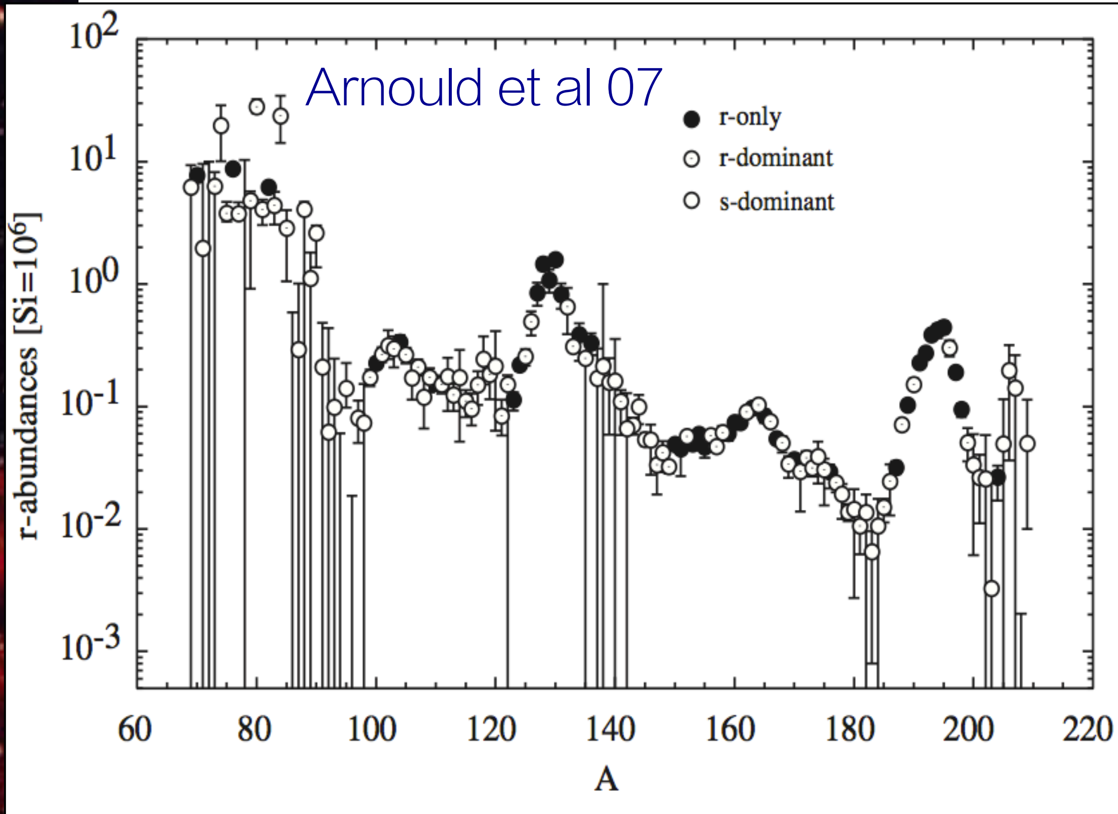
neutron capture abundances



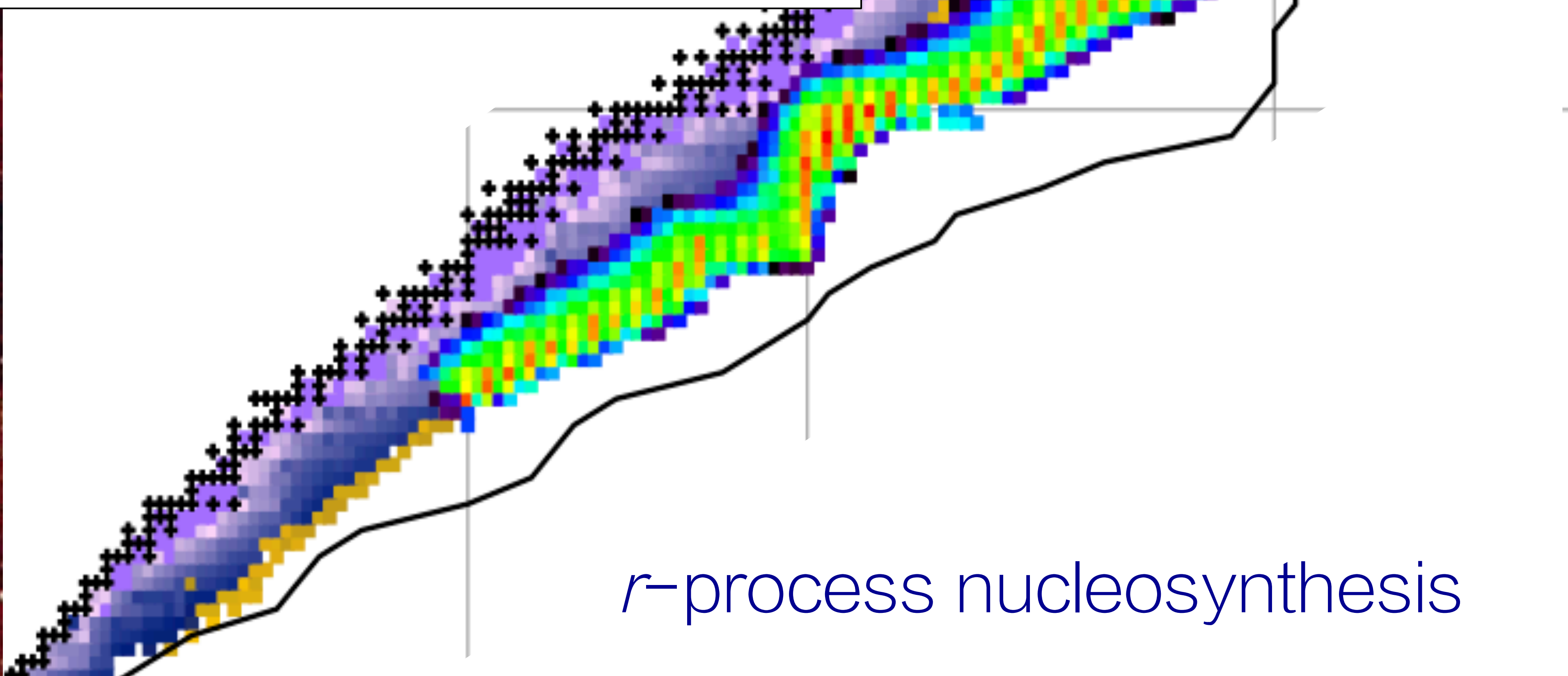
neutron capture abundances







solar system
r–process
residuals



r–process nucleosynthesis

r–process nuclear network calculations

$$\frac{dY(Z,A)}{dt} = Y(Z,A-1)\lambda_{(n,\gamma)}^{Z,A-1} + Y(Z,A+1)\lambda_{(\gamma,n)}^{Z,A+1} + Y(Z-1,A)\lambda_{\beta}^{Z-1,A}$$

$$+\sum Y(Z-1,A+x)\lambda_{\beta xn}^{Z-1,A+x}$$

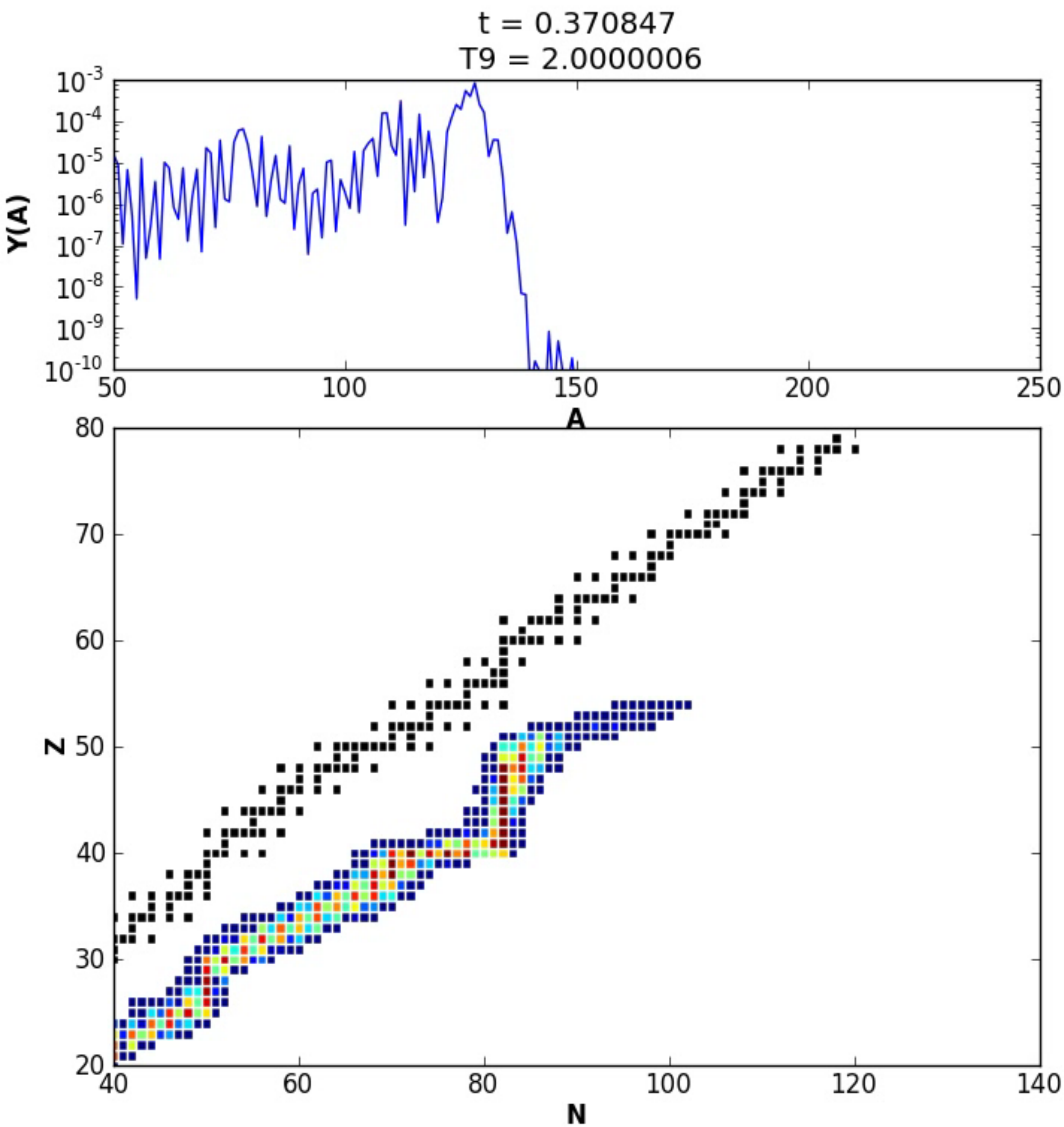
$$-\mathrm{Y(Z,A)}\left[\lambda_{(n,\gamma)}^{Z,A} + \lambda_{(\gamma,n)}^{Z,A} + \lambda_{\beta}^{Z,A} + \sum \lambda_{\beta xn}^{Z,A}\right]$$

$\lambda_{(n,\gamma)}^{Z,A}$ neutron capture rate

$\lambda_{(\gamma,n)}^{Z,A}$ photodissociation rate $\propto \mathrm{e}^{-S_n/kT}$

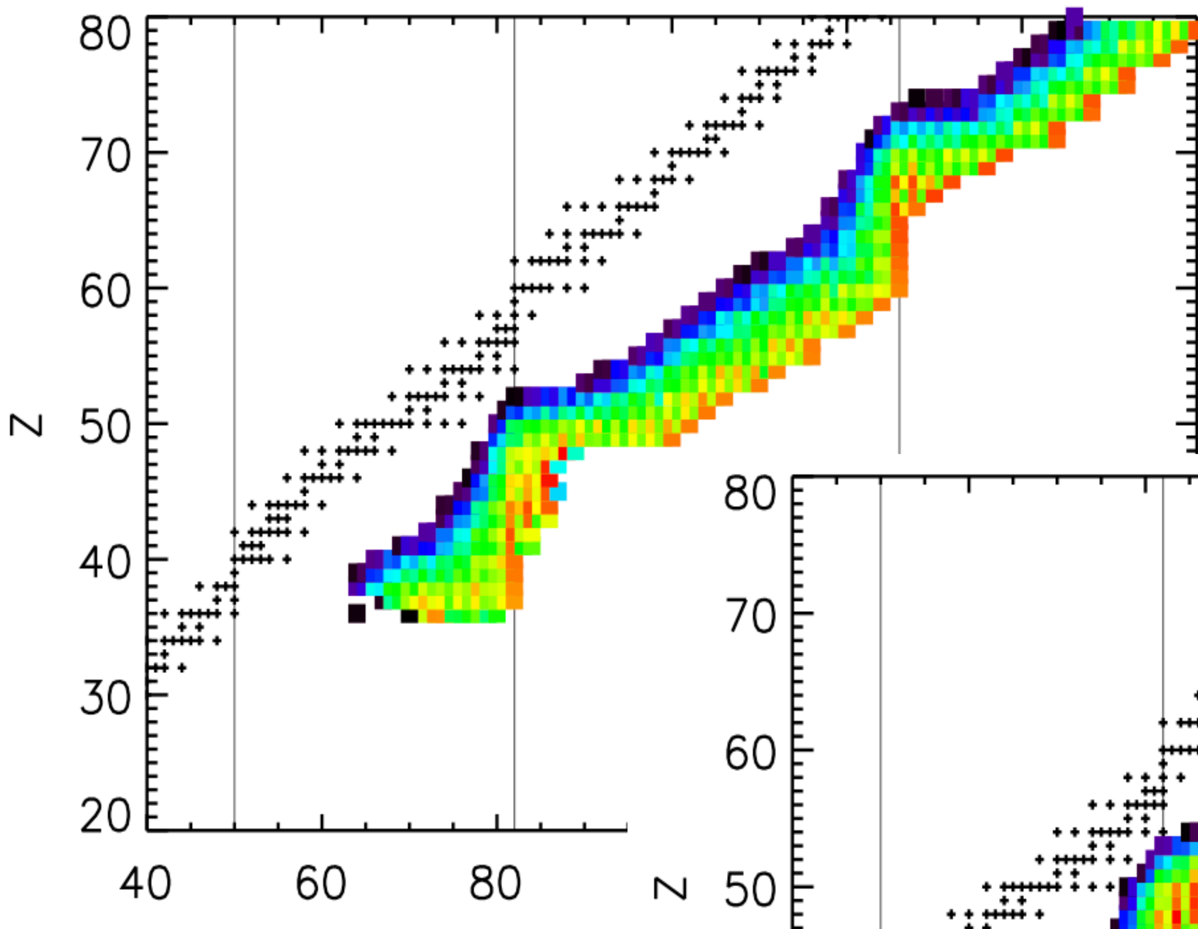
$\lambda_{\beta}^{Z,A}$ beta decay rate $\sim Q_{\beta}^{5}$

$\lambda_{\beta xn}^{Z,A}$ rate for beta decay followed by emission of x neutrons

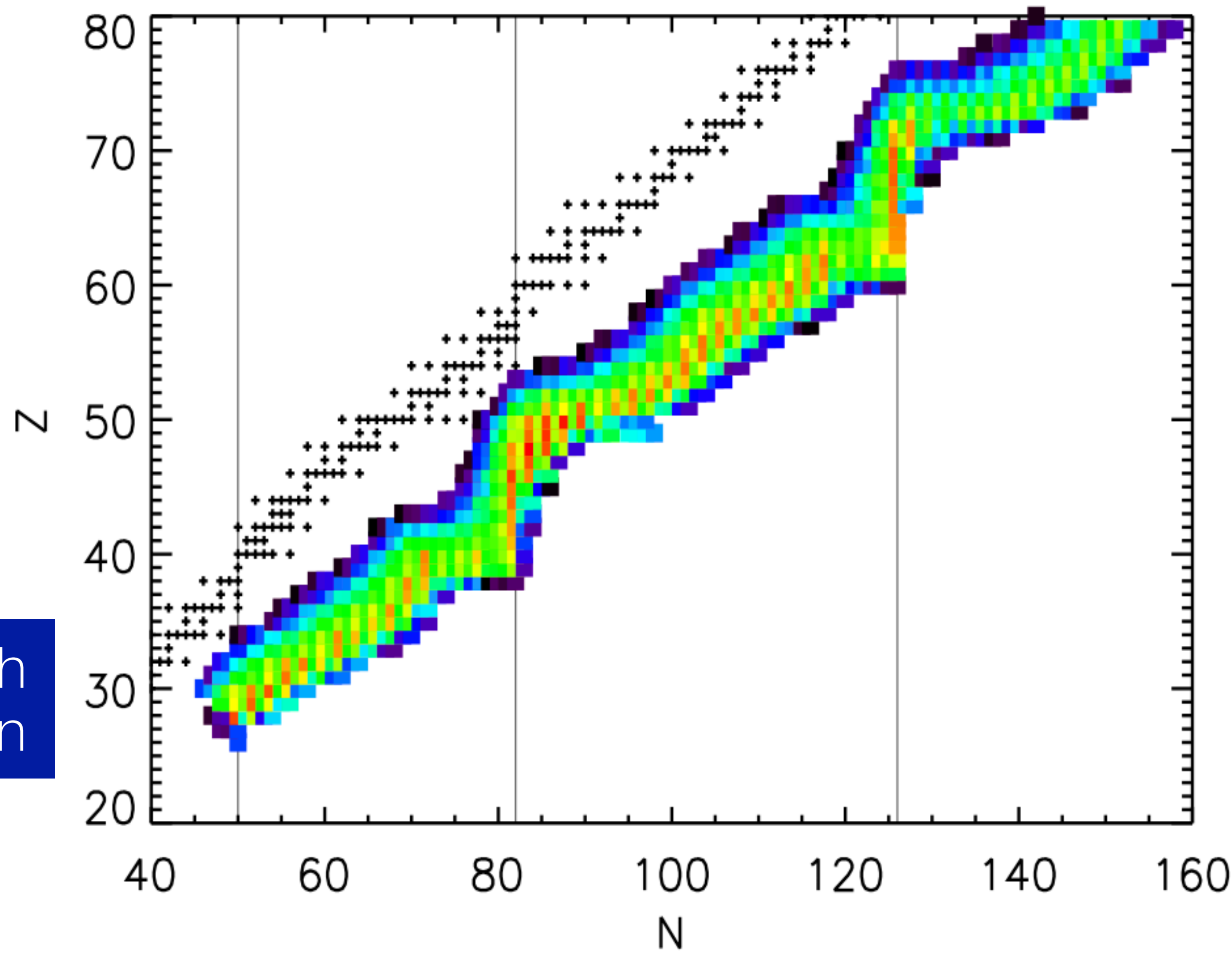


movie by
M Mumpower

r-process abundance pattern signatures

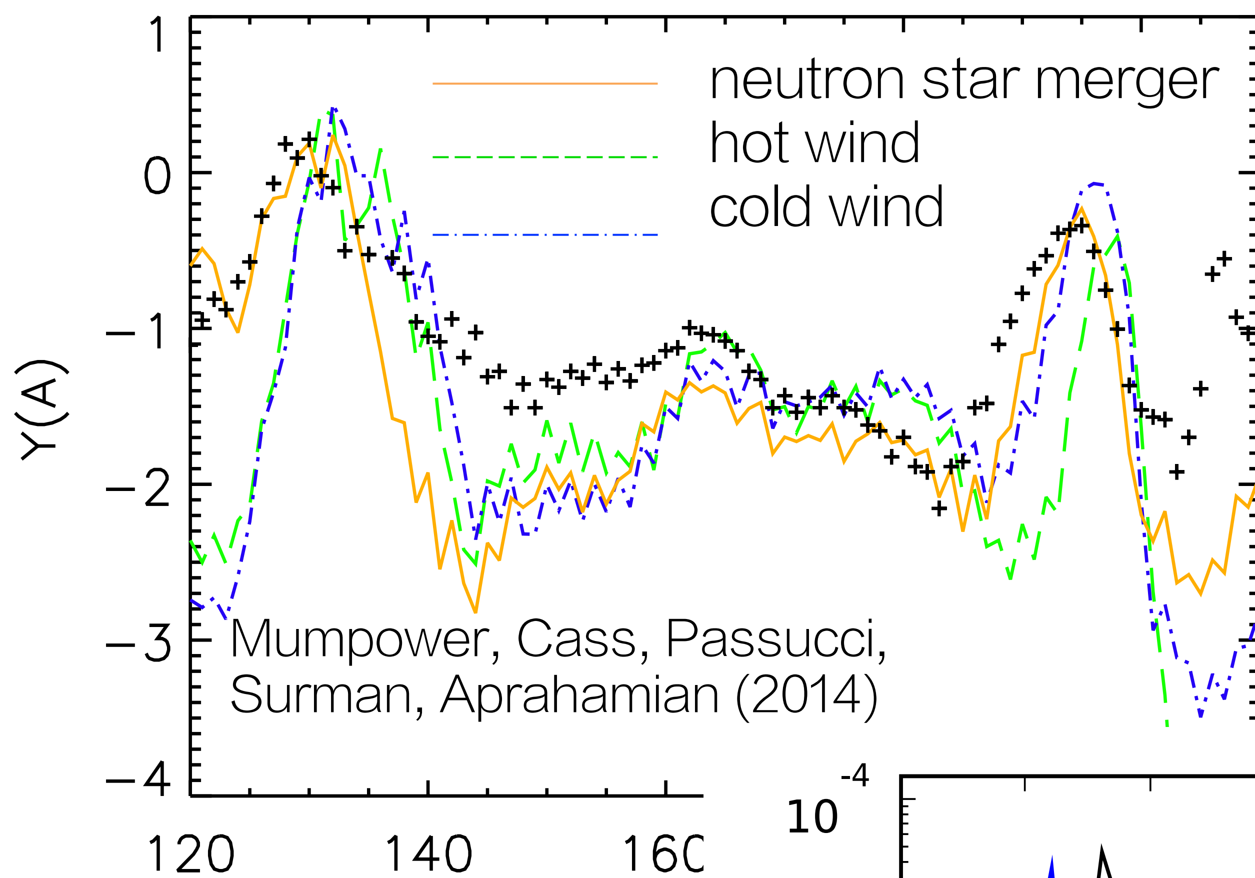


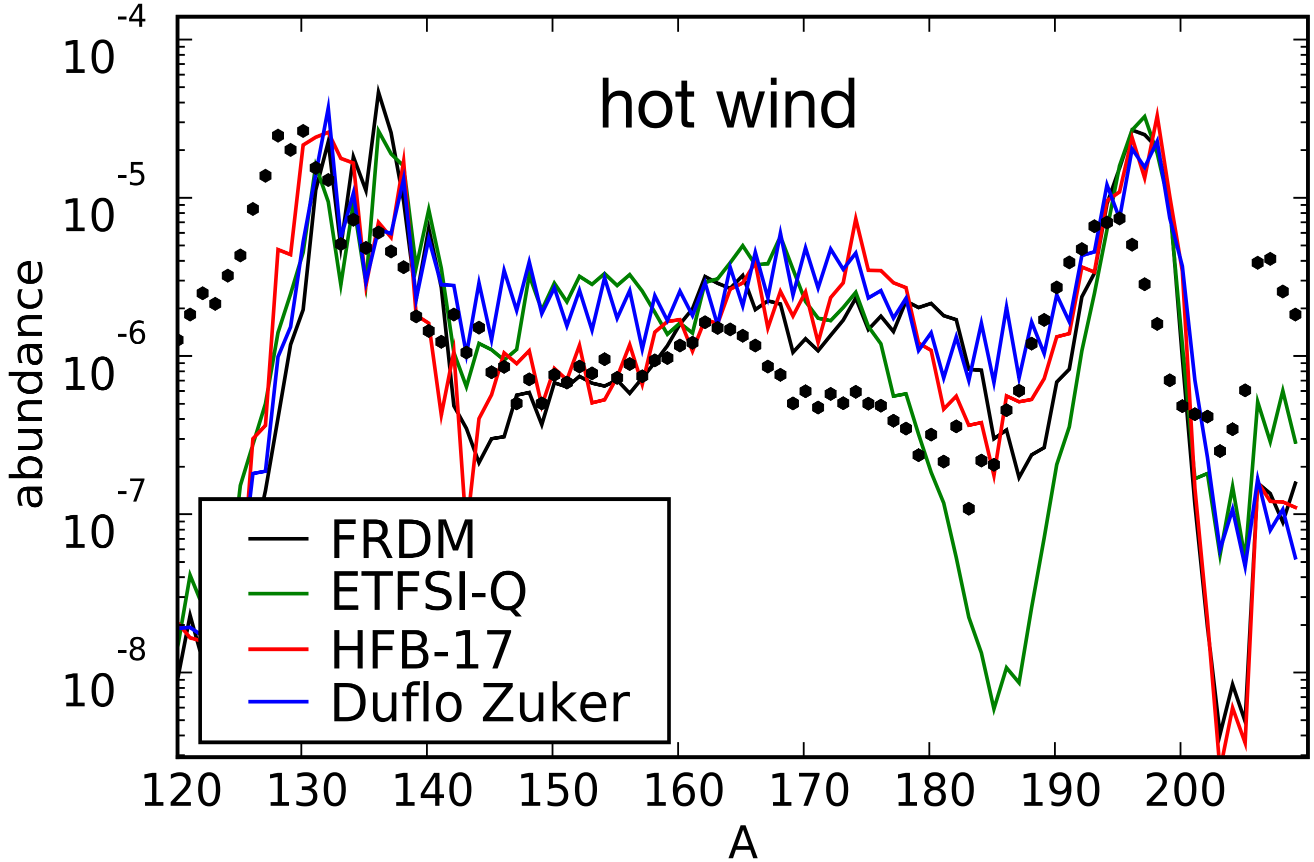
very neutron rich
fission cycling



barely neutron rich
limit seed production

r–process abundance pattern signatures



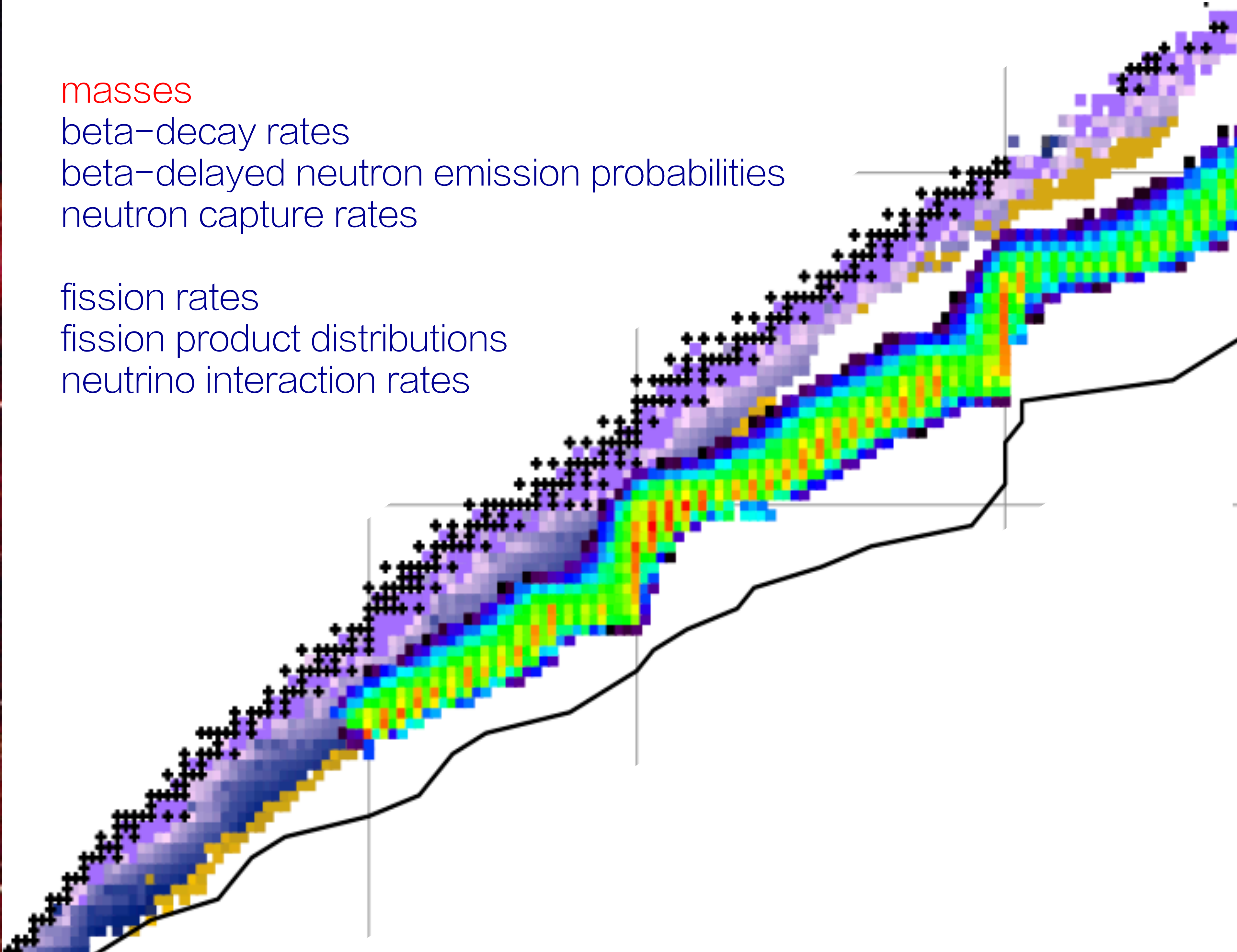


Arcones & Martinez-Pinedo, 2011

r–process simulations: required nuclear data

masses
beta–decay rates
beta–delayed neutron emission probabilities
neutron capture rates

fission rates
fission product distributions
neutrino interaction rates



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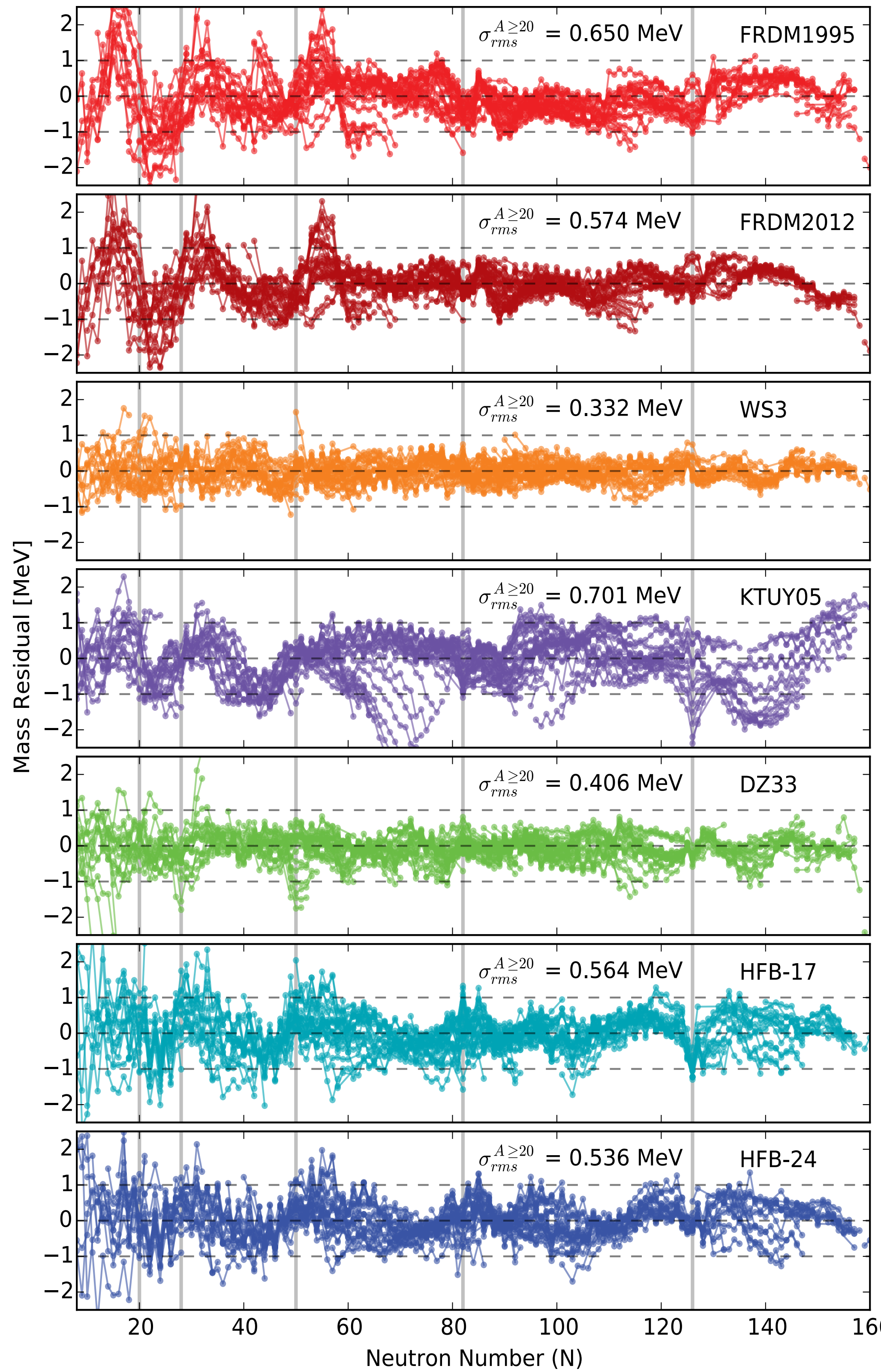
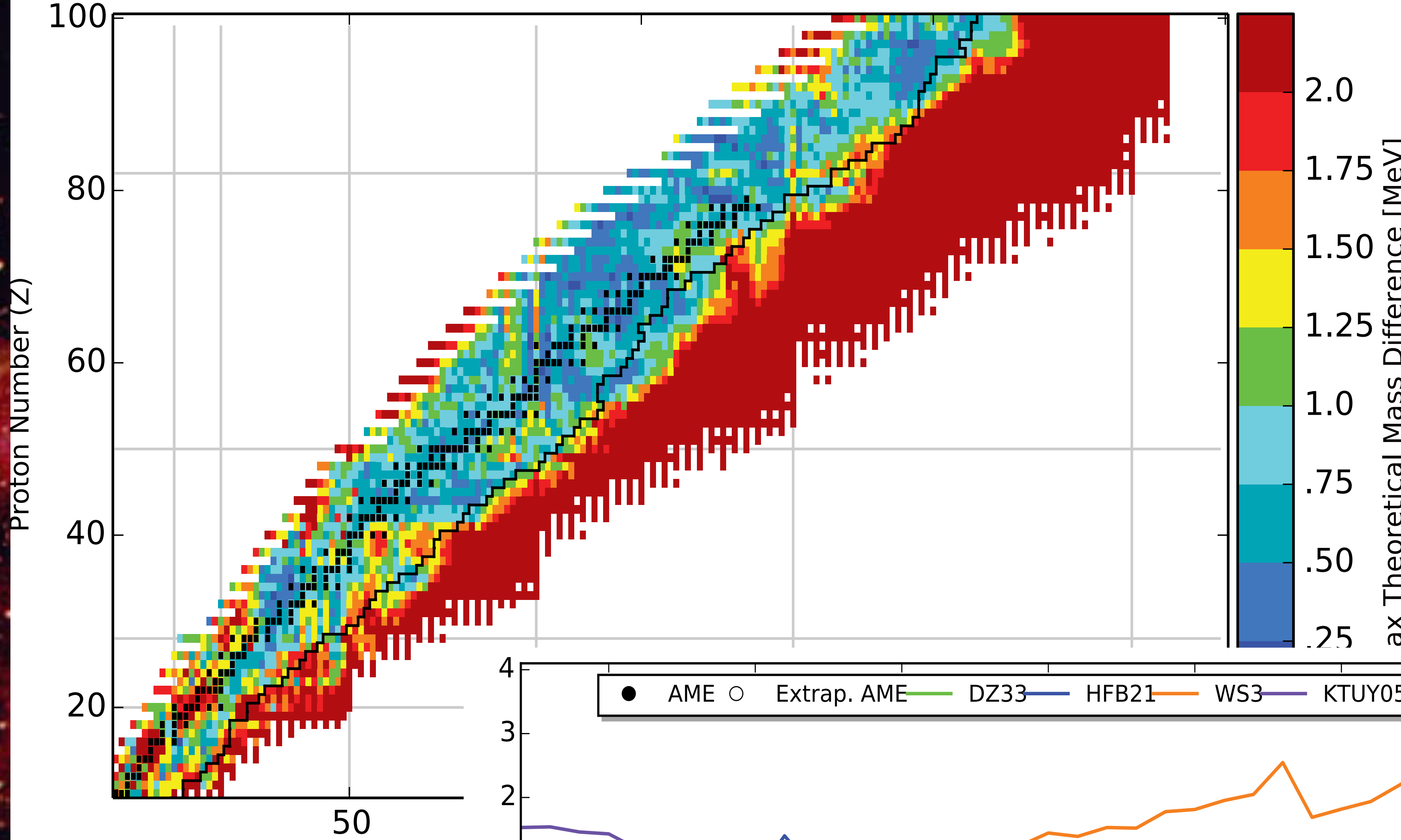
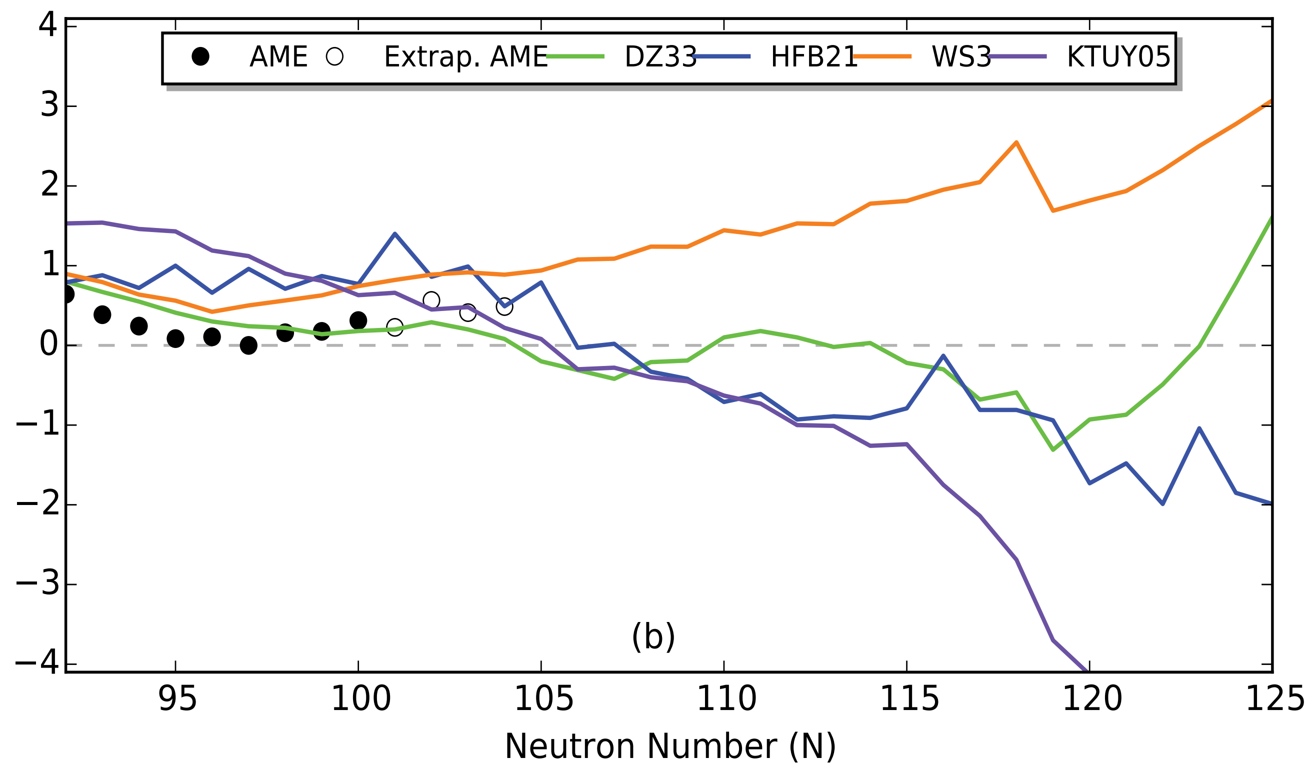
mass models

compared to the 2012
Atomic Mass Evaluation



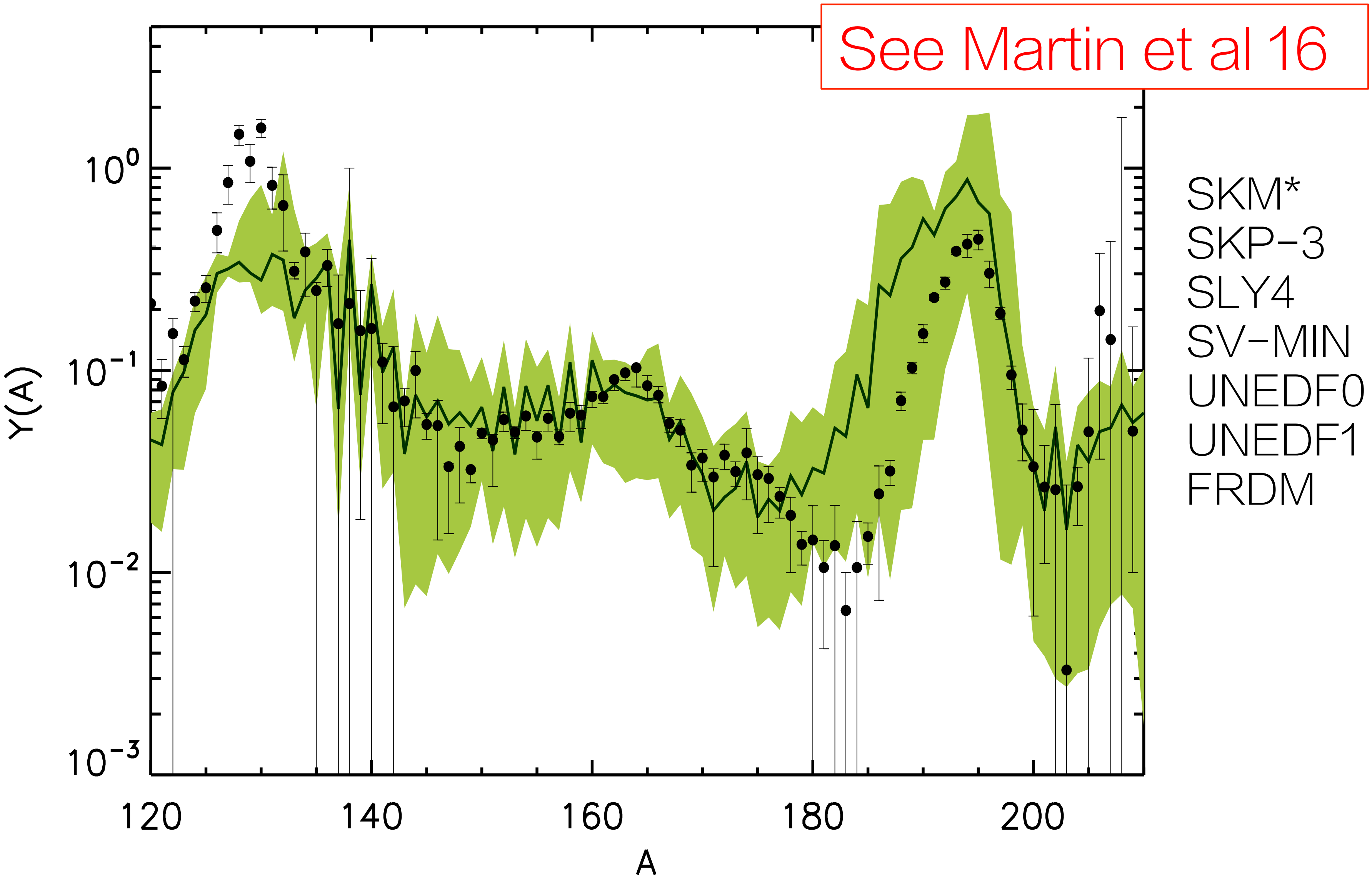
Mumpower, Surman,
McLaughlin,
Aprahamian 16





Mumpower, Surman,
McLaughlin,
Aprahamian 16

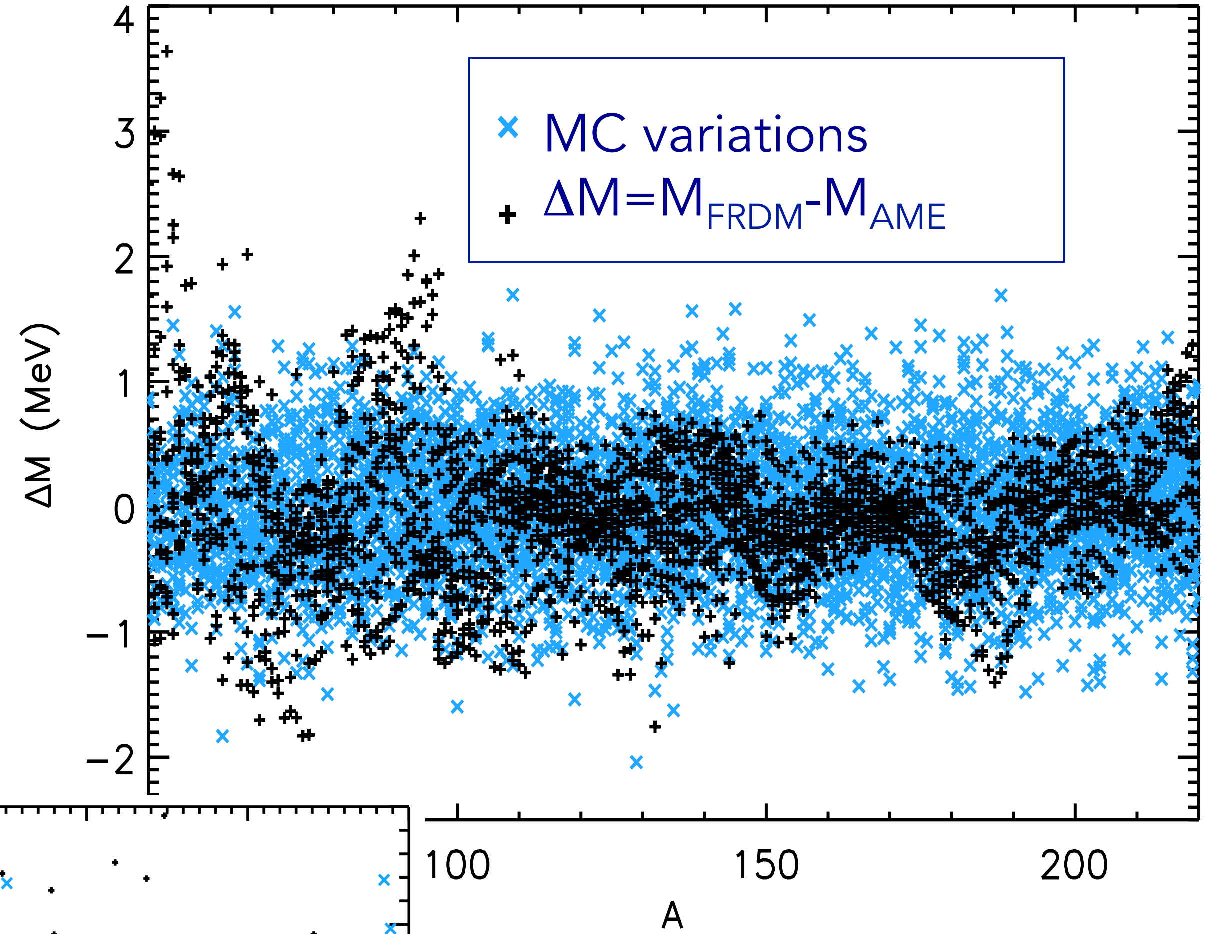
systematic uncertainties in nuclear masses: impact on *r*–process simulations

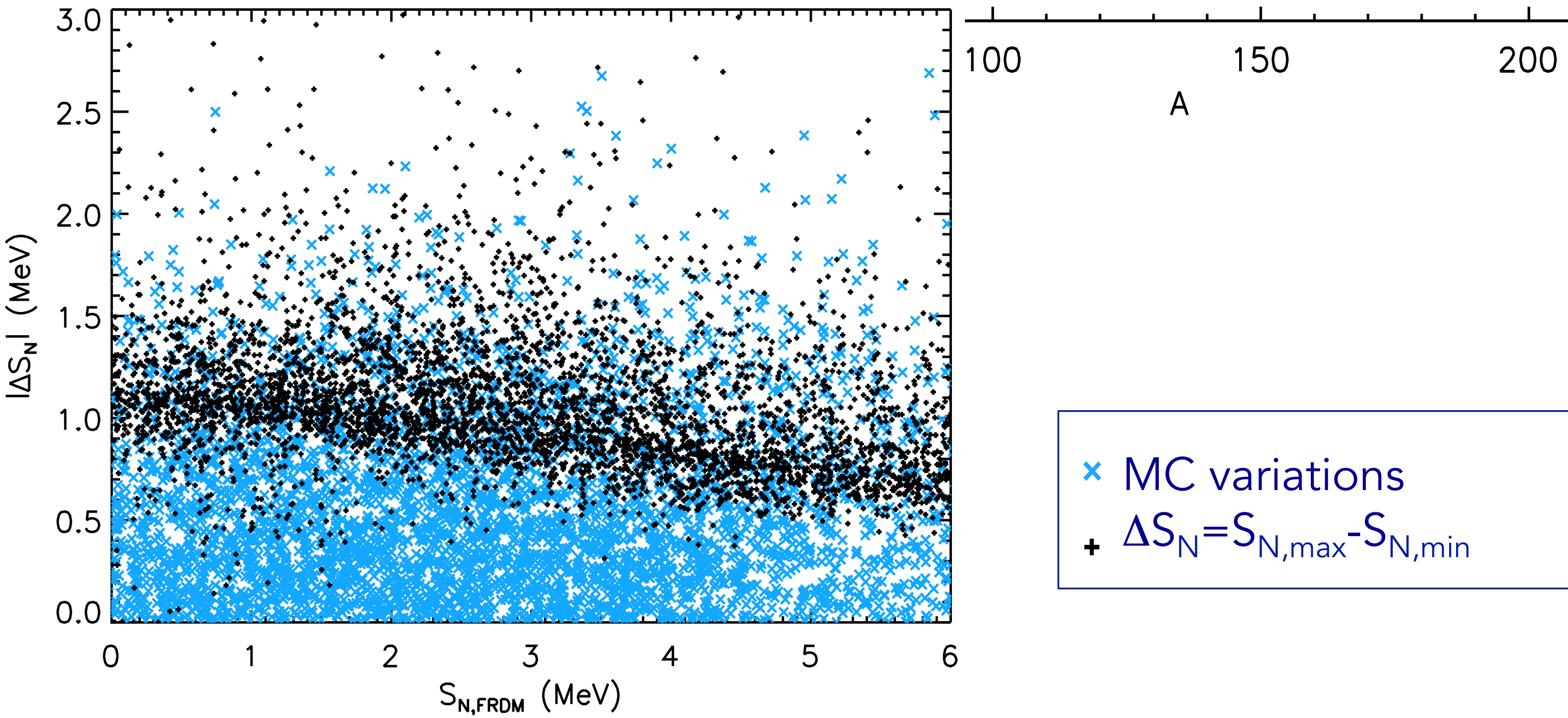


r–process calculations by Mumpower, McLaughlin, Surman; masses from massexplorer.frib.msu.edu, Olsen, Nazarewicz

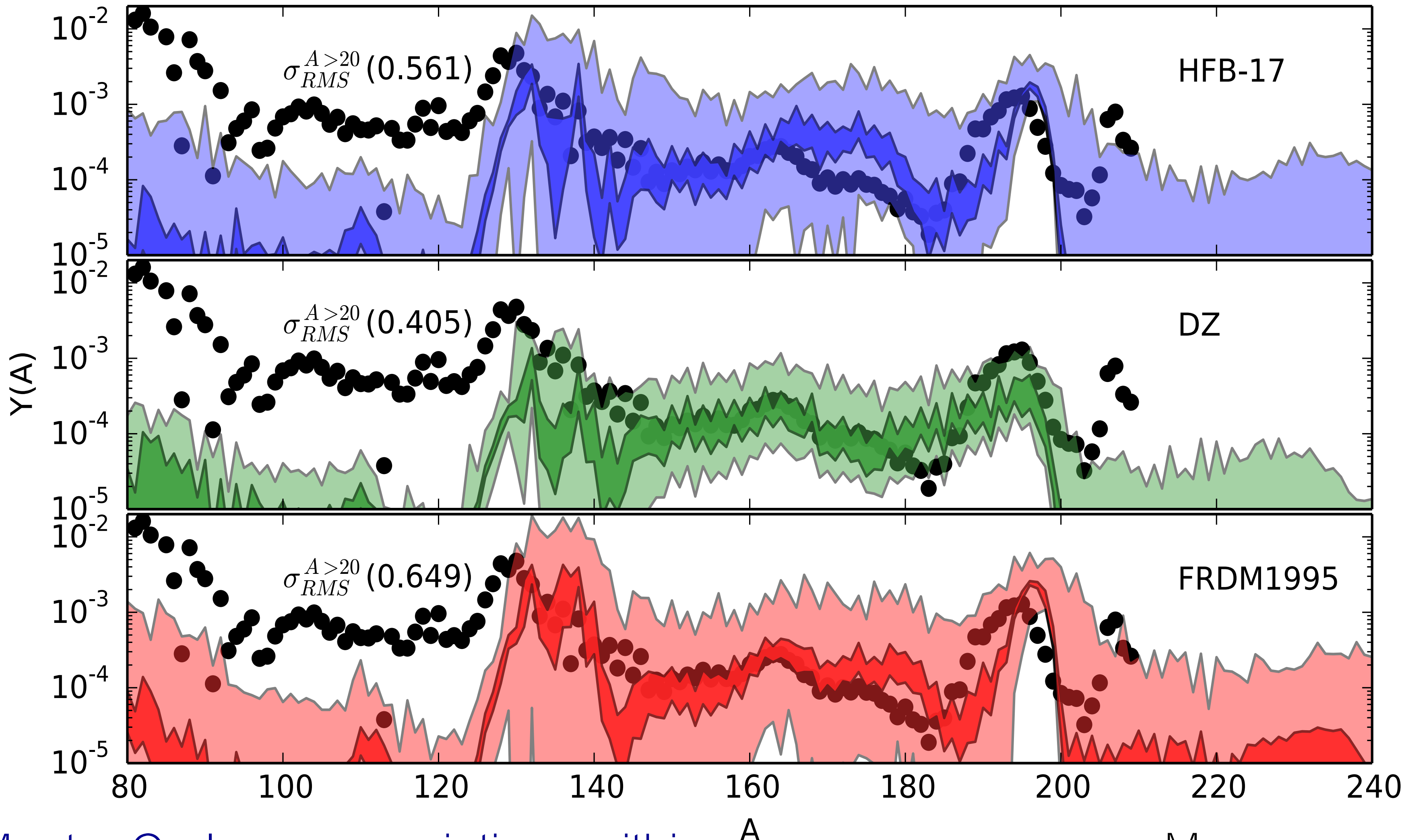
statistical uncertainties in nuclear masses

Surman, Mumpower, Aprahamian 16





statistical uncertainties in nuclear masses: impact on *r*–process simulations



Monte–Carlo mass variations within:

mass model $\boldsymbol{\sigma}_{\mathrm{RMS}}$ (wide light–shaded band)

100 keV (narrow dark–shaded band)

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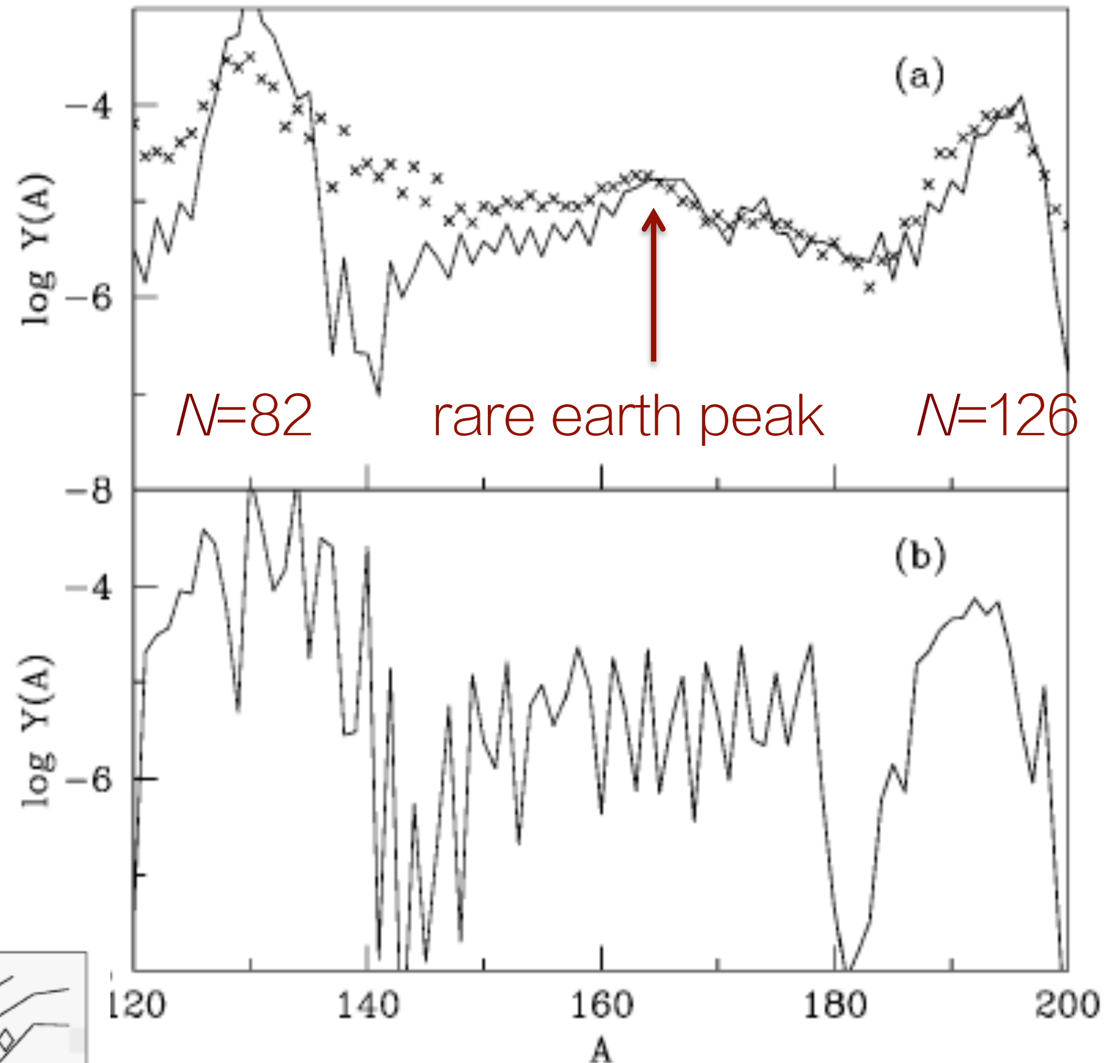
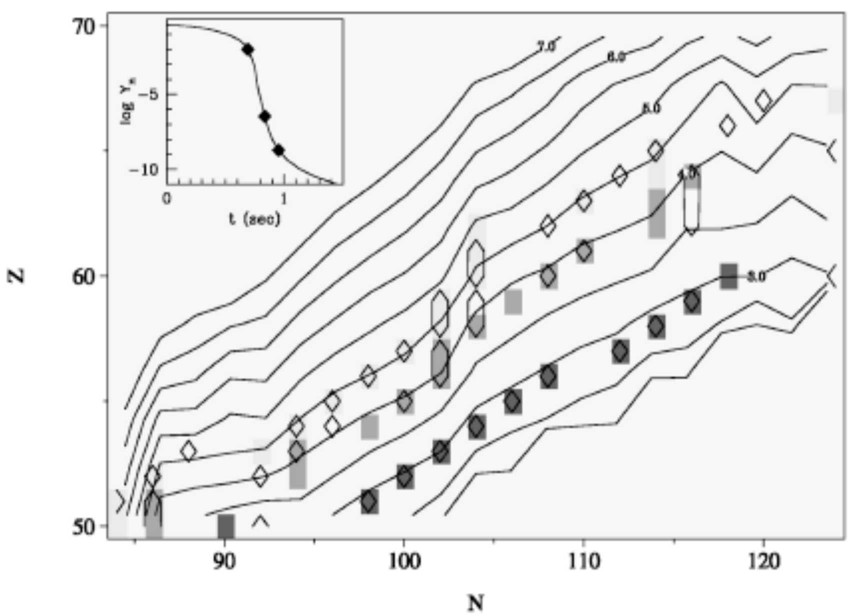
rare earth peak

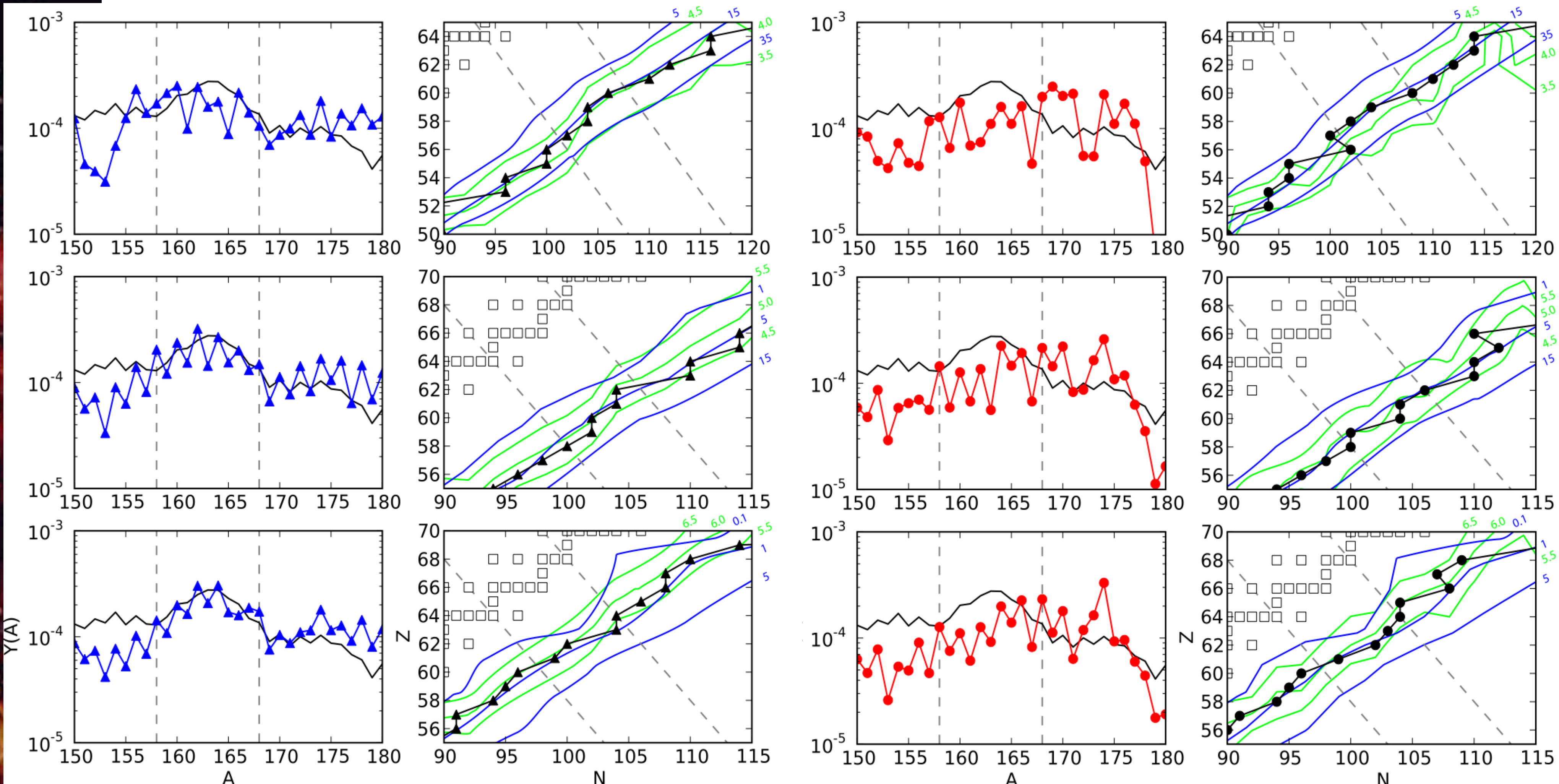
Its formation mechanism is sensitive to both the astrophysical conditions of the late phase of the *r*–process and the nuclear physics of the nuclei populated at this time





Surman, Engel, Bennett, Meyer 97

rare earth peak formation



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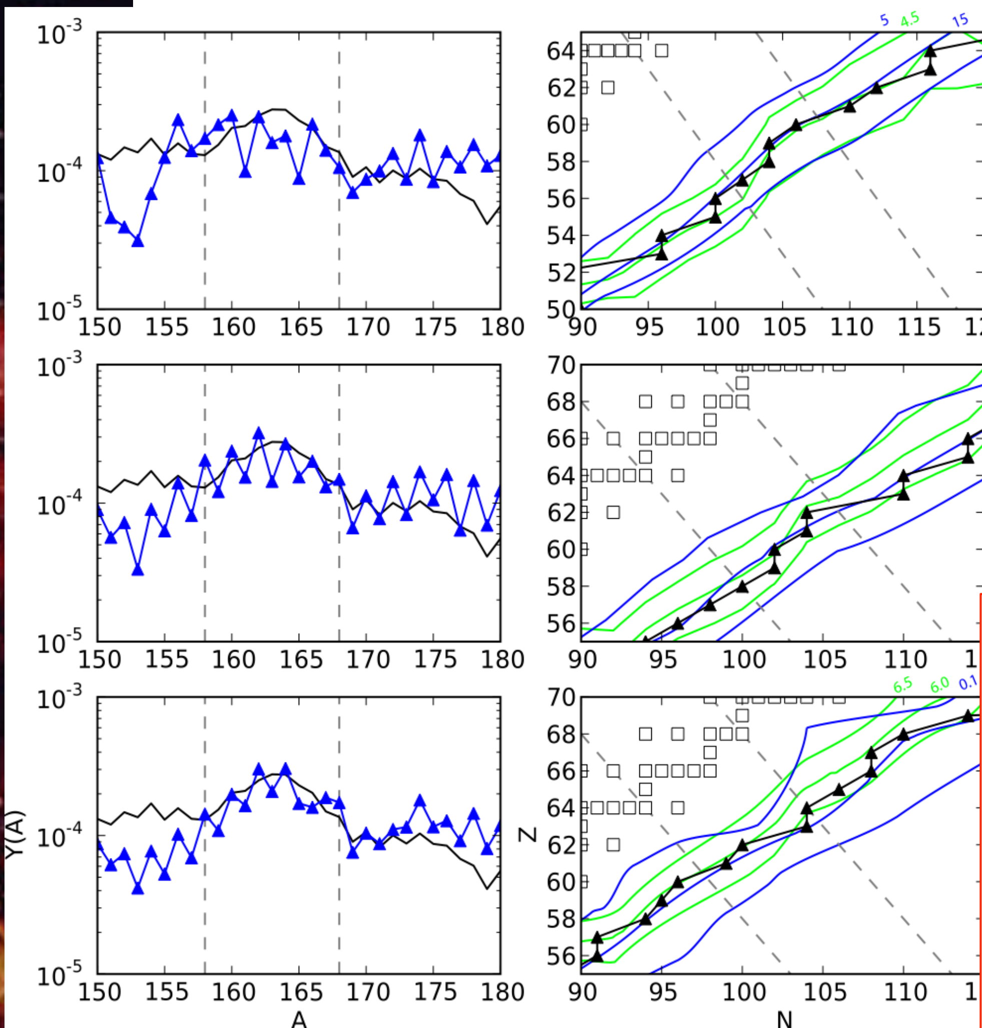
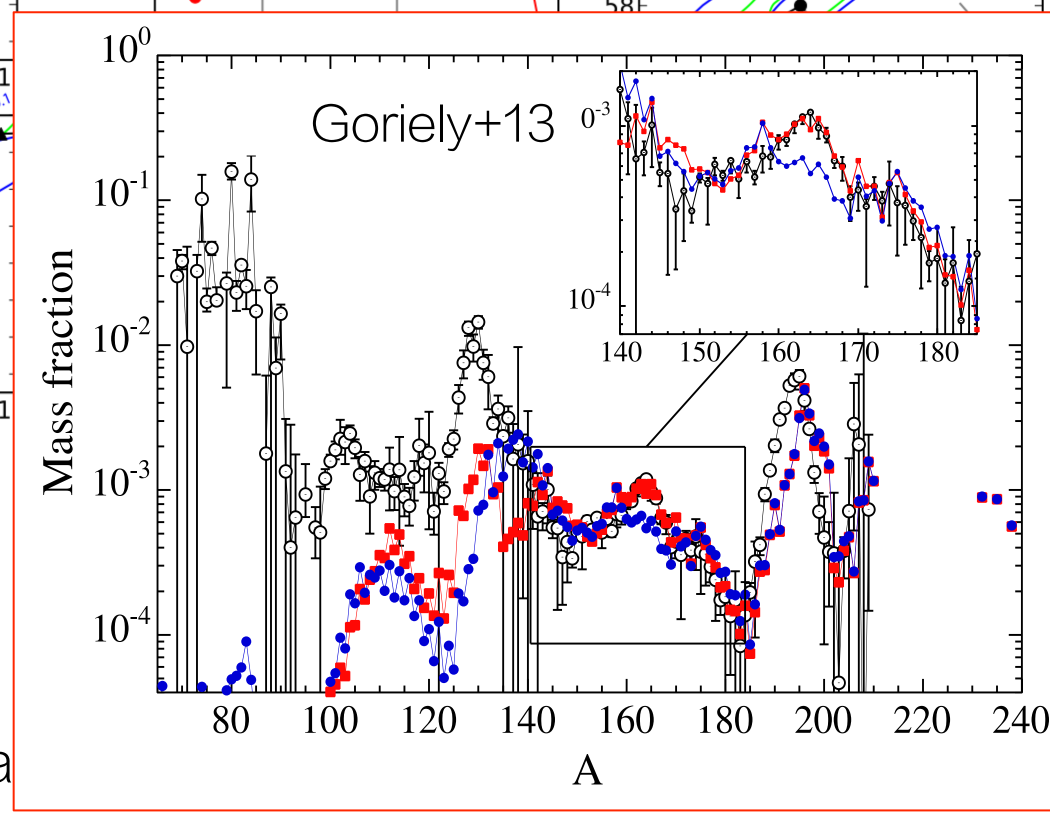
Mumpower, McLaughlin, Surman 12

rare earth peak formation

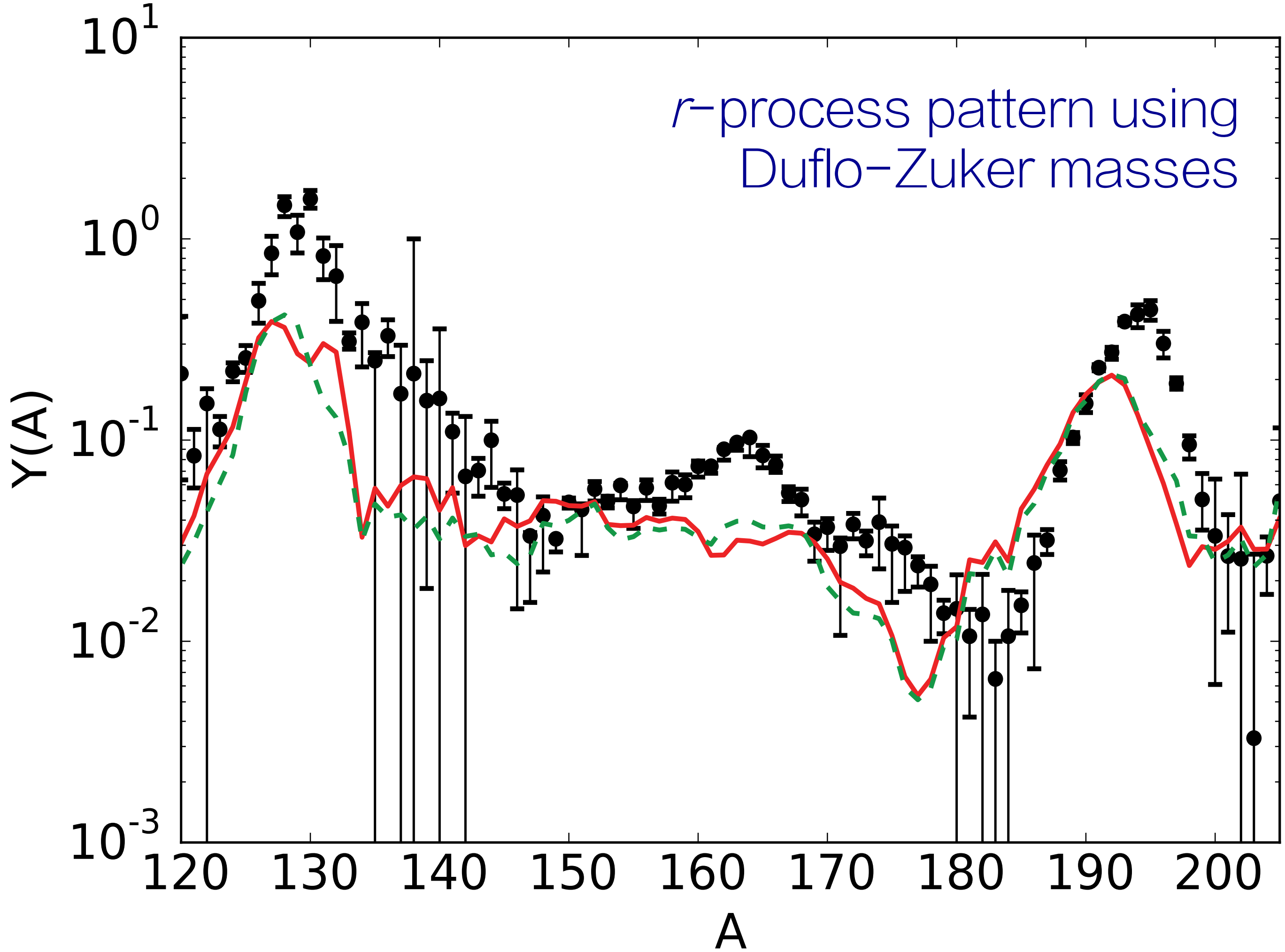


FRDM



Mumpower, McLaughlin, Surma

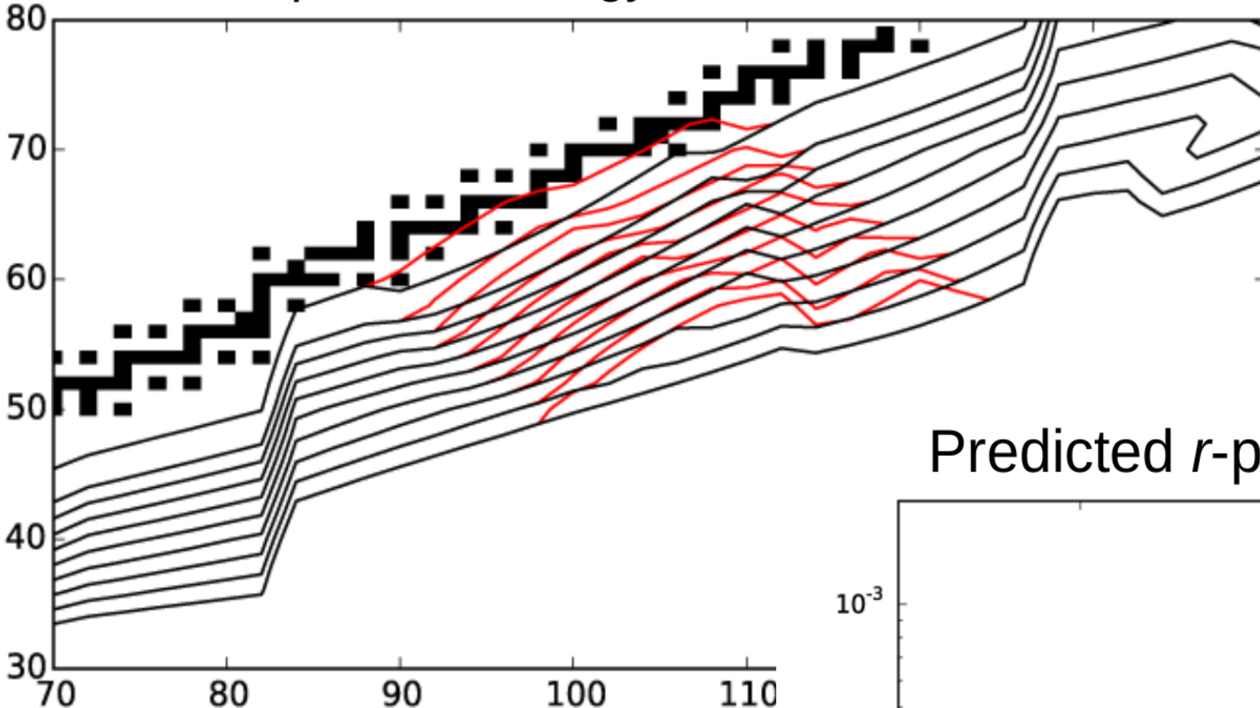
reverse-engineering the rare earth masses



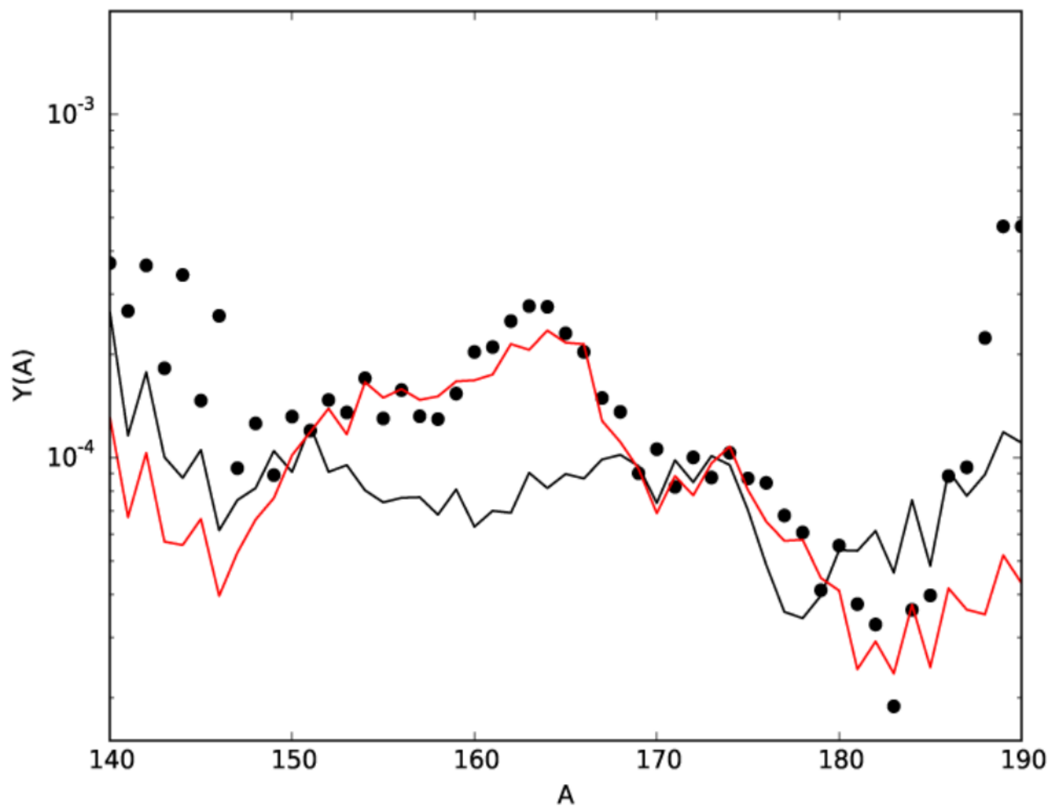
Mumpower, McLaughlin, Surman, Steiner arXiv:1603.02600v1

Monte Carlo variations of DZ parameters

1 neutron separation energy contours for even-N nuclei

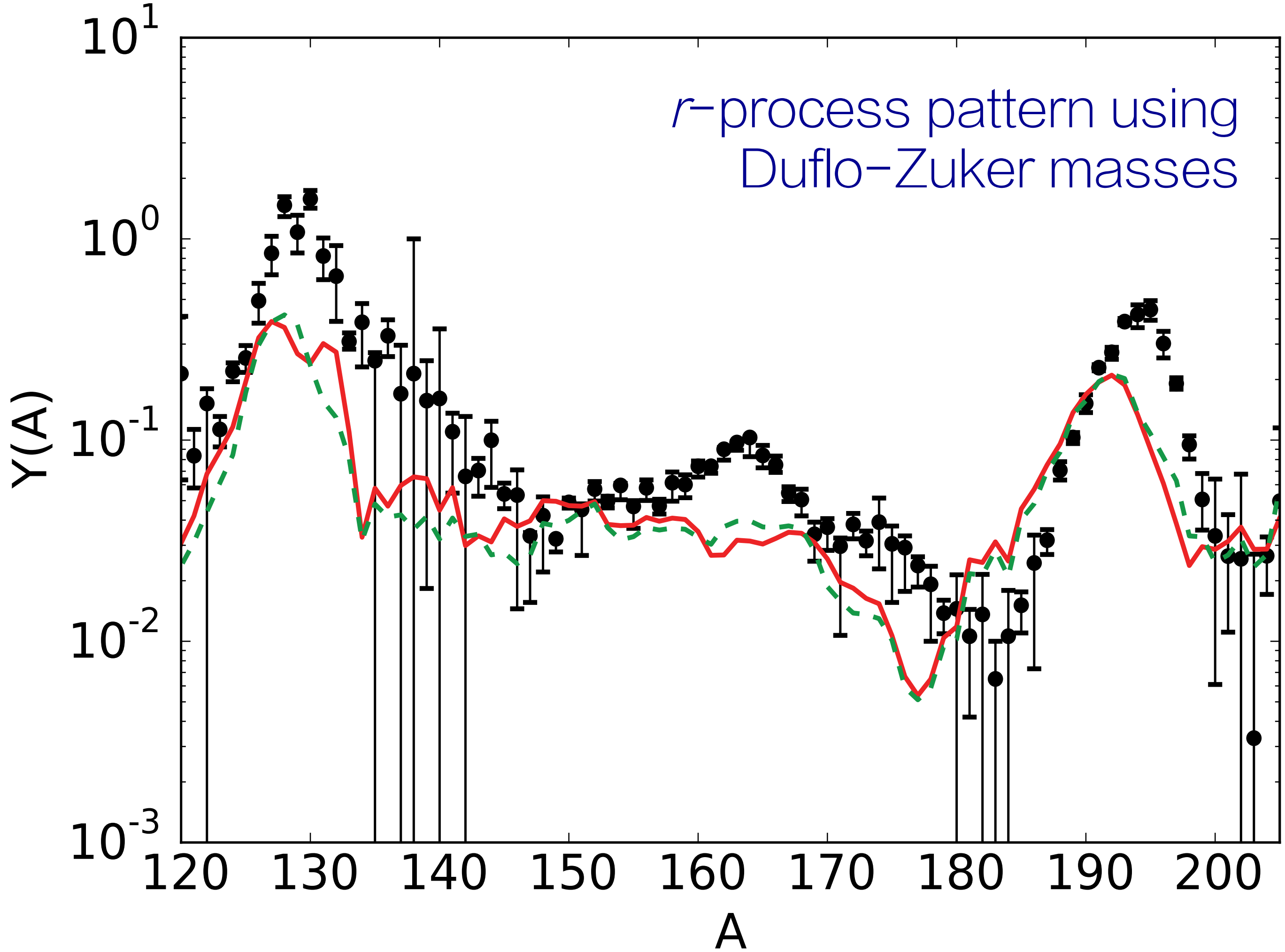


Predicted *r*-process abundances



figures by M Mumpower

reverse-engineering the rare earth masses

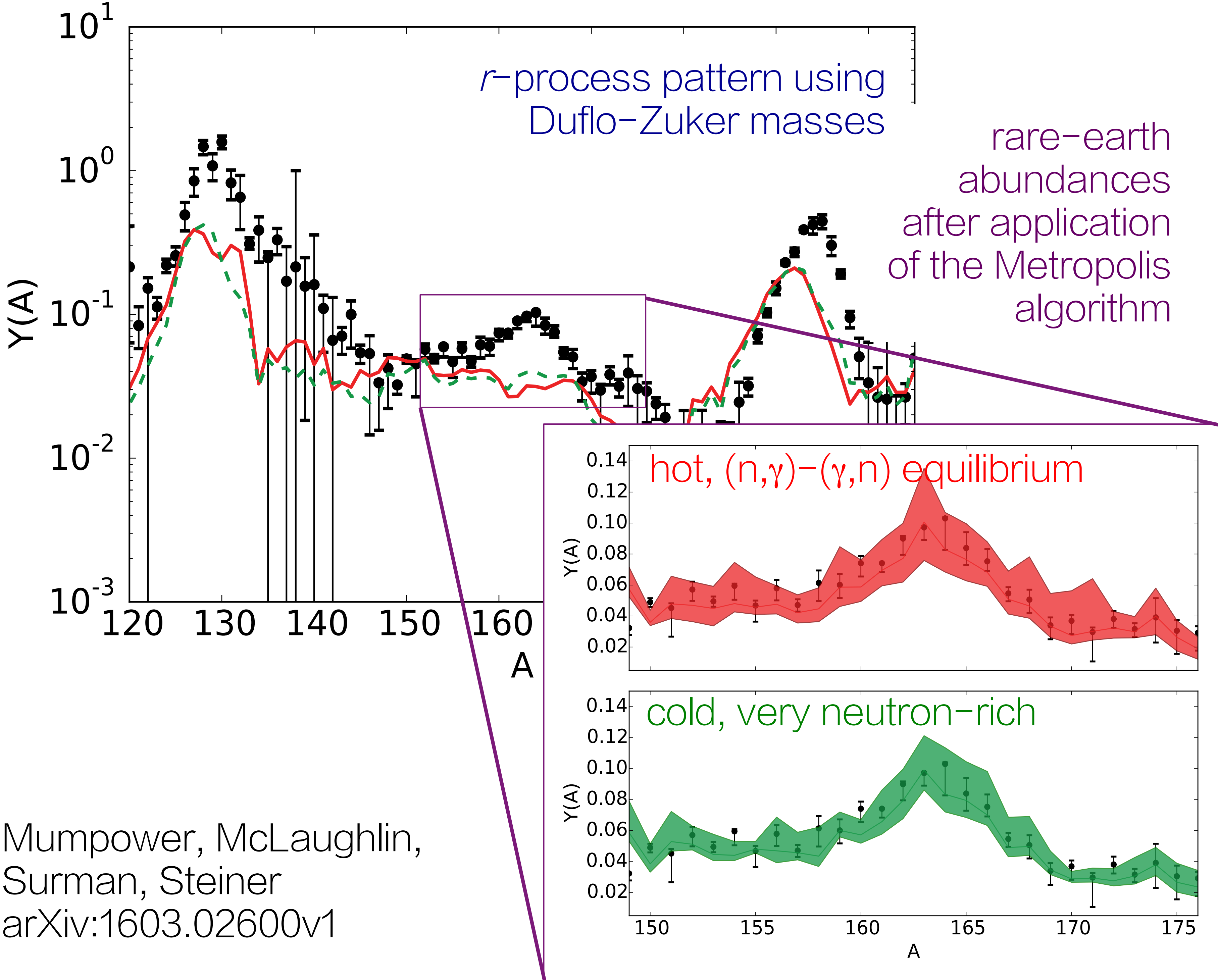


mass modification parameterization:

$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

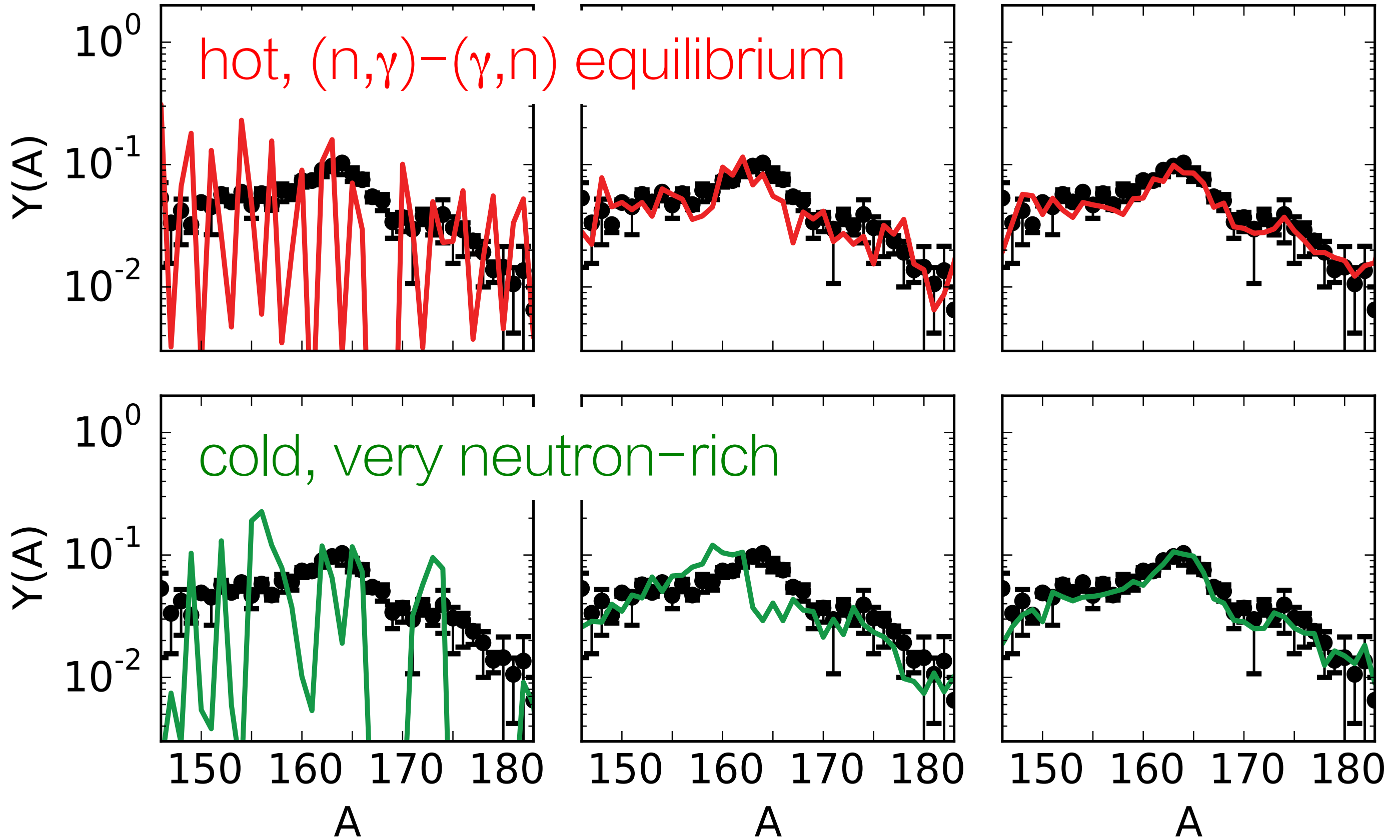
Mumpower, McLaughlin, Surman, Steiner arXiv:1603.02600v1

reverse-engineering the rare earth masses



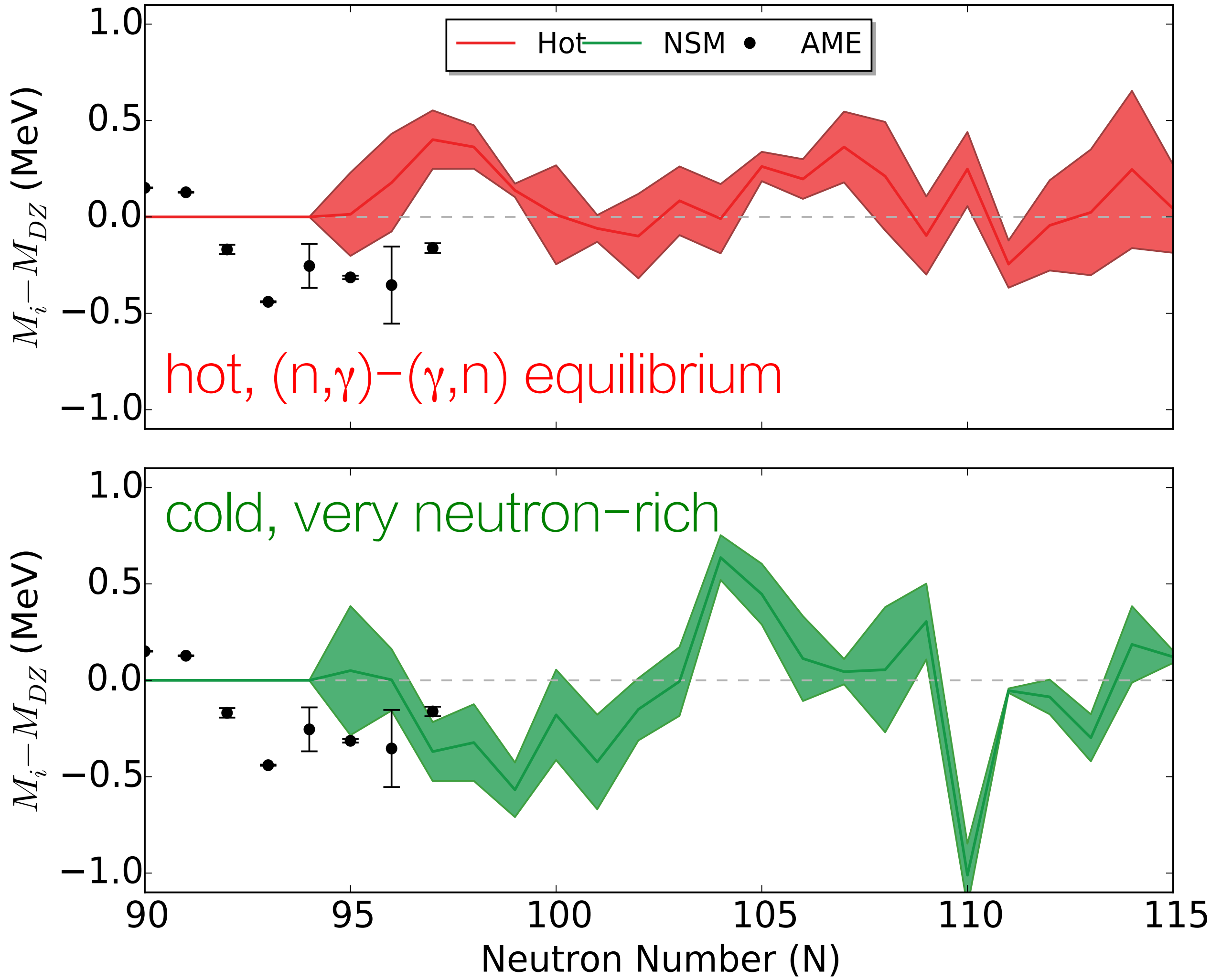
Mumpower, McLaughlin,
Surman, Steiner
arXiv:1603.02600v1

rare earth peak formation comparison



Mumpower, McLaughlin, Surman, Steiner arXiv:1603.02600v1

predicted trends in rare earth masses



Neodymium ($Z = 60$) isotopic chain

Mumpower, McLaughlin, Surman, Steiner arXiv:1603.02600v1

summary

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

The capacity of 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

Once nuclear physics uncertainties are reduced, we can exploit details of the *r*-process abundance pattern such as the rare earth peak to constrain the astrophysical conditions and, ultimately, determine the *r*-process site