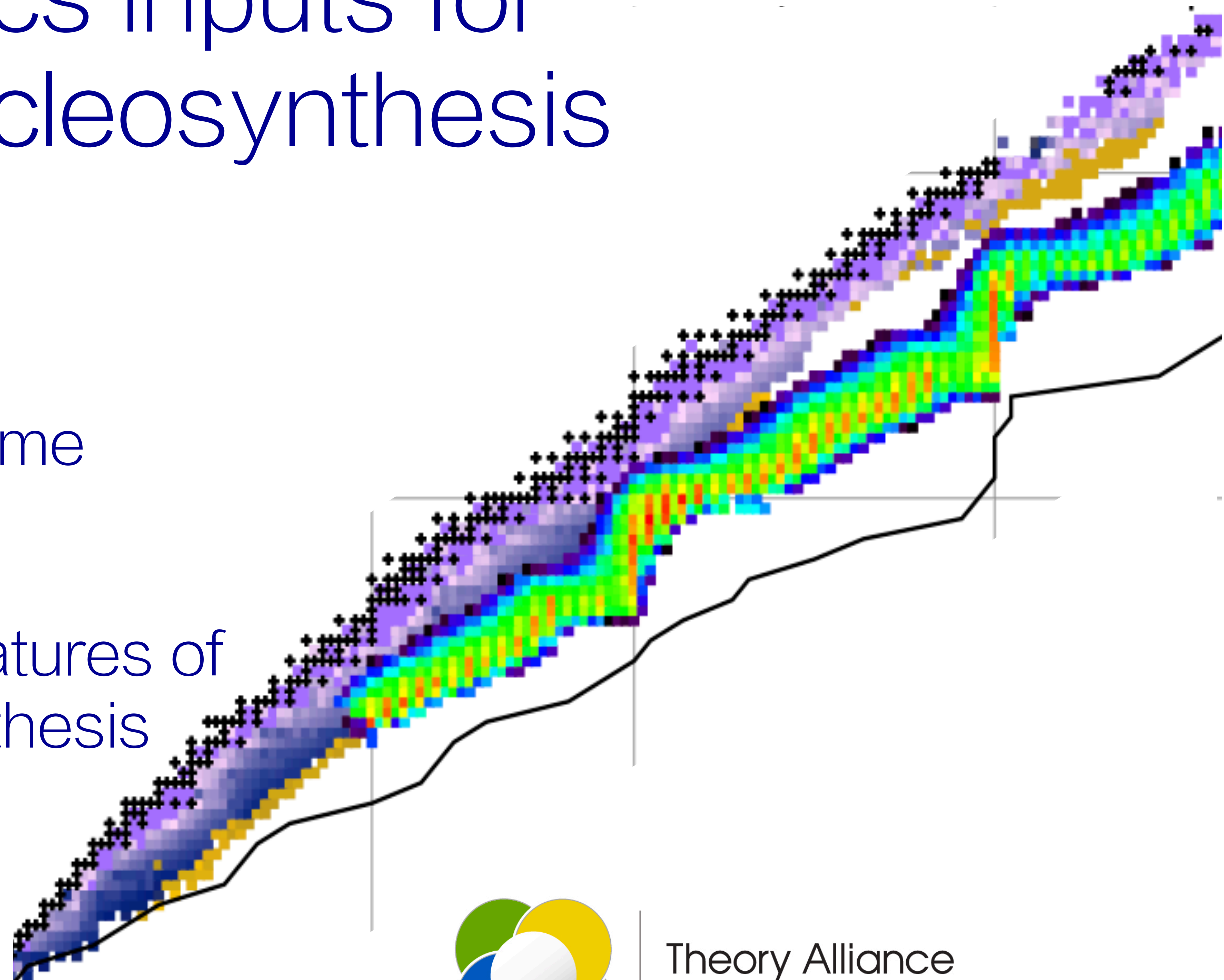
nuclear physics inputs for *r*–process nucleosynthesis

Rebecca Surman
University of Notre Dame

INT 17–2b
Electromagnetic Signatures of *r*–Process Nucleosynthesis

24–28 July 2017

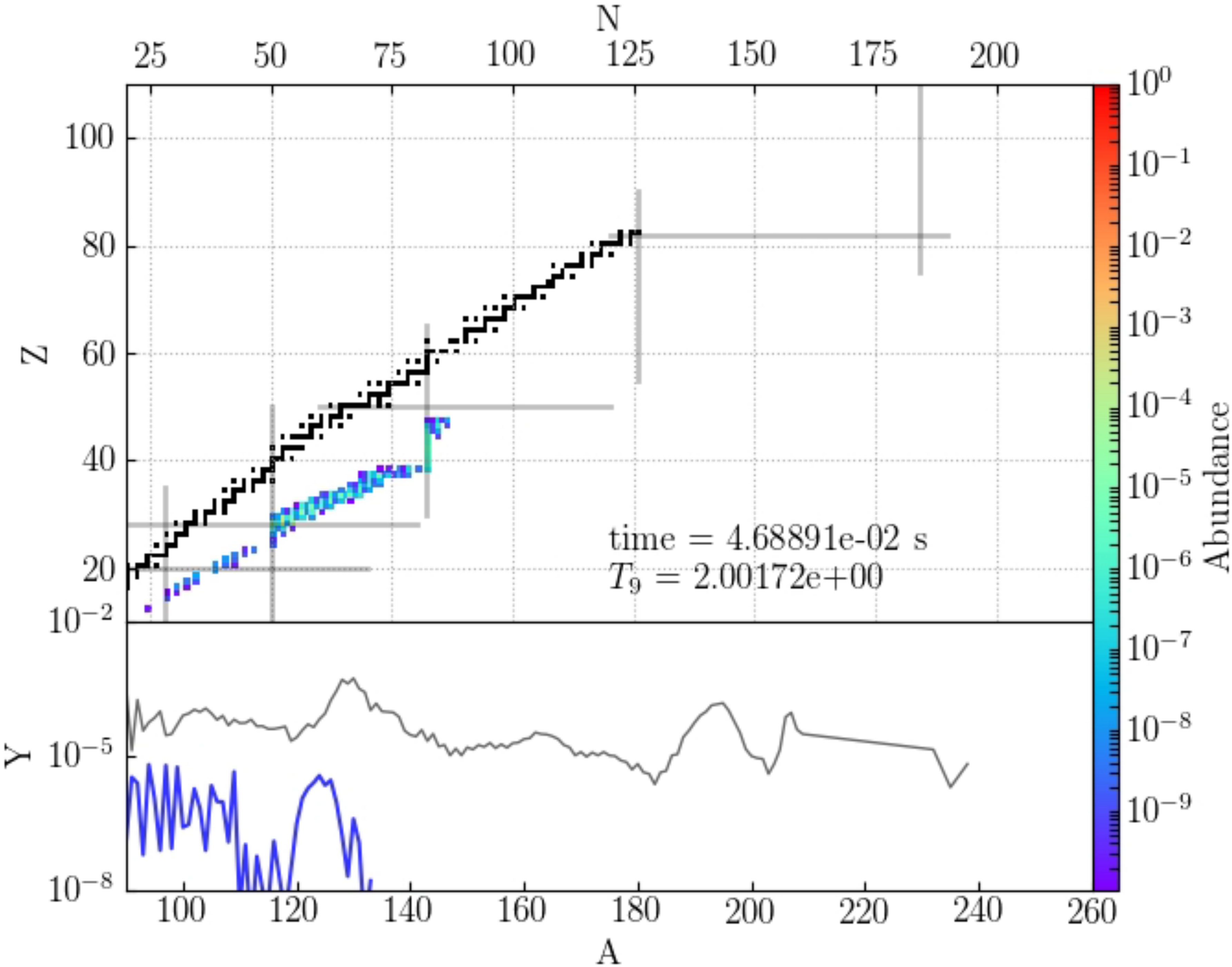


Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

UNIVERSITY OF NOTRE DAME
College of Science

U.S. DEPARTMENT OF ENERGY
Office of Science

JINA–CEE



calculation and movie by Erika Holmbeck, nsm trajectory from Just+2015

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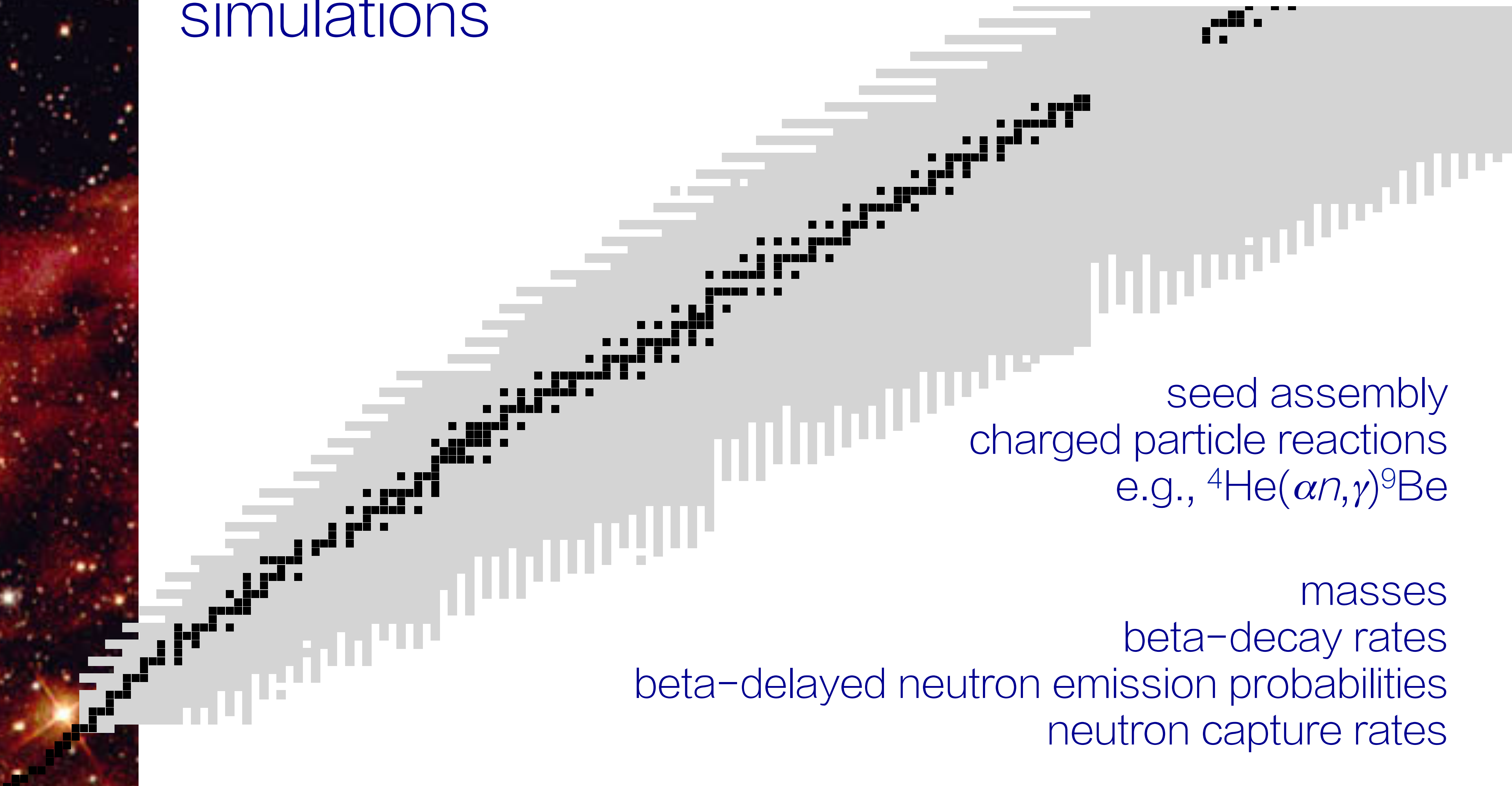
nuclear data required for *r*−process simulations



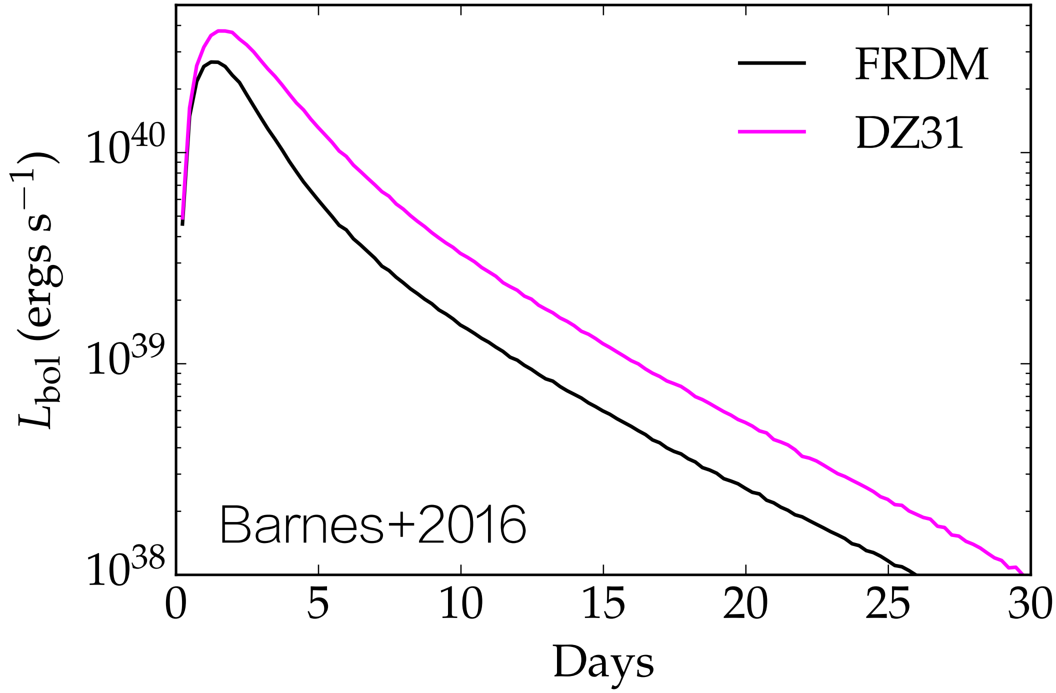
seed assembly
charged particle reactions
e.g., $^{4}\mathrm{He}(\alpha n,\gamma)^{9}\mathrm{Be}$

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

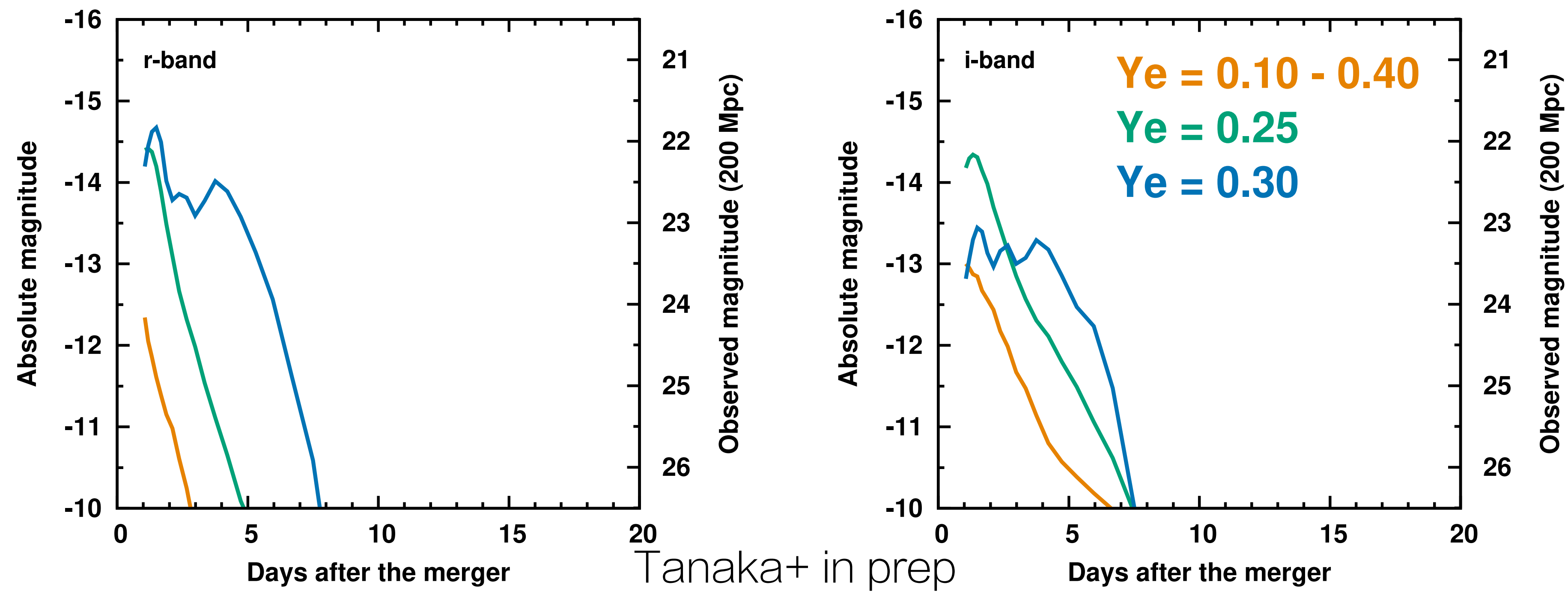
fission rates
fission product distributions
neutrino interactions

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

EM transient



see talk of
Masaomi Tanaka



Tanaka+ in prep

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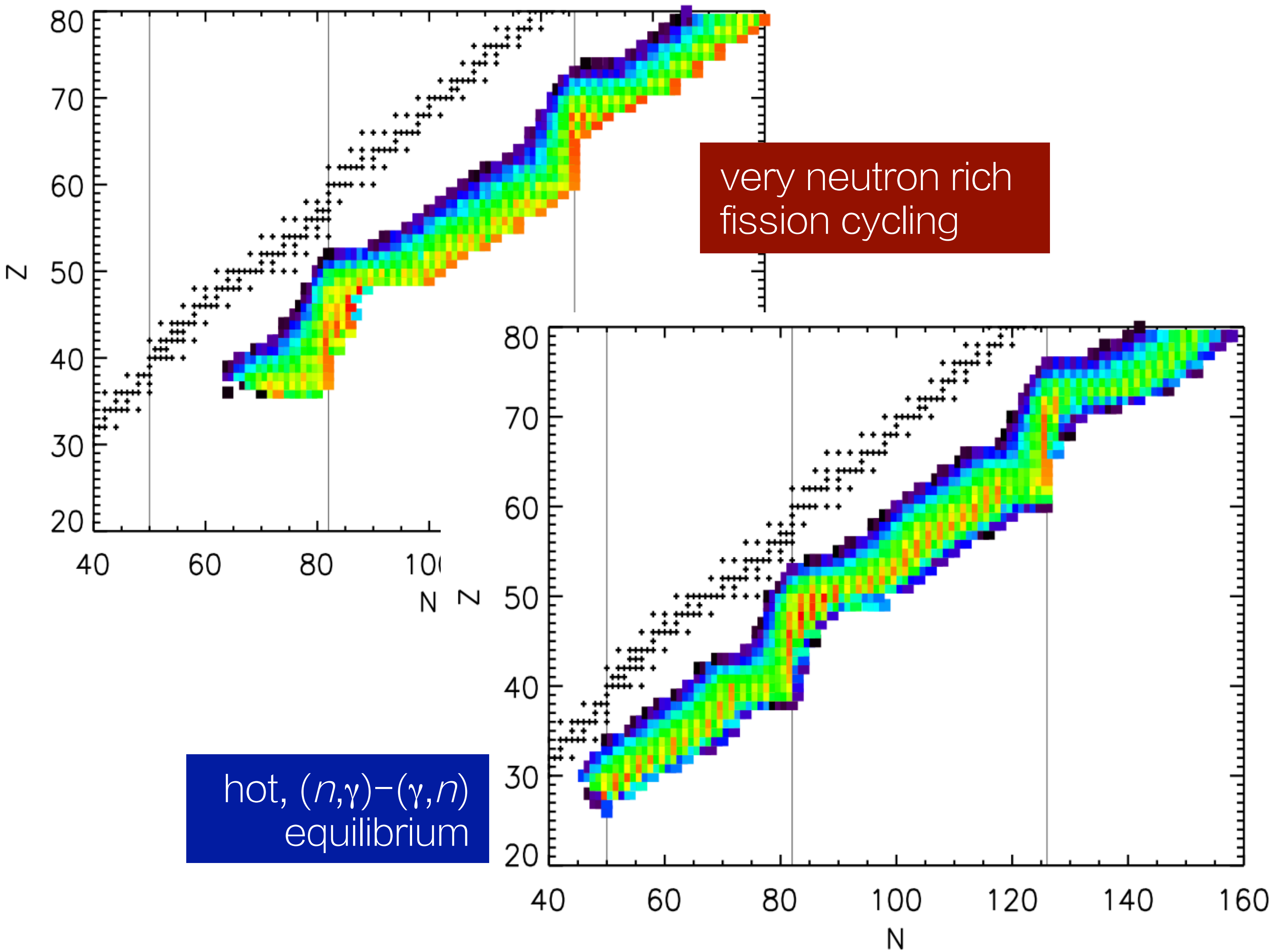
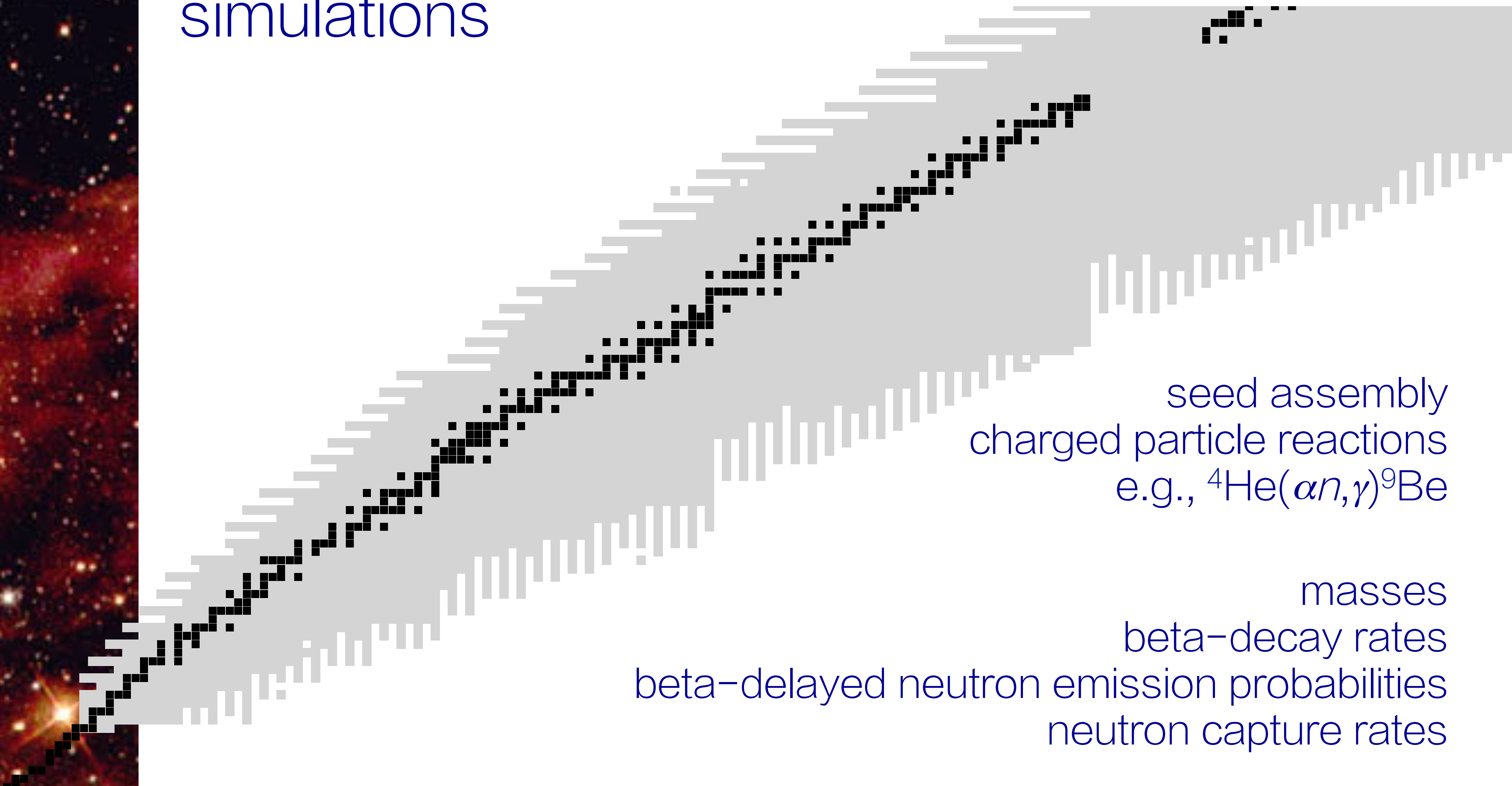
r−process abundance pattern signatures



nuclear data required for *r*−process simulations



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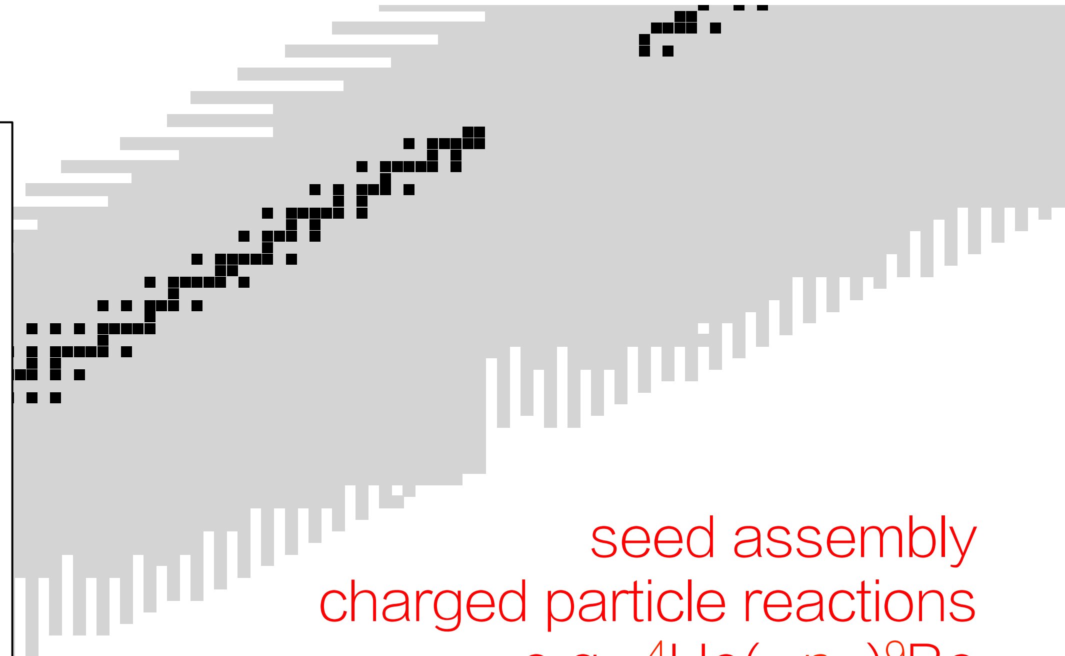

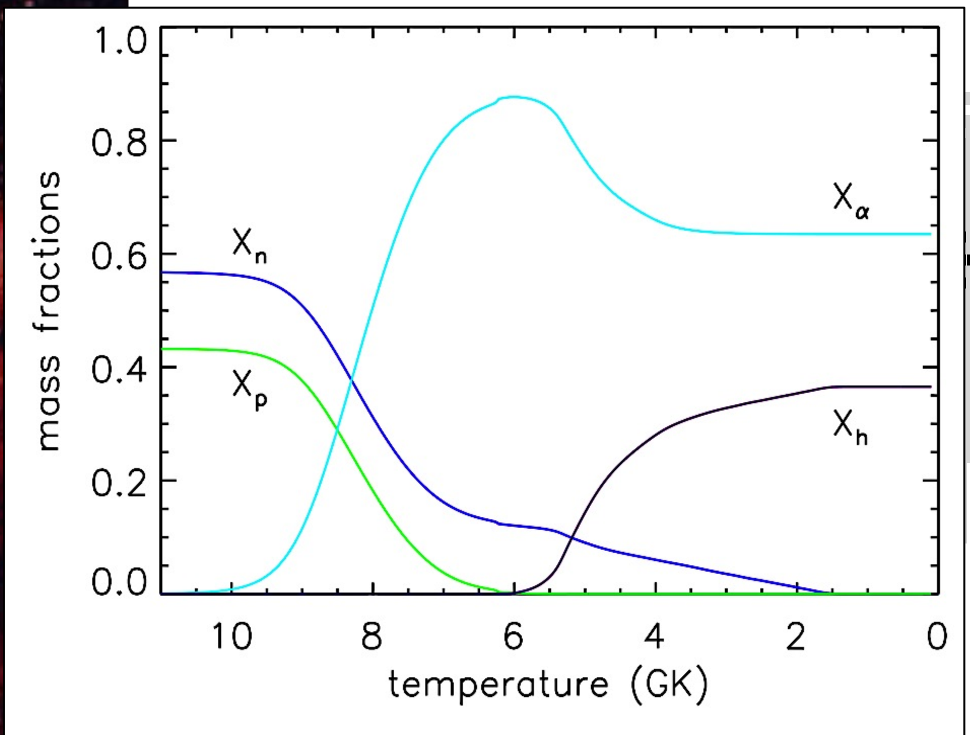

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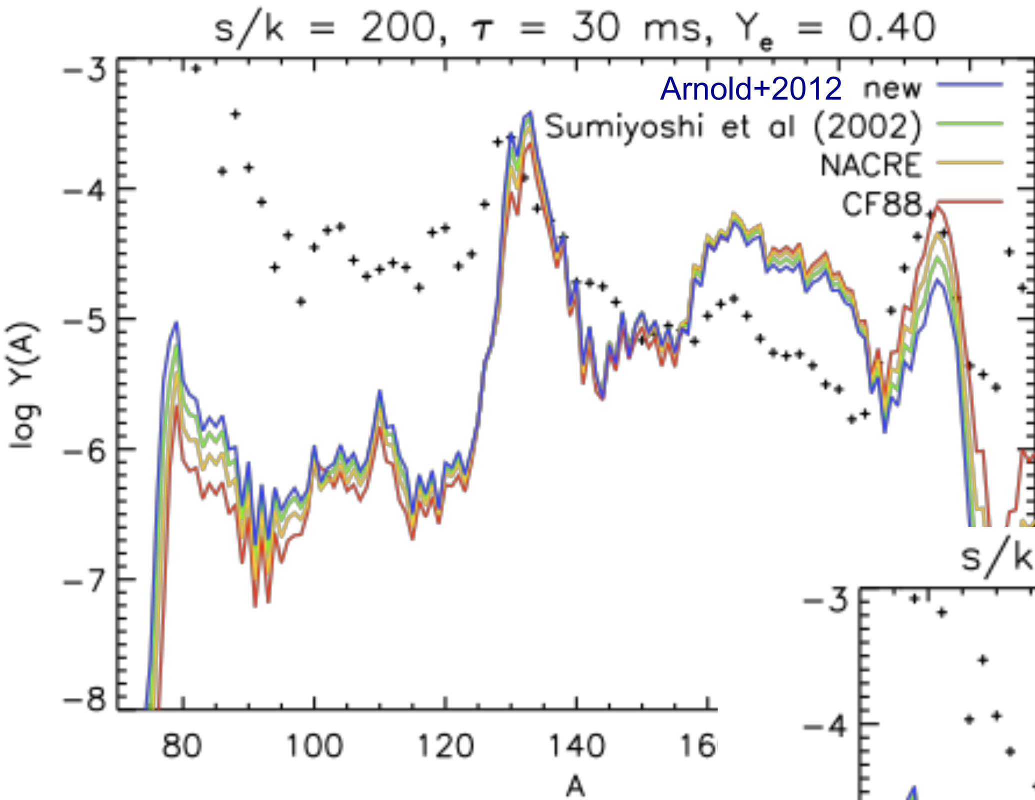
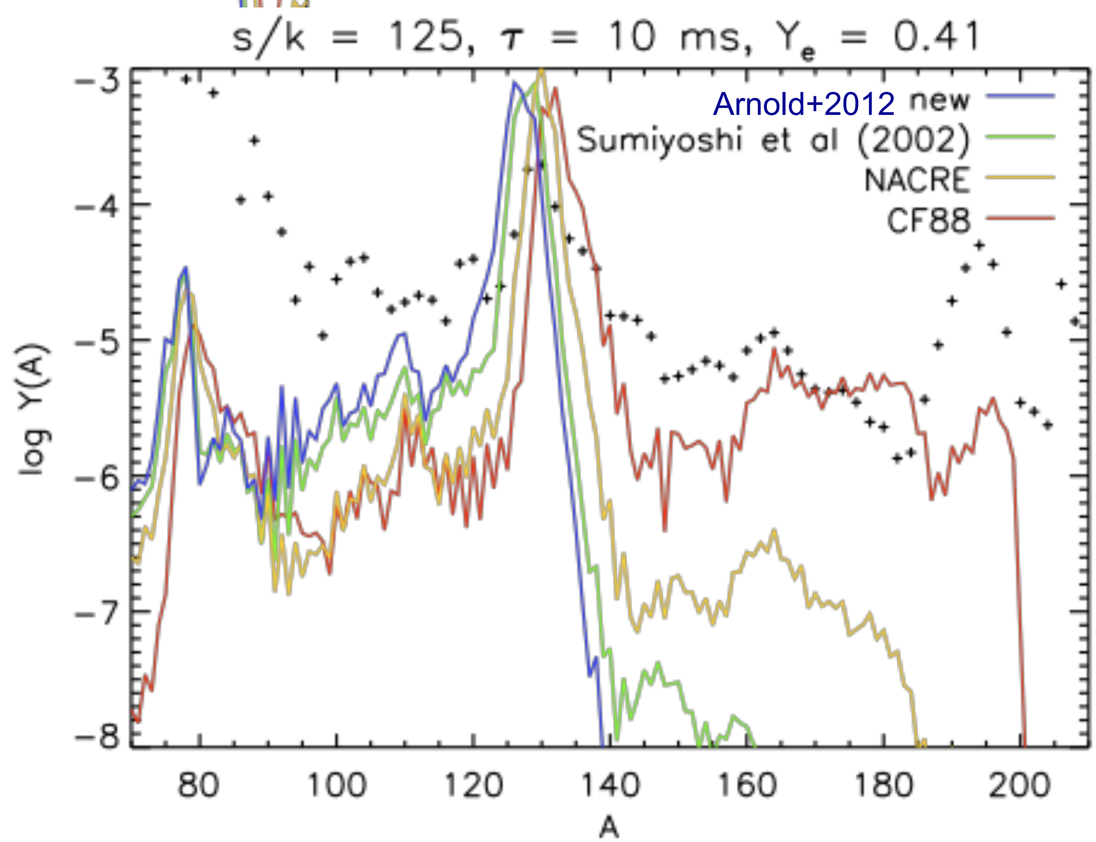
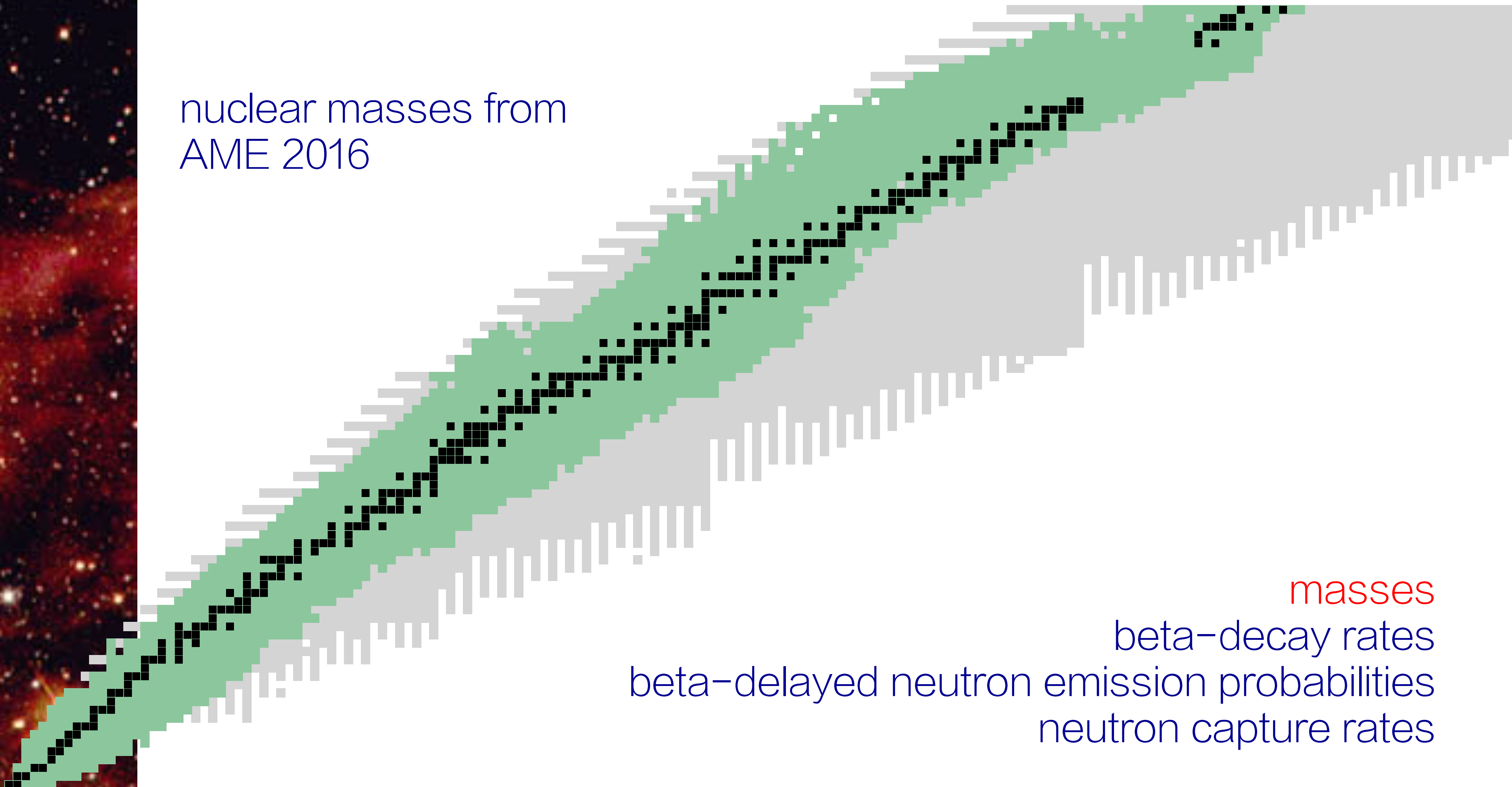
required nuclear data: $^{4}He(\alpha n,\gamma)^{9}Be$





required nuclear data: masses

nuclear masses from
AME 2016



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nuclear masses from
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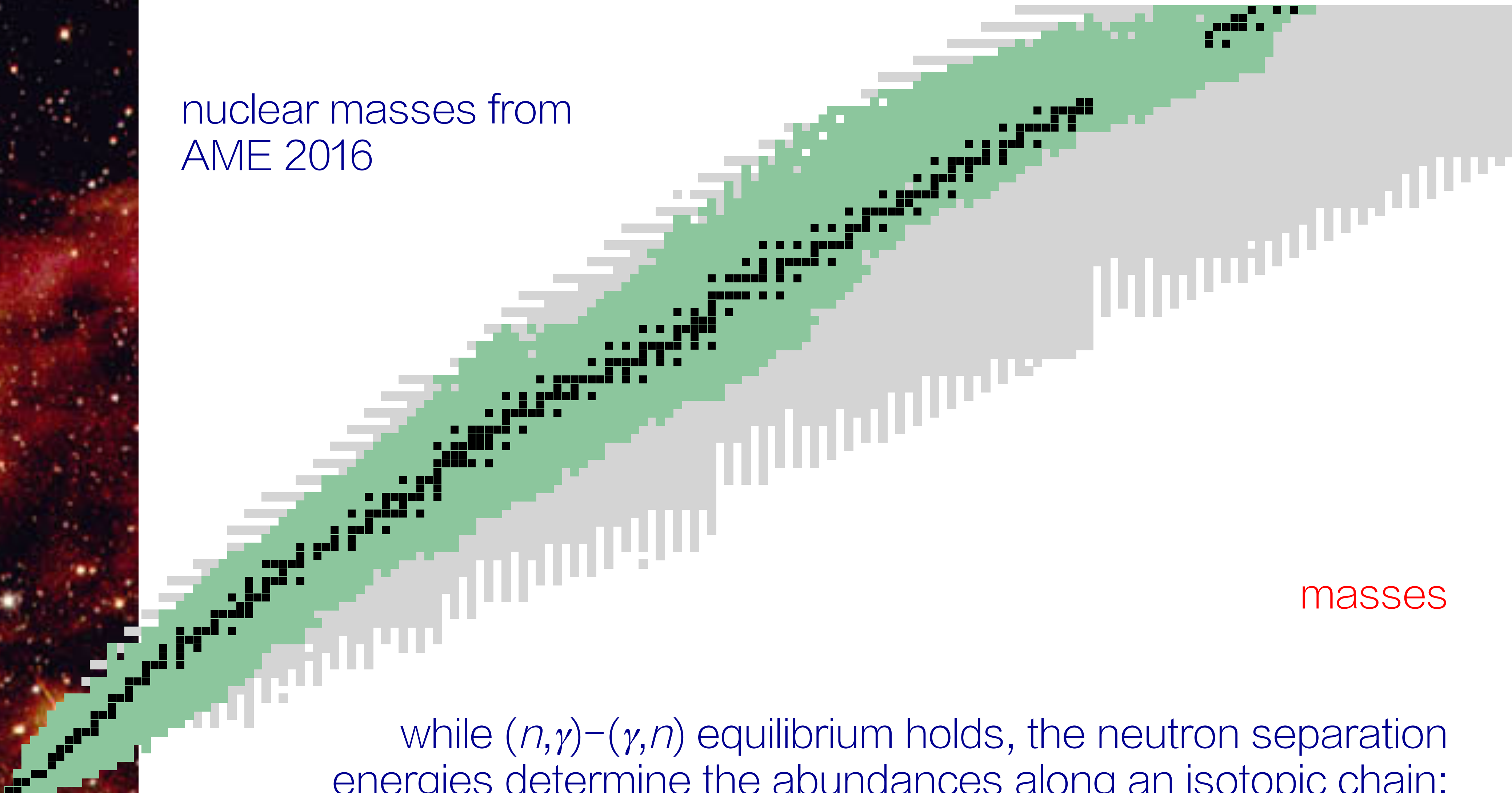
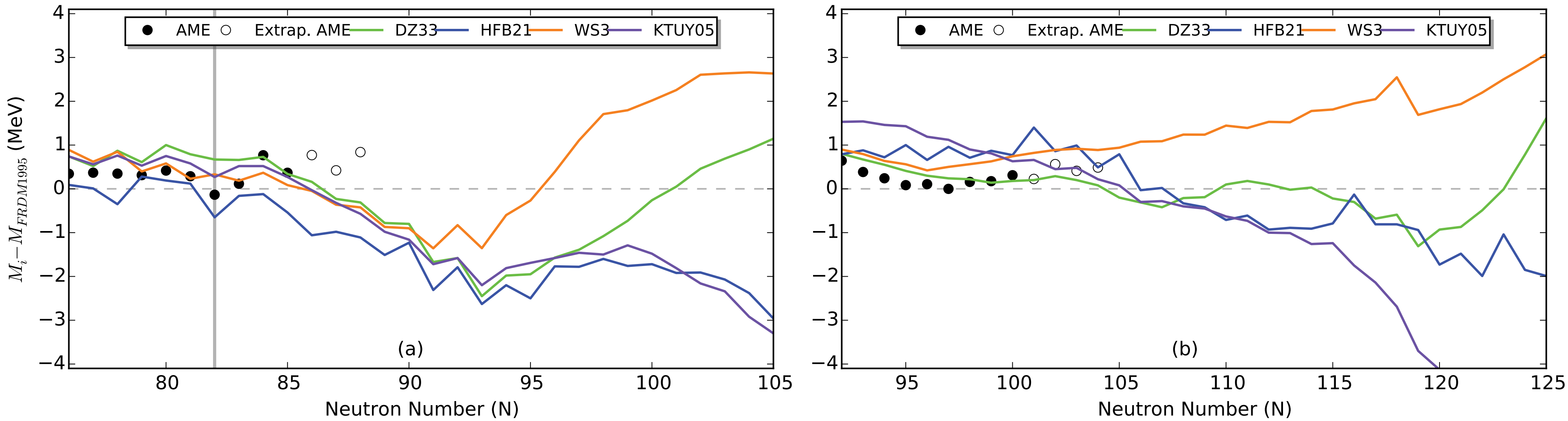


masses

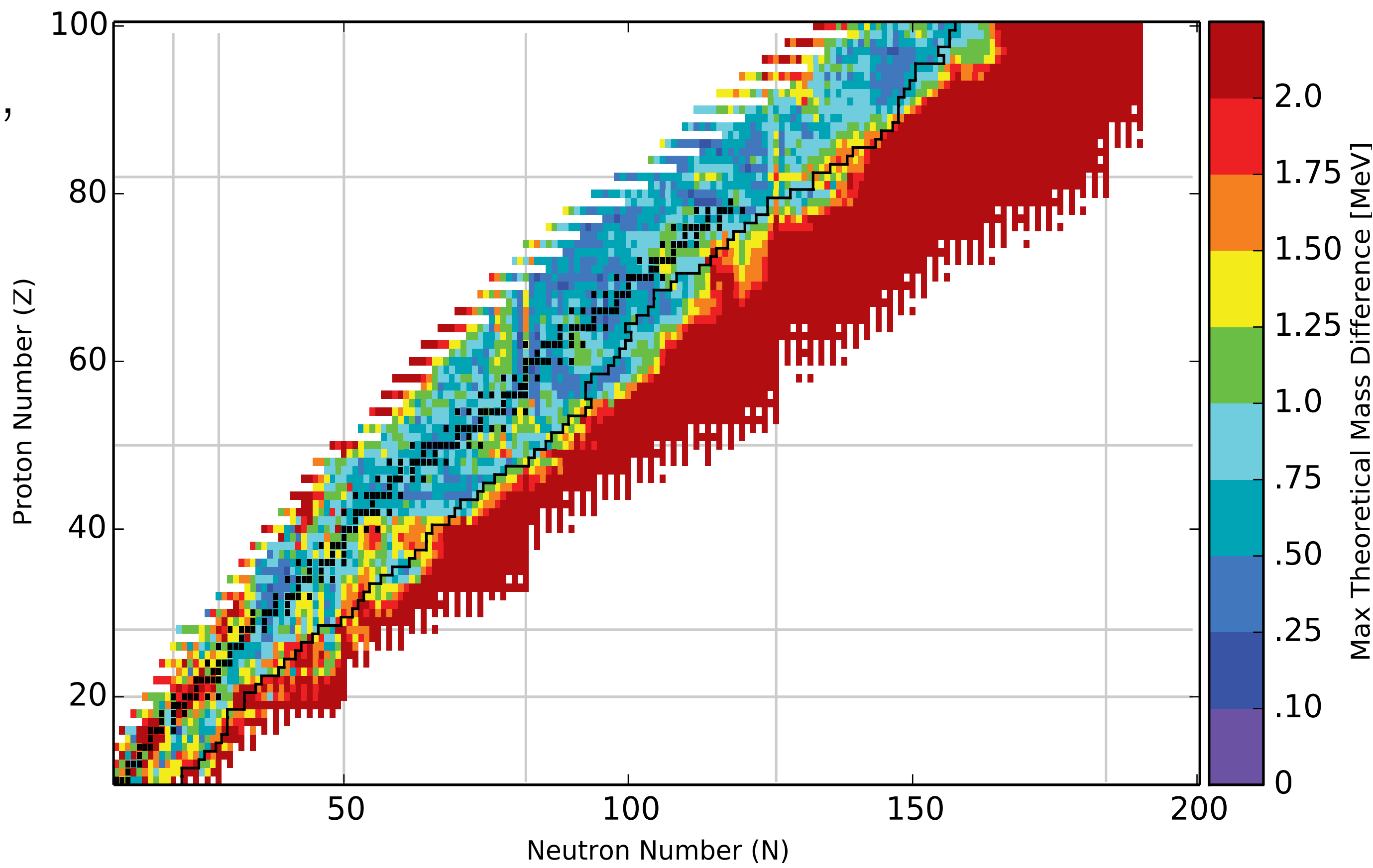
while $(n,\gamma)-(\gamma,n)$ equilibrium holds, the neutron separation energies determine the abundances along an isotopic chain:

$$\frac{Y_{eq}(Z,A+1)}{Y_{eq}(Z,A)} = \frac{G(Z,A+1)}{2G(Z,A)} n_n \left(\frac{2\pi\hbar N_A}{m_n kT}\right)^{3/2} \exp\left[\frac{S_n(Z,A+1)}{kT}\right]$$

r−process uncertainties: masses



Mumpower, Surman, McLaughlin, Aprahamian 2016



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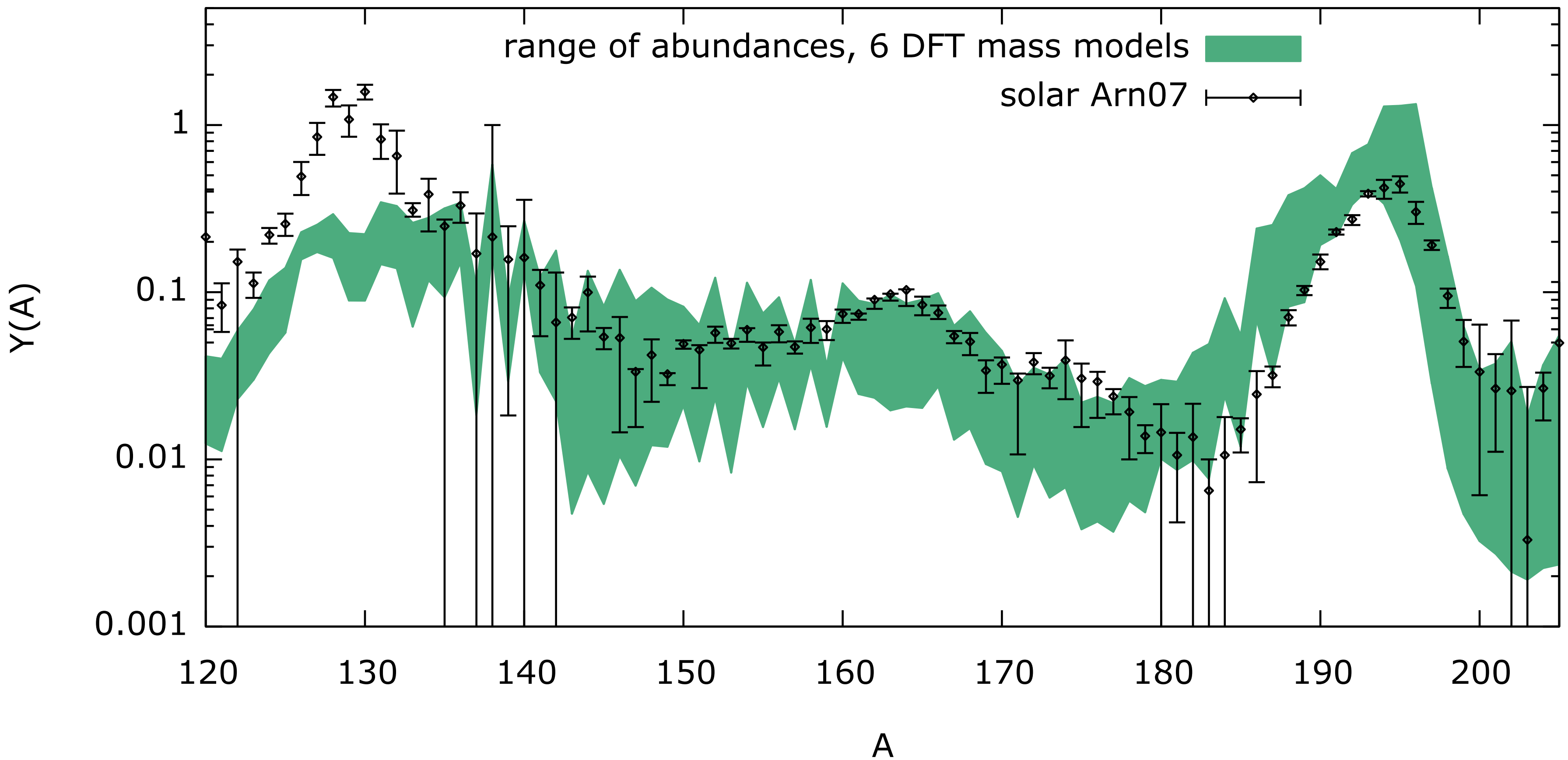
r-process uncertainties: masses



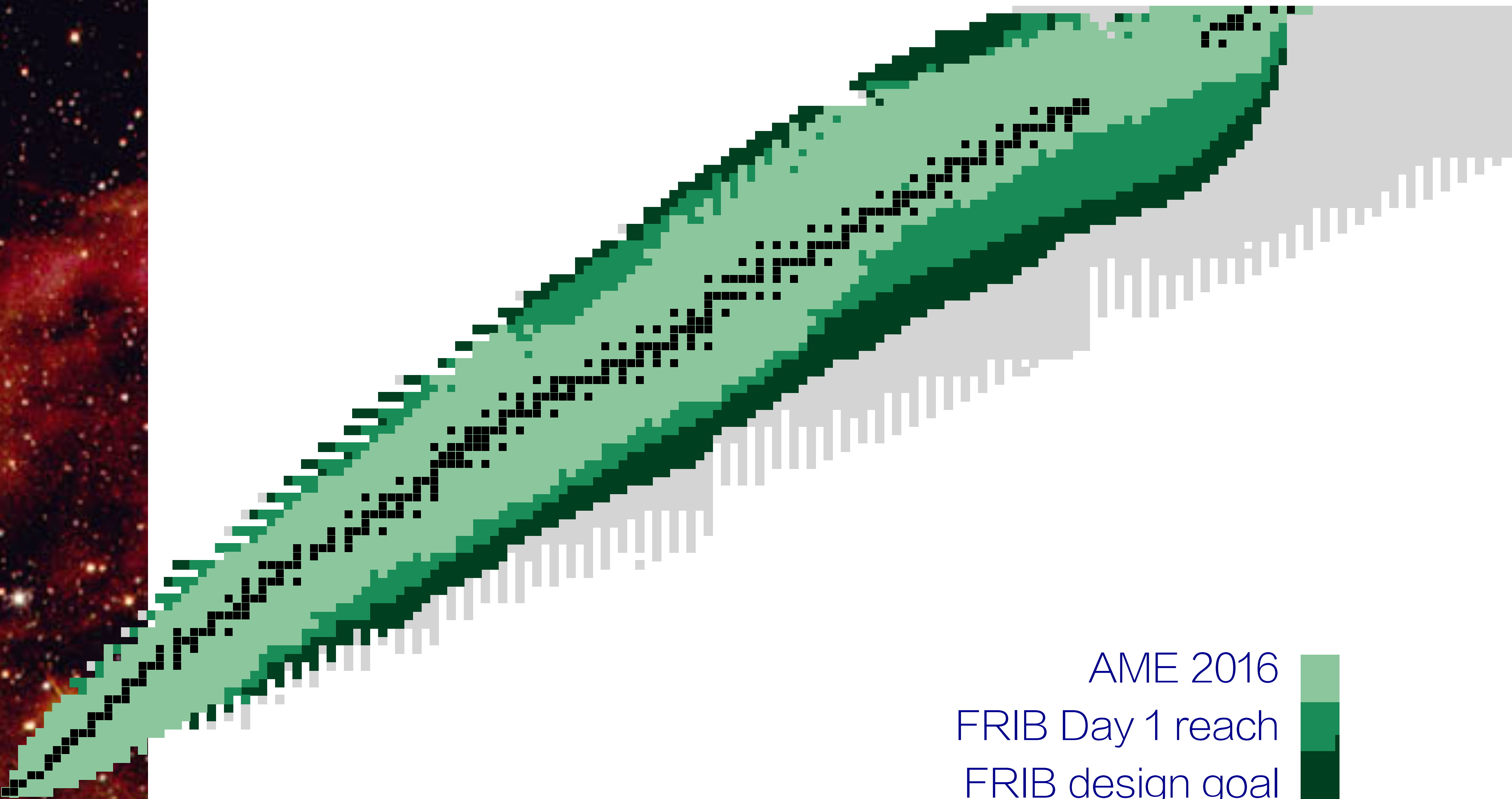
Surman, Mumpower, McLaughlin 2016

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

SKM*
SKP-3
SLY4
SV-MIN
UNEDF0
UNEDF1

see also Martin+2016

experimental prospects at FRIB: masses



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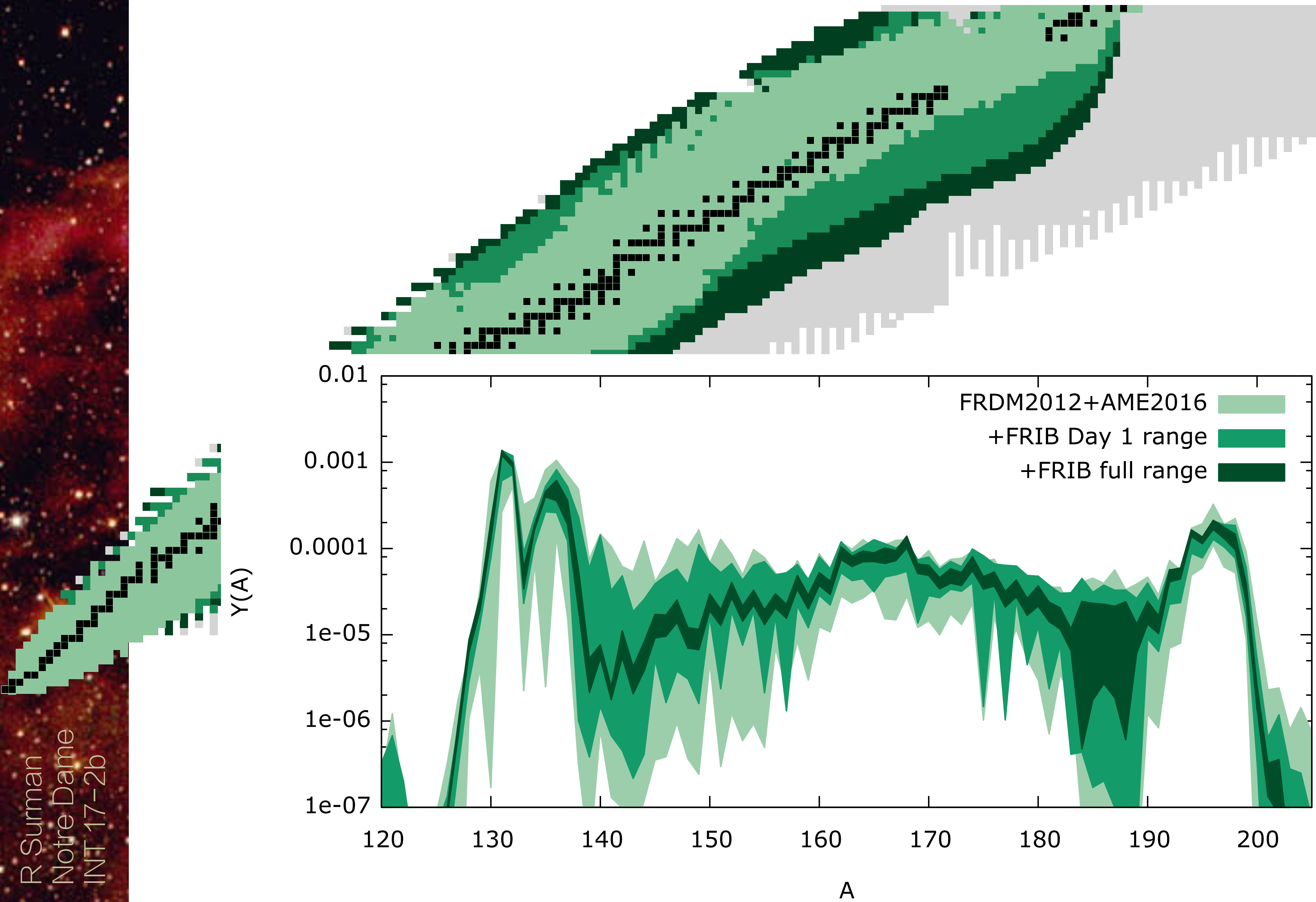
experimental prospects at FRIB: masses



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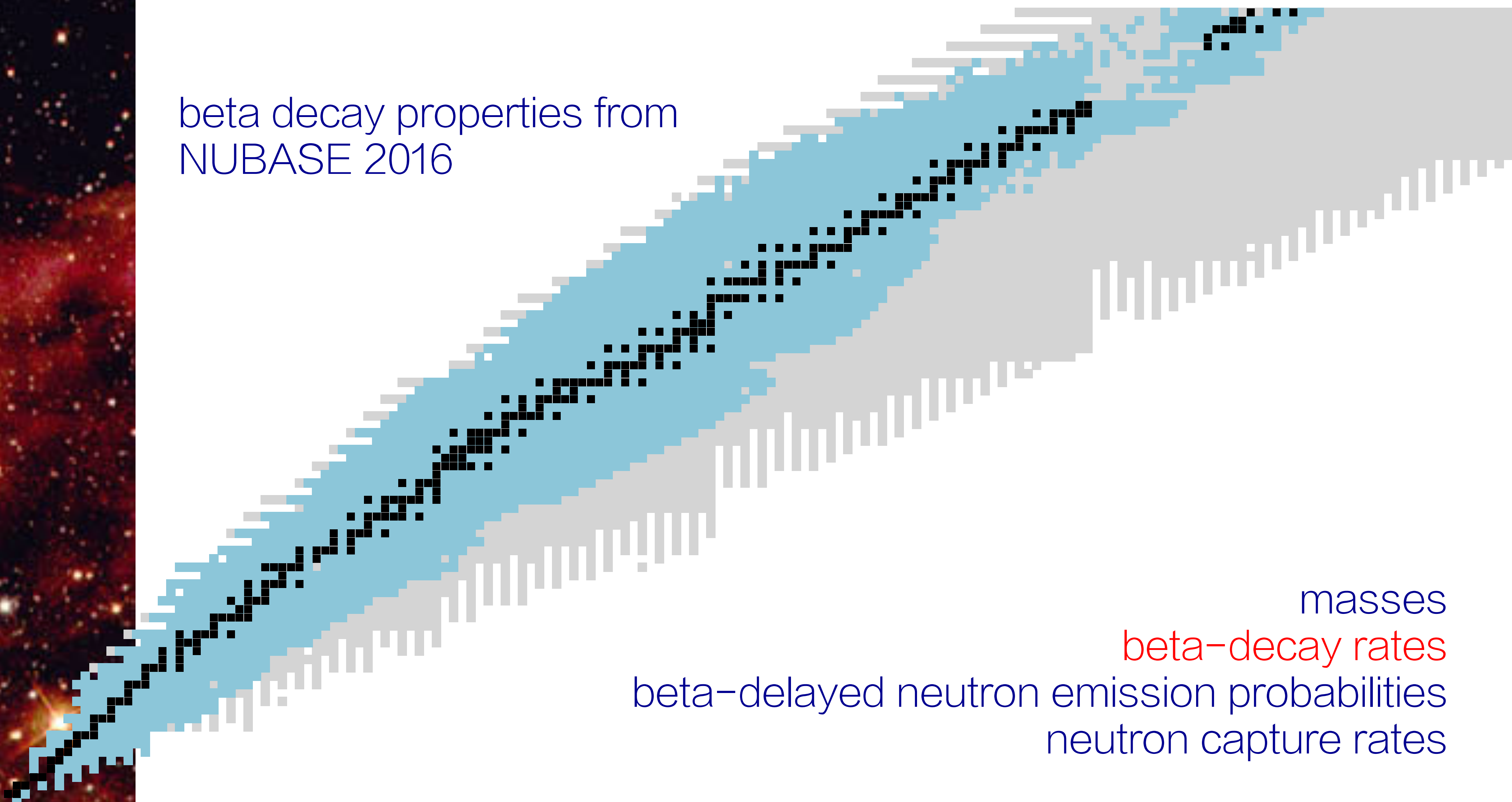
required nuclear data: beta decay

beta decay properties from
NUBASE 2016



masses
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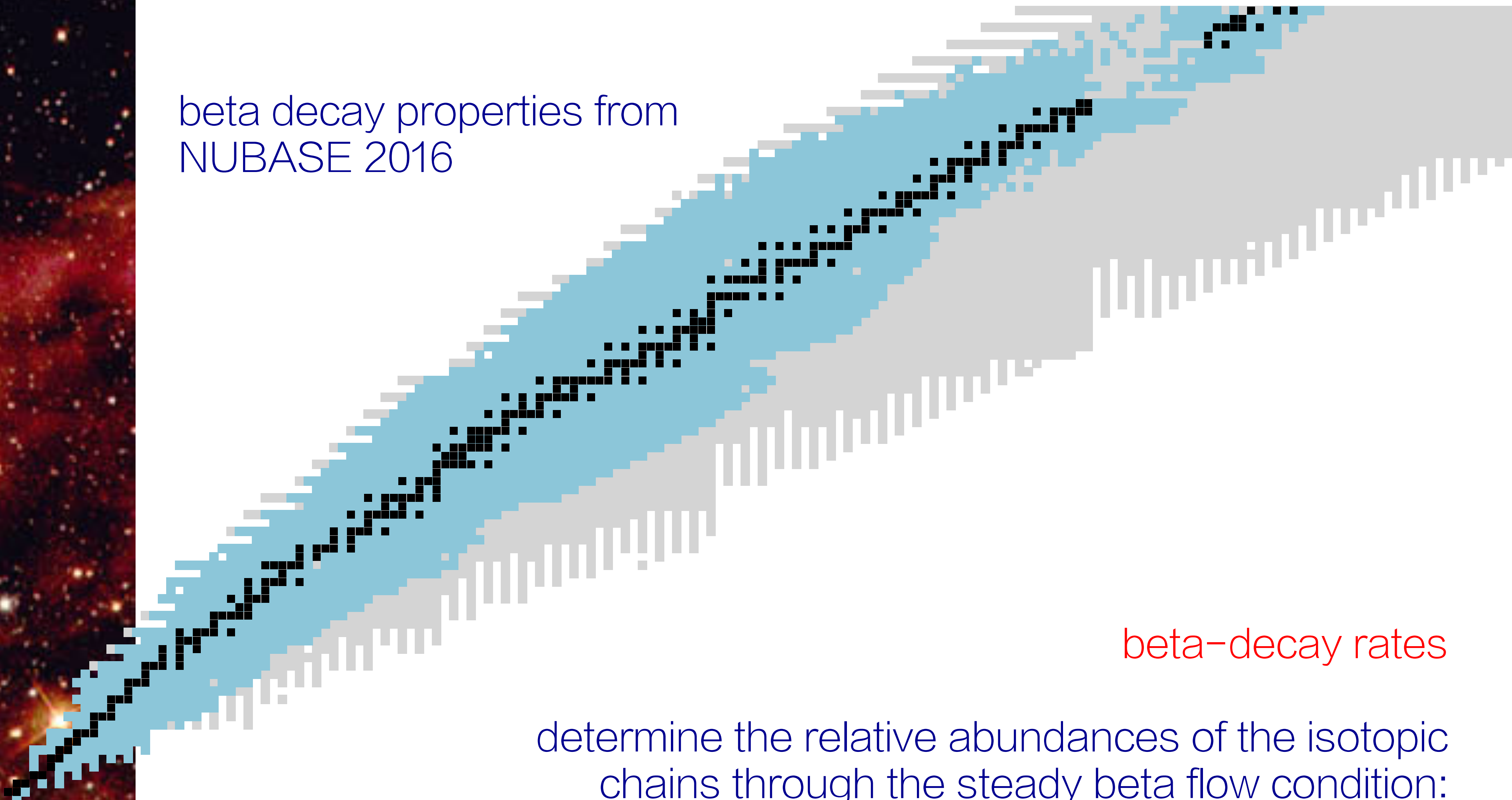

beta−decay rates

determine the relative abundances of the isotopic chains through the steady beta flow condition:

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

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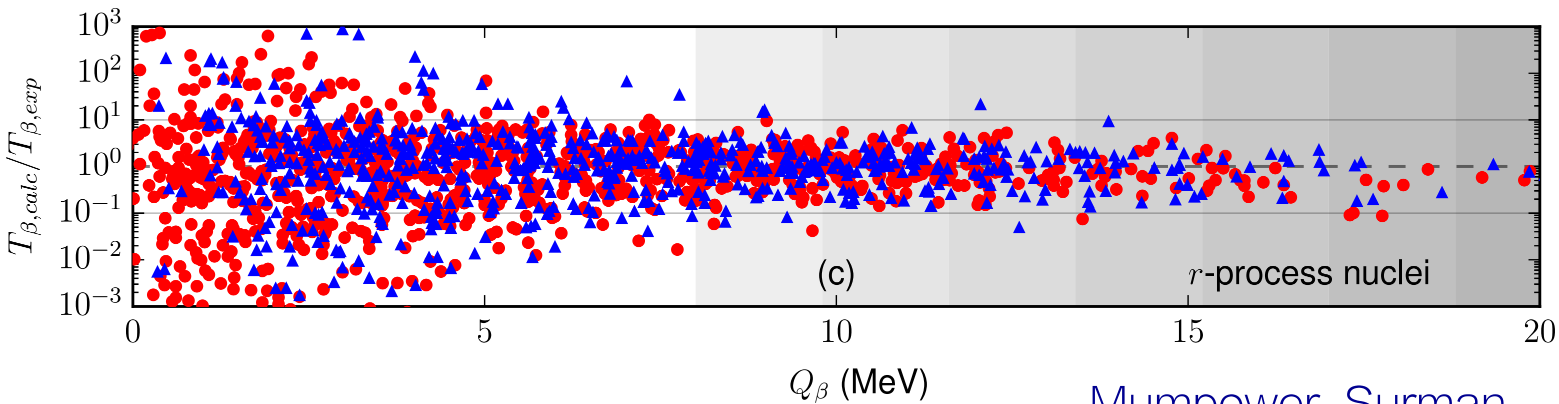
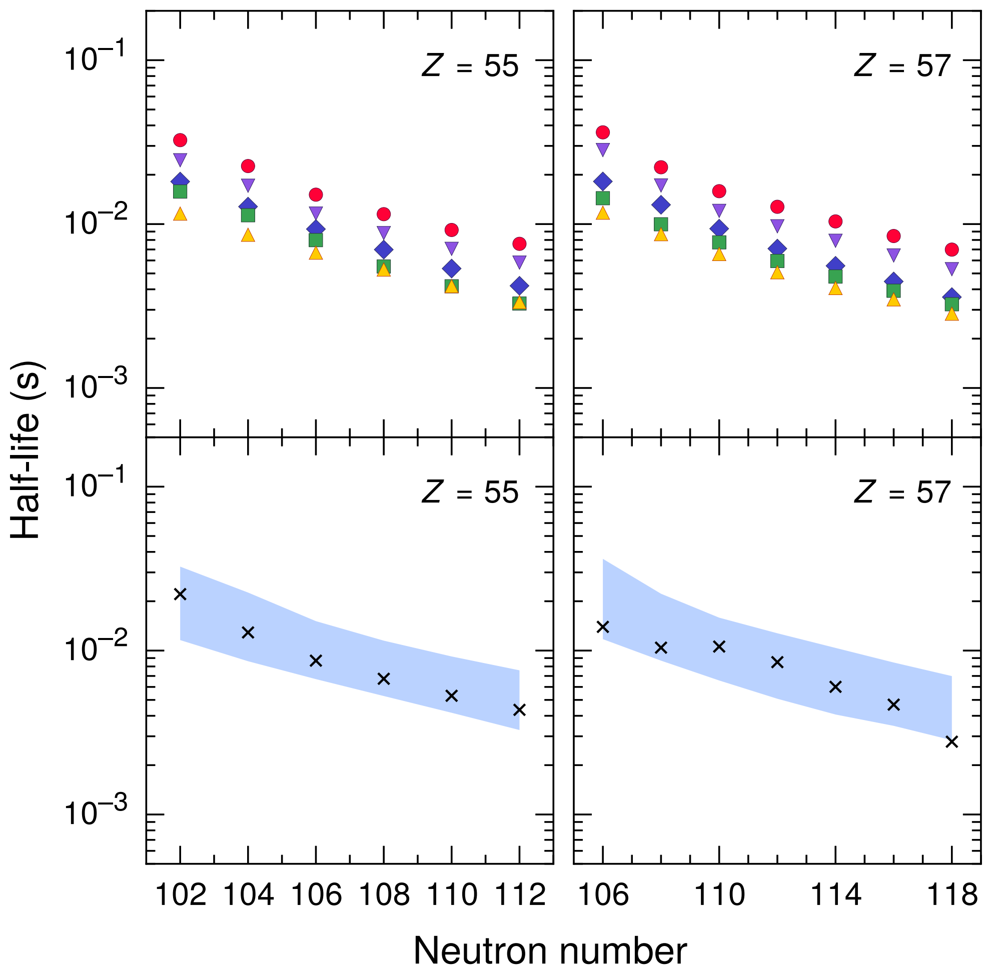
r–process uncertainties: beta decay rates

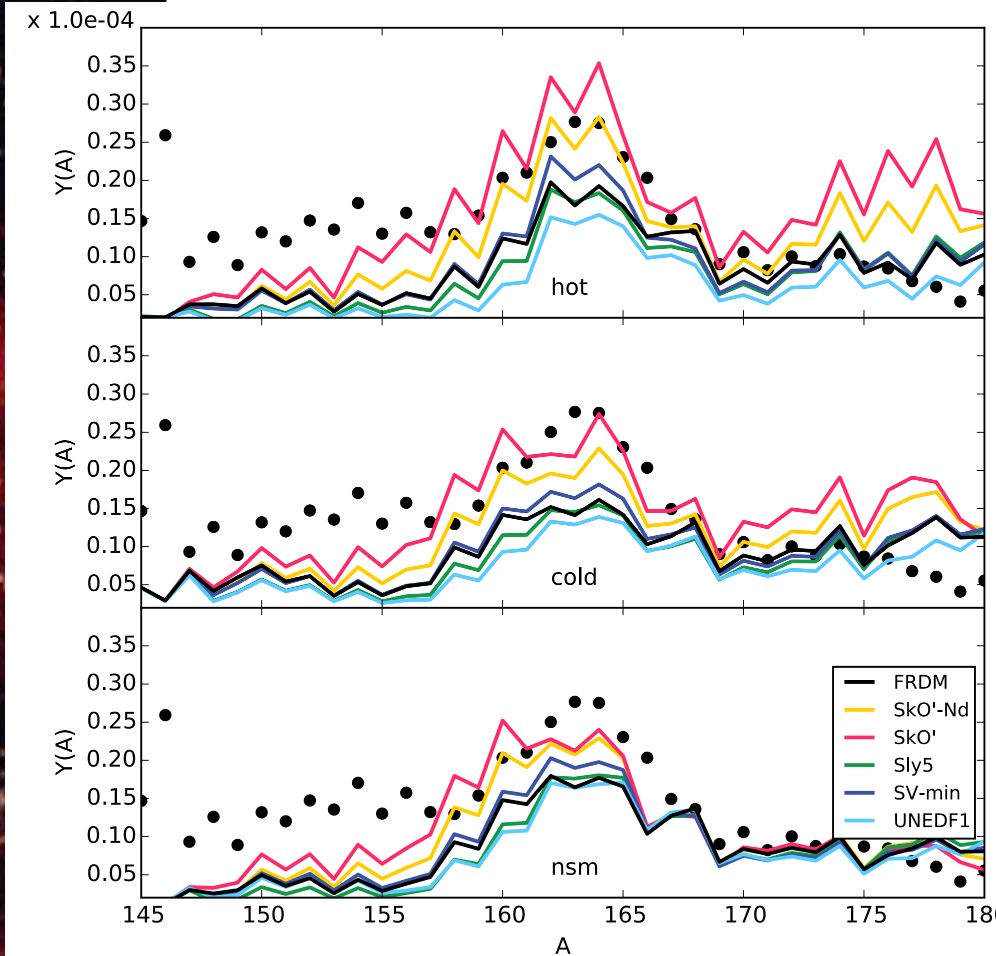


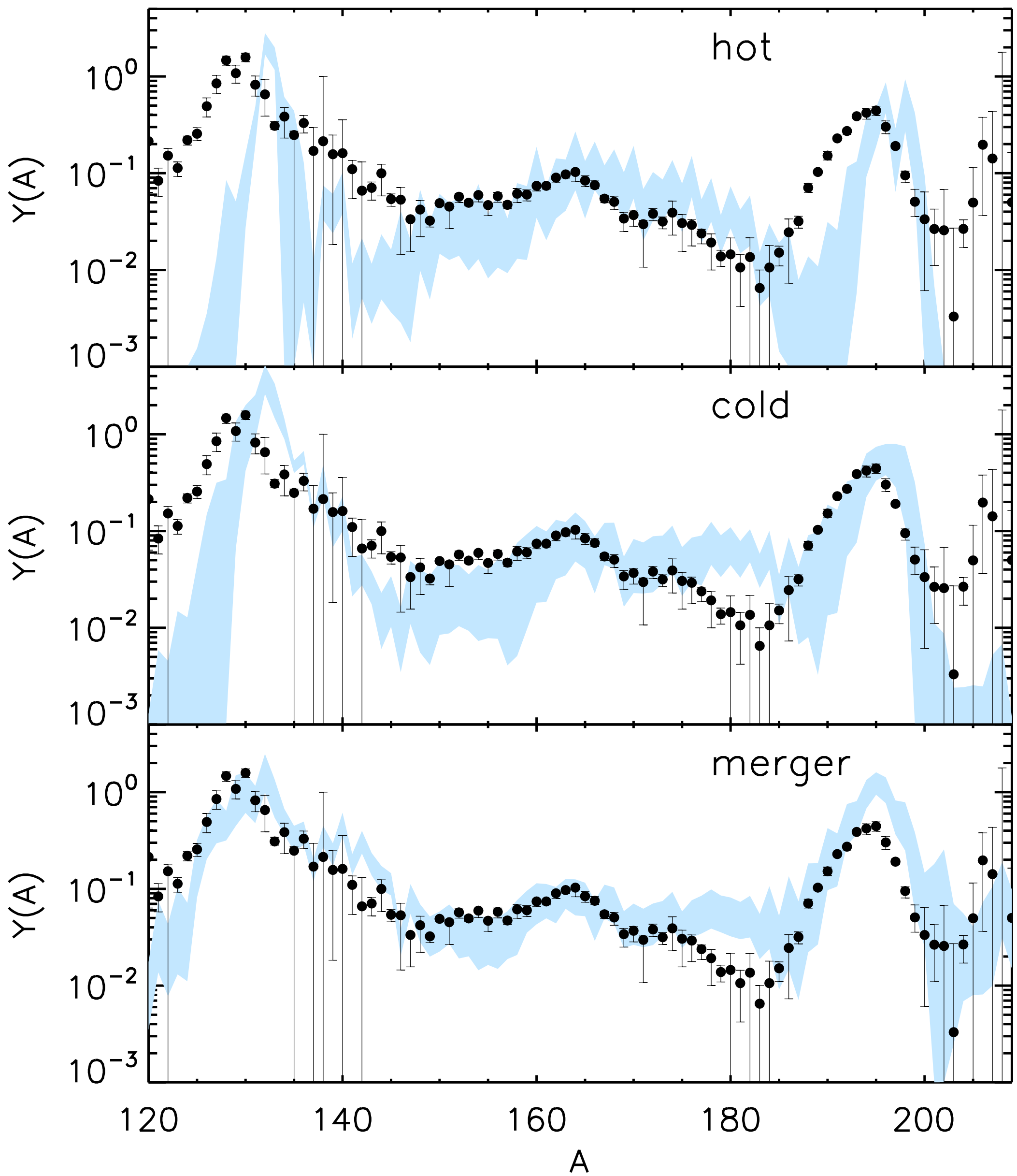
Mumpower, Surman, McLaughlin, Aprahamian 2016



Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016

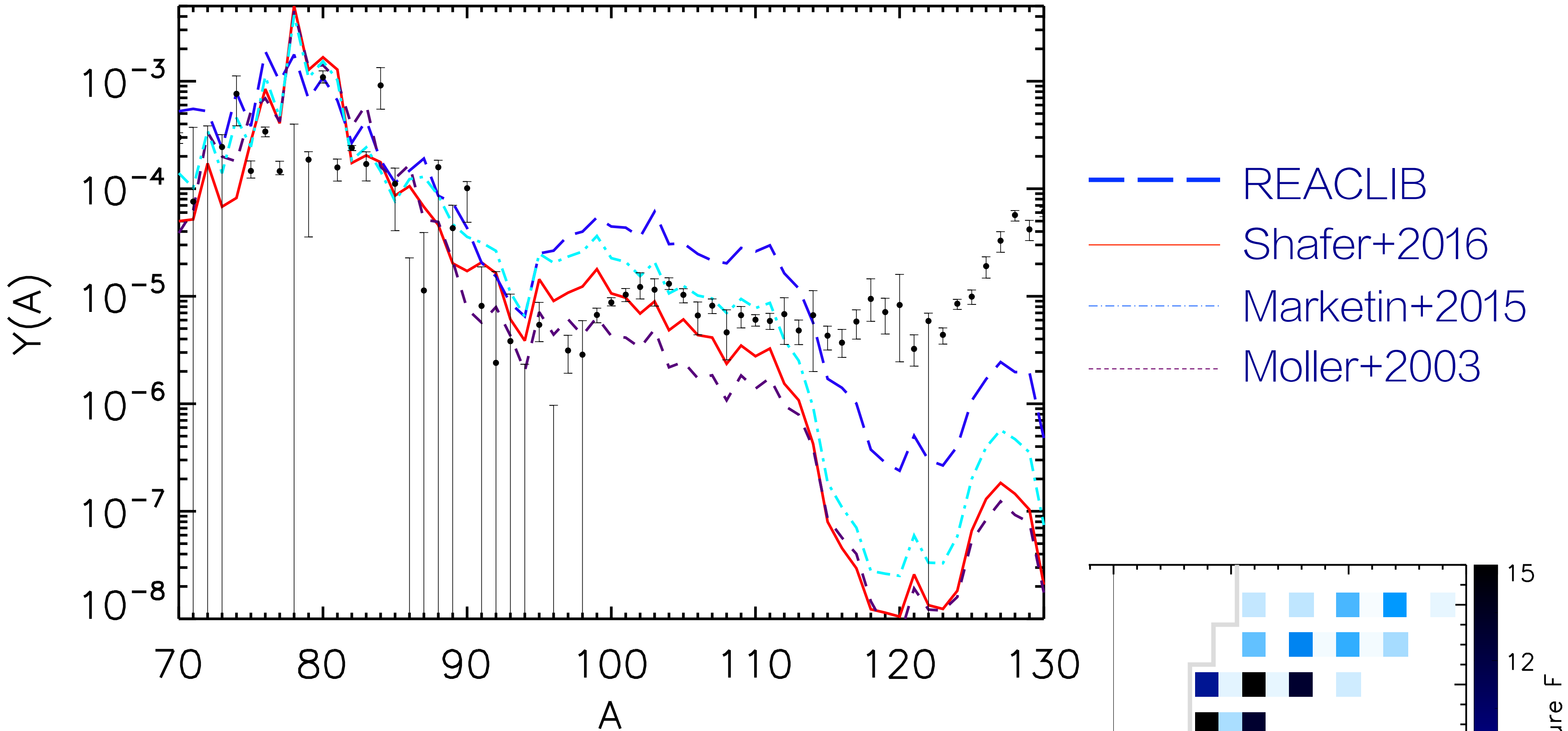
r−process uncertainties: beta decay rates



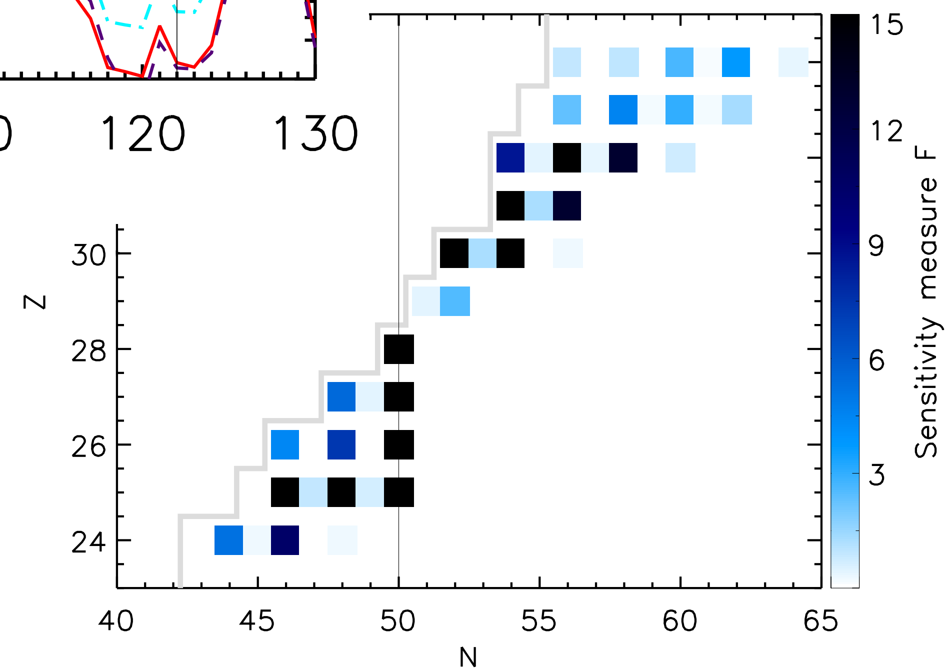


Shafer, Engel, Fröhlich,
McLaughlin, Mumpower,
Surman 2016

r–process uncertainties: beta decay rates



Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016



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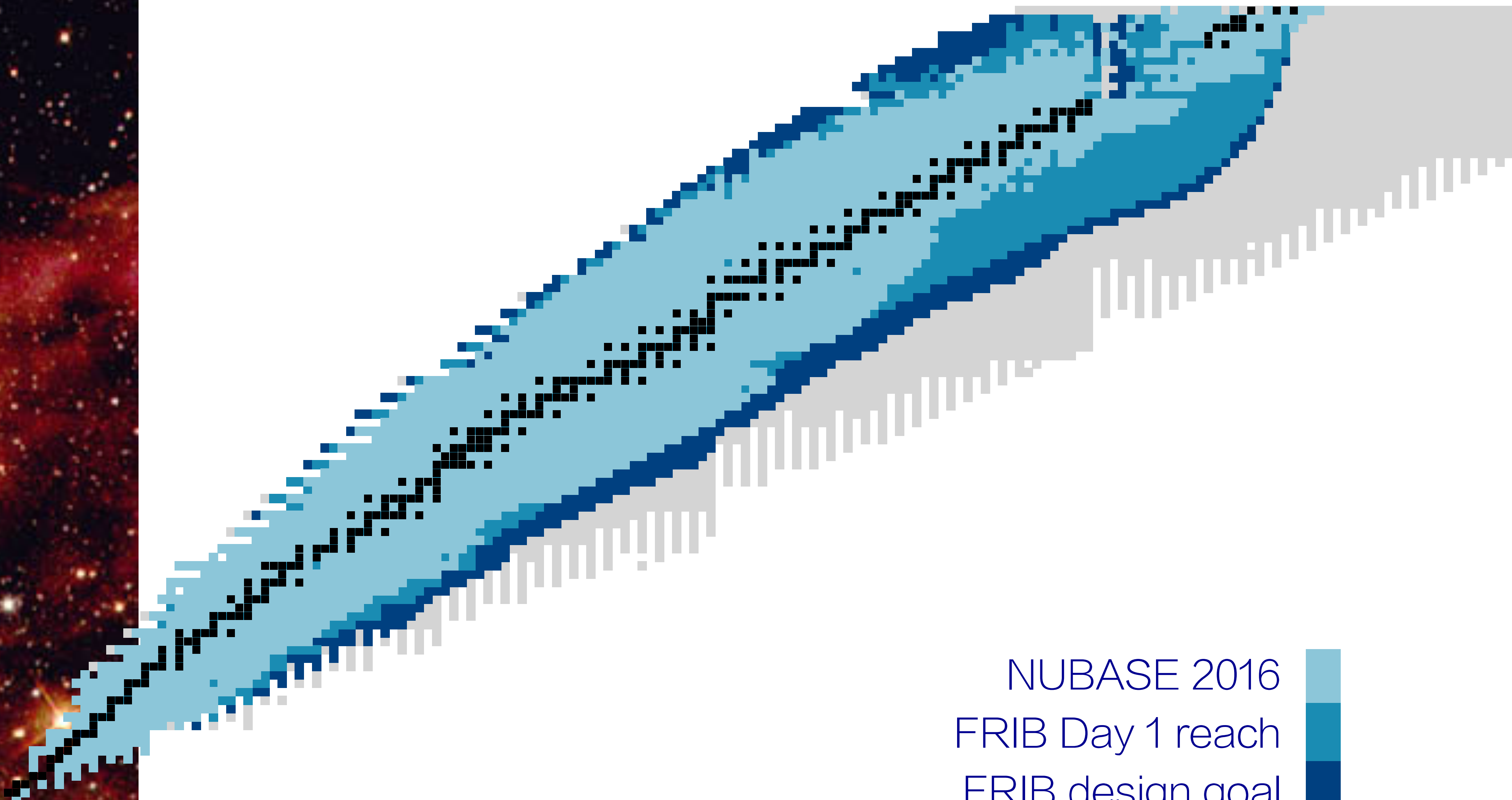
experimental prospects at FRIB: beta decay



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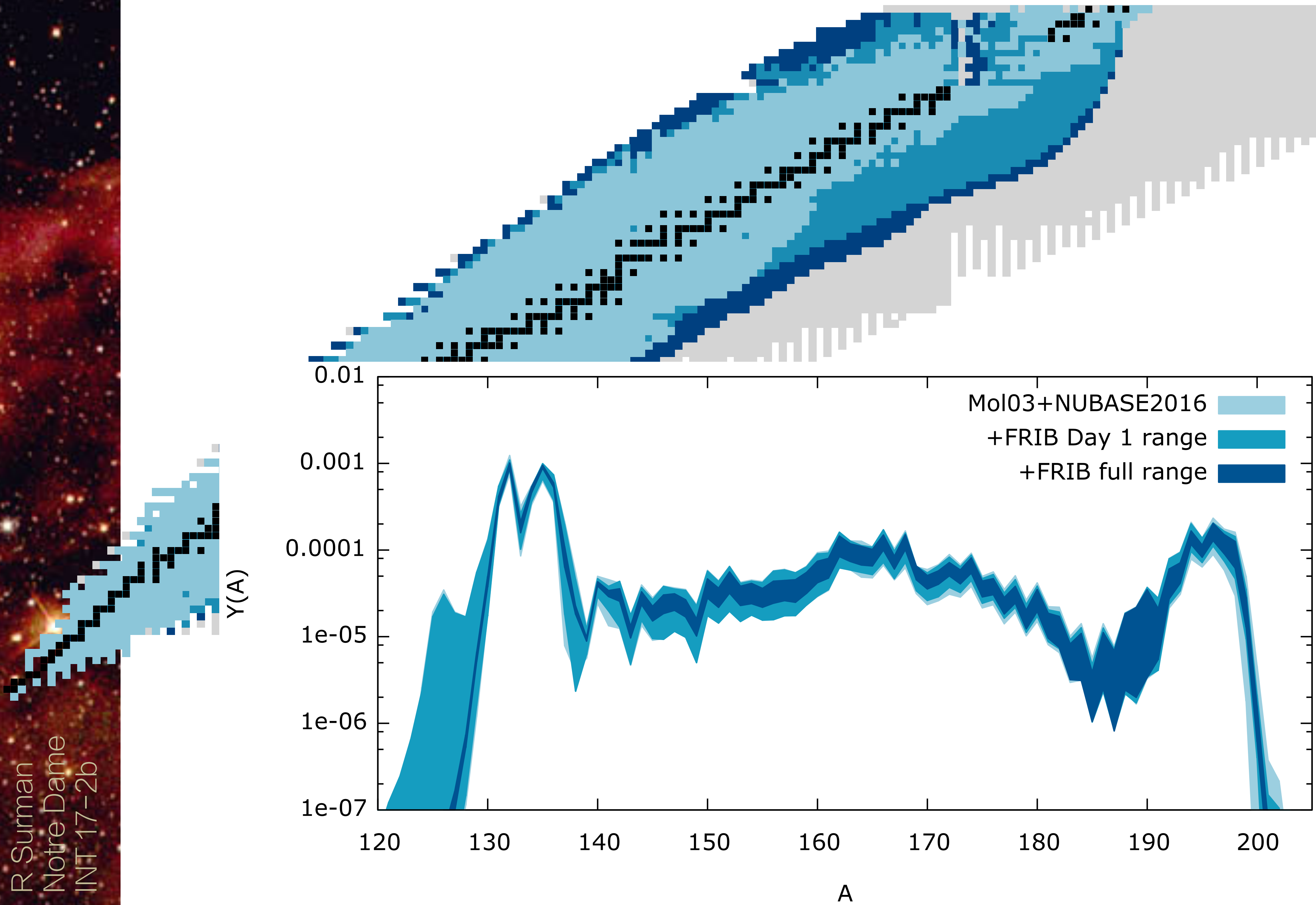
experimental prospects at FRIB: beta decay



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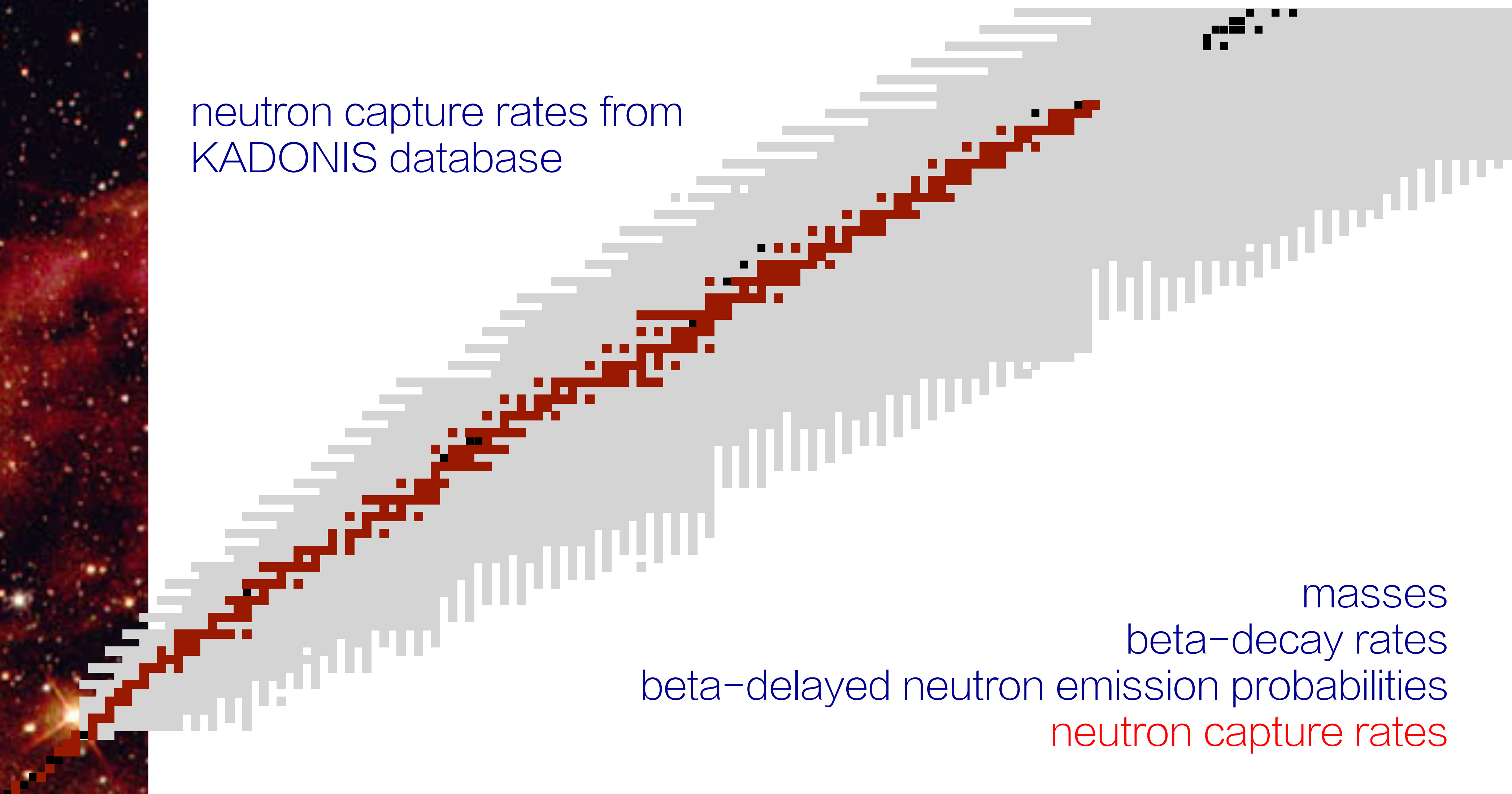
required nuclear data: neutron capture rates

neutron capture rates from
KADONIS database



masses
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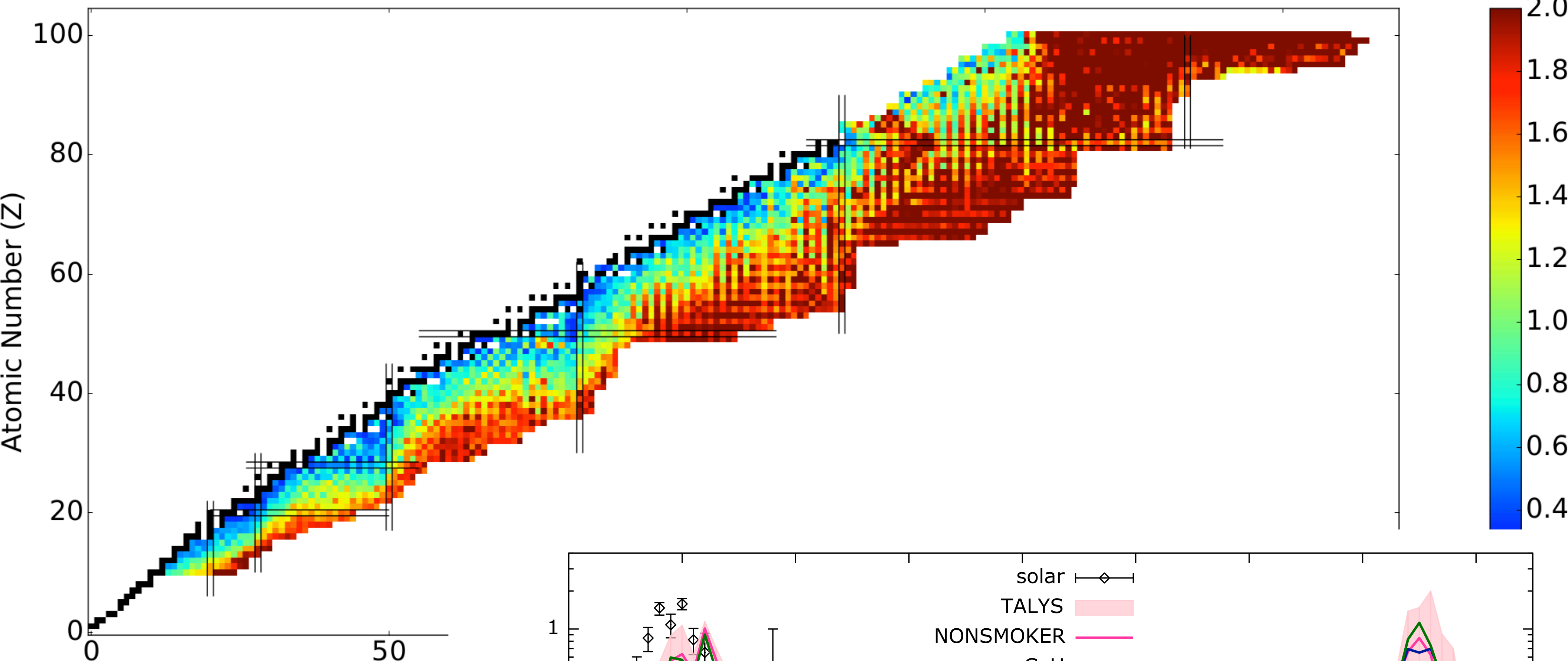
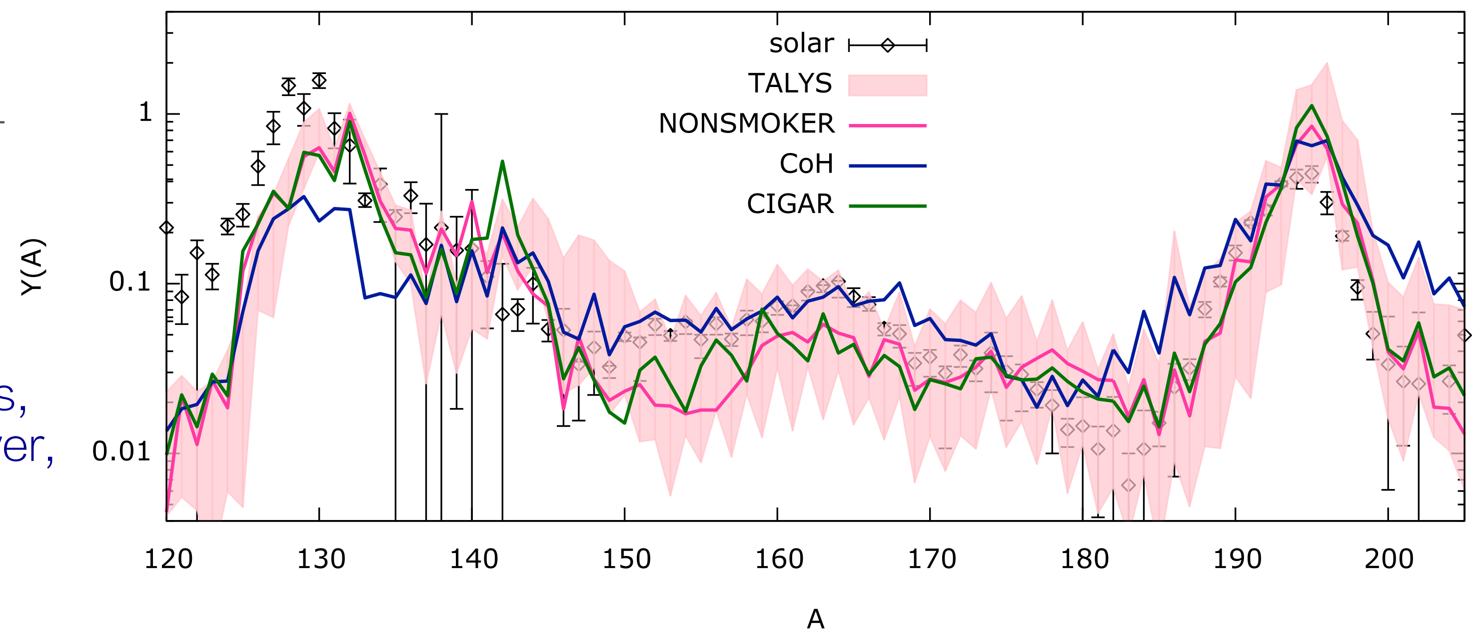
fission product distributions
neutrino interactions

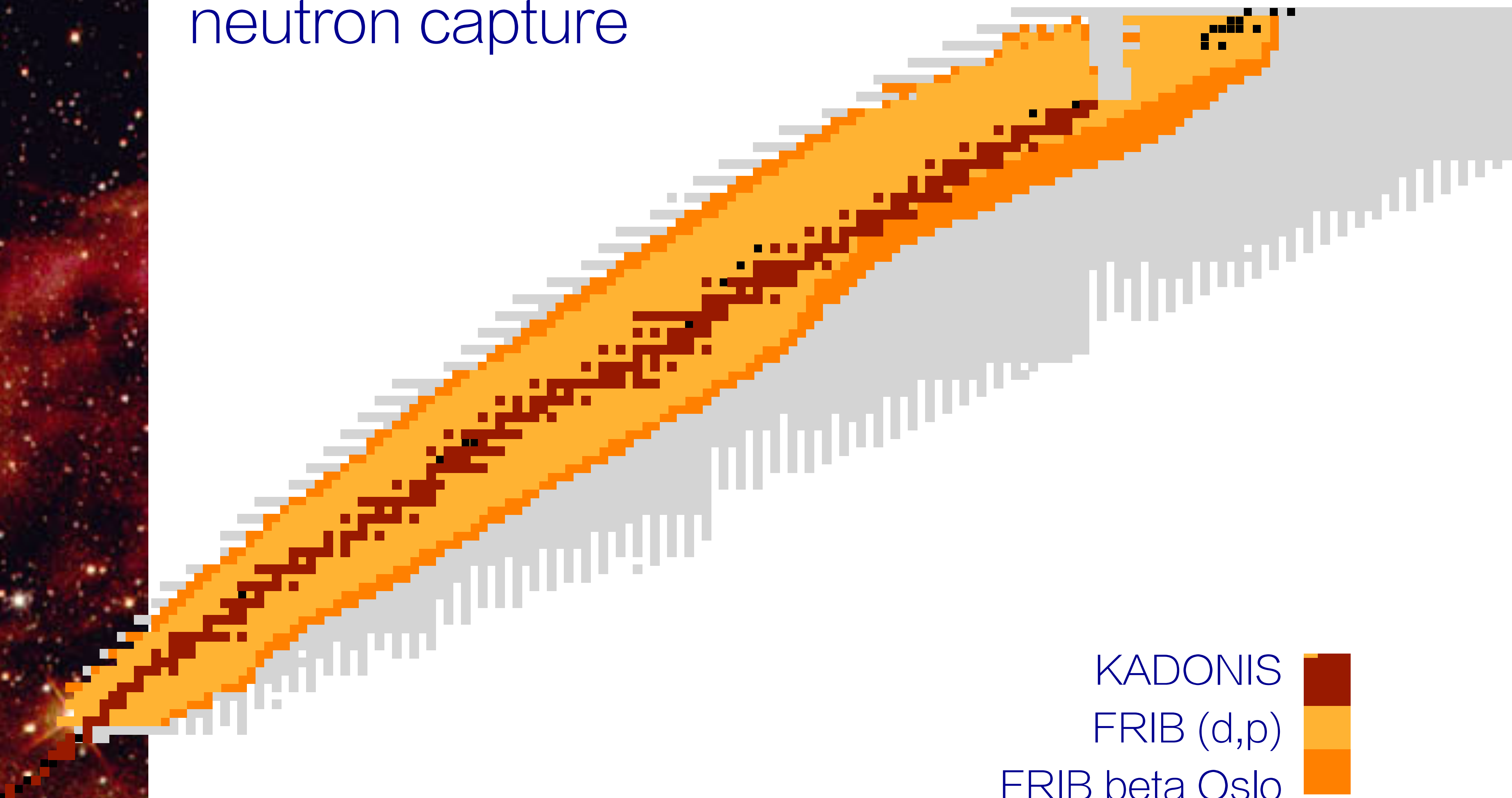
r−process uncertainties: neutron capture rates





Nikas, Perdikakis, Beard, Mumpower, Surman, in preparation

experimental prospects at FRIB: neutron capture



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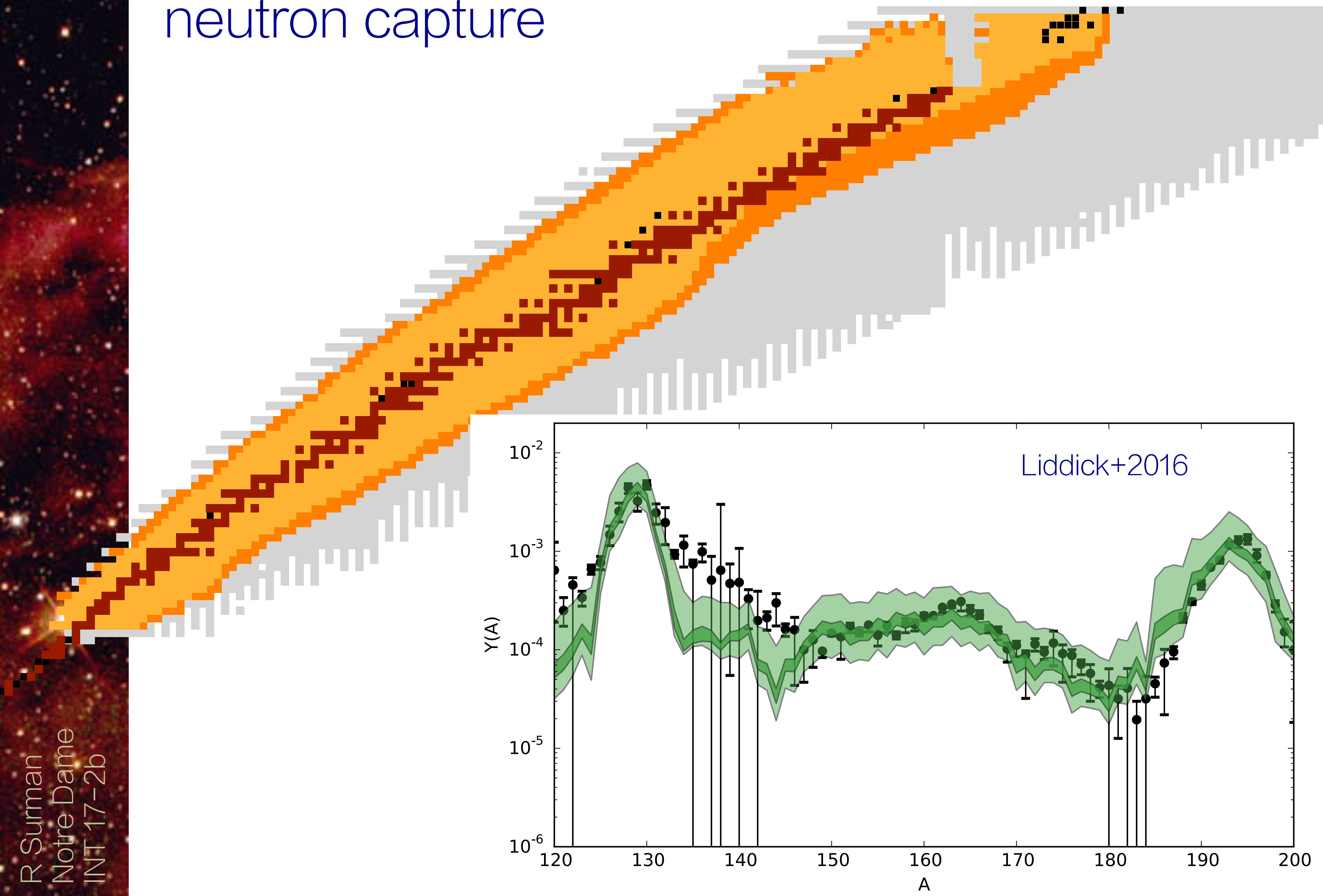
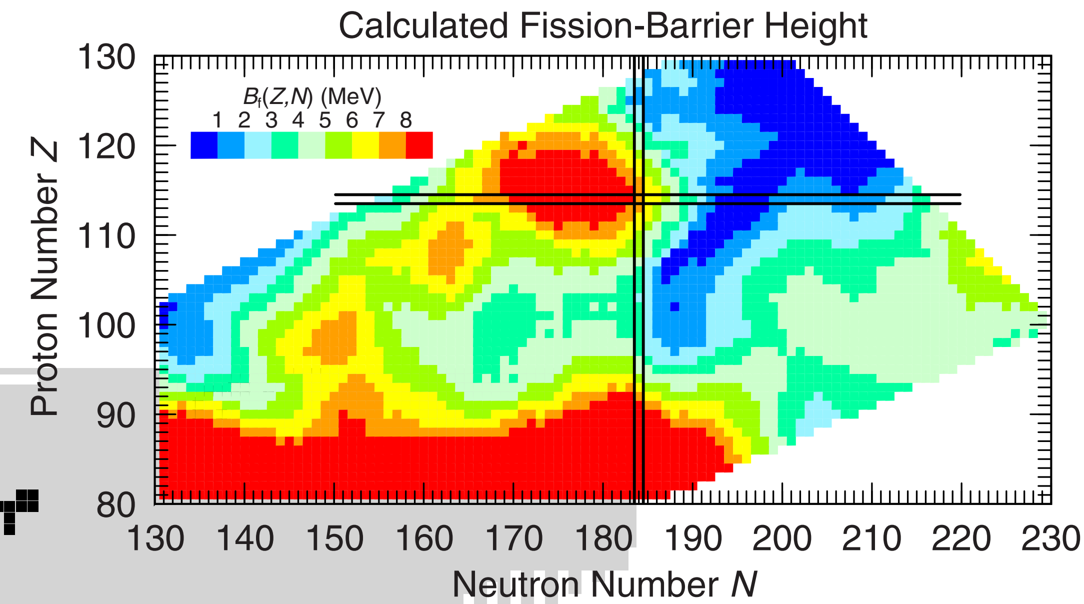
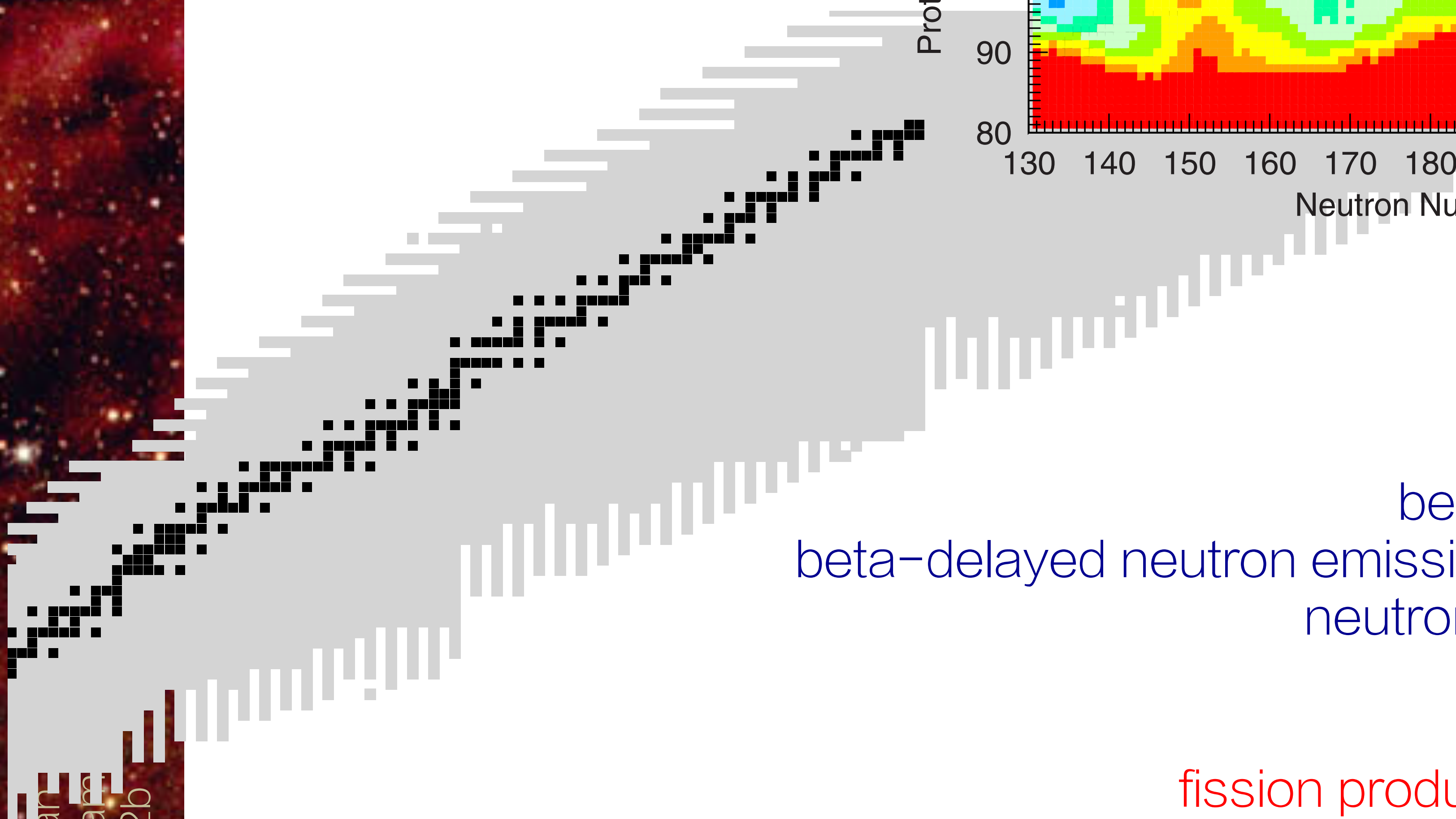
experimental prospects at FRIB: neutron capture



required nuclear data: fission properties



Moller+2015



masses
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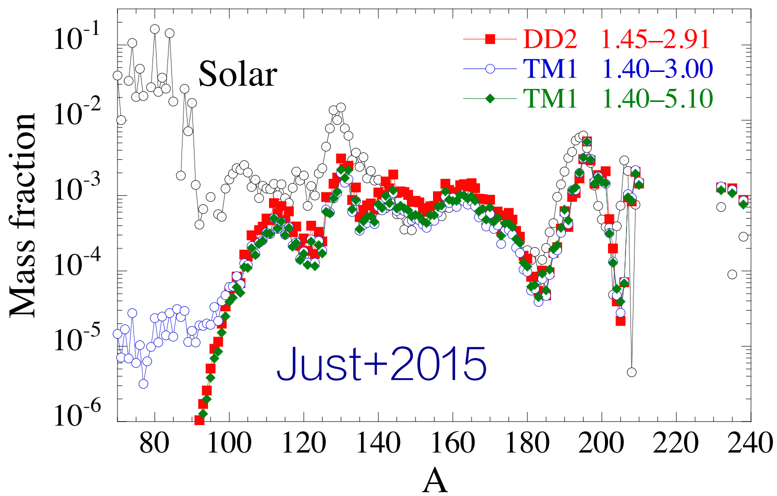
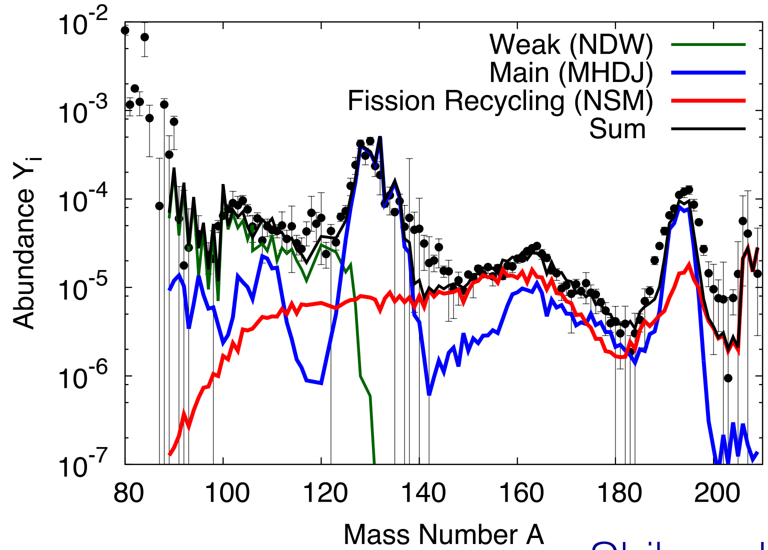
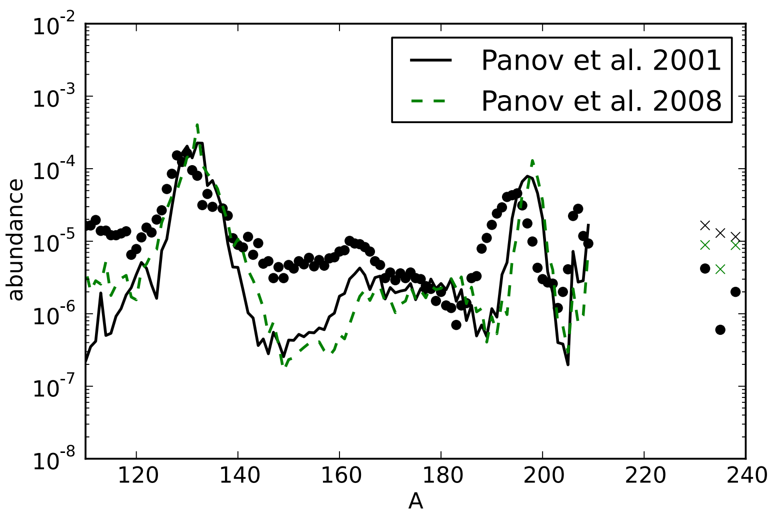
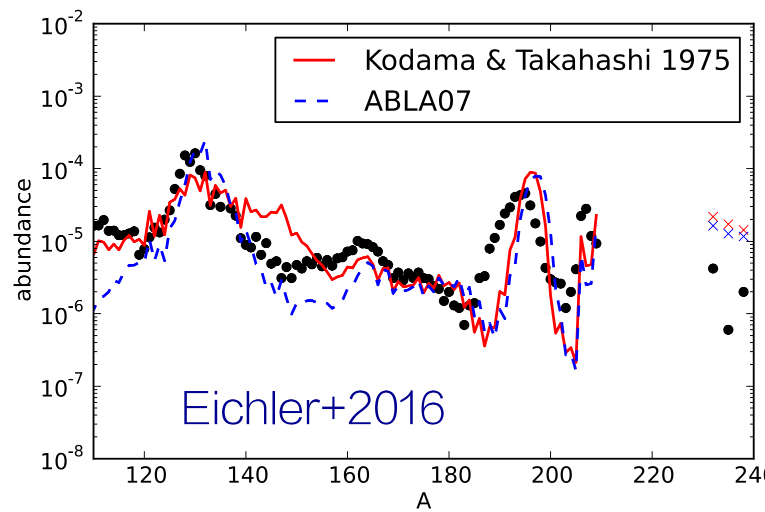
r−process uncertainties: fission





Shibagaki+2016





FIRE: Fission In R−process Elements
US DOE/NNSA Topical Collaboration

required input data: neutrinos

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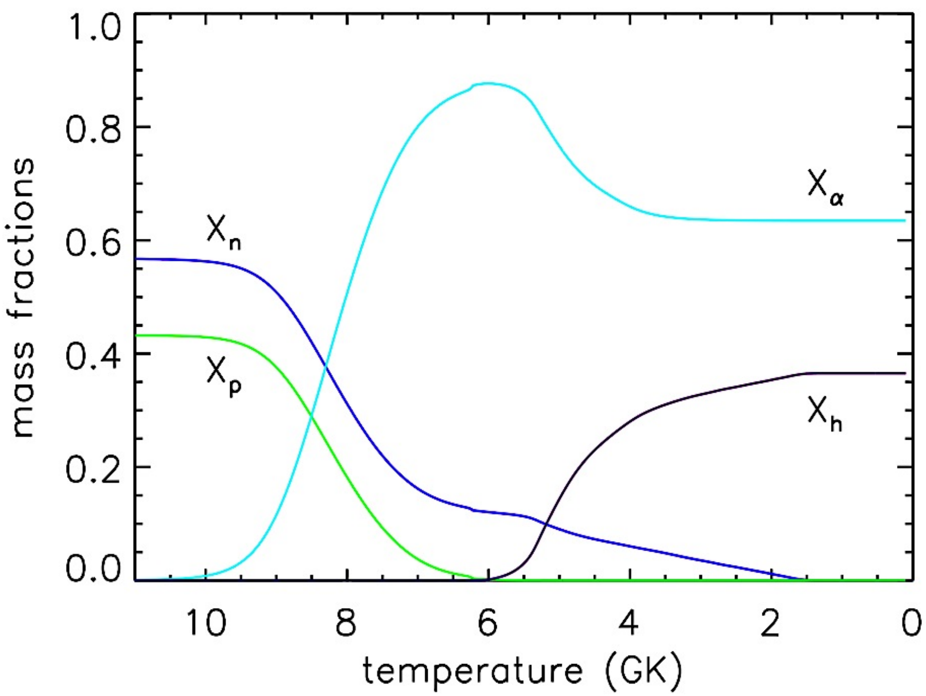
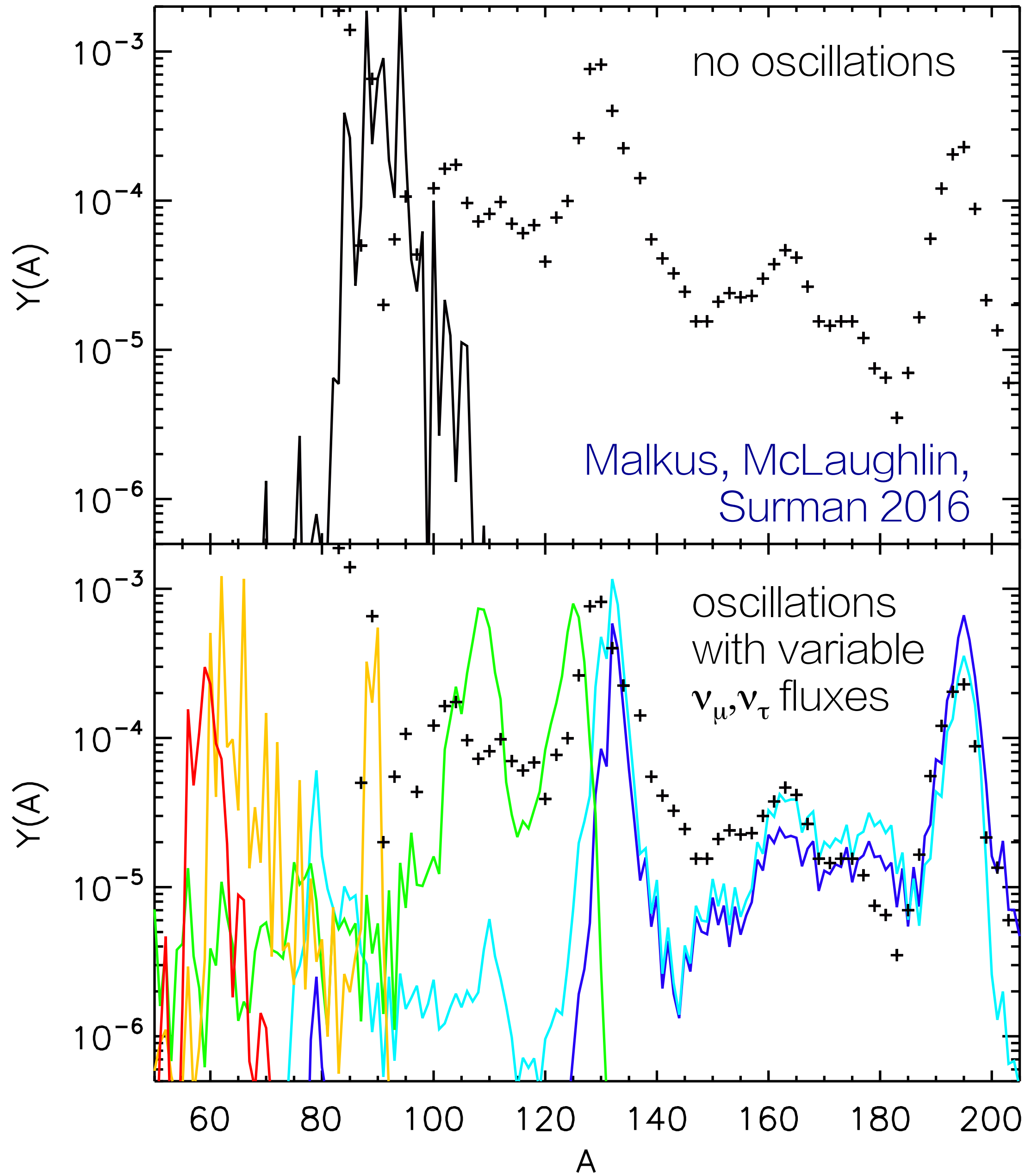
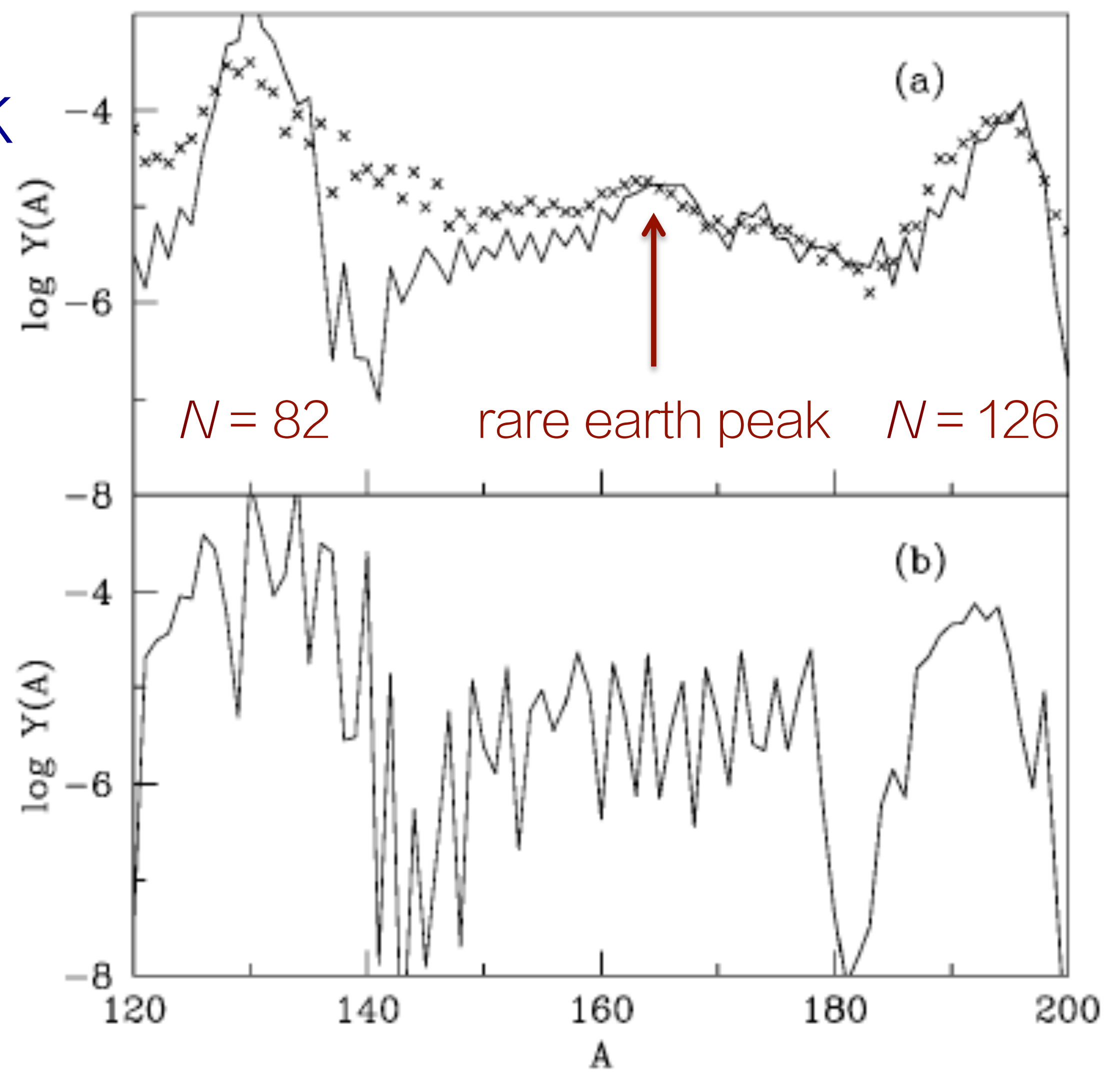
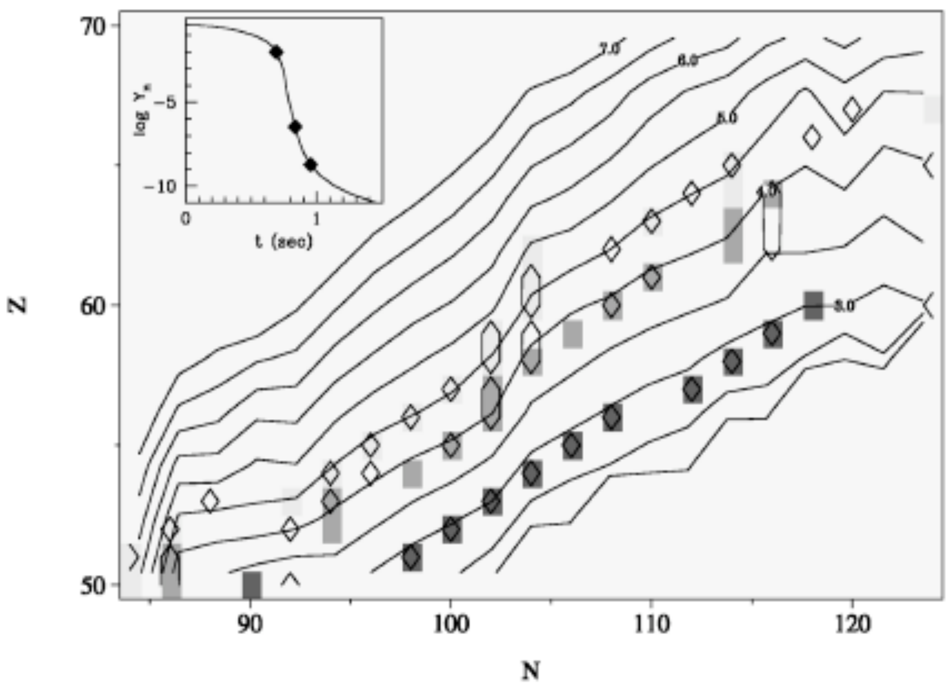




the rare earth peak

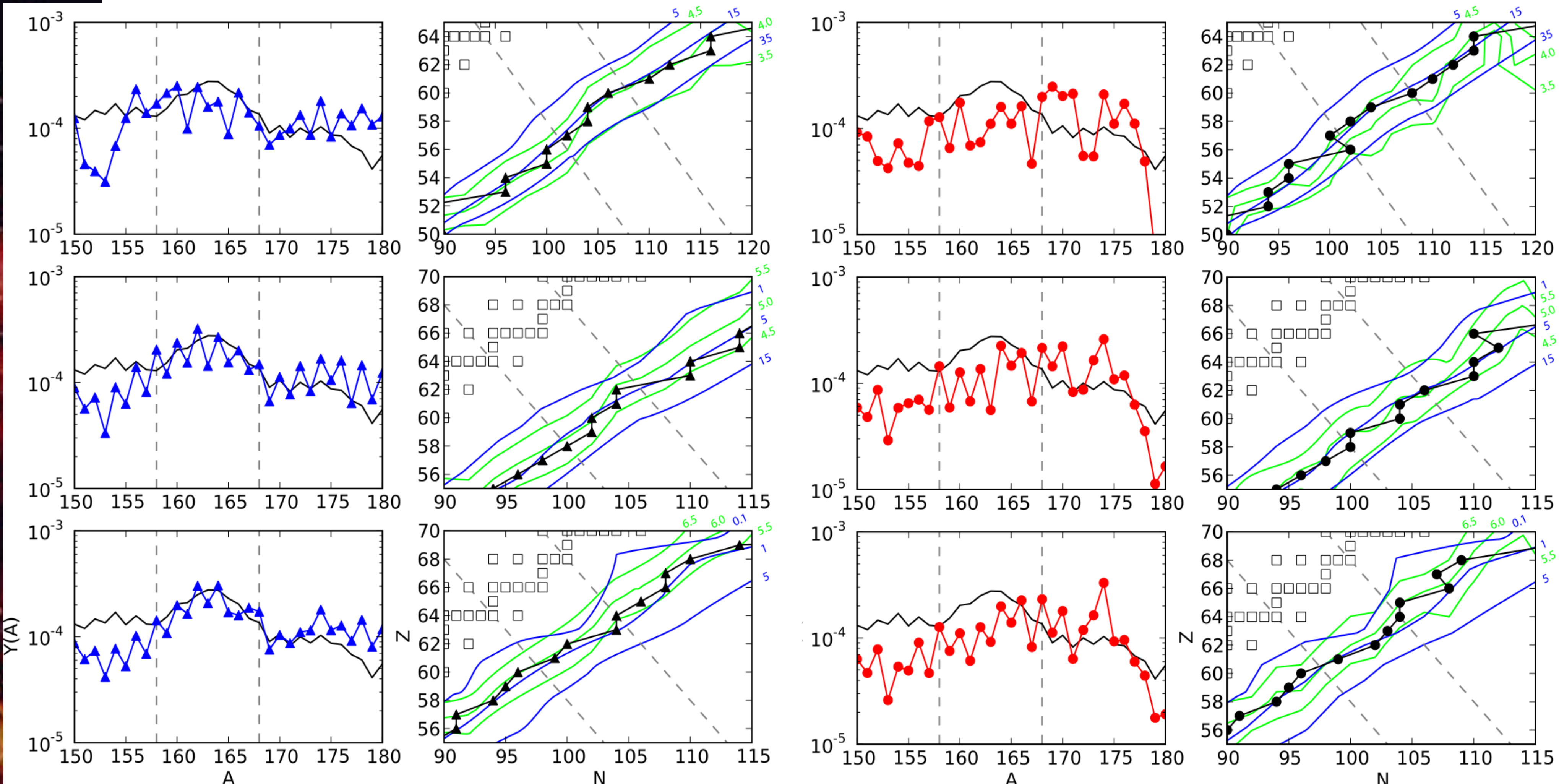
Its formation mechanism is sensitive to both the astrophysical conditions of the late phase of the *r*–process and the nuclear physics of the nuclei populated at this time





Surman, Engel, Bennett, Meyer 1997

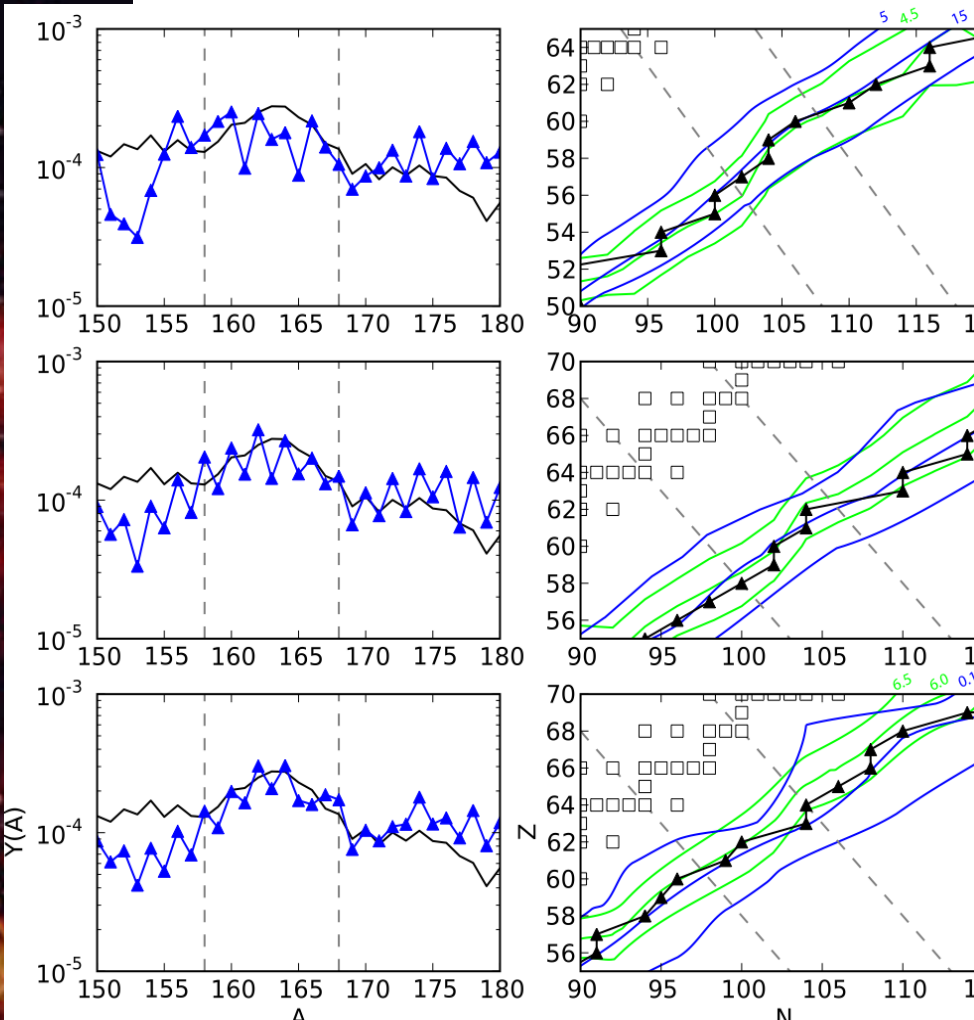
rare earth peak formation

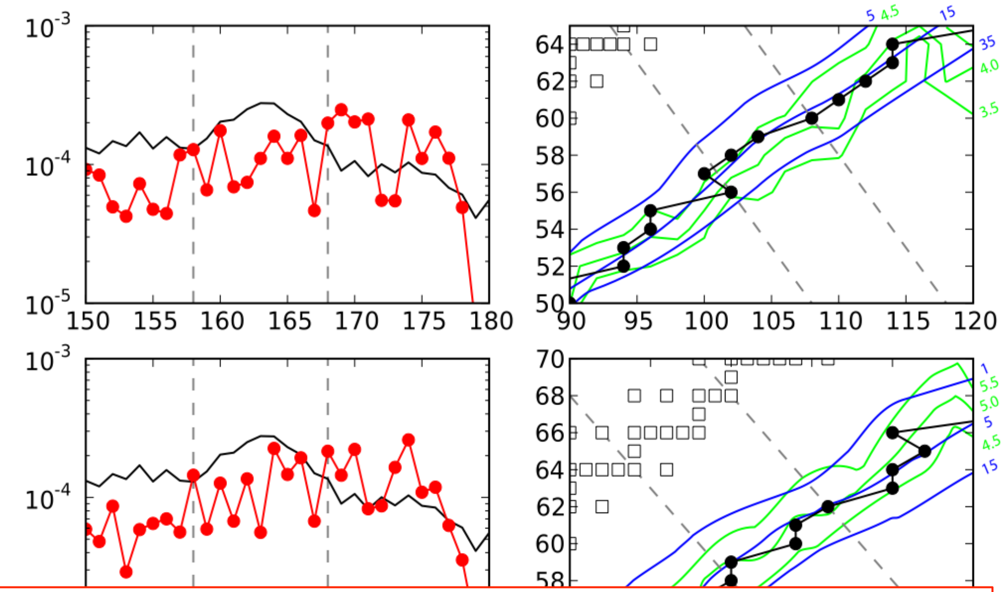


FRDM HFB-21

Mumpower, McLaughlin, Surman 2012

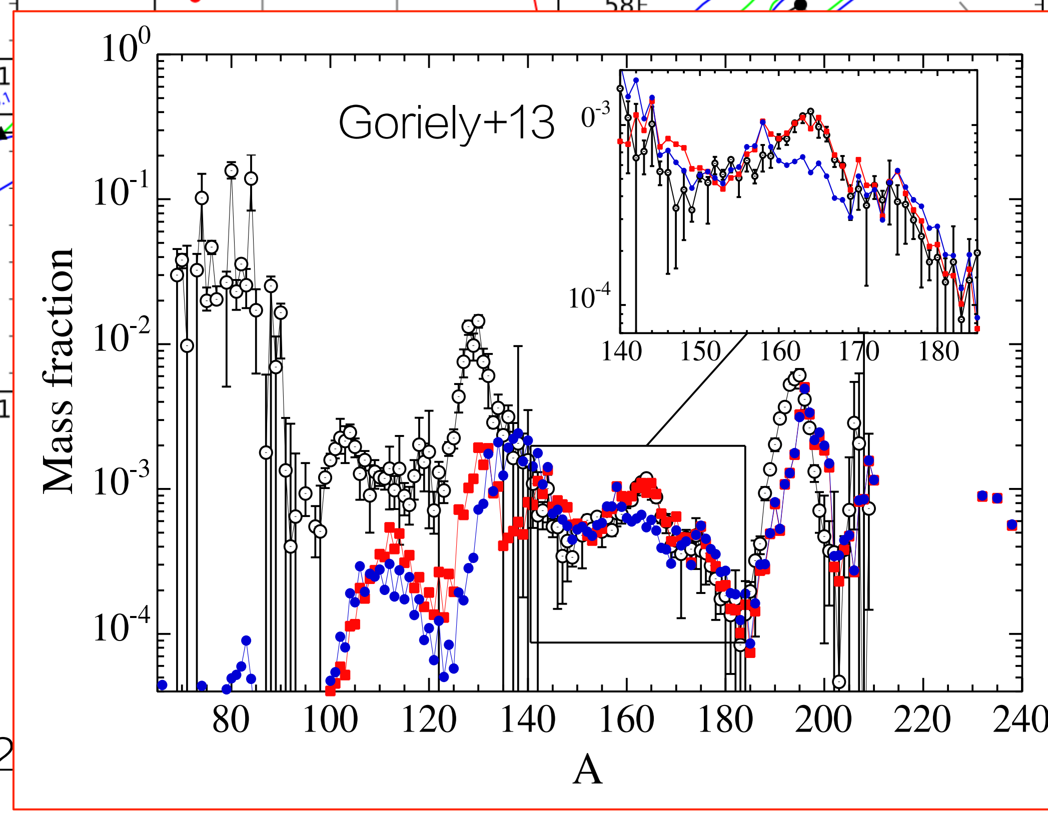
rare earth peak formation





FRDM

Mumpower, McLaughlin, Surman 2012



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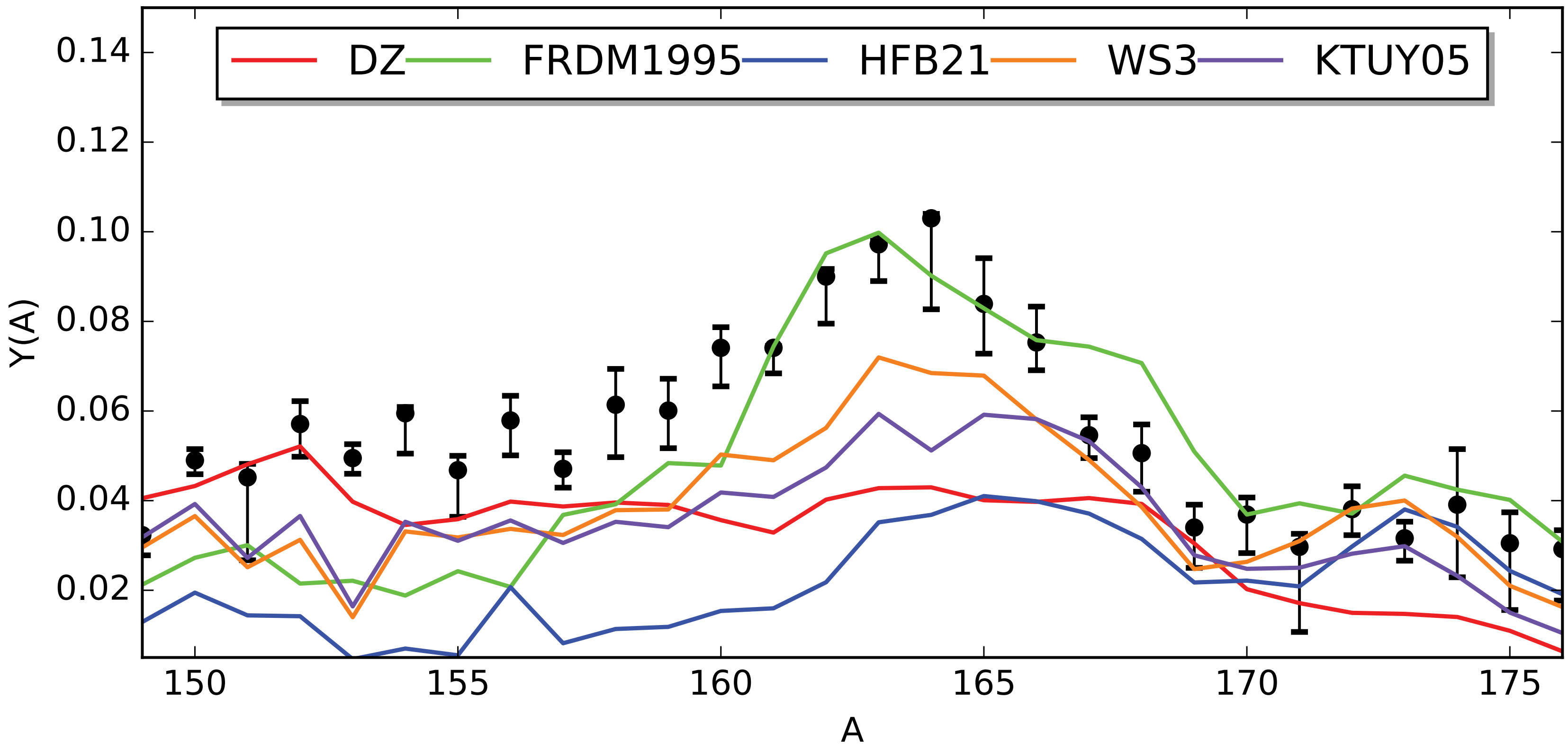
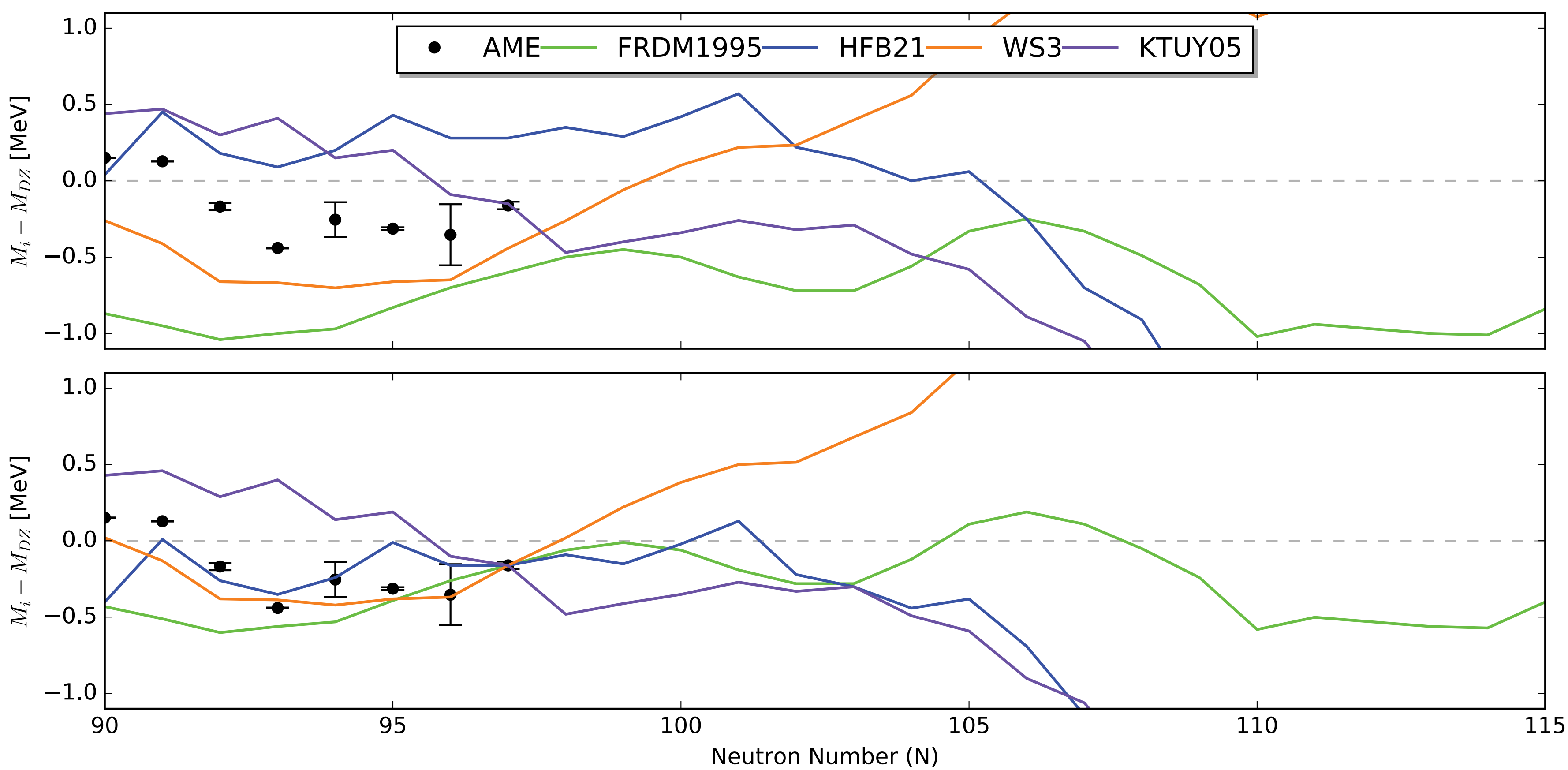
rare earth peak formation and nuclear masses



Mumpower, McLaughlin, Surman, Steiner JPhys G 2017

rare earth peak formation and nuclear masses



Neodymium ($Z = 60$) isotopic chain

Mumpower, McLaughlin, Surman, Steiner JPhys G 2017

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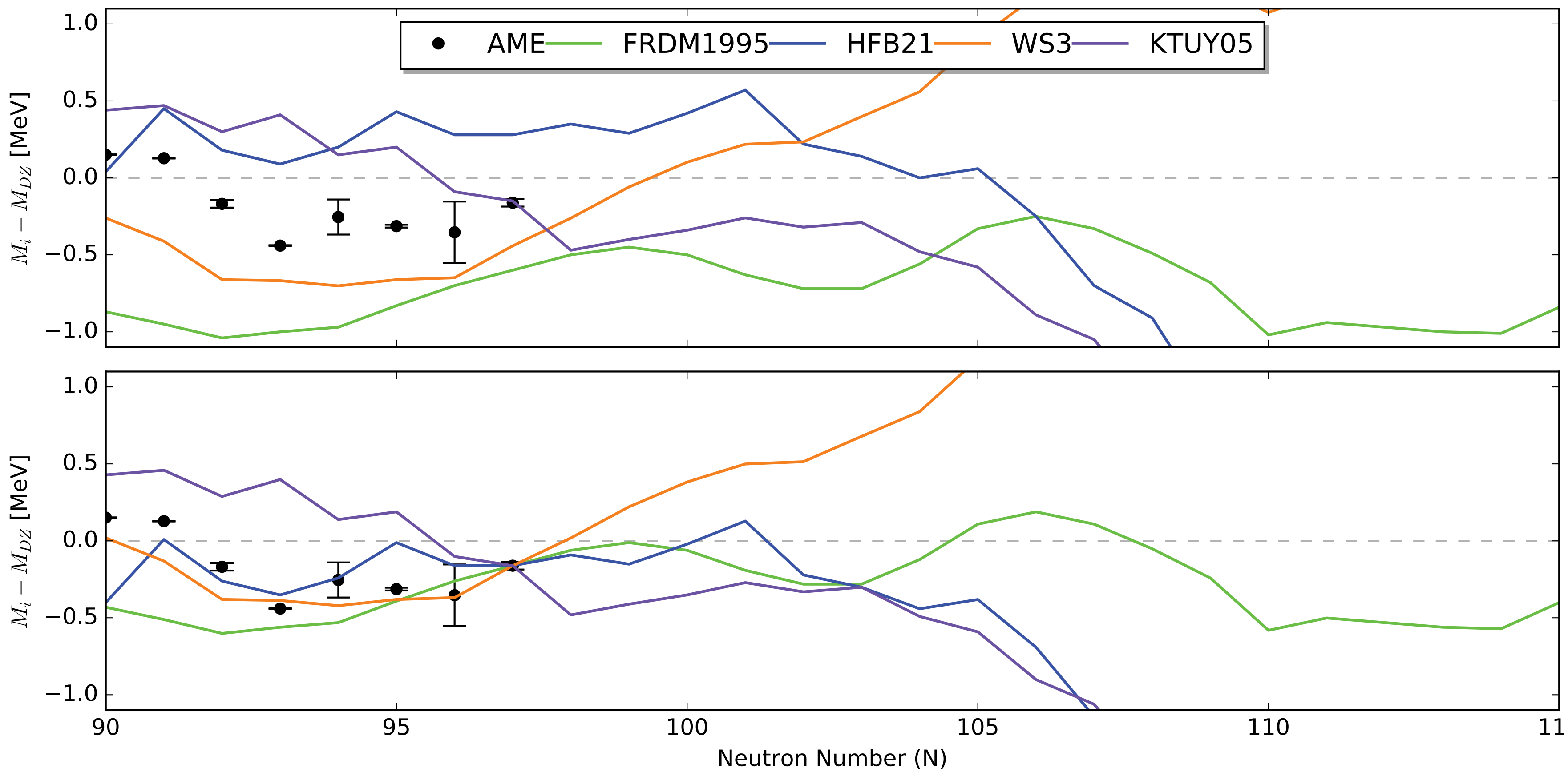
reverse-engineering rare earth masses

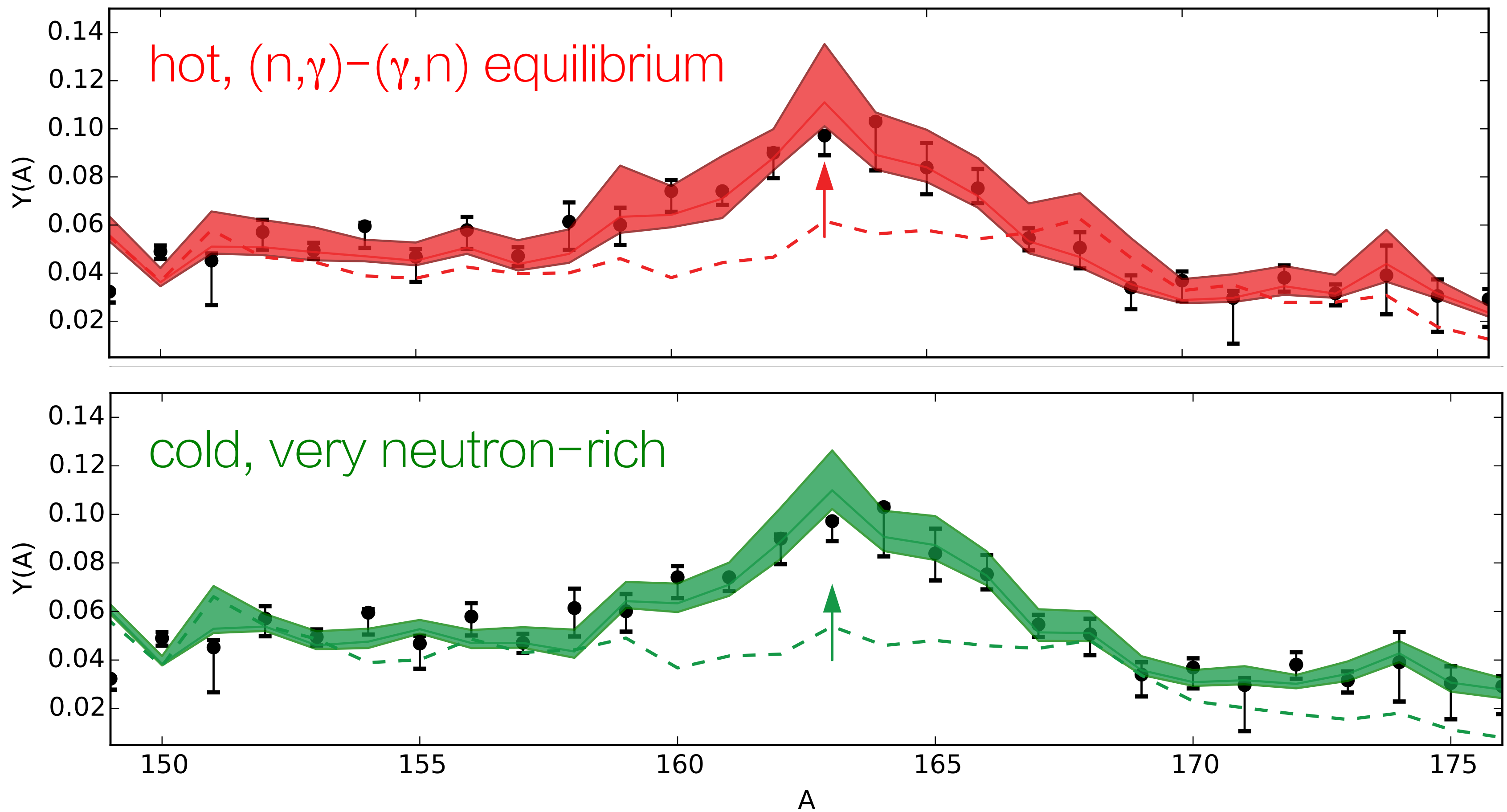


mass modification parameterization:

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

Mumpower, McLaughlin, Surman, Steiner JPhys G 2017

reverse-engineering rare earth masses



Mumpower, McLaughlin, Surman, Steiner JPhys G 2017

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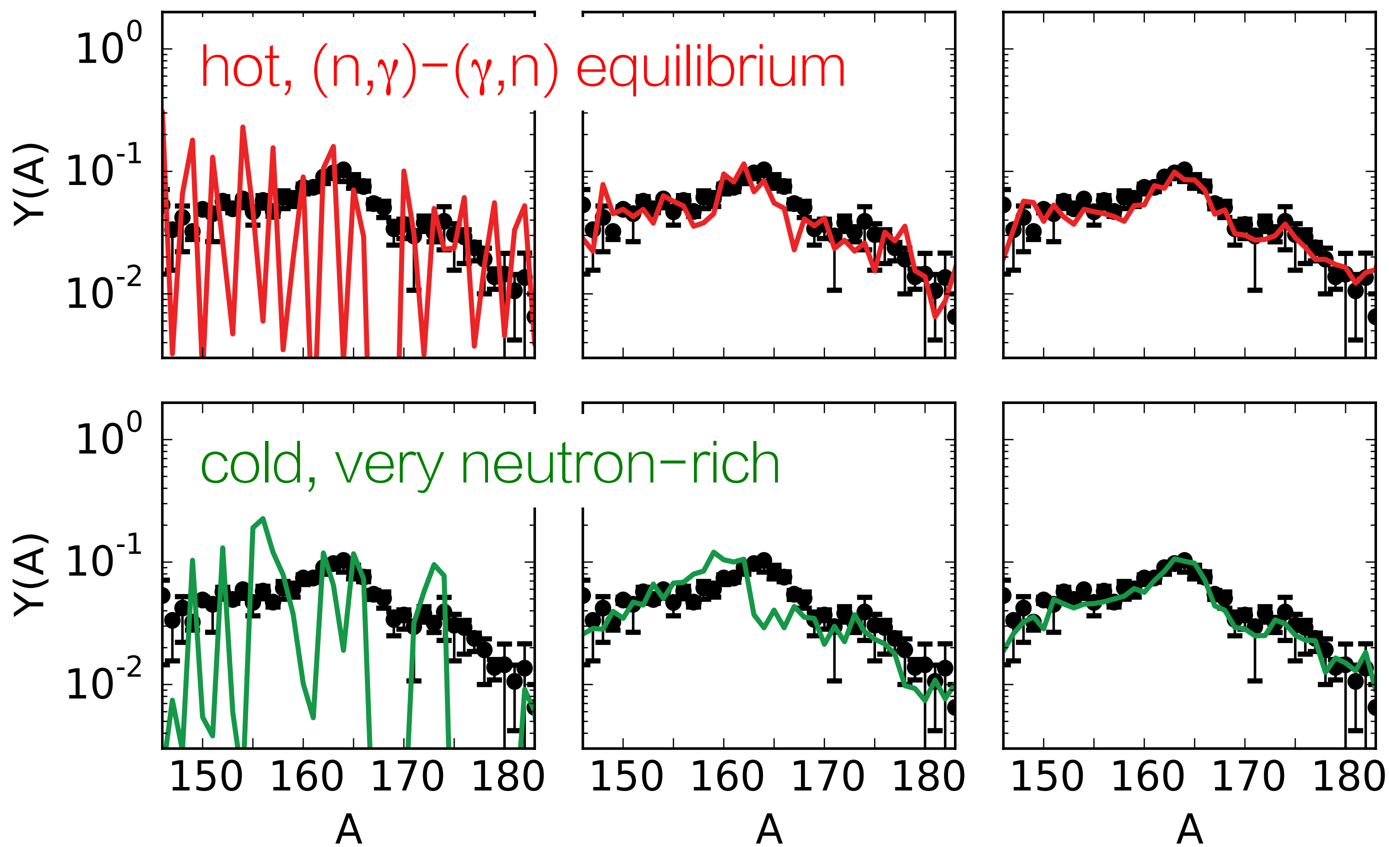
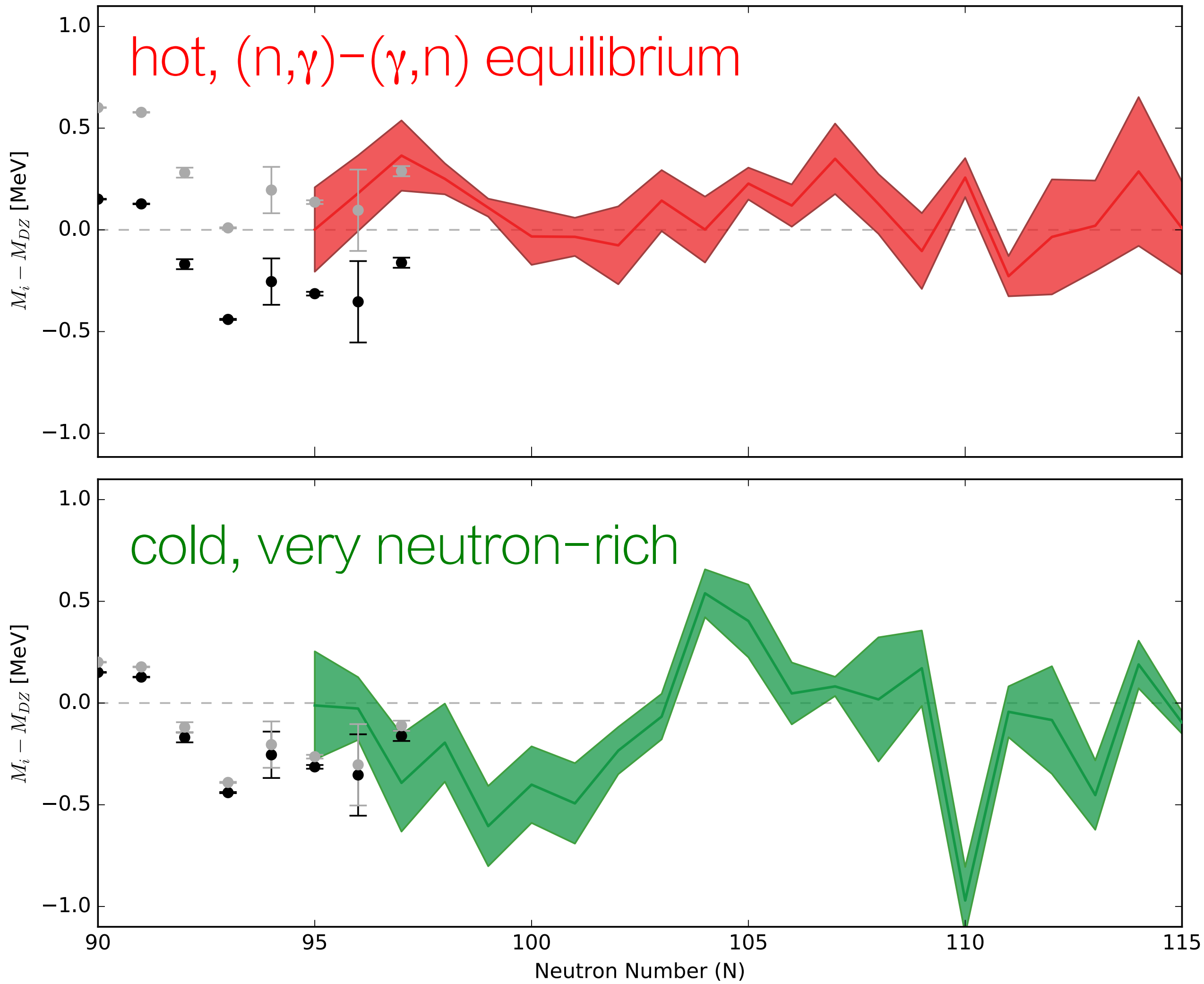
rare earth peak formation comparison



Mumpower, McLaughlin, Surman, Steiner ApJ 2016

theory-only predicted mass surfaces

Neodymium ($Z = 60$) isotopic chain



Mumpower, McLaughlin, Surman, Steiner ApJ 2016

summary

Evidence increasingly suggests compact object mergers are the primary site of synthesis of the heaviest elements, though many uncertainties remain.

On the nuclear physics side, current and next−generation radioactive beam facilities will continue to push the boundaries of measurements of extremely neutron−rich nuclei.

As nuclear physics uncertainties are reduced, we can exploit details of the *r*−process abundance pattern, such as the rare earth peak, to explore the nature of *r*−process environments.

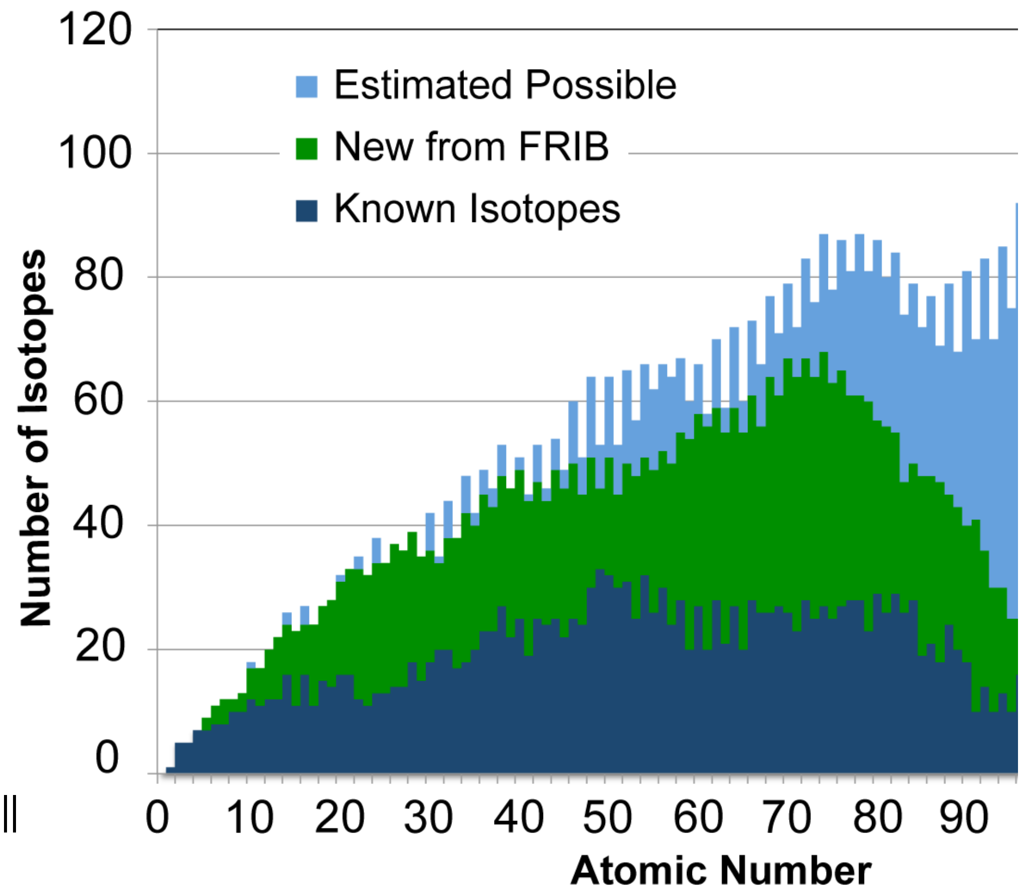


figure from B Sherrill