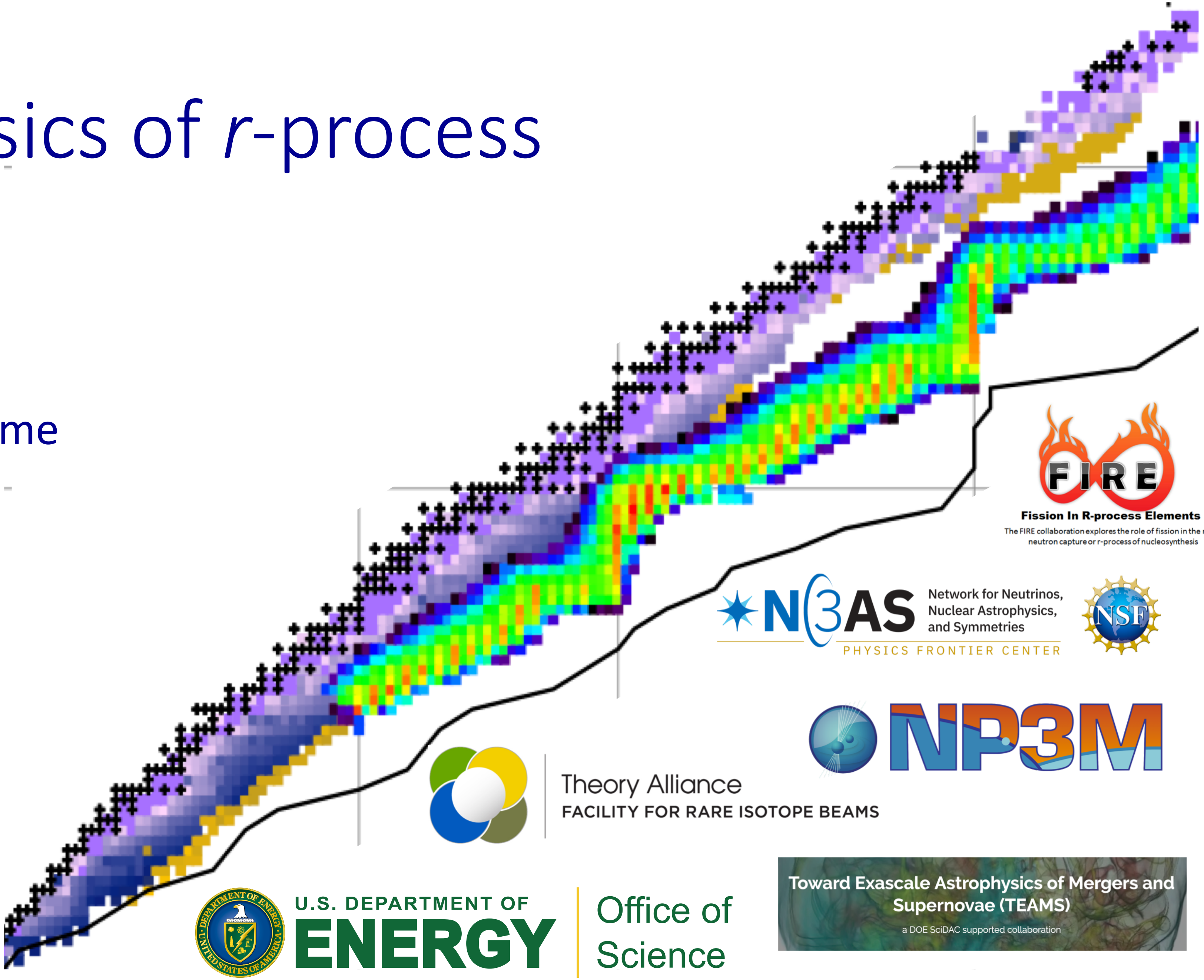
Nuclear physics of *r*-process observables

Rebecca Surman
University of Notre Dame

MICRA, ECT*
15 Sept 2023



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

N3AS
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

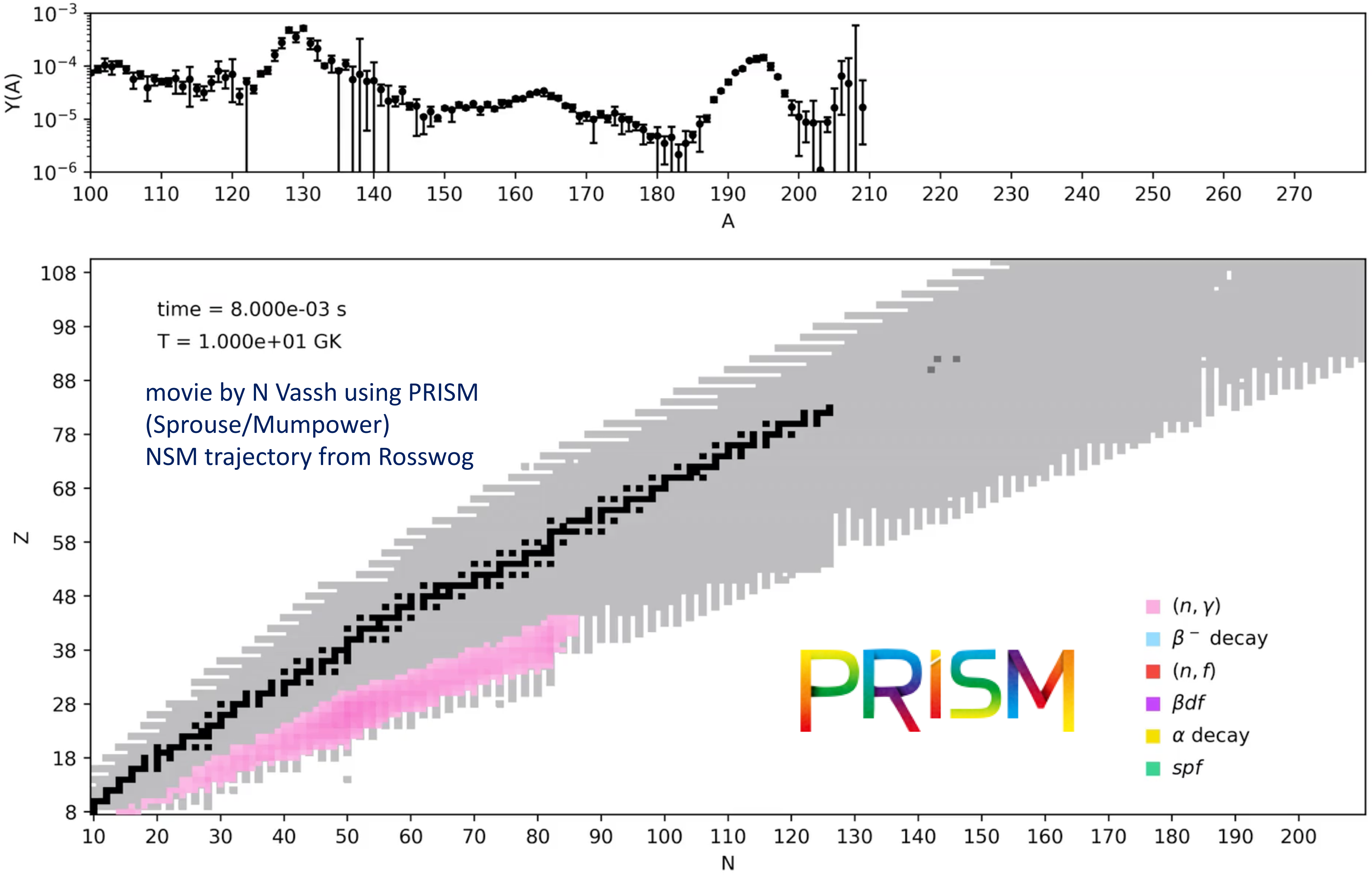
NSF

NP3M

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

U.S. DEPARTMENT OF ENERGY
Office of Science

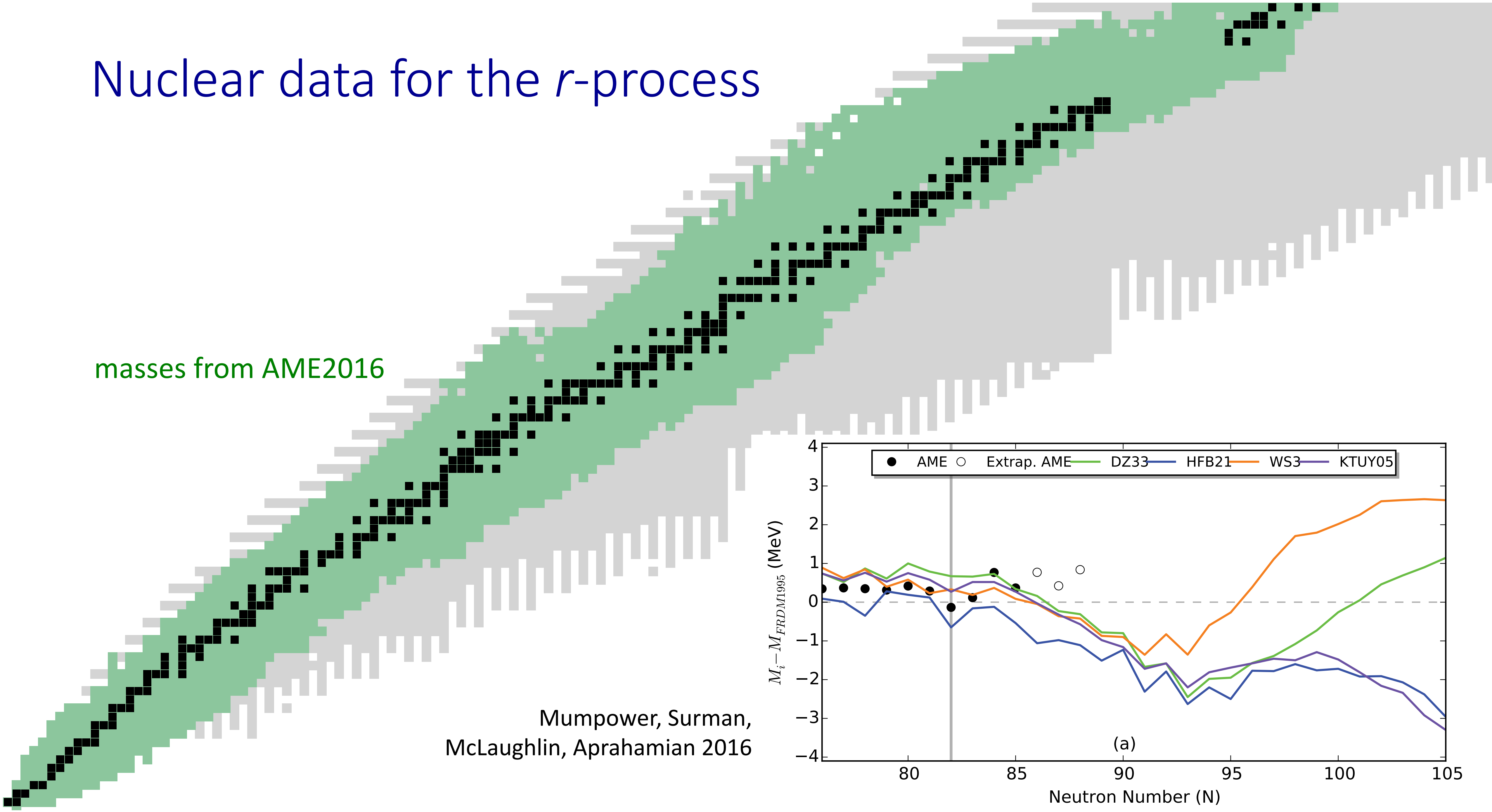
Toward Exascale Astrophysics of Mergers and Supernovae (TEAMS)
a DOE SciDAC supported collaboration



Y(A)
A
time = 8.000e-03 s
T = 1.000e+01 GK
movie by N Vassh using PRISM
(Sprouse/Mumpower)
NSM trajectory from Rosswog
Z
N
PRISM
(n, γ)
β⁻ decay
(n, f)
βdf
α decay
spf

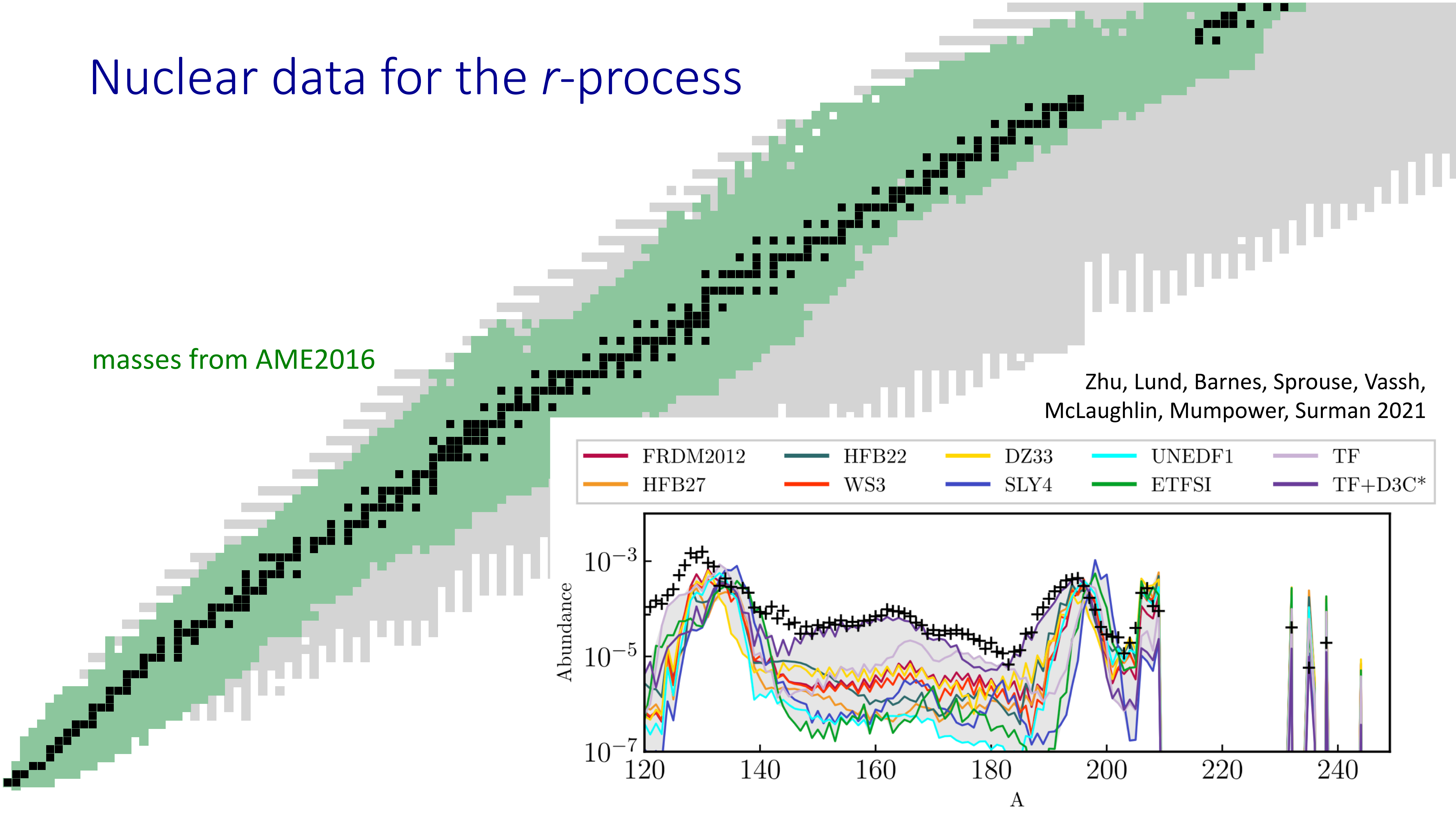
Nuclear data for the *r*-process

masses from AME2016



Mumpower, Surman,
McLaughlin, Aprahamian 2016

Nuclear data for the *r*-process

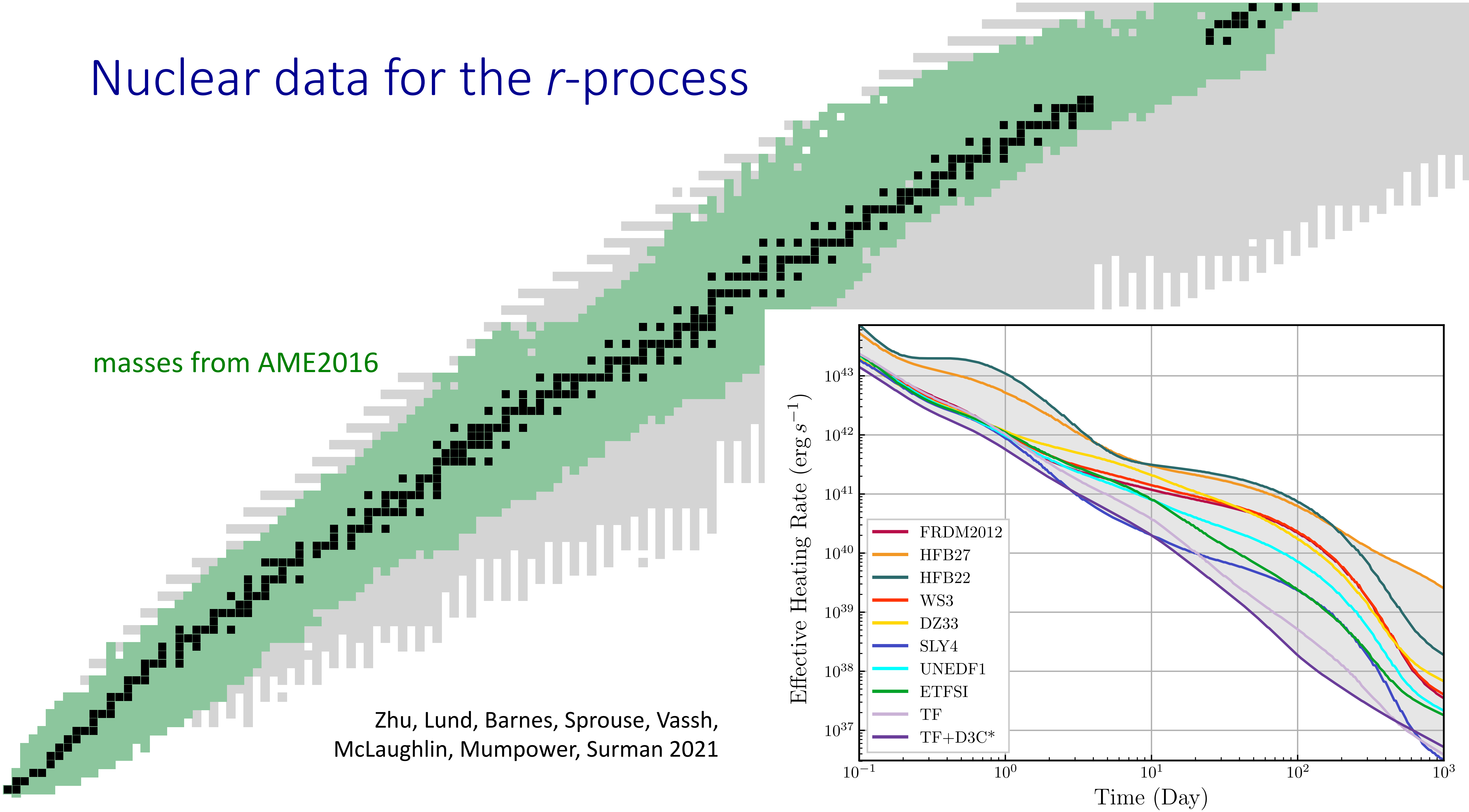


Zhu, Lund, Barnes, Sprouse, Vassh, McLaughlin, Mumpower, Surman 2021

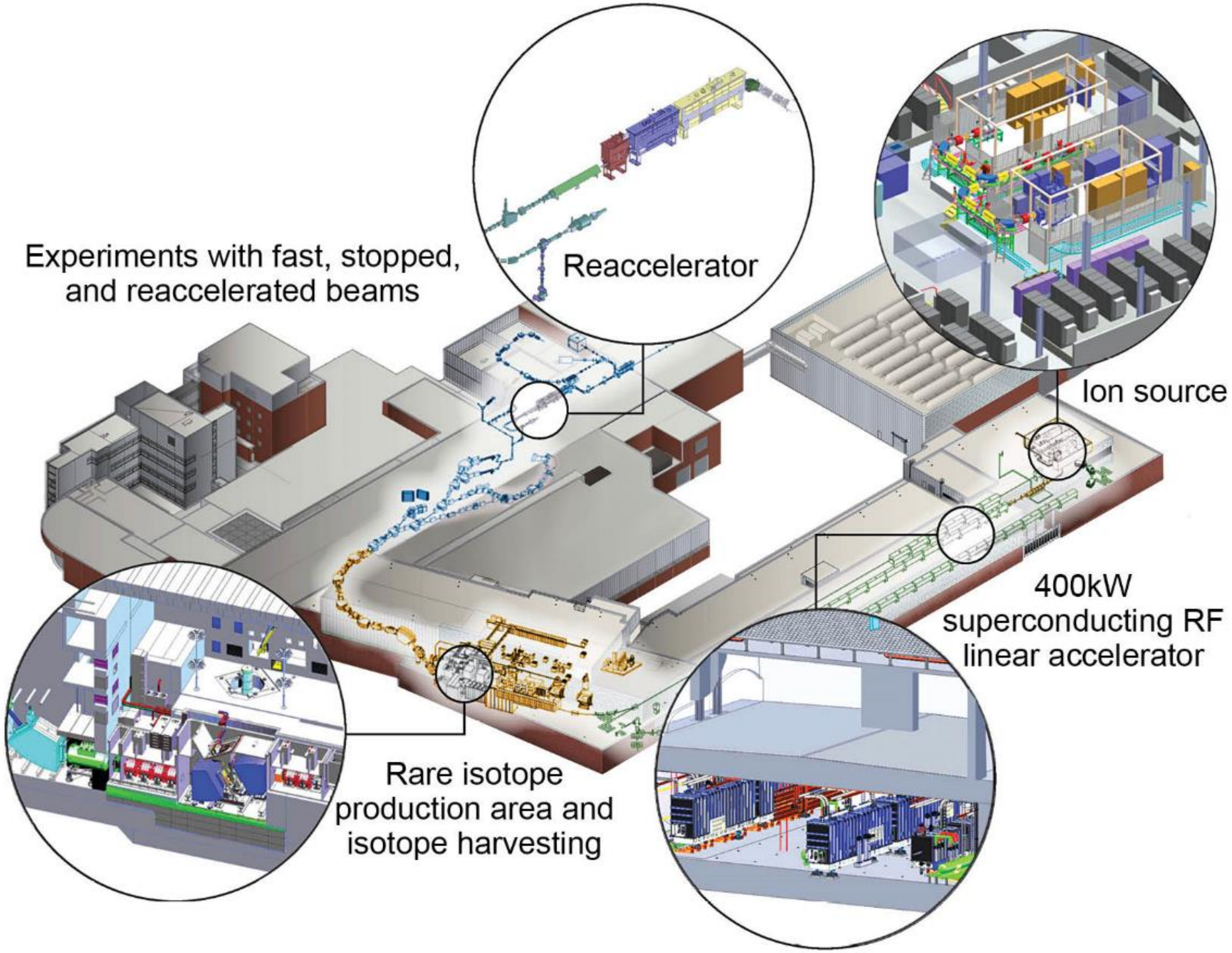
Nuclear data for the *r*-process

masses from AME2016

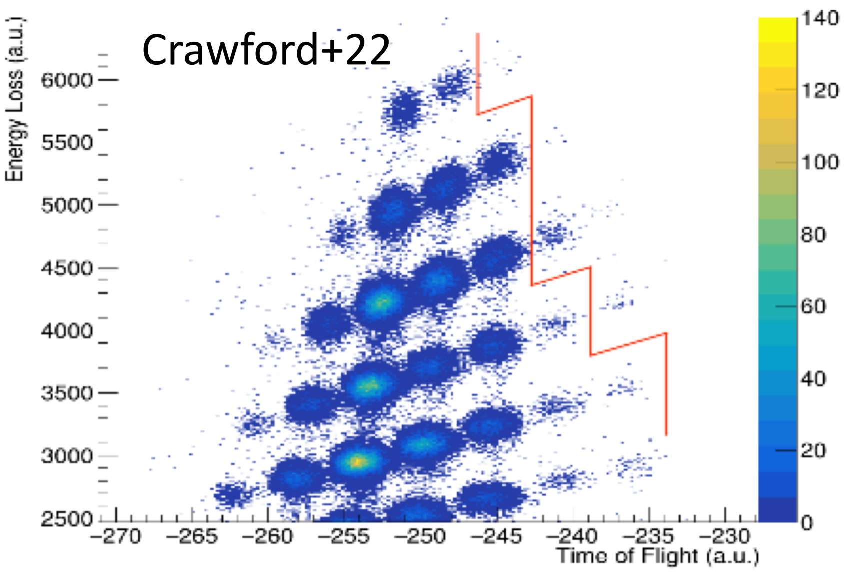
Zhu, Lund, Barnes, Sprouse, Vassh, McLaughlin, Mumpower, Surman 2021



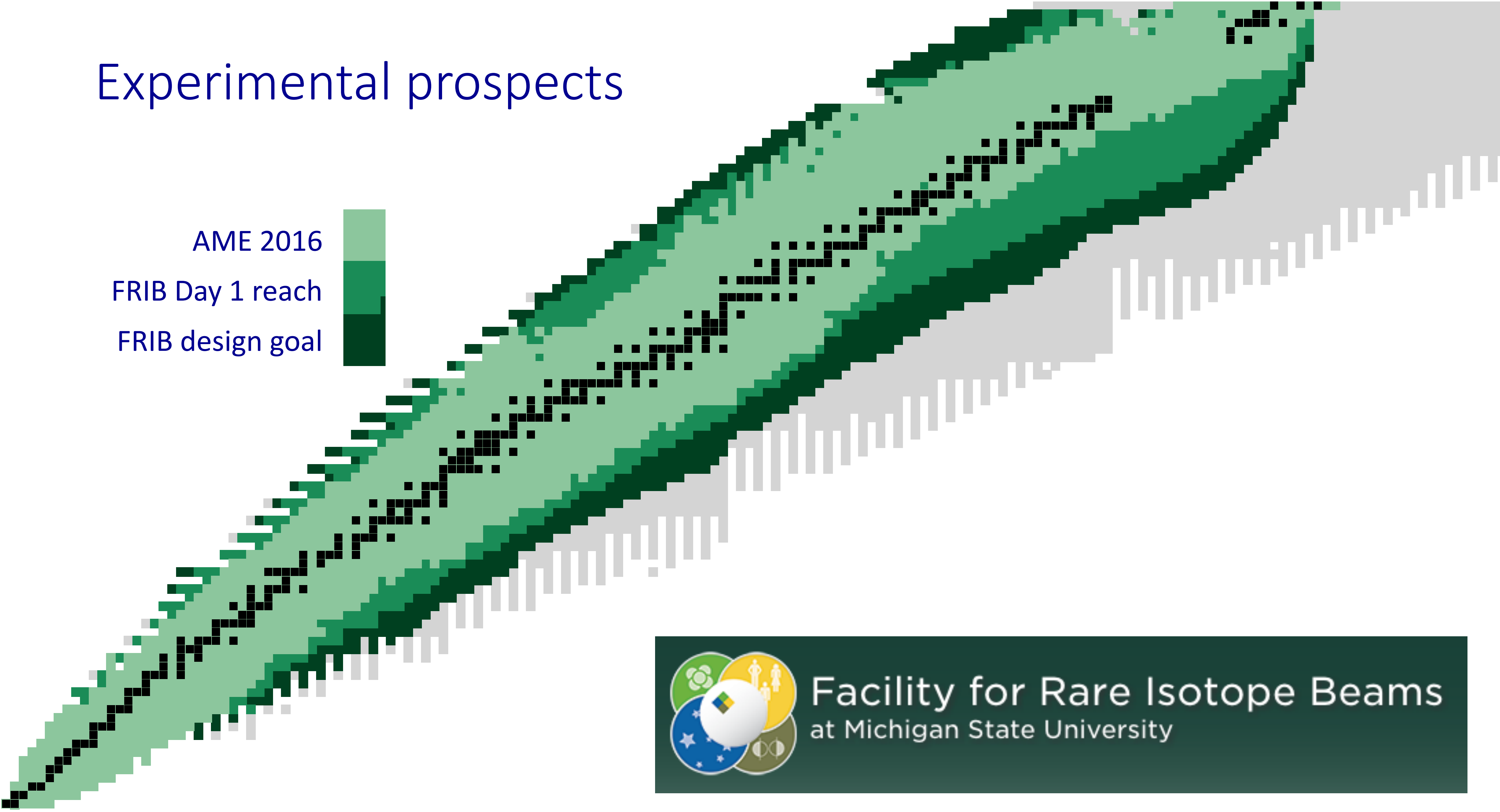
Facility for Rare Isotope Beams



First experiment started 9 May 2022



Experimental prospects



Facility for Rare Isotope Beams
at Michigan State University

Interpreting observables of *r*-process nucleosynthesis

- What observables are currently limited by nuclear uncertainties that could be addressed in the FRIB era?

- Are there distinguishing observables that rise above nuclear uncertainties?

- What can we learn about nuclear physics far from stability from *r*-process observables?

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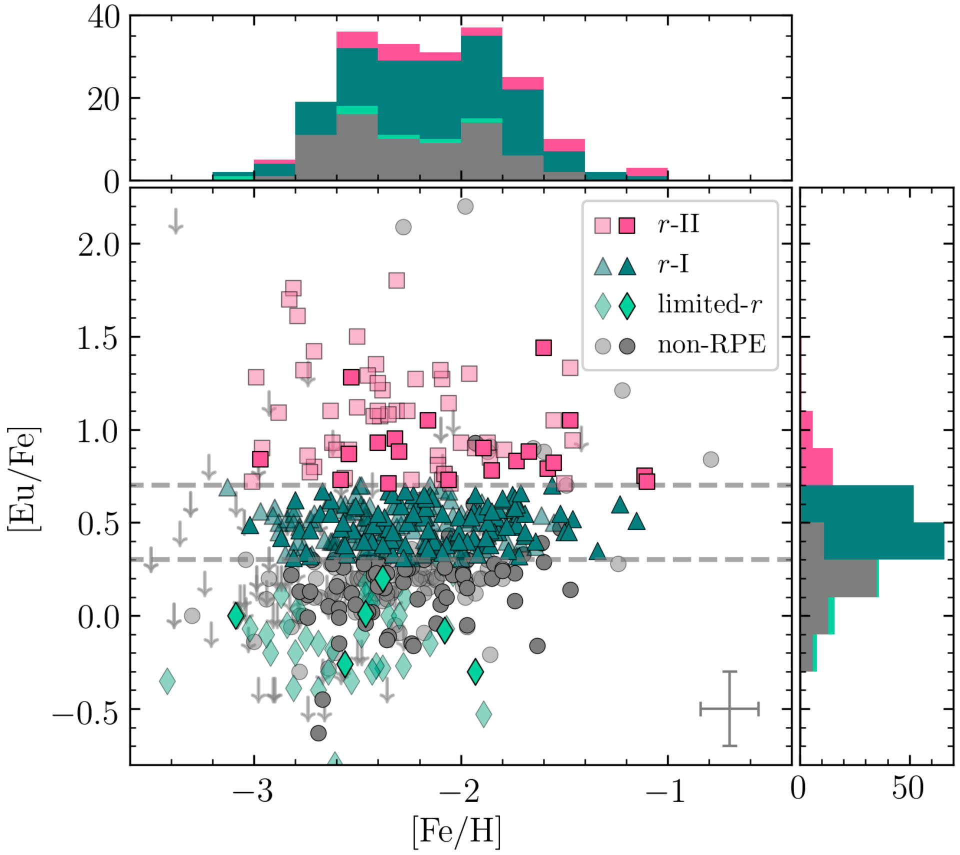
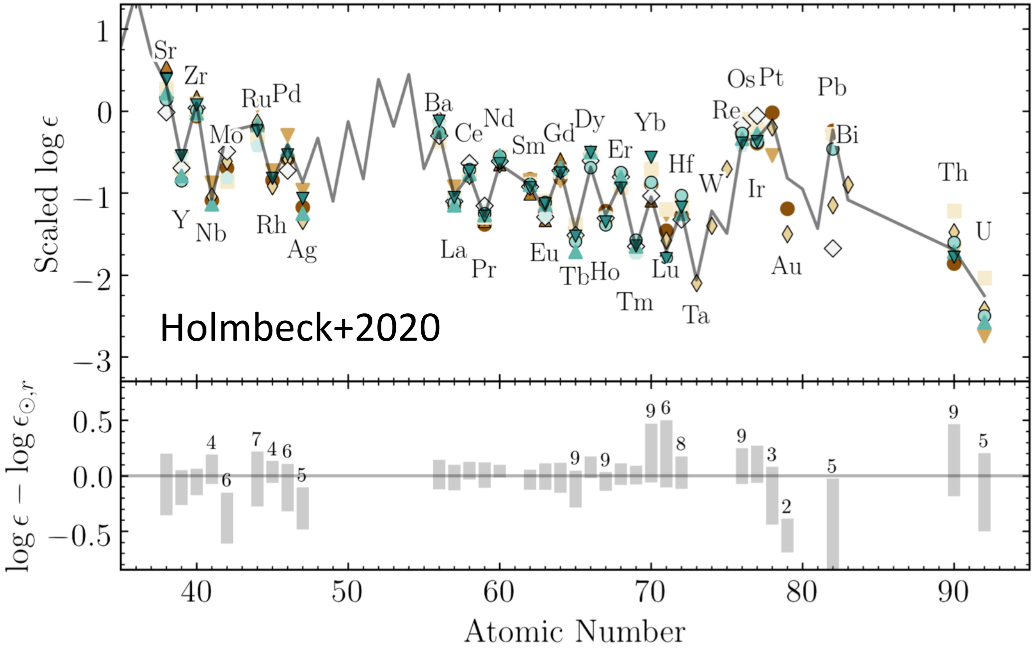
Abundances from metal-poor stars



Hansen+2018, Sakari+2018, Ezzeddine+2020, Holmbeck+2020

R-Process Alliance est. 2017



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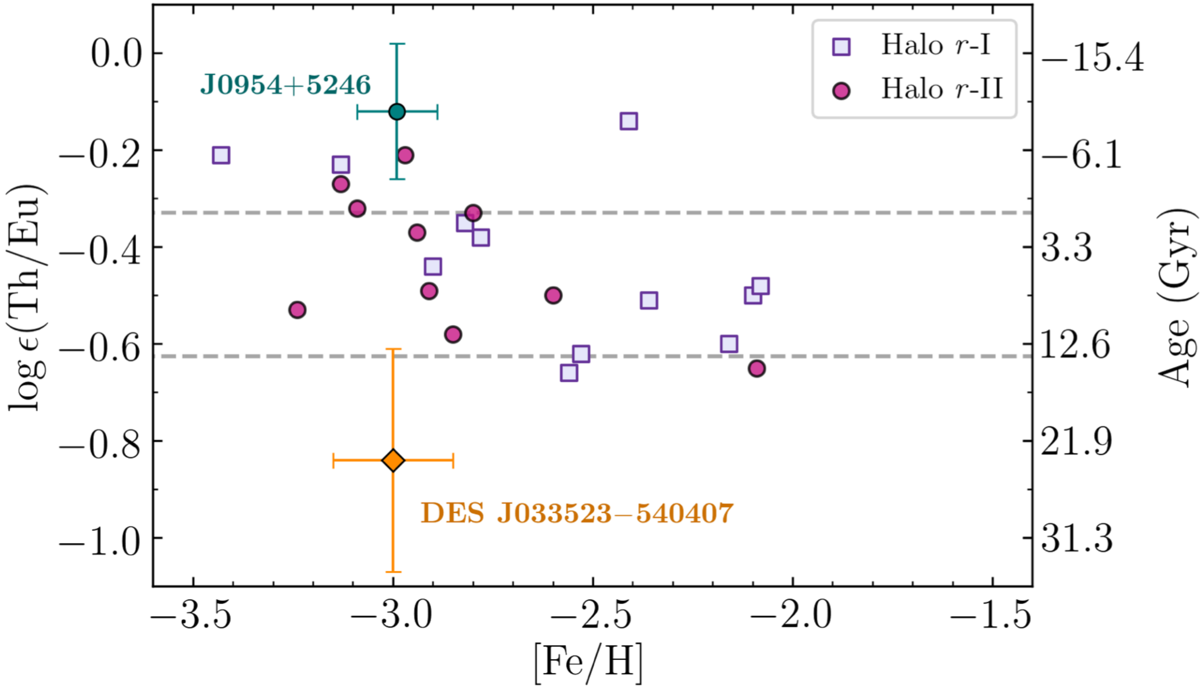
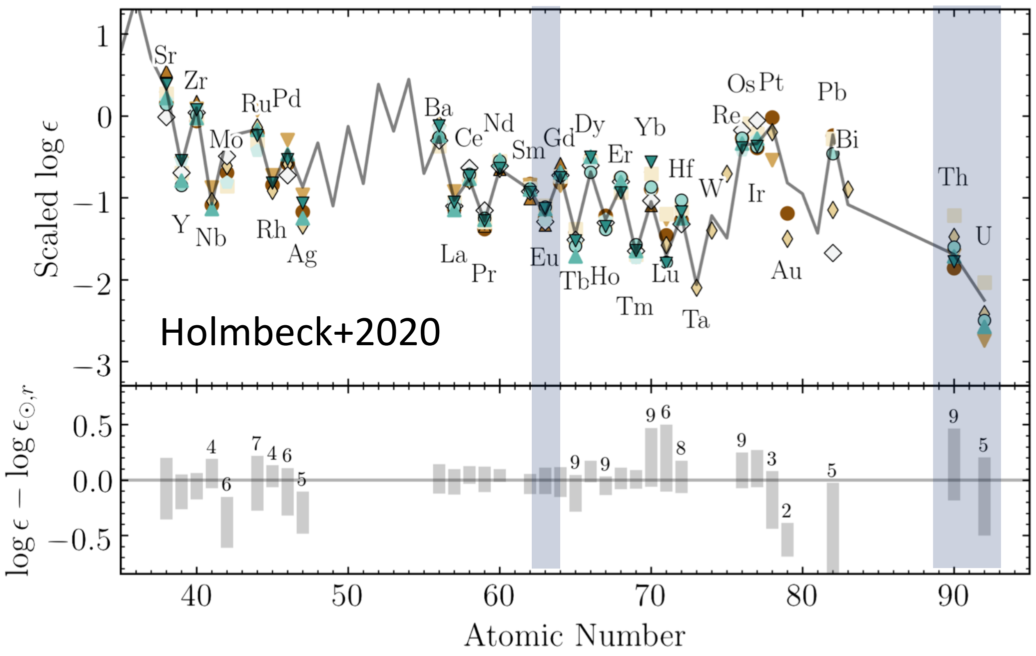
Actinide abundance variability



Holmbeck+2019

R-Process Alliance est. 2017



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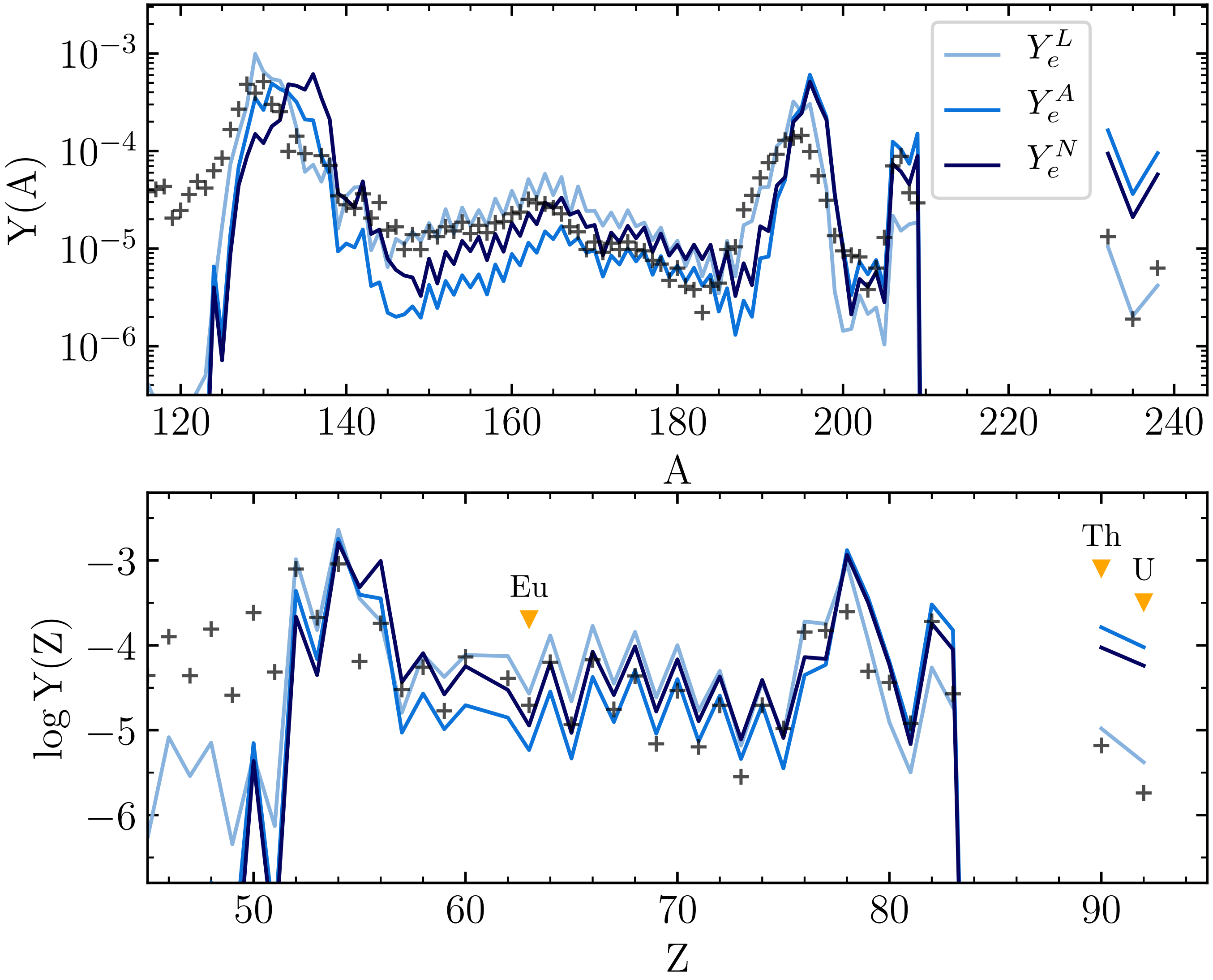
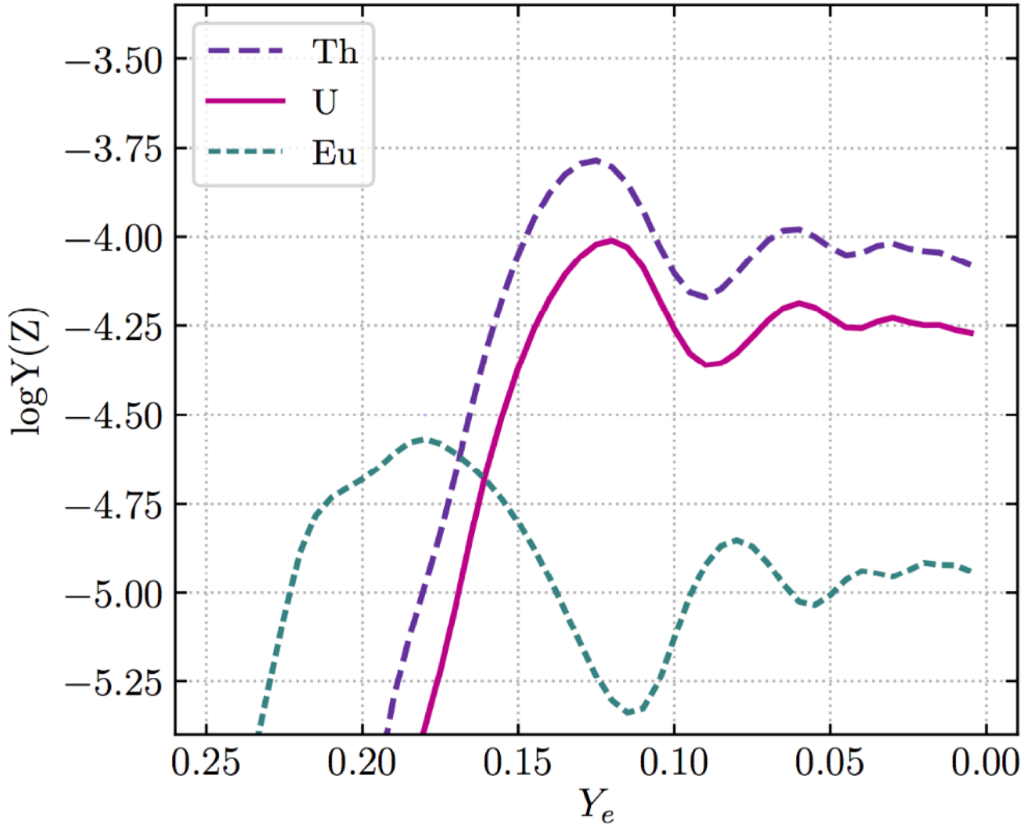
simulations of actinide production





Holmbeck, Sprouse, Mumpower, Vassh, Surman, Beers, Kawano 2019

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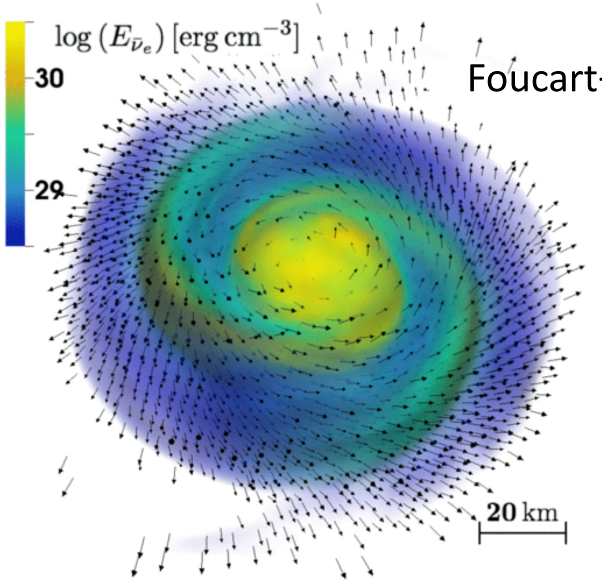
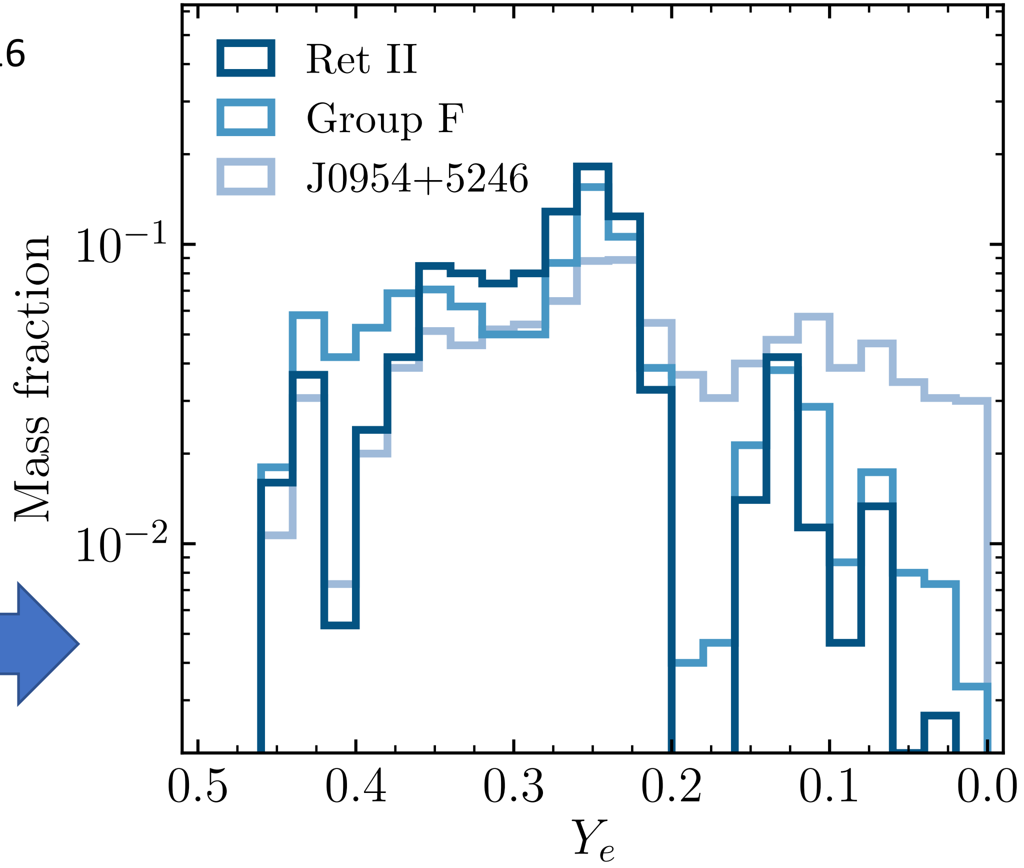
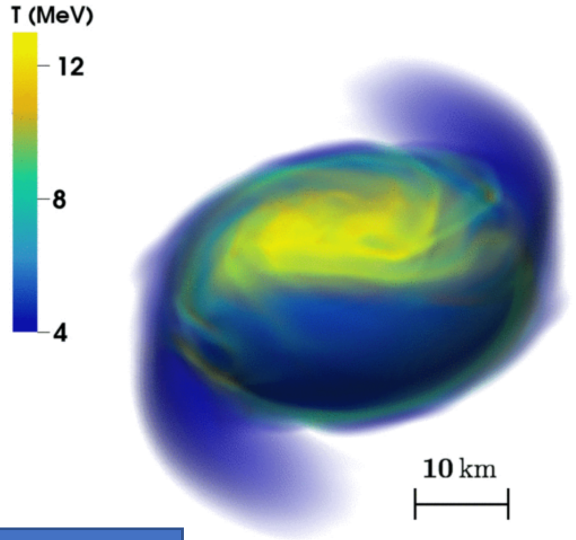
actinide dilution via two ejecta components



Foucart+16





accretion disk outflows are expected to be less neutron-rich

dynamical ejecta is expected to be very neutron-rich

Holmbeck, Frebel, McLaughlin, Mumpower, Sprouse, Surman 2019

$$Y_e = \frac{1}{1 + (n/p)}$$

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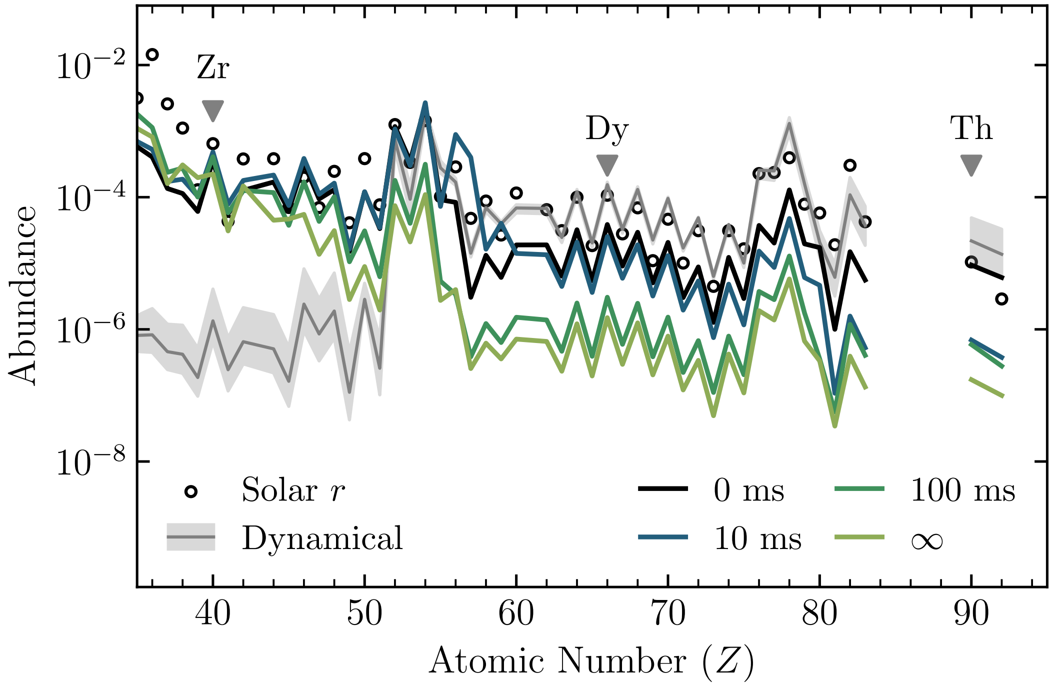
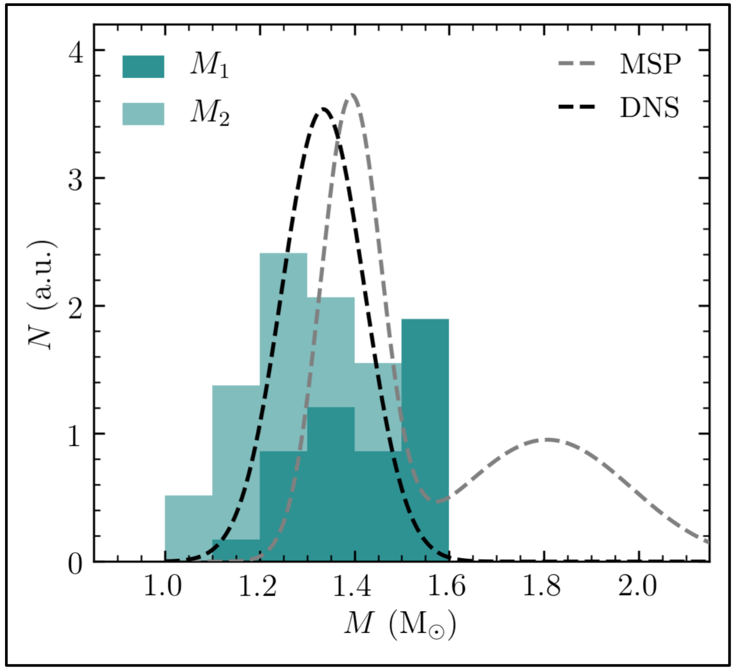
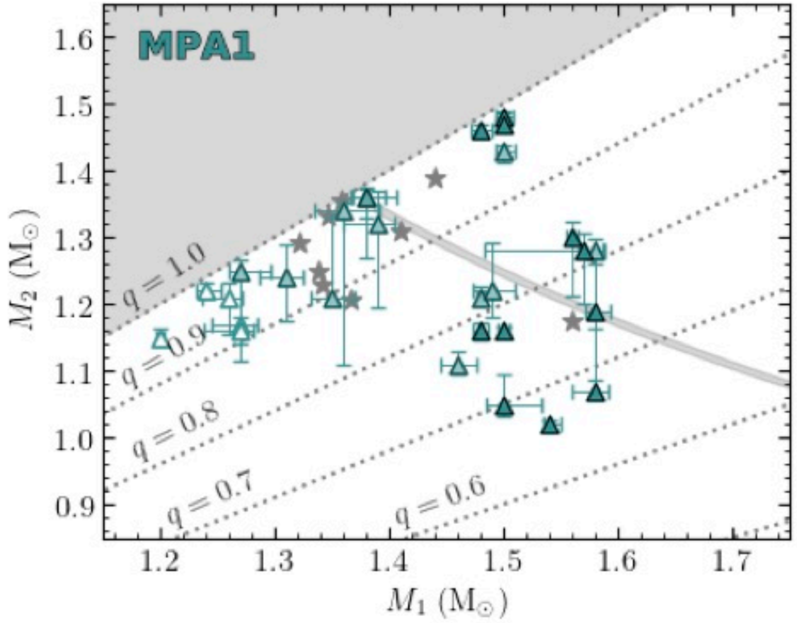
NSM properties from metal-poor star elemental ratios







Holmbeck, Frebel, McLaughlin, Surman, Fernandez, Metzger, Mumpower, Sprouse 2021

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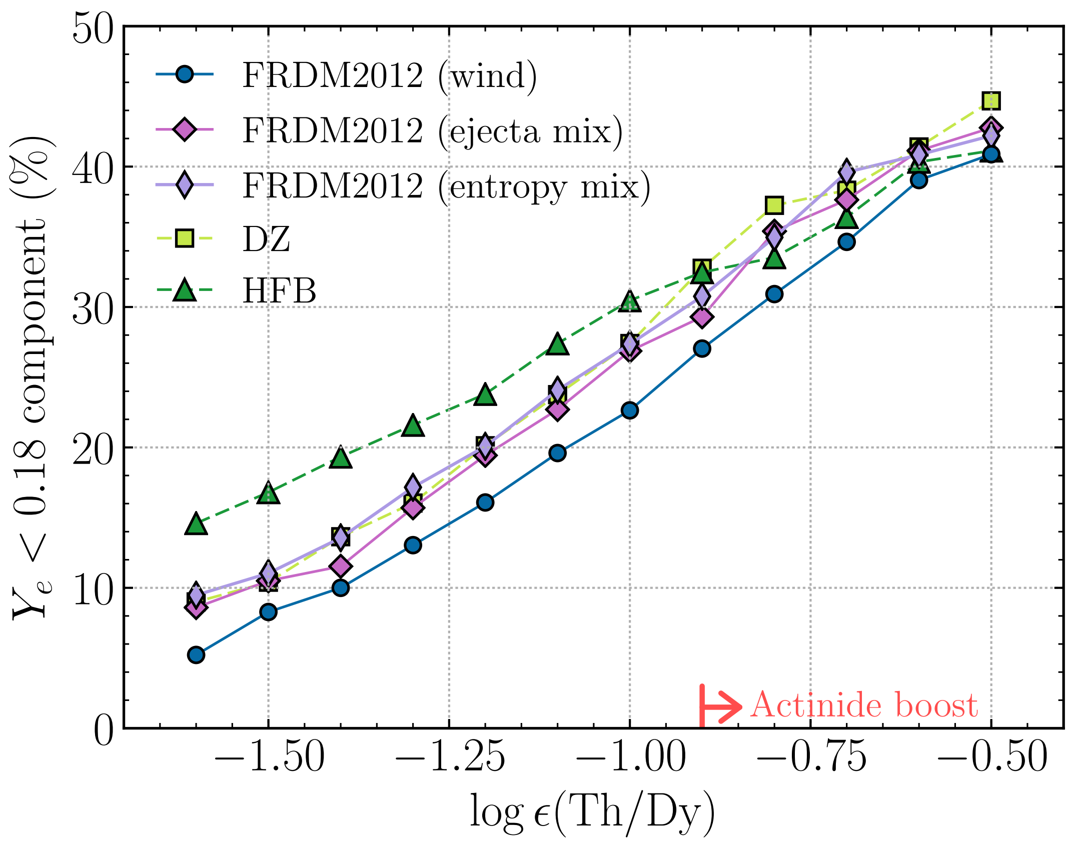
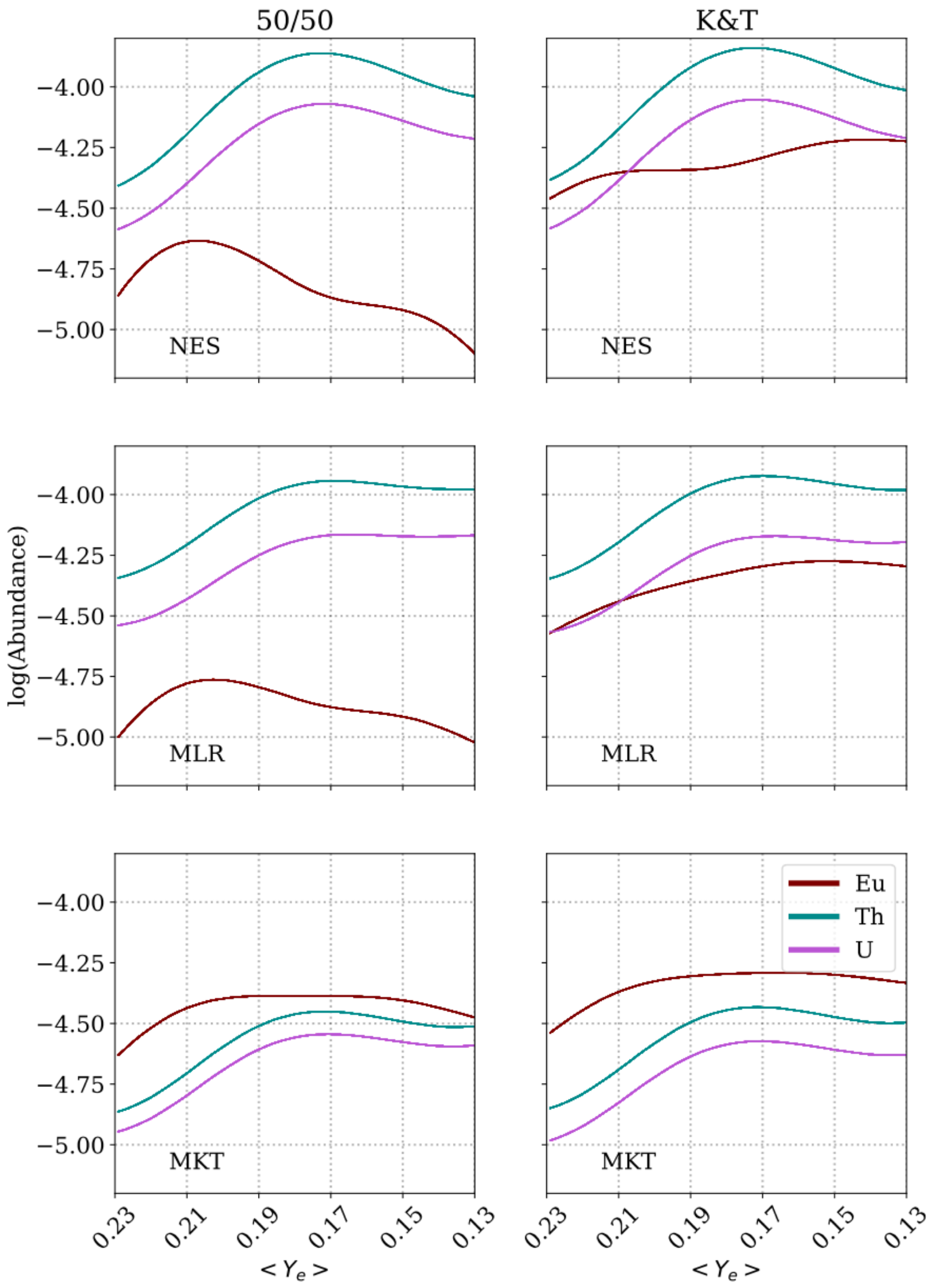
nuclear physics variations



Holmbeck, Frebel, McLaughlin, Mumpower, Sprouse, Surman 2019



Lund, Engel, McLaughlin, Mumpower, Ney, Surman 2023

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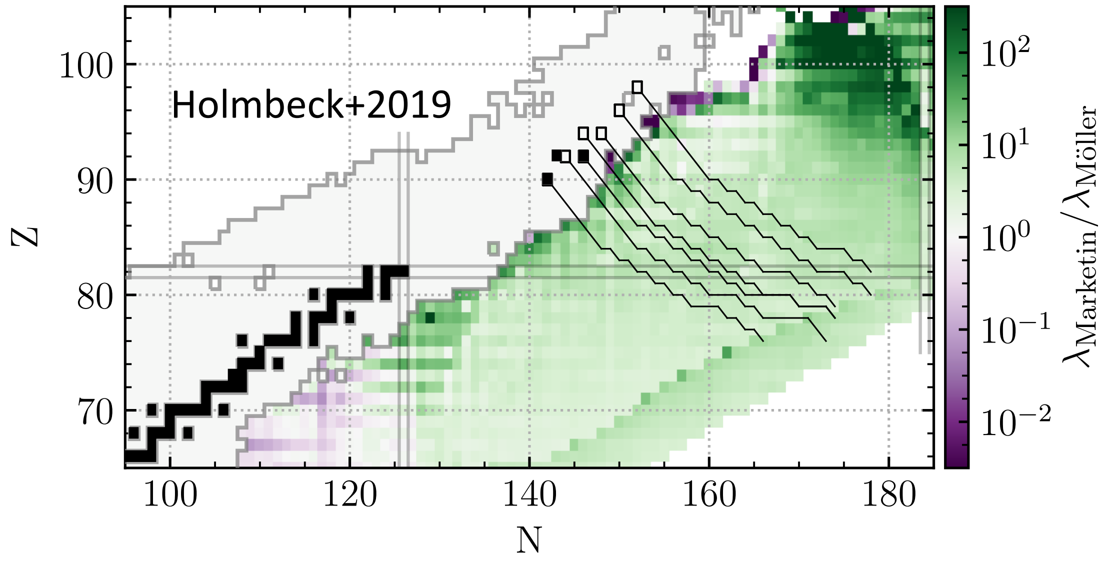
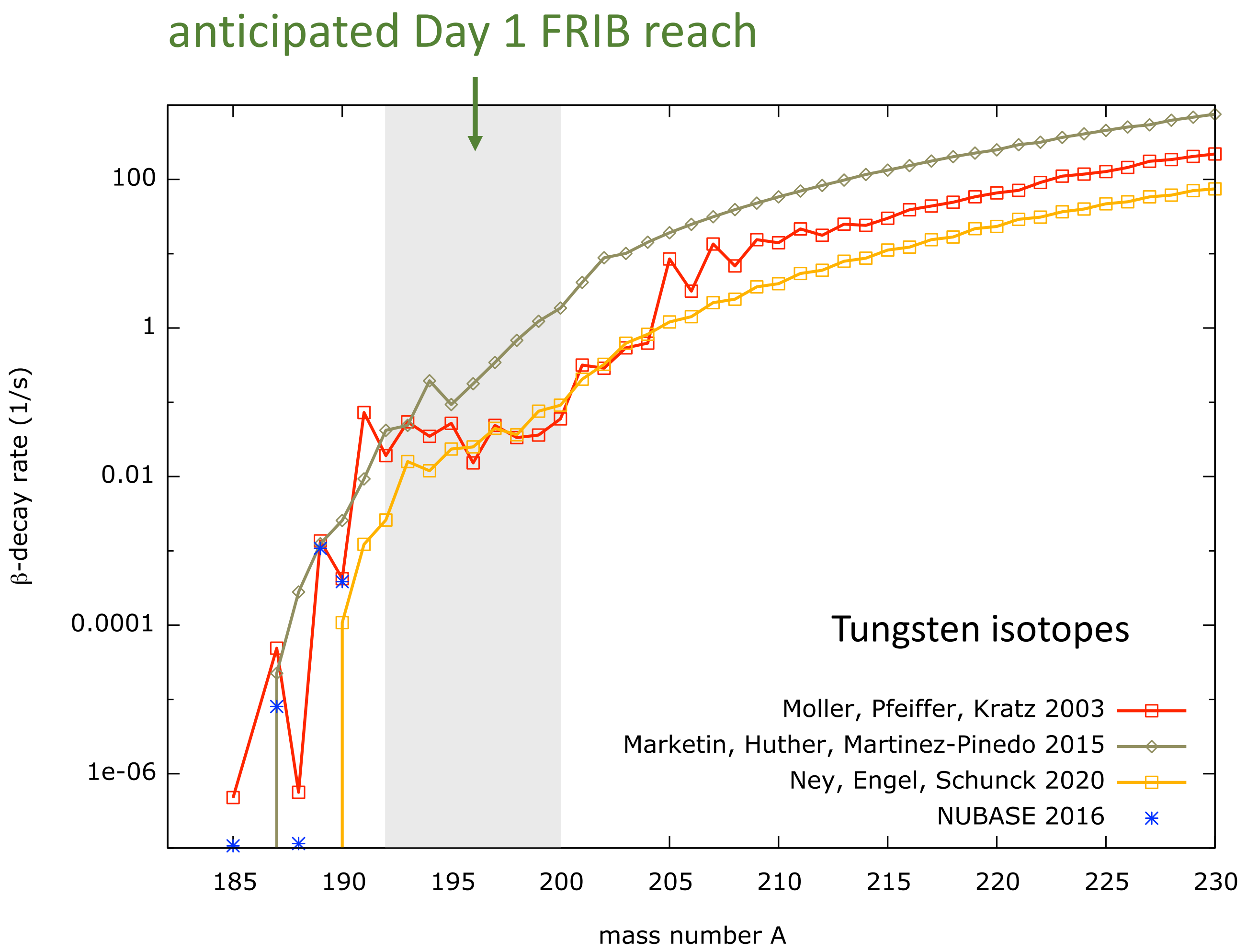
β decay and actinide production



Facility for Rare Isotope Beams
at Michigan State University

FRIB FDSi Day 1 proposal
N = 126 region halflives
Estrade+2021



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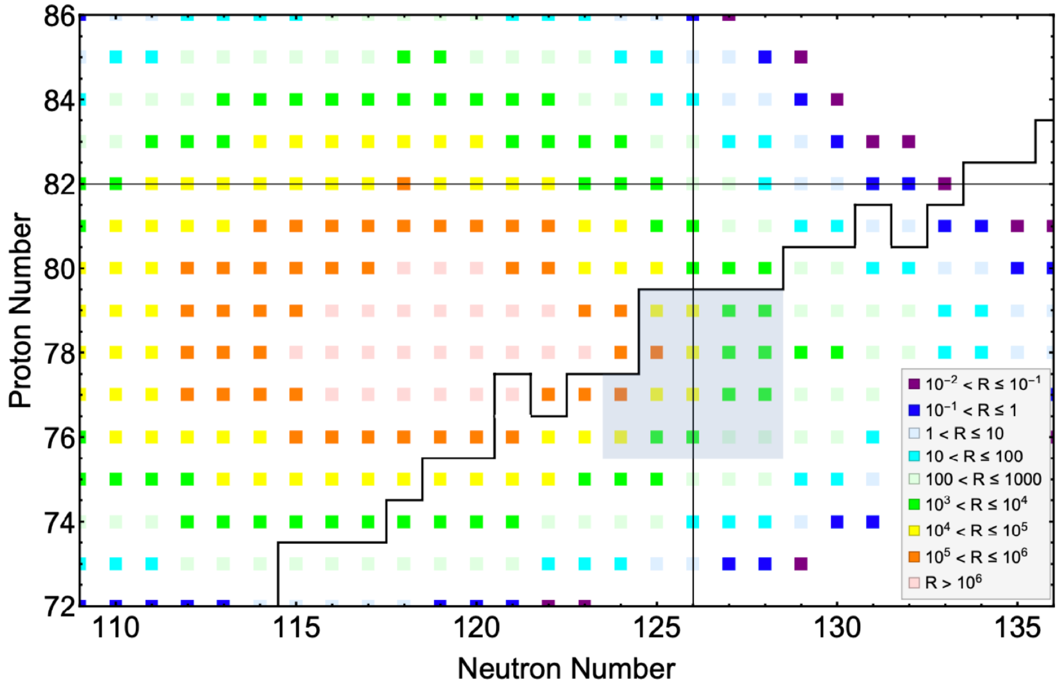
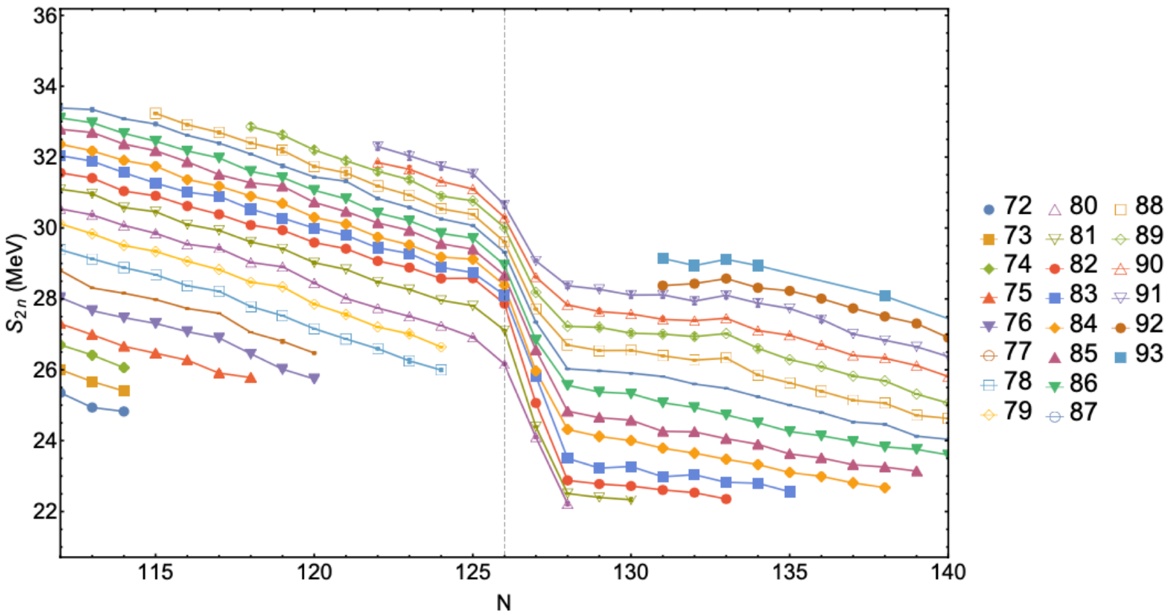
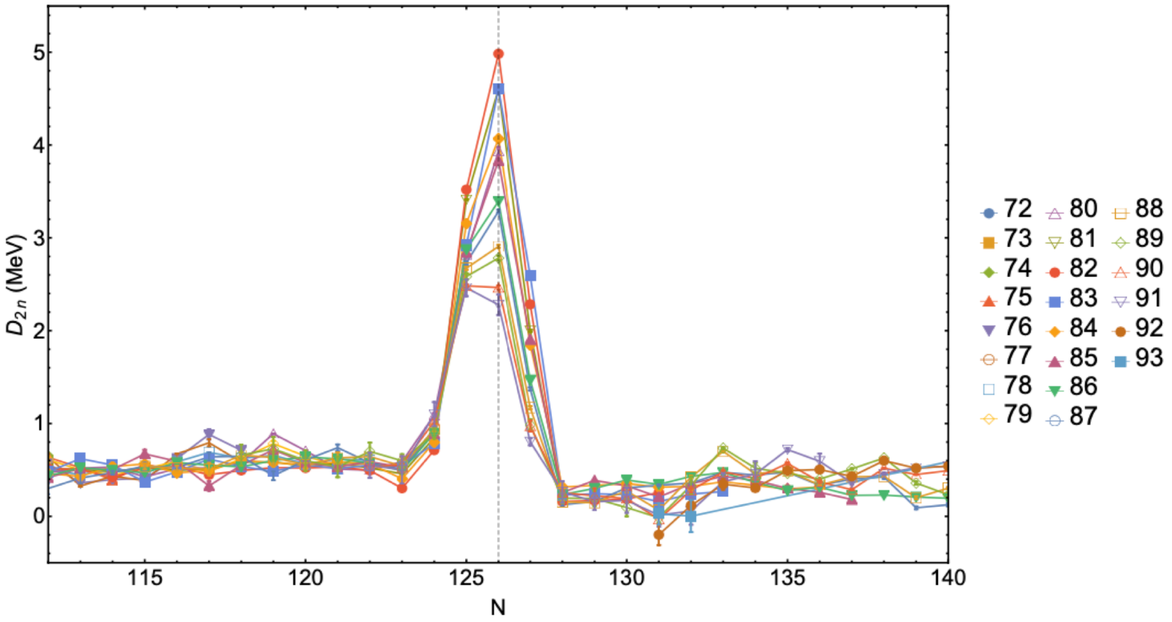
nuclear masses and actinide production







Argonne NATIONAL LABORATORY

ANL N = 126 Factory proposal
N = 126 region masses
Liu+2022

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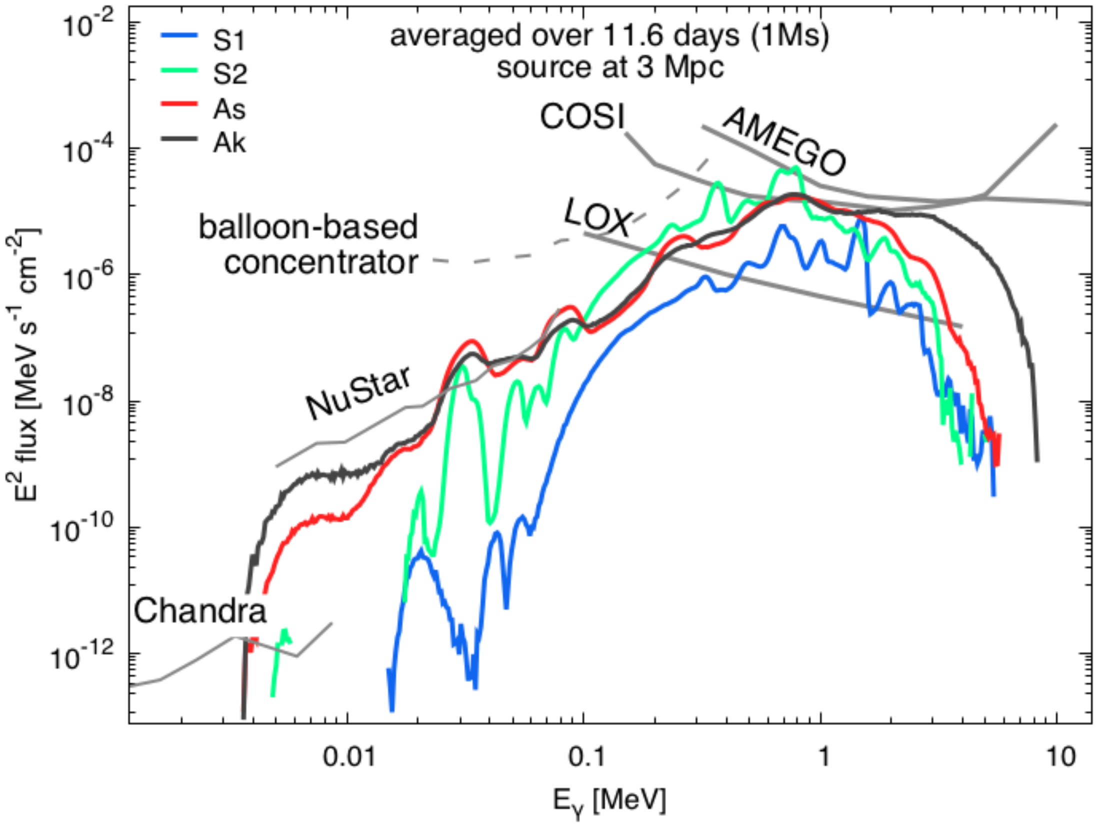
Actinide observables: gamma rays



Korobkin, Hungerford, Fryer, Mumpower, Misch, Sprouse, Lippuner, Surman, Couture, Bloser, Shirazi, Evan, Vestrand, Miller 2020

also Hotokezaka+2016; Li 2019; Wu+2019; Ruiz-Lapuente, Korobkin 2020

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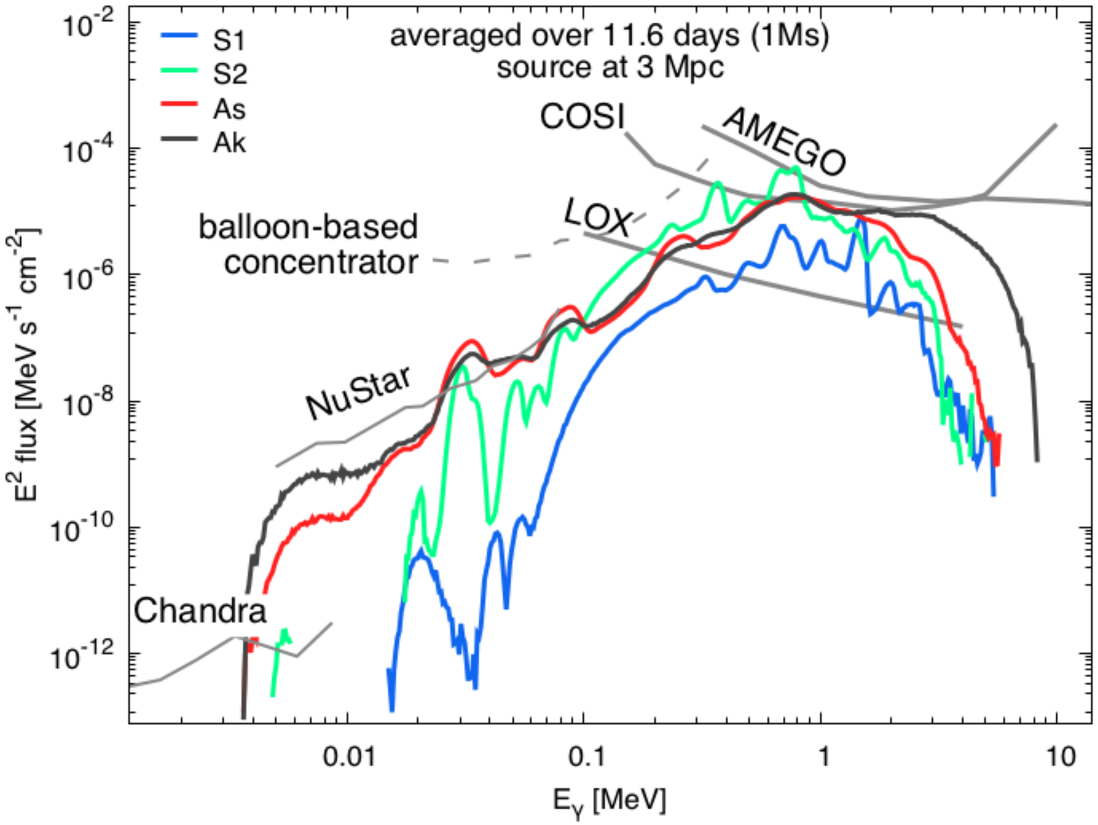

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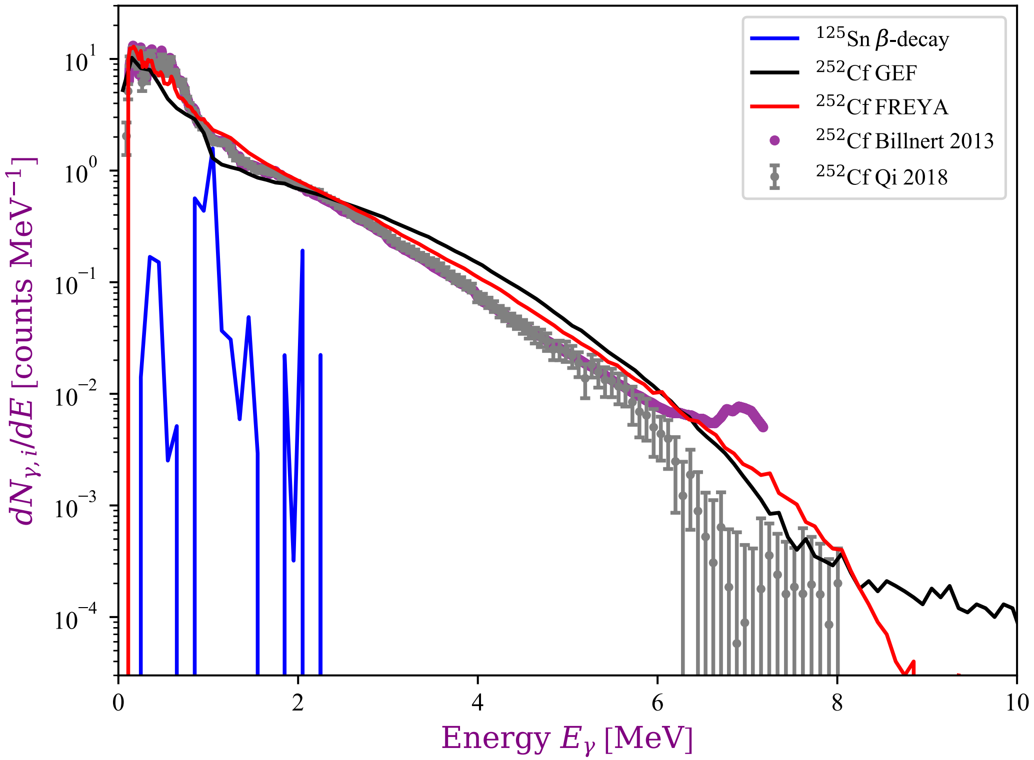

Wang, Vassh, Sprouse, Mumpower, Vogt, Randrup, Surman, ApJL 2020

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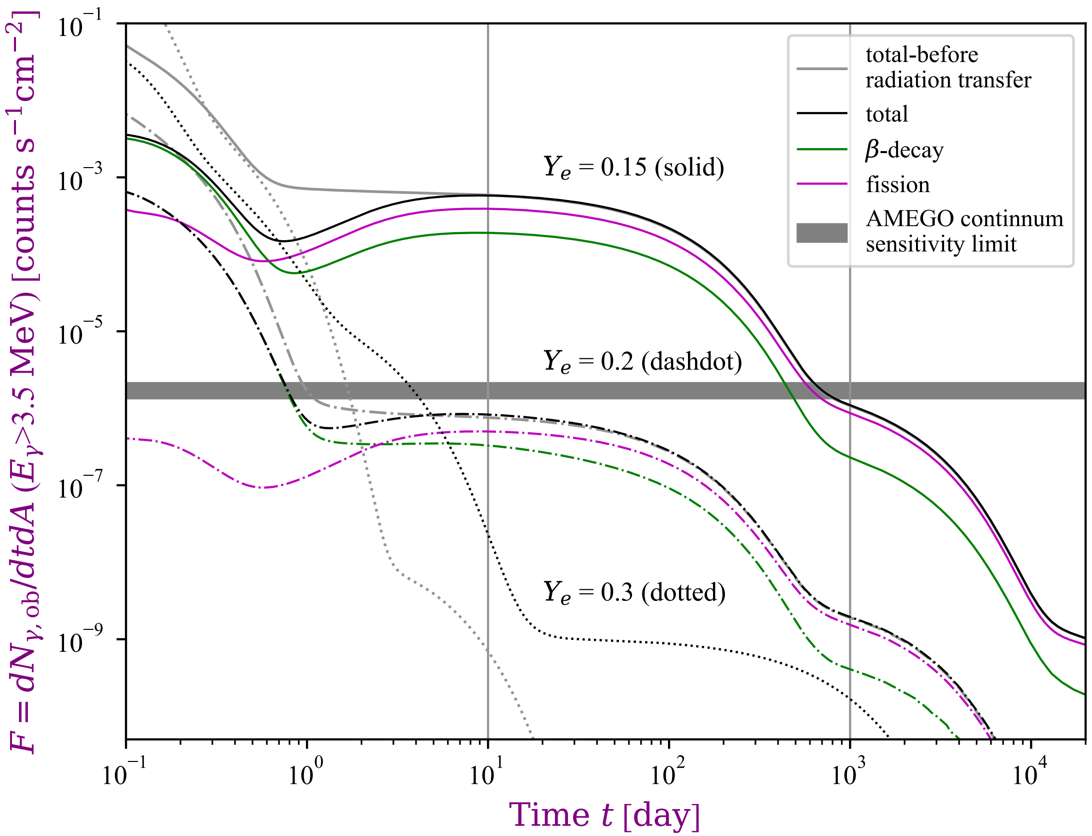

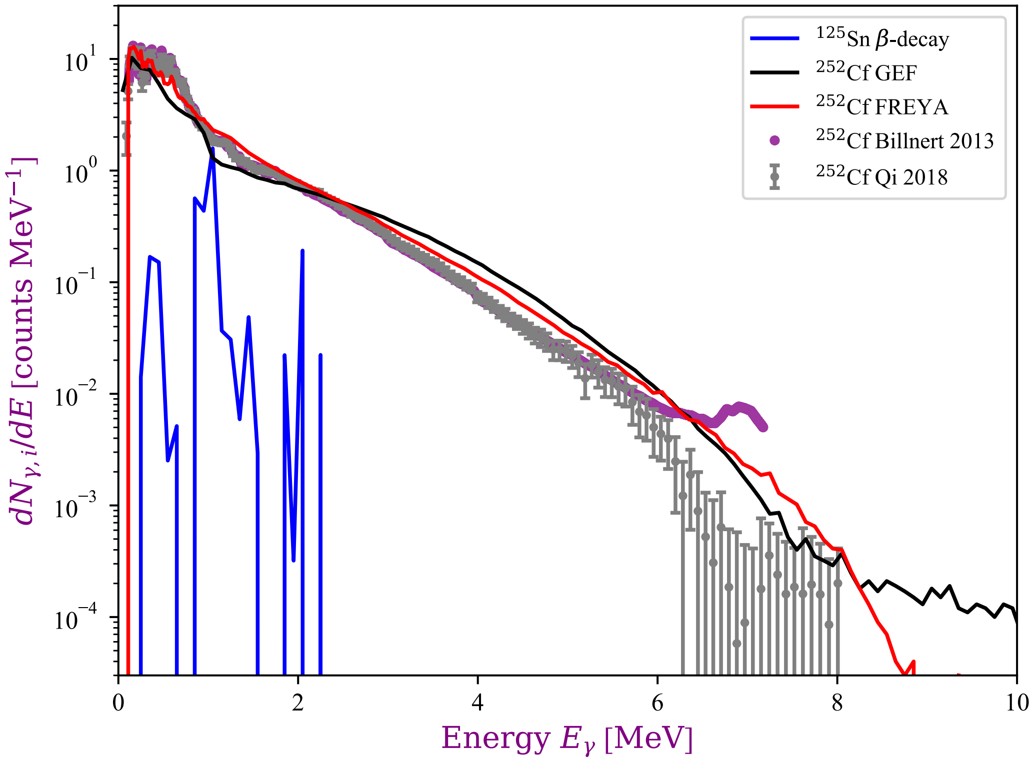

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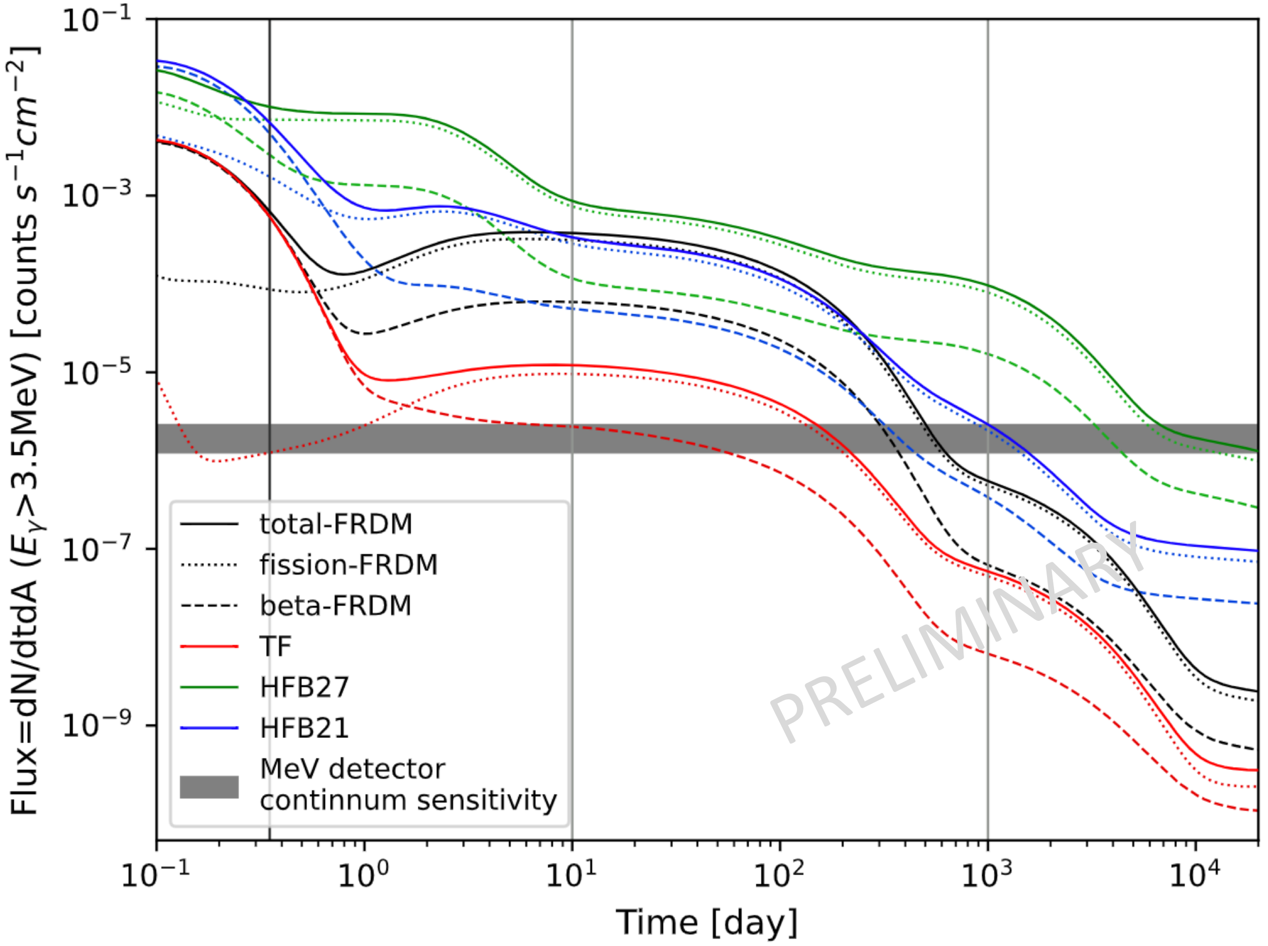
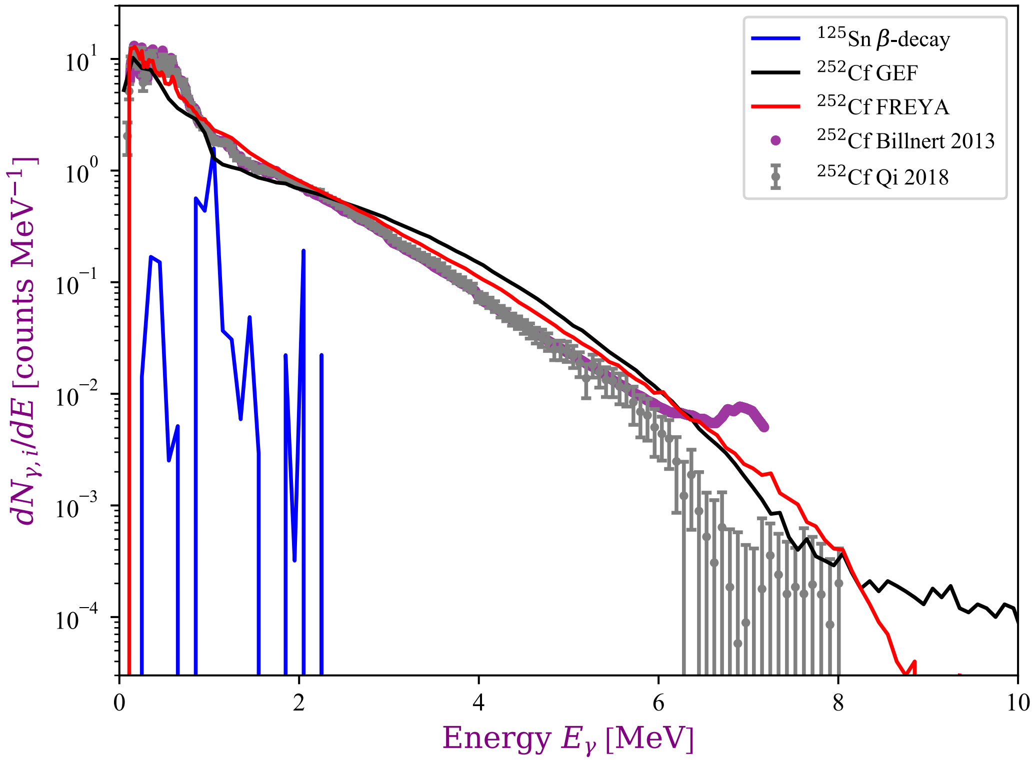


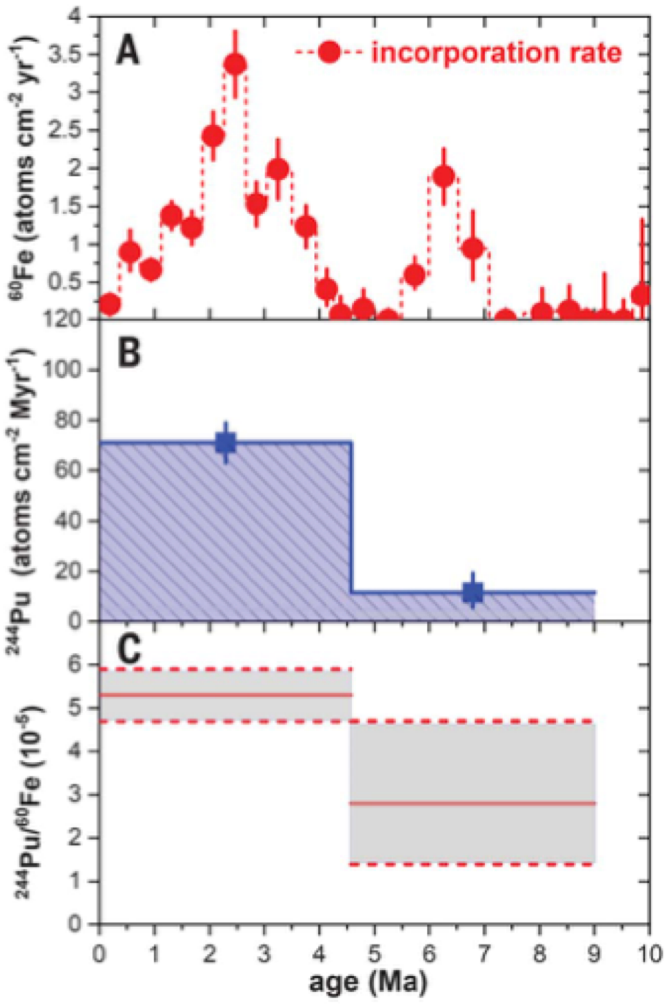
Wang+ in preparation 2023

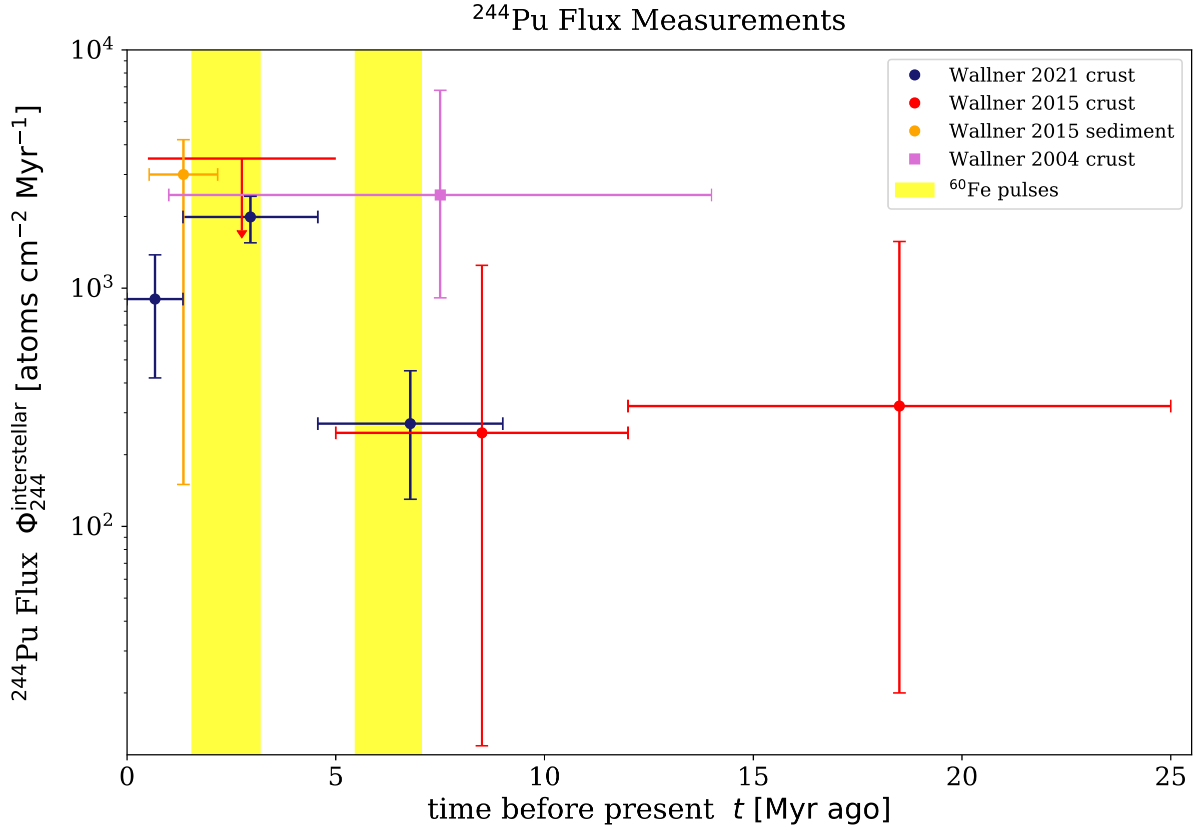


Wang, Vassh, Sprouse, Mumpower, Vogt, Randrup, Surman, ApJL 2020

Actinide observables: ^{60}Fe and ^{244}Pu in Fe-Mn crusts

Wallner+2021





Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021

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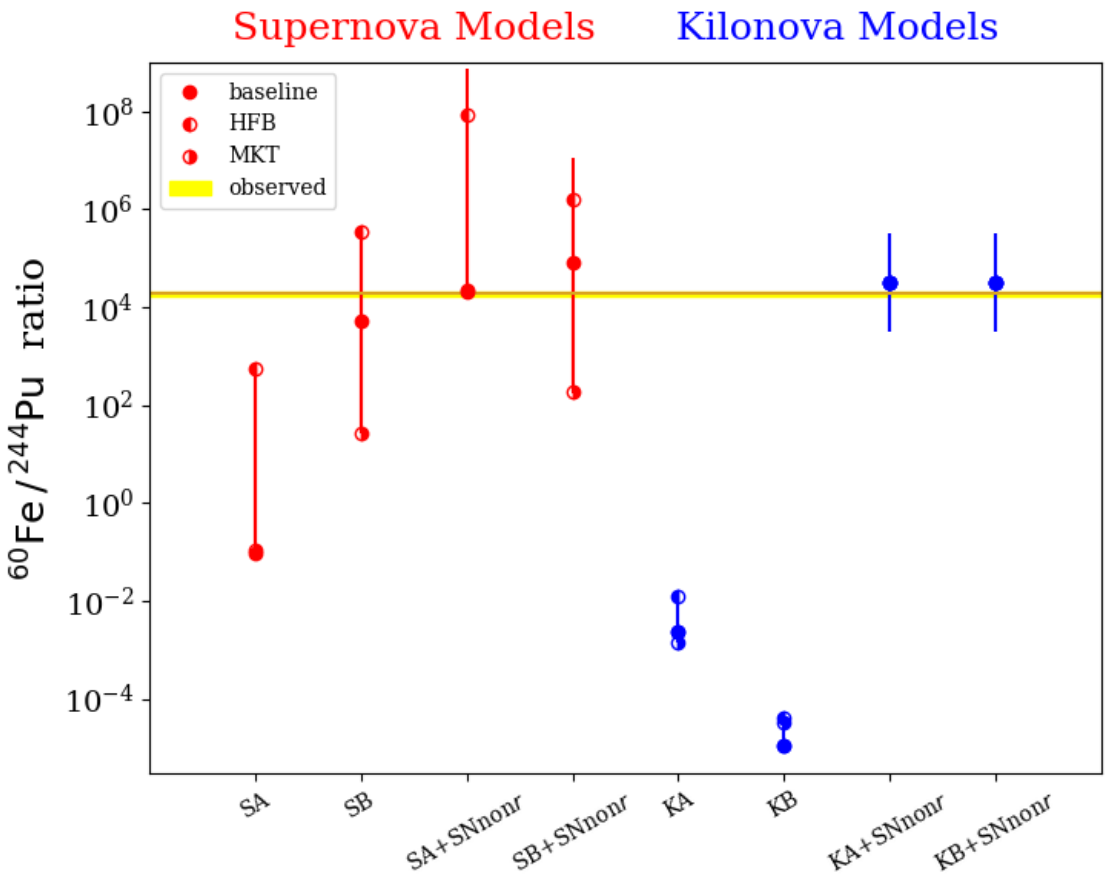

Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;
Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2023

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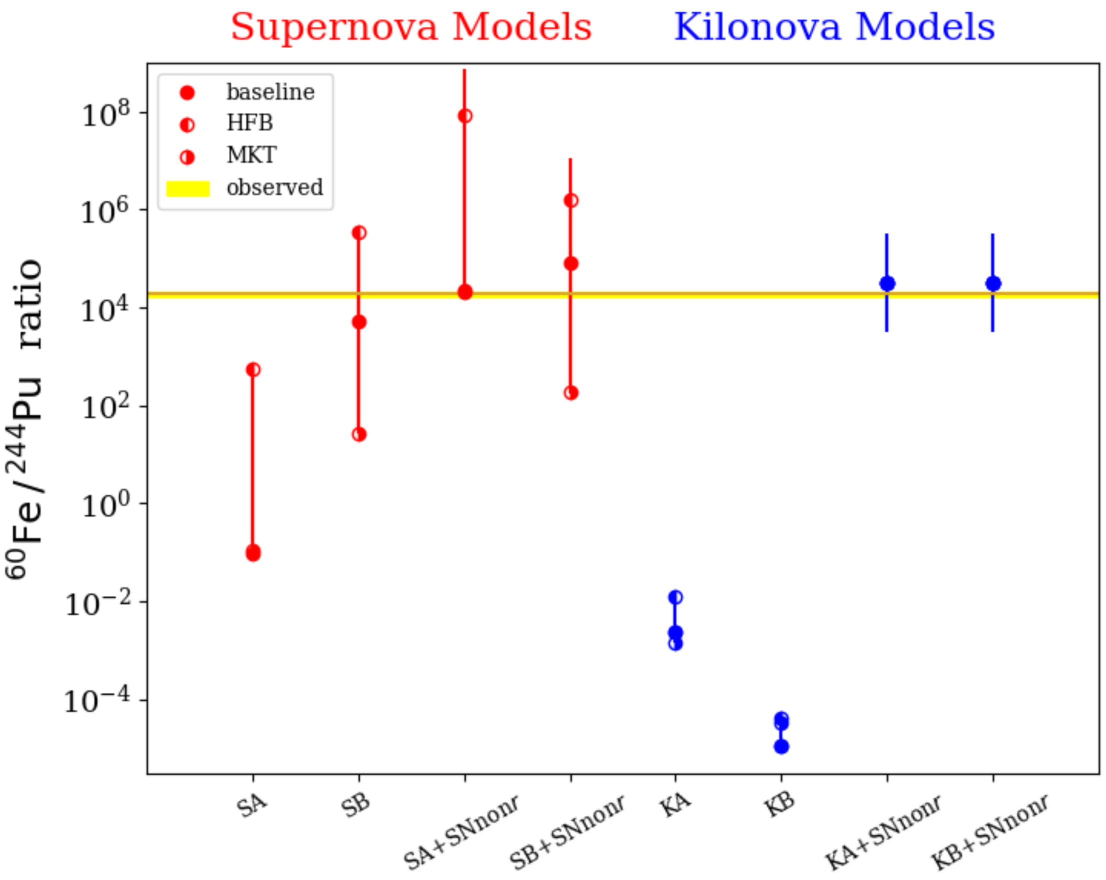

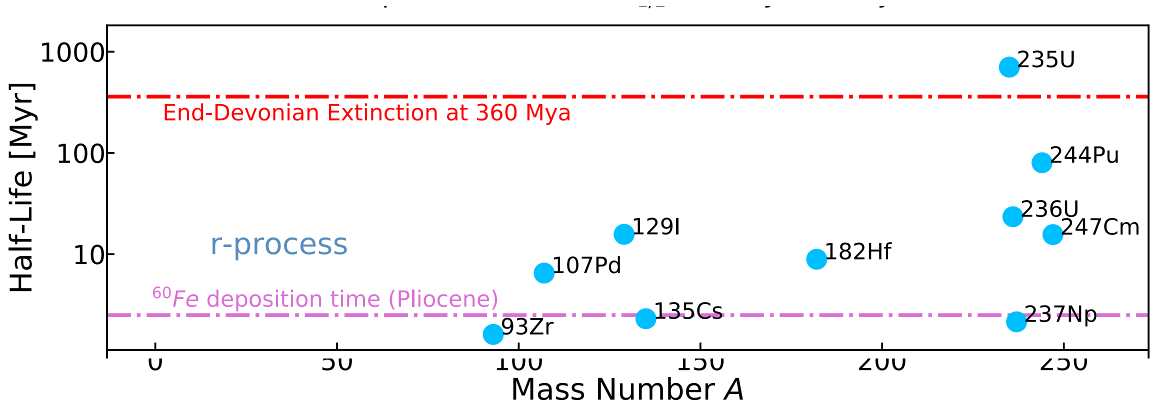

Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;
Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2023

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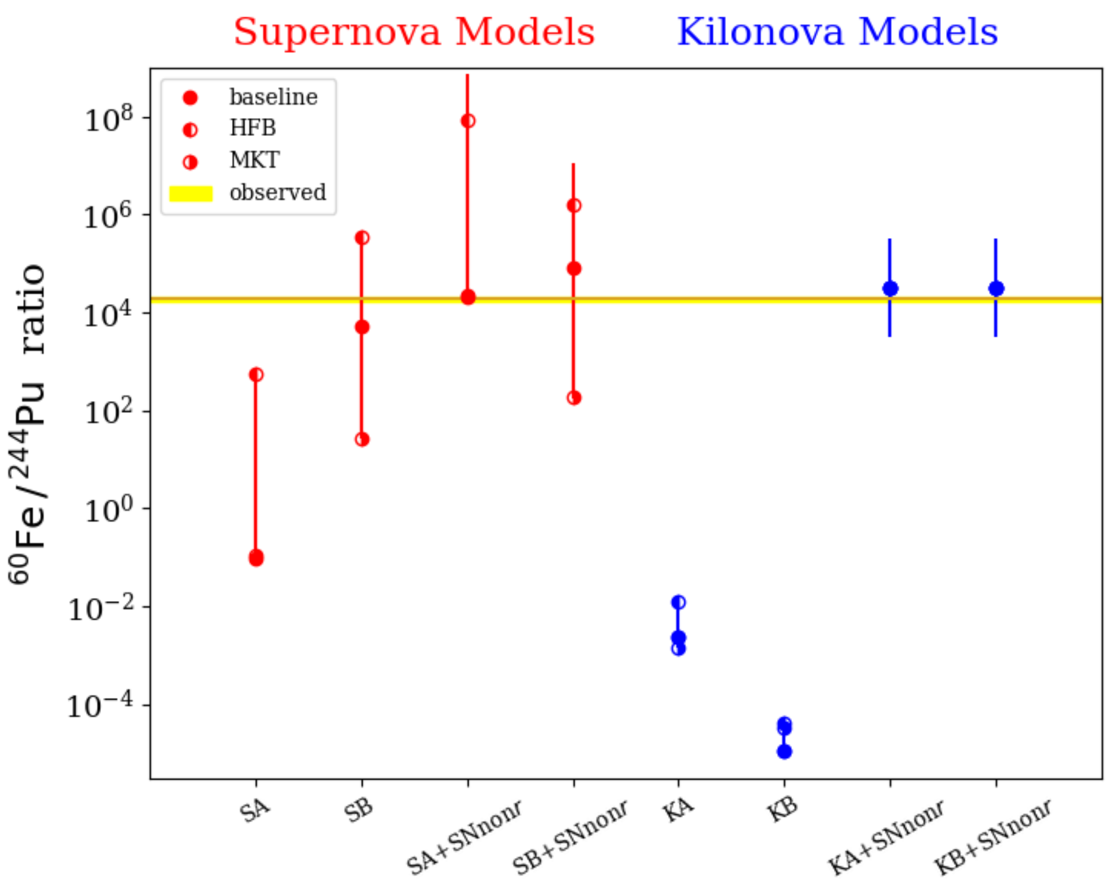

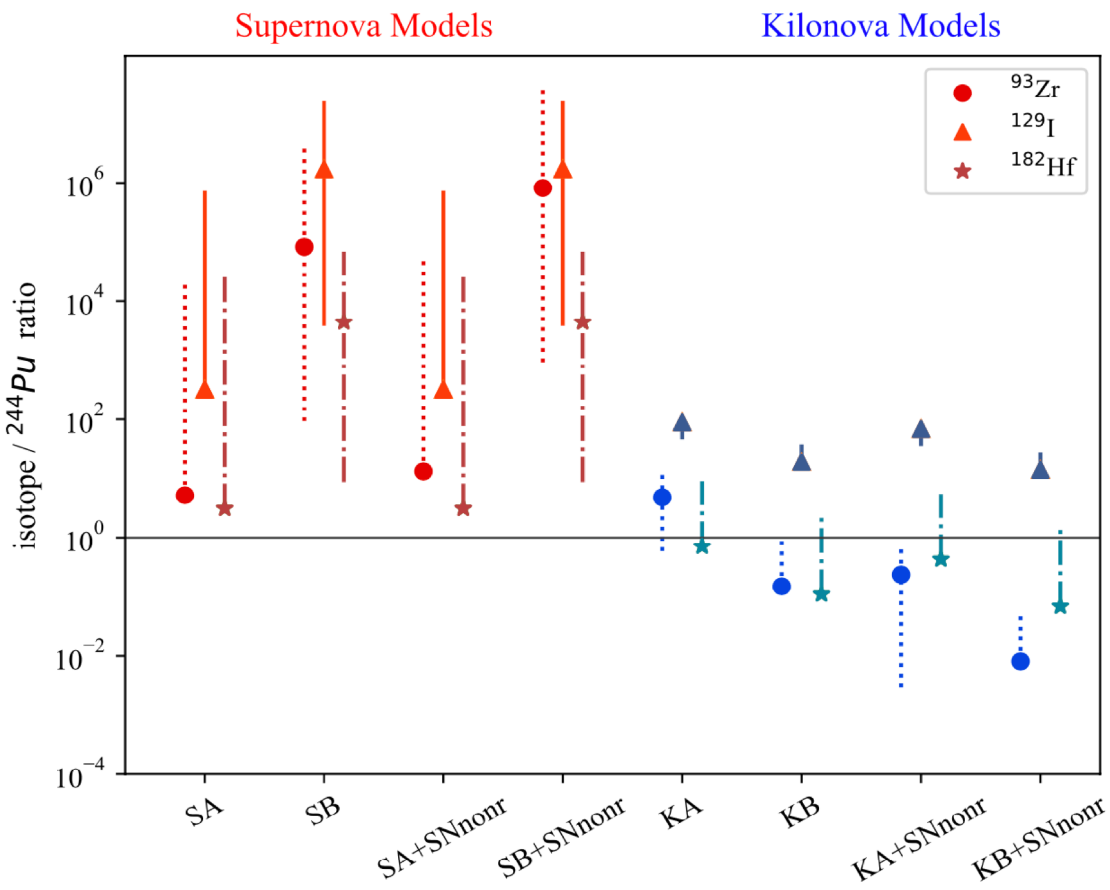

Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;
Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2023

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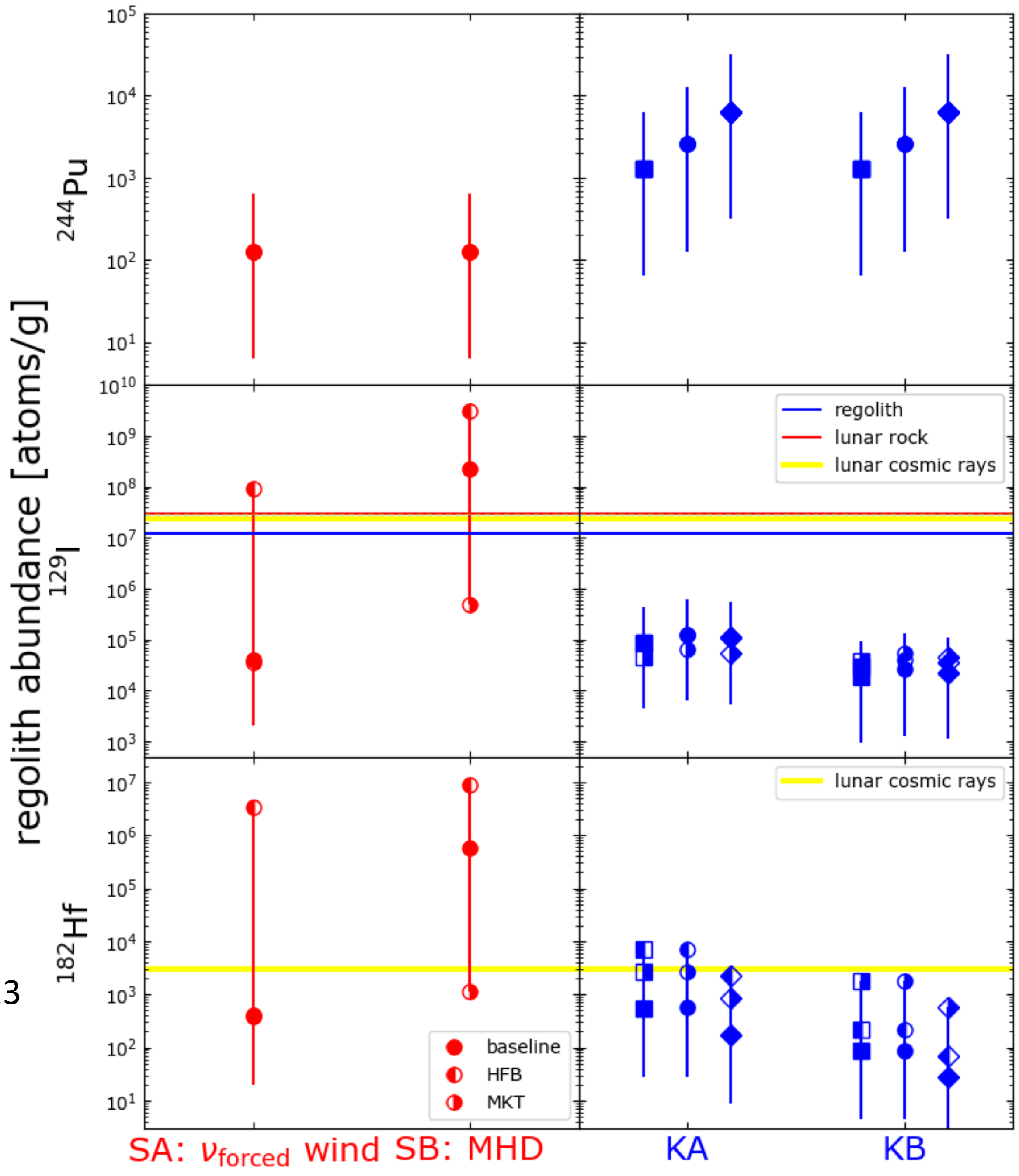
Actinide observables: lunar regolith



Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2023

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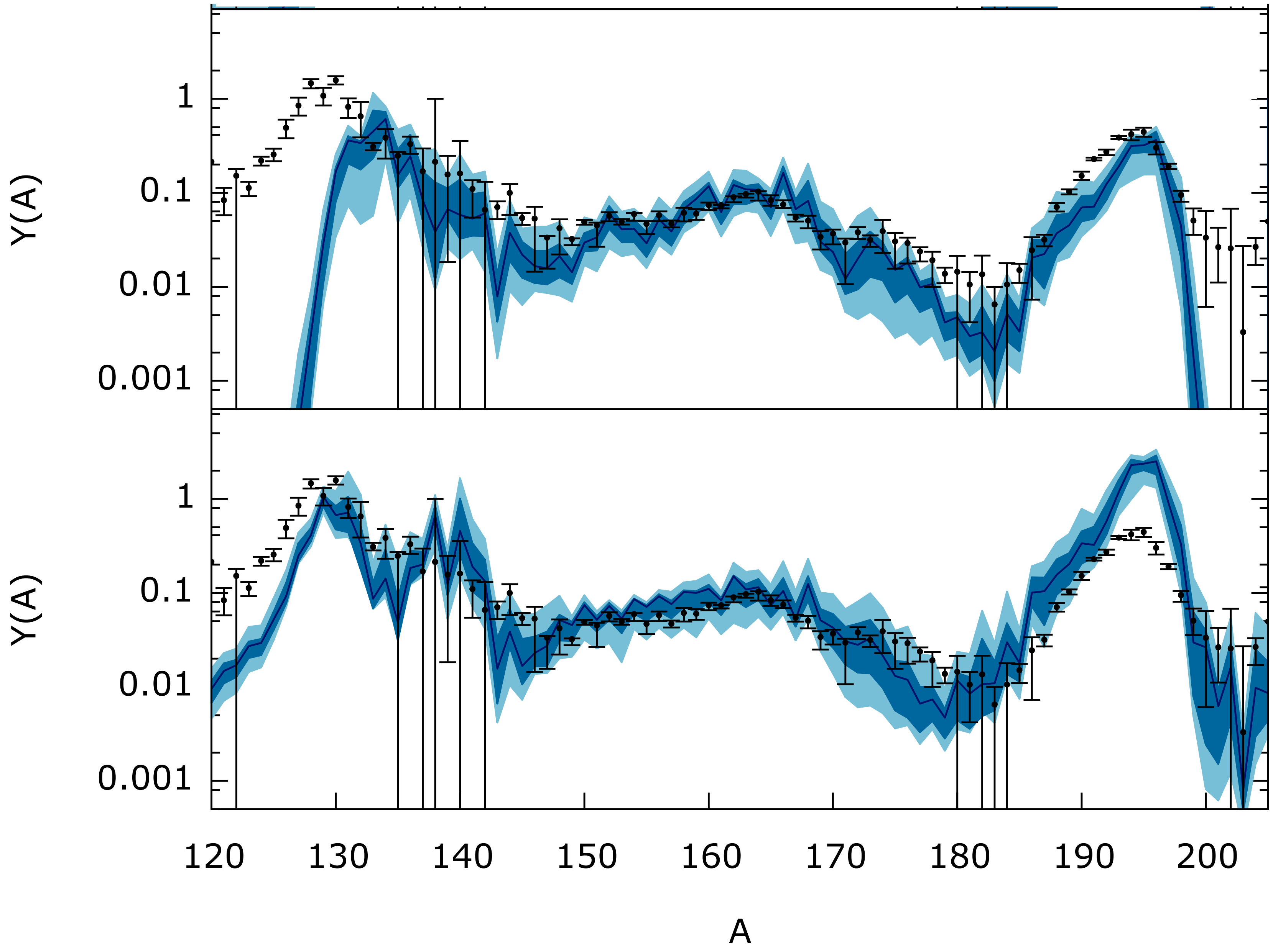
UNEDF1 masses



Sprouse, Navarro Perez, Surman, Mumpower, McLaughlin, Schunck 2020

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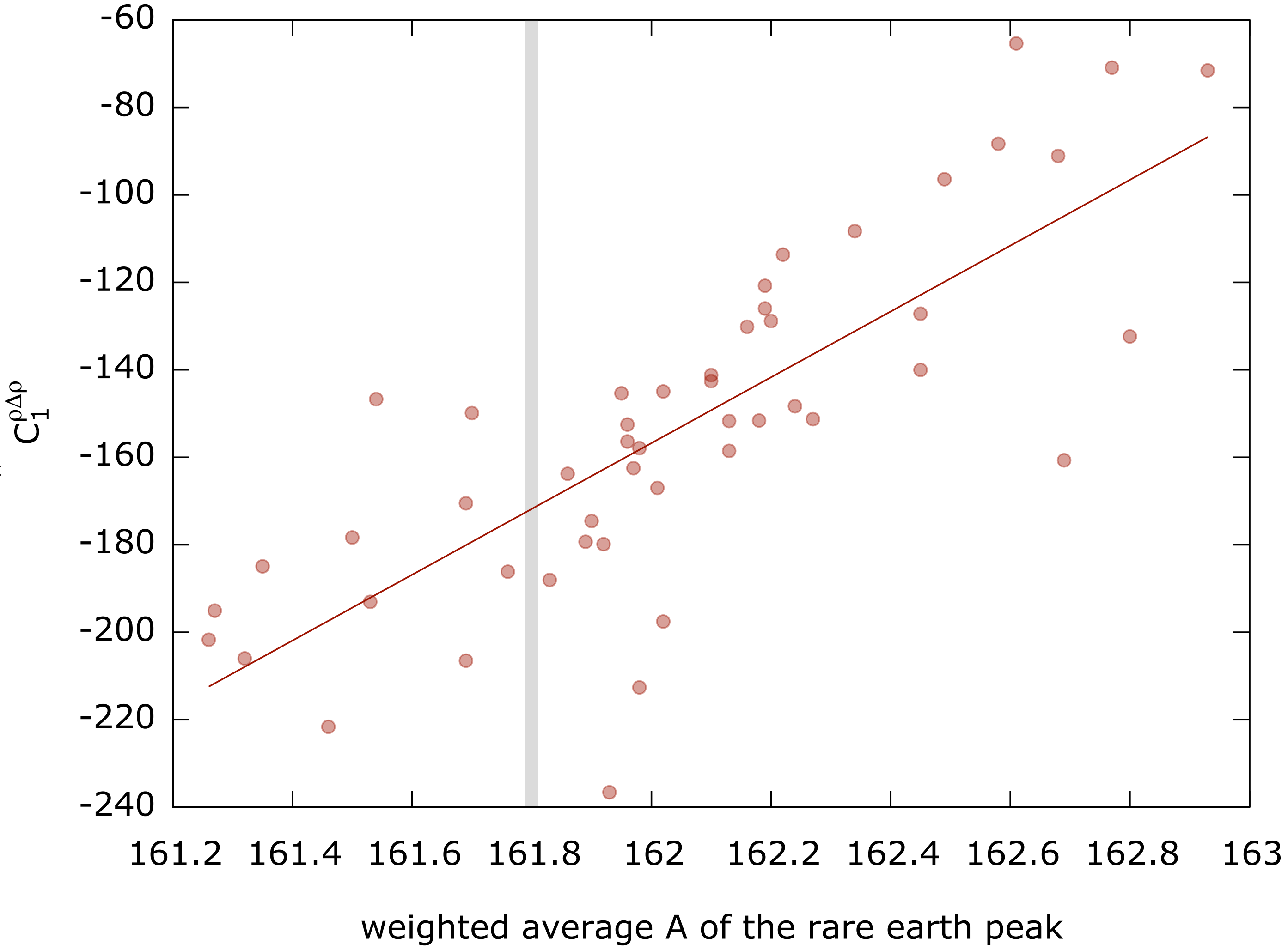
UNEDF1 masses

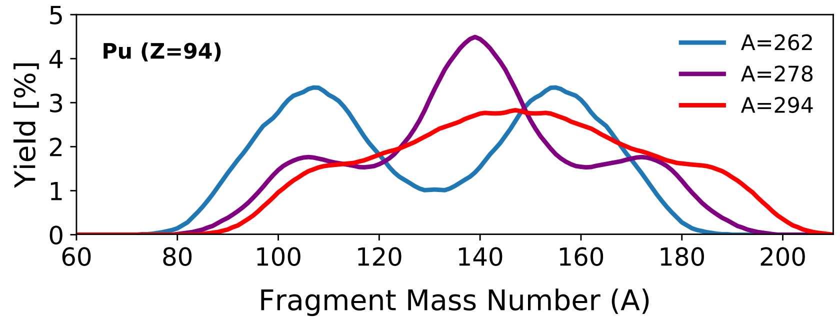
TABLE II: Optimized parameter set UNEDF1. Listed are bounds used in the optimization, final optimized parameter values, standard deviations, and 95% confidence intervals.

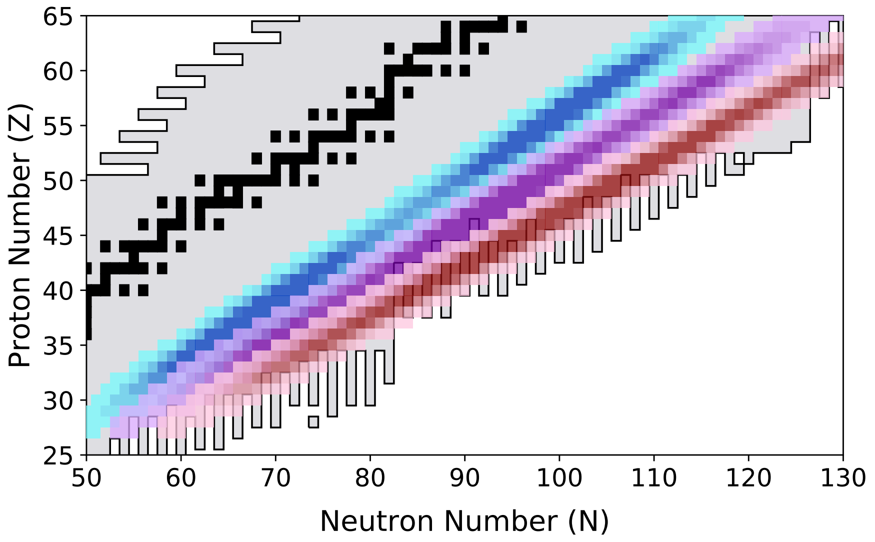
x	Bounds	$\hat{\mathbf{x}}^{(\mathrm{fin.})}$	σ	95% CI
ρ_c	[0.15,0.17]	0.15871	0.00042	[0.158, 0.159]
E^{NM}/A	[-16.2,-15.8]	-15.800	–	–
K^{NM}	[220, 260]	220.000	–	–
$a_{\mathrm{sym}}^{\mathrm{NM}}$	[28, 36]	28.987	0.604	[28.152, 29.822]
$L_{\mathrm{sym}}^{\mathrm{NM}}$	[40, 100]	40.005	13.136	[21.841, 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]

Sprouse, Navarro Perez, Surman, Mumpower, McLaughlin, Schunck 2020

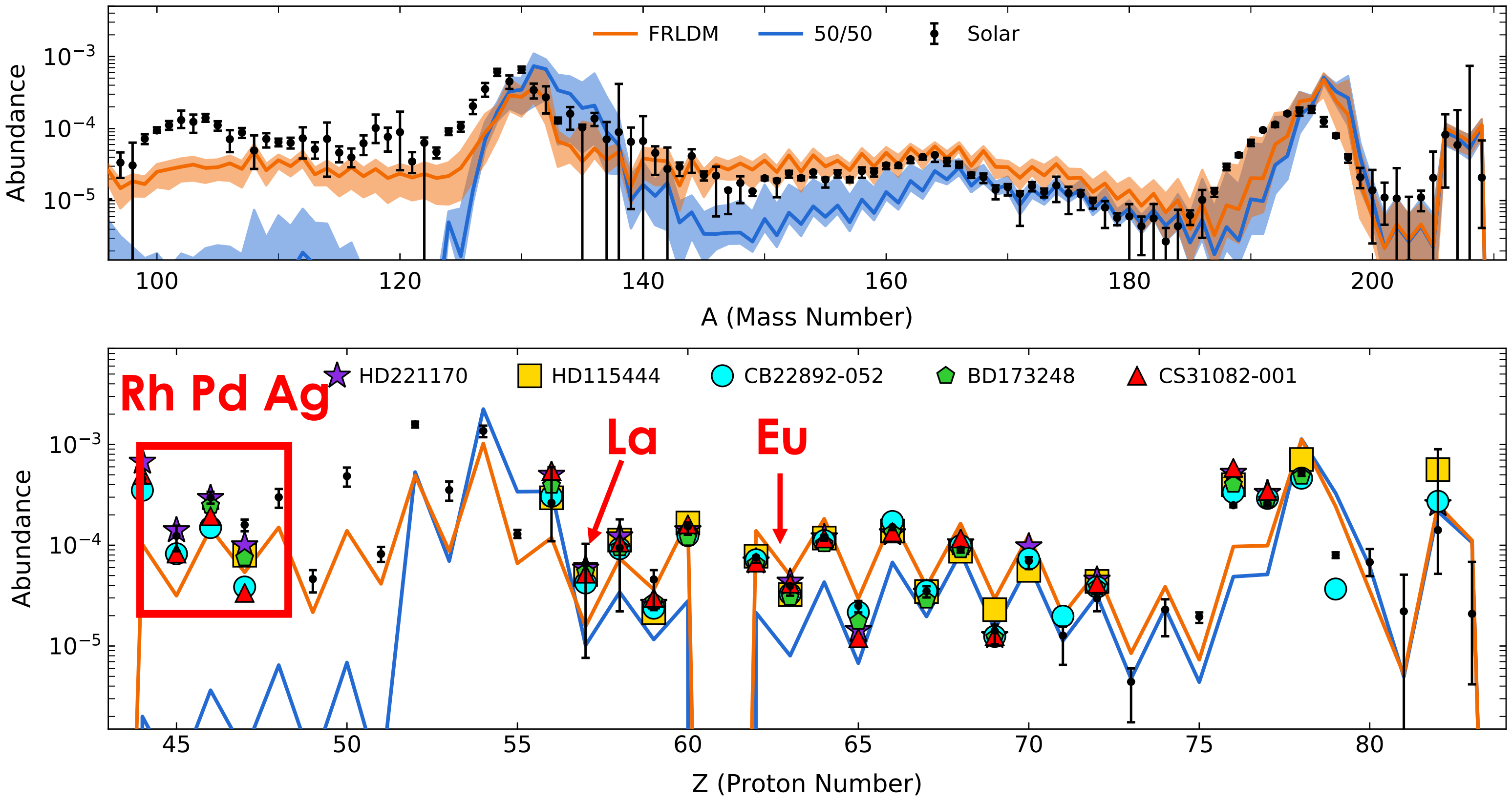


Fission yield signatures





Vassh, Mumpower, McLaughlin, Sprouse, Surman 2020



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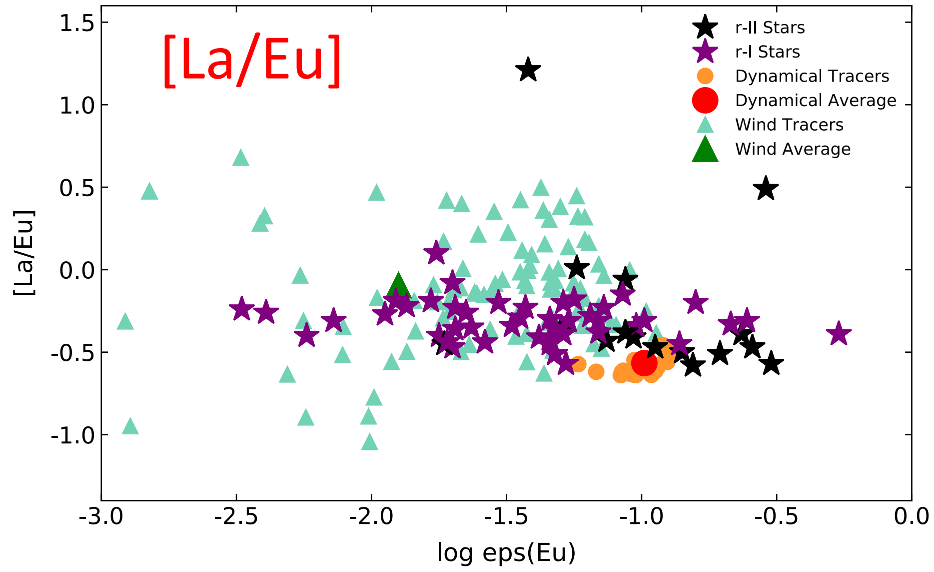
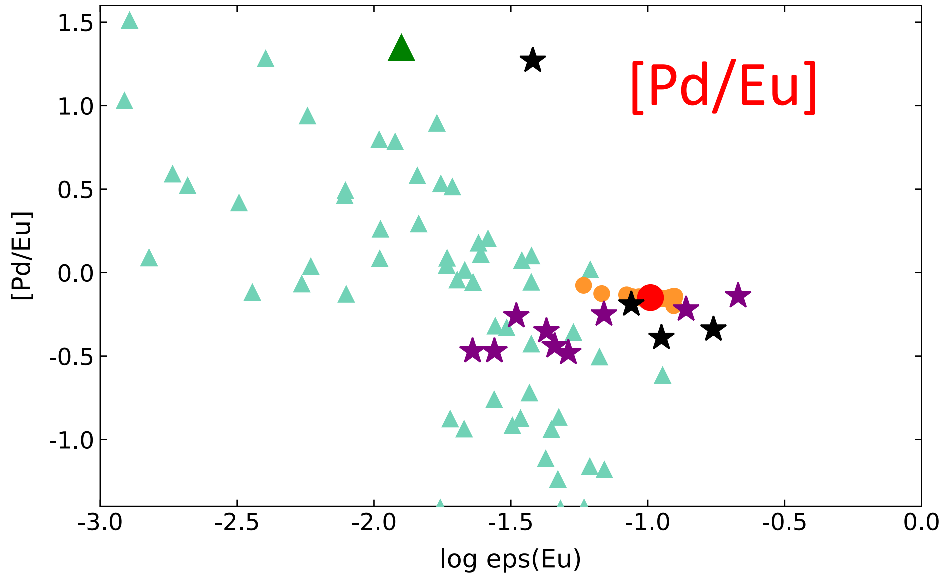
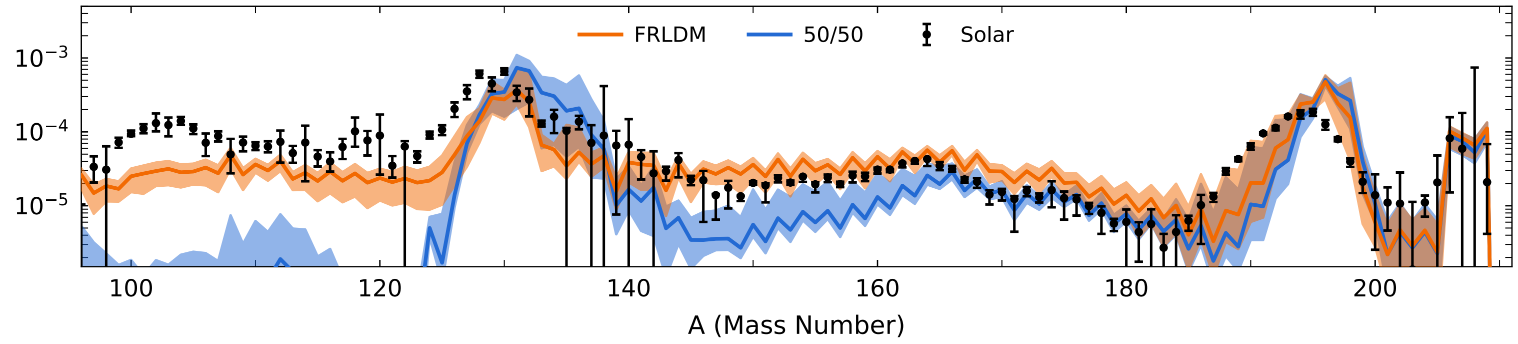
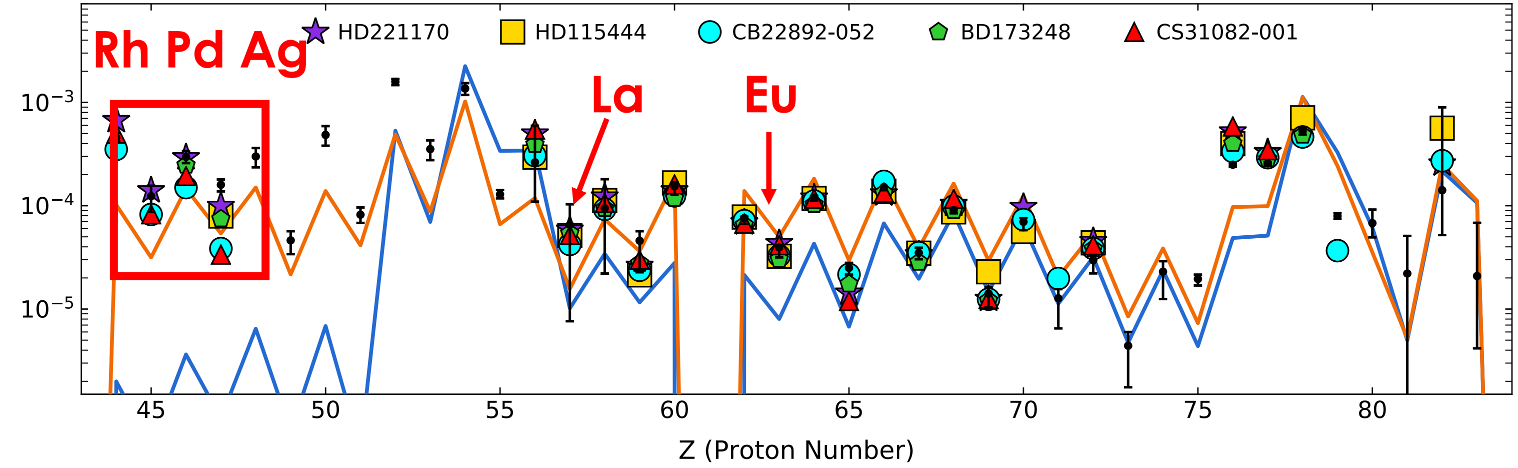


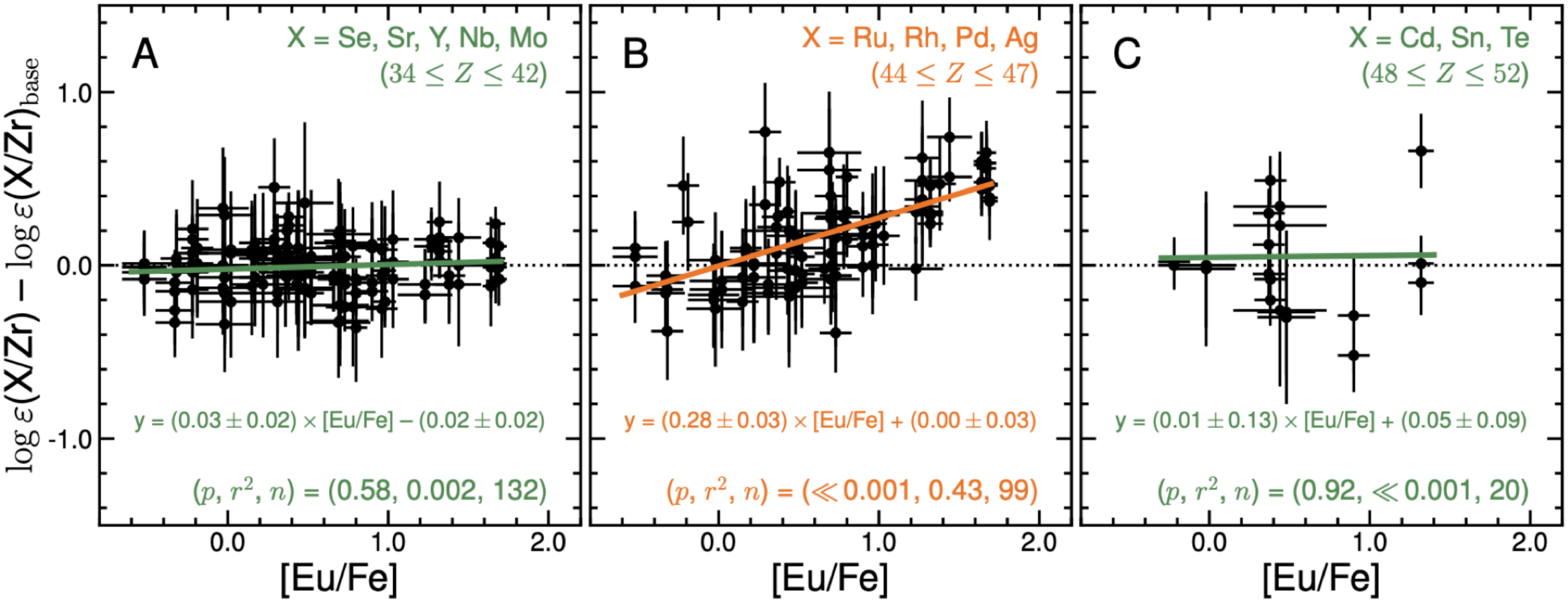


Vassh, Mumpower, McLaughlin, Sprouse, Surman 2020





Fission yield signatures



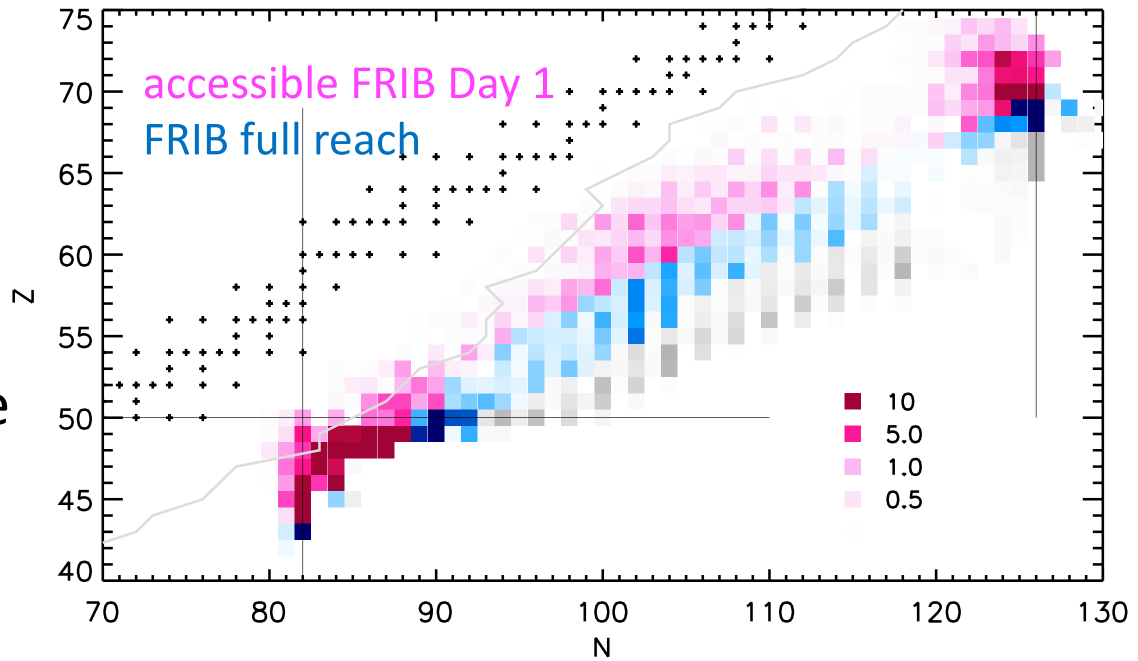
Roederer+ submitted 2023

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.

Despite considerable progress in the past several years, including the first direct detection of an *r*-process event, the *r*-process site(s) has not been definitively determined.

The neutrino and nuclear physics of candidate events remains poorly understood. FRIB has the potential to reduce key nuclear uncertainties, facilitating accurate interpretations of *r*-process observables such as abundance patterns and light curves.



Mumpower, Surman, McLaughlin, Aprahamian, JPPNP 2016