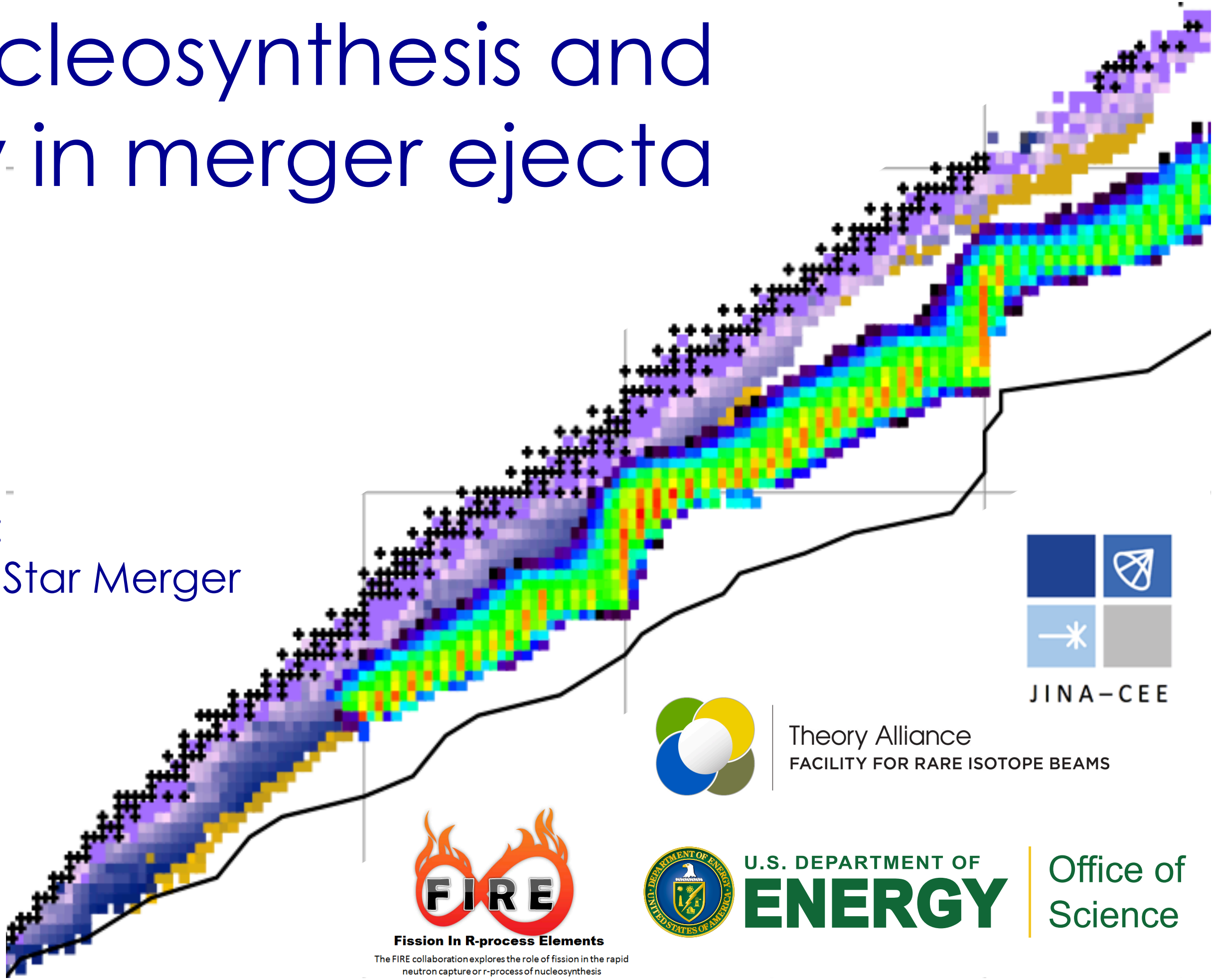
r-process nucleosynthesis and radioactivity in merger ejecta

Rebecca Surman
University of Notre Dame

KITP Program GW170817:
The First Double Neutron Star Merger
5-8 December 2017



UNIVERSITY OF NOTRE DAME
College of Science

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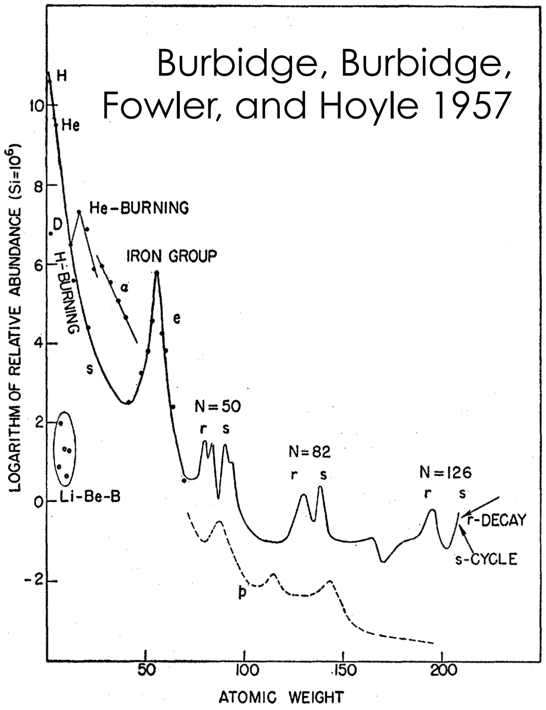
Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

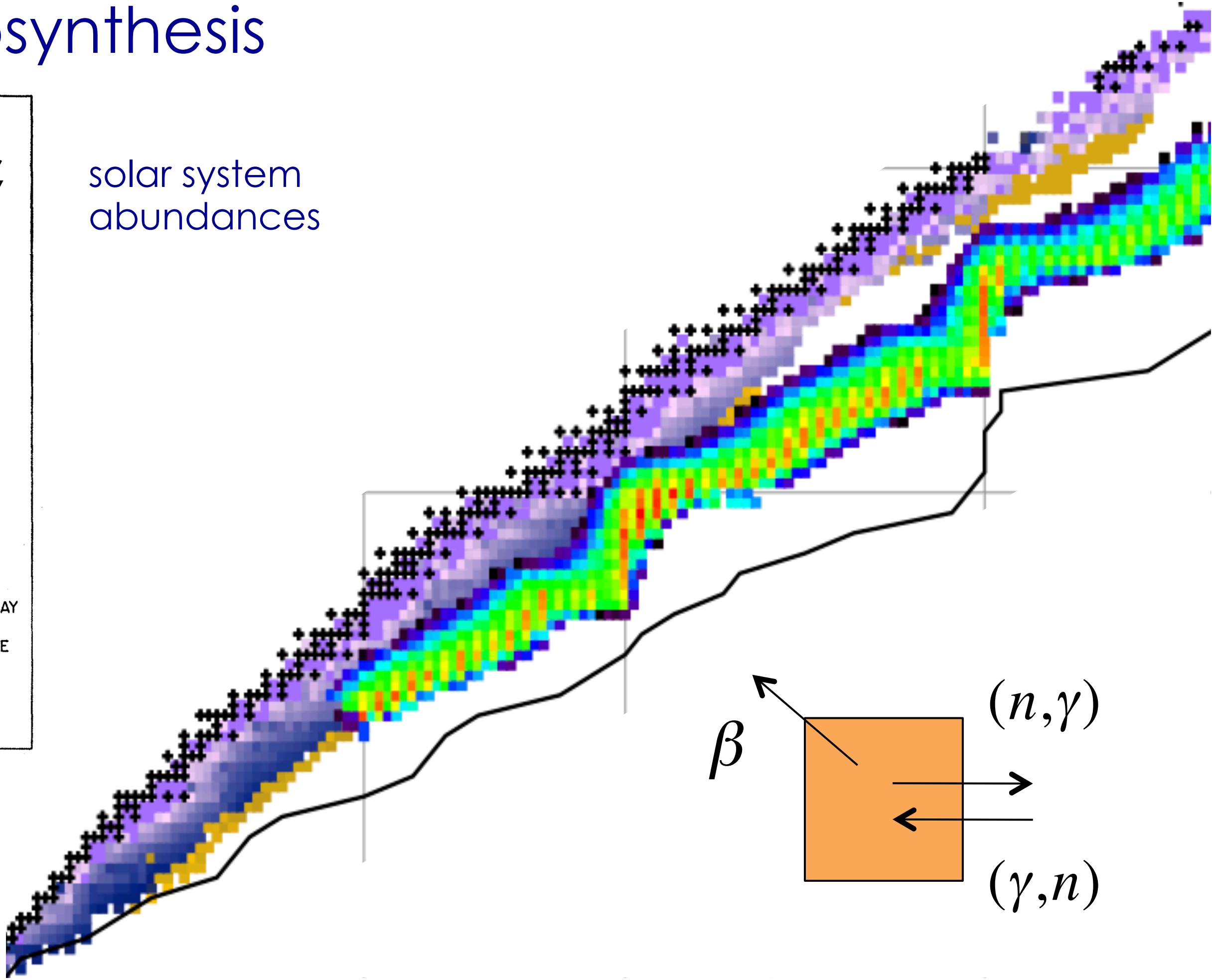
FIRE
Fission In R-process Elements
The FIRE collaboration explores the role of fission in the rapid neutron capture or r-process of nucleosynthesis

U.S. DEPARTMENT OF ENERGY
Office of Science

r-process nucleosynthesis



solar system abundances



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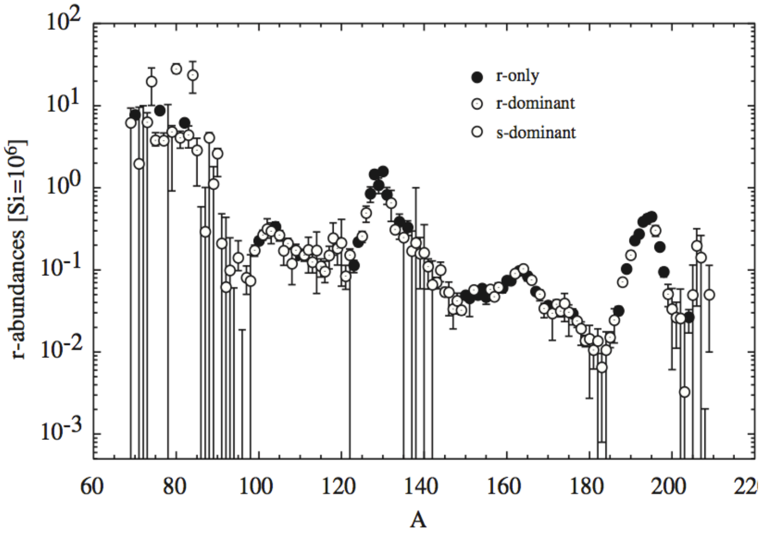
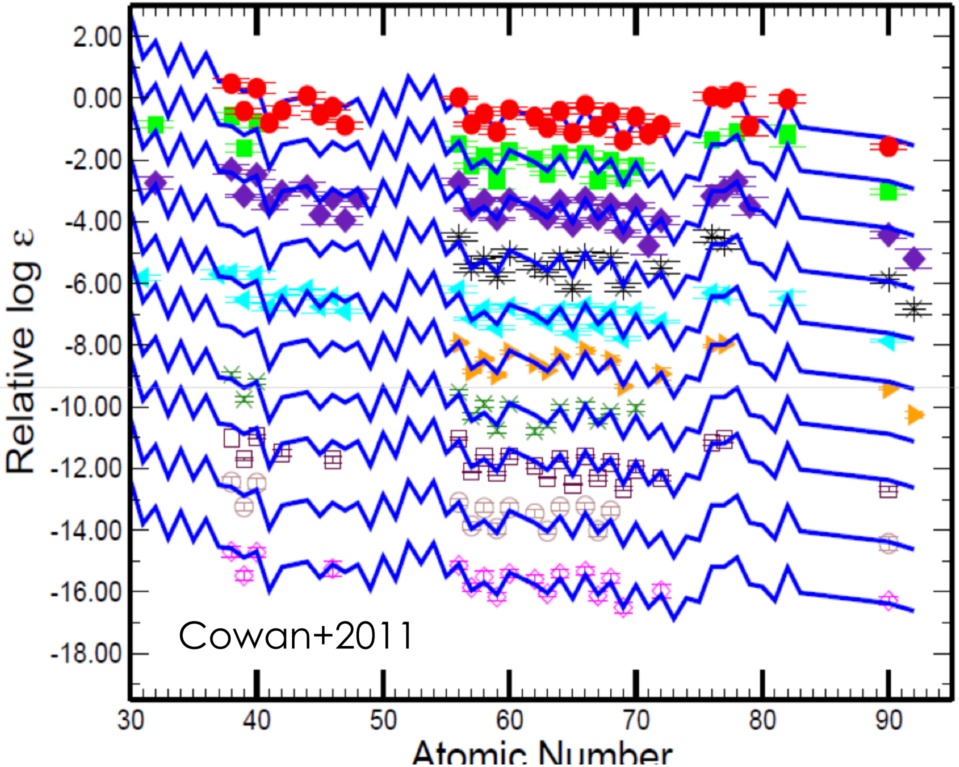
r-process elements in metal-poor stars



Arnould+2007

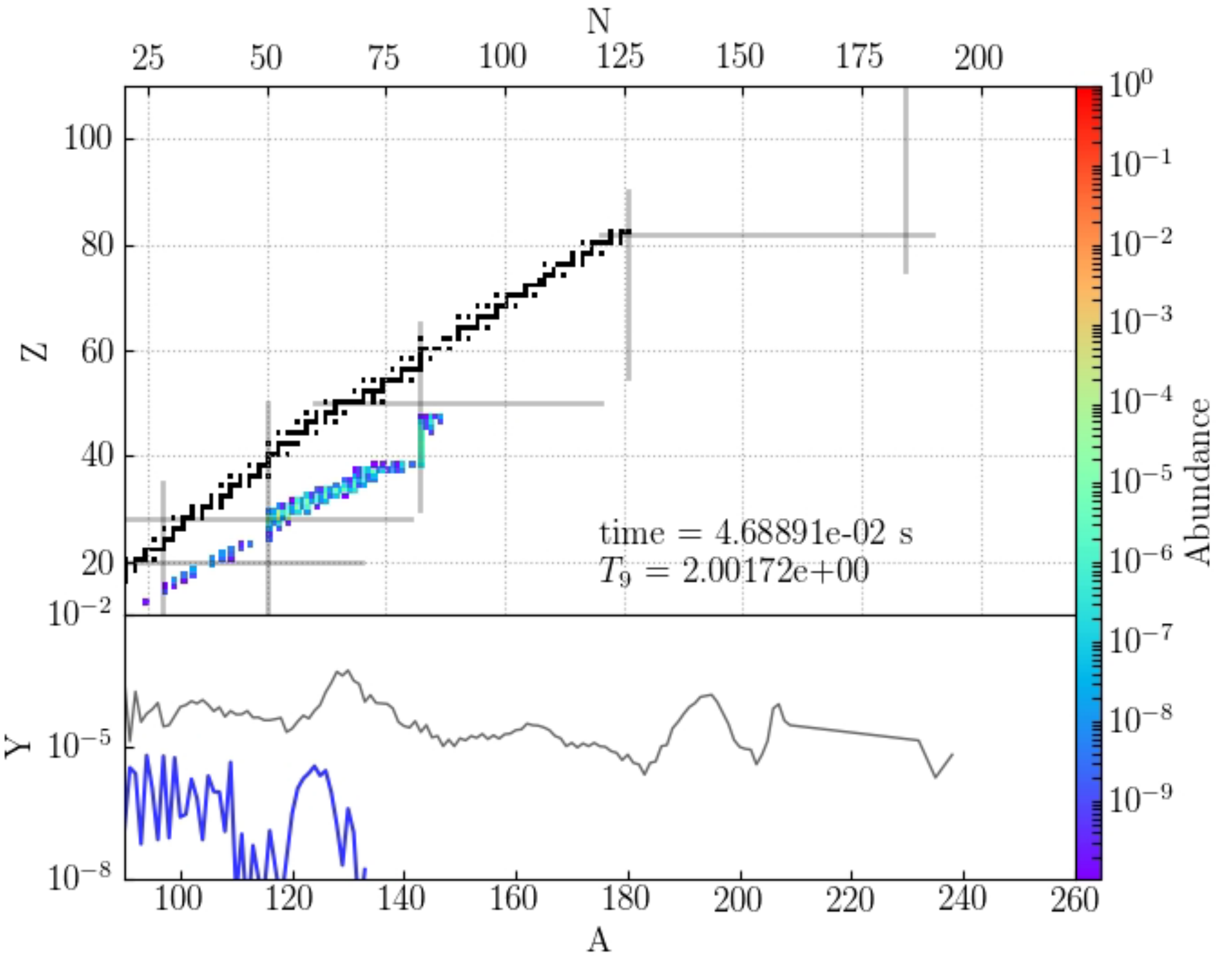
solar system
r-process residuals



Cowan+2011

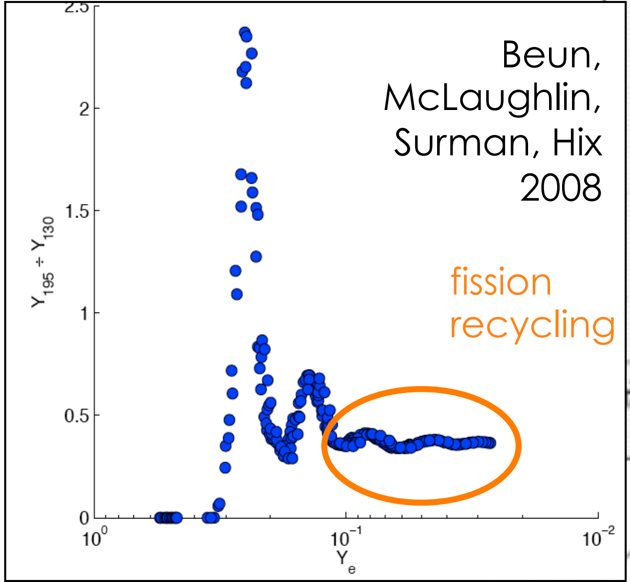
elemental abundances
from *r*-process-enhanced
metal-poor stars

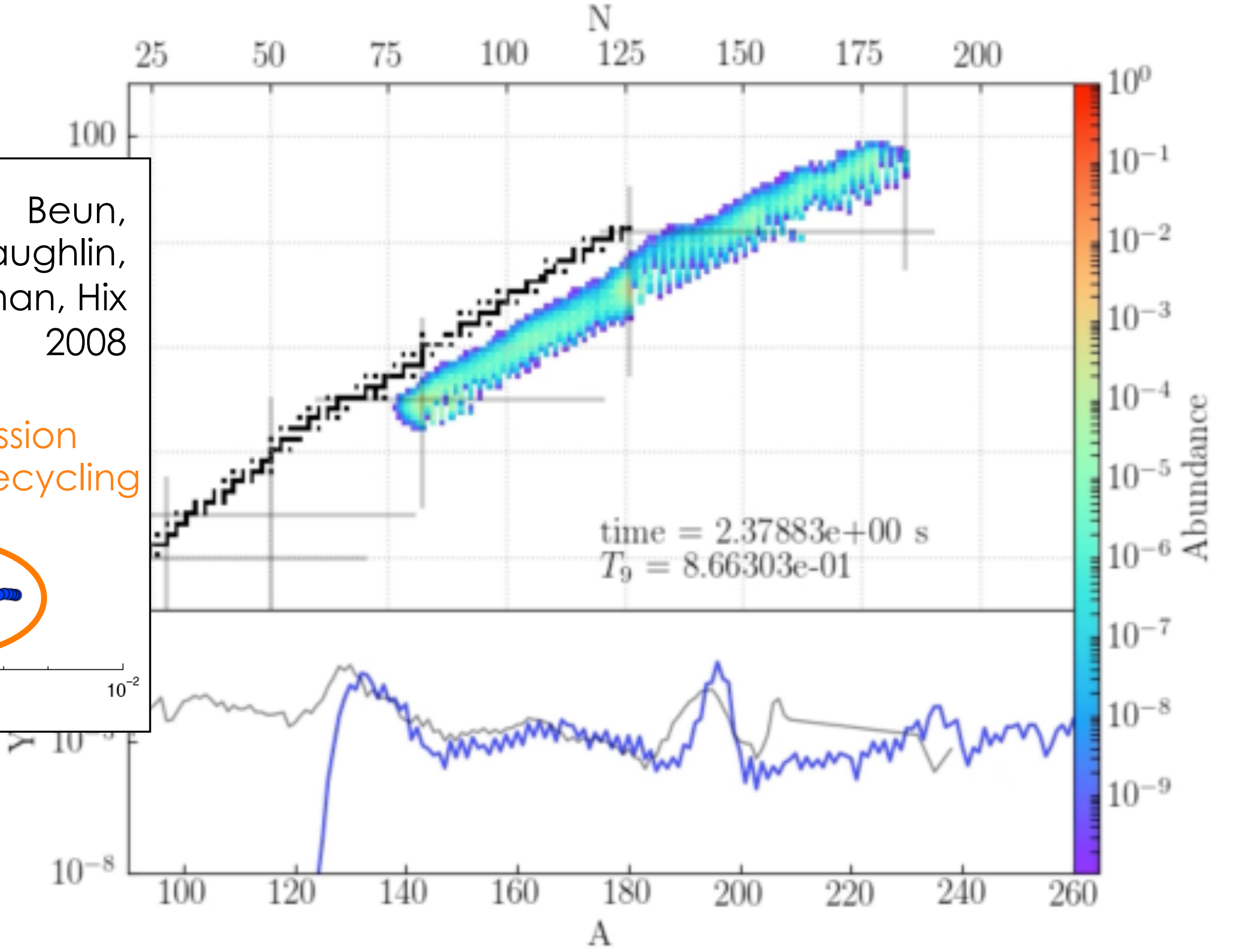
r-process simulations



network calculation by
E. Holmbeck, T. Sprouse
NSM trajectory from
Just+15

r-process simulations





network calculation by E. Holmbeck, T. Sprouse
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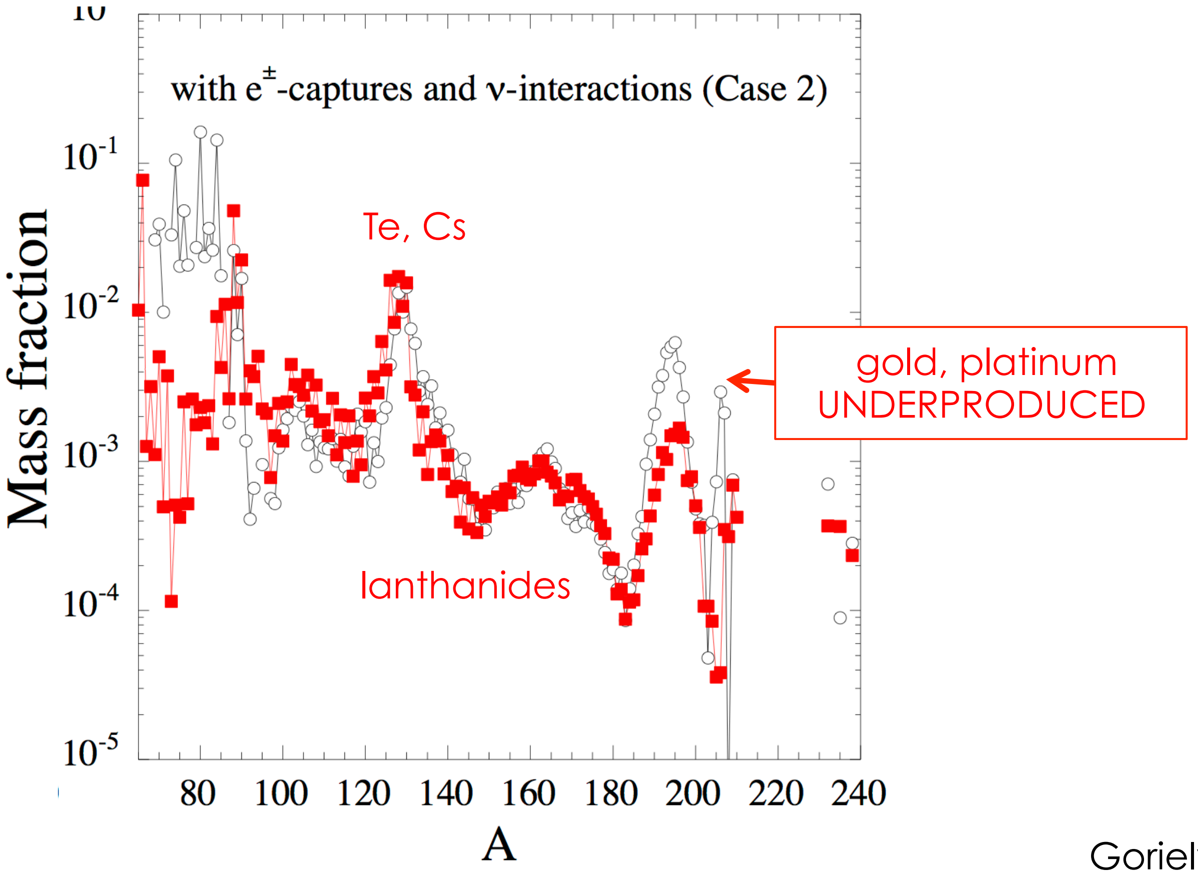
integrated nucleosynthesis with neutrinos



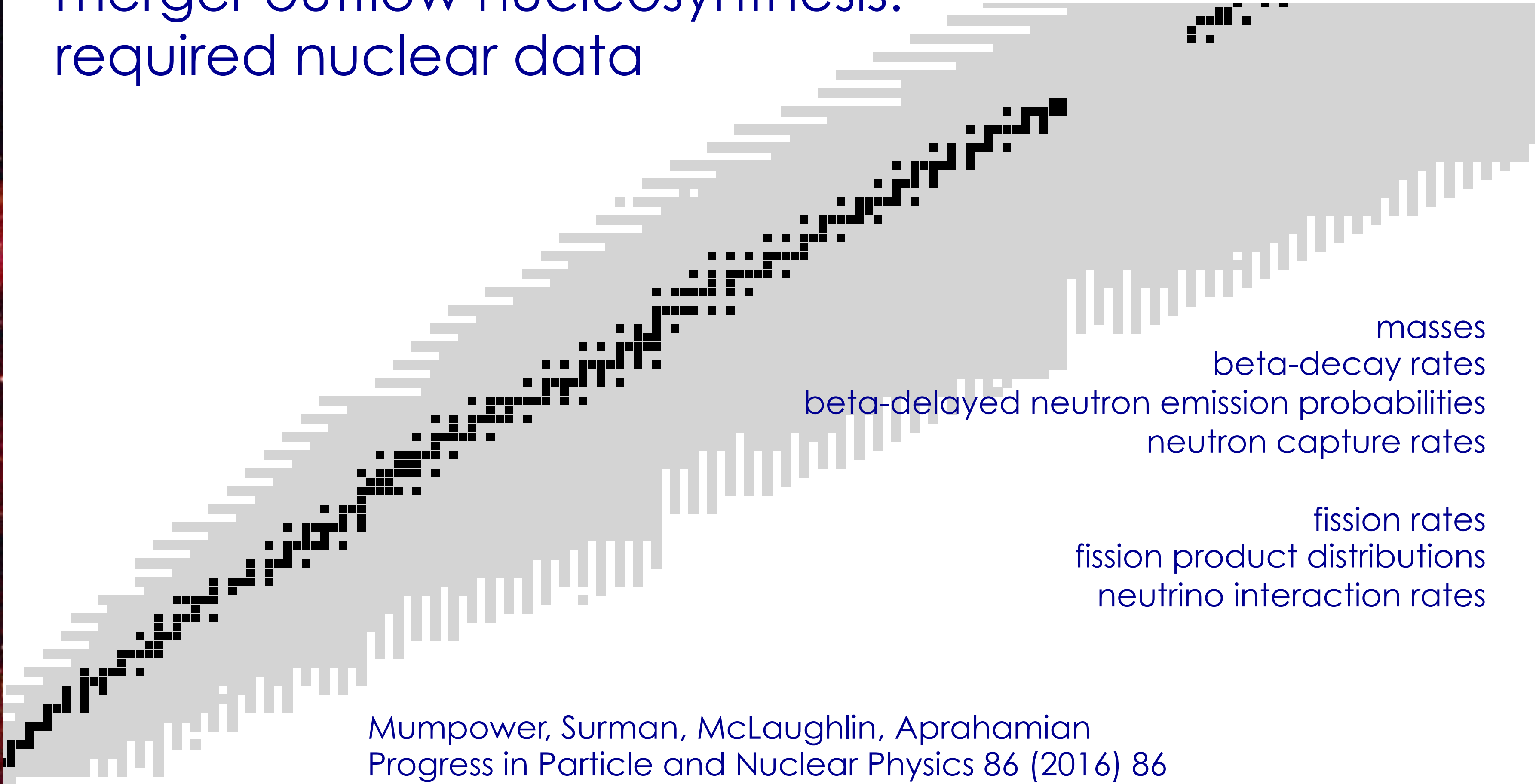
Goriely+2015

GW170817 and the *r* process: open questions

Are neutron star mergers responsible for the production of all *r*-process elements, or do multiple distinct sites contribute?

Can we understand neutron star merger nucleosynthesis from first principles?

merger outflow nucleosynthesis: required nuclear data



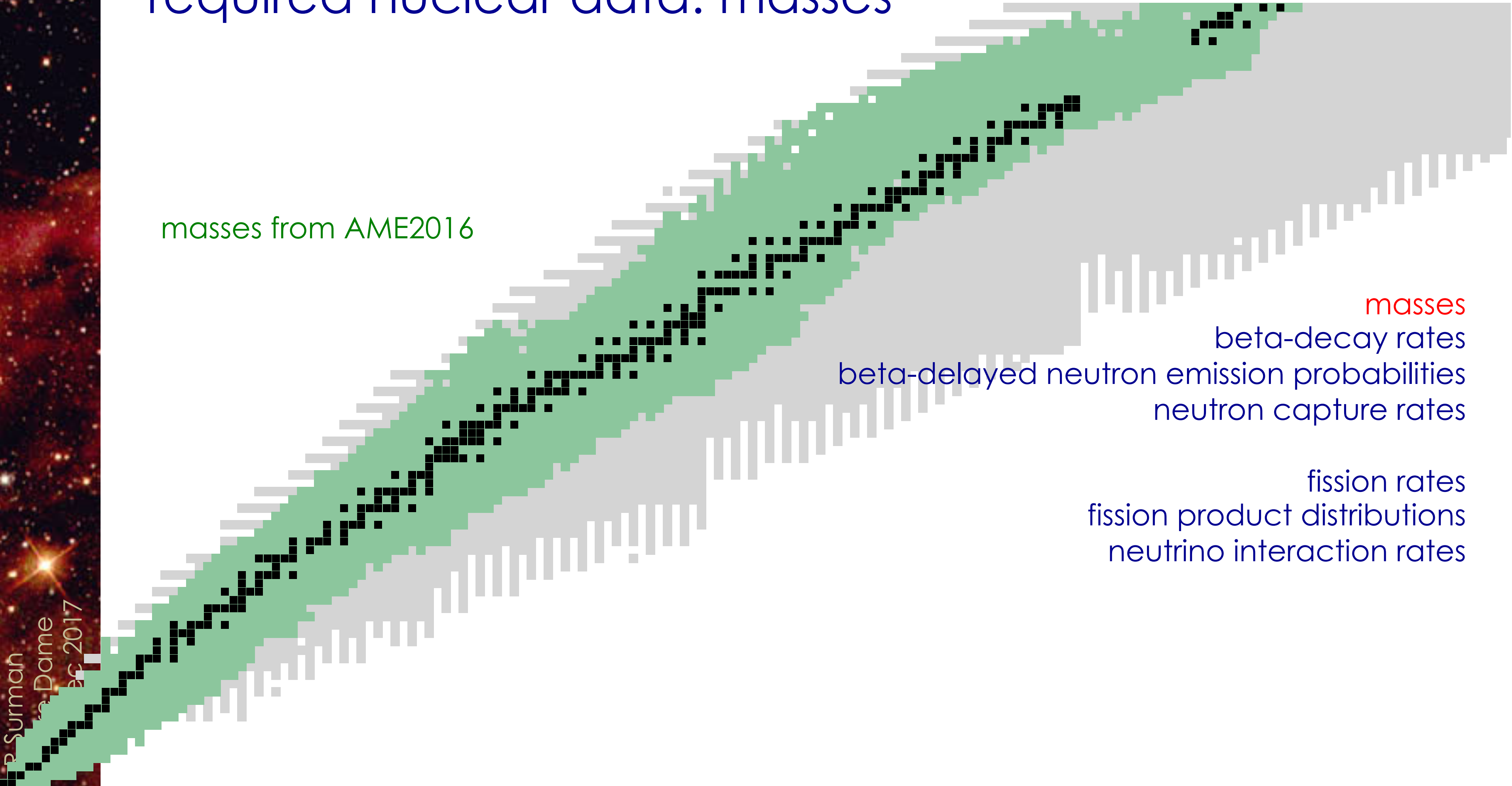
masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates

fission rates
fission product distributions
neutrino interaction rates

Mumpower, Surman, McLaughlin, Aprahamian
Progress in Particle and Nuclear Physics 86 (2016) 86

required nuclear data: masses

masses from AME2016



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

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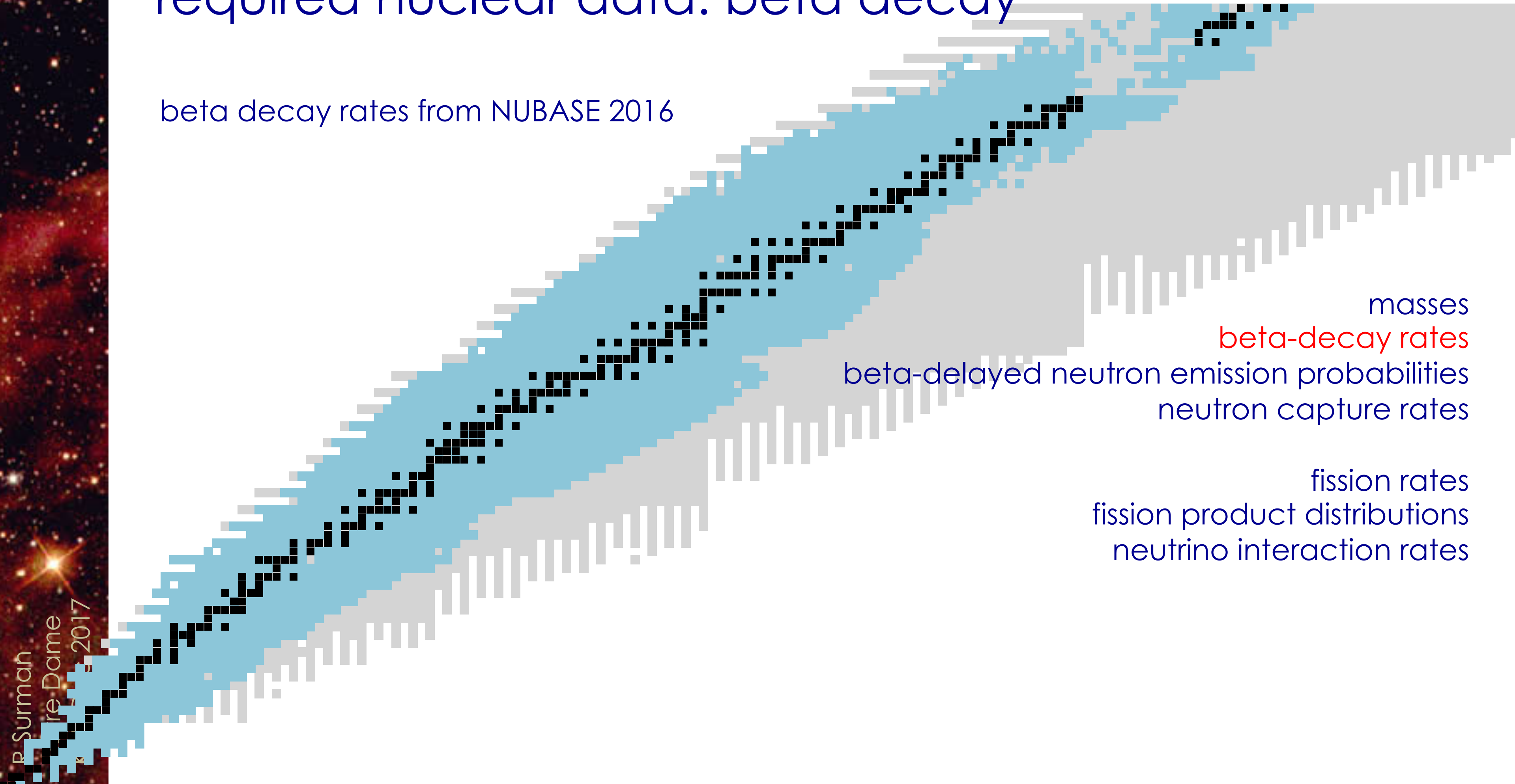
neutrino interaction rates

required nuclear data: beta decay

beta decay rates from NUBASE 2016

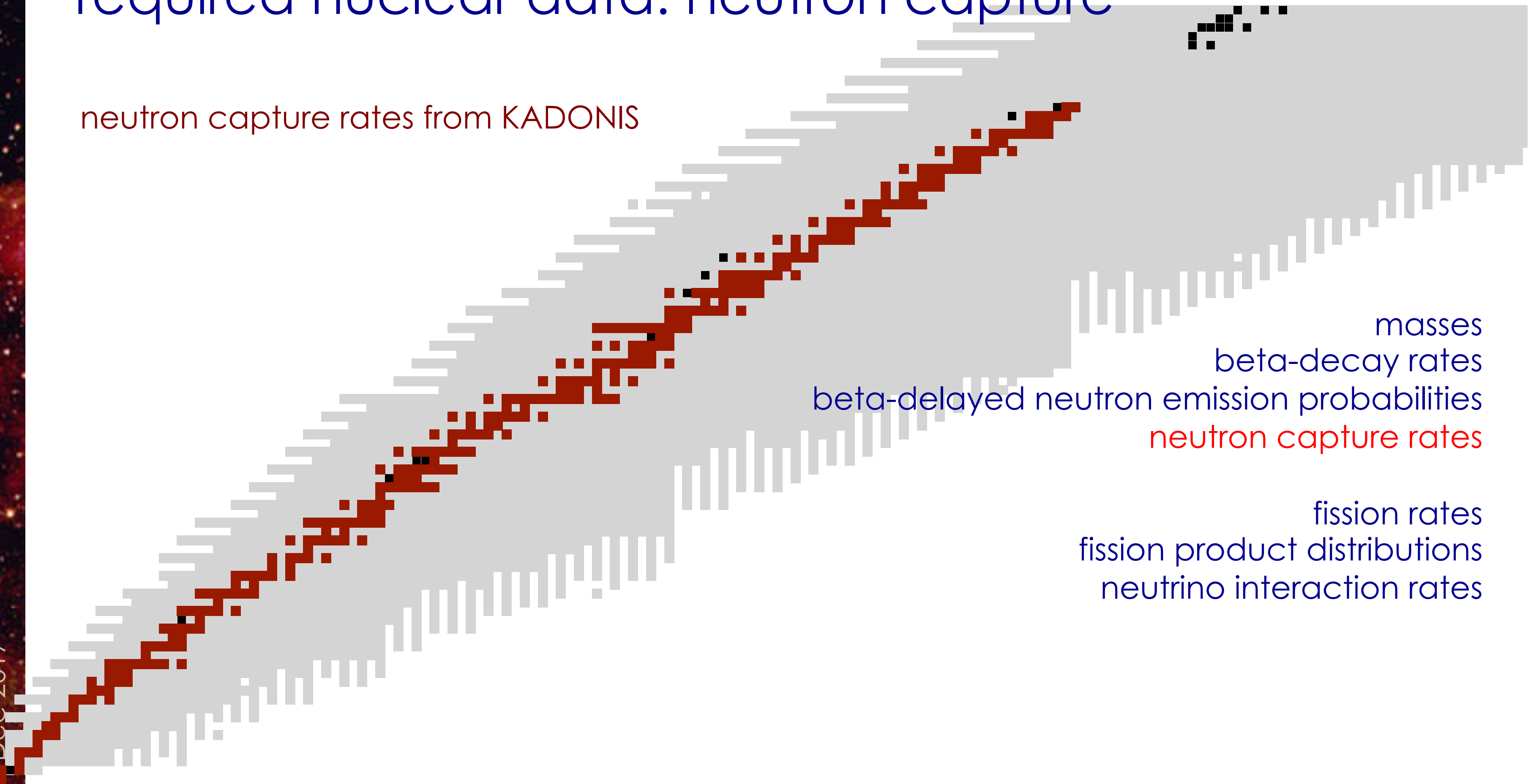


masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates

fission rates
fission product distributions
neutrino interaction rates

required nuclear data: neutron capture

neutron capture rates from KADONIS



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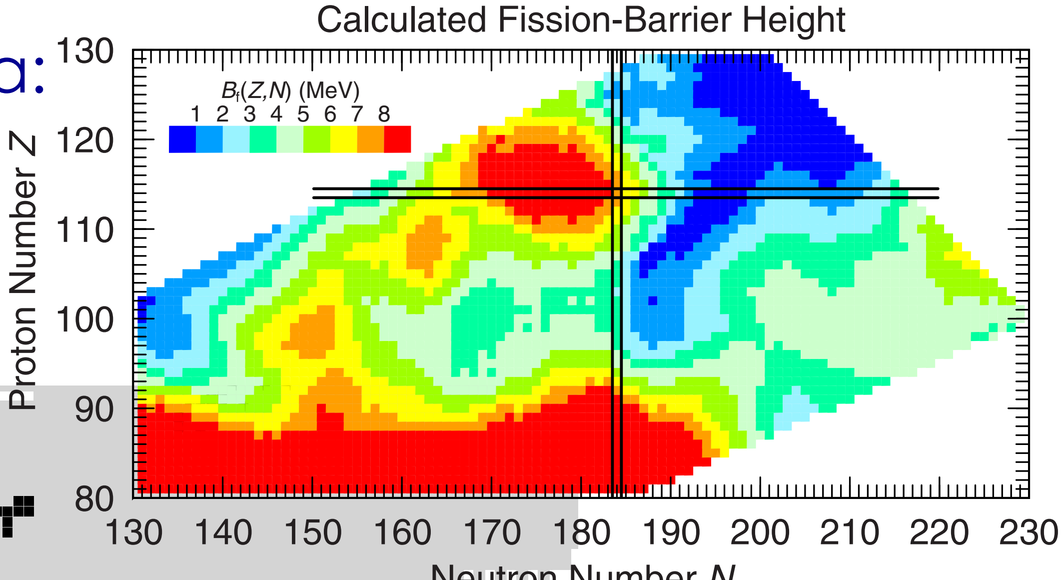
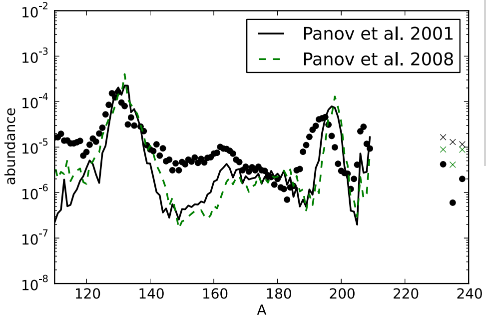
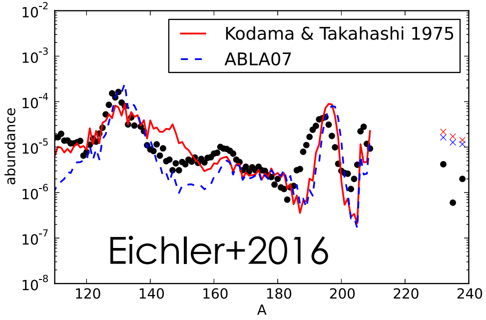
required nuclear data: fission properties

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

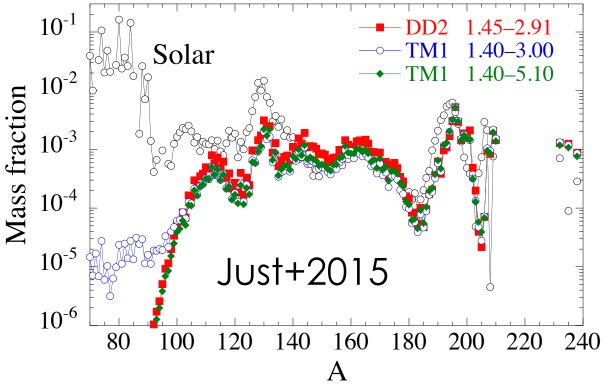


Möller+2015





Eichler+2016



Just+2015

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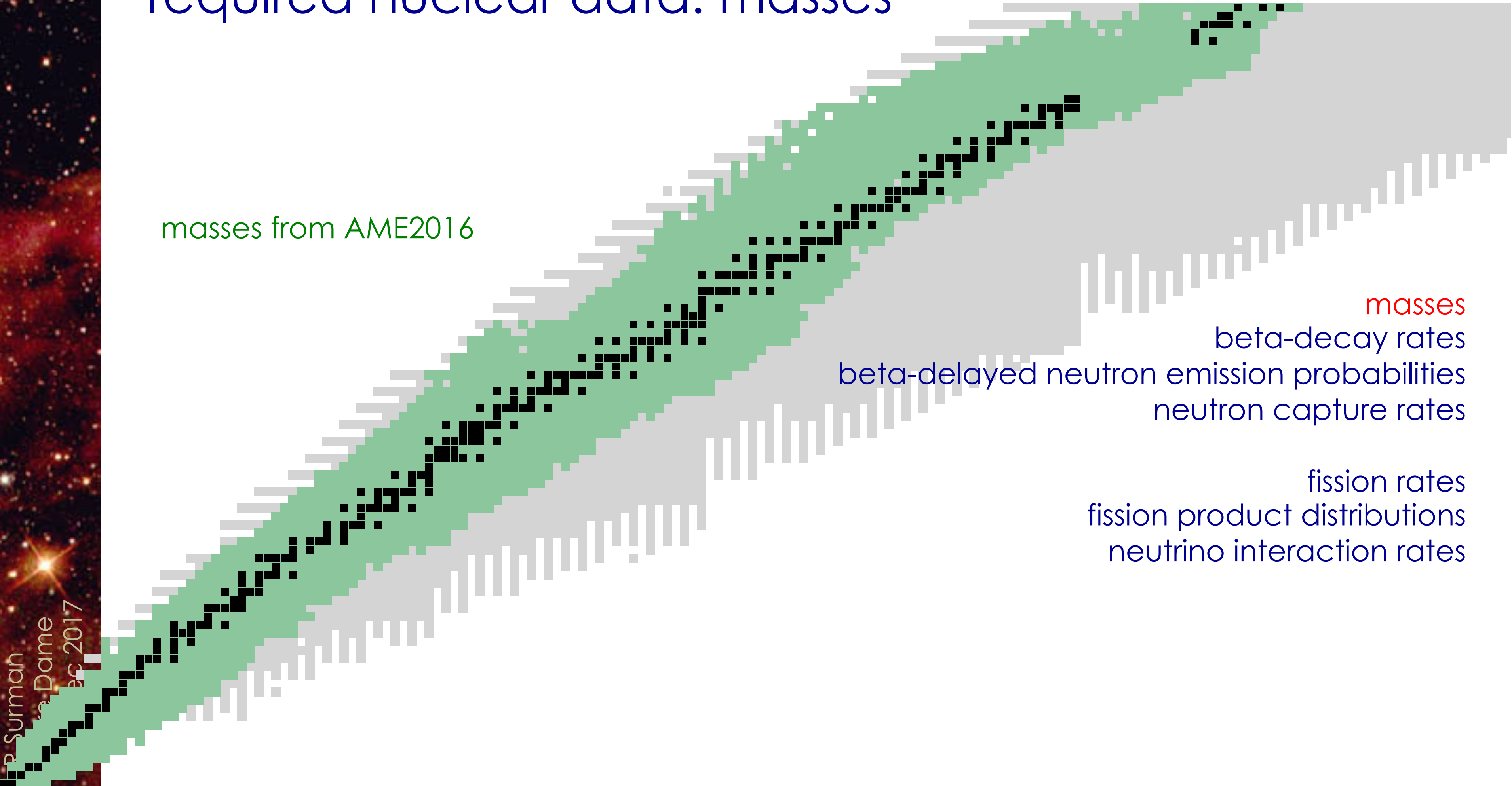
required nuclear data: masses

masses from AME2016



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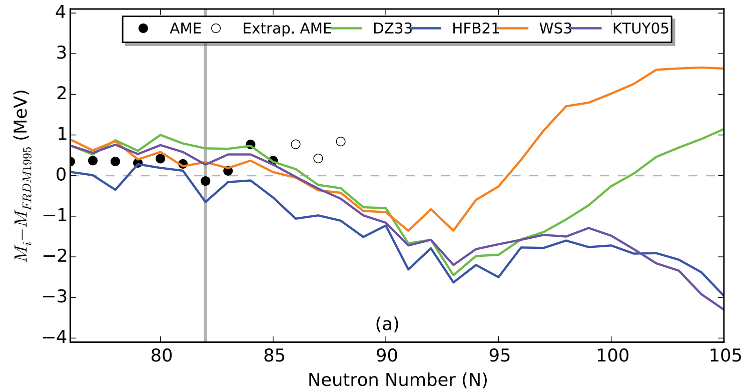
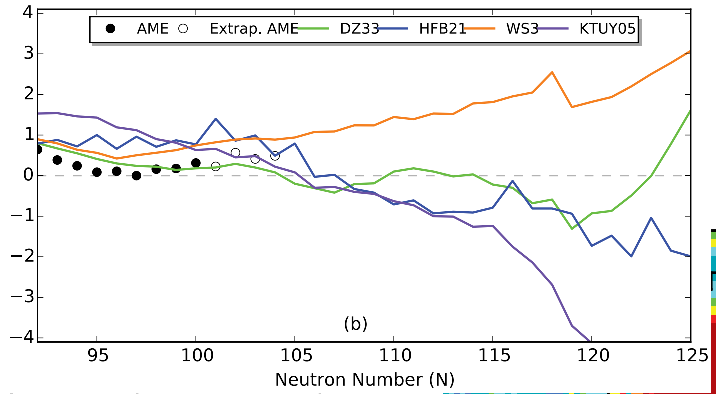
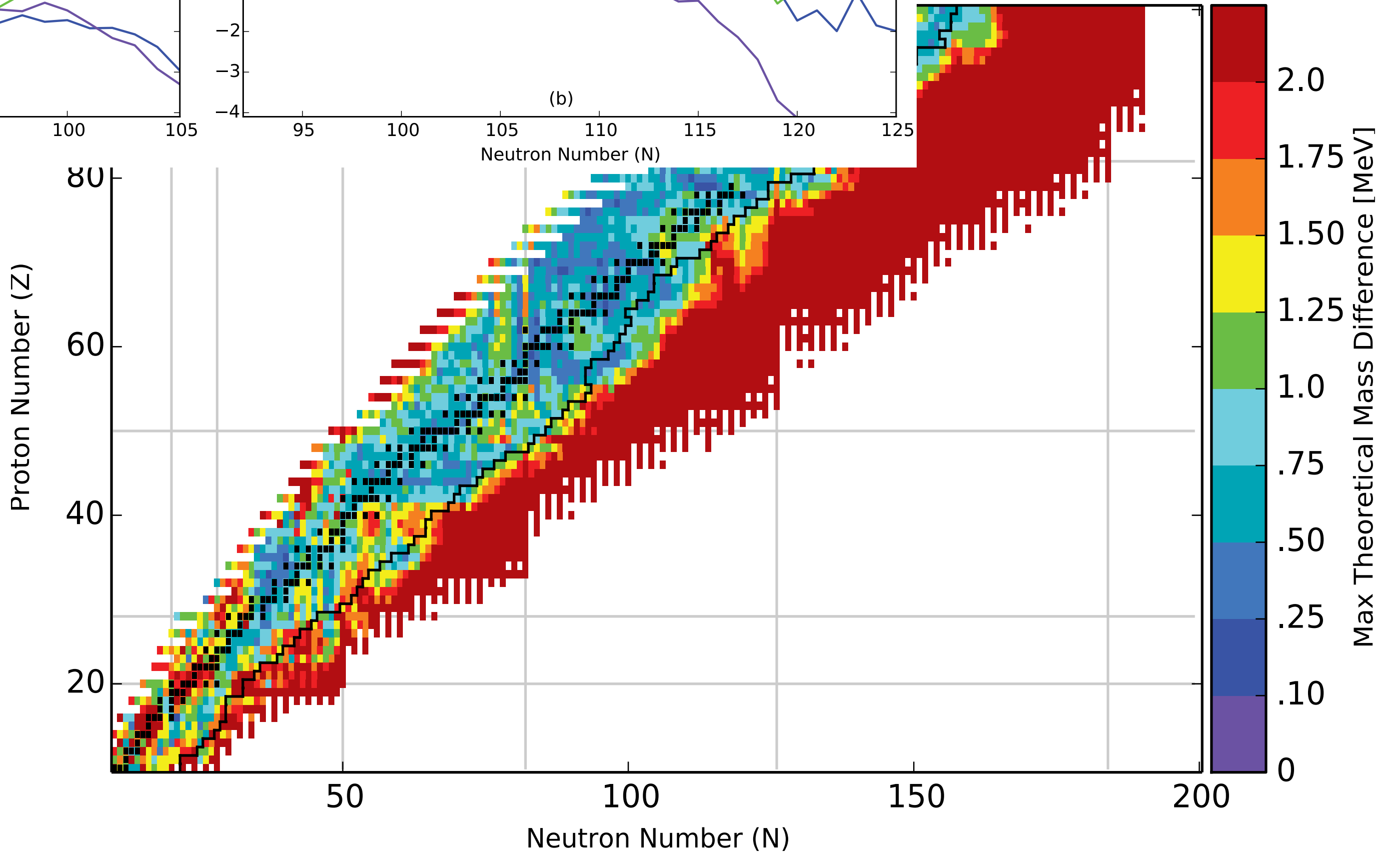


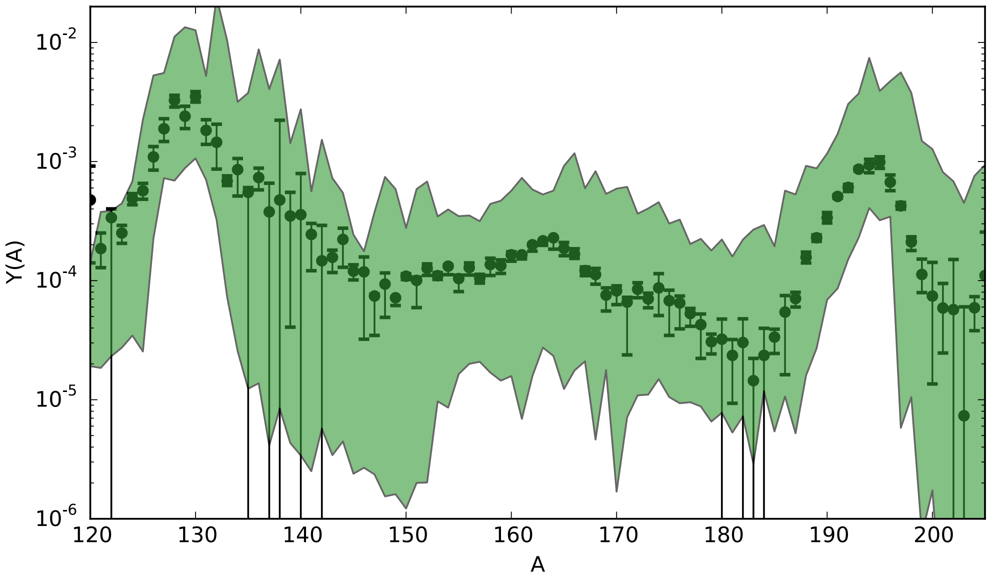


mass uncertainties

Mumpower, Surman, McLaughlin, Aprahamian 2016



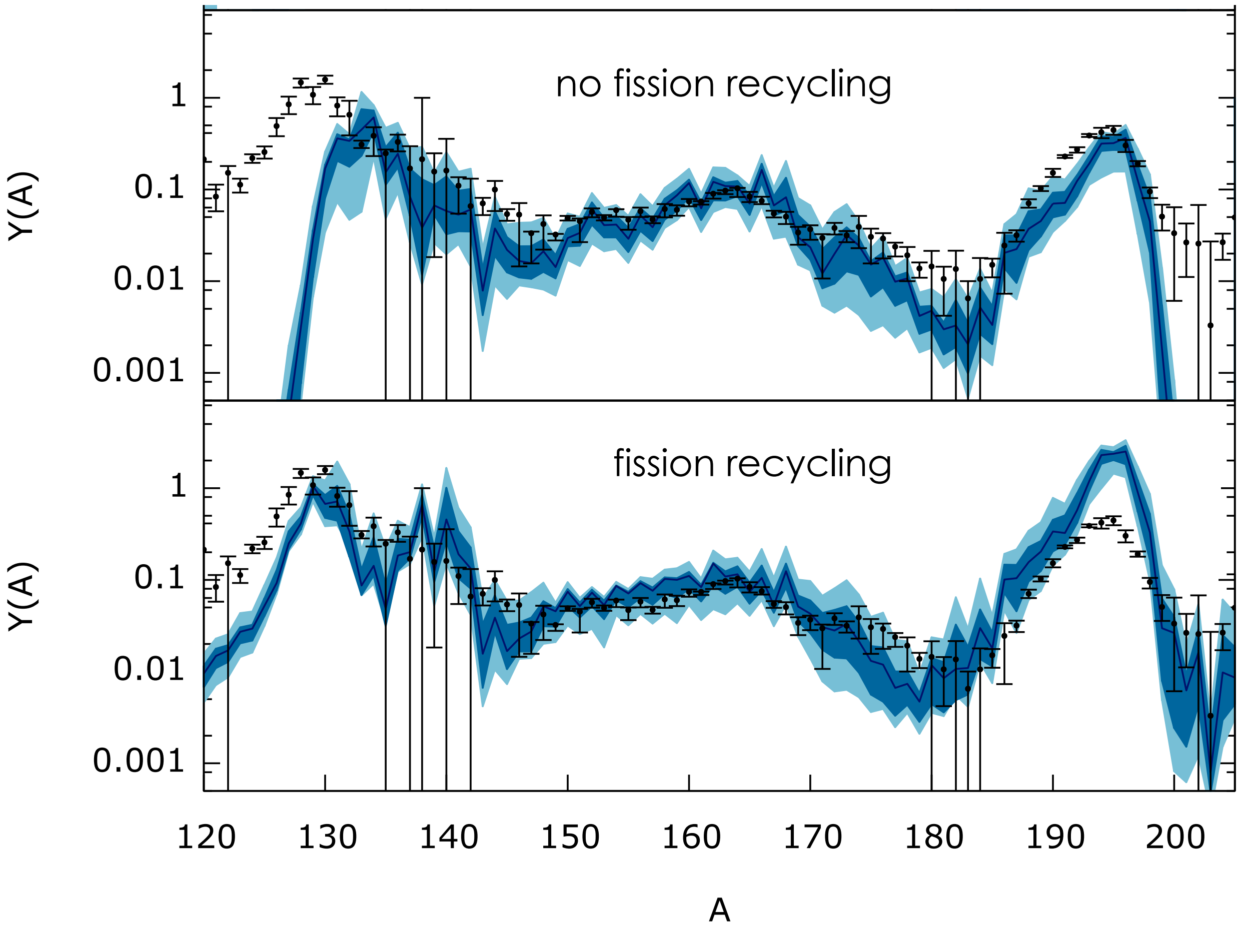
impact of random uncorrelated mass uncertainties



Surman, Mumpower, McLaughlin 2016

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

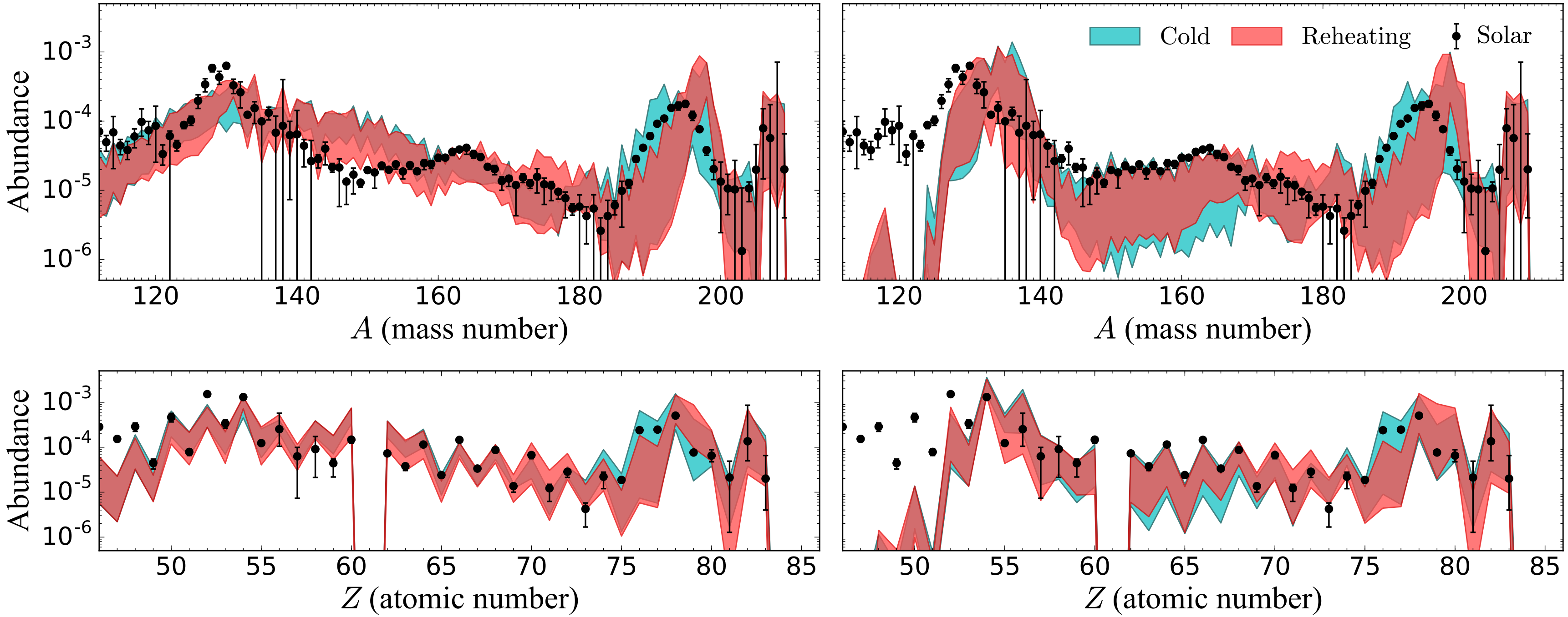
impact of random correlated mass uncertainties



50 mass tables generated using the UNEDF1 functional with uncertainties

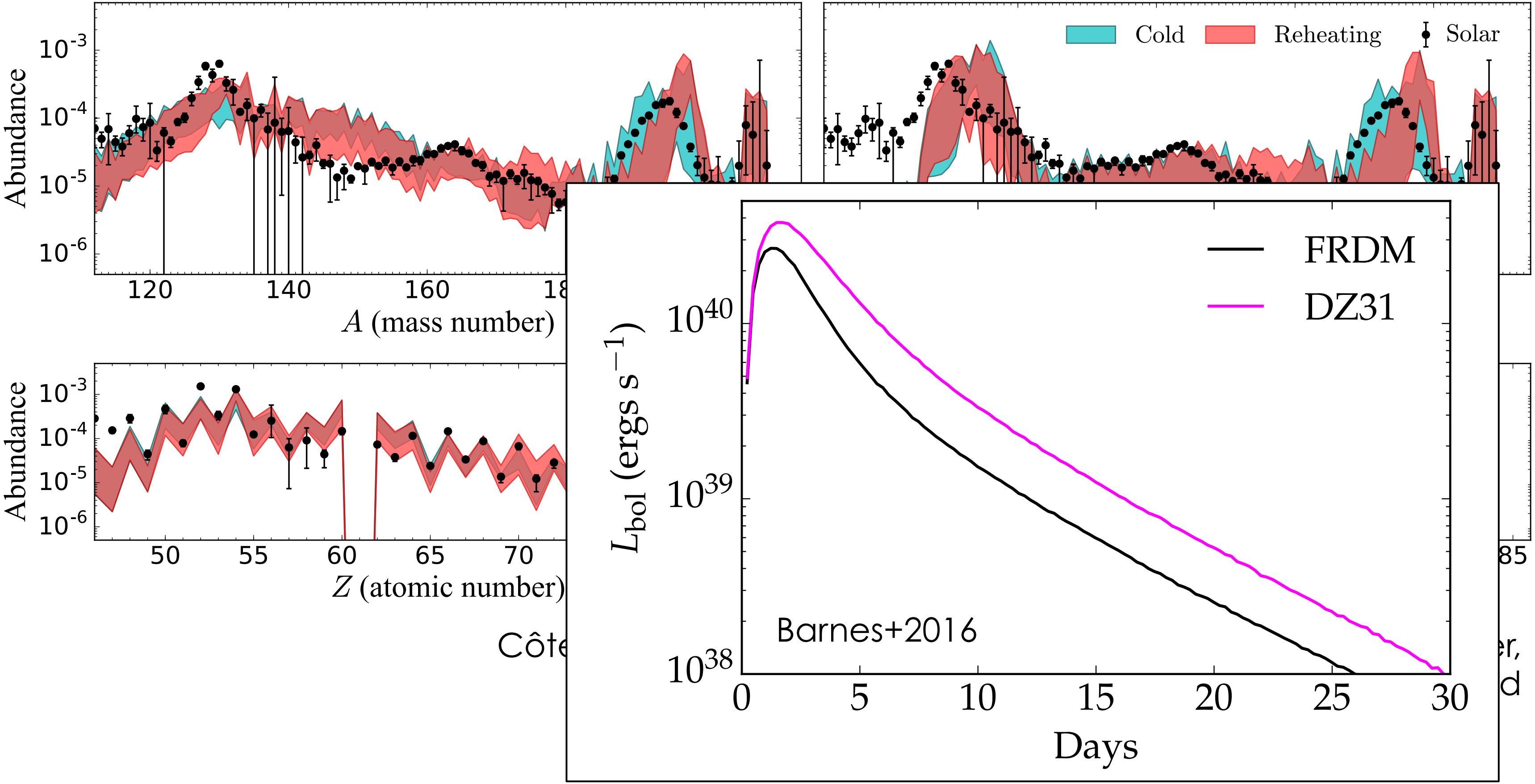
Surman, Navarro Perez, Mumpower, McLaughlin, Schunck, in preparation

impact of systematic mass uncertainties



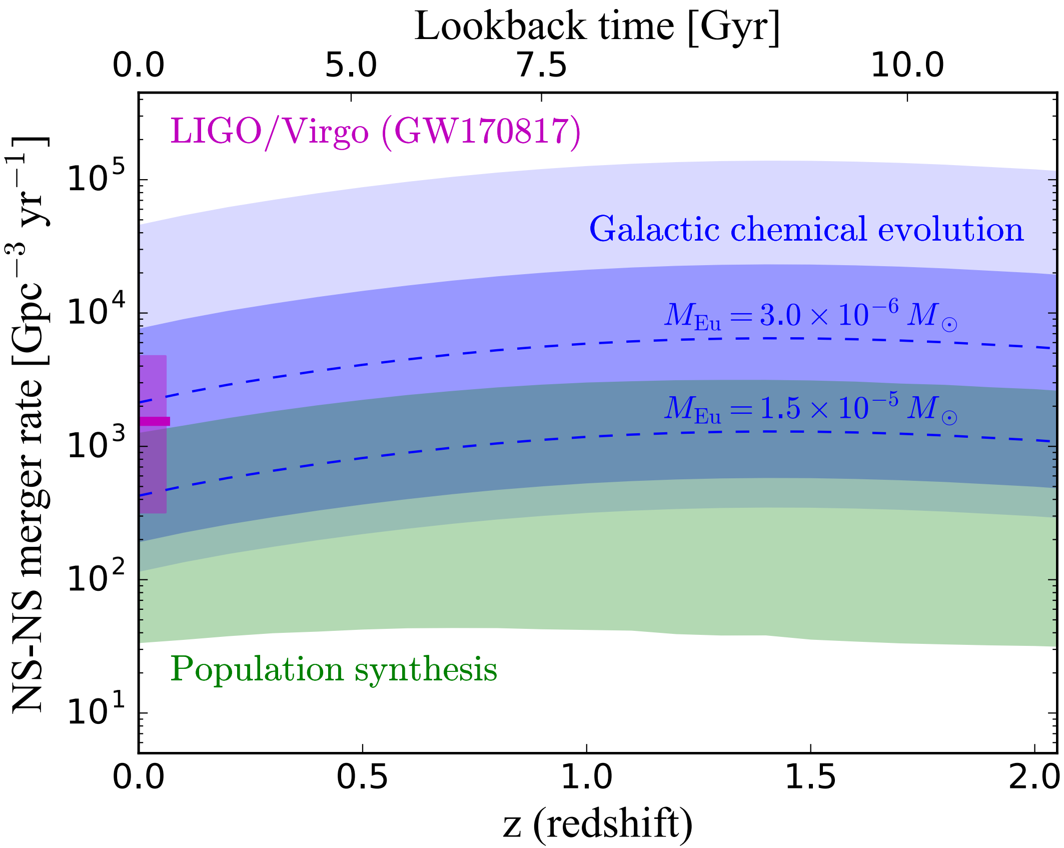
Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman, Wollaeger, submitted

impact of systematic mass uncertainties



Côte … er, … d

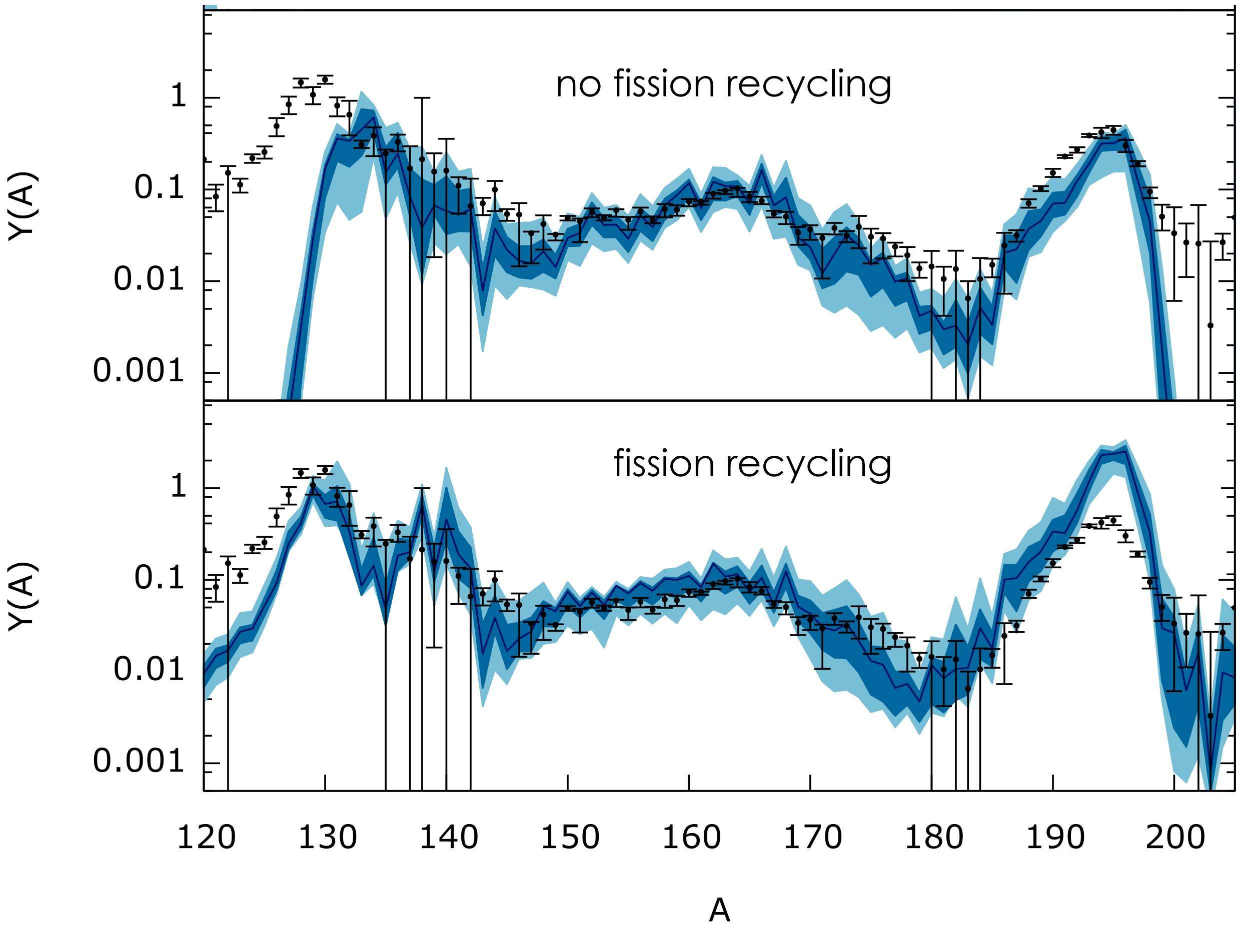
GRB170817A/SSS17a + galactic chemical evolution



Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman, Wollaeger, submitted

can we use *r*-process astrophysical conditions to learn about nuclear physics?

impact of random correlated mass uncertainties



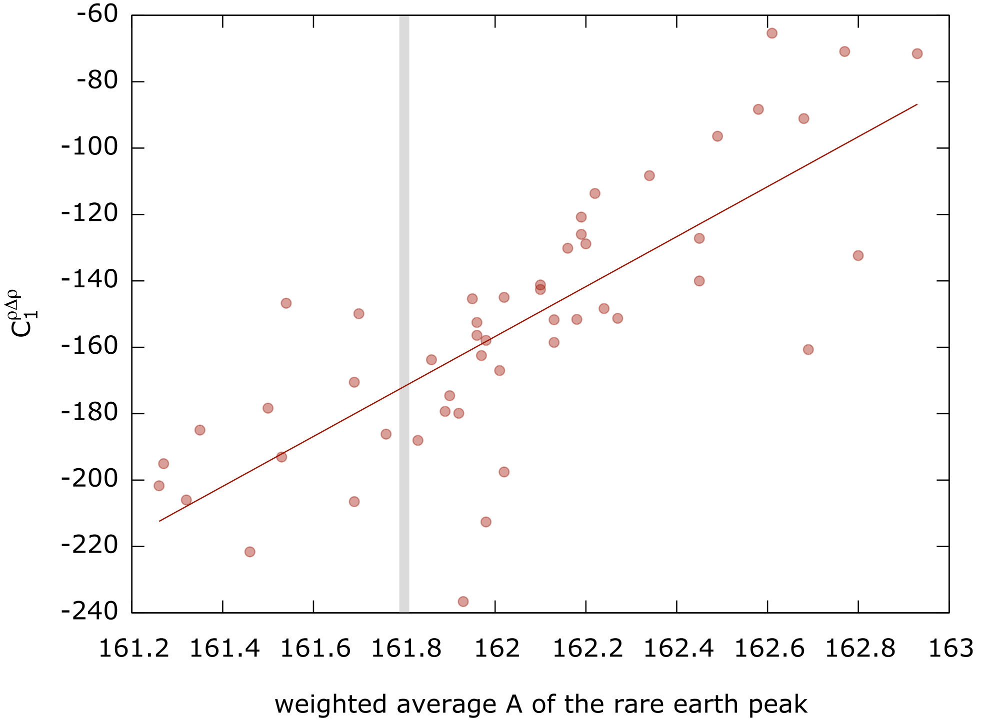
50 mass tables generated using the UNEDF1 functional with uncertainties

Surman, Navarro Perez, Mumpower, McLaughlin, Schunck, in preparation

correlations between UNEDF1 parameters and *r*-process pattern features

TABLE II: Optimized parameter set UNEDF1. Listed are bounds used in the optimization, final optimized parameter values, standard deviations, and 95% confidence intervals.

x	Bounds	$\hat{\mathbf{x}}^{(\mathrm{fin.})}$	σ	95% CI
ρ_c	[0.15,0.17]	0.15871	0.00042	[0.158, 0.159]
E^{NM}/A	[-16.2,-15.8]	-15.800	–	–
K^{NM}	[220, 260]	220.000	–	–
$a_{\mathrm{sym}}^{\mathrm{NM}}$	[28, 36]	28.987	0.604	[28.152, 29.822]
$L_{\mathrm{sym}}^{\mathrm{NM}}$	[40, 100]	40.005	13.136	[21.841, 58.168]
$1/M_s^*$	[0.9, 1.5]	0.992	0.123	[0.823, 1.162]
$C_0^{\rho\Delta\rho}$	$[-\infty,+\infty]$	-45.135	5.361	[-52.548, -37.722]
$C_1^{\rho\Delta\rho}$	$[-\infty,+\infty]$	-145.382	52.169	[-217.515, -73.250]
V_0^n	$[-\infty,+\infty]$	-186.065	18.516	[-211.666, -160.464]
V_0^p	$[-\infty,+\infty]$	-206.580	13.049	[-224.622,-188.538]
$C_0^{\rho\nabla J}$	$[-\infty,+\infty]$	-74.026	5.048	[-81.006, -67.046]
$C_1^{\rho\nabla J}$	$[-\infty,+\infty]$	-35.658	23.147	[-67.663, -3.654]



Surman, Navarro Perez, Mumpower, McLaughlin, Schunck, in preparation

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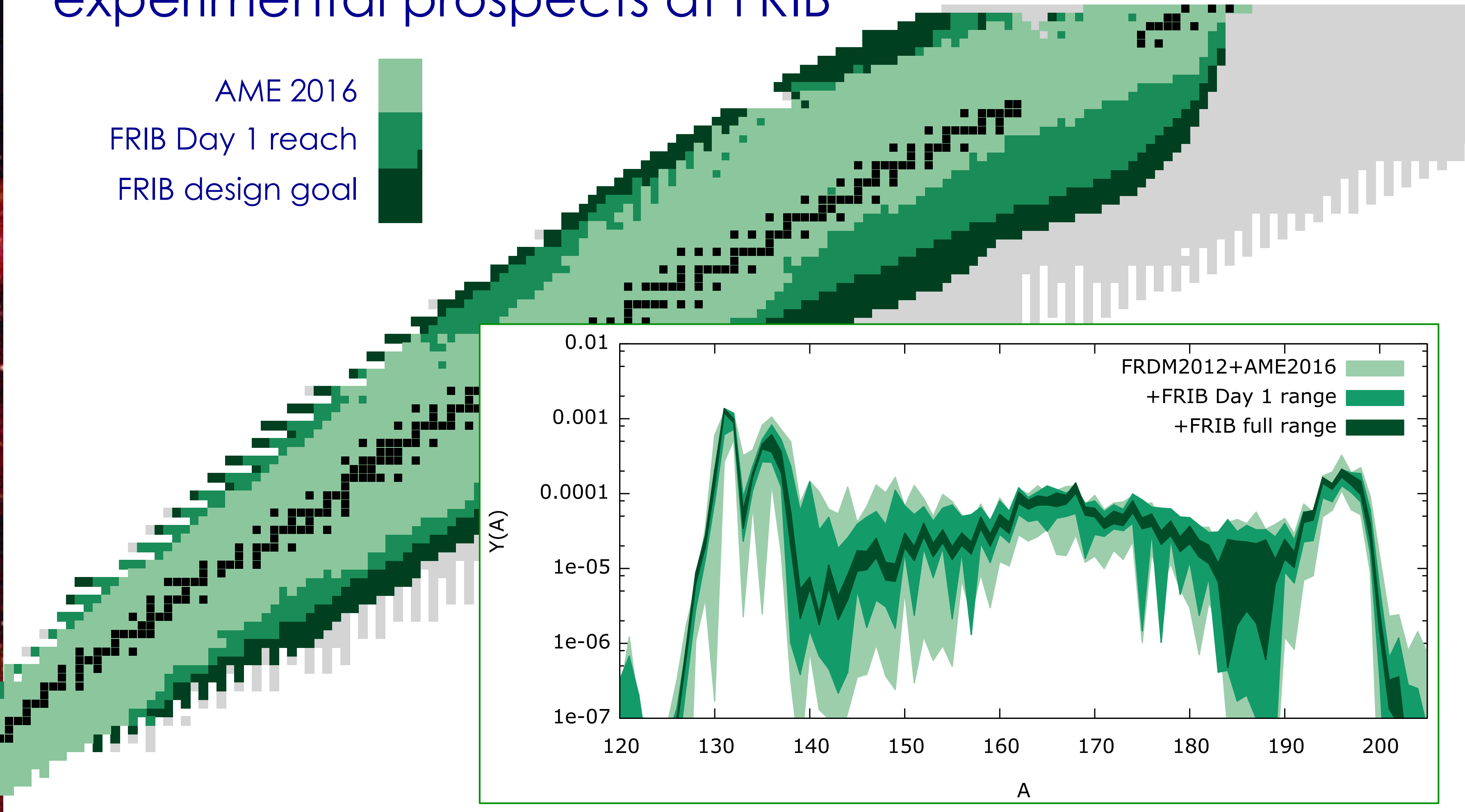
KITP Dec 2017

experimental prospects at FRIB

Facility for Rare Isotope Beams
at Michigan State University

experimental prospects at FRIB



can we use nuclear physics to learn about *r*-process astrophysical conditions?

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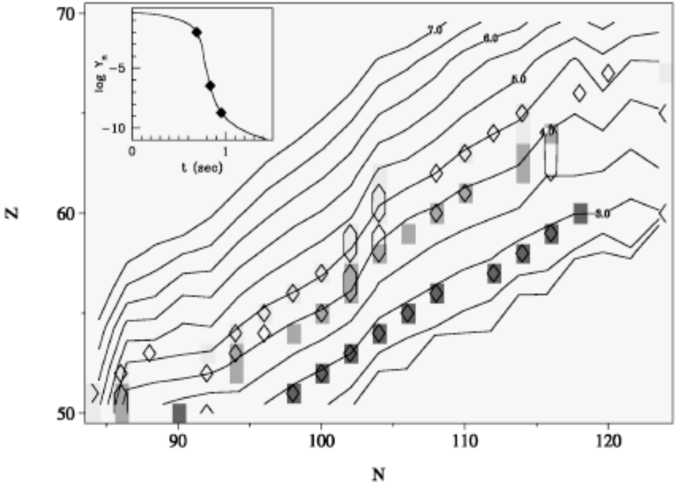
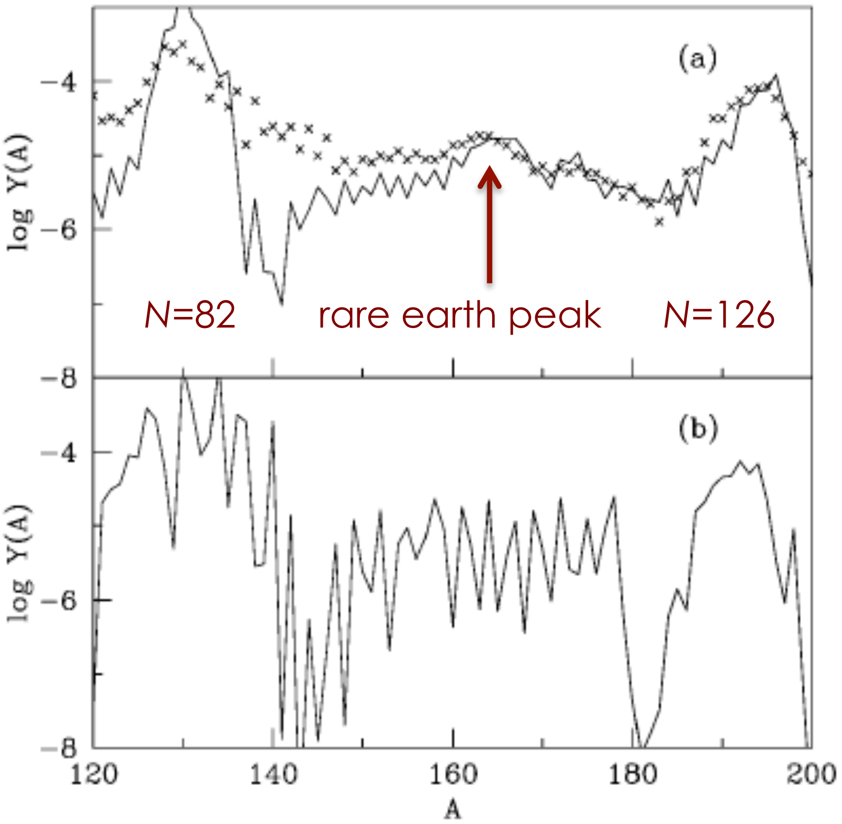
deducing *r*-process conditions from abundance pattern details: the rare earth peak

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



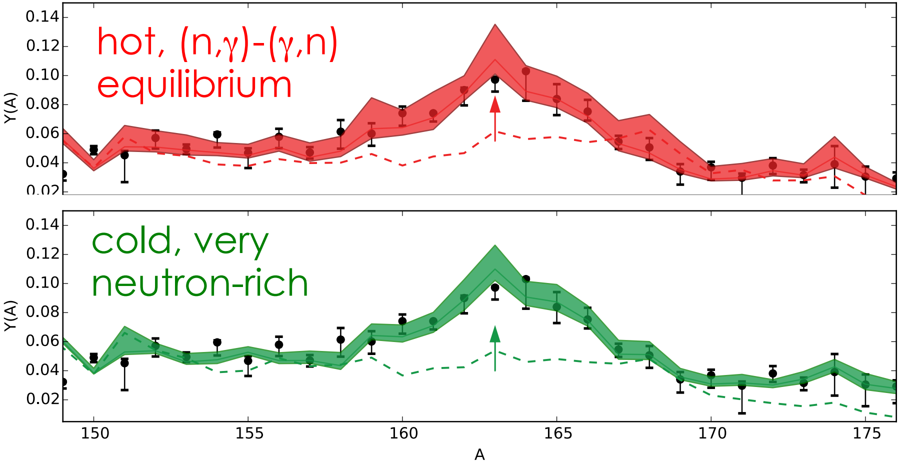
Surman+1998



deducing *r*-process conditions from abundance pattern details: the rare earth peak

mass modification parameterization:

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



Mumpower, McLaughlin, Surman, Steiner, 2016

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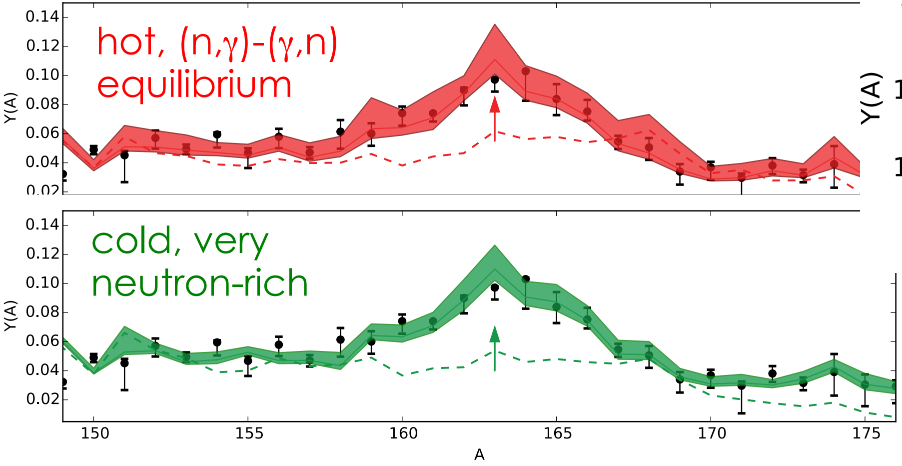

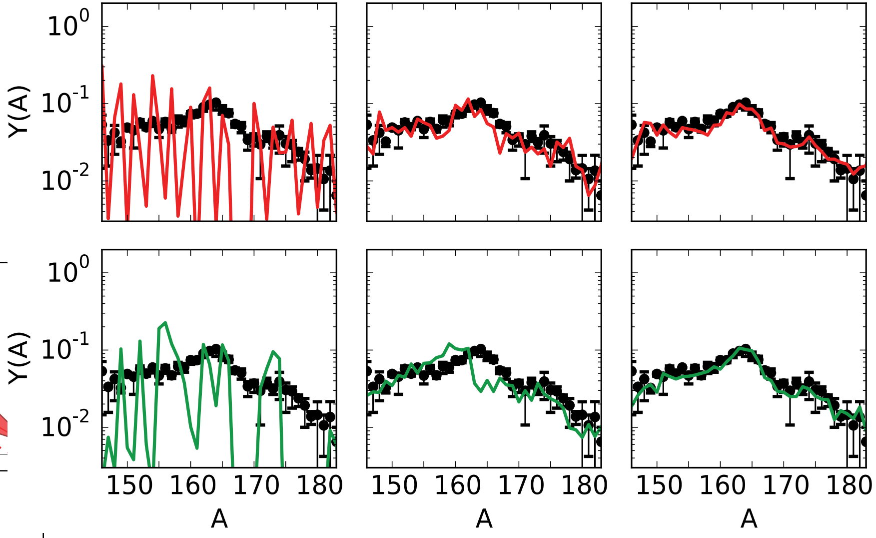

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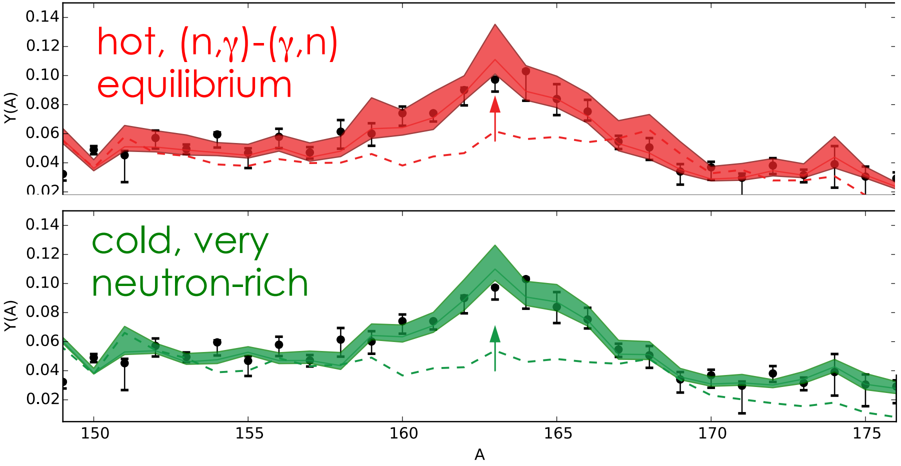
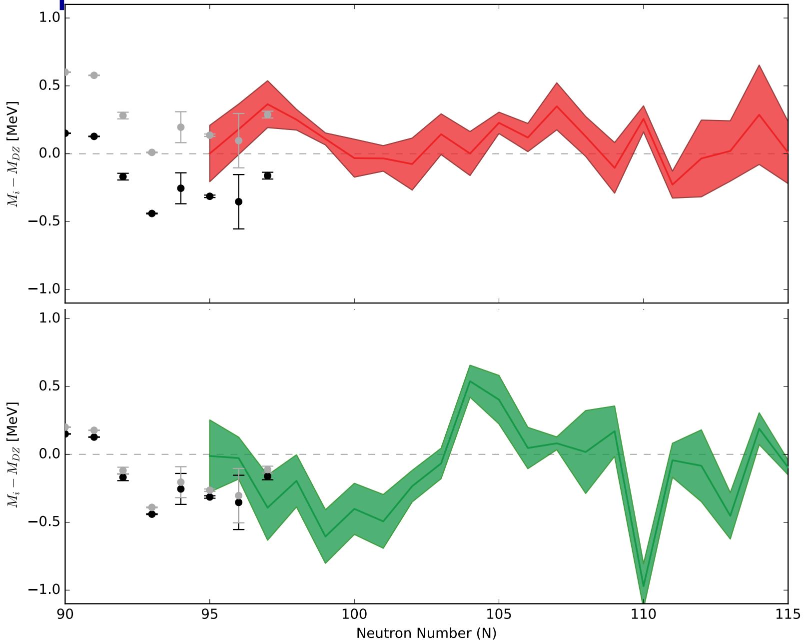
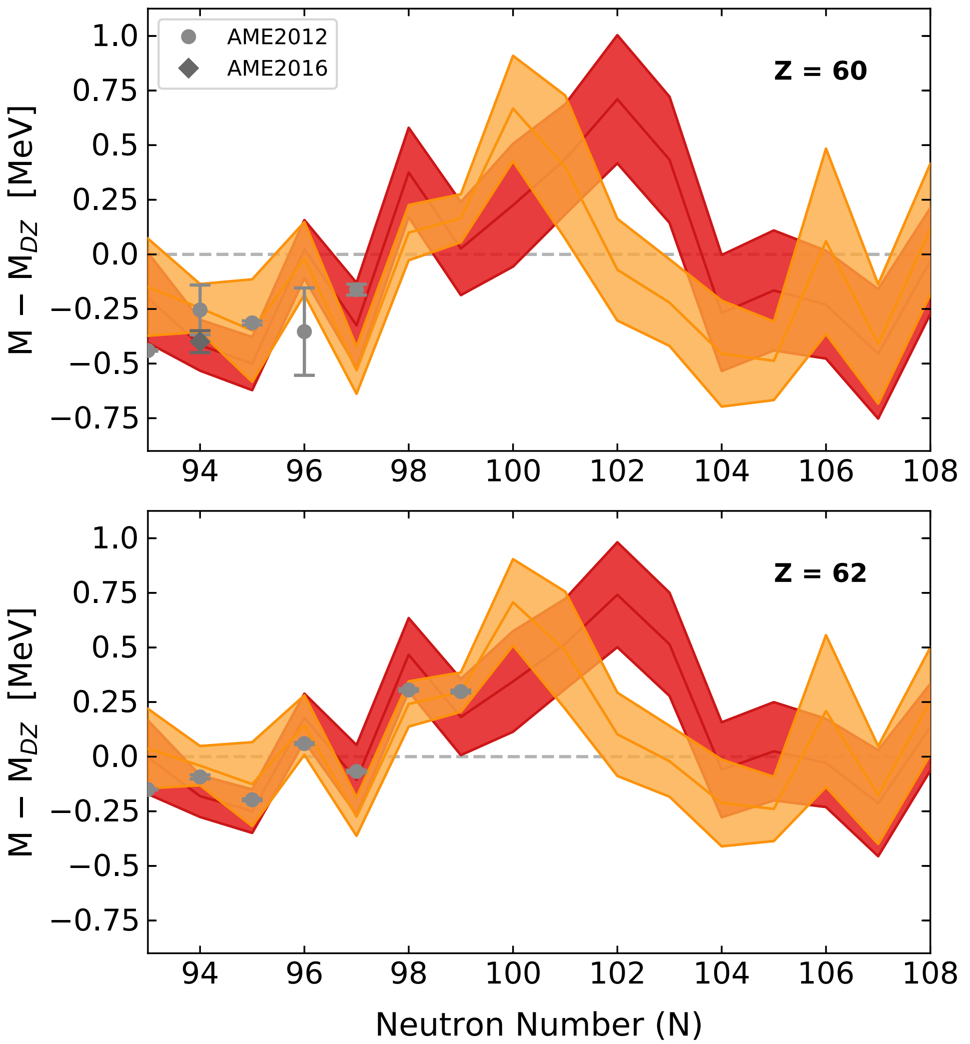




predicted mass trends for the Neodymium (Z = 60) isotopic chain

Mumpower, McLaughlin, Surman, Steiner, 2016

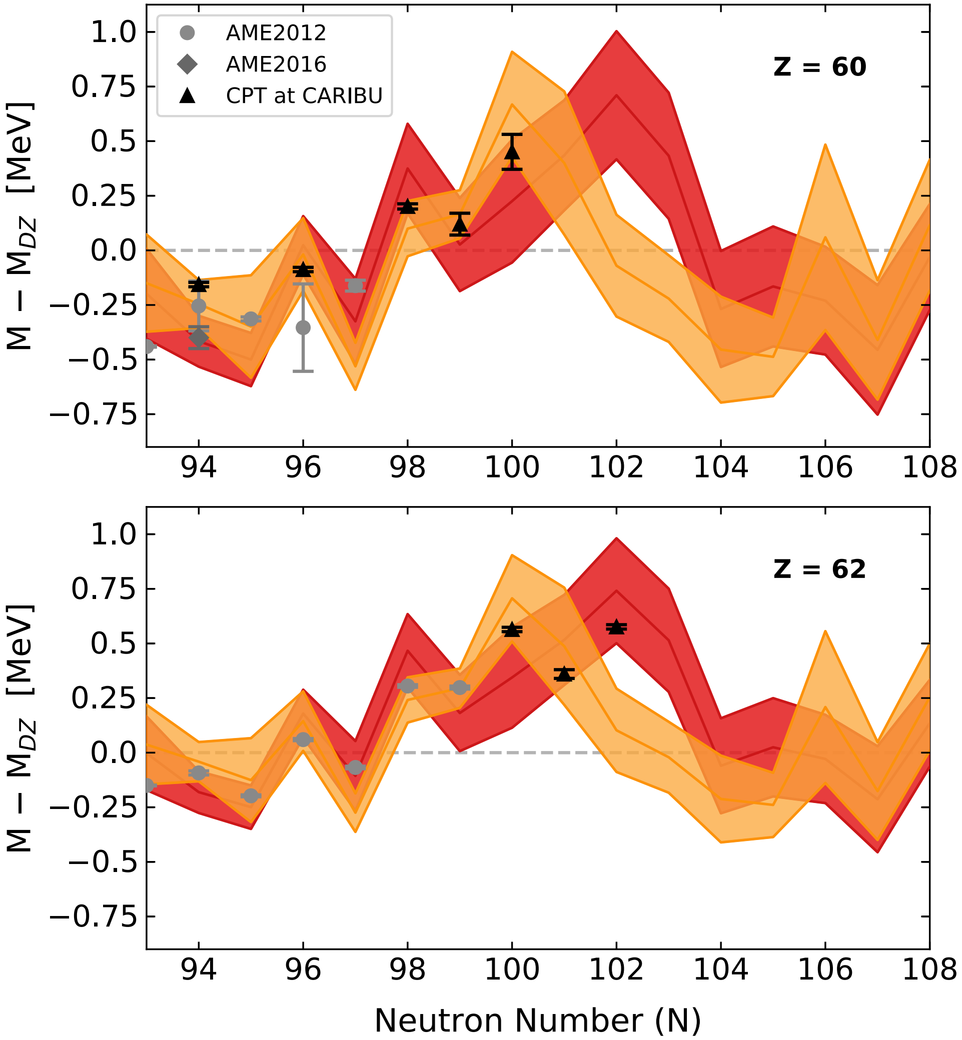
updated reverse engineering calculations



hot, (n,γ)-(γ,n) equilibrium example

In preparation, figure by Nicole Vassh

updated reverse engineering calculations



hot, (n,γ)-(γ,n) equilibrium example

In preparation, figure by Nicole Vassh

summary

The origin of the heaviest elements in the *r*-process of nucleosynthesis has been one of the greatest mysteries in nuclear astrophysics for decades.

Evidence from a variety of directions – including the neutron star merger discovery GW170817/GRB170817A/SSS17a – increasingly points to neutron star mergers as an important source of *r*-process elements, but more work is needed.

For the NSM electromagnetic signal to be fully understood, advances in astrophysical modeling, neutrino oscillation physics, and nuclear physics are required. On the nuclear side, the next generation of radioactive beam facilities offers great promise to reach the increasingly neutron-rich nuclei that are key for *r*-process abundance predictions.