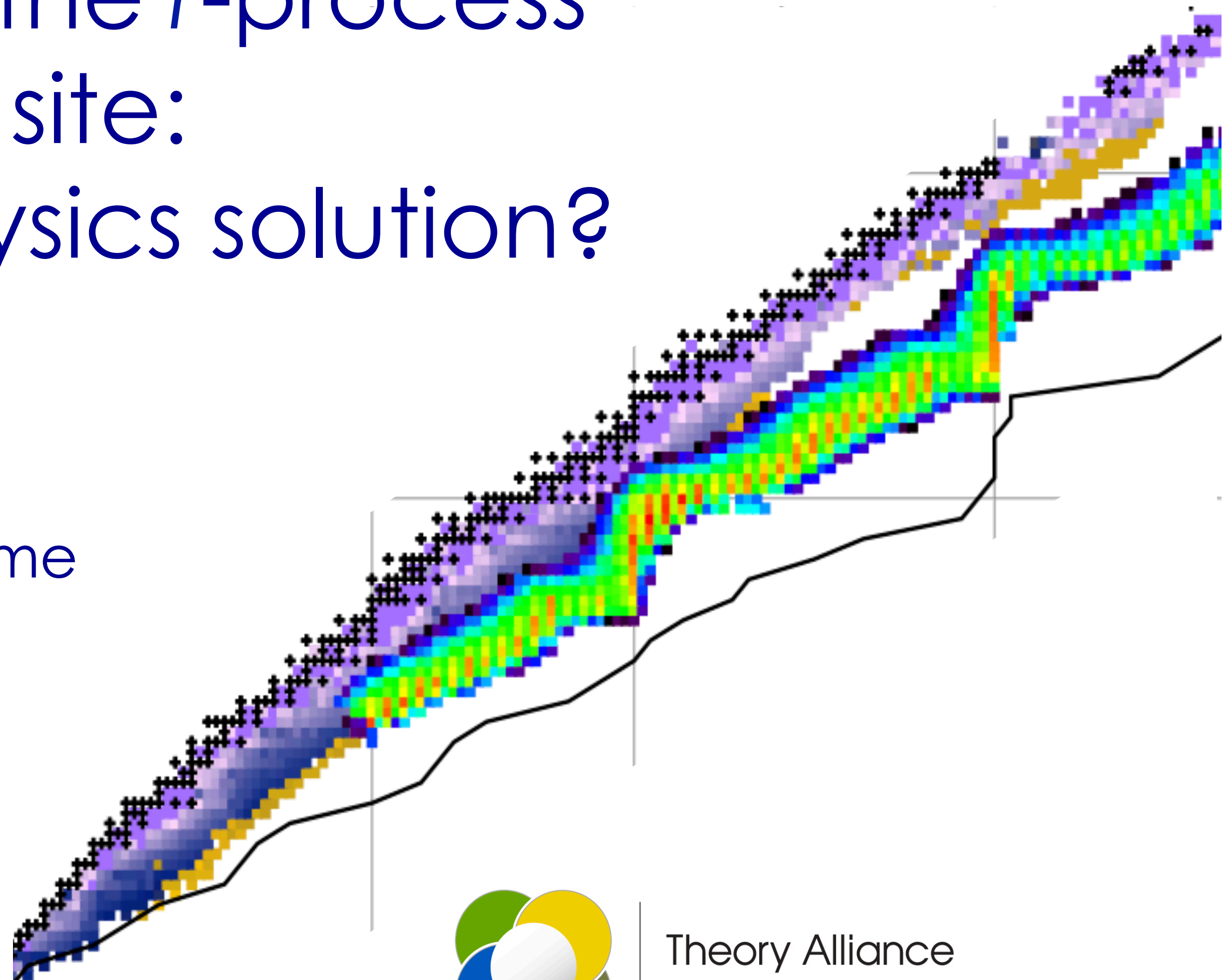
the puzzle of the *r*-process astrophysical site: a nuclear physics solution?

Rebecca Surman
University of Notre Dame

INPC 2016
Adelaide, Australia
14 Sept 2016

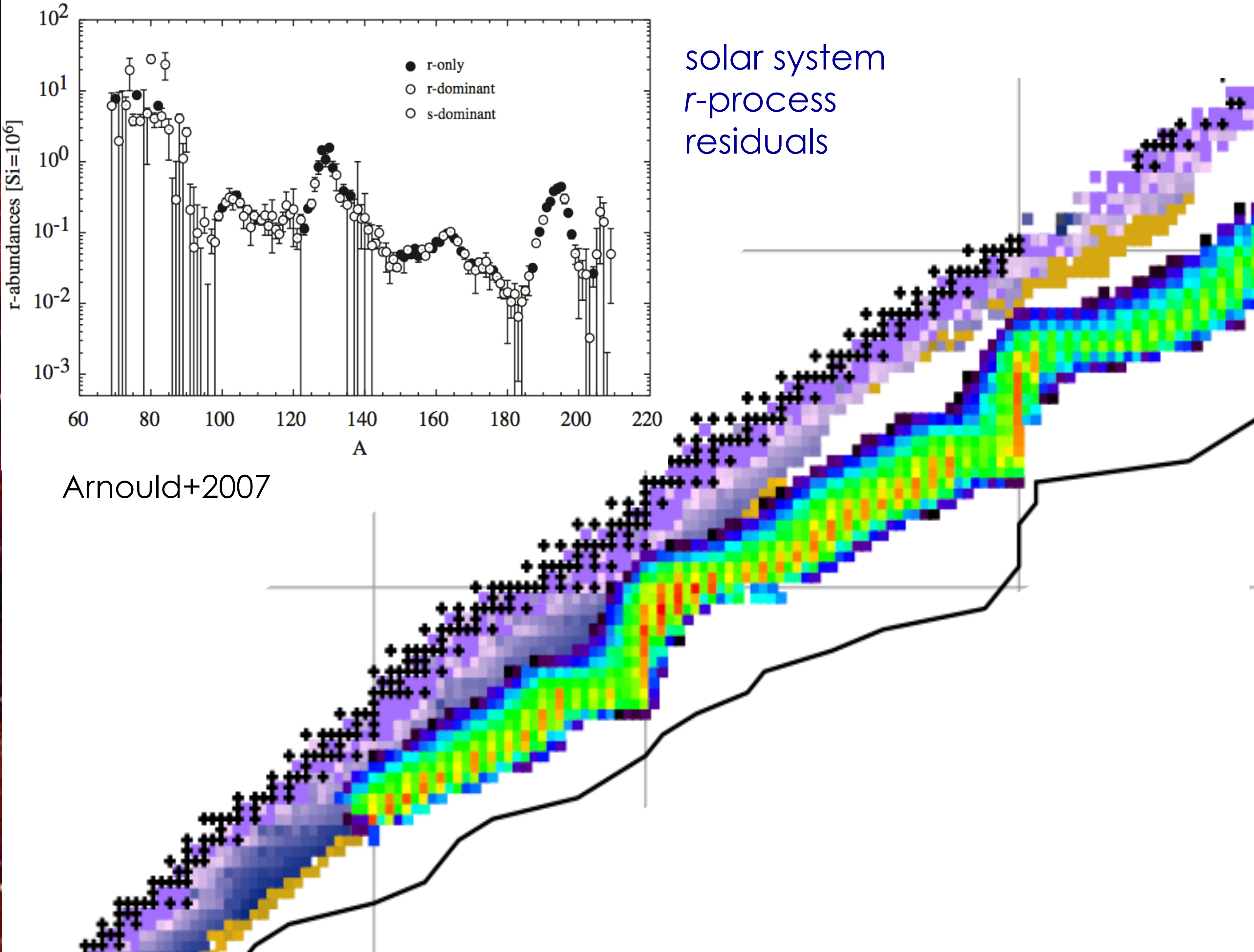


Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

UNIVERSITY OF NOTRE DAME
College of Science

JINA–CEE

r-process nucleosynthesis

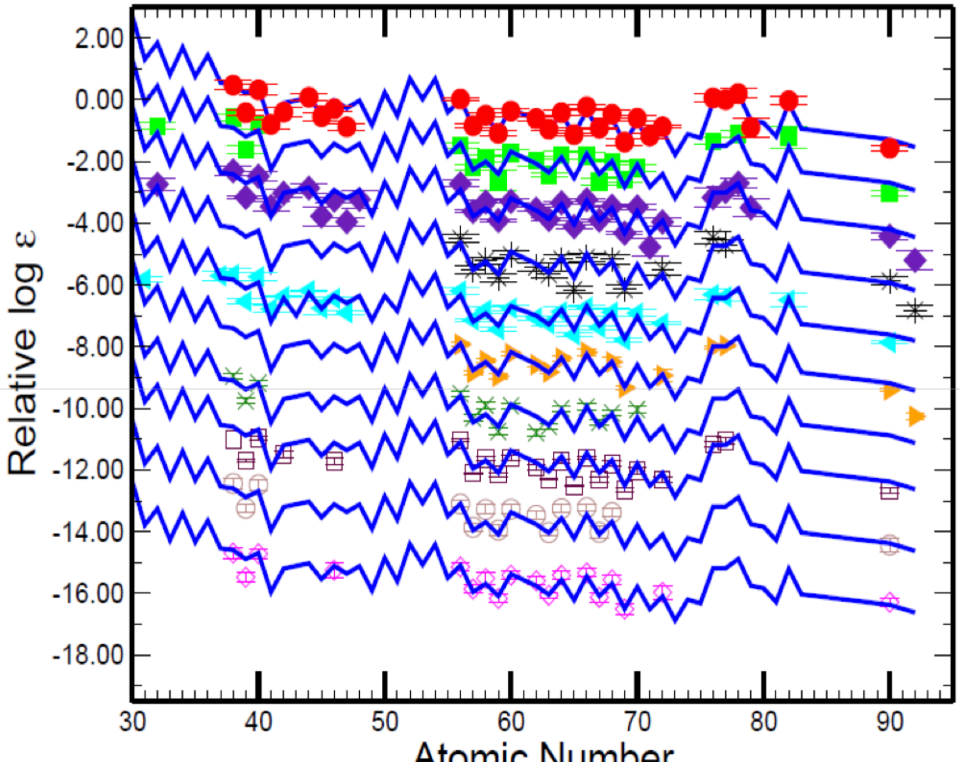


Arnould+2007

solar system
r-process
residuals

R Surman, Notre Dame
INPC Adelaide
14 Sept 16

r-process nucleosynthesis



Cowan+2011

elemental abundances from *r*-process-enhanced metal-poor halo stars

r-process site: core-collapse supernovae?

NASA/Skyworks

neutrino-driven wind

e.g., Meyer+1992, Woosley+1994, Takahashi+1994, Witti+1994, Fuller & Meyer 1995, McLaughlin+1996, Qian & Woosley 1996, Hoffman +1997, Otsuki+2000, Thompson +2001, Terasawa+2002, Liebendorfer+2005, Wanajo 2006, Arcones+2007, Huedepohl+2010, Fischer+2010, Roberts & Reddy 2012, Martinez-Pinedo+2014, Chakraborty+ 2015, Goriely & Janka 2016, etc., etc.

neutron-rich MHD jets

e.g., Cameron 2003, Kotake+2004, Nishimura+2006, Fujimoto+2008, Winteler+2012, Mösta+2014, Nakamura+2015, Tsujimoto+2015, Nishimura+2015, Shibagaki+2016, etc.

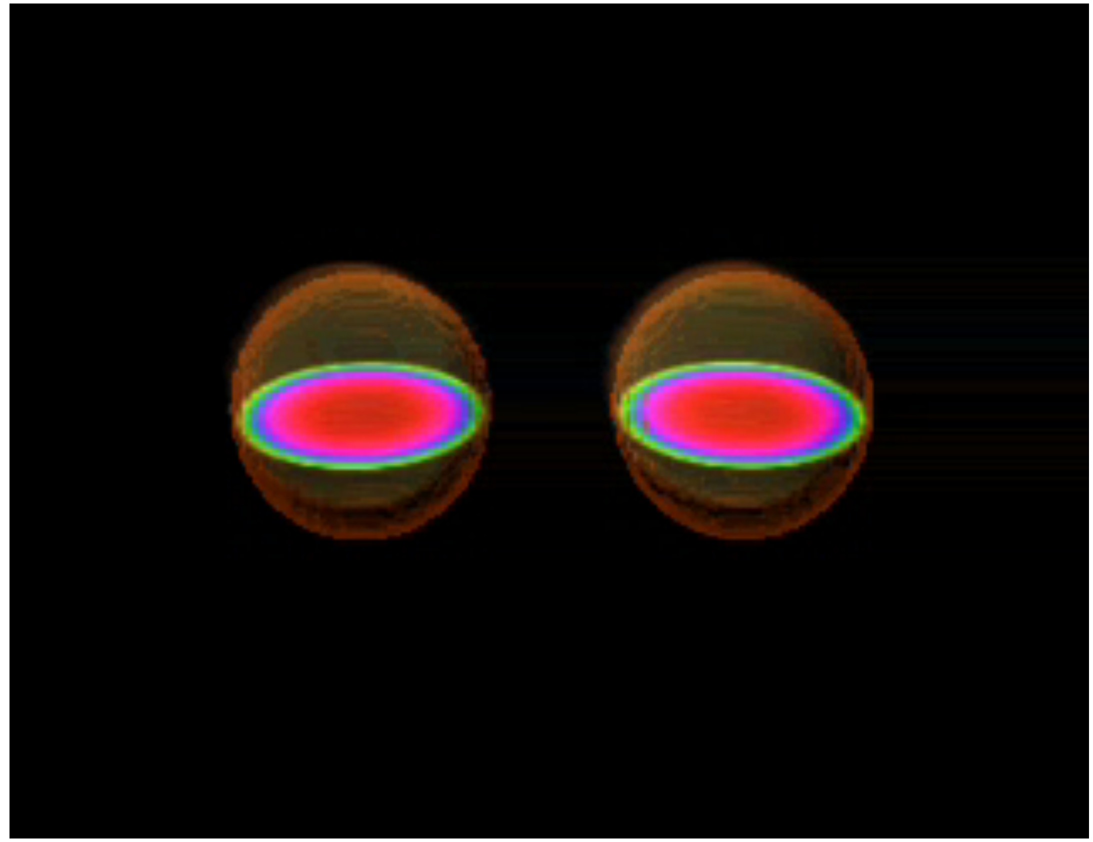
collapsars/lGRBs

e.g., Beloborodov 2003, Nagataki+2003, Surman & McLaughlin 2005, Nagataki +2006, Fryer+2006, Fujimoto+2007, Tominaga 2009, Maeda & Tominaga 2009, Nomoto+ 2010, Horiuchi+2012, Shibata & Tominaga 2012, Malkus+2012, Nakamura +2013, Fujibayashi+2015, etc.

r-process site: compact object mergers?

cold/mildly heated prompt ejecta

e.g., Lattimer & Schramm 1974, 1976, Meyer 1989, Frieburghaus+1999, Goriely +2005, Wanajo & Ishimaru 2006, Oechslin+2007, Nakamura+2011, Goriely +2011, Korobkin+2012, Wanajo+2014, Just+2015, Mendoza-Temis+2015, Eichler+2015, etc., etc.

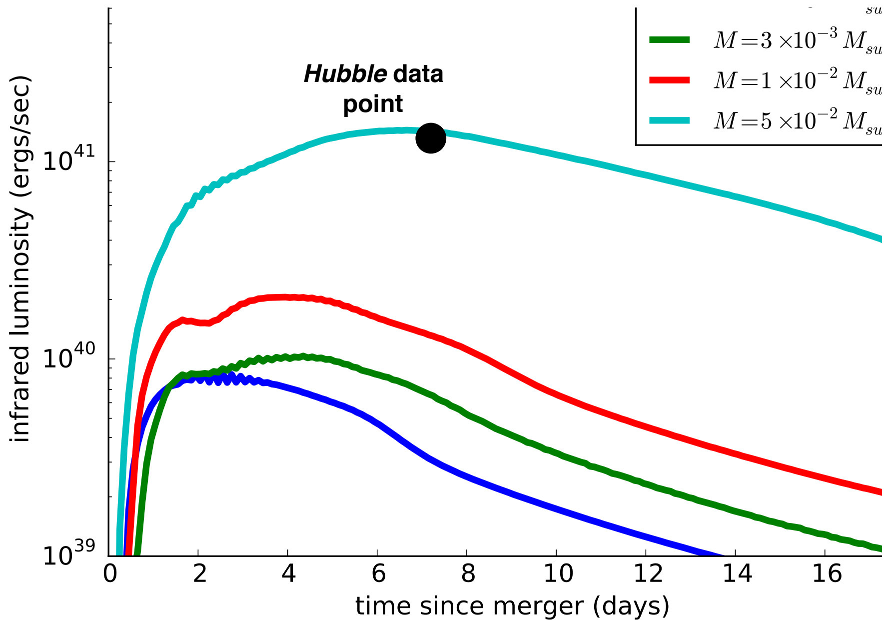


NASA/Skyworks

accretion disk ejecta

e.g., Pruet, Thompson, & Hoffman 2004, Surman & McLaughlin 2004, Arai+2004, Fujimoto+2004, Surman, McLaughlin, & Hix 2006, Barzilay & Levinson 2008, Metzger, Thompson, & Quataert 2008, Kizivat+2010, Wanajo & Janka 2012, Caballero+2012, Wanajo+2014, Perego+2014, Just+2015, Radice+2016, etc.

can mergers account for all *r*-process data?



Tanvir+2013, Berger 2013: observations of a kilonova candidate

Mathews & Cowan 1990, Argast+2004: merger timescale too slow

Matteucci+2014, Ishimaru+2015: if coalescence time is ~ 1 Myr

Wanderman & Piran 2014: delay times for sGRB ~3 Gyr

can mergers account for all *r*-process data?

microturbulence were 150K, 0.3 dex, and 0.15 k
Table 1, the temperature errors were 200K due t

NSMs is much longer than ∼ 300 Myr, it is too
reproduce observations.

4.5. *The rate of neutron star mergers*

The yields of r-process elements in our models
lated to the NSM rate as already mentioned i
though the Galactic rate of NSMs is highly unc
The estimated Galactic NSM rate is 10^{-6} to 10^{-}
based on three observed binary pulsars (Abadi
2010a). Table 5 lists yields of models discussed her
ure 13 shows predicted [Eu/Fe] as a function of
assuming different NSM rate. Figure 13 (a) a
represent models with the NSM fractions $f_{\rm NSM}$ =
(mr0.001) and $f_{\rm NSM} = 0.1$ (mr0.1), respectively. T
responding NSM rate in a MW-like galaxy is ∼ 10
(mr0.001) and ∼ 10^{-3} yr^{-1} (mr0.1). Model m
predicts larger scatter and a smaller number of s
[Fe/H] < −3 than m000. Model mr0.001 has [
dispersion by more than 3 dex at [Fe/H] = −2.
dition, there remains ∼ 1 dex dispersion even fo
with [Fe/H] > −2. In contrast, model mr0.1 p
smaller scatter than m000, though it does not s
be inconsistent with observations. Such tendenc
also seen in Argast et al. (2004), Komiya et al.
and van de Voort et al. (2015).

Our fiducial model, m000, reproduces the ol
r-process ratio as discussed in §4.2. The NS
of m000 for a MW-like galaxy is ∼ 10^{-4} yr^{-1}
total mass of r-process elements produced b
NSM corresponds to ∼ $10^{-2}M_\odot$. The value is
tent with recent nucleosynthesis calculations: 1
to $10^{-2}M_\odot$ (e.g., Goriely et al. 2011; Korobki
2012; Hotokezaka et al. 2013; Bauswein et al.
Wanajo et al. 2014).

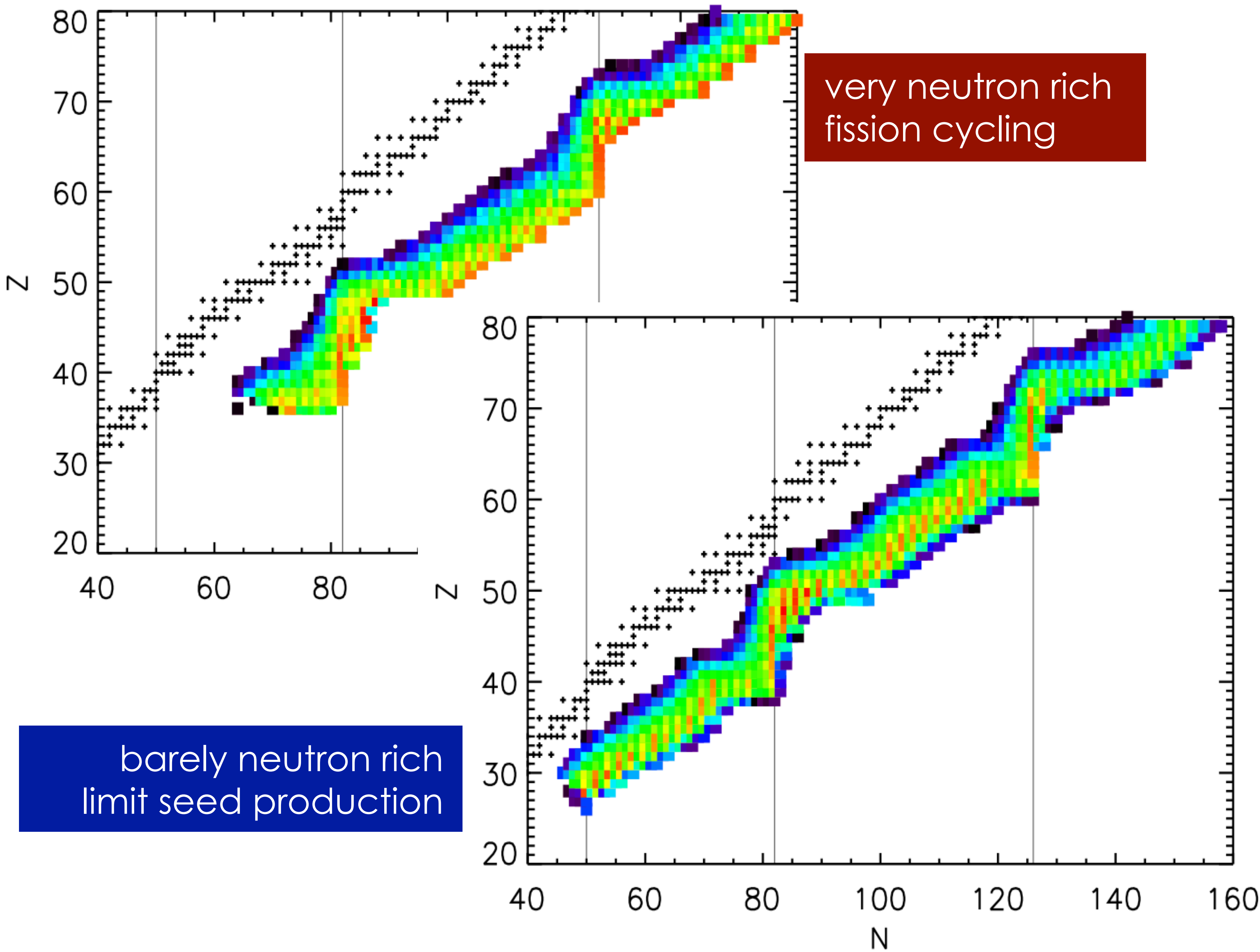
Ji+2016

Hirai+2015

Hirai+2015, Ji+2016:
UFD galaxies account for low-metallicity enrichment

R Surman, Notre Dame
INPC Adelaide
14 Sept 16

r-process abundance pattern signatures



very neutron rich
fission cycling

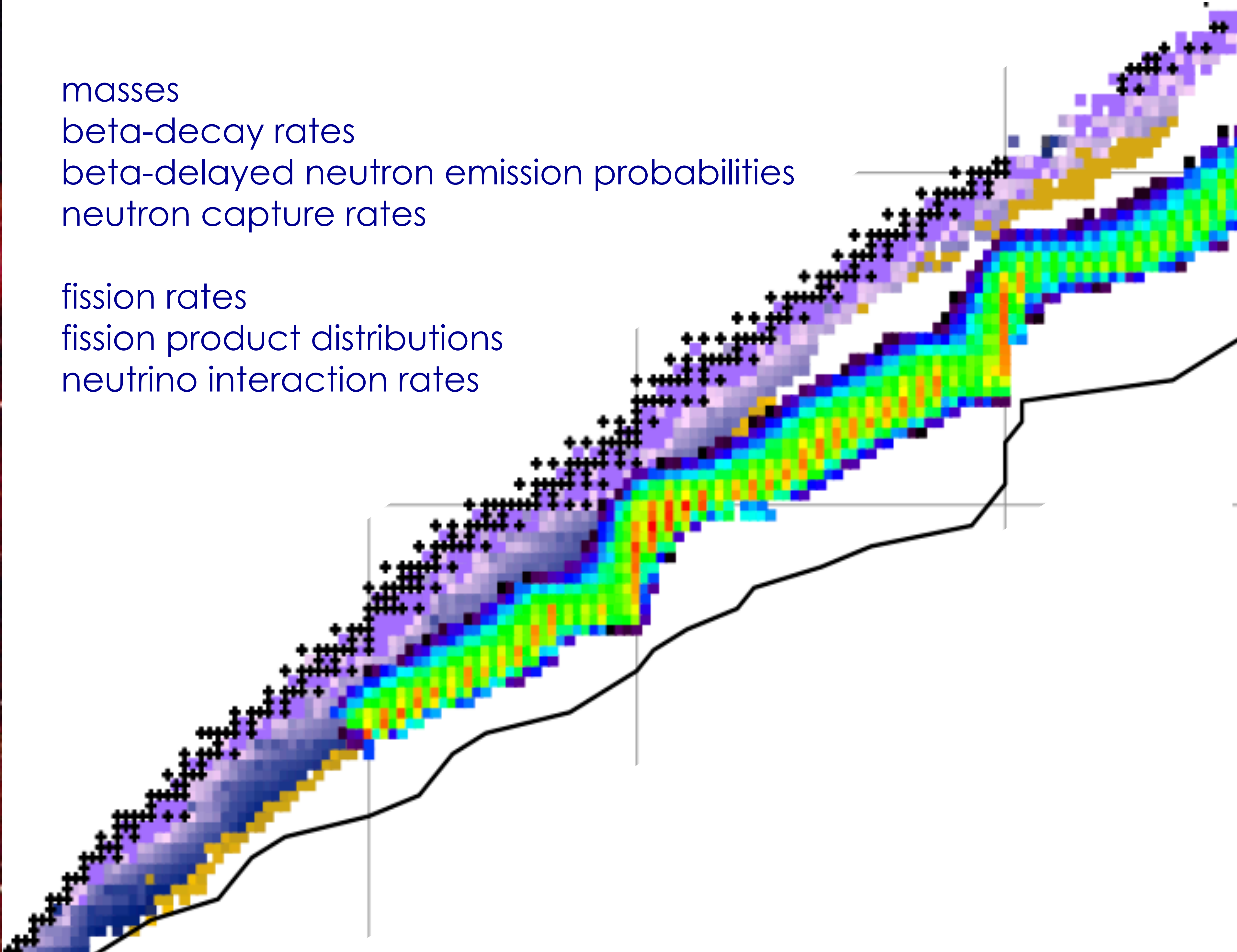
barely neutron rich
limit seed production

R Surman, Notre Dame
INPC Adelaide
14 Sept 16

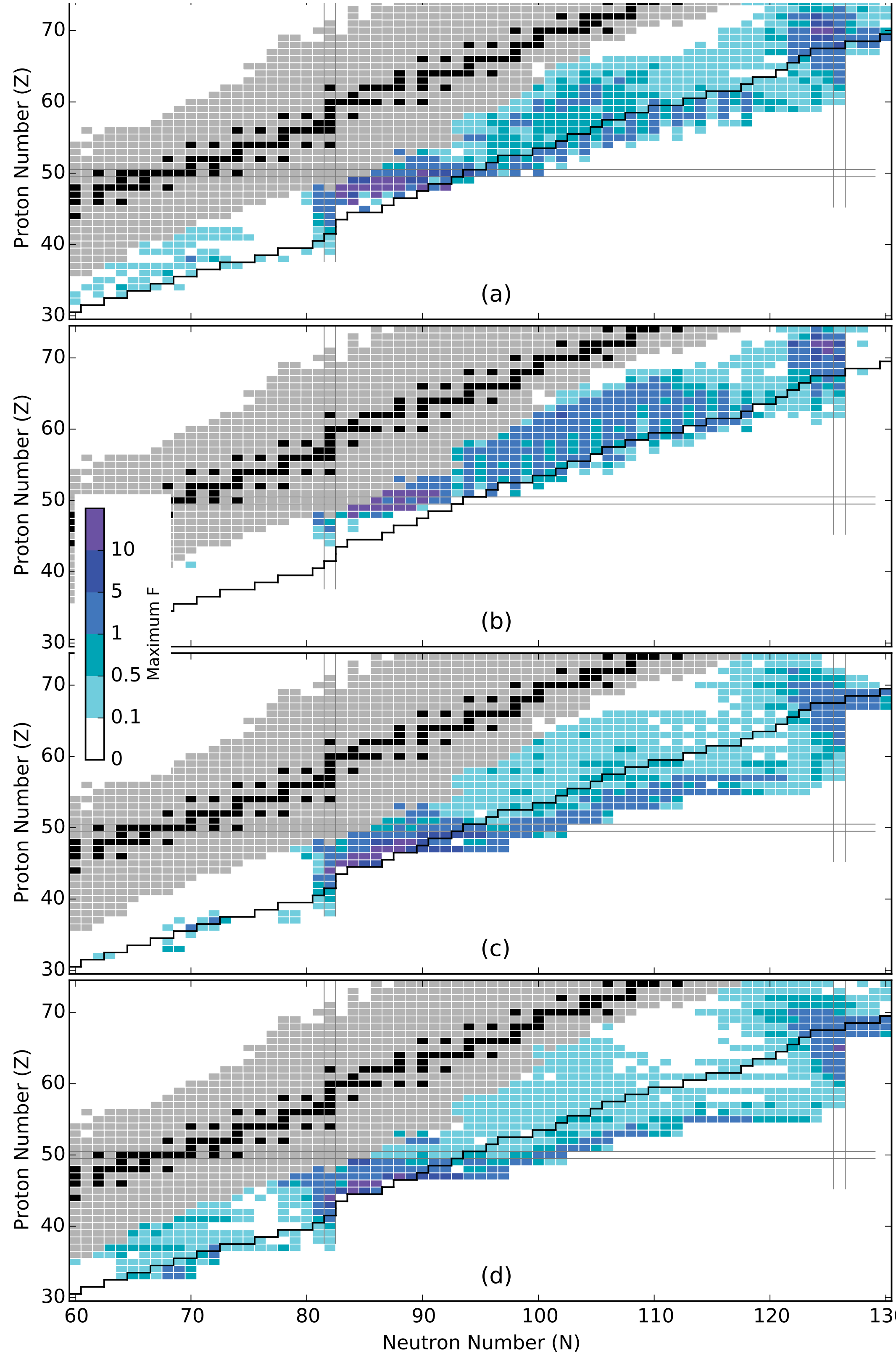
r-process simulations: required nuclear data

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

fission rates
fission product distributions
neutrino interaction rates



r-process simulations: required nuclear data



sensitivity study review:
Mumpower, Surman, McLaughlin, Aprahamian
Progress in Particle and Nuclear Physics 86 (2016) 86

r-process simulations: required nuclear data

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

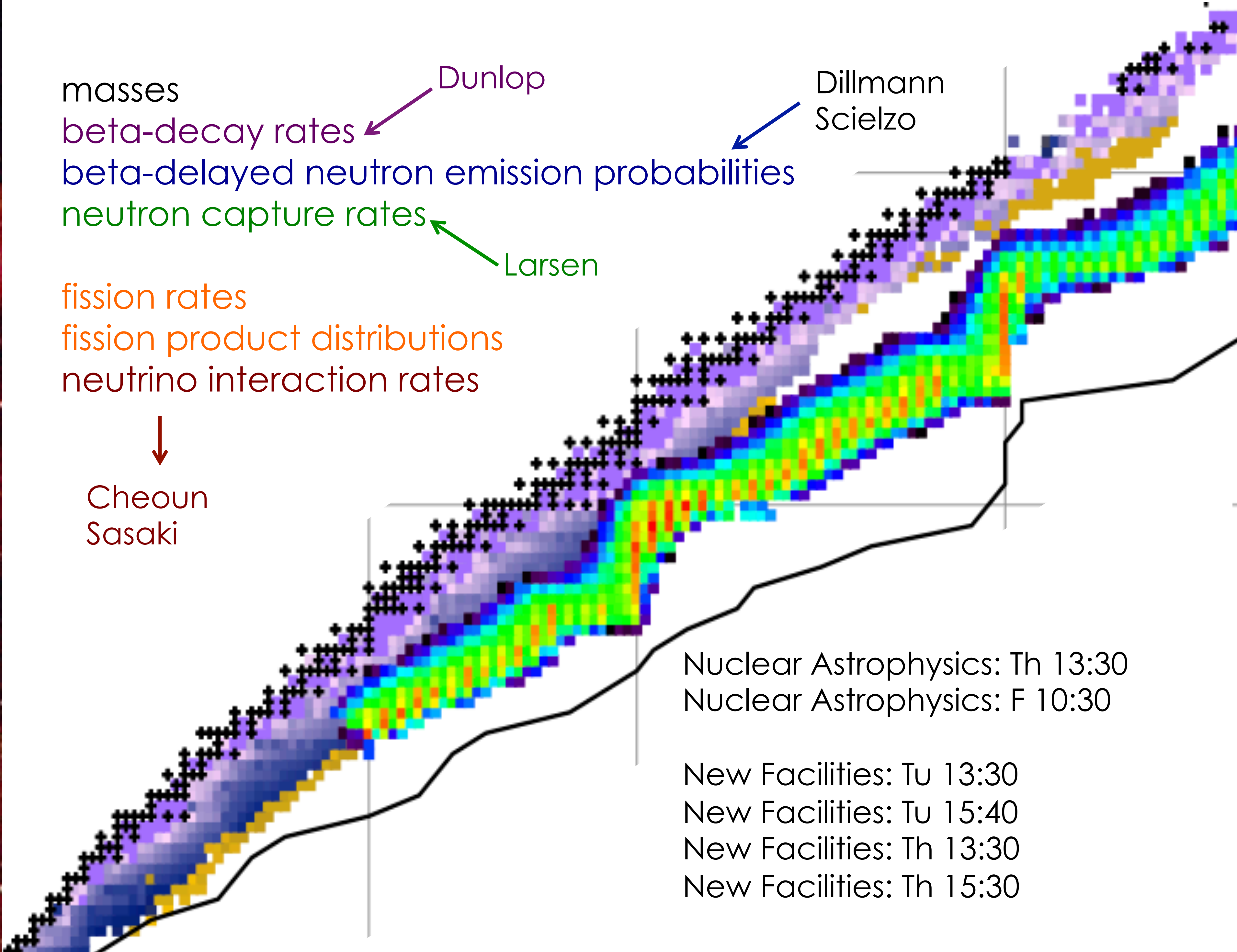
fission rates
fission product distributions
neutrino interaction rates

Dunlop

Dillmann
Scielzo

Larsen

Cheoun
Sasaki



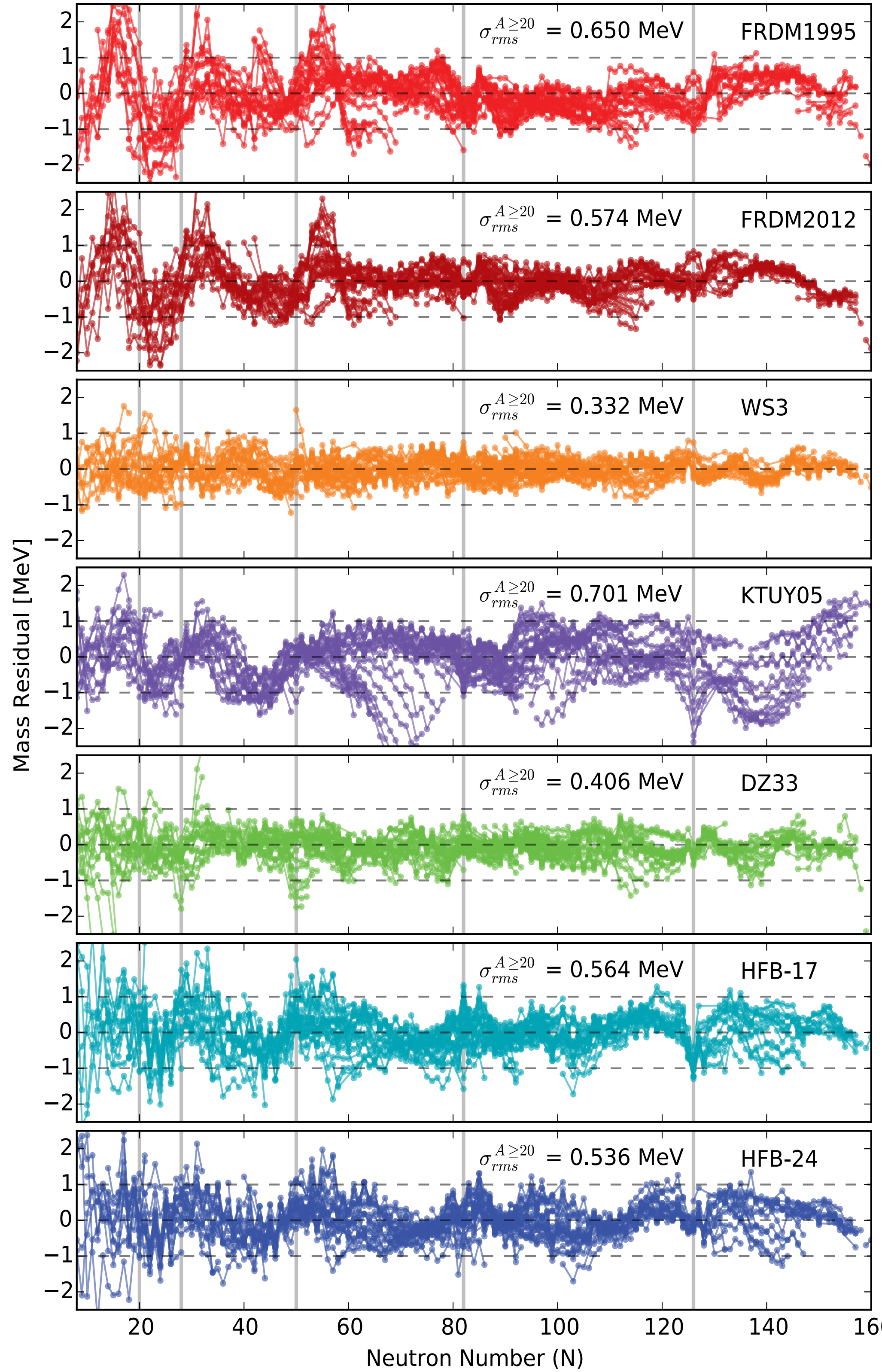
Nuclear Astrophysics: Th 13:30
Nuclear Astrophysics: F 10:30

New Facilities: Tu 13:30
New Facilities: Tu 15:40
New Facilities: Th 13:30
New Facilities: Th 15:30

mass models

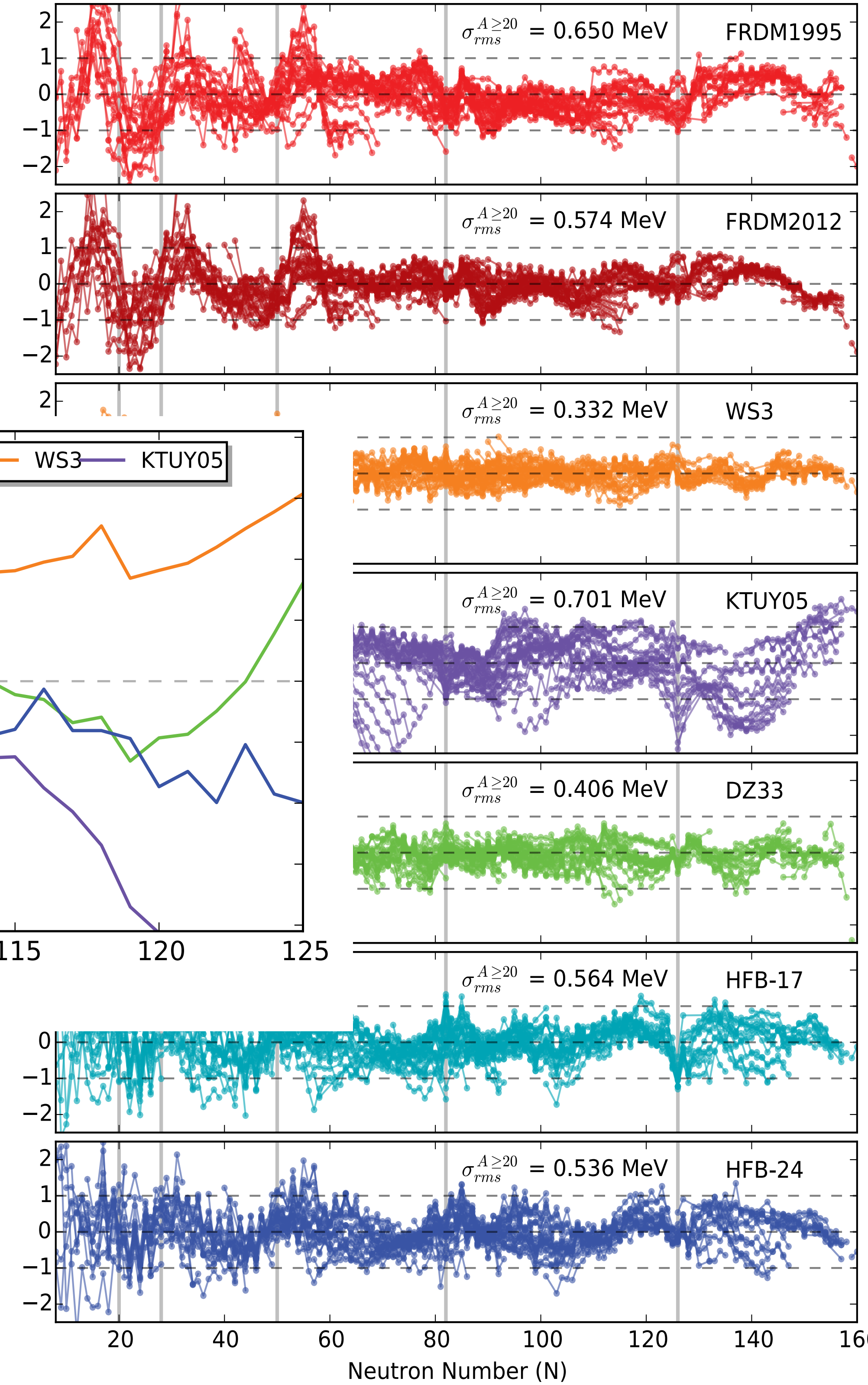
compared to the 2012 Atomic Mass Evaluation

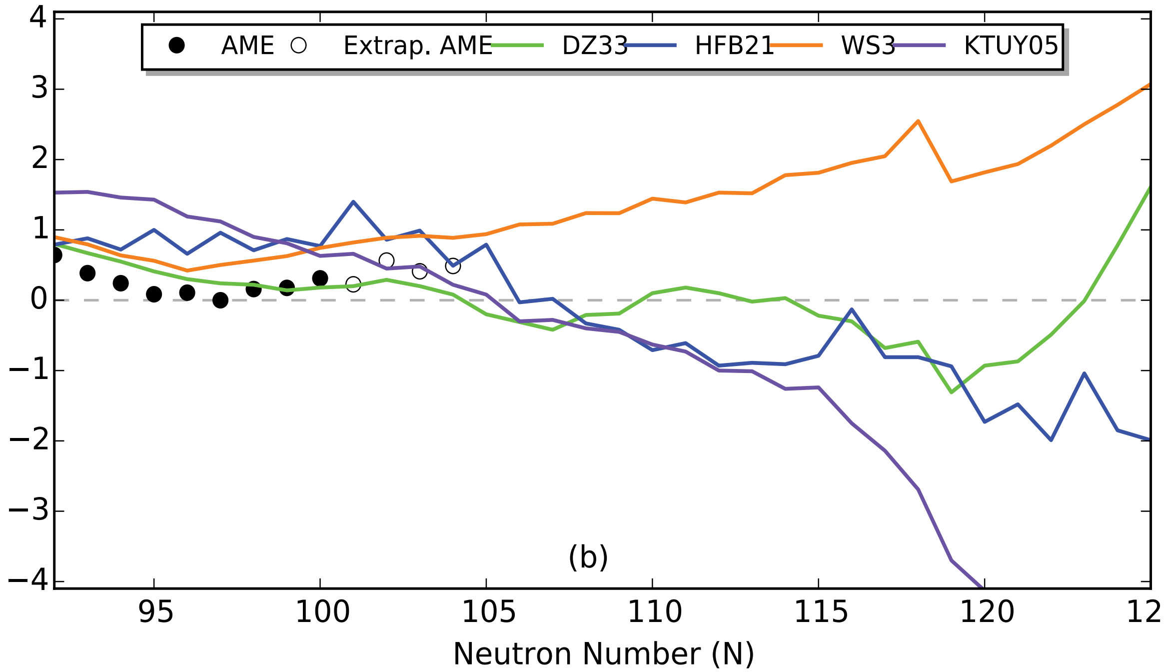
Mumpower, Surman, McLaughlin, Aprahamian 2016



mass models

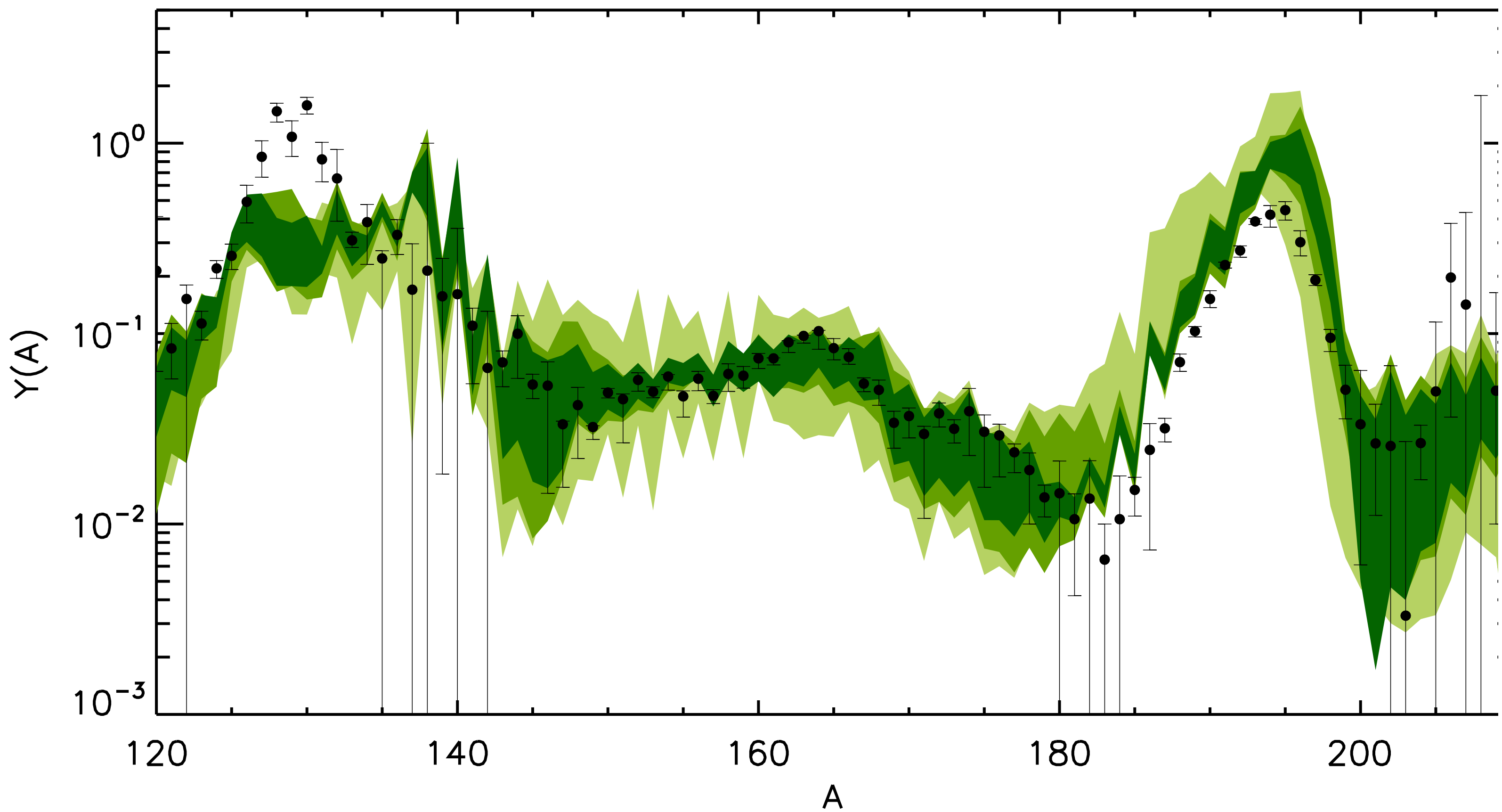
compared to the 2012 Atomic Mass Evaluation





Mumpower, Surman, McLaughlin, Aprahamian 2016

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



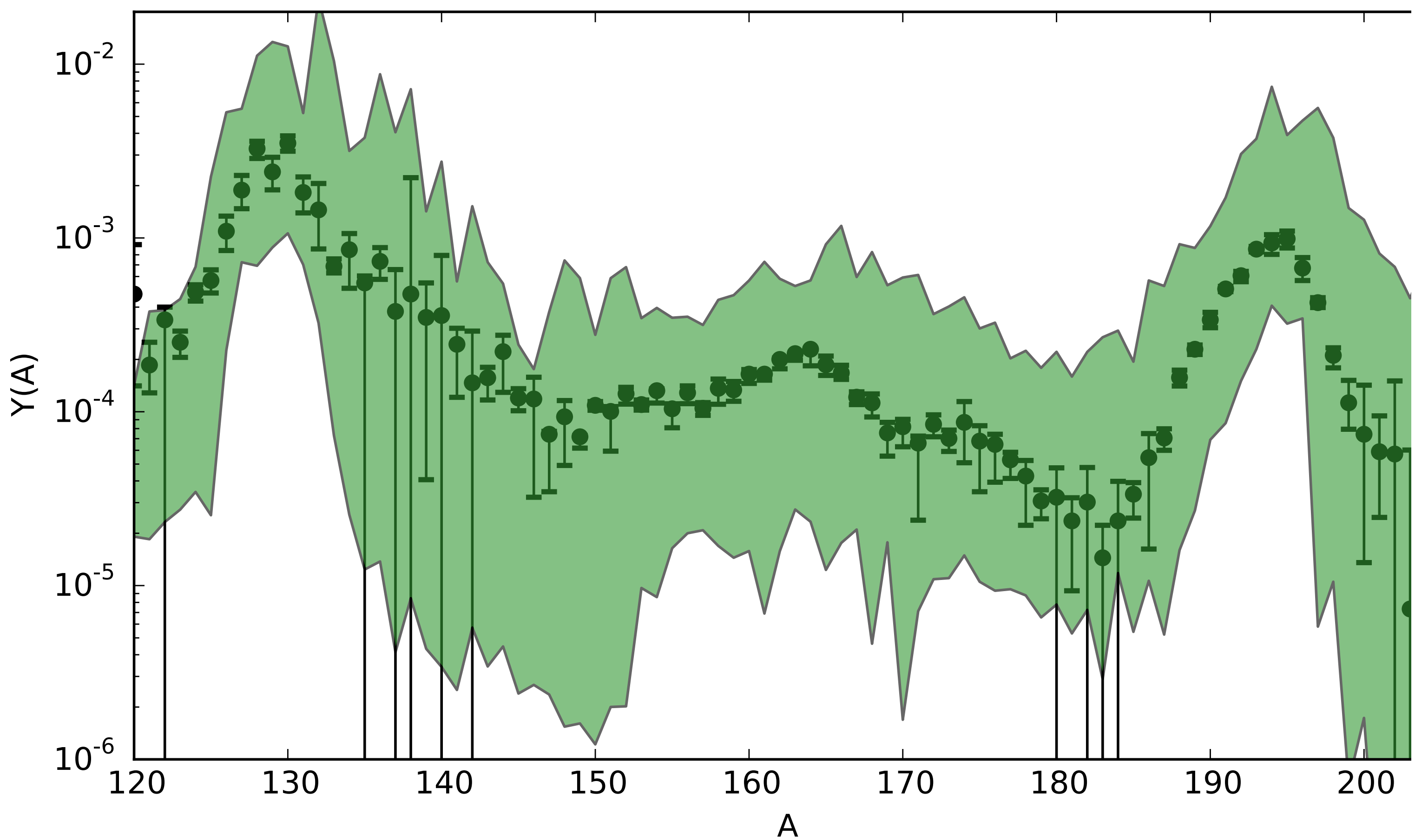
Surman, Mumpower, McLaughlin 2016, submitted

masses from massexplorer.frib.msu.edu: Olsen, Nazarewicz:

SKM*
SKP-3
SLY4
SV-MIN
UNEDF0
UNEDF1

see also Martin+2016

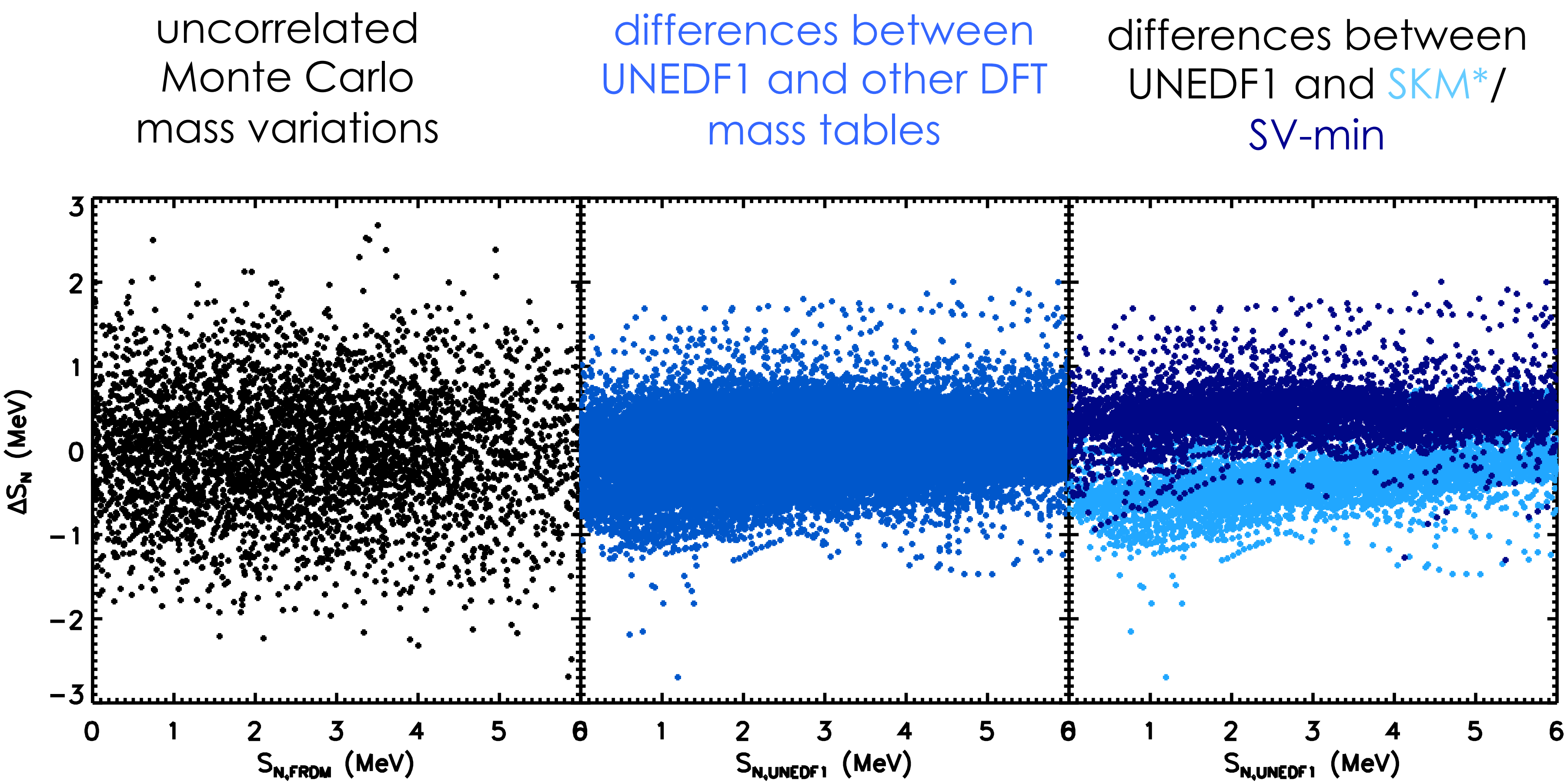
random uncorrelated uncertainties in masses: impact on *r*-process simulations



Surman, Mumpower, McLaughlin 2016, submitted

FRDM masses + Monte Carlo variations within mass model rms (~0.5 MeV)

neutron separation energy variations



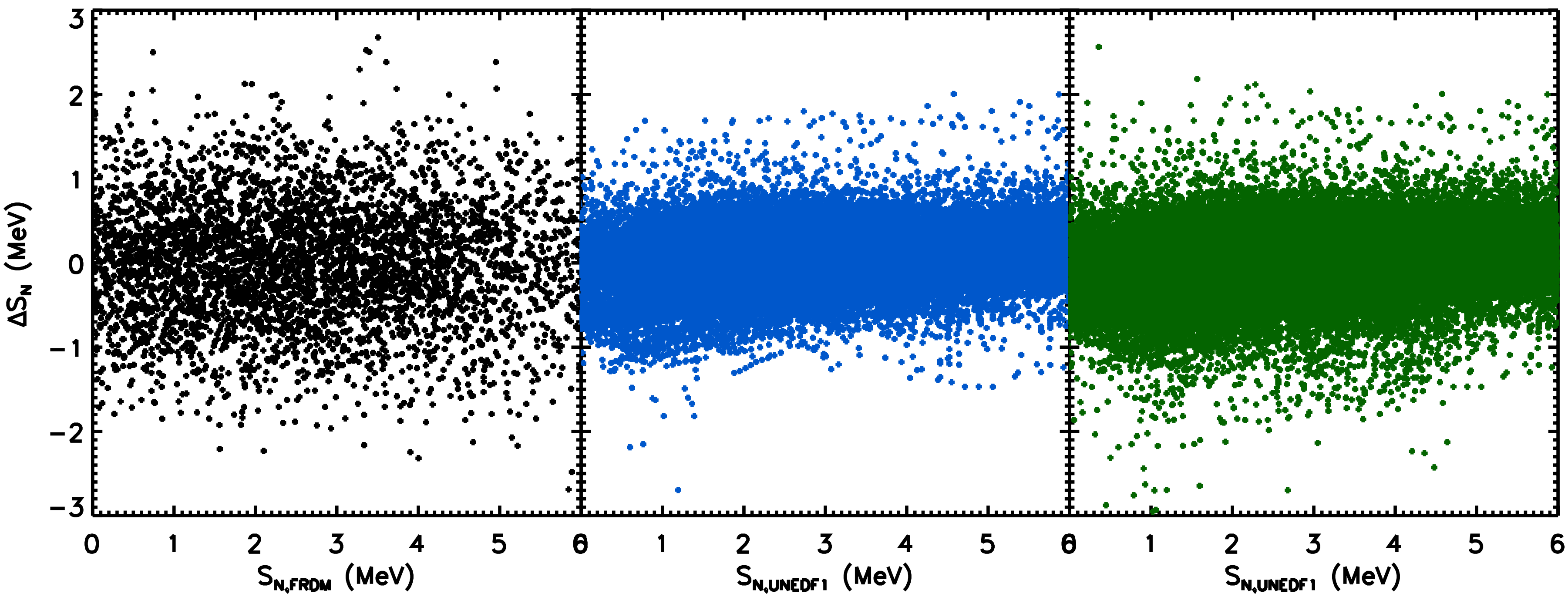
Surman, Mumpower, McLaughlin 2016, submitted

neutron separation energy variations

uncorrelated Monte Carlo mass variations

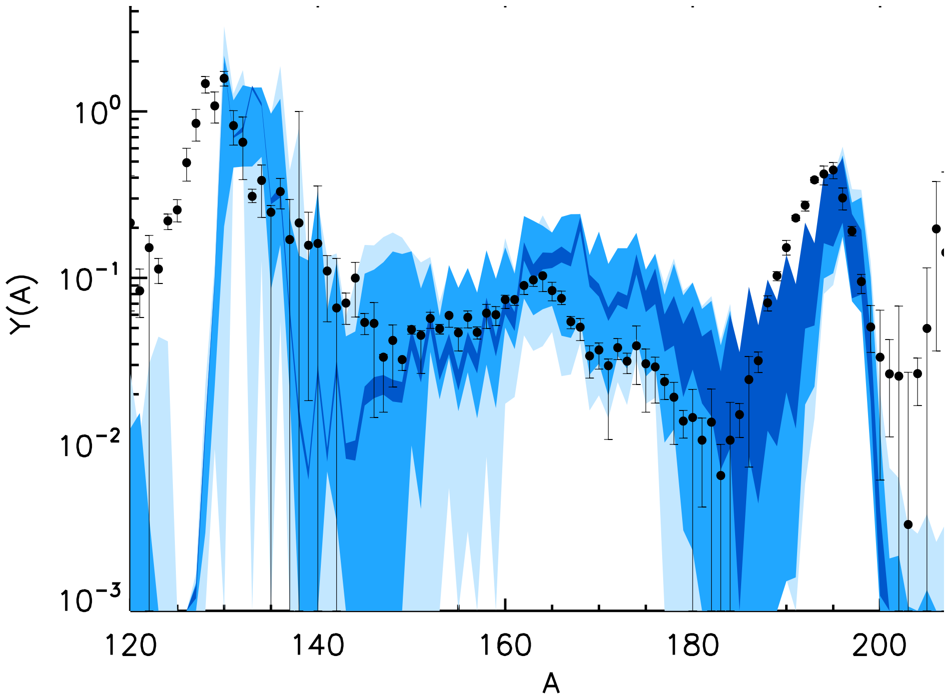
differences between UNEDF1 and other DFT mass tables

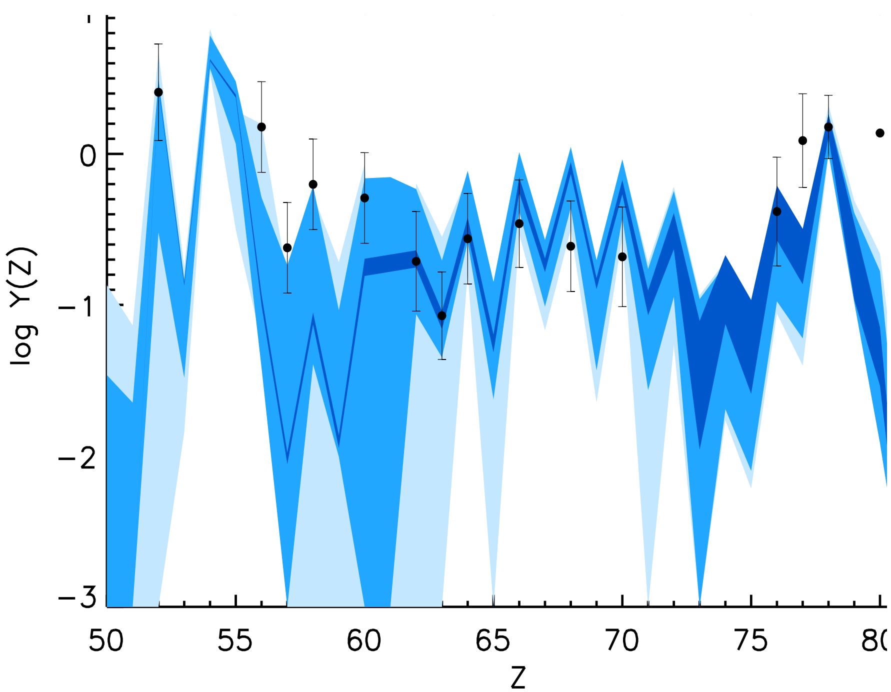
differences between UNEDF1 and other mass tables

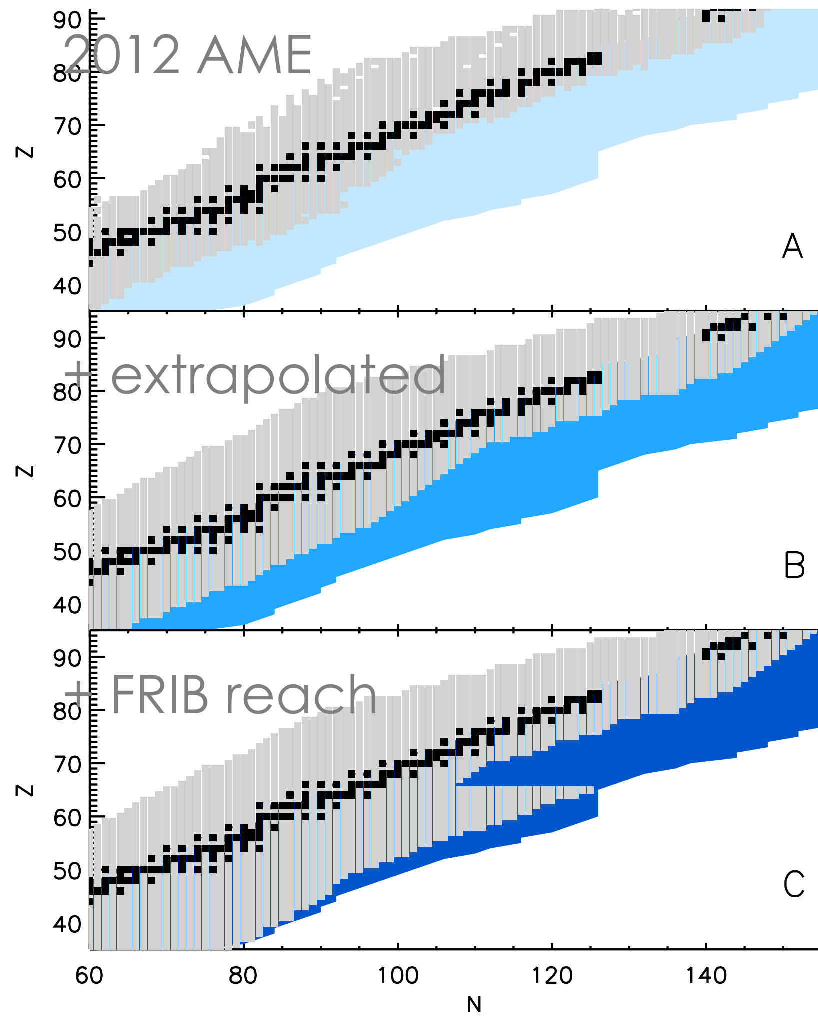


Surman, Mumpower, McLaughlin 2016, submitted

impact of upcoming measurements



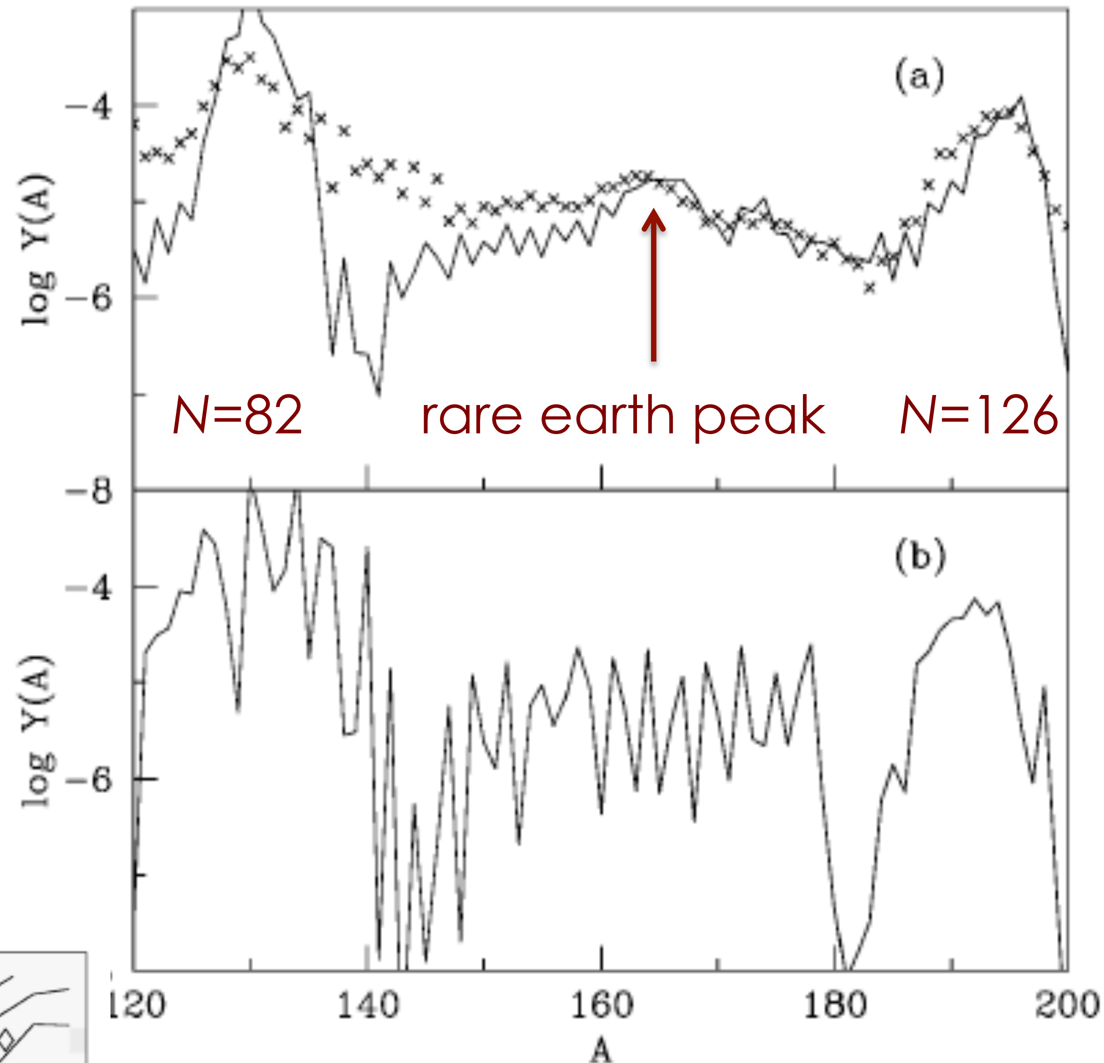


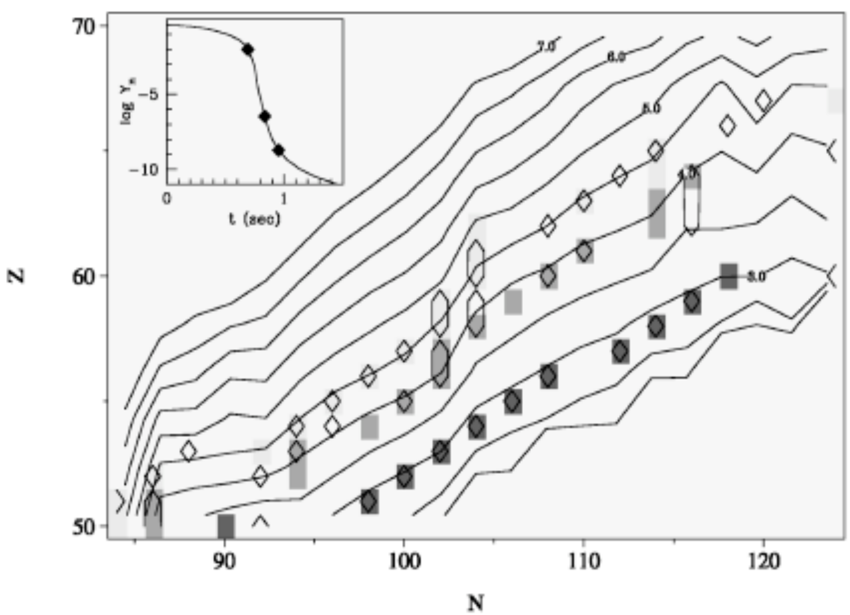


Surman, Mumpower, Aprahamian, *APP B* 2016

rare earth peak

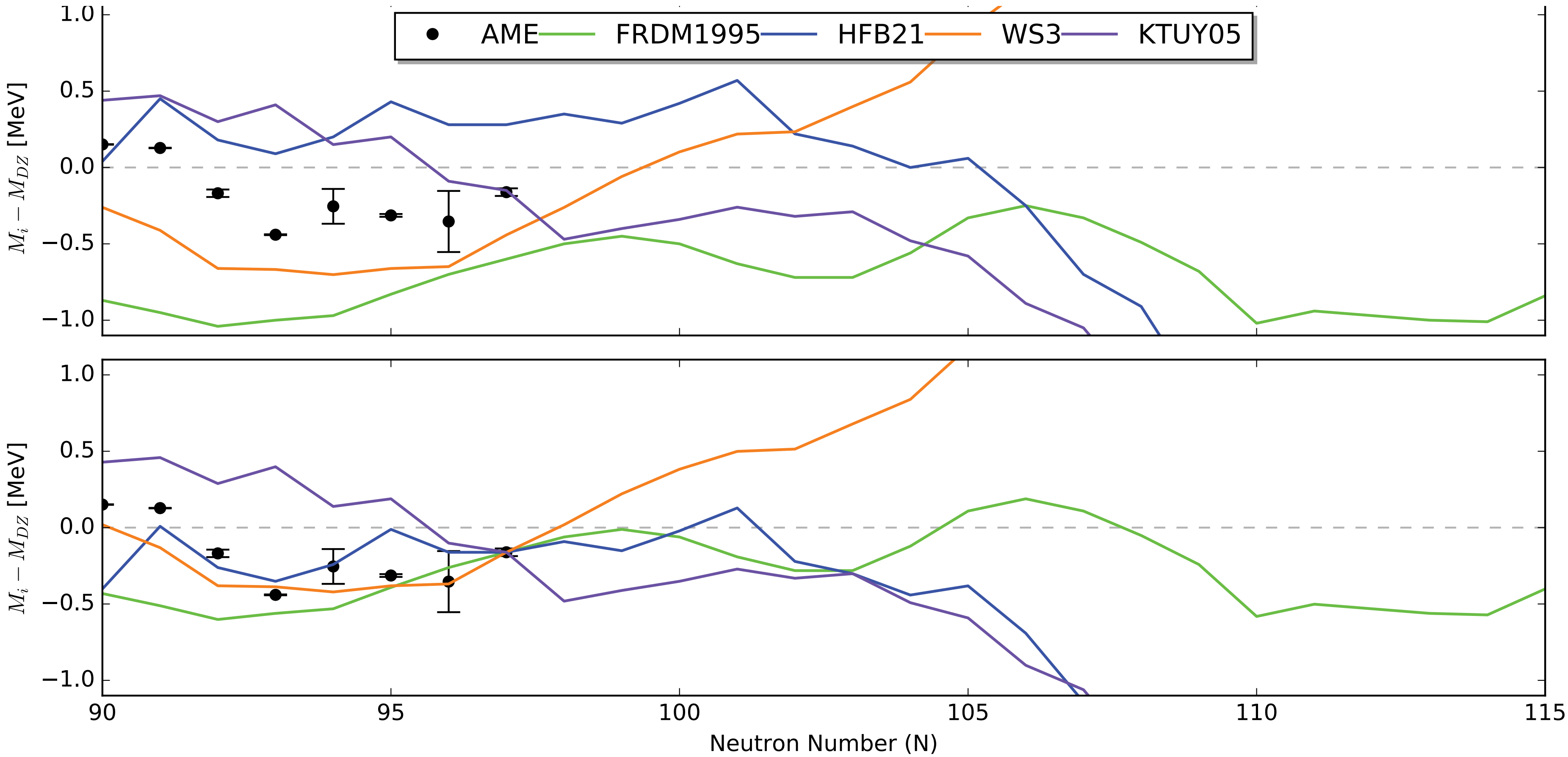
Its formation mechanism is sensitive to both the astrophysical conditions of the late phase of the *r*-process and the nuclear physics of the nuclei populated at this time





Surman, Engel, Bennett, Meyer 1997

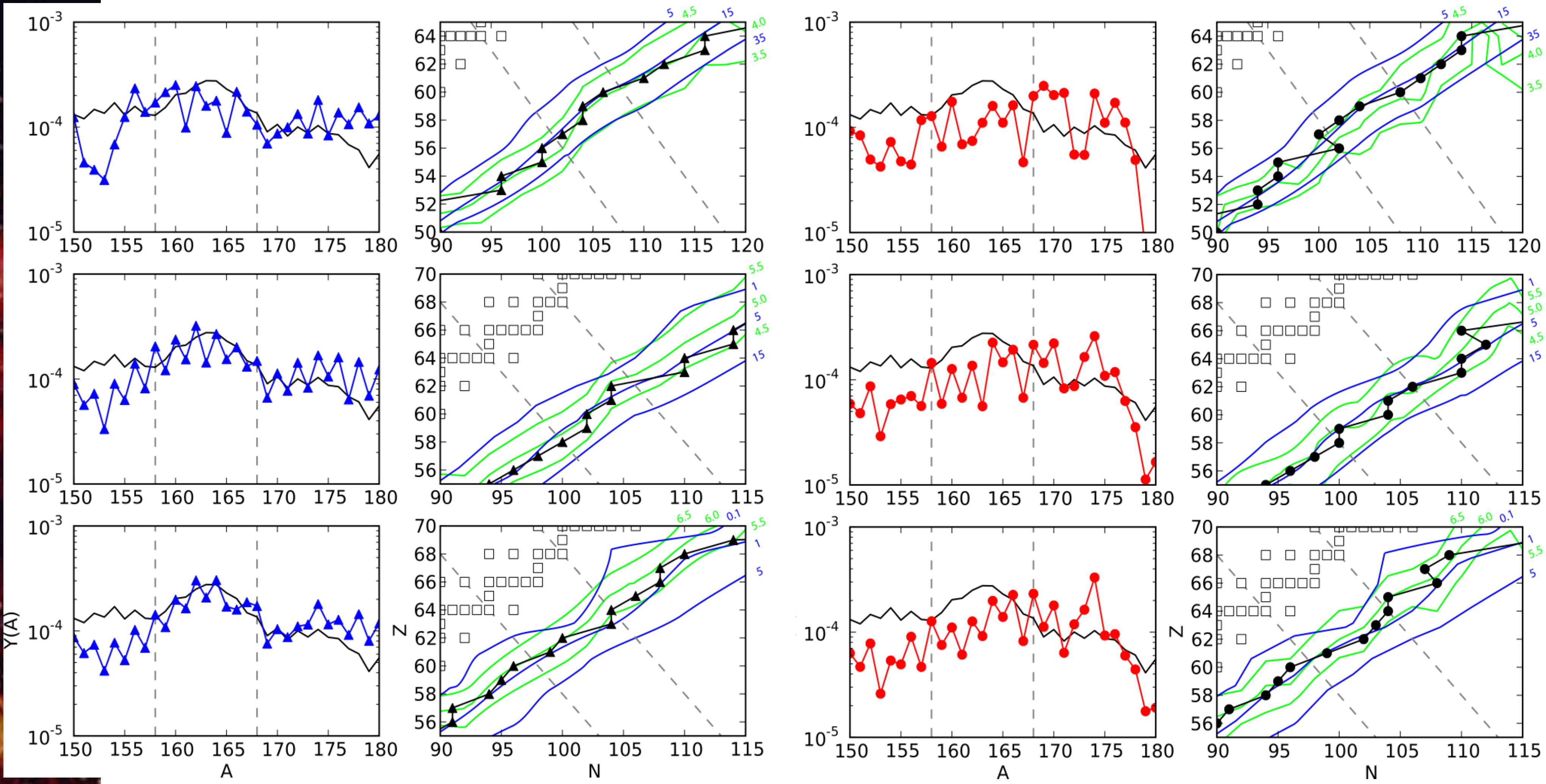
trends in the rare earth masses



Neodymium (Z = 60) isotopic chain

Mumpower, McLaughlin, Surman, Steiner, in preparation

rare earth peak formation

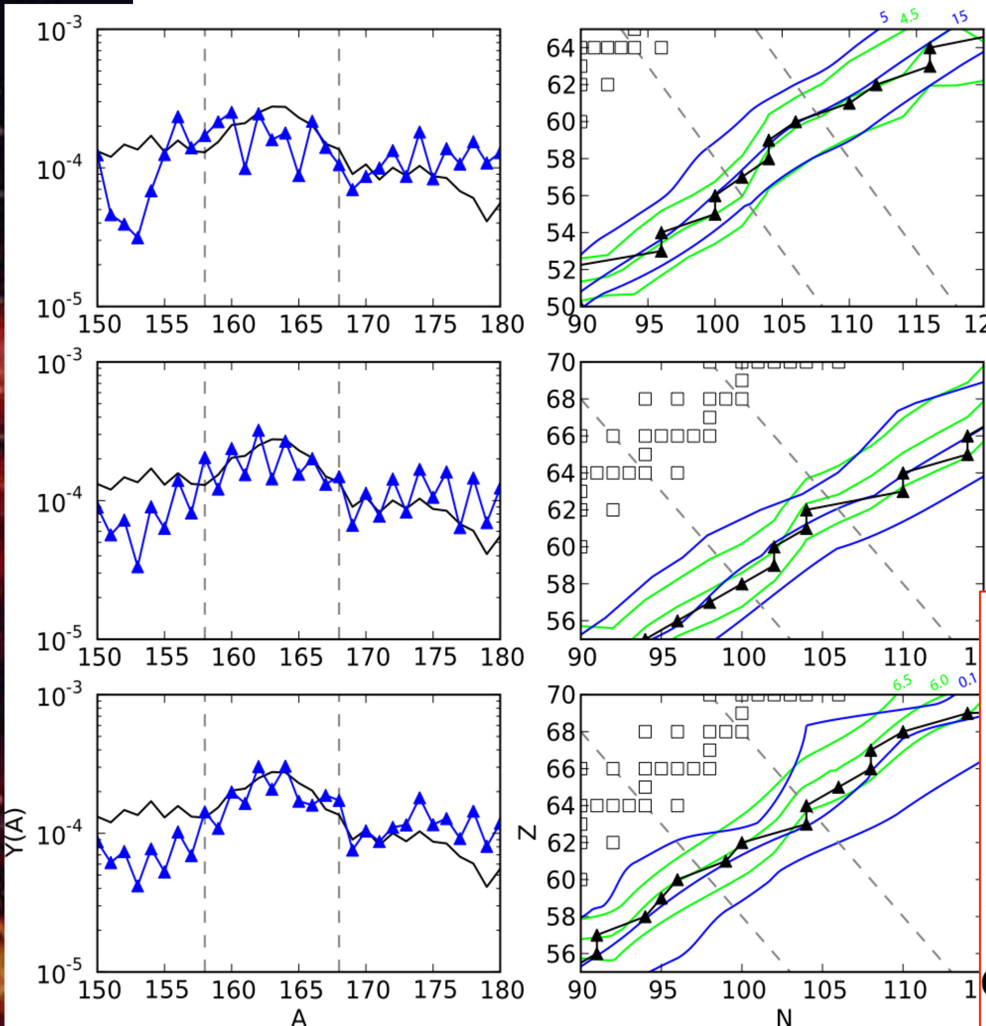


FRDM

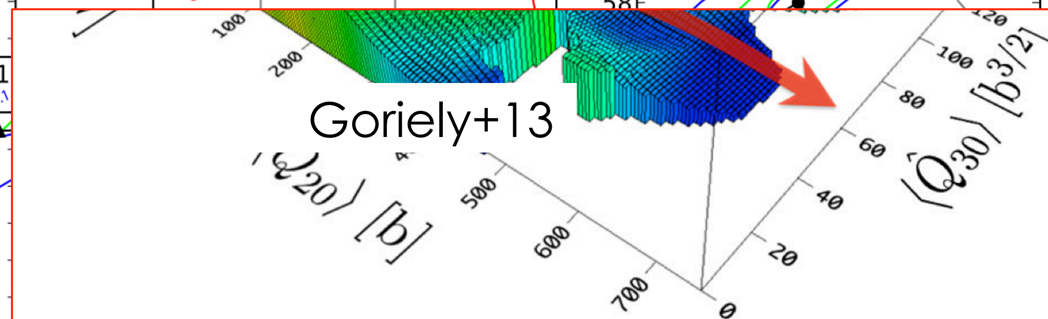
HFB-21

Mumpower, McLaughlin, Surman 2012

rare earth peak formation



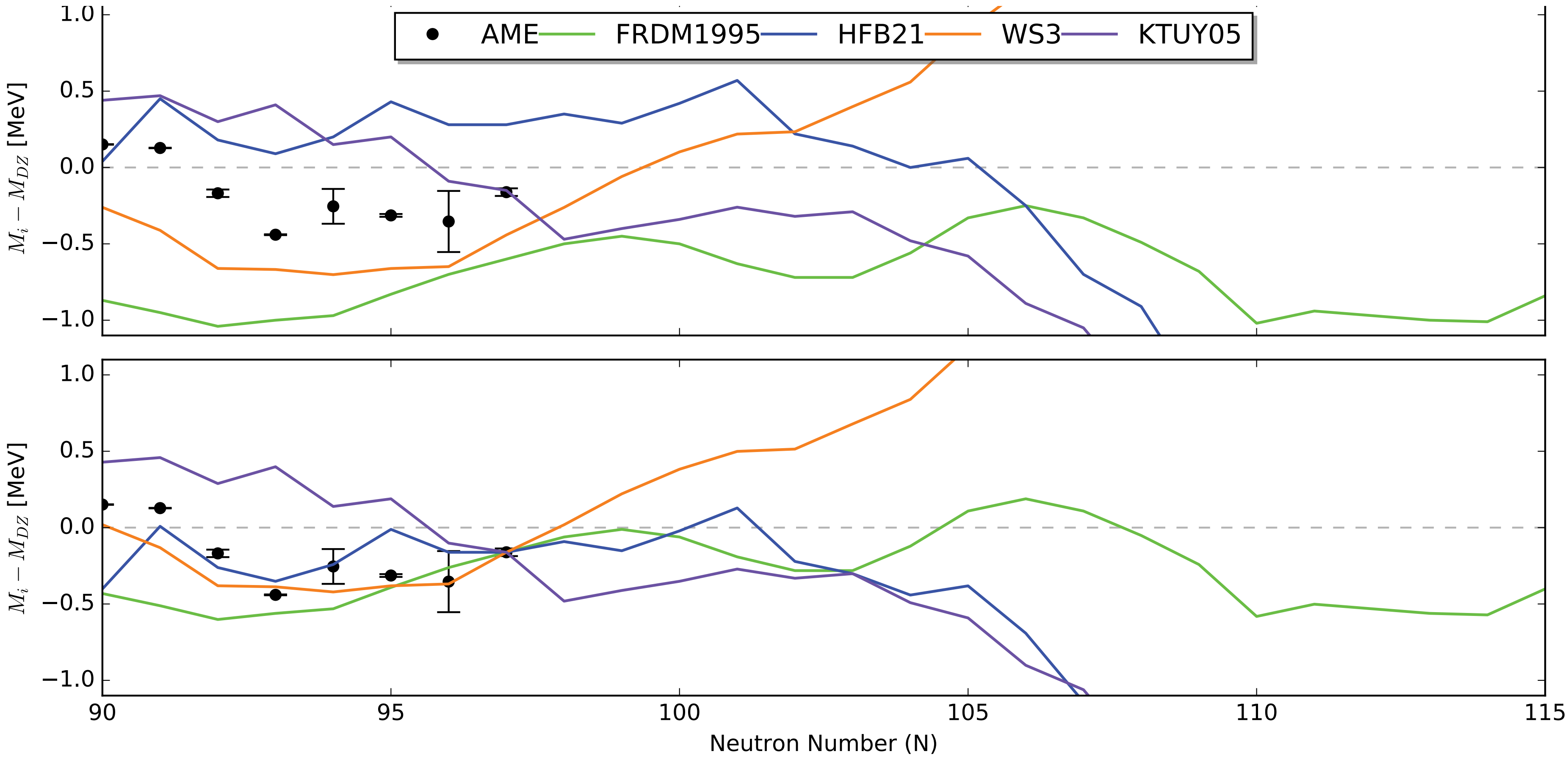
FRDM



G. 3 (color online). ^{278}Cf potential energy surface a
nction of the quadrupole $\langle\hat{Q}_{20}\rangle$ and octupole $\langle\hat{Q}_{30}\rangle$ defor
ons. Both asymmetric fission valleys are depicted by the
rows.

Mumpower, McLaughlin, Surman

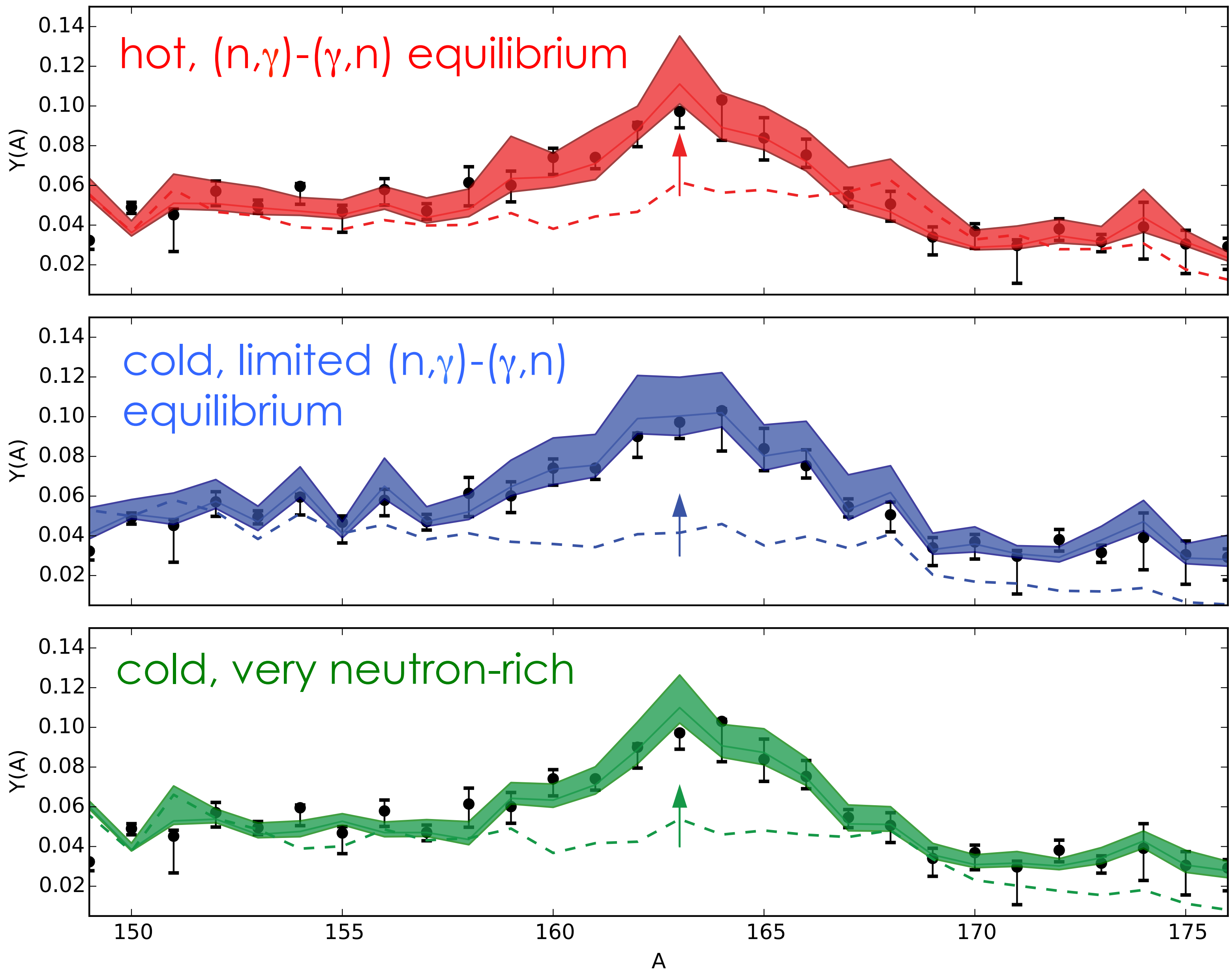
reverse-engineering the rare earth masses



mass modification parameterization:

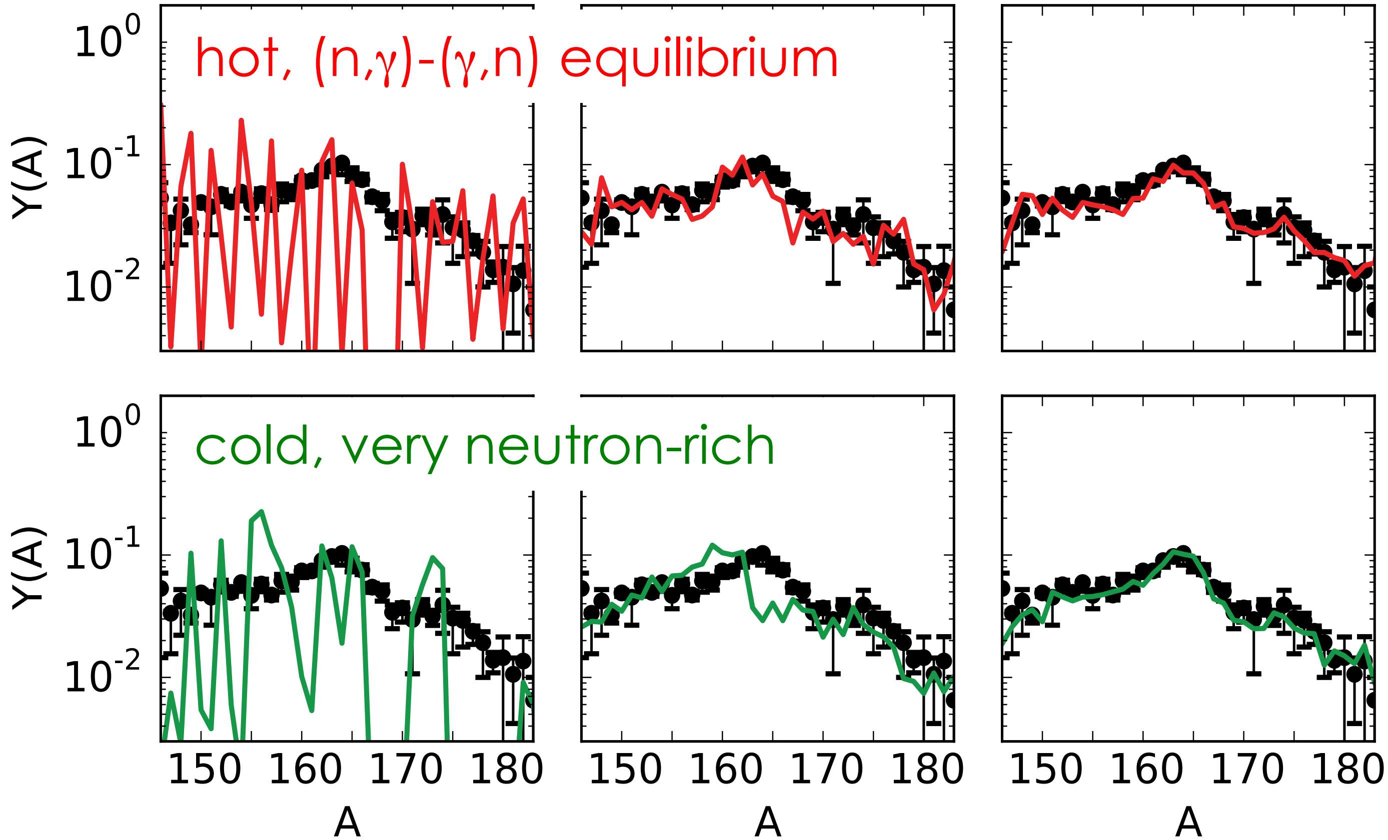
Mumpower, McLaughlin, Surman, Steiner, in preparation

reverse-engineering the rare earth masses



Mumpower, McLaughlin, Surman, Steiner, in preparation

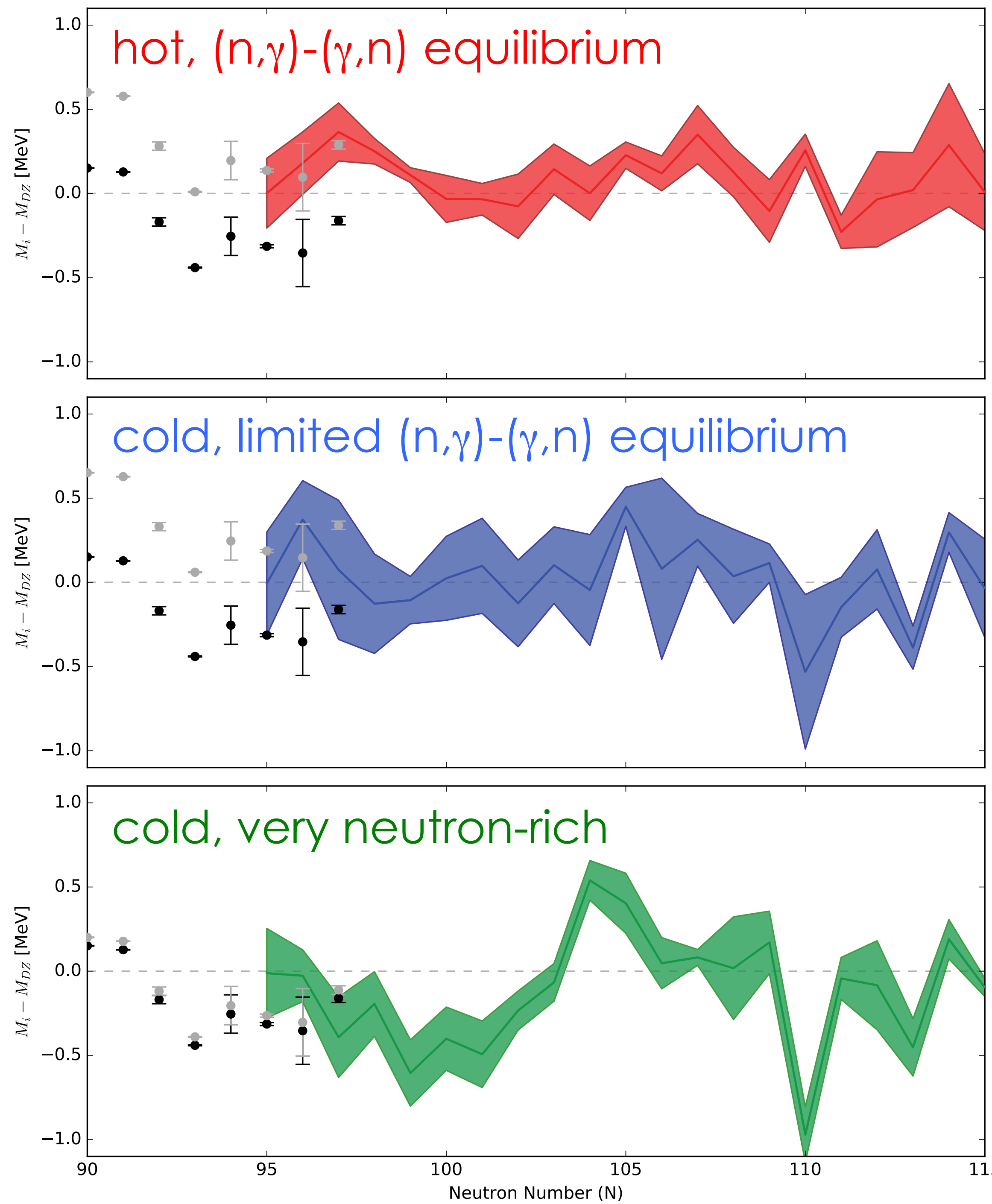
rare earth peak formation comparison



Mumpower, McLaughlin, Surman, Steiner arXiv:1603.02600v1

predicted mass surfaces

Neodymium (Z = 60)
isotopic chain



Mumpower,
McLaughlin,
Surman, Steiner,
in preparation

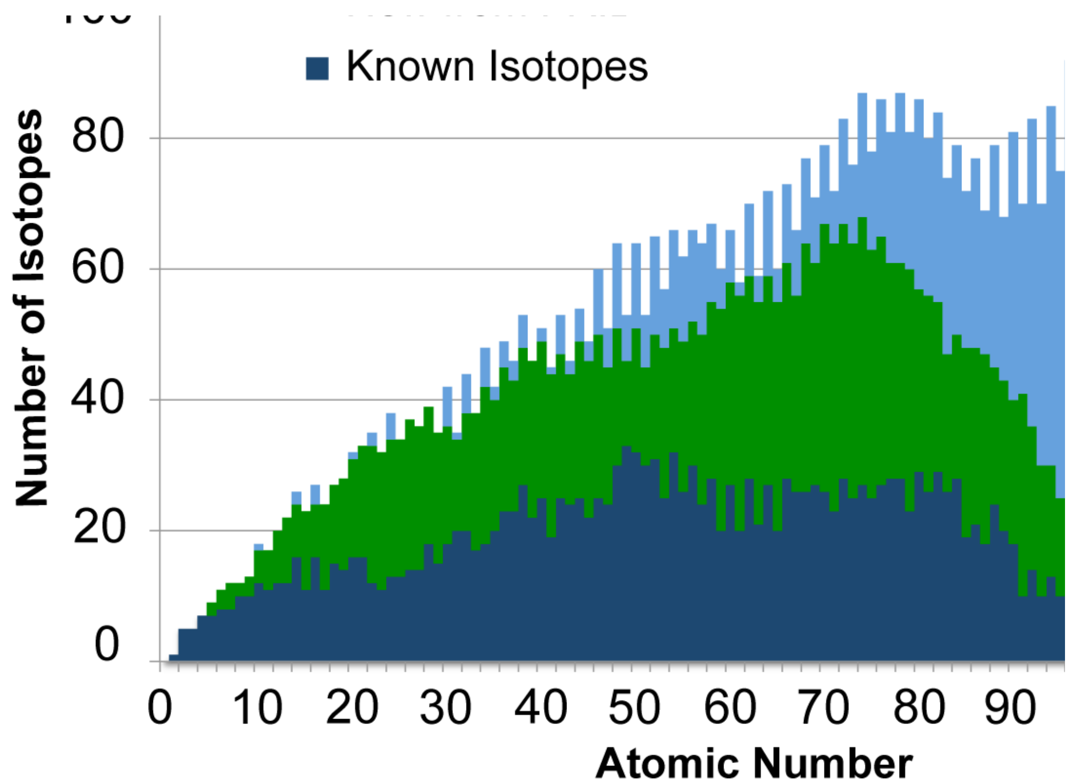
R Surman, Notre Dame
INPC Adelaide
14 Sept 16

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



FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University