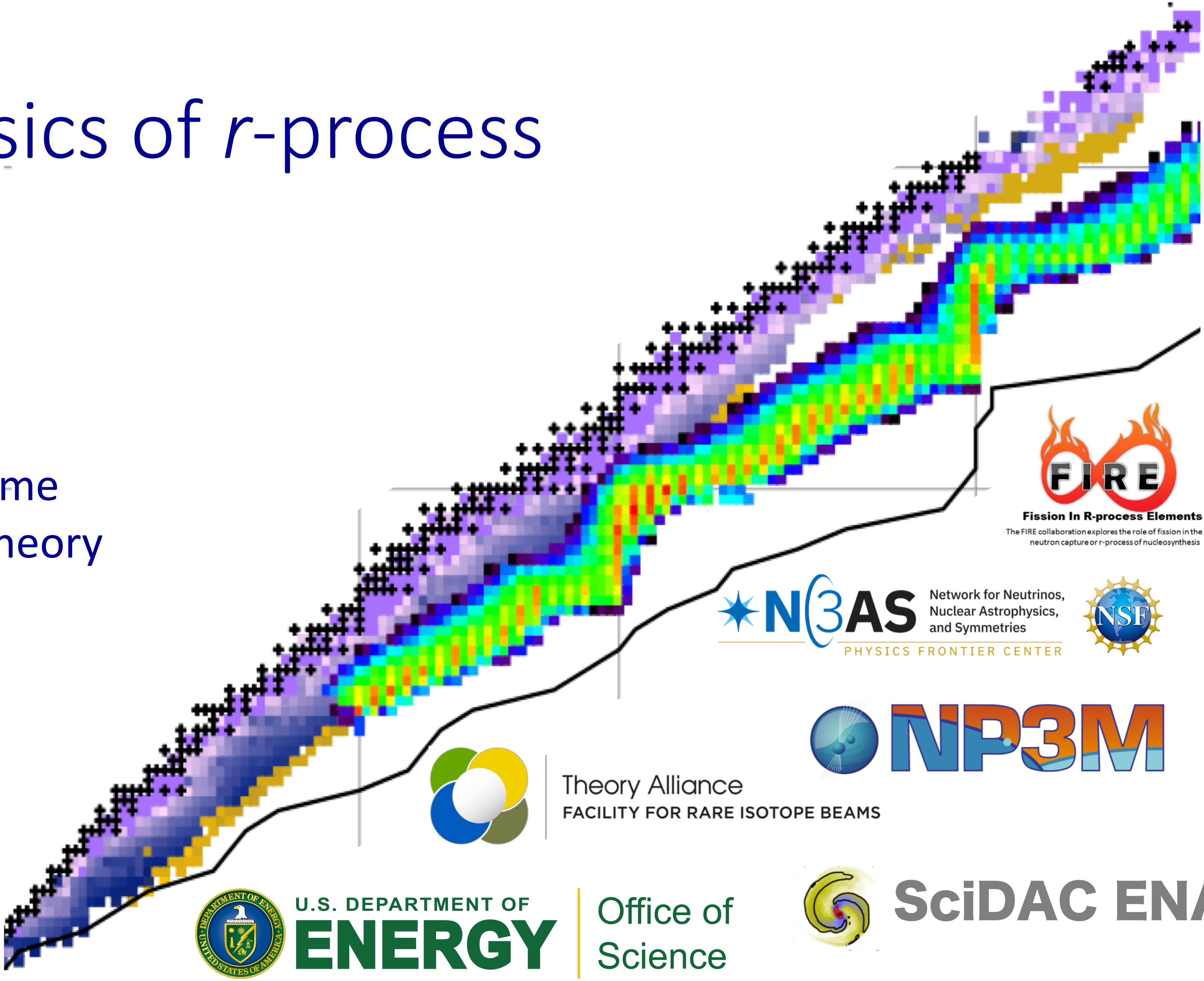
Nuclear physics of *r*-process observables

Rebecca Surman
University of Notre Dame
Institute for Nuclear Theory

CaNPAN Jam
3 May 2024



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

SciDAC ENAF

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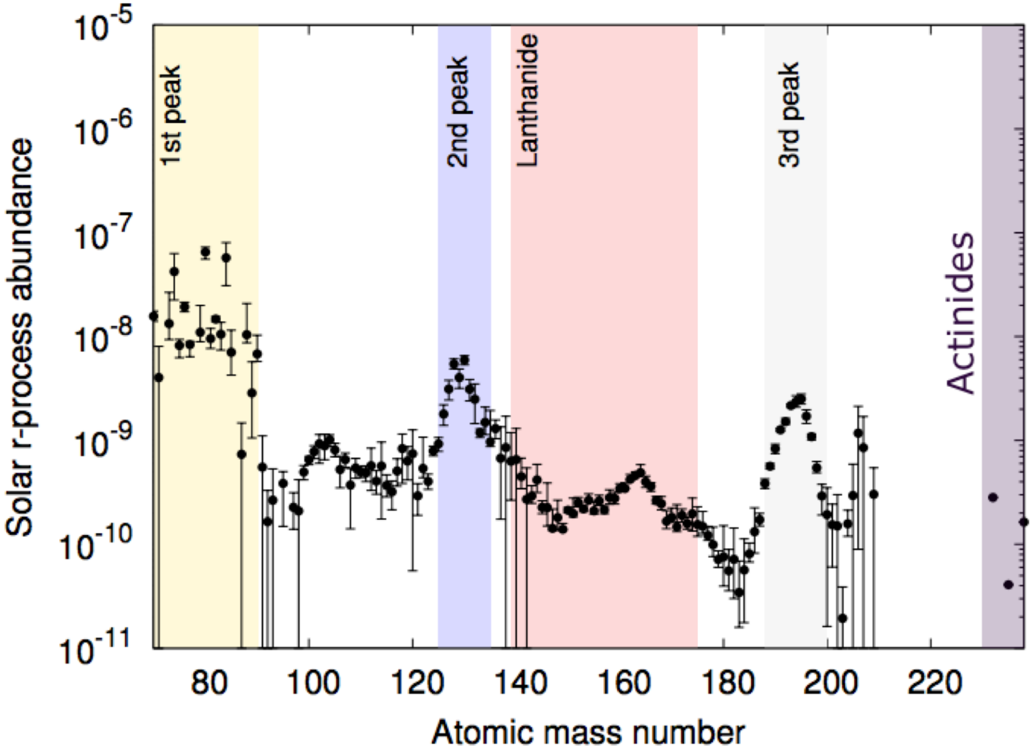
r-process nucleosynthesis

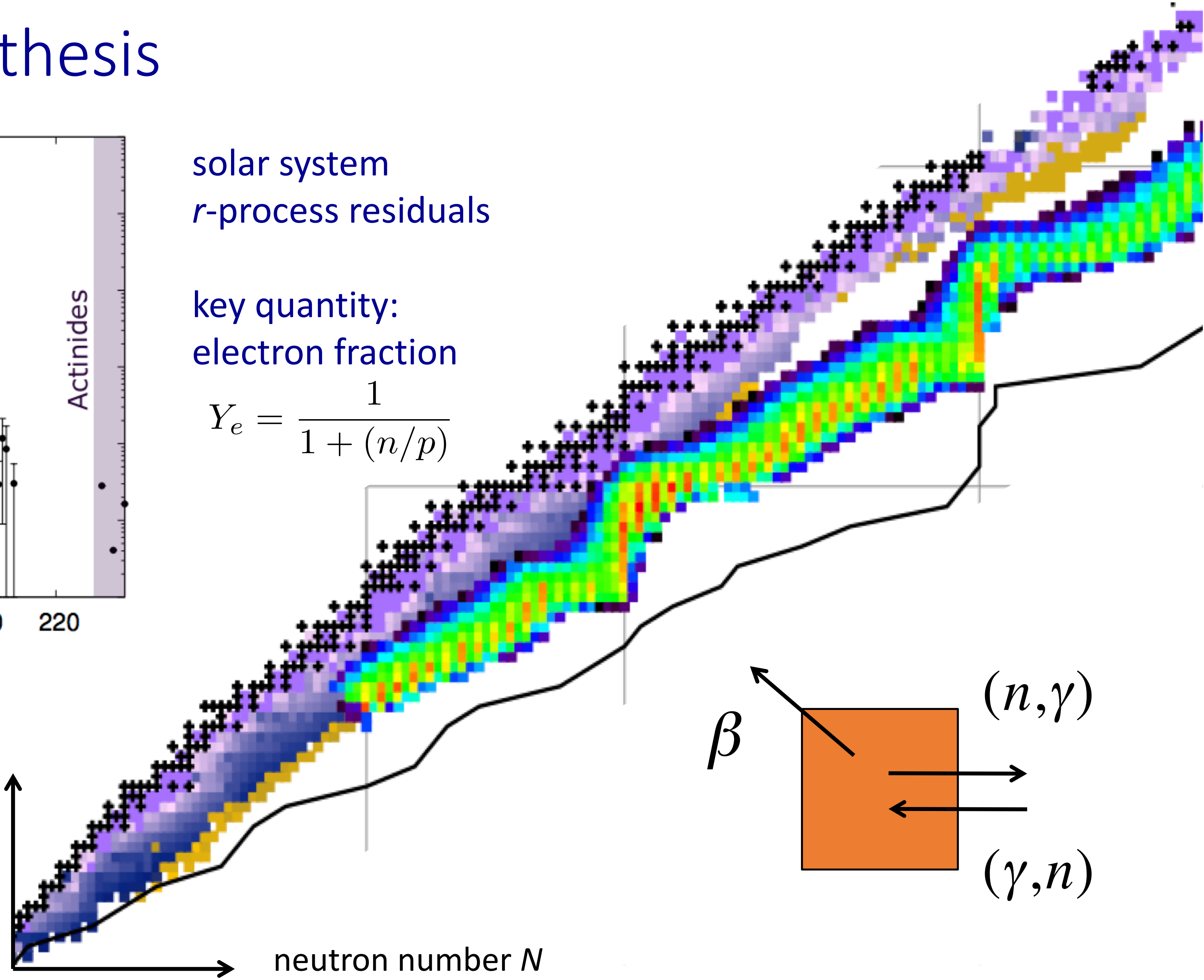


Arnould+2007, Hotokezaka+2018

solar system
r-process residuals

key quantity:
electron fraction

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



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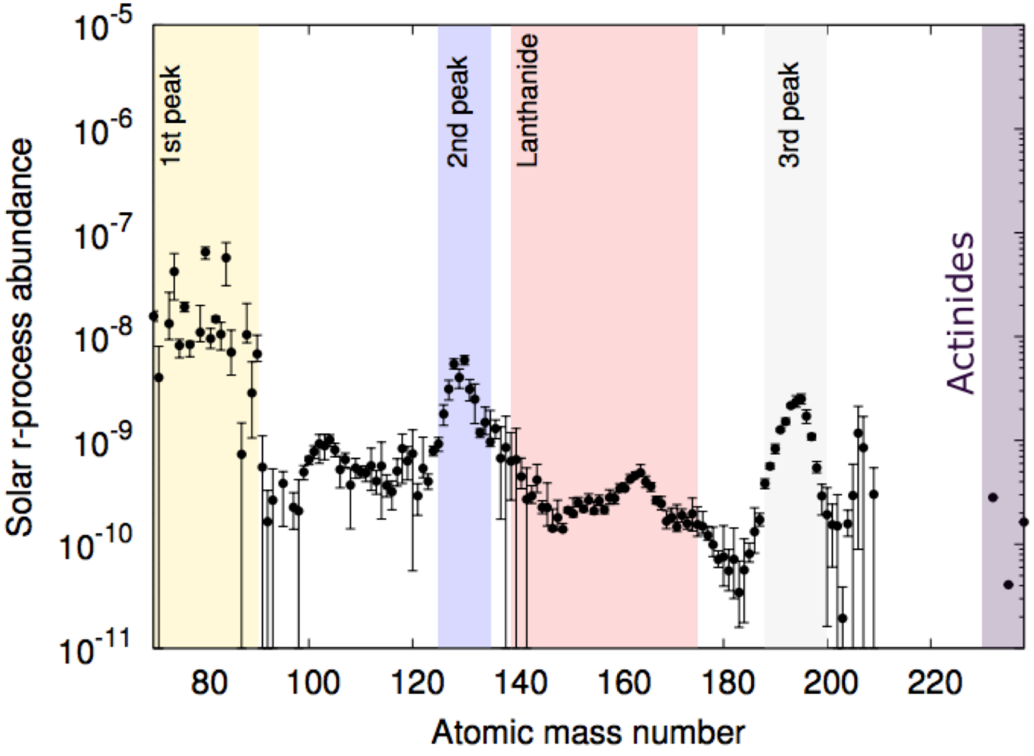
r-process observables: abundance patterns

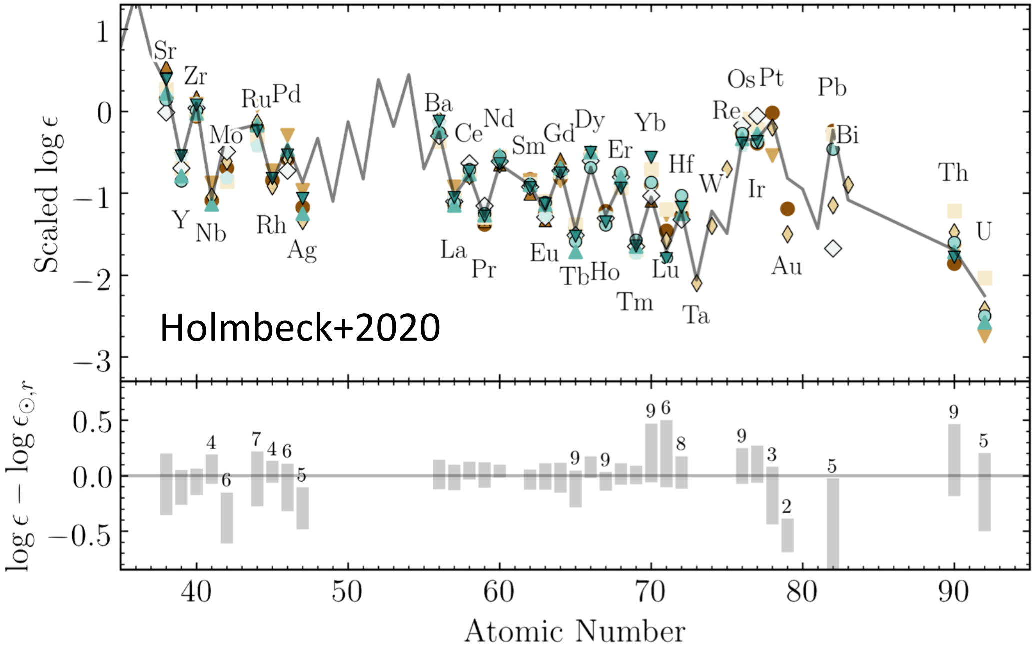


Arnould+2007, Hotokezaka+2018

solar system
r-process residuals

R-Process Alliance est. 2017

r-process elements
in metal-poor stars



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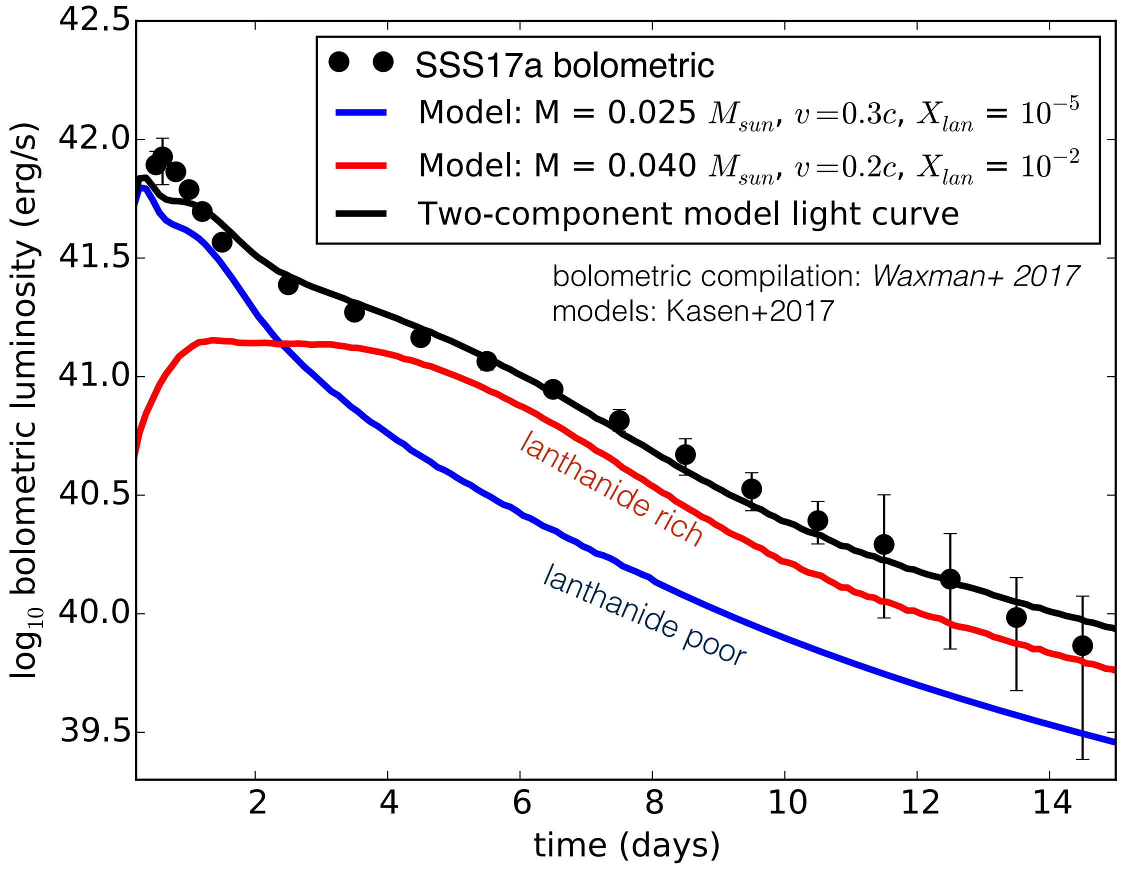
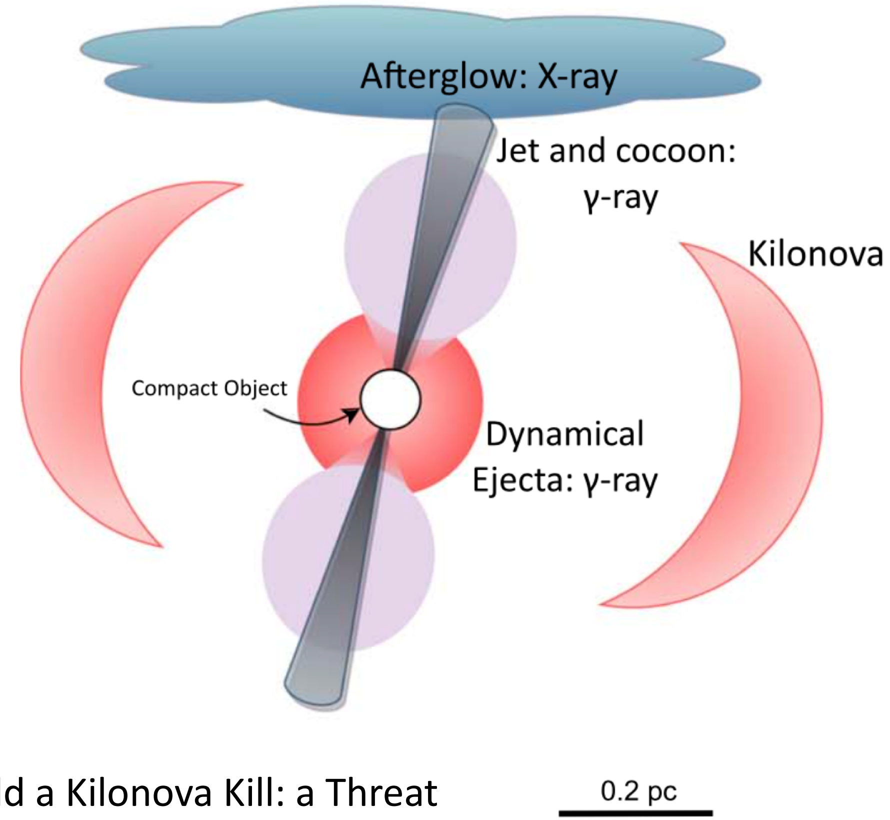
r-process observables: electromagnetic signatures

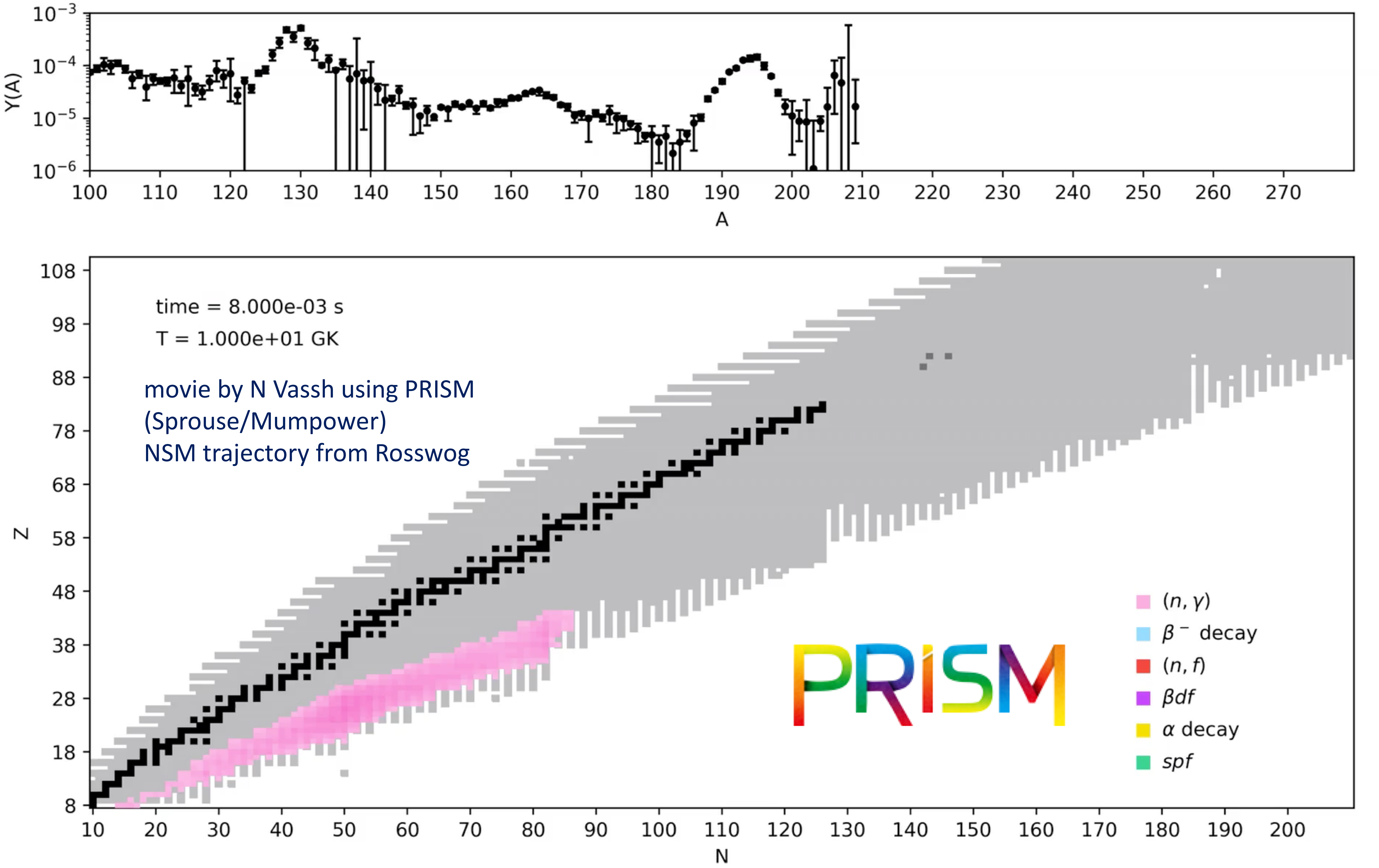
kilonova SSS17a bolometric light curve





"Could a Kilonova Kill: a Threat Assessment"

Perkins, Ellis, Fields, Hartmann, Liu, McLaughlin, Surman, Wang 2024



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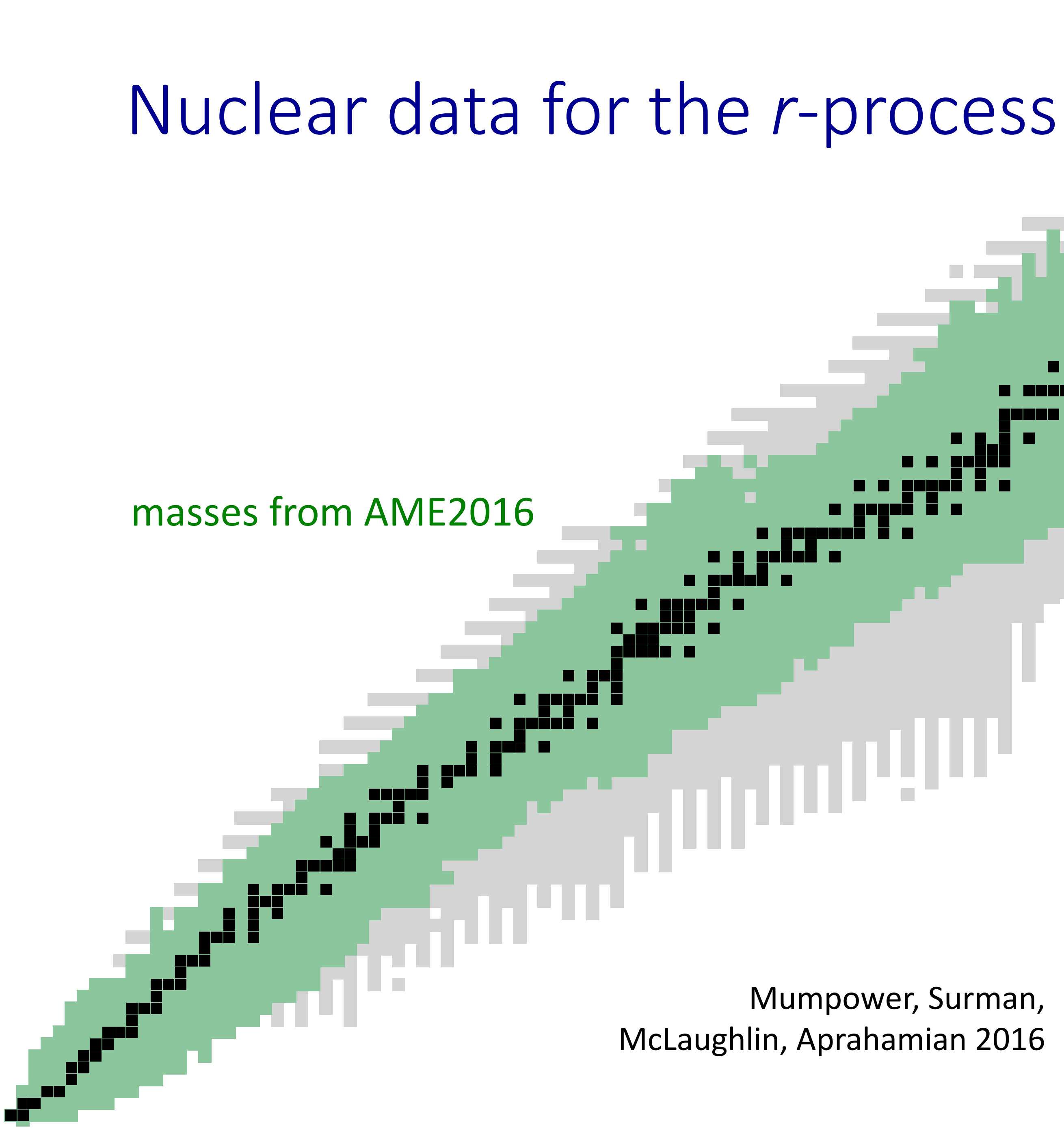
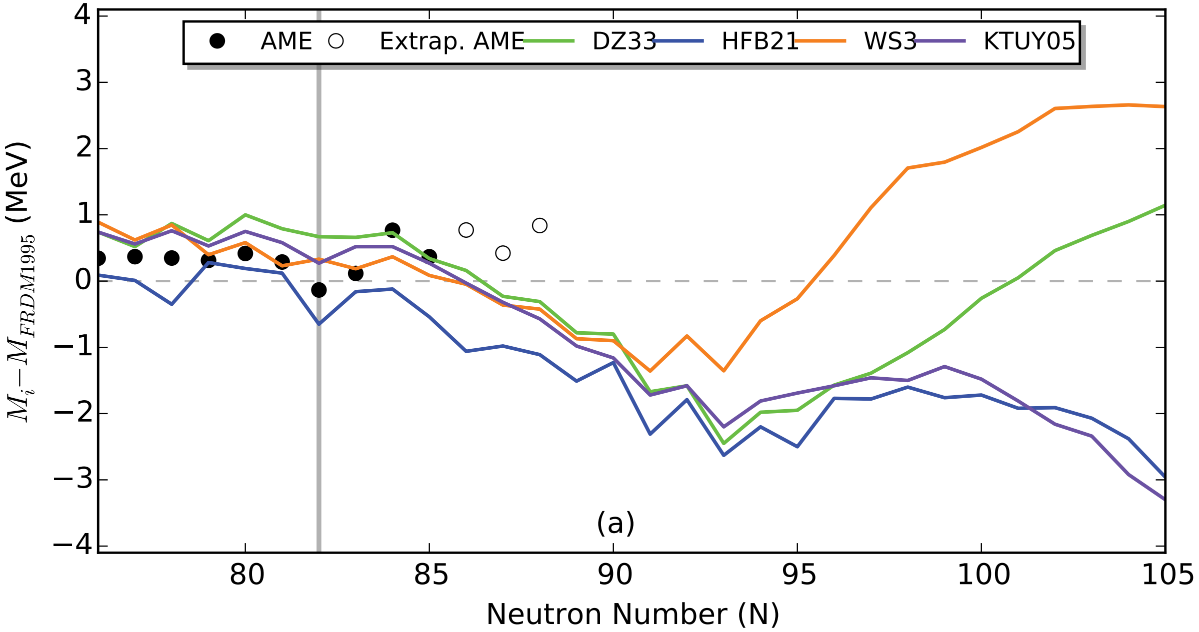
Nuclear data for the *r*-process

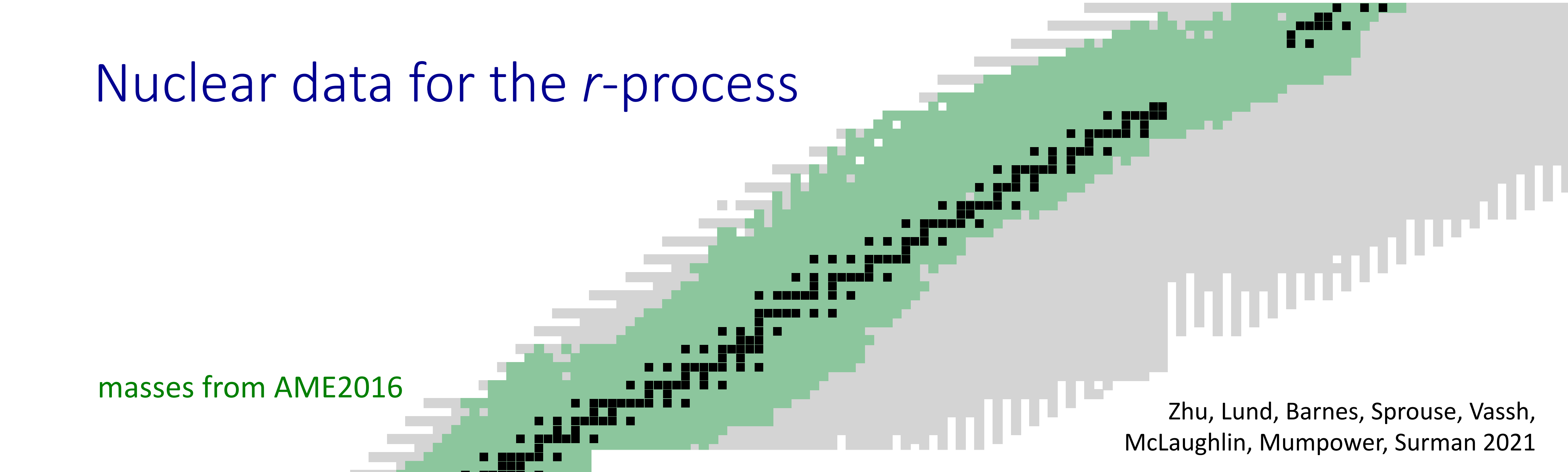


masses from AME2016

Mumpower, Surman,
McLaughlin, Aprahamian 2016

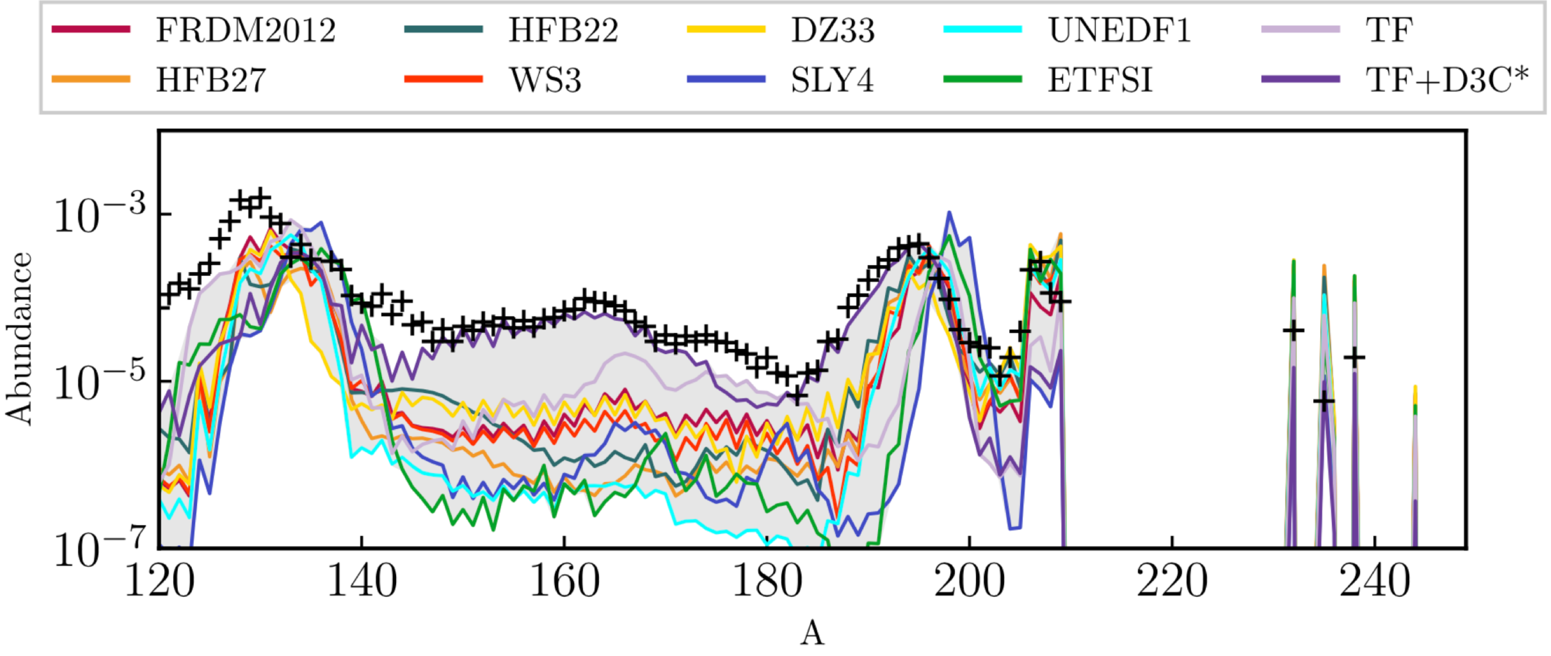


Nuclear data for the *r*-process



masses from AME2016

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



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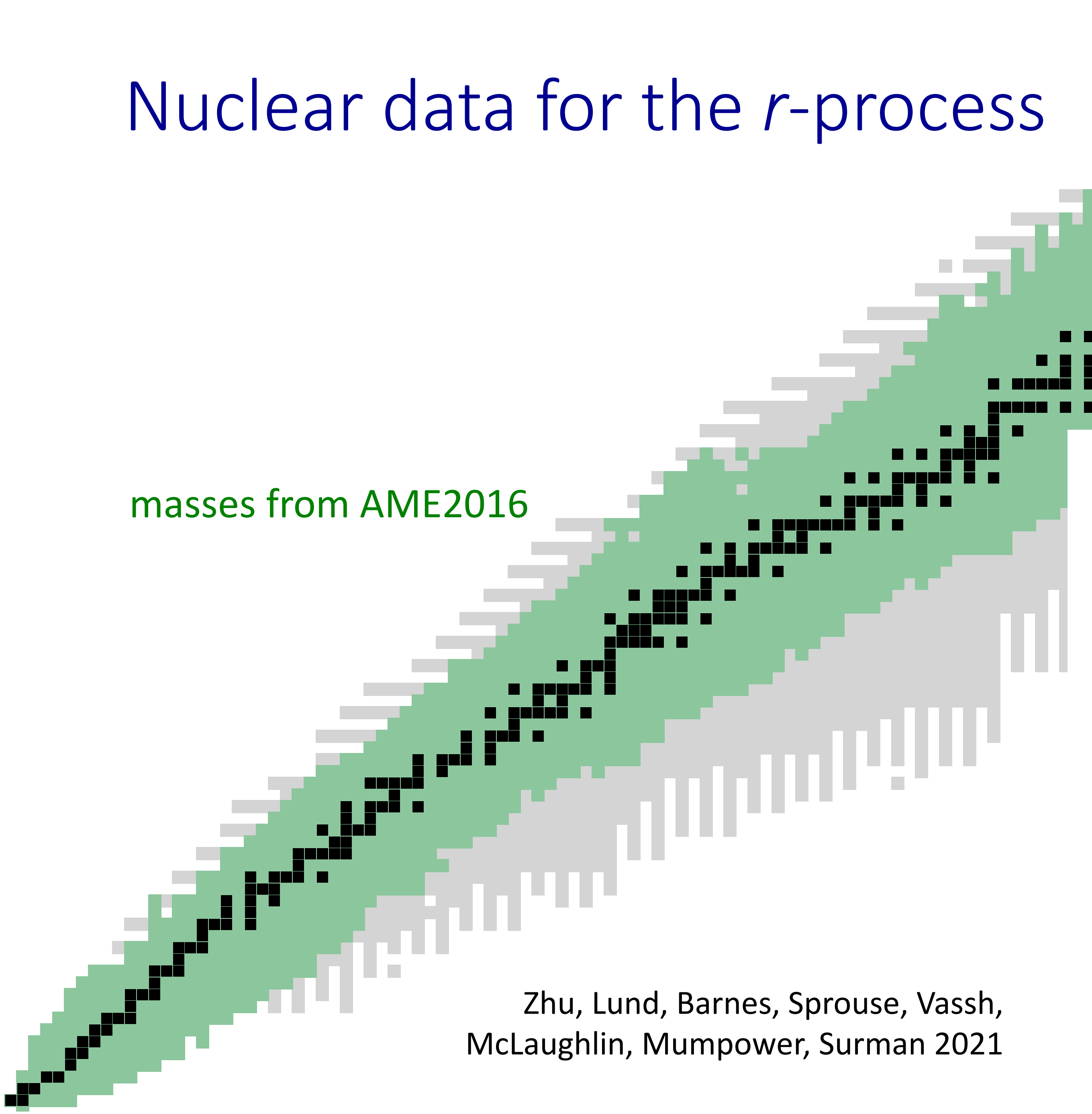

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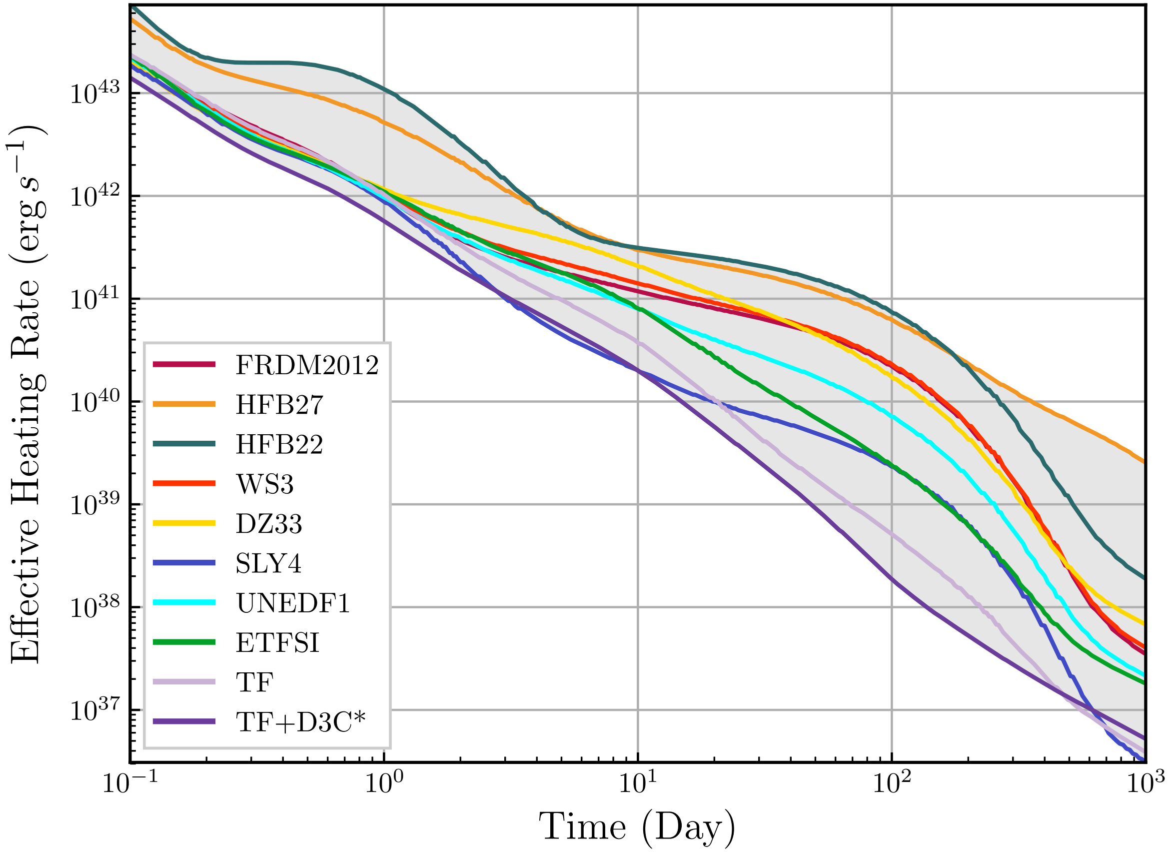
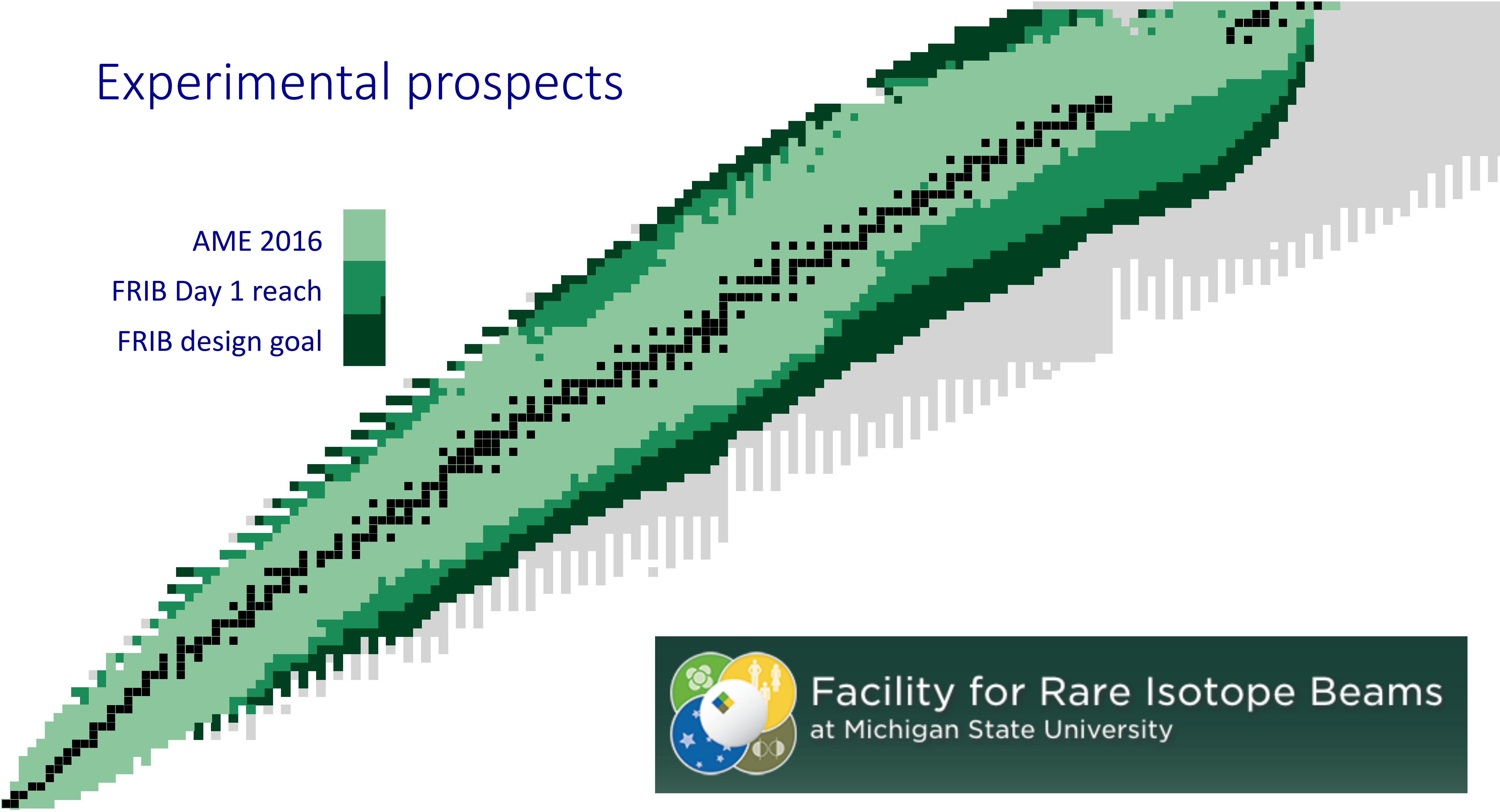
Zhu, Lund, Barnes, Sprouse, Vassh, McLaughlin, Mumpower, Surman 2021



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/ARIEL/FAIR era?

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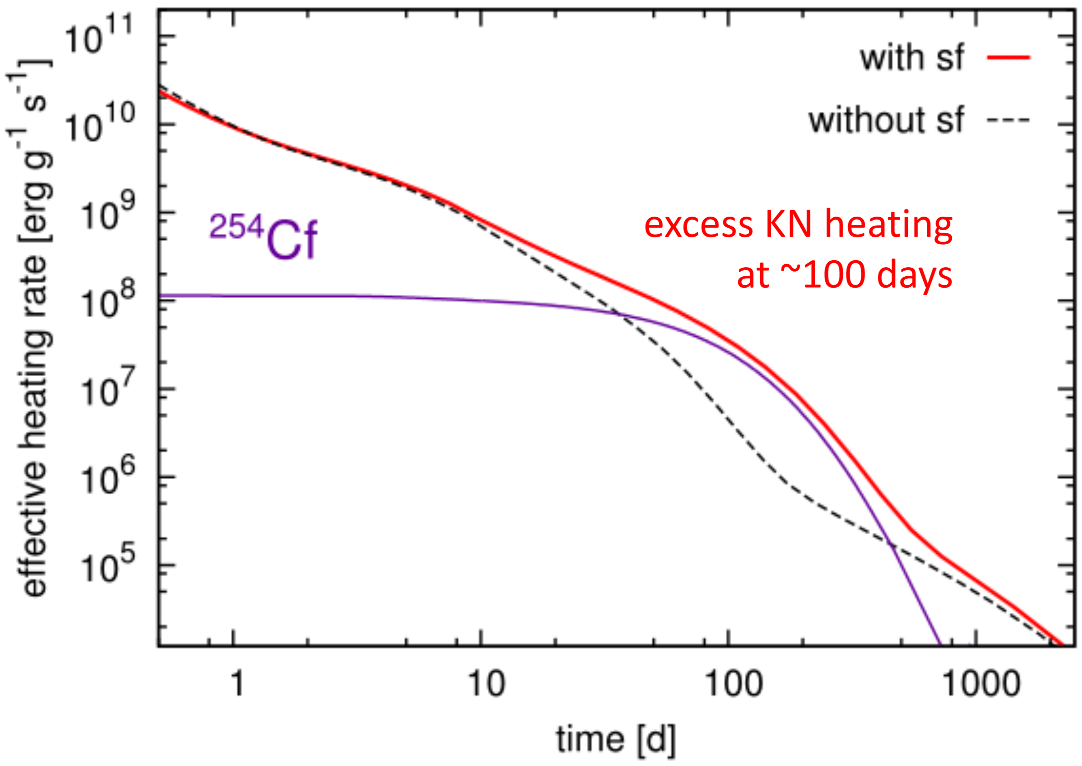
Did the GW170817 merger produce actinides?



Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, ApJL 2018

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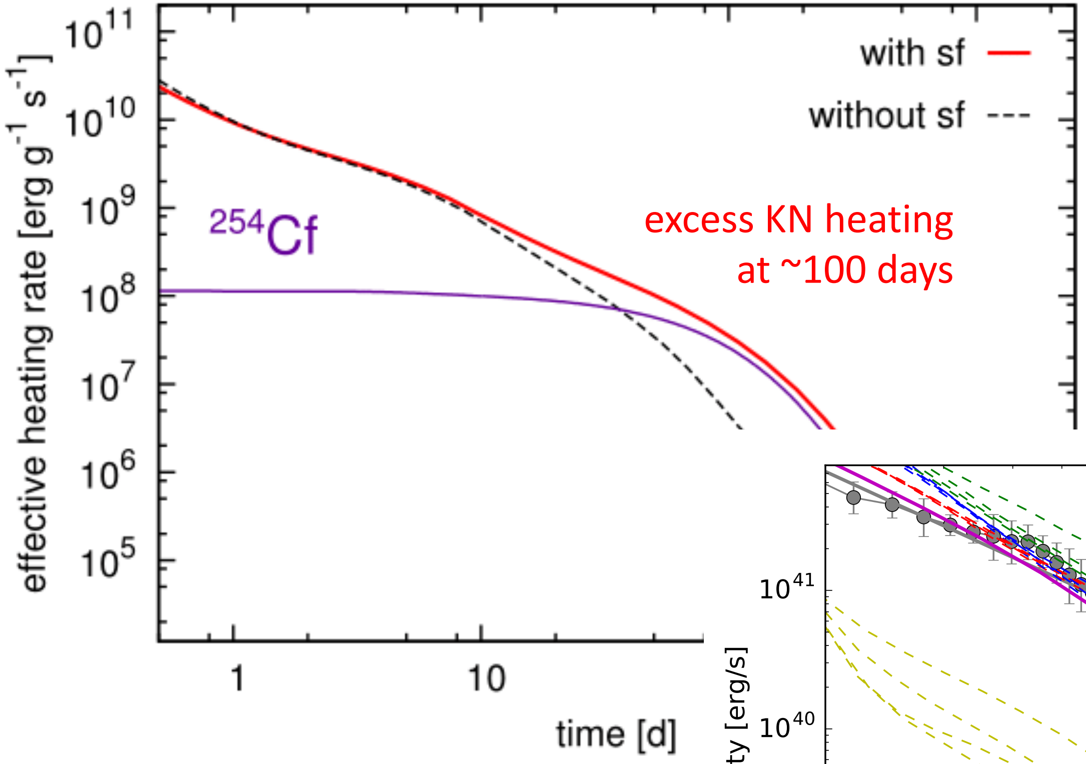
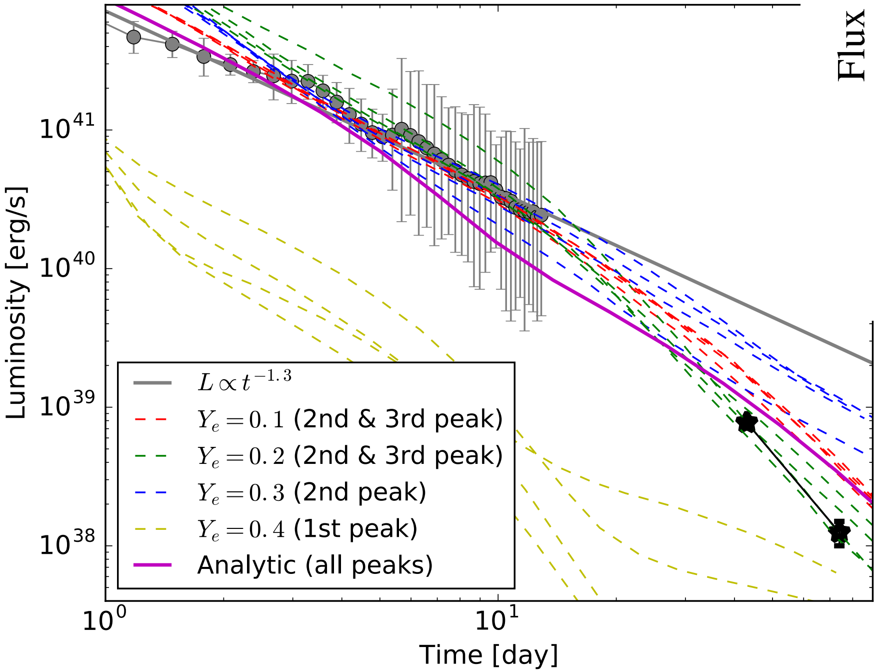
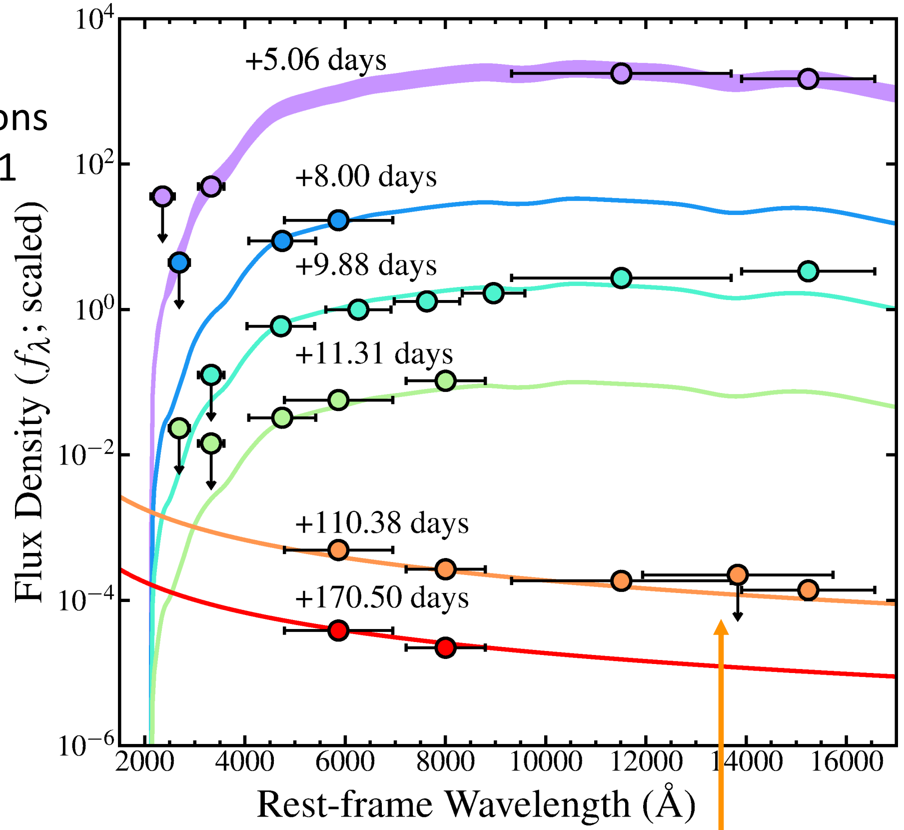


Zhu, Wollaeger, Vassh, Surman, Sprouse, Möller, McLaughlin, Korobkin, Jaffke, Even, Couture, Barnes, ApJL 2018

Spitzer mid-infrared
Kasliwal+2019



HST observations
Kilpatrick+2021



data at ~100 days matches a GRB afterglow

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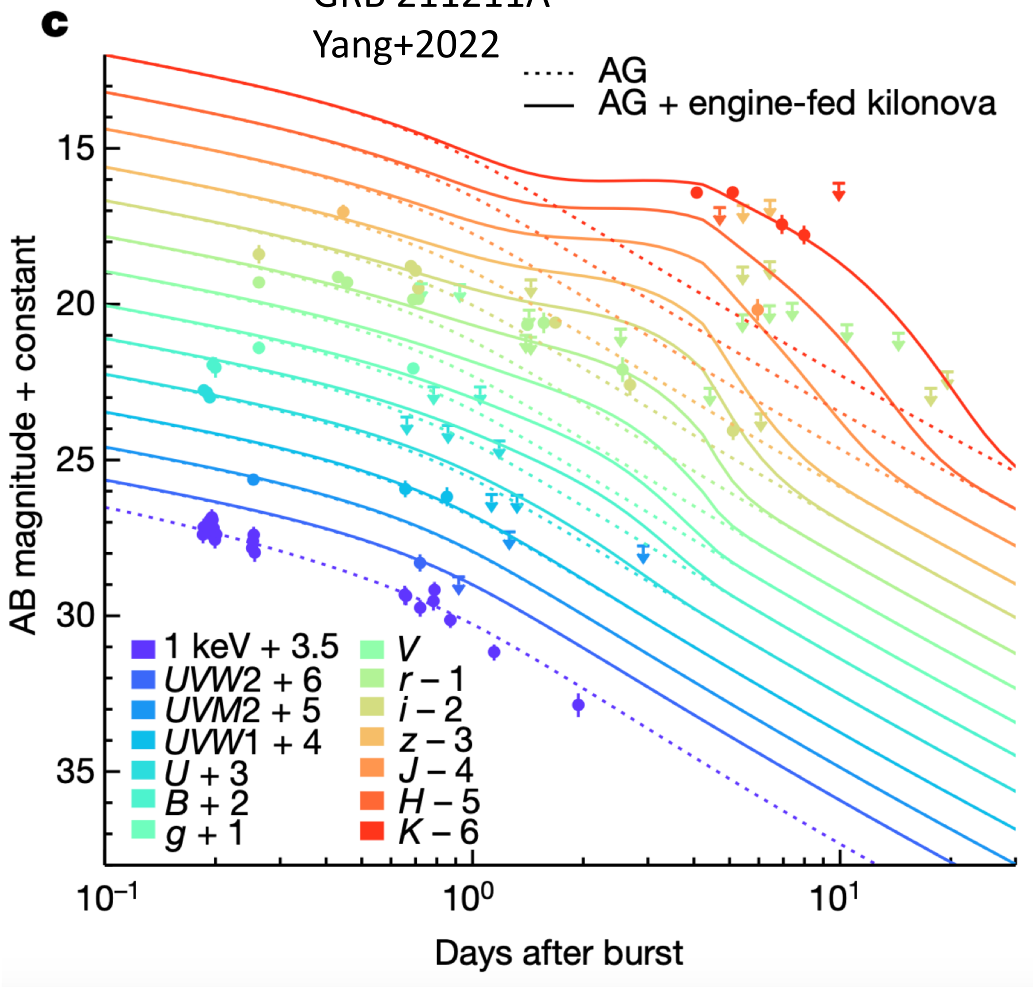
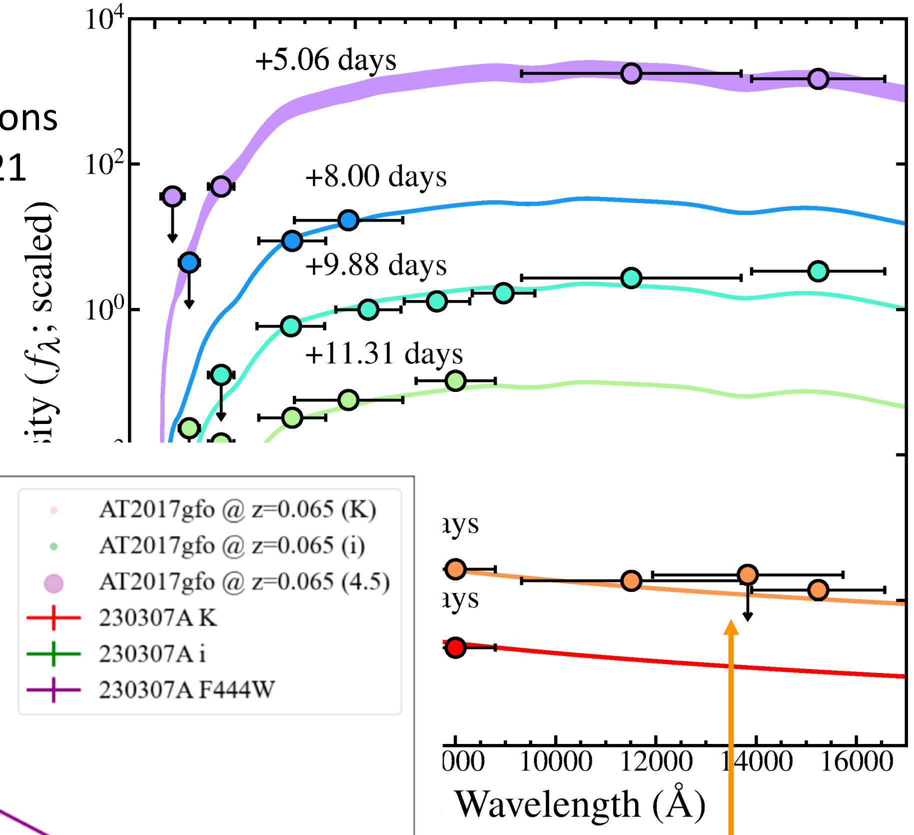
Subsequent KNe show similar late time behavior

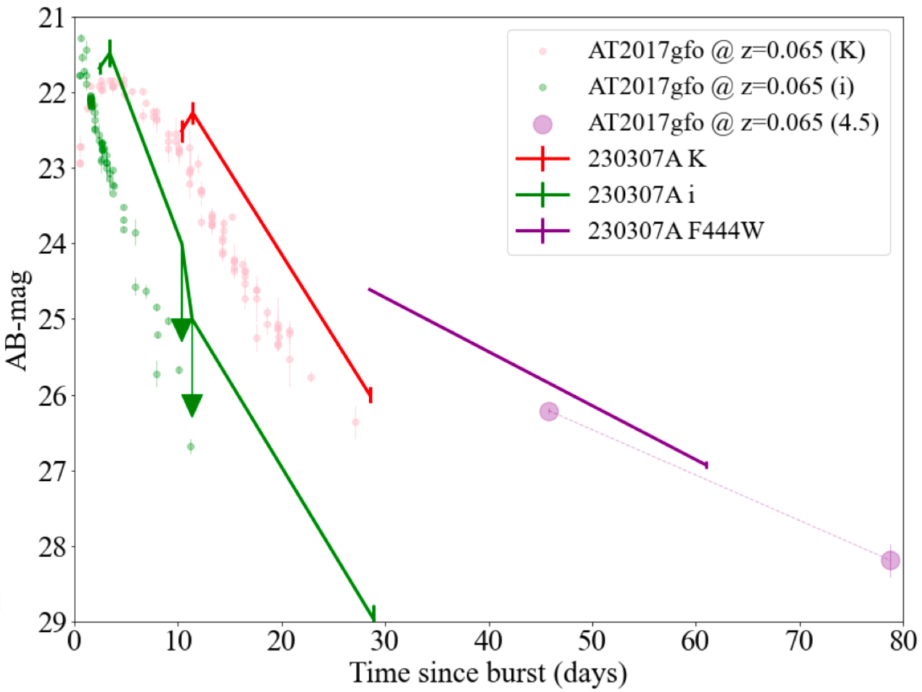
GRB 211211A
Yang+2022



HST observations
Kilpatrick+2021

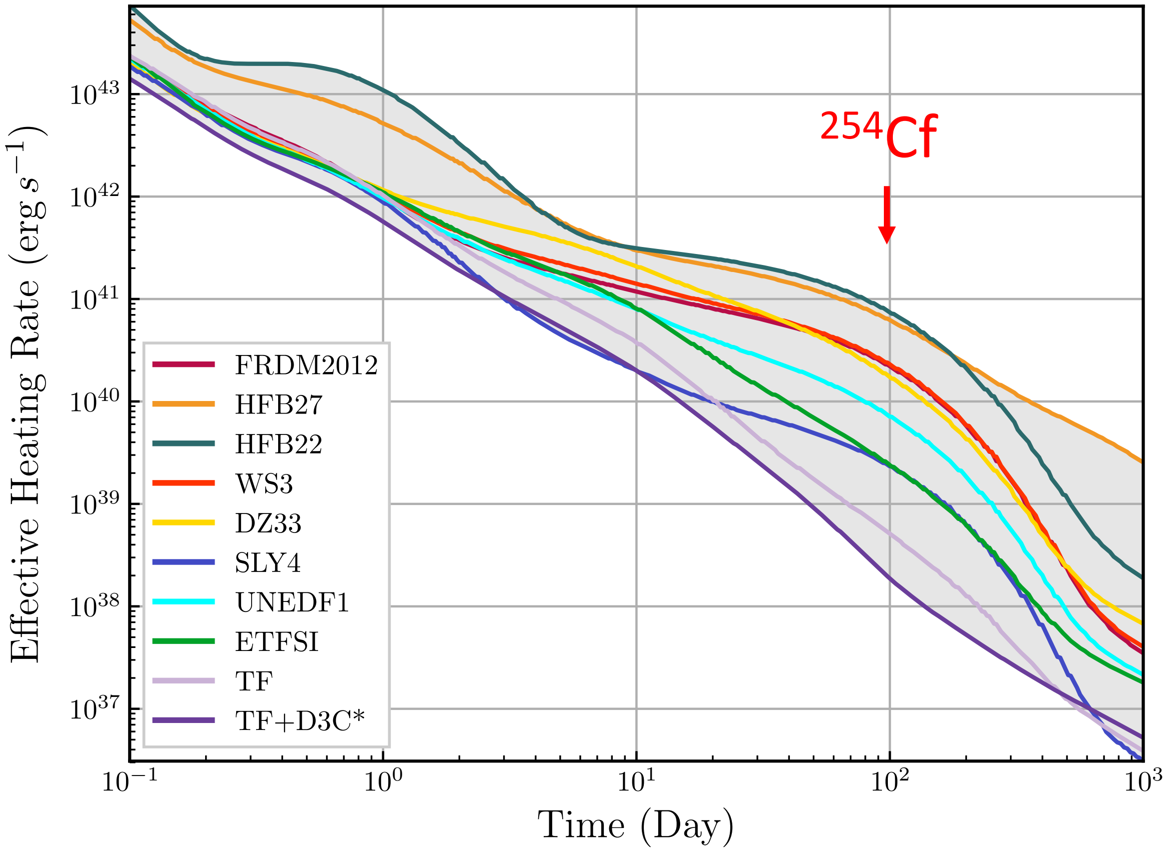


GRB 230307A
Levan+2023

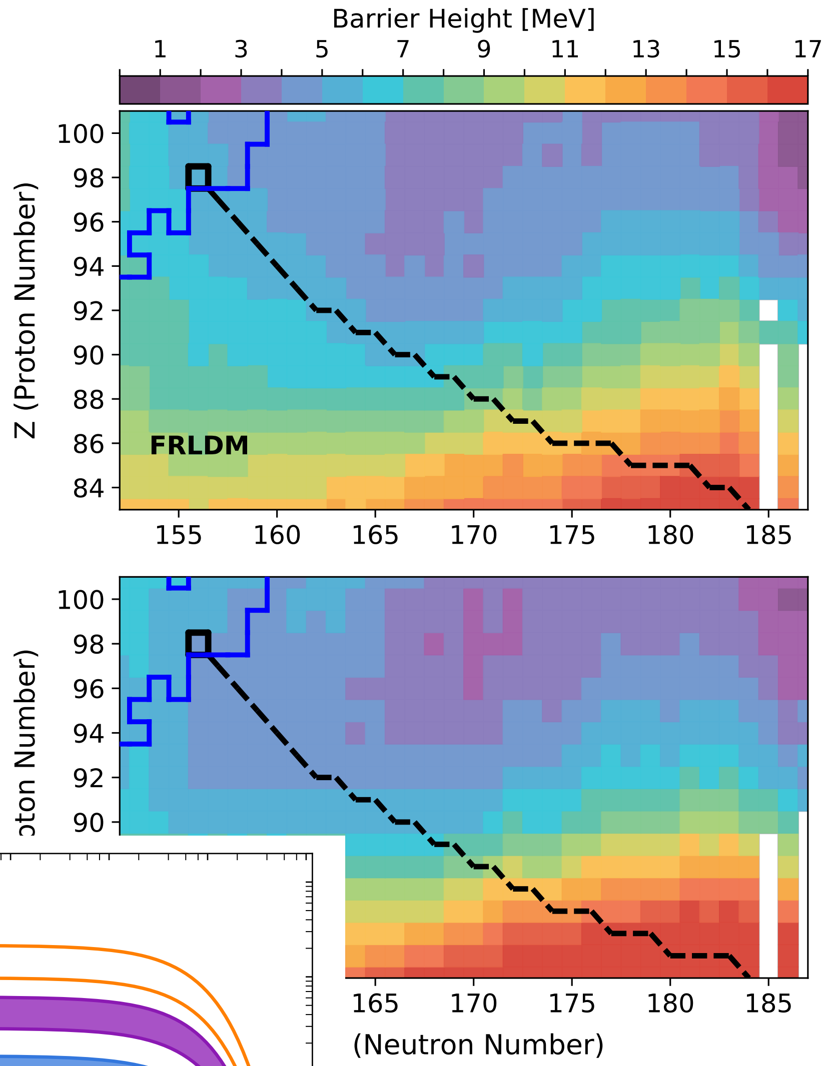


data at ~100 days matches a GRB afterglow

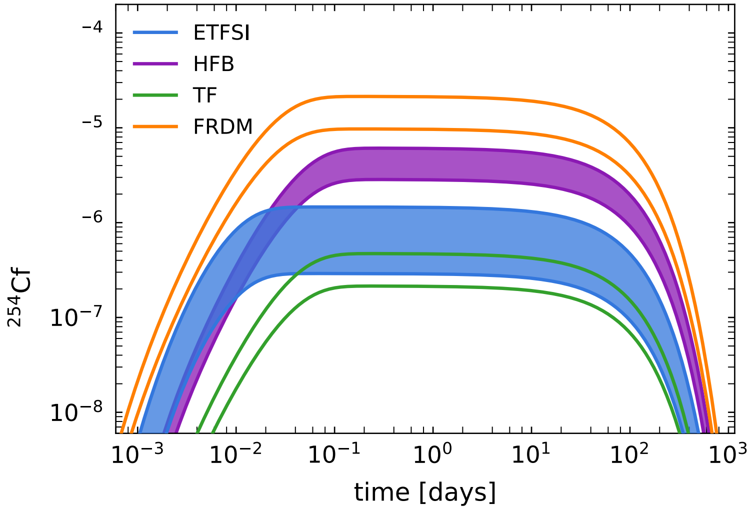
^{254}Cf: dependence on nuclear inputs



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



Vassh, Vogt, Surman, Randrup, Sprouse, Mumpower, Jaffke, Shaw, Holmbeck, Zhu, McLaughlin, 2018



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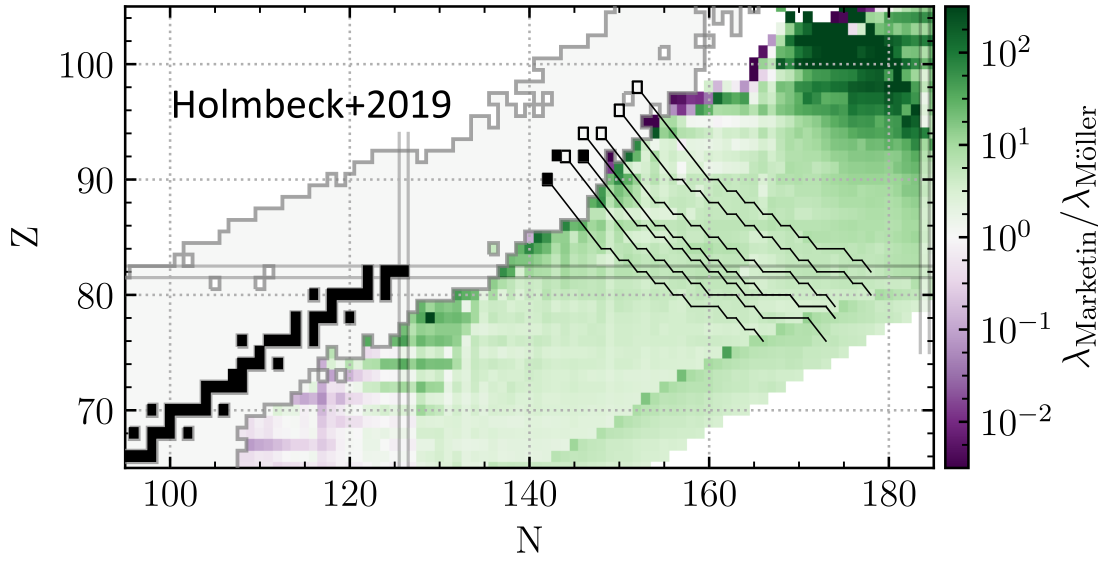
β decay and actinide production



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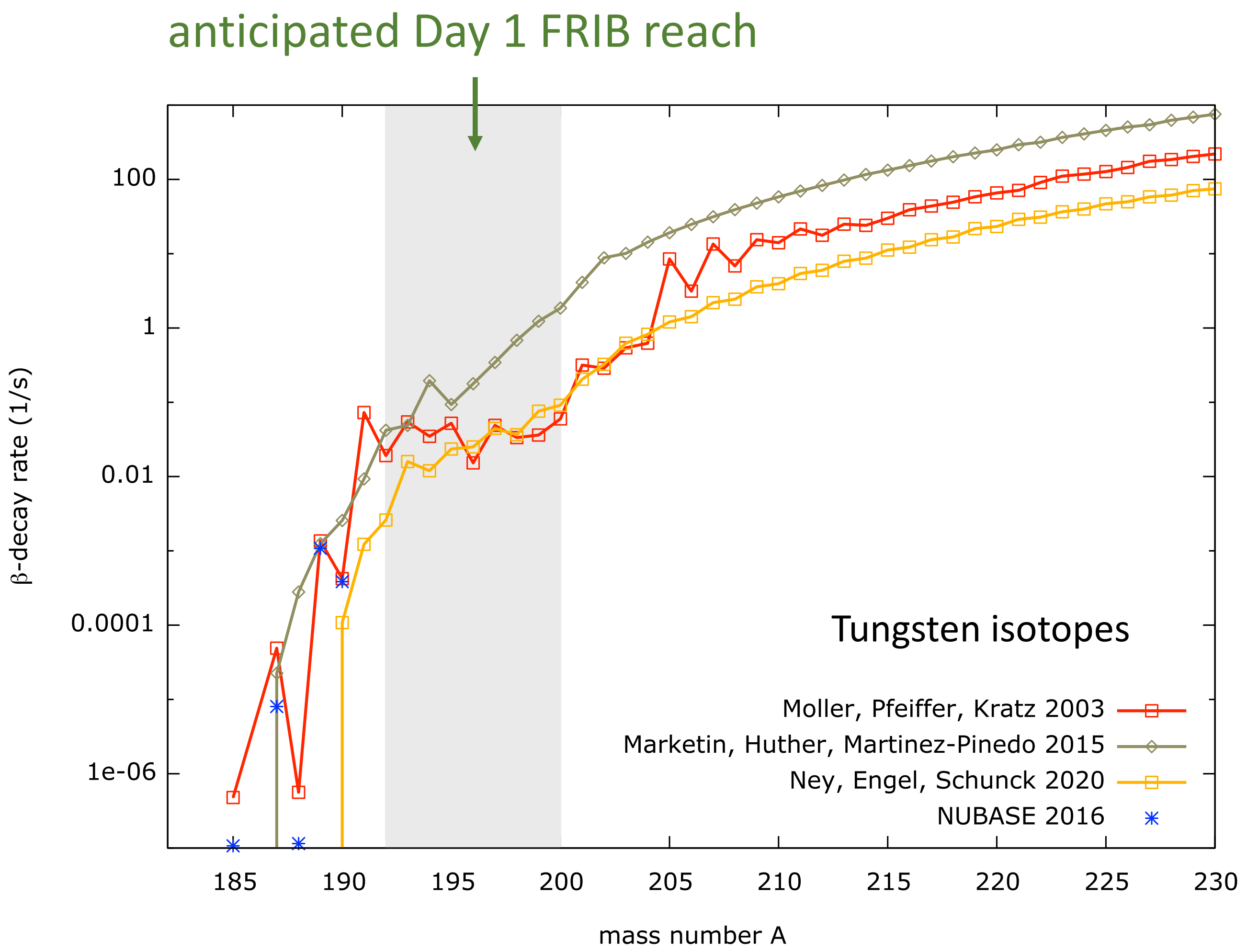
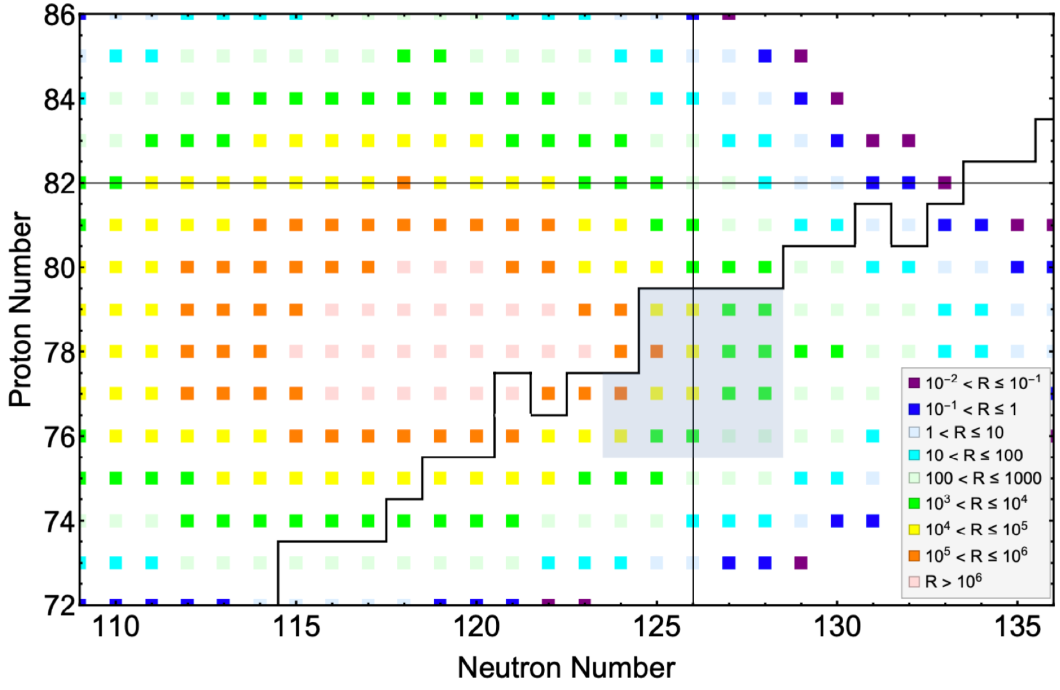
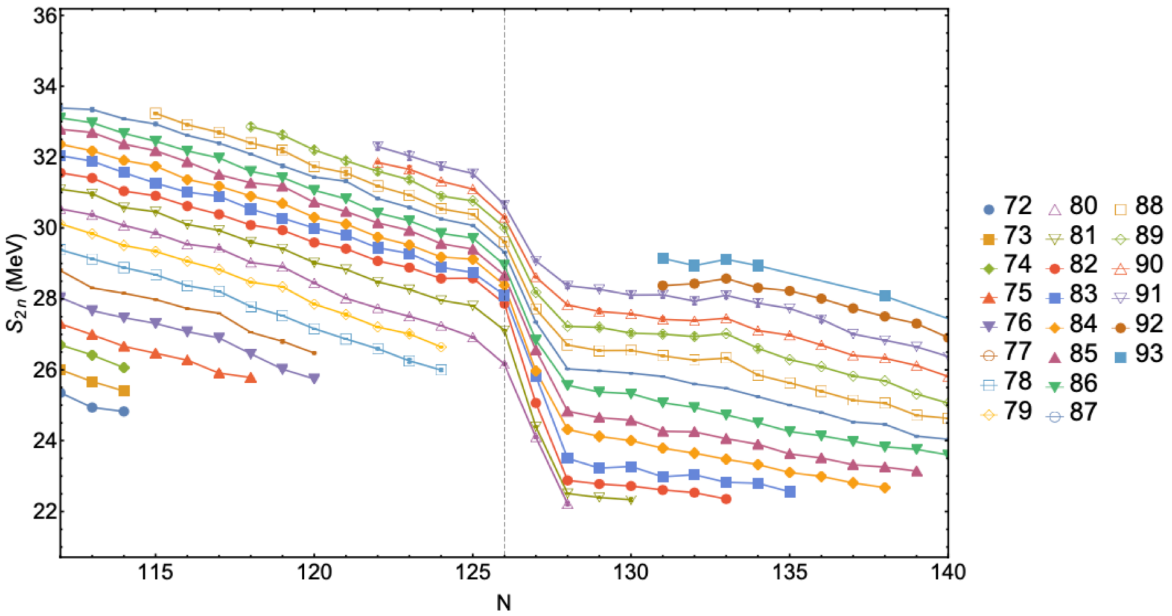
at Michigan State University

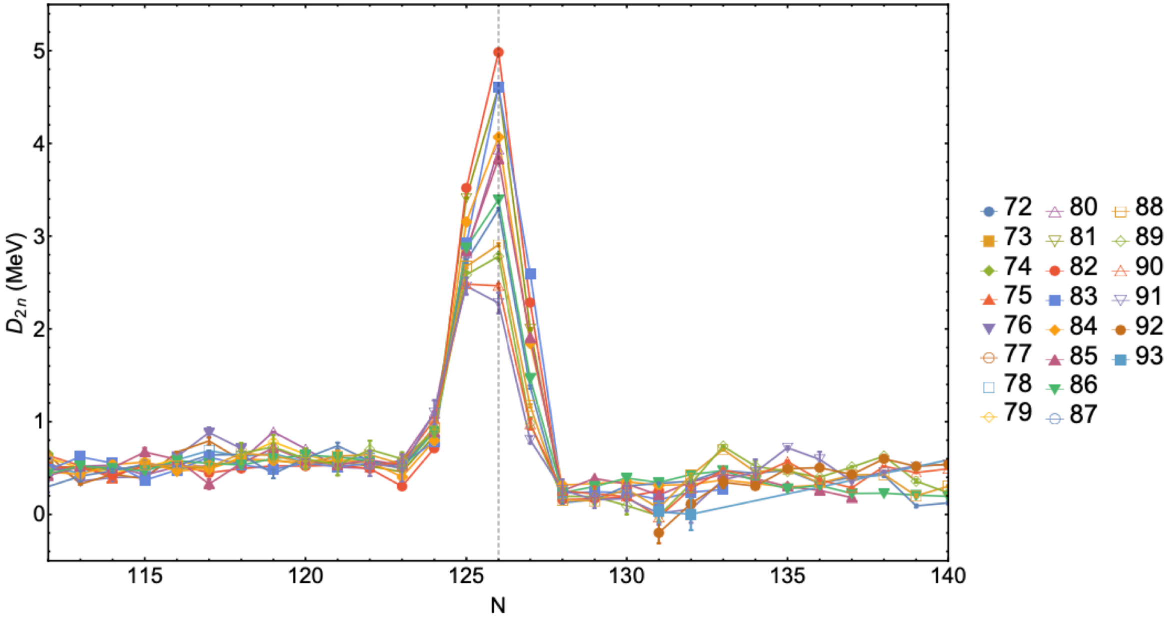
FRIB FDSi Day 1 proposal
N = 126 region halflives
Estrade+2021



Nuclear masses and actinide production







ANL N = 126 Factory proposal

N = 126 region masses

Liu+2022

Argonne NATIONAL LABORATORY

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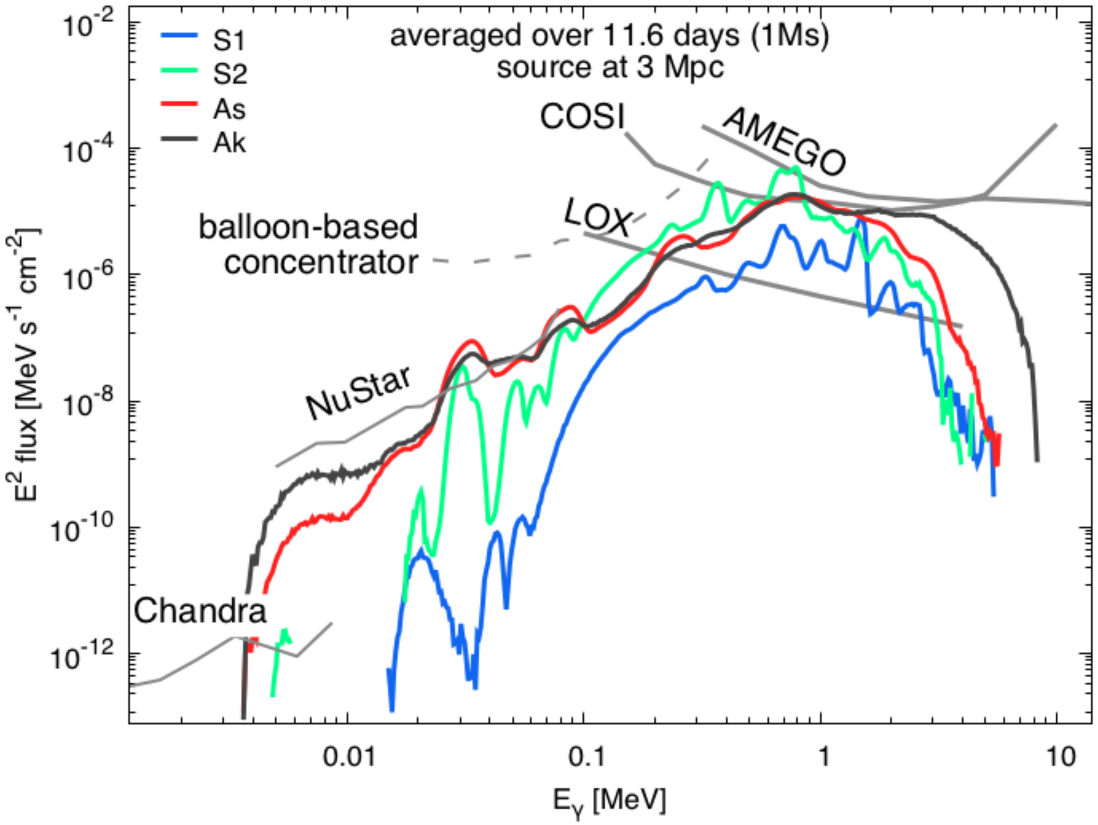
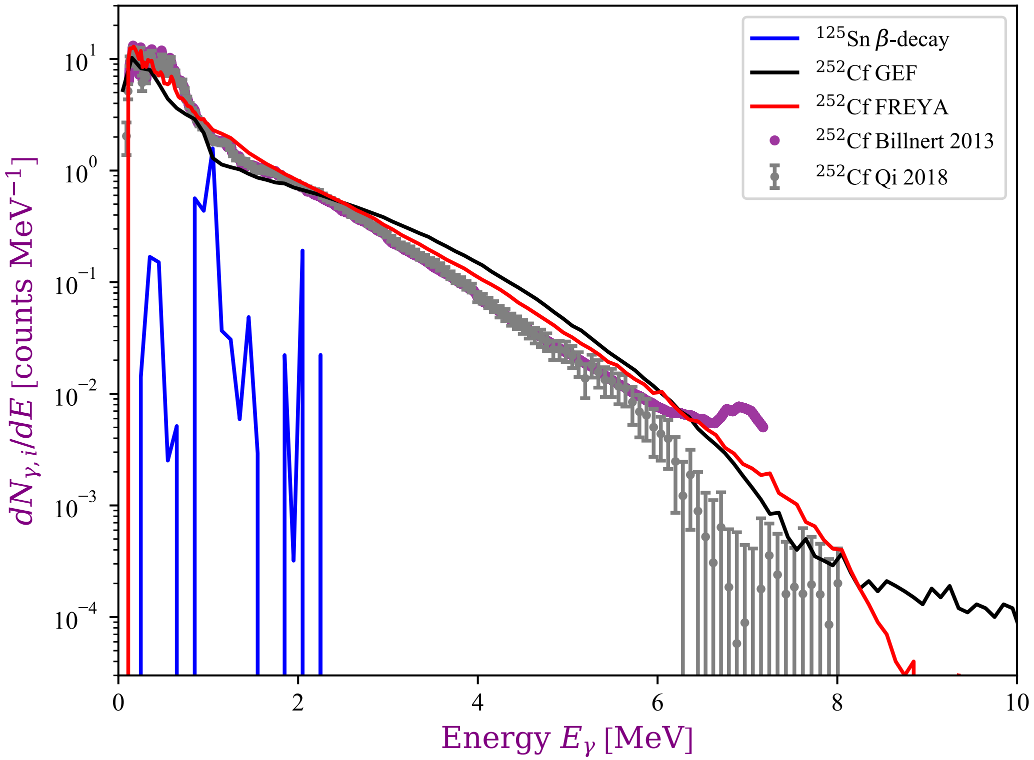
Actinide observables: gamma rays



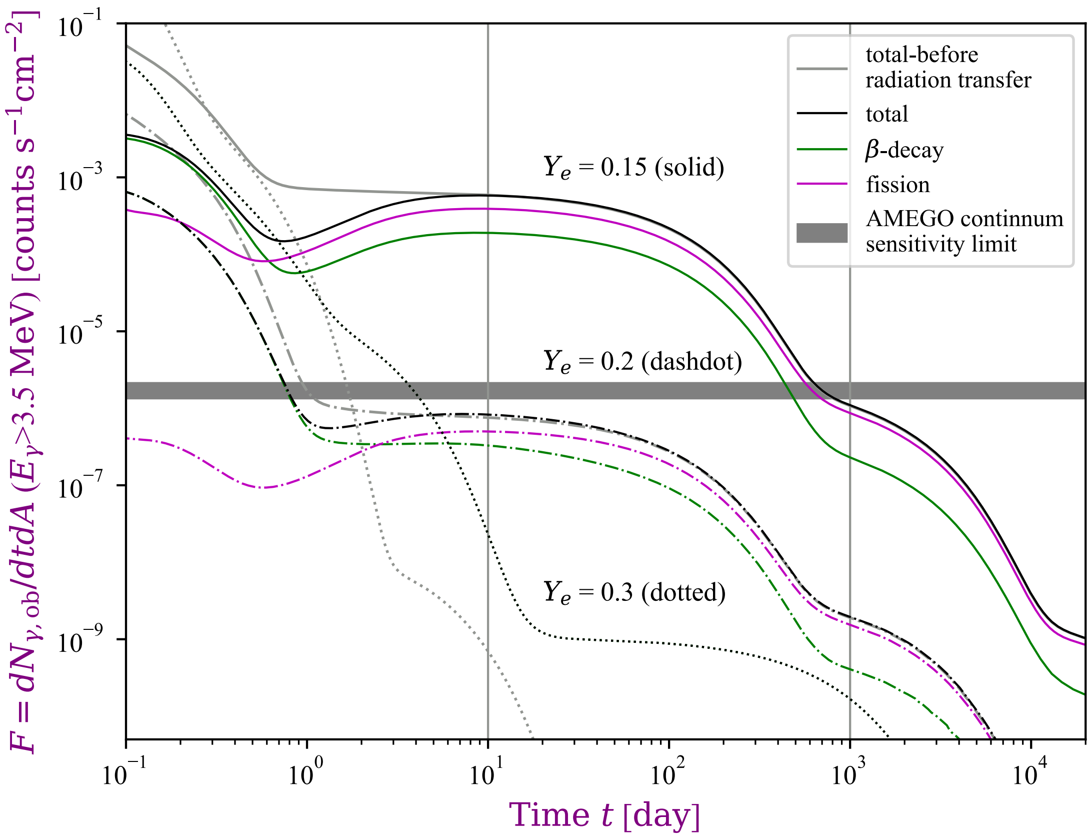


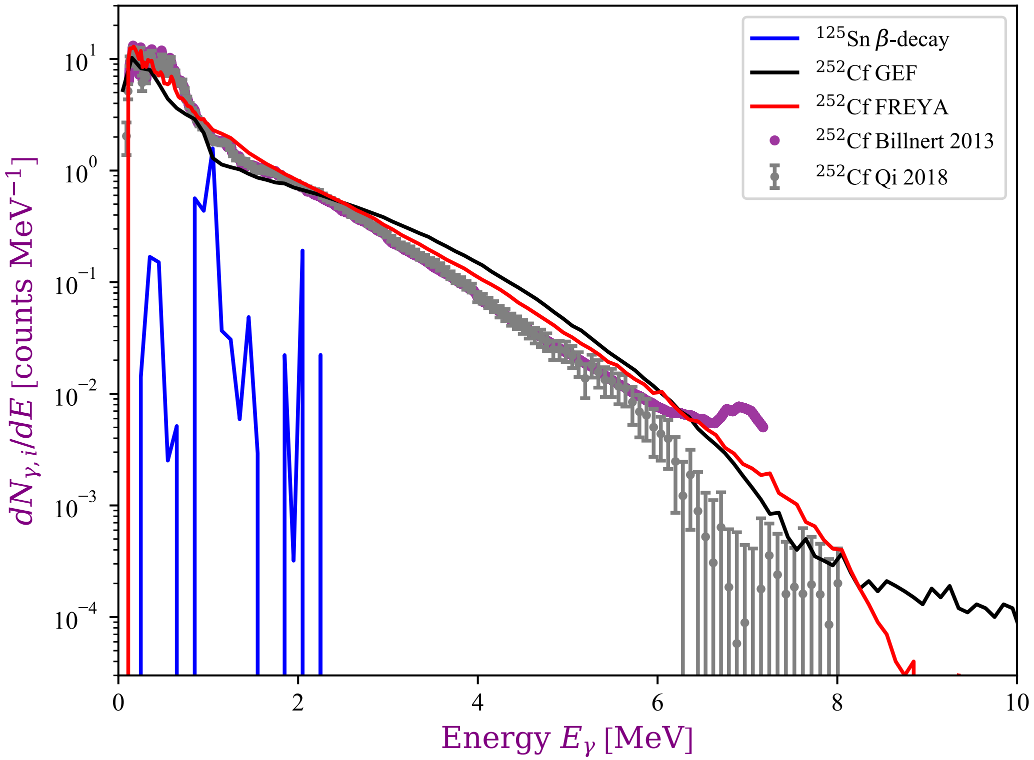
Korobkin, Hungerford, Fryer, Mumpower, Misch, Sprouse, Lippuner, Surman, Couture, Bloser, Shirazi, Evan, Vestrand, Miller 2020

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

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

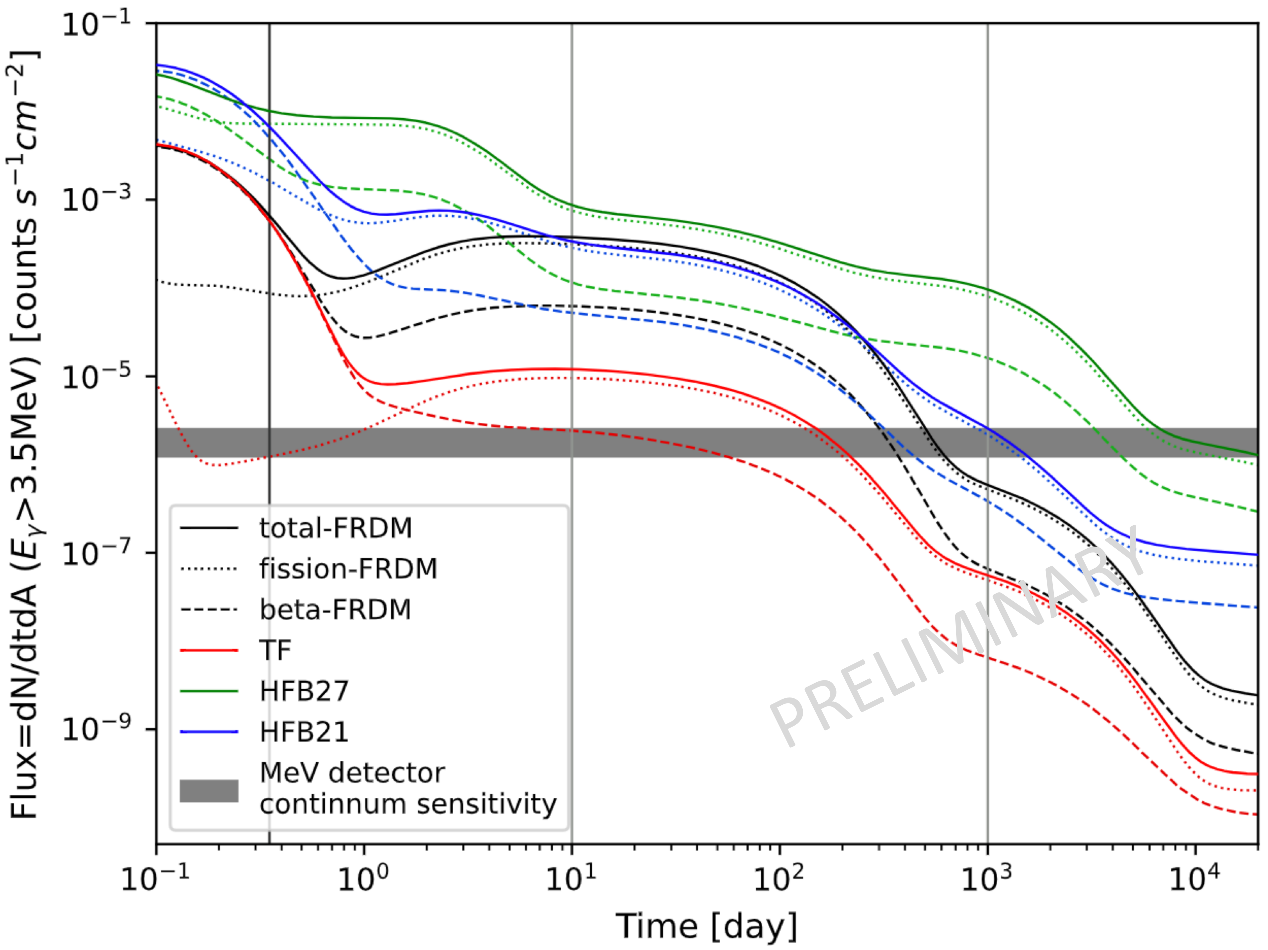
Actinide observables: gamma rays



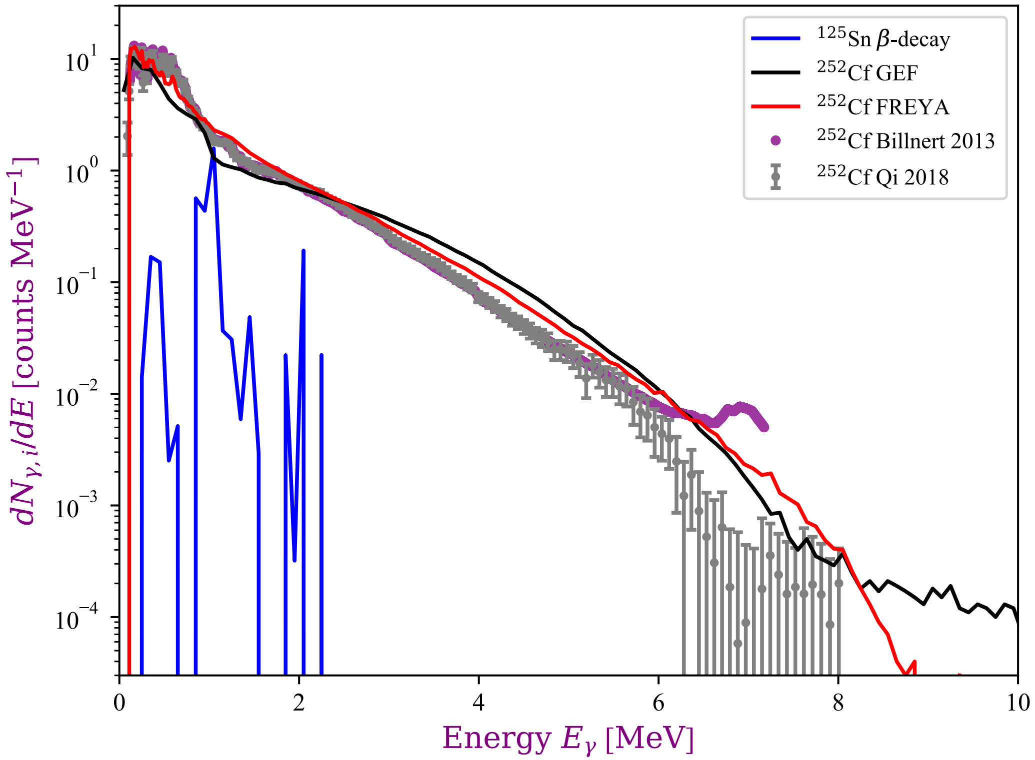


Wang, Vassh, Sprouse, Mumpower, Vogt, Randrup, Surman, ApJL 2020

Actinide observables: gamma rays



Wang+ in preparation 2024



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

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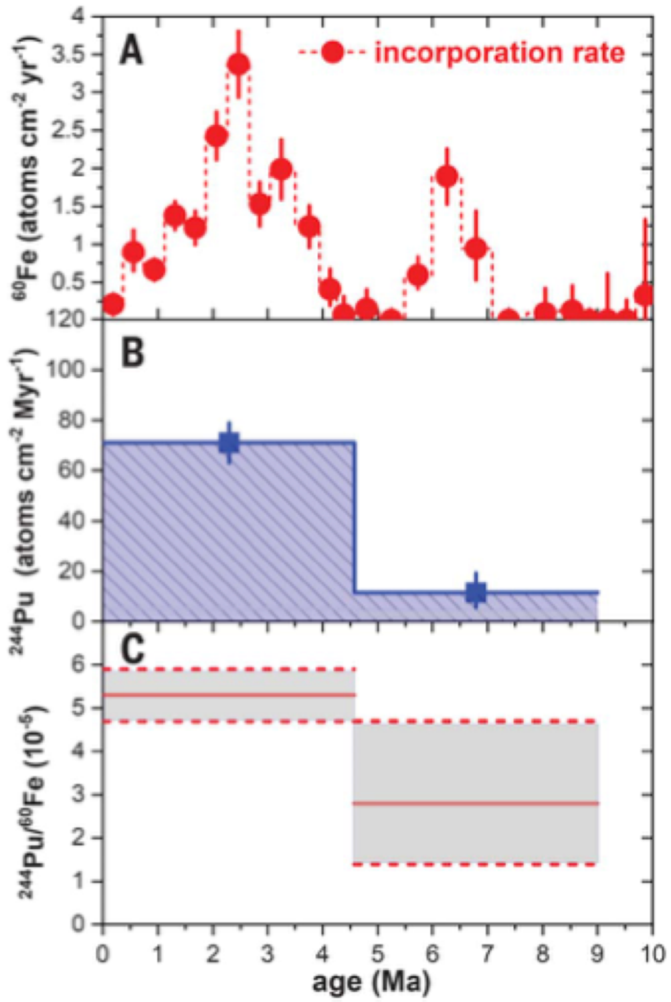
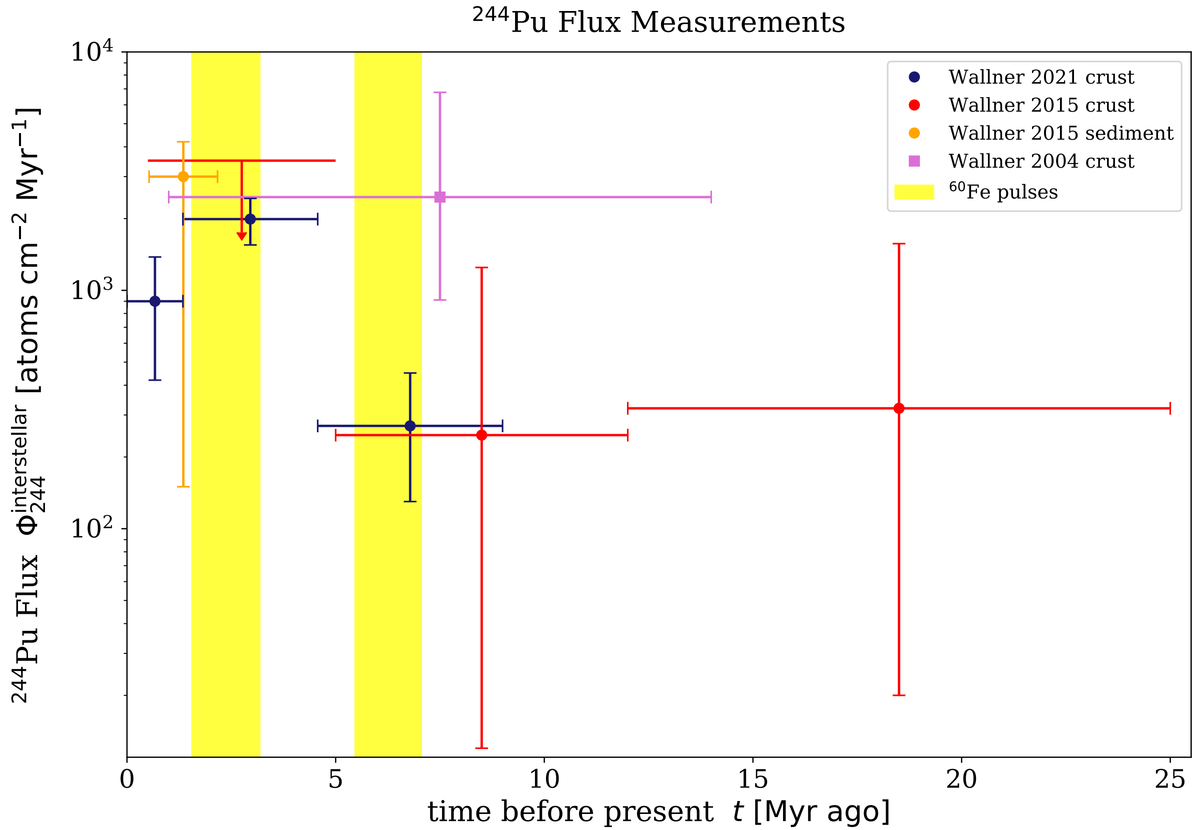
Actinide observables: ^{60}Fe and ^{244}Pu in Fe-Mn crusts

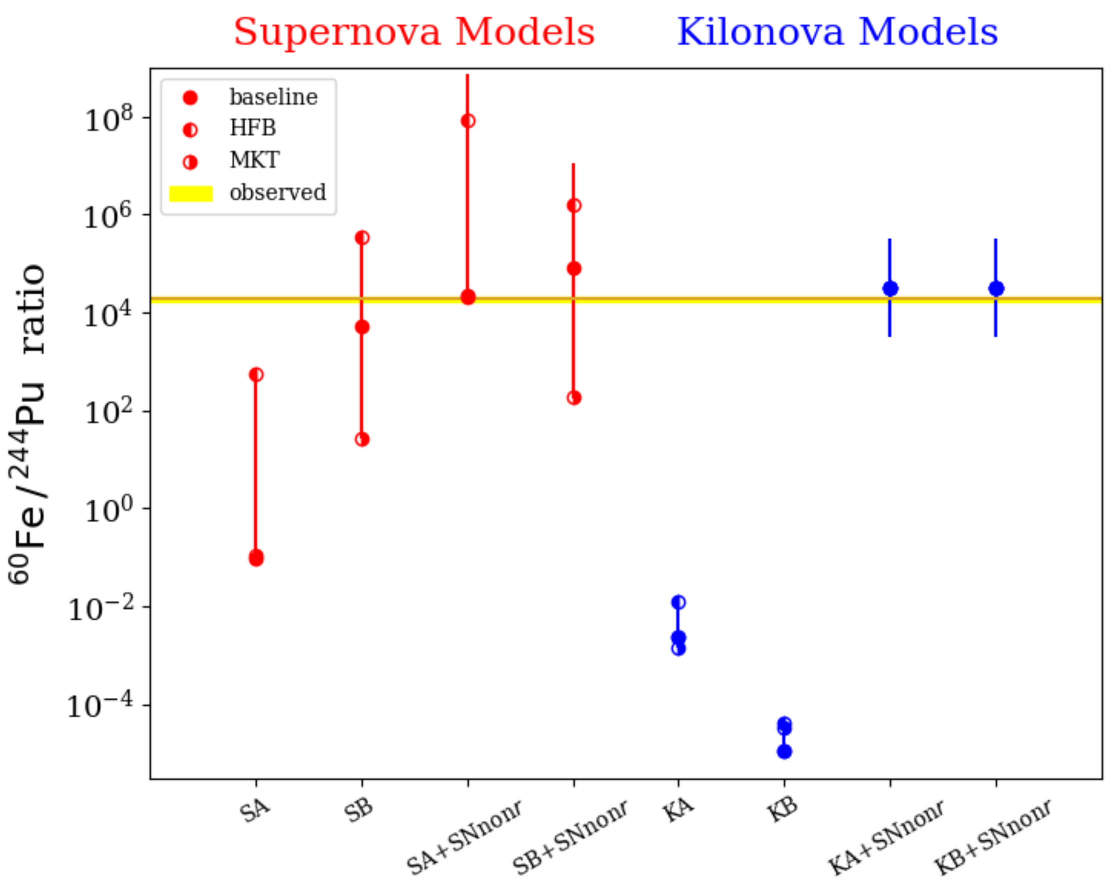
Wallner+2021





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

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



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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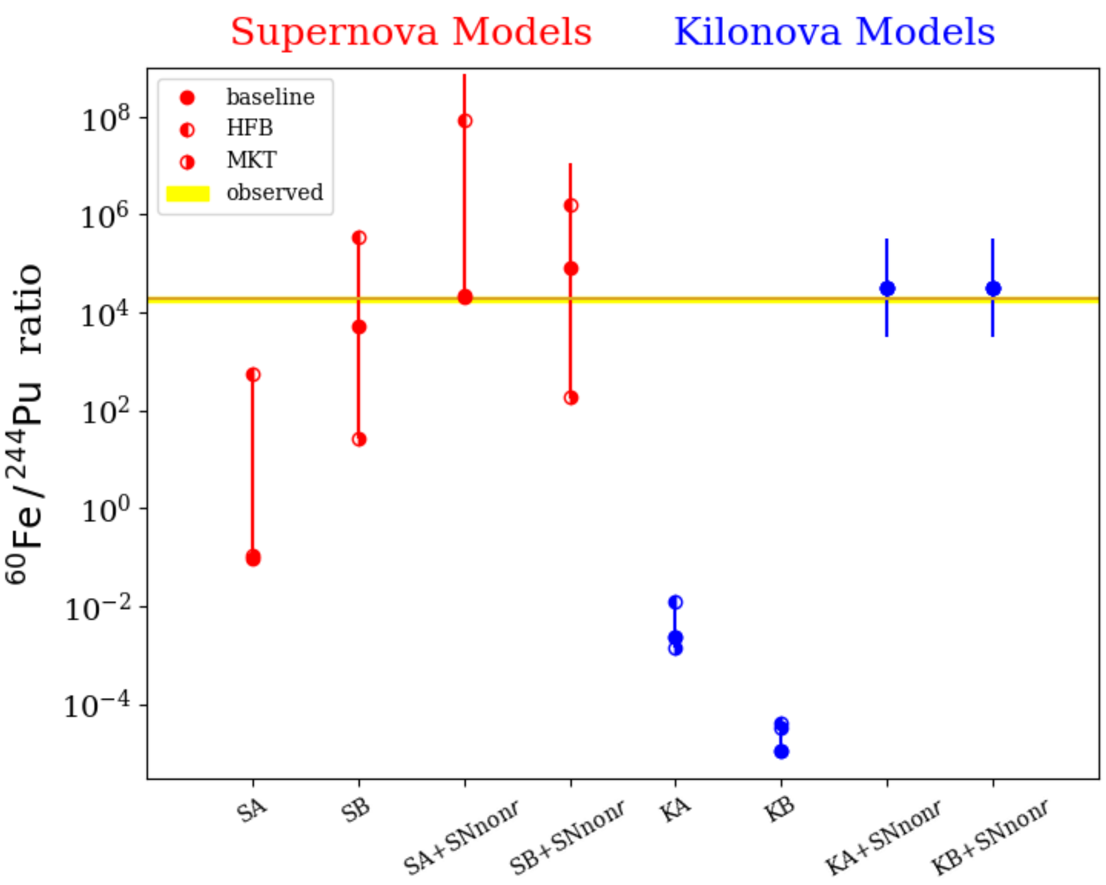

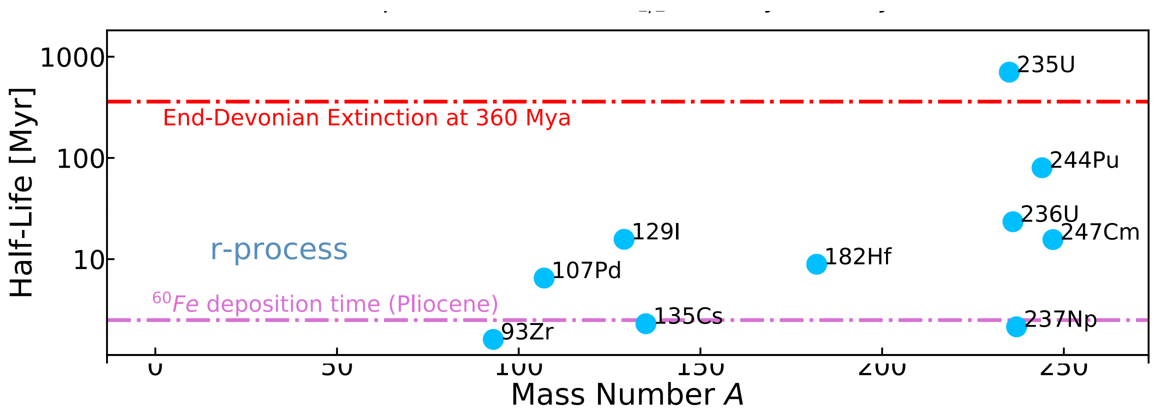

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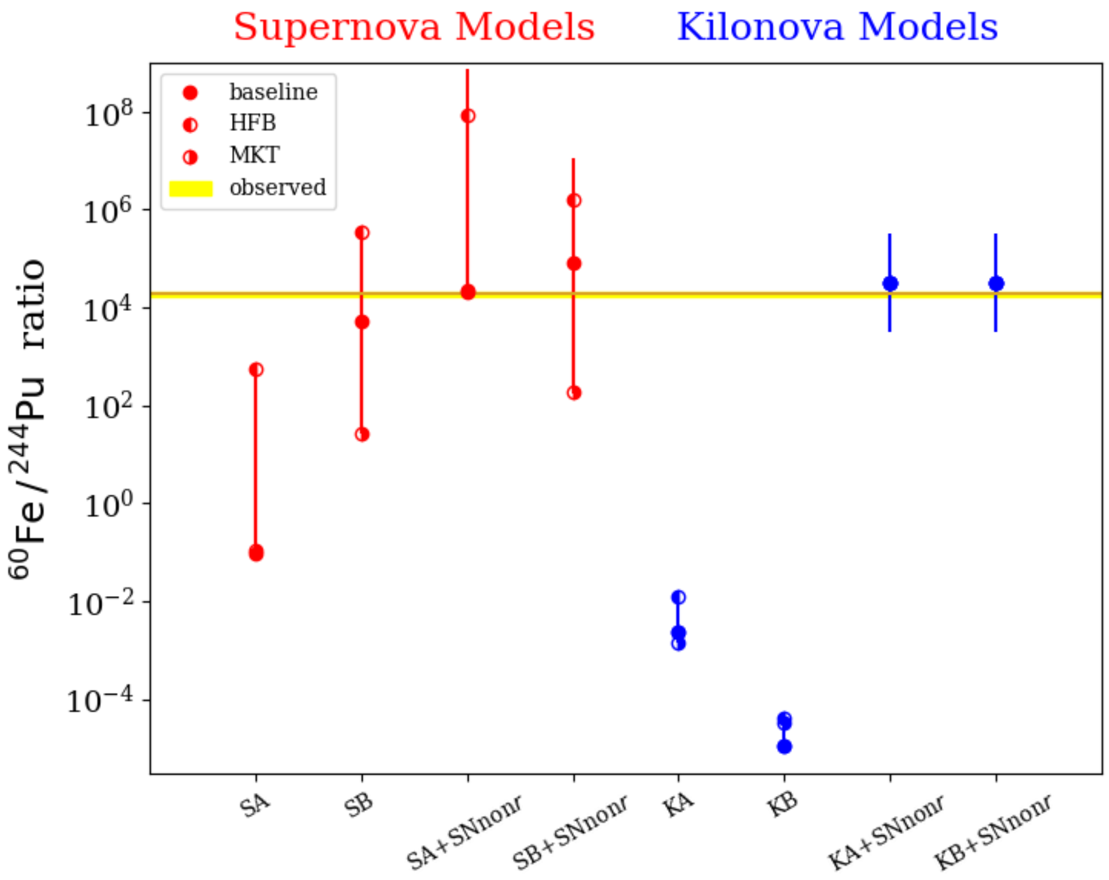

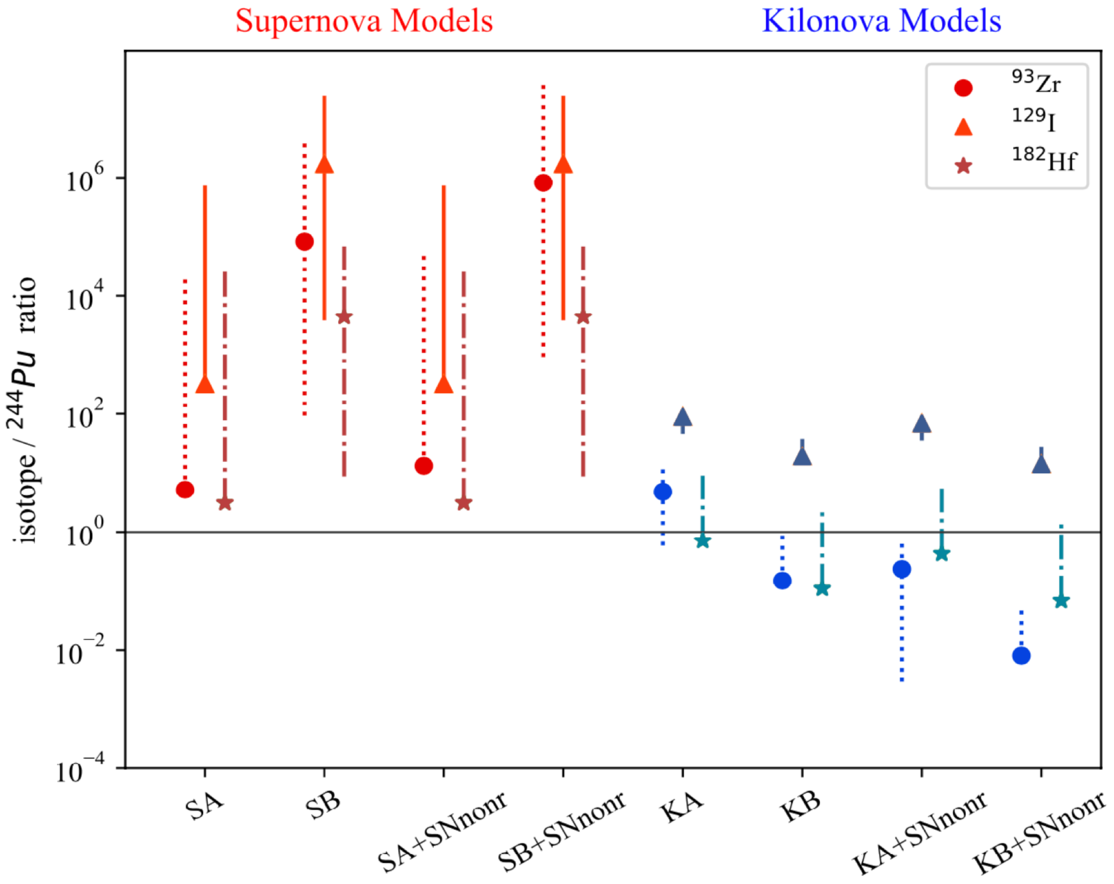

Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;
Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2023

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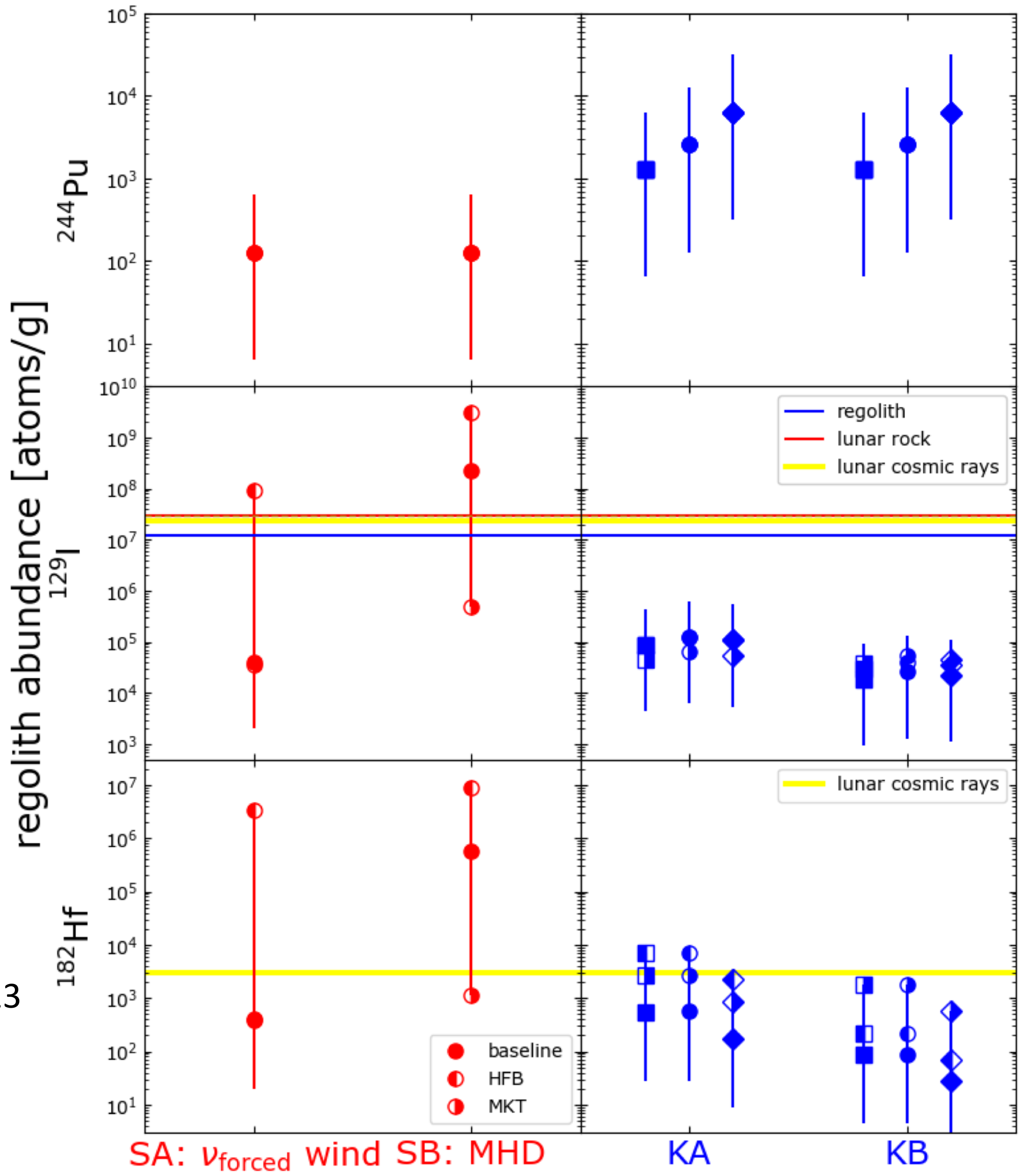
Actinide observables: lunar regolith



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

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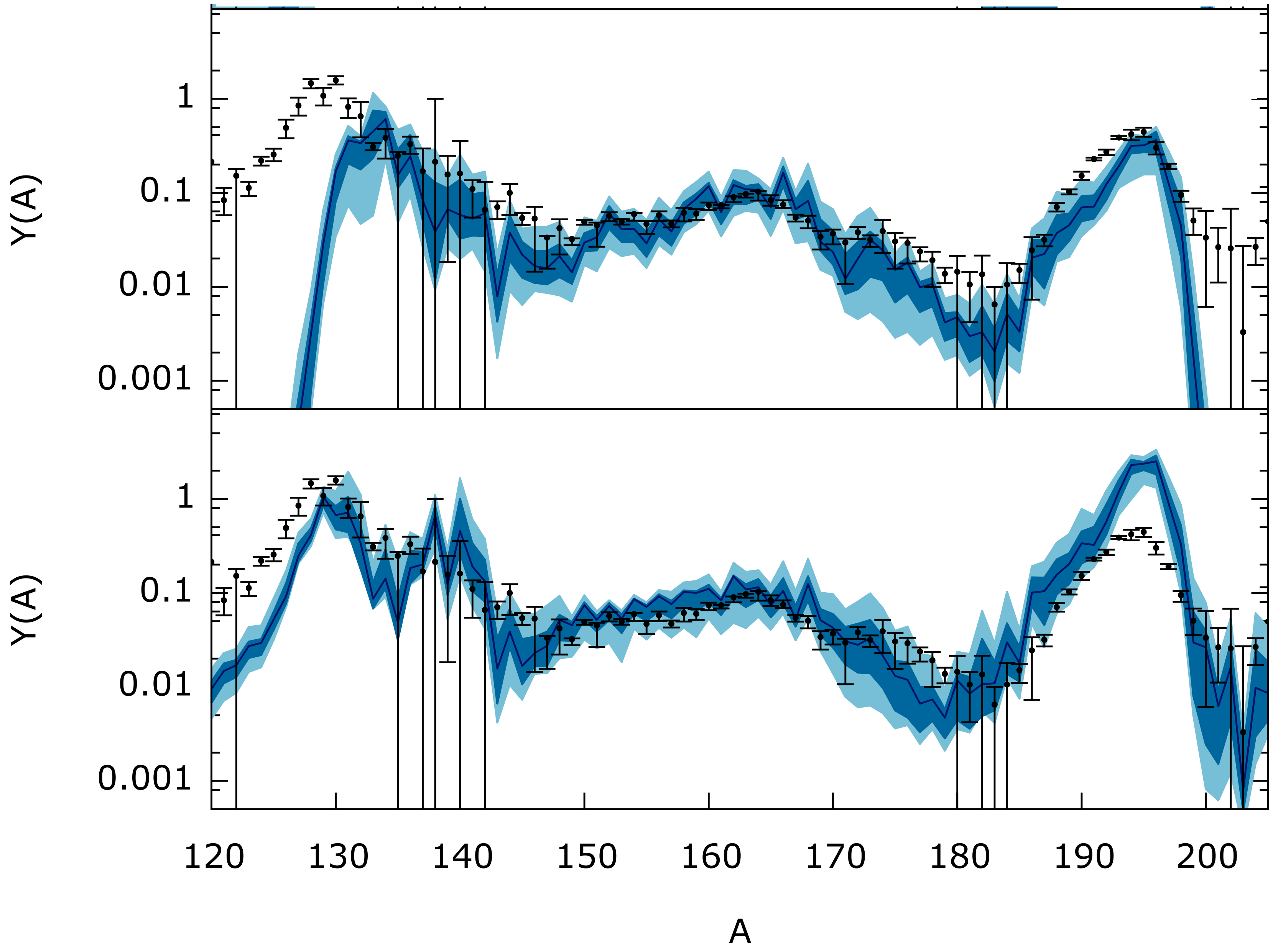
UNEDF1 masses



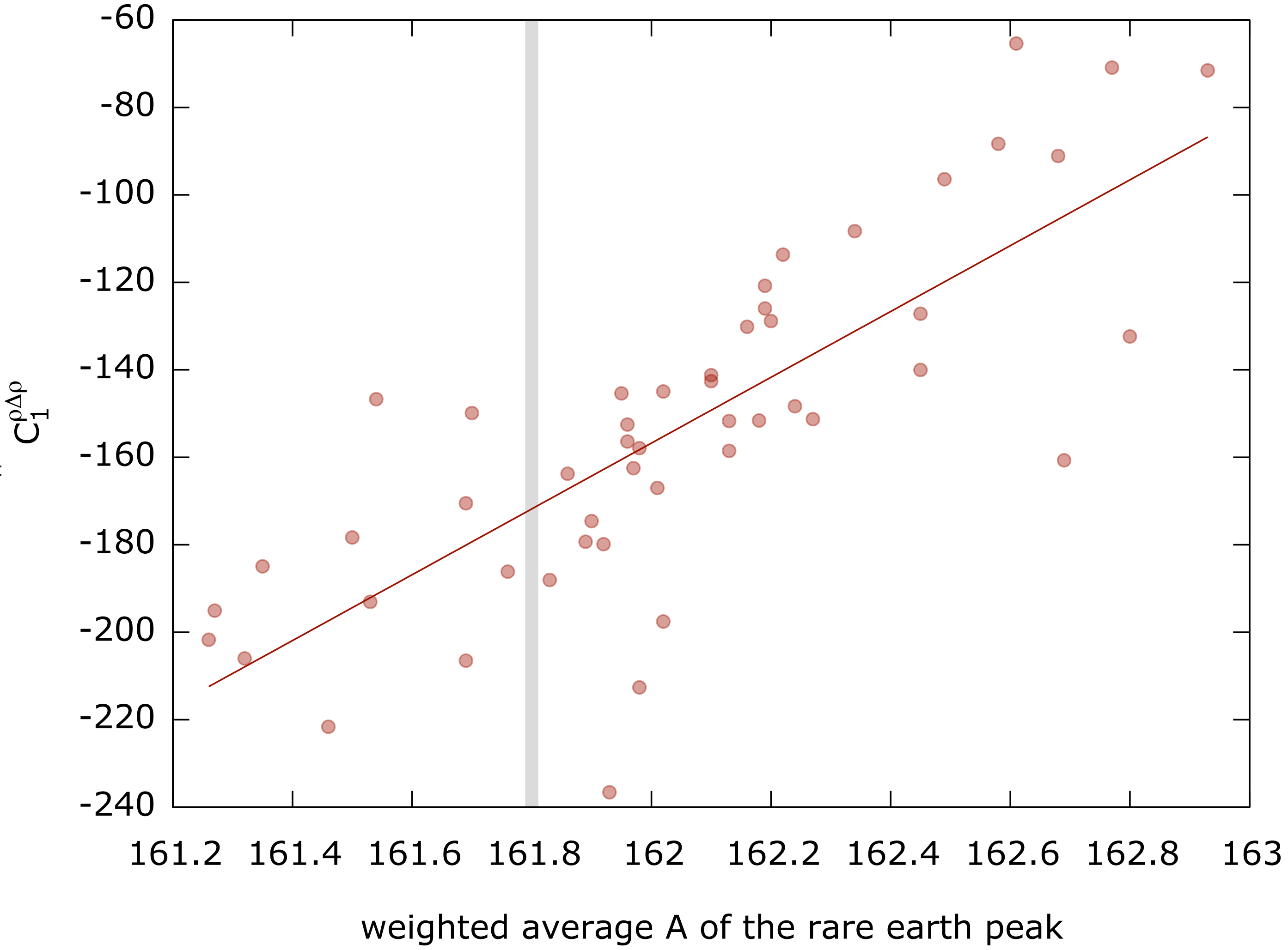
Sprouse, Navarro Perez, Surman, Mumpower, McLaughlin, Schunck 2020

UNEDF1 masses

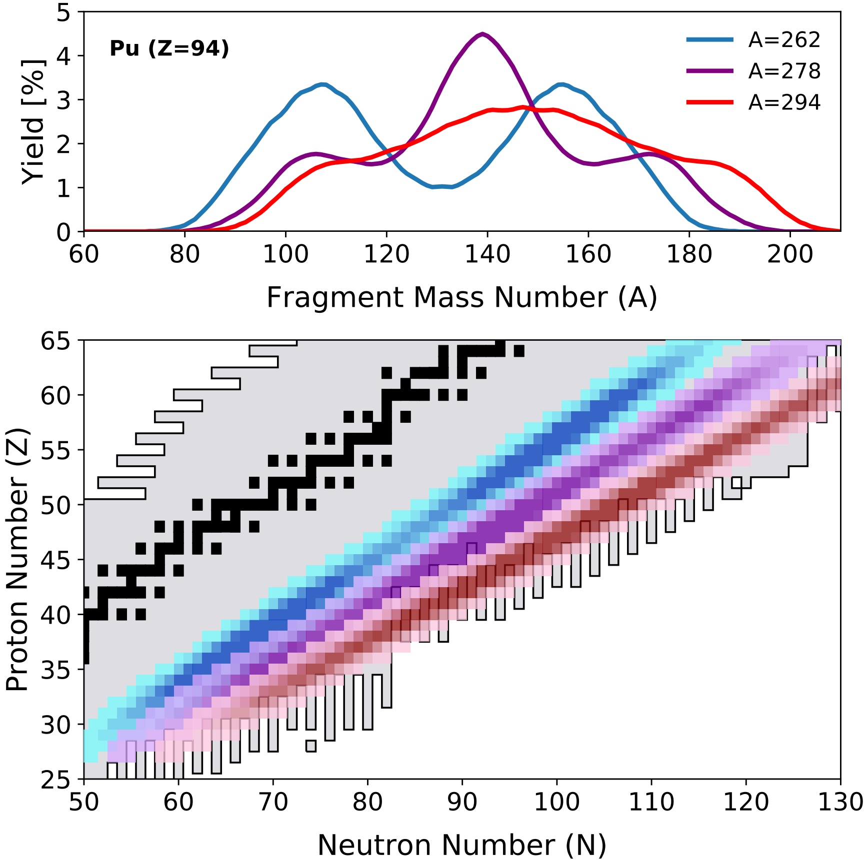
TABLE II: Optimized parameter set UNEDF1. Listed are bounds used in the optimization, final optimized parameter values, standard deviations, and 95% confidence intervals.

$\mathbf{x}$	Bounds	$\hat{\mathbf{x}}^{(\text{fin.})}$	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	–	–
$a_{\text{sym}}^{\text{NM}}$	[28, 36]	28.987	0.604	[28.152, 29.822]
$L_{\text{sym}}^{\text{NM}}$	[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]

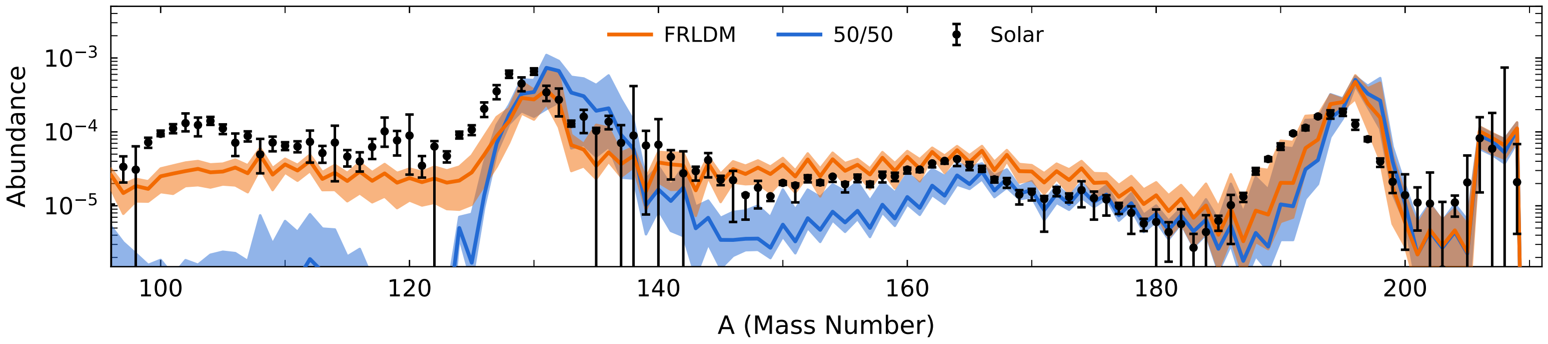
Sprouse, Navarro Perez, Surman, Mumpower, McLaughlin, Schunck 2020

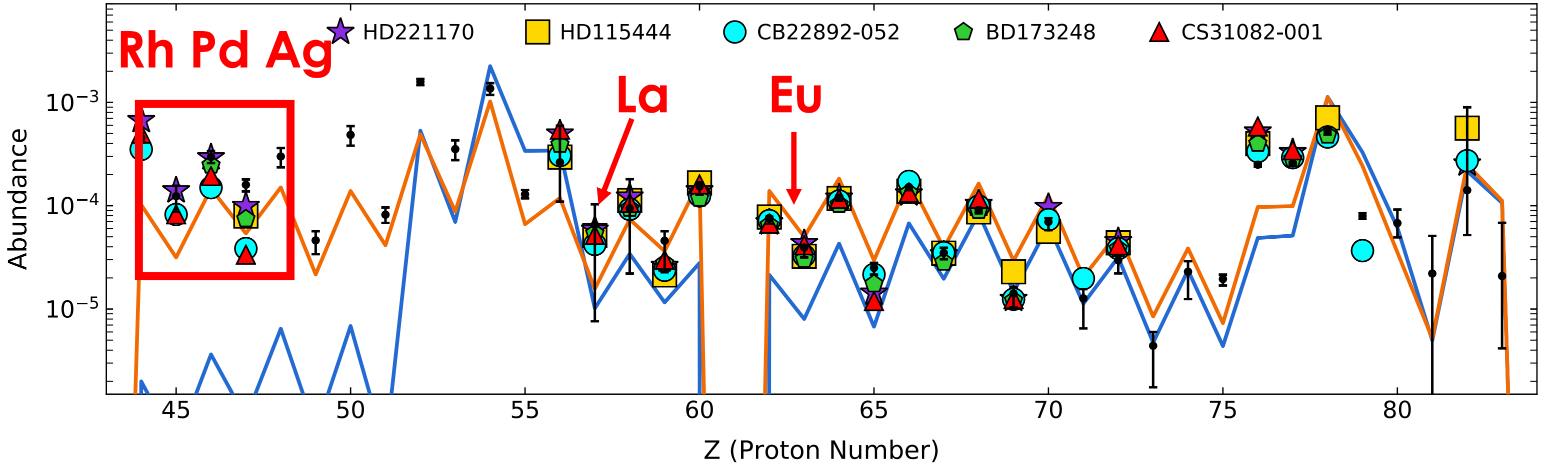


Fission yield signatures



Vassh, Mumpower, McLaughlin, Sprouse, Surman 2020





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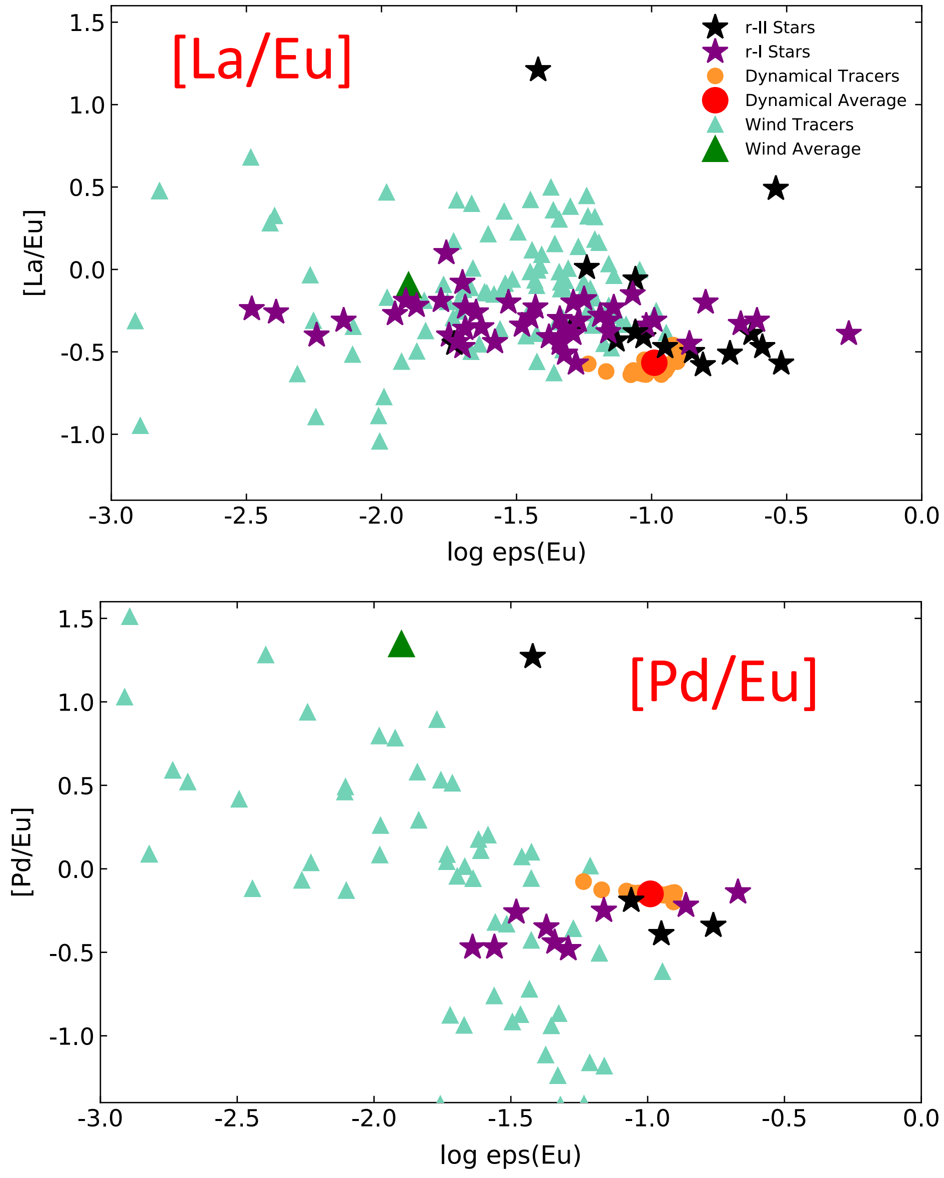
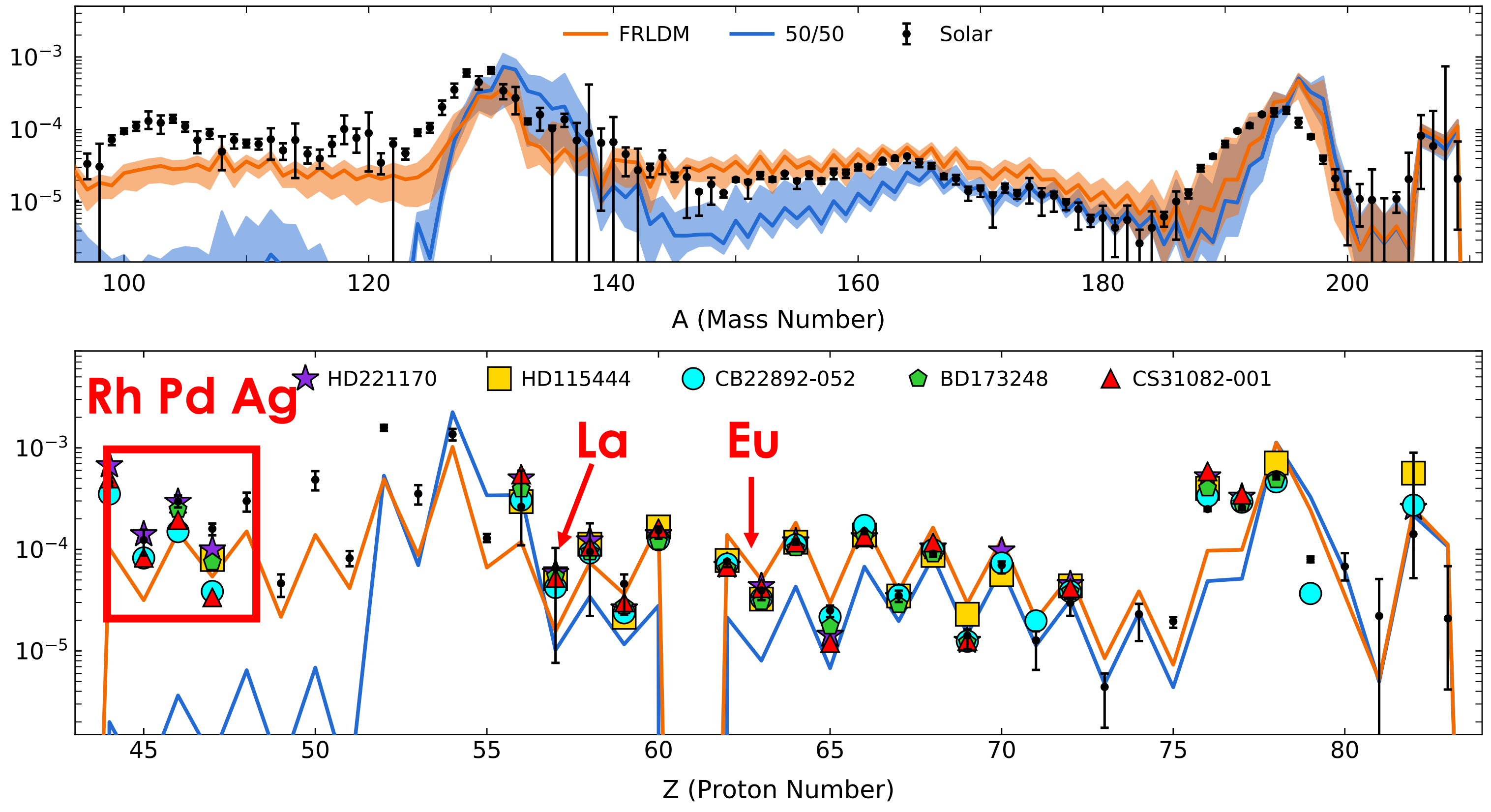
Fission yield signatures

Vassh, Mumpower, McLaughlin, Sprouse, Surman 2020





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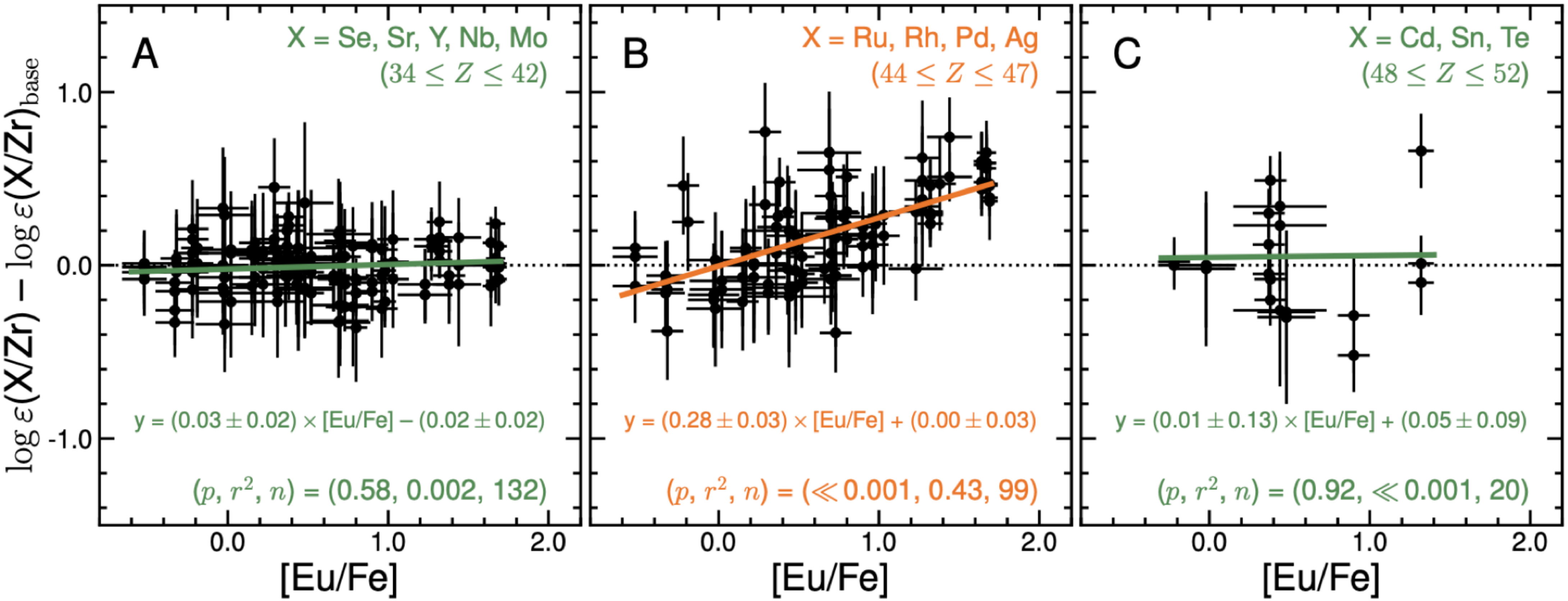

Roederer, Vassh, Holmbeck, Mumpower, Surman, Cowan, Beers, Ezzeddine, Frebel, Hansen, Placco, Sakari, *Science* 2023

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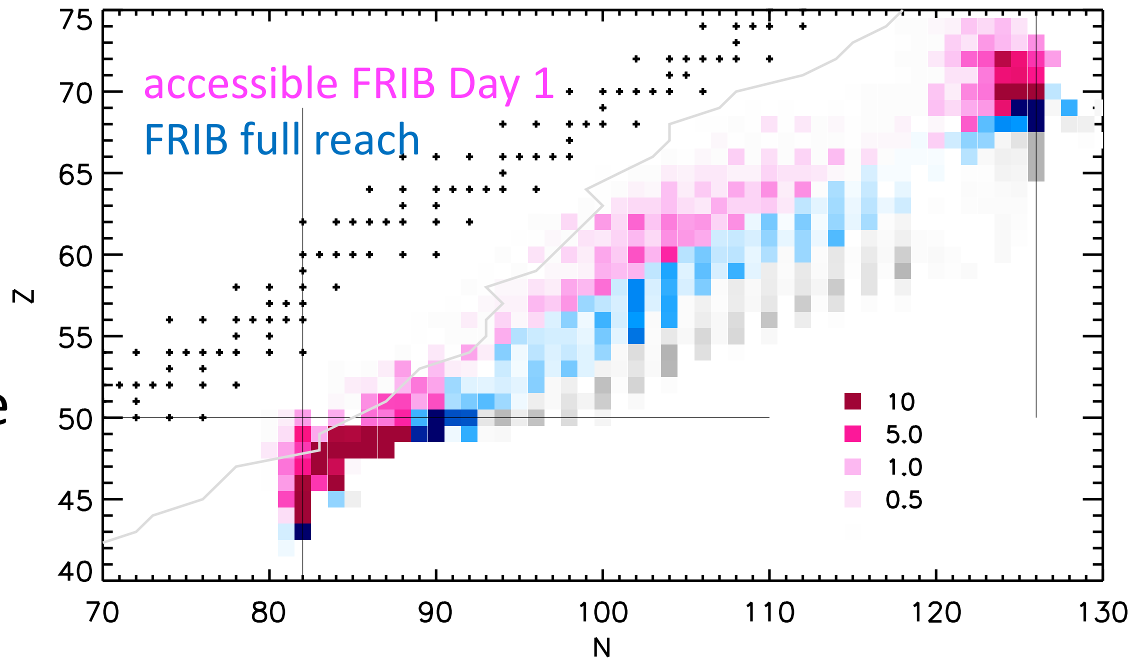
summary

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, the N=126 factory, ARIEL, and FAIR have 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