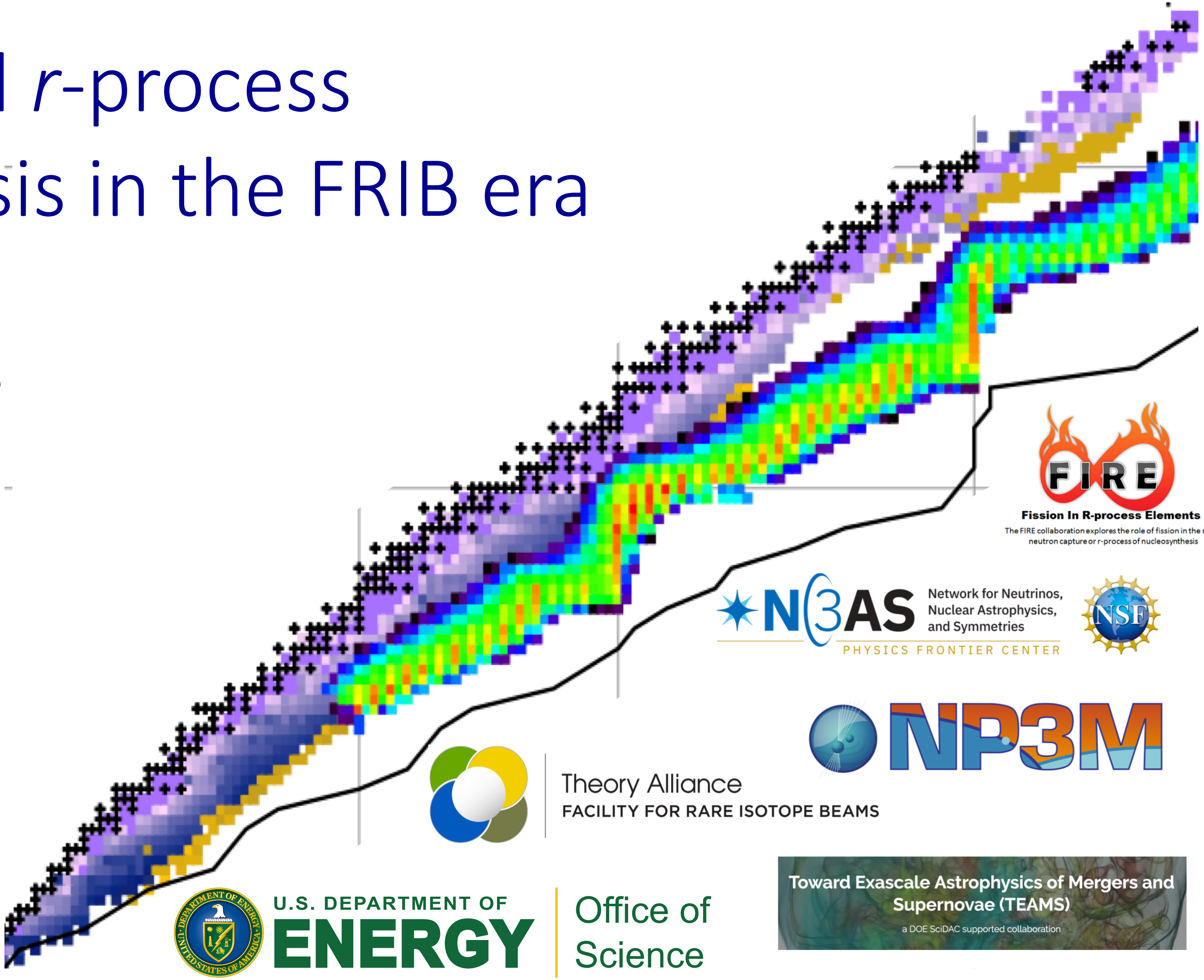
Neutrinos and *r*-process nucleosynthesis in the FRIB era

Rebecca Surman
University of Notre Dame

INT 23-2
8 Aug 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

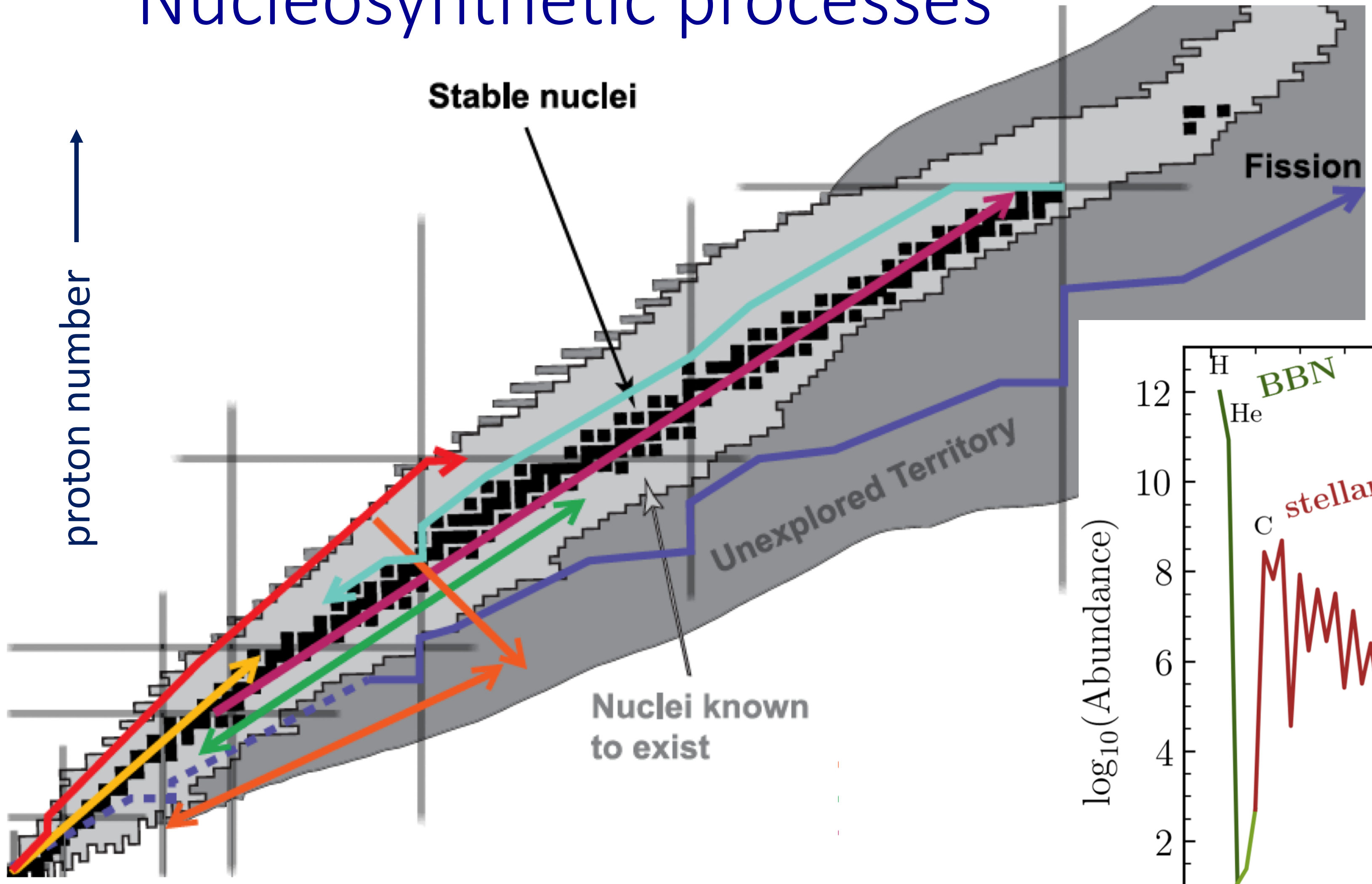
NP3M

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

U.S. DEPARTMENT OF ENERGY | Office of Science

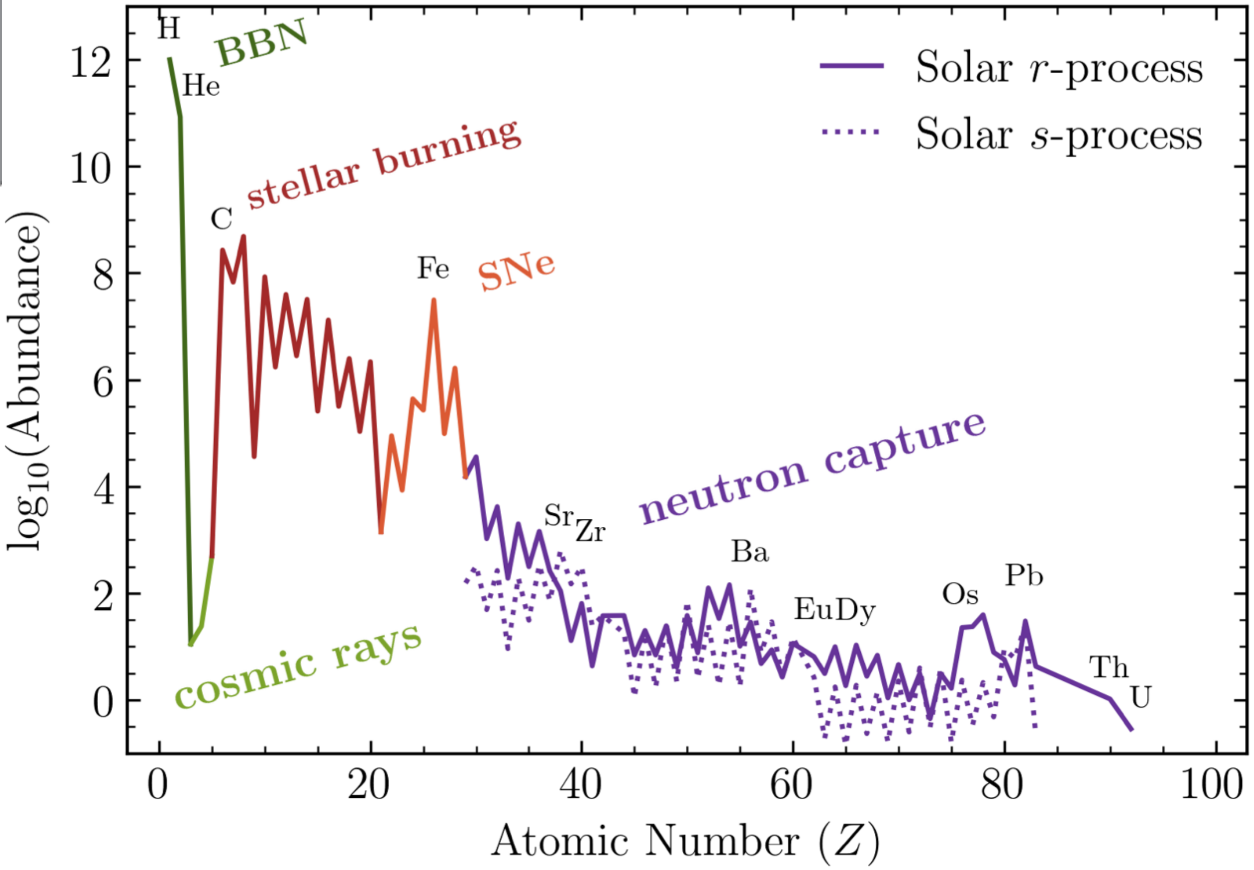
Toward Exascale Astrophysics of Mergers and Supernovae (TEAMS)
a DOE SciDAC supported collaboration

Nucleosynthetic processes



from Timmes/Schatz/Spyrou

data from Lodders 2003
figure by E Holmbeck



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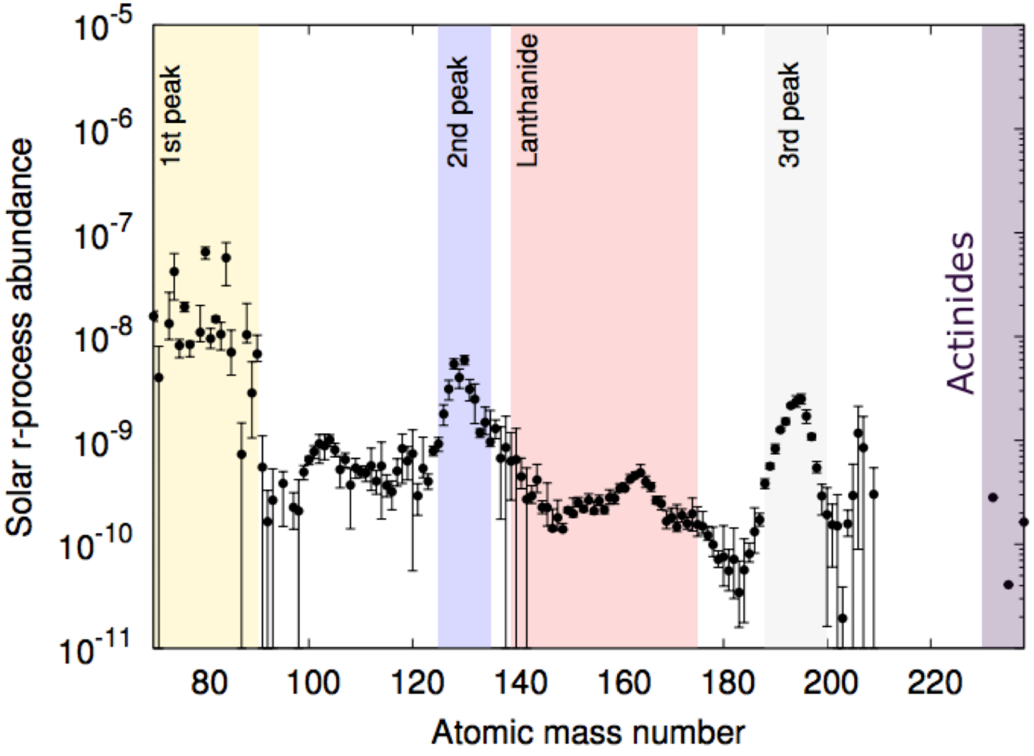
r-process nucleosynthesis

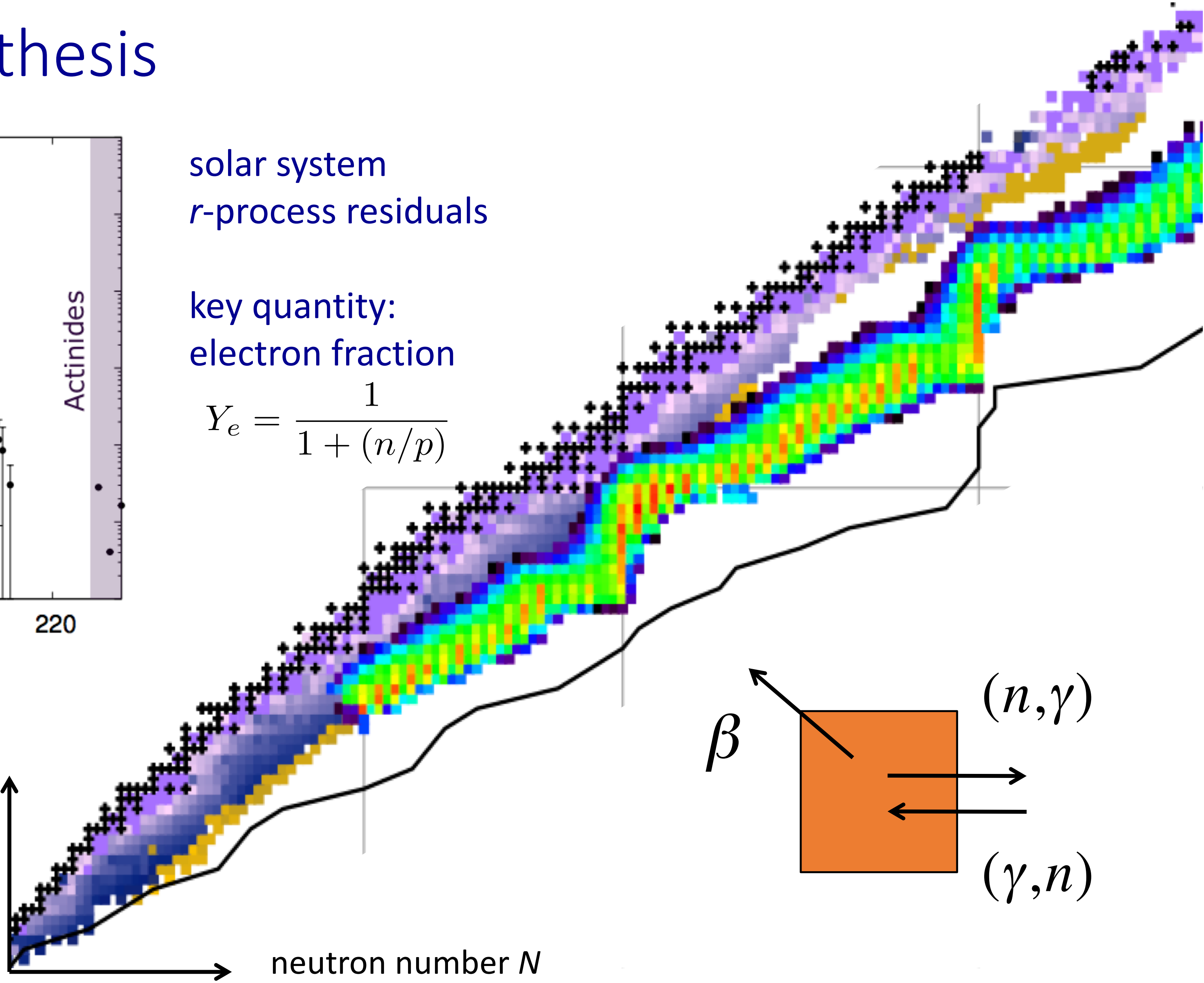


Arnould+2007, Hotokezaka+2018

solar system
r-process residuals

key quantity:
electron fraction

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



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neutrinos and *r*-process nucleosynthesis

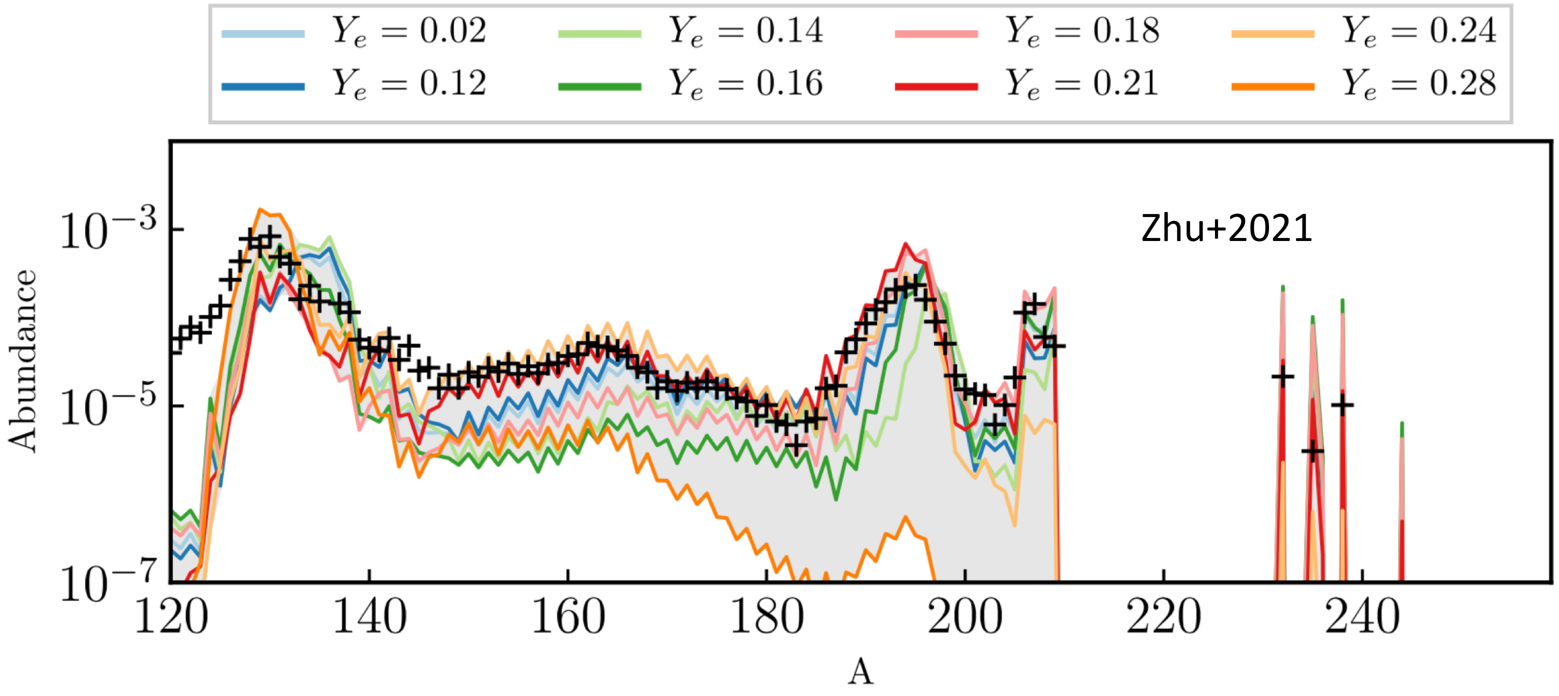
Neutrinos can influence the:

- Initial electron fraction
- Entropy per baryon
- Free nucleons available for capture following seed formation

key quantity:
electron fraction

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

$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$



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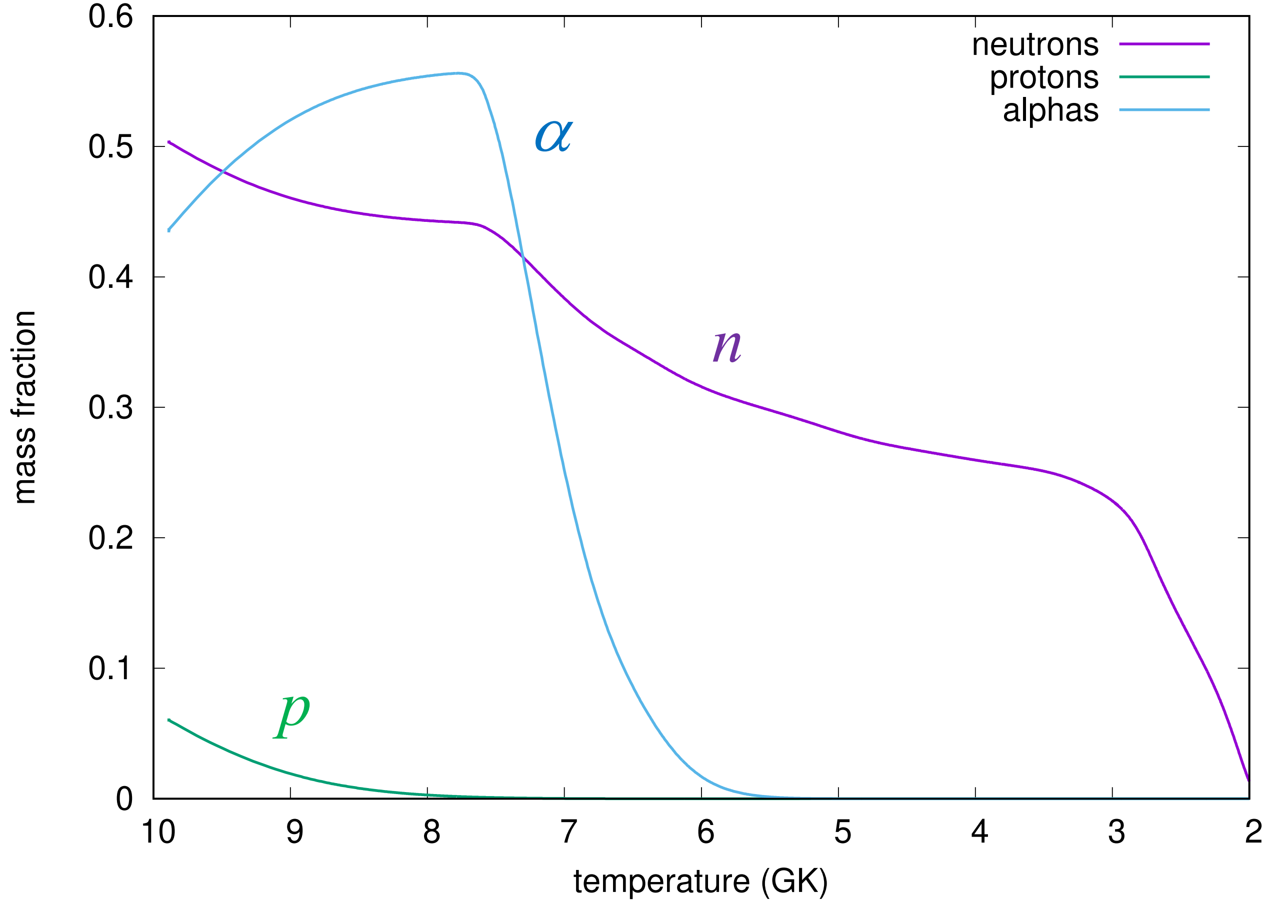
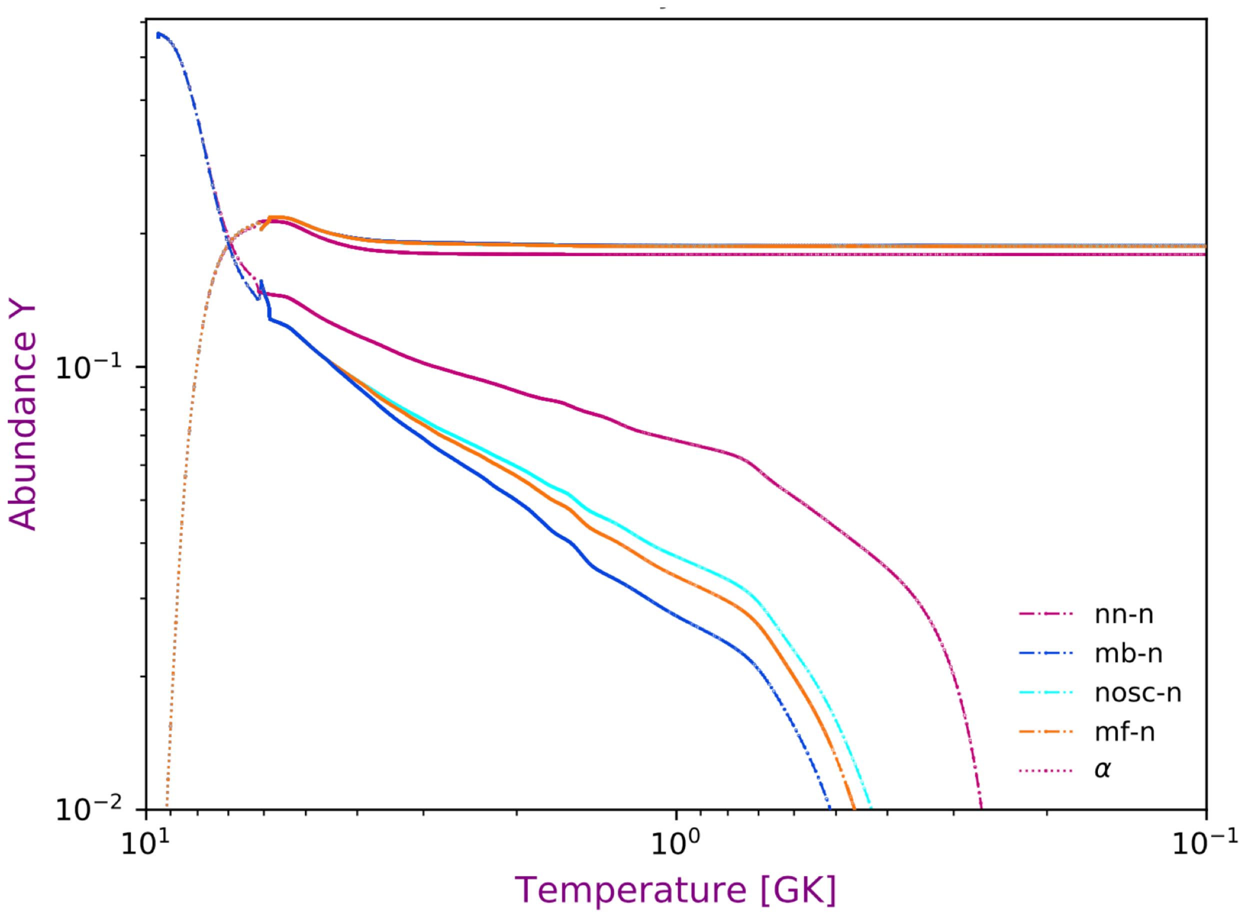
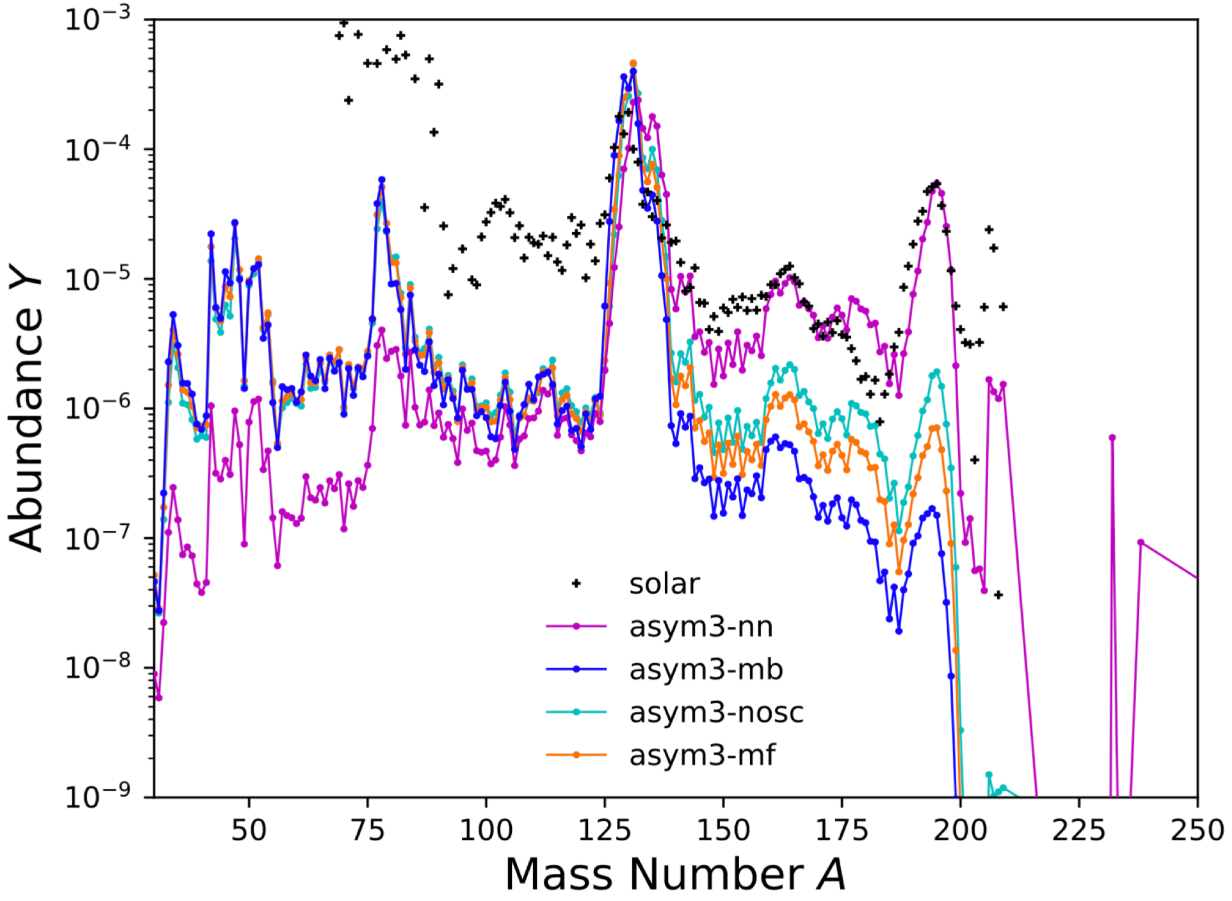


neutrino oscillations and *r*-process nucleosynthesis





$$\nu_e + n \rightleftharpoons p + e^-$$
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Balantekin, Cervia, Patwardhan, Surman, Wang, in preparation

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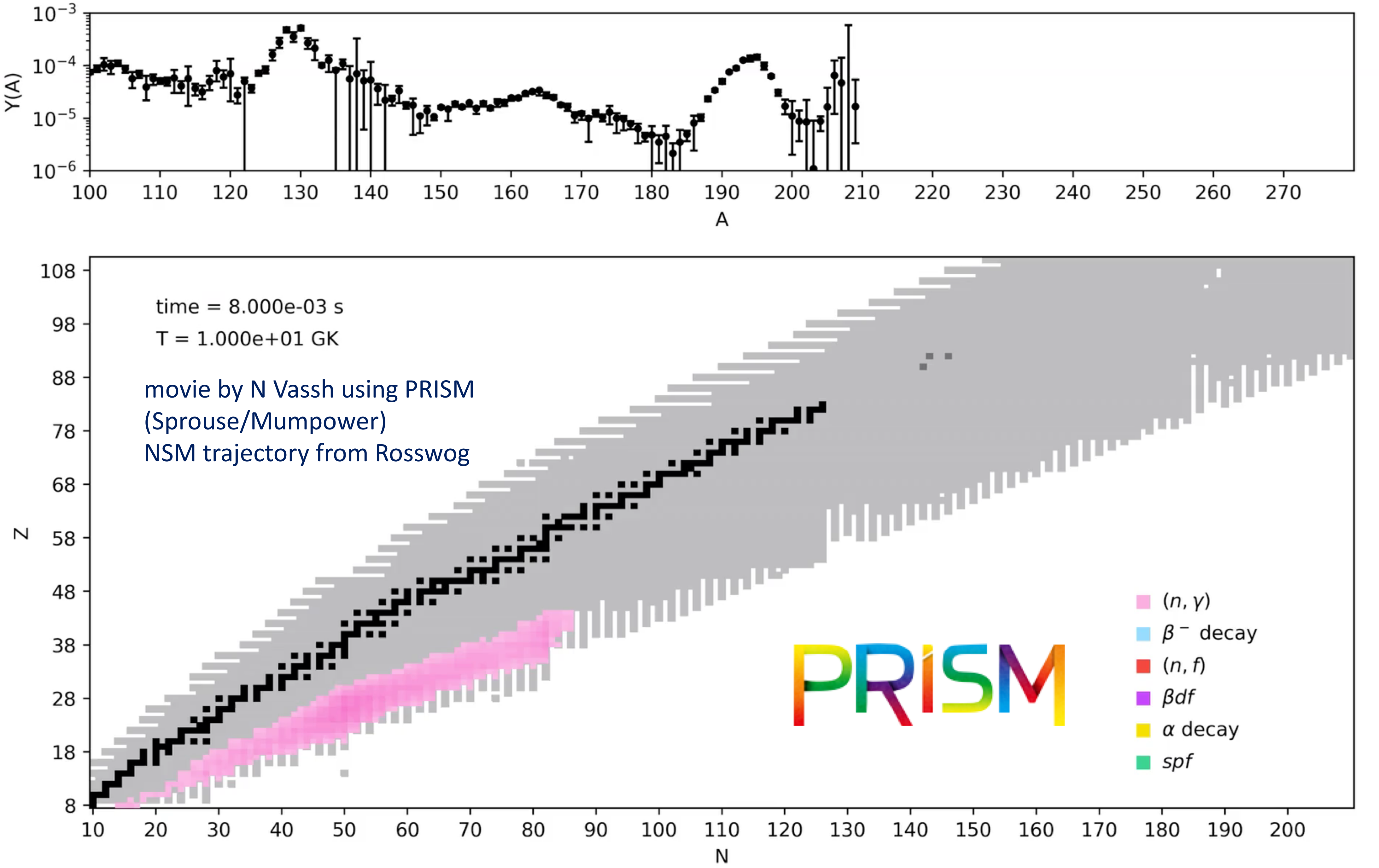

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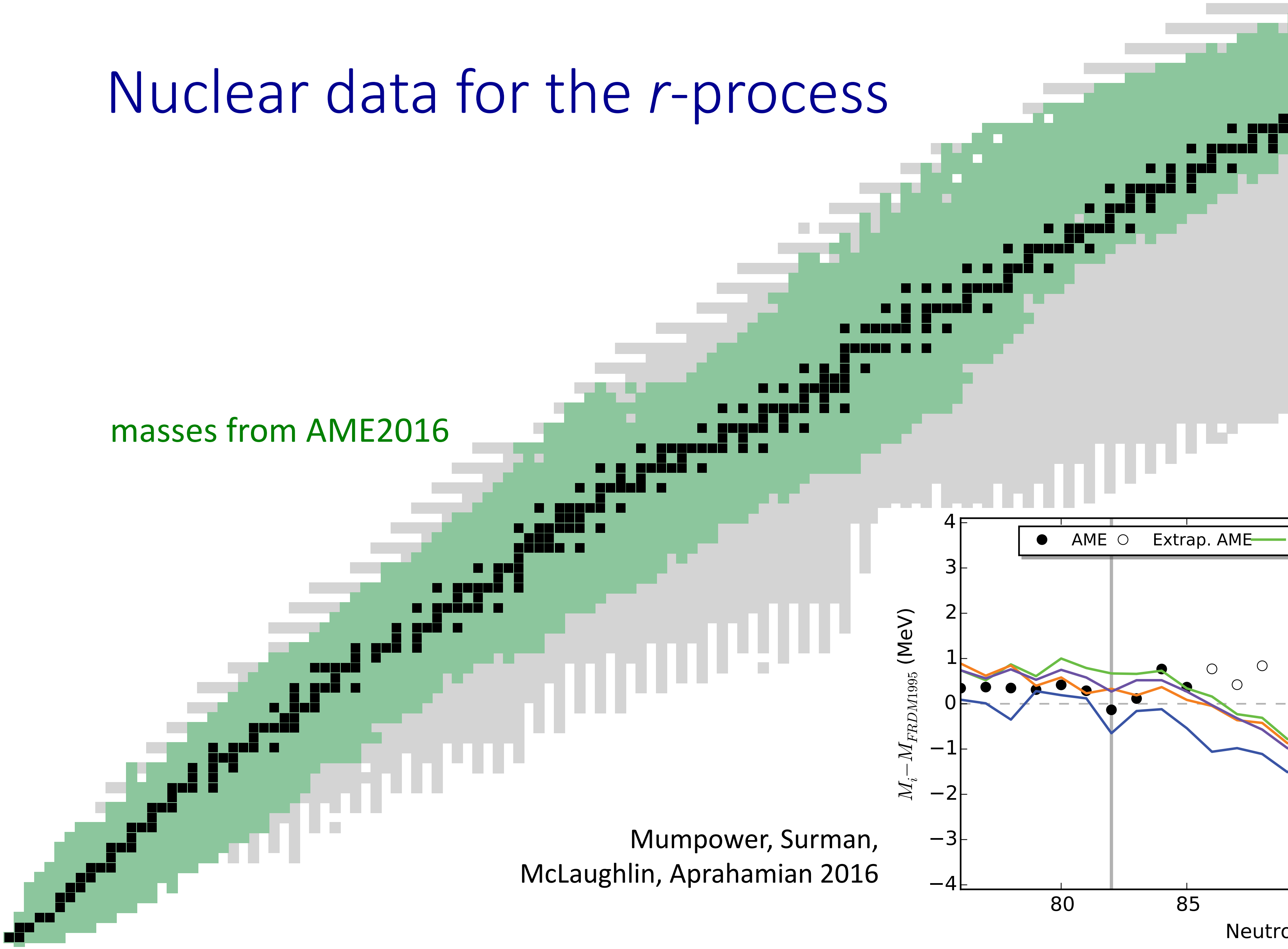
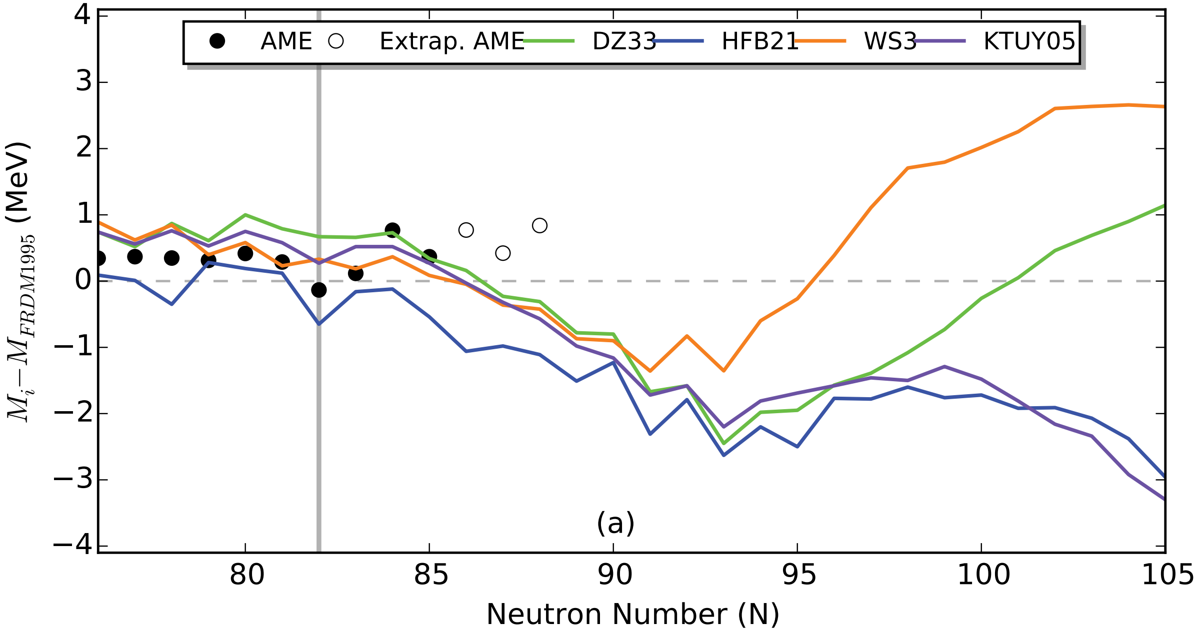
Nuclear data for the *r*-process



masses from AME2016

Mumpower, Surman,
McLaughlin, Aprahamian 2016



Nuclear data for the *r*-process

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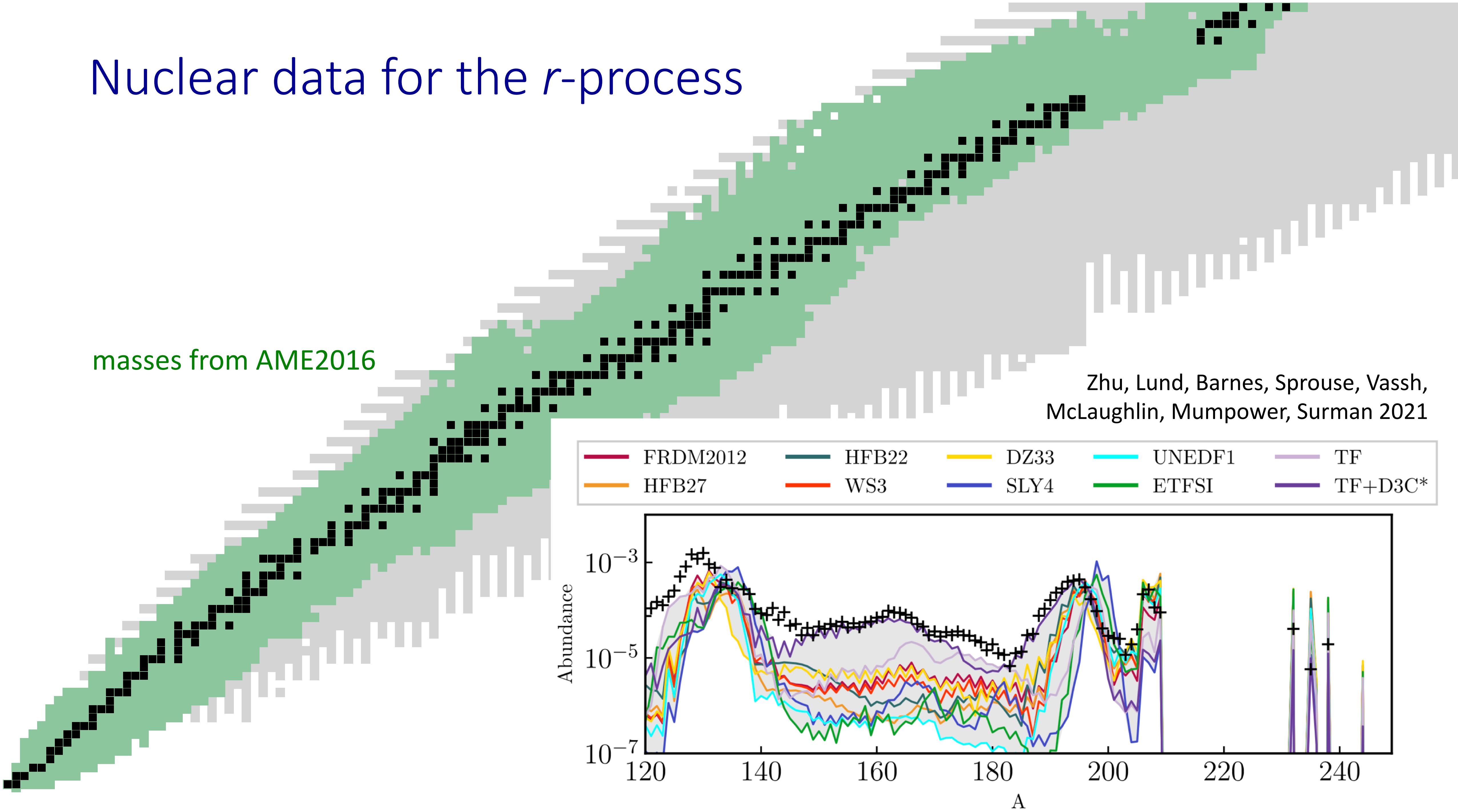
Zhu, Lund, Barnes, Sprouse, Vassh, McLaughlin, Mumpower, Surman 2021



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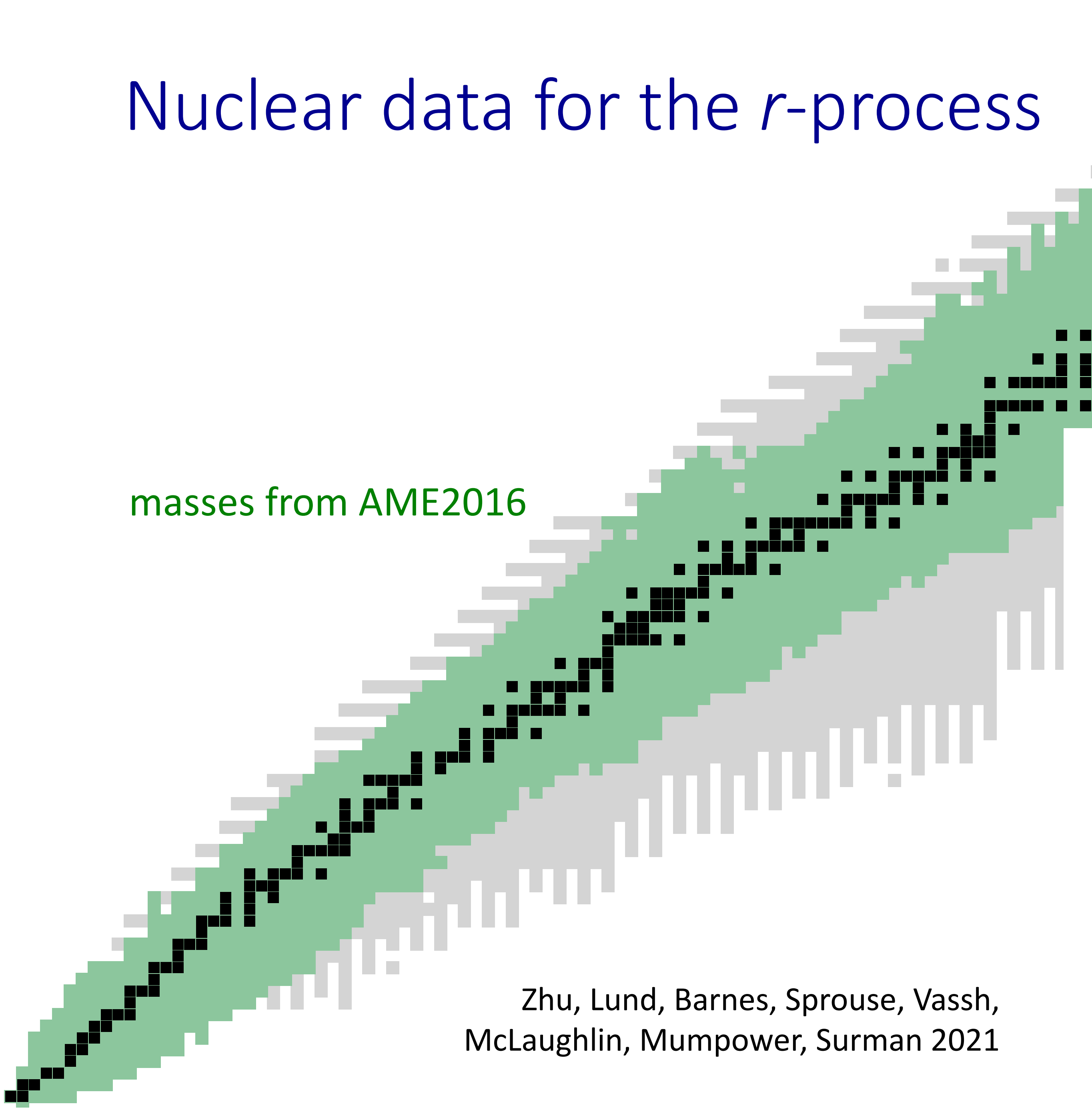

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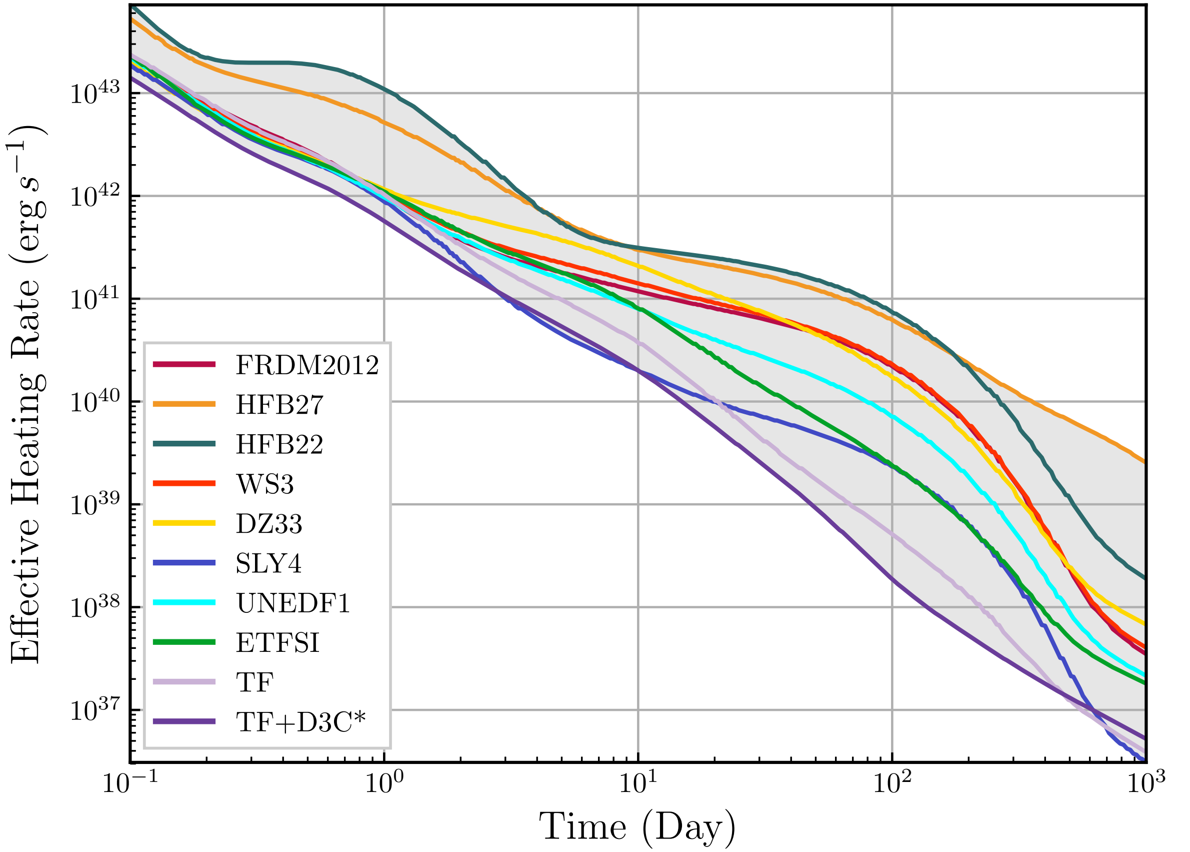
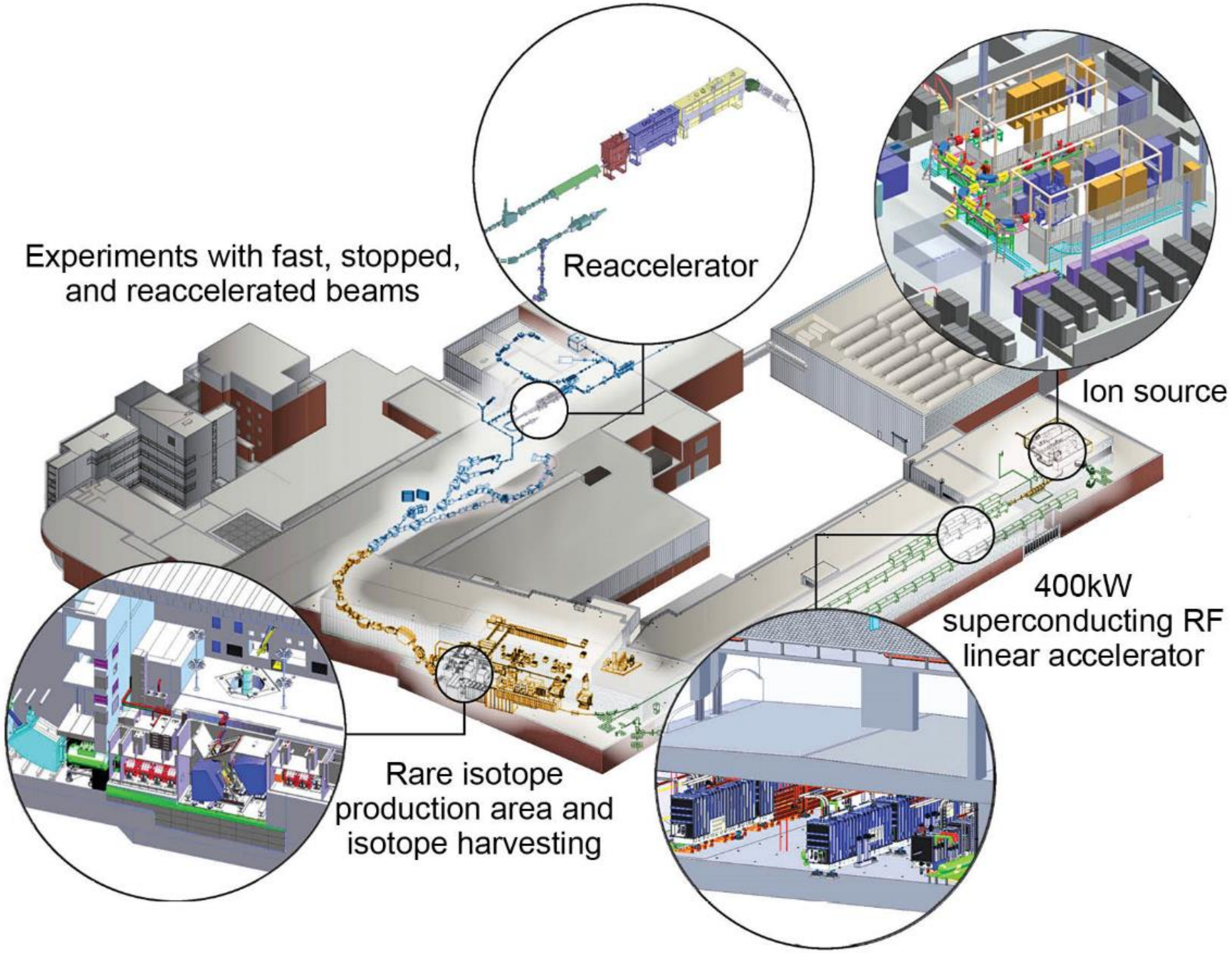
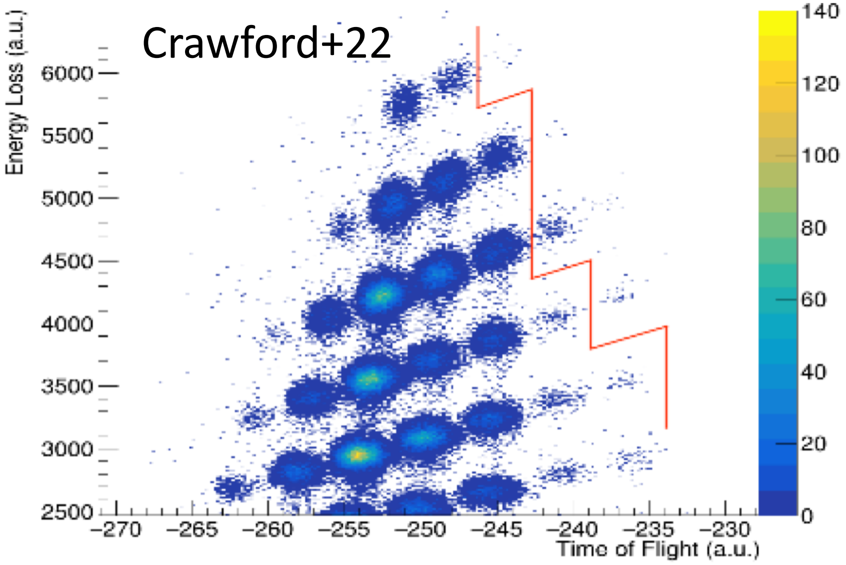


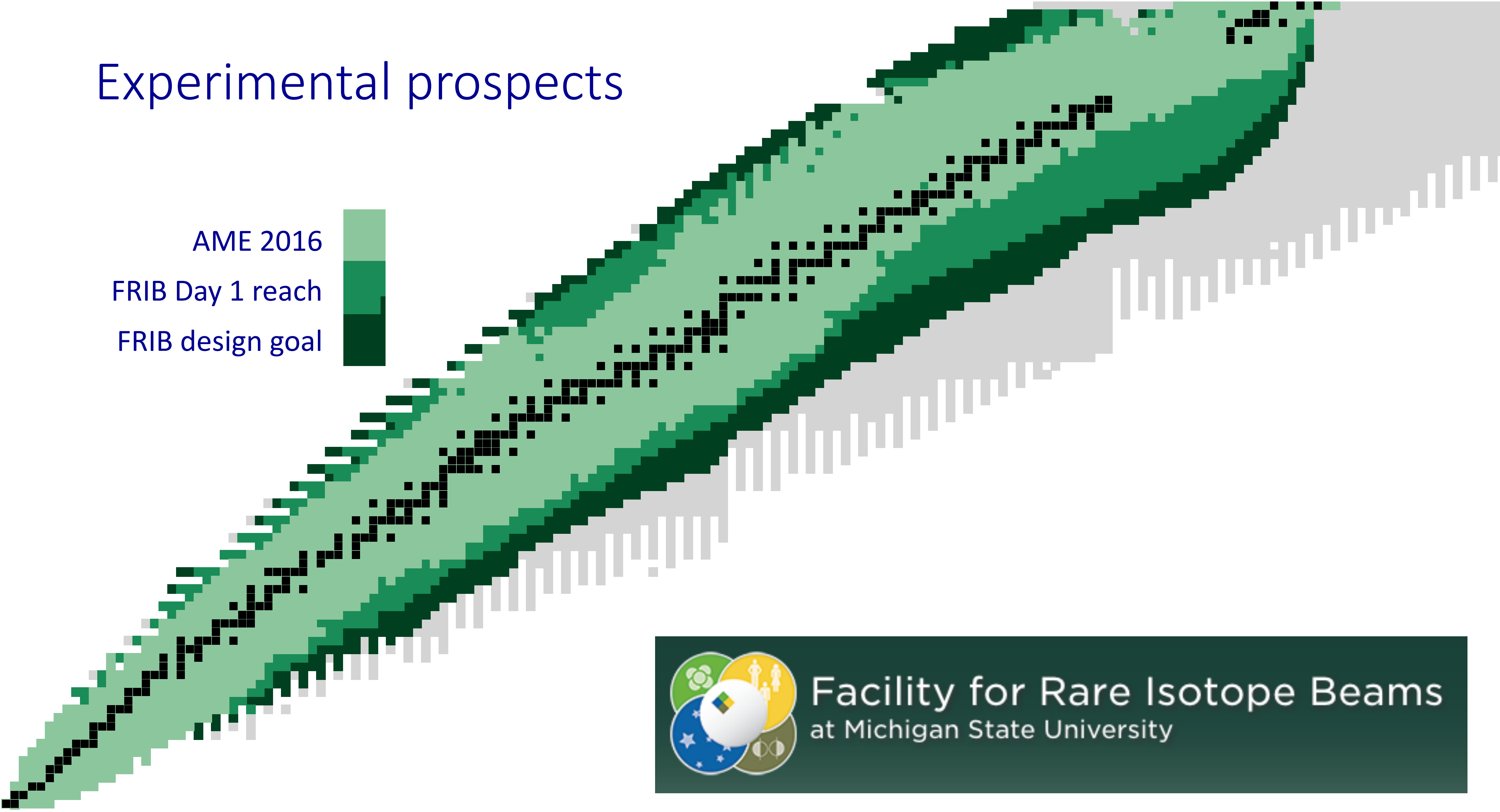
Facility for Rare Isotope Beams



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?
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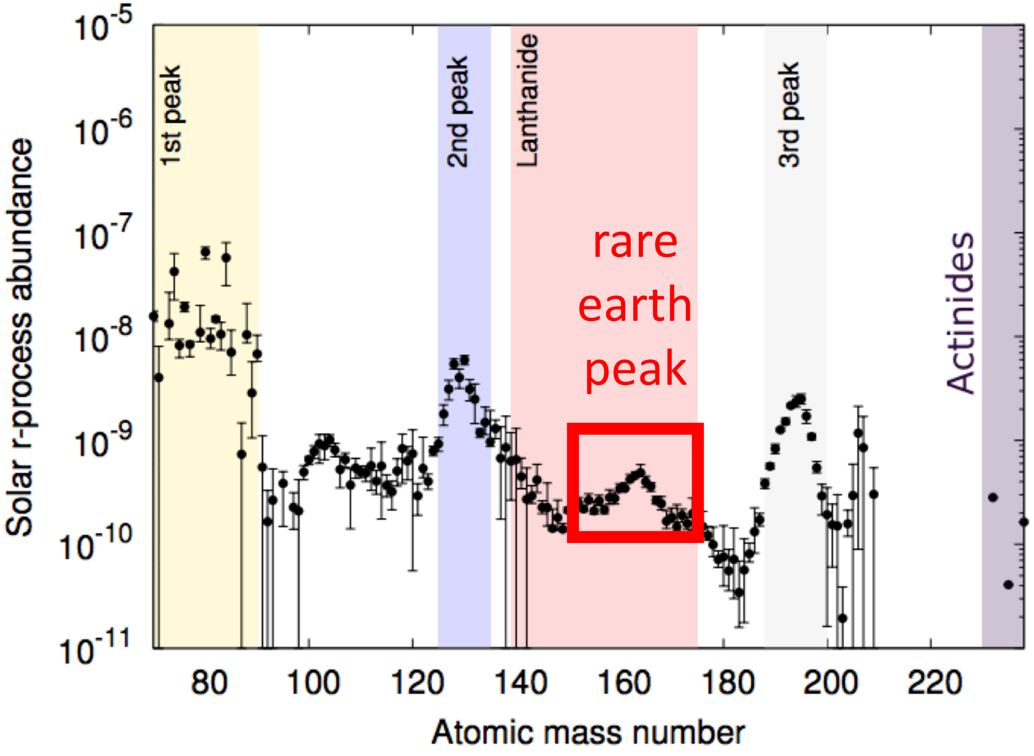
nuclear masses and the rare earth peak



Arnould+2007, Hotokezaka+2018

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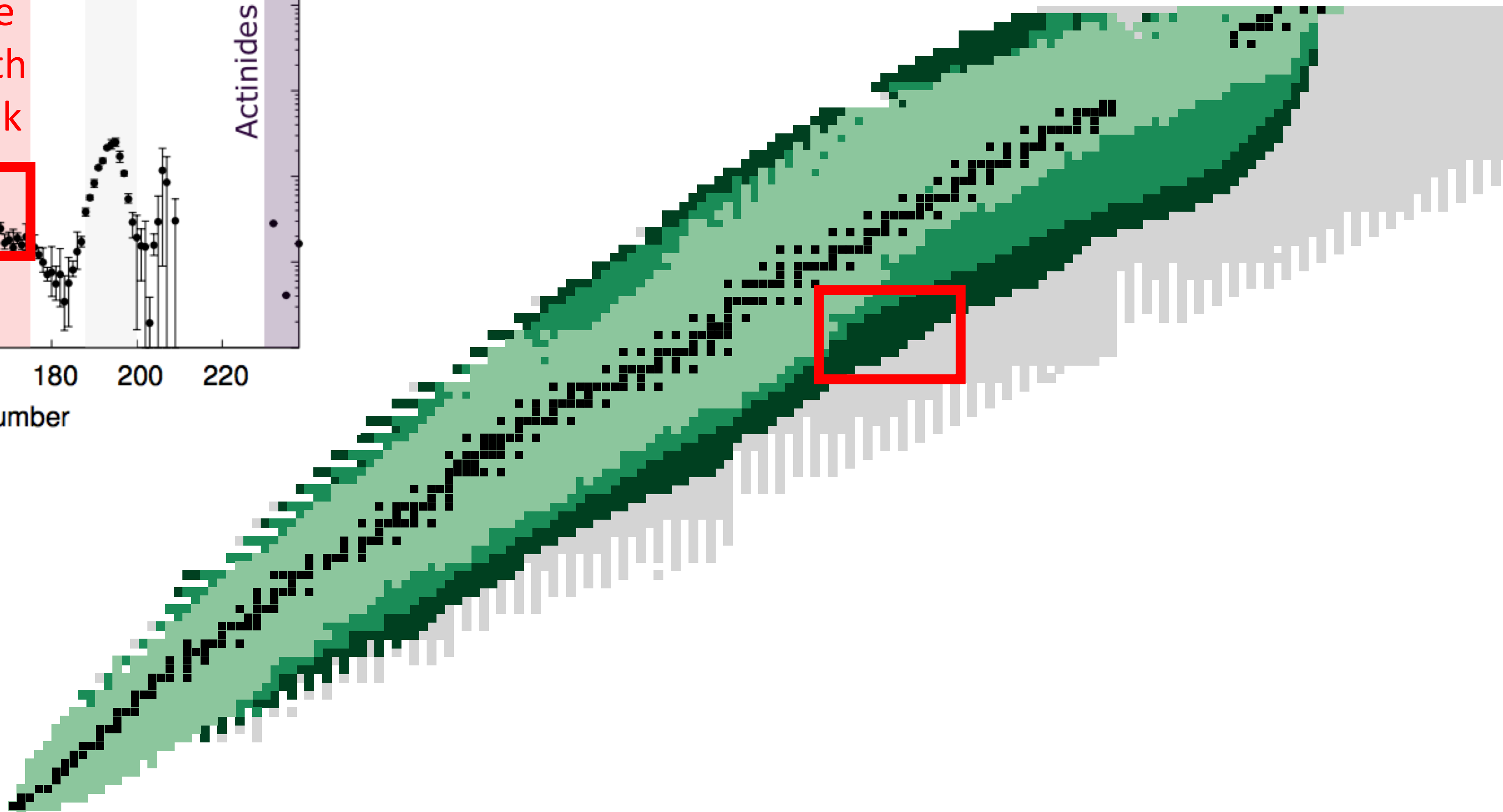
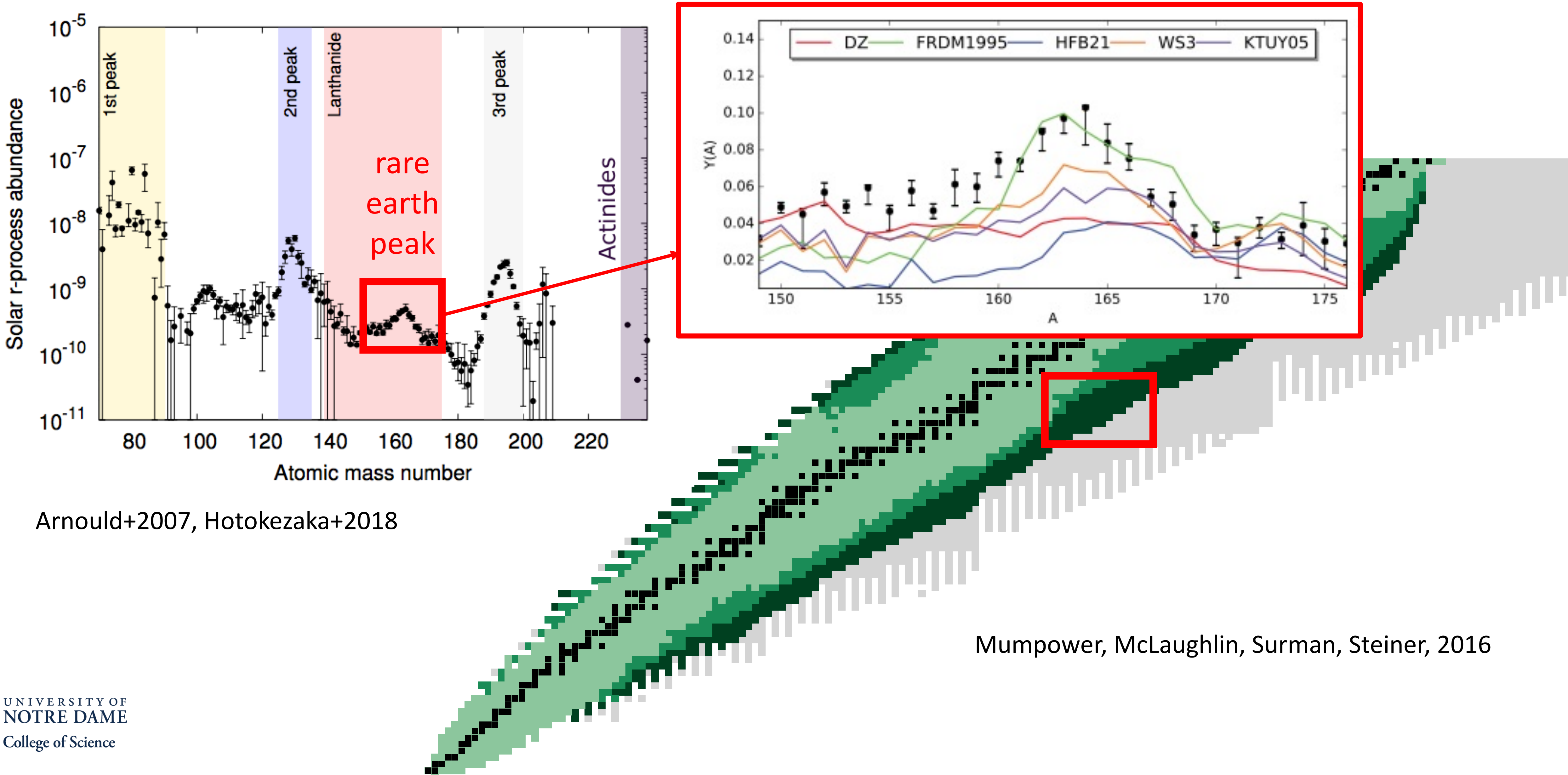


nuclear masses and the rare earth peak



Arnould+2007, Hotokezaka+2018

Mumpower, McLaughlin, Surman, Steiner, 2016

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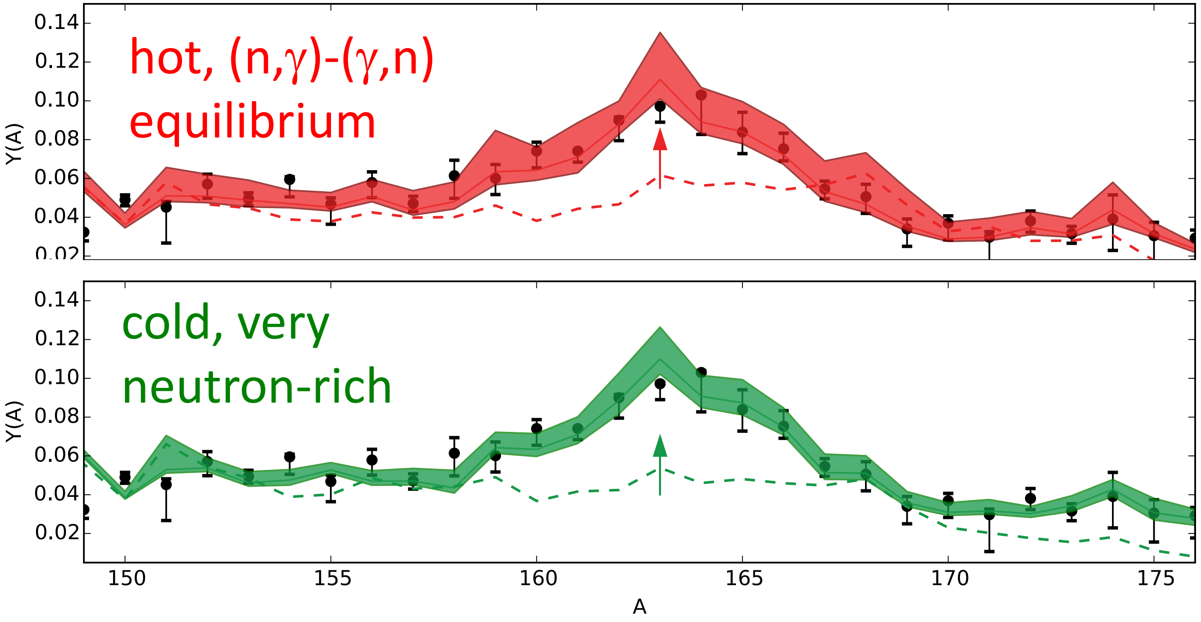
deducing *r*-process conditions from abundance pattern details: the rare earth peak

mass modification parameterization:

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



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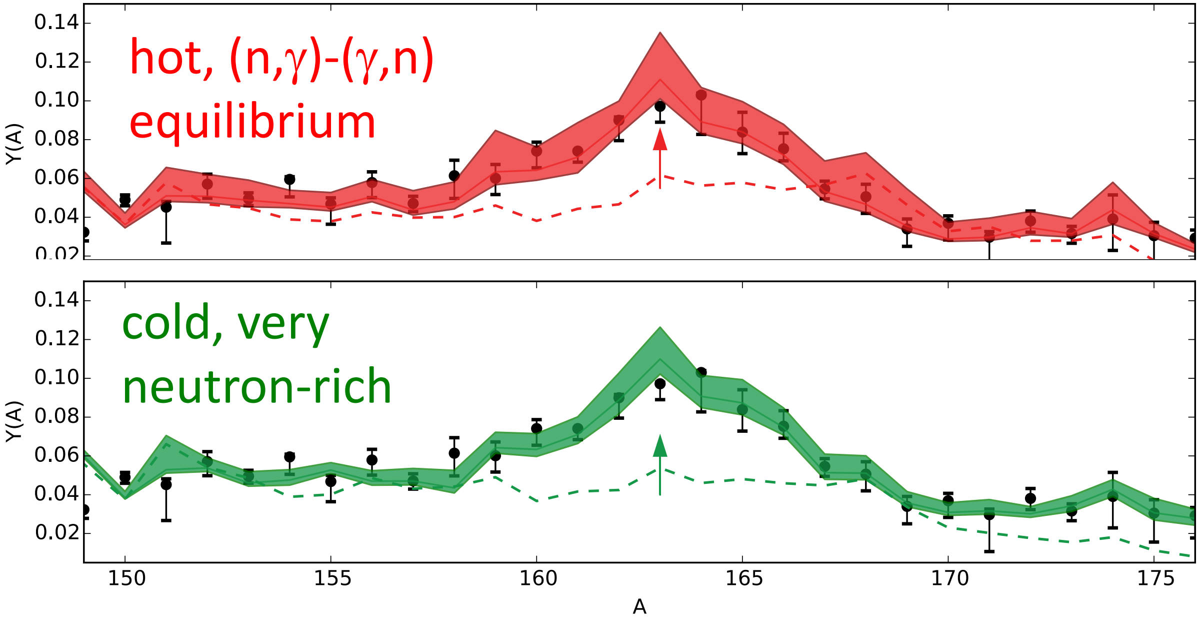
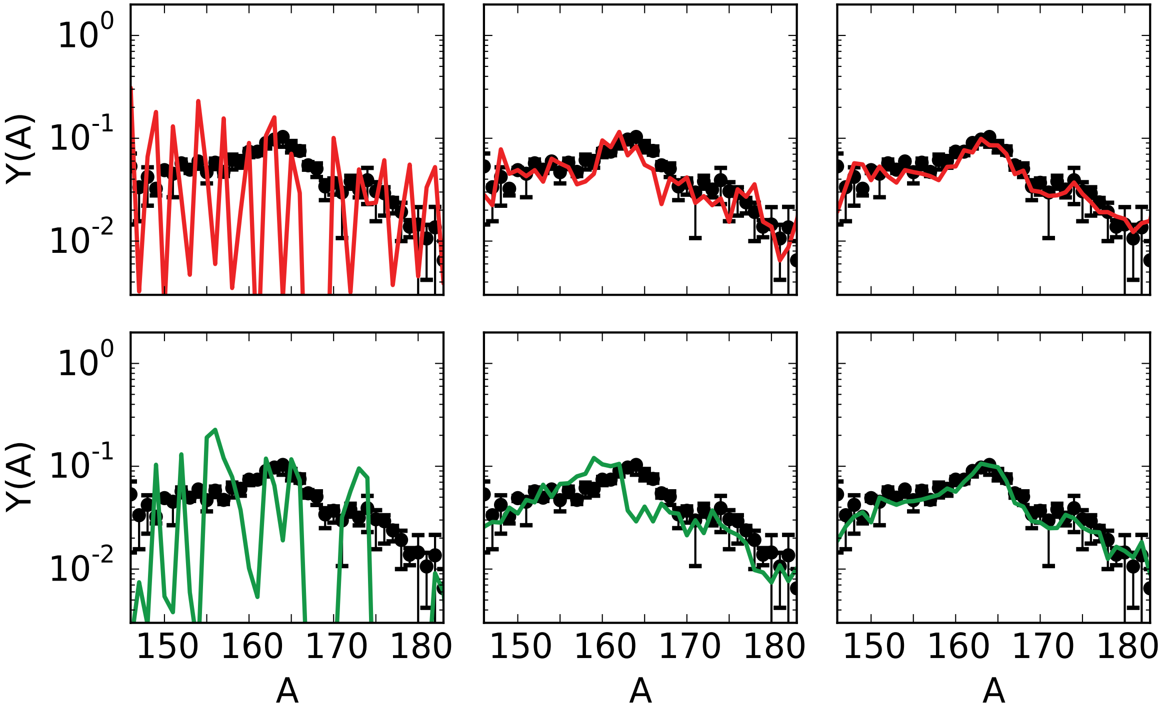


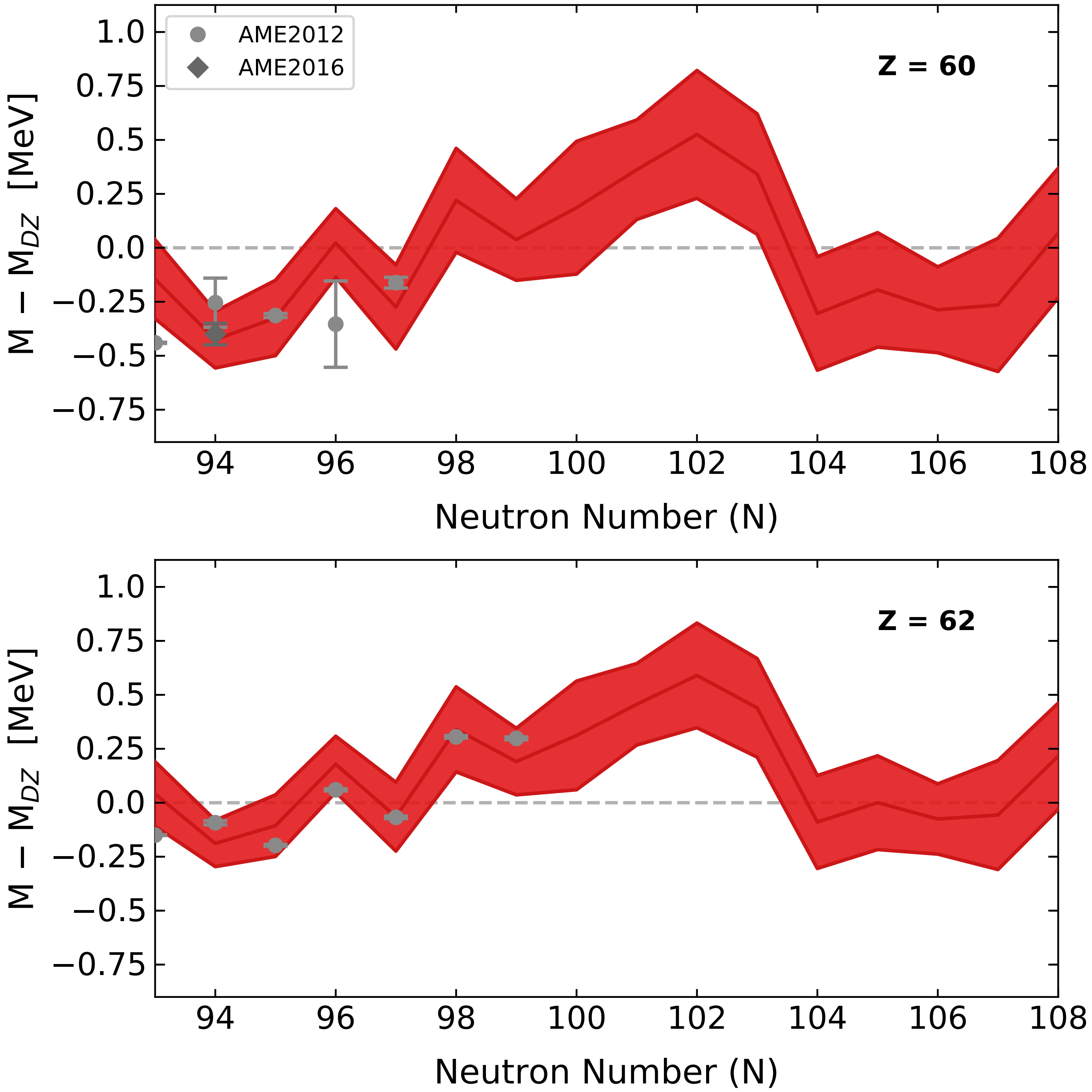


Mumpower, McLaughlin, Surman, Steiner, 2016

reverse-engineering results for a hot wind *r*-process

Nicole Vassh,
FIRE/ND postdoc
now TRIUMF scientist

Orford, Vassh+ PRL 2018

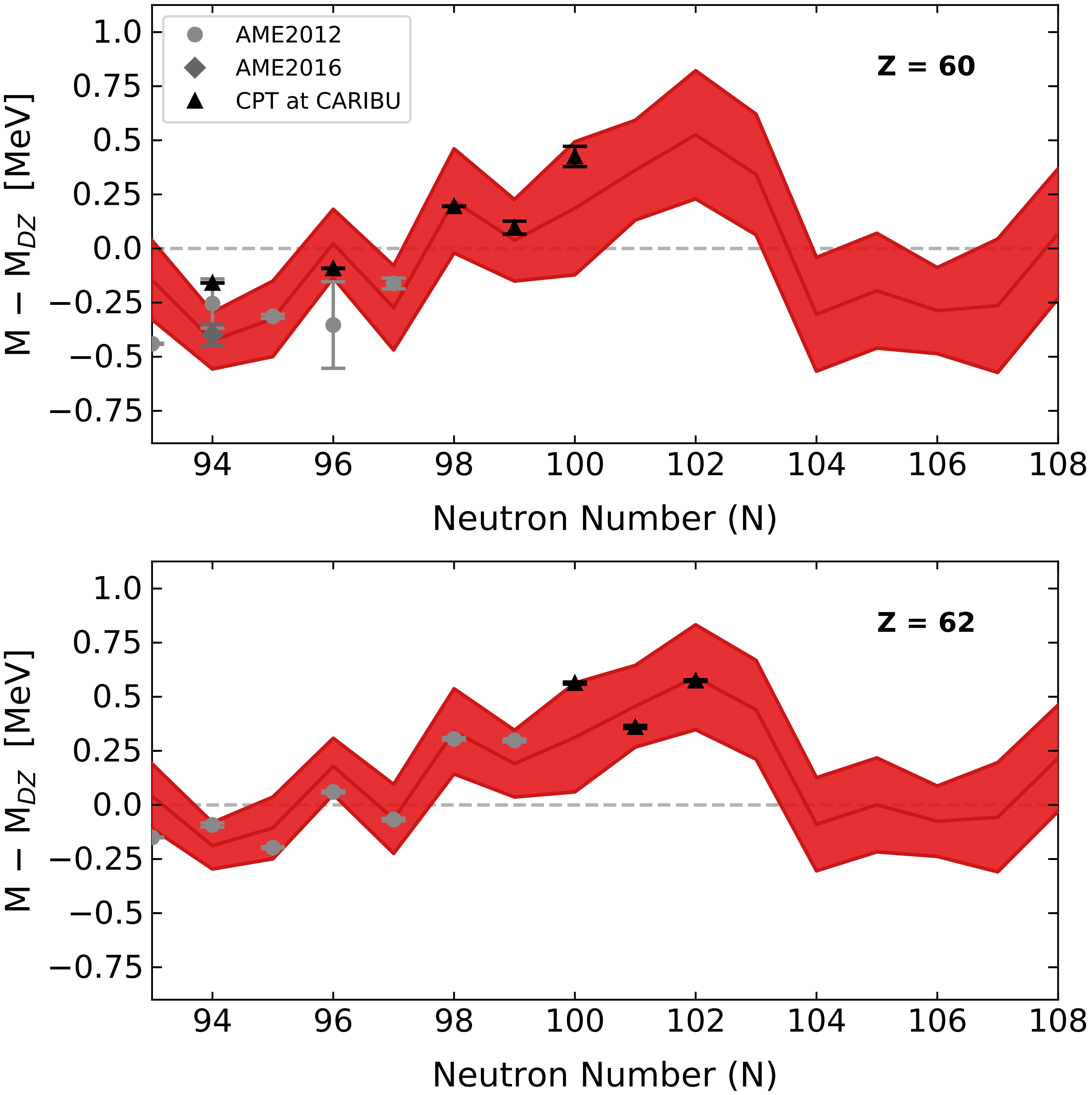


reverse-engineering results for a hot wind *r*-process + new experimental masses

Nicole Vassh,
FIRE/ND postdoc
now TRIUMF scientist

Orford, Vassh+ PRL 2018

Experimental data from CPT at CARIBU (ANL)



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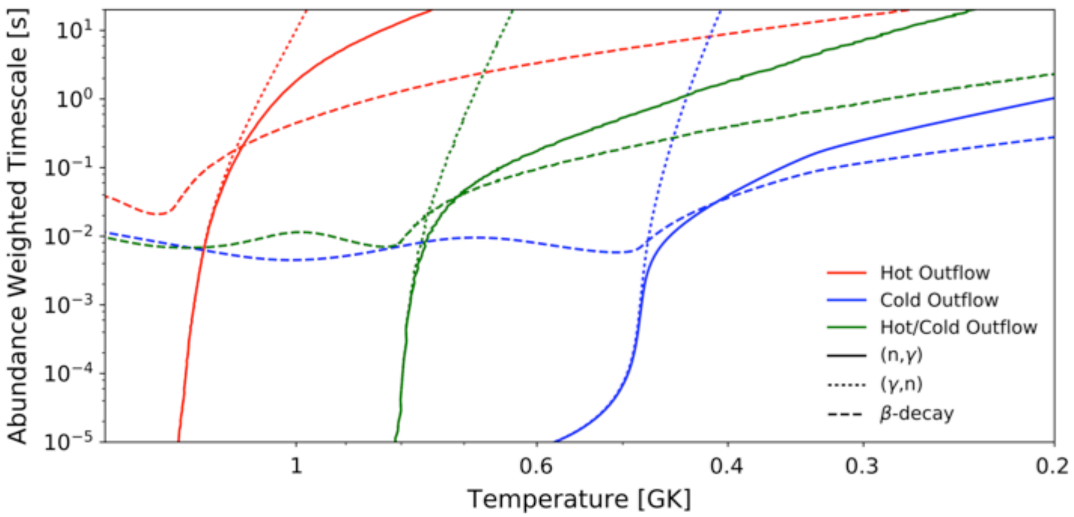
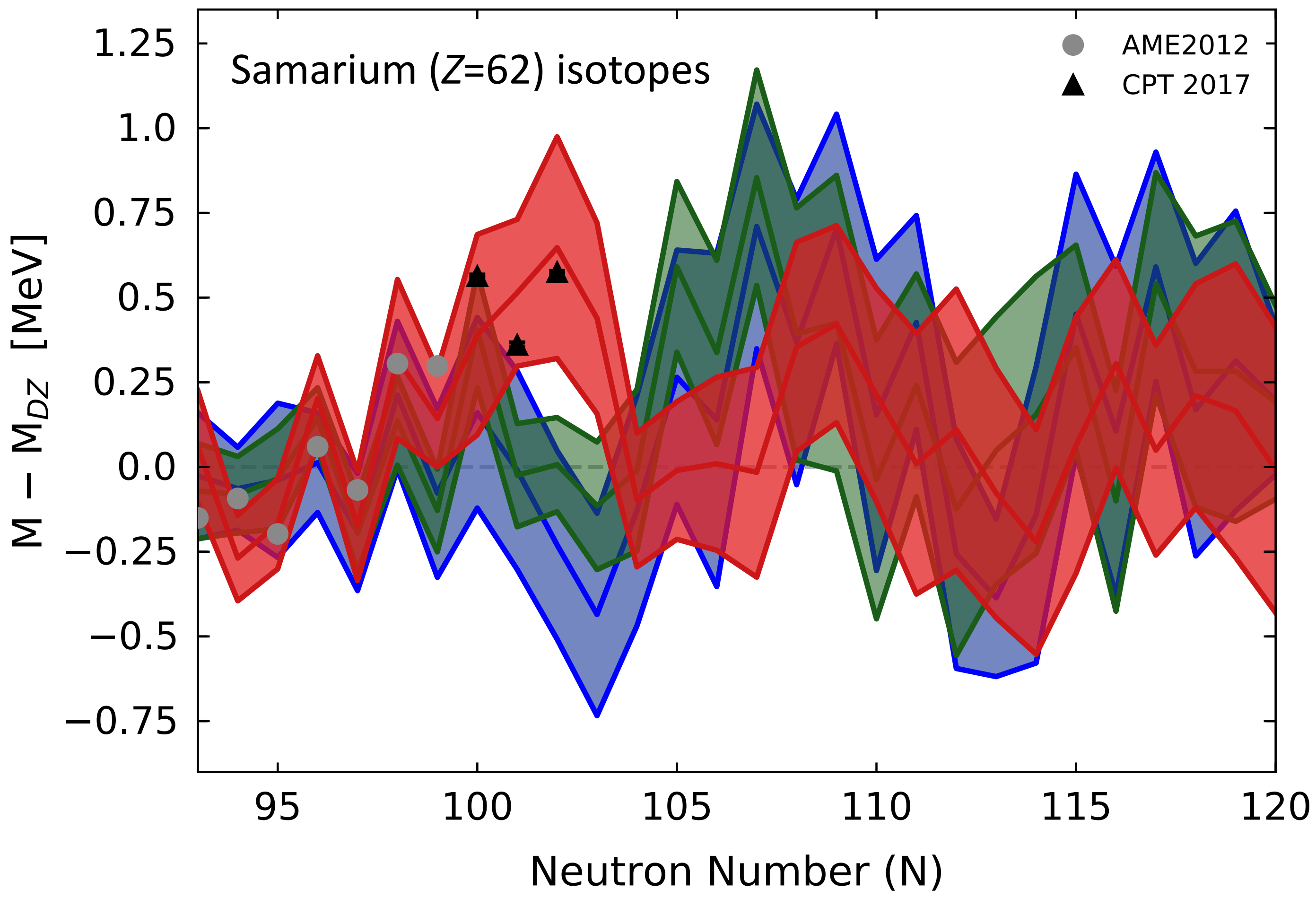
rare earth peak formation and *r*-process dynamics



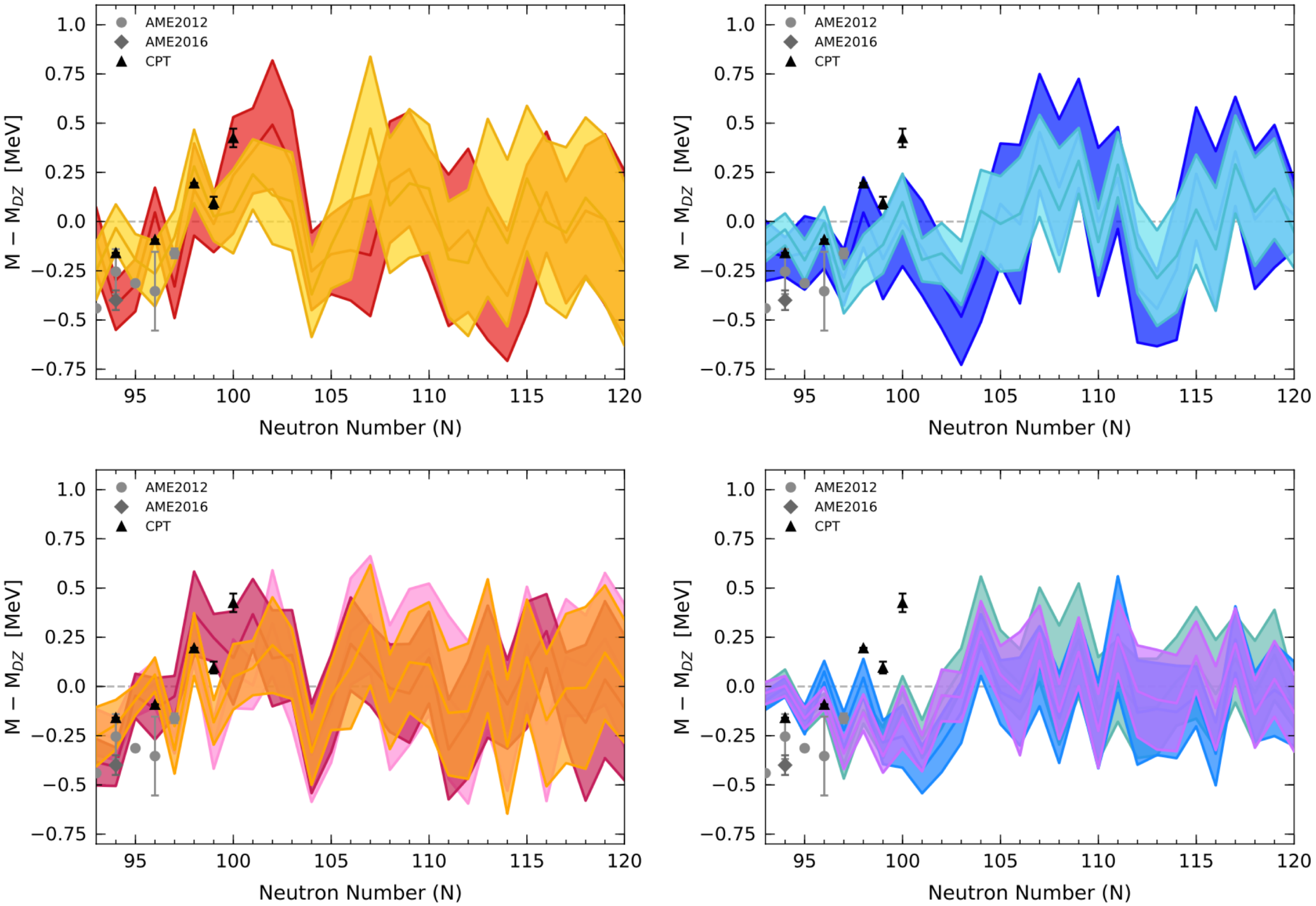


reverse-engineered nuclear mass predictions for three types of astrophysical environments compared to experimental data

Vassh, McLaughlin, Mumpower, Surman 2021

rare earth peak formation and fission products

Neodymium (Z=60) isotopes



Vassh, McLaughlin, Mumpower, Surman 2022

rare earth peak experimental prospects

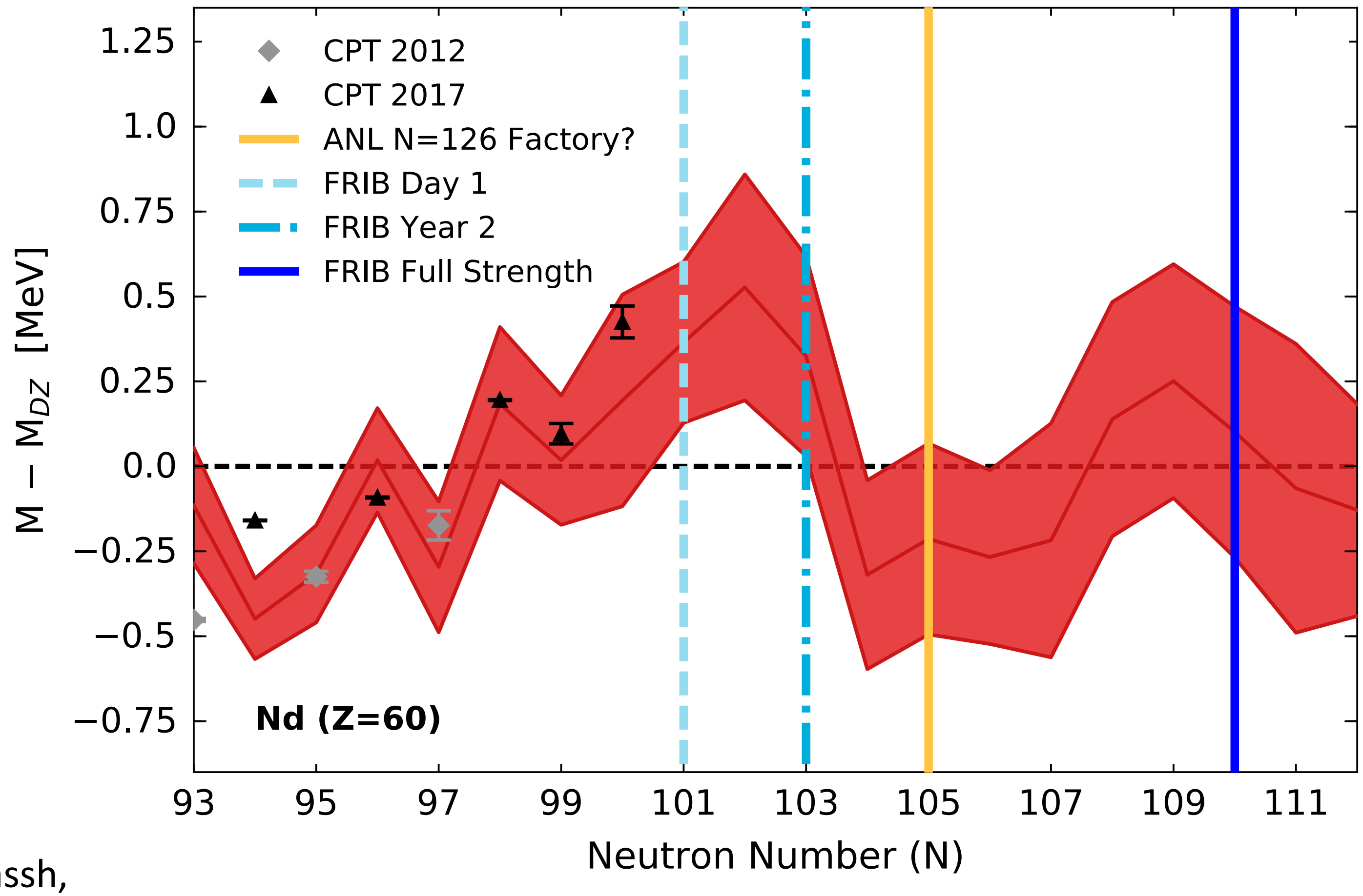


Figure by N Vassh, Aprahamian+2018

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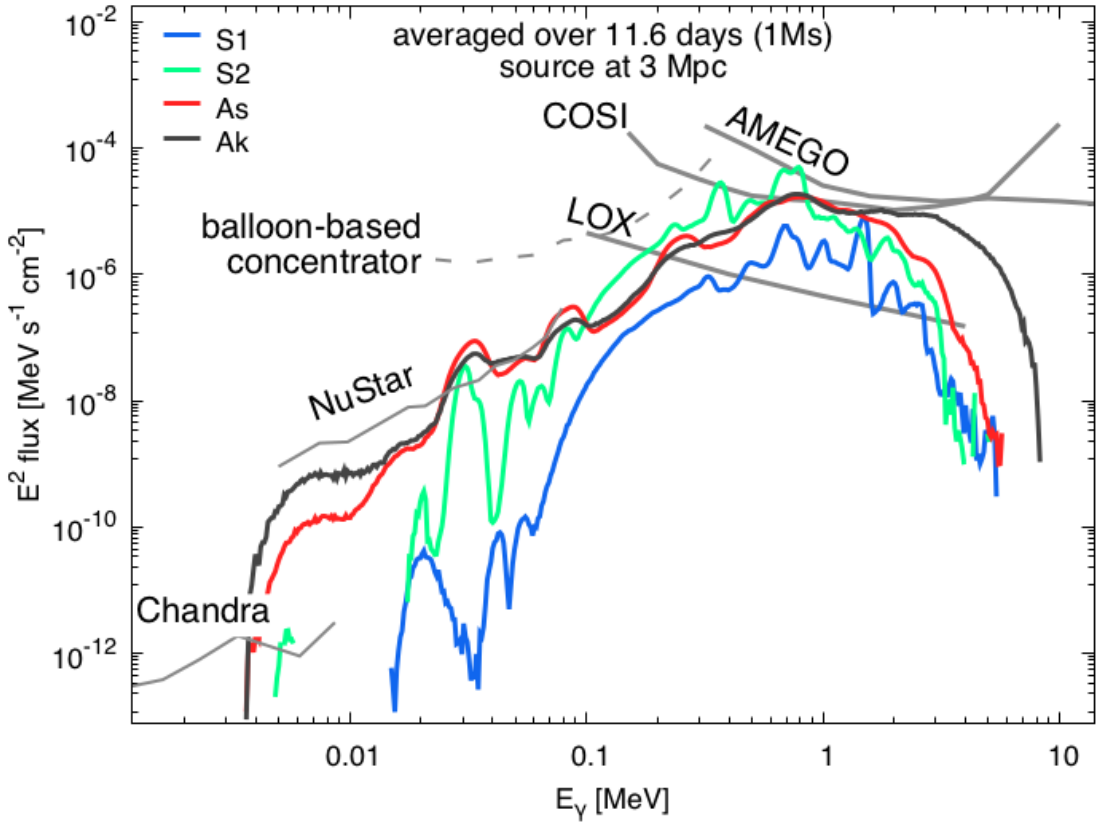
Actinide observables: gamma rays



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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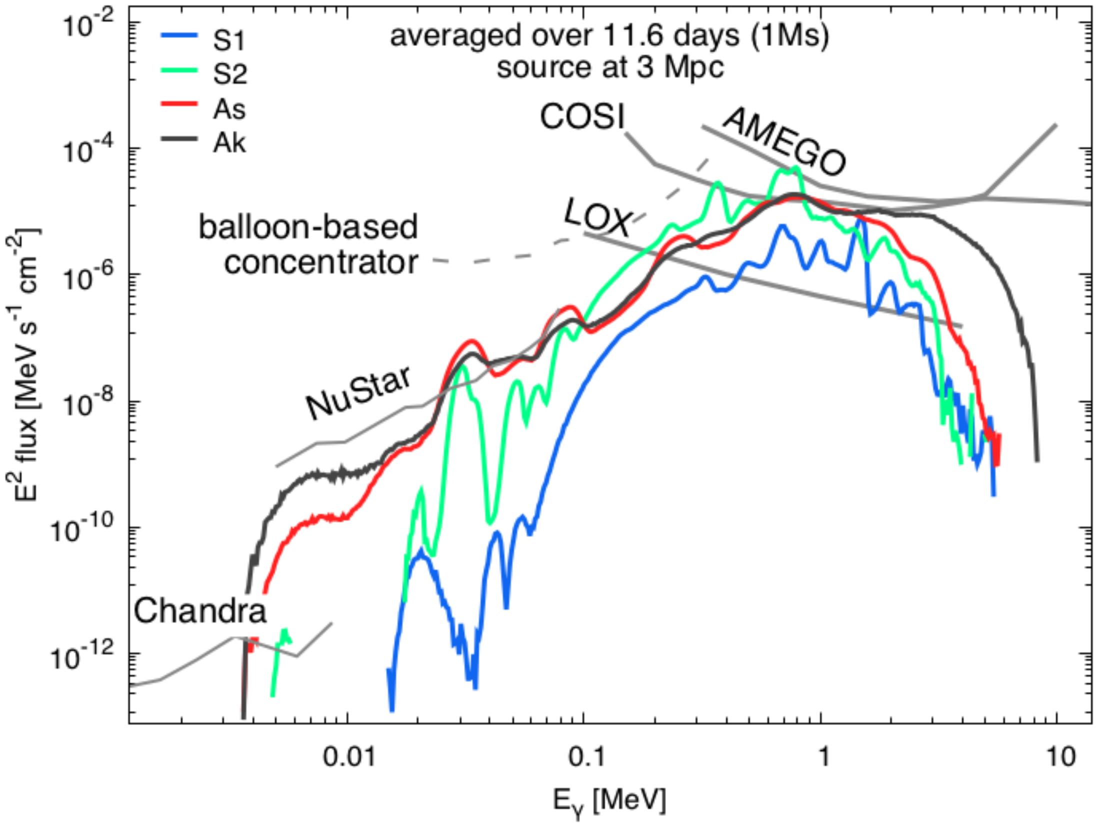

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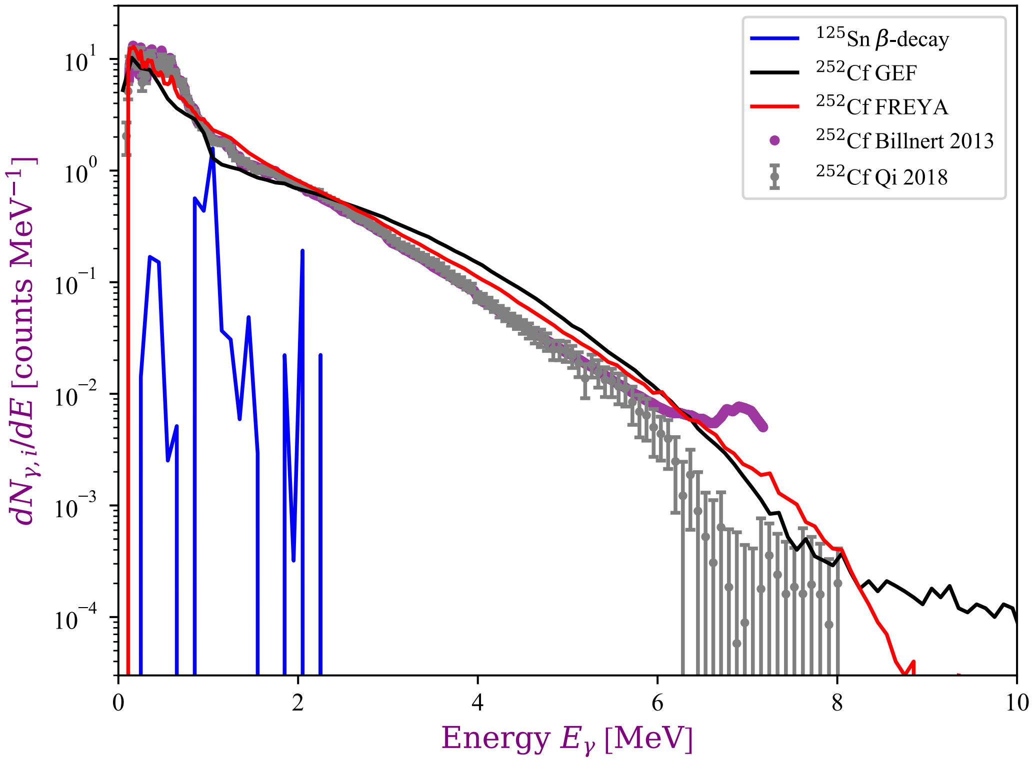

Wang, Vassh, Sprouse, Mumpower, Vogt, Randrup, Surman, ApJL 2020

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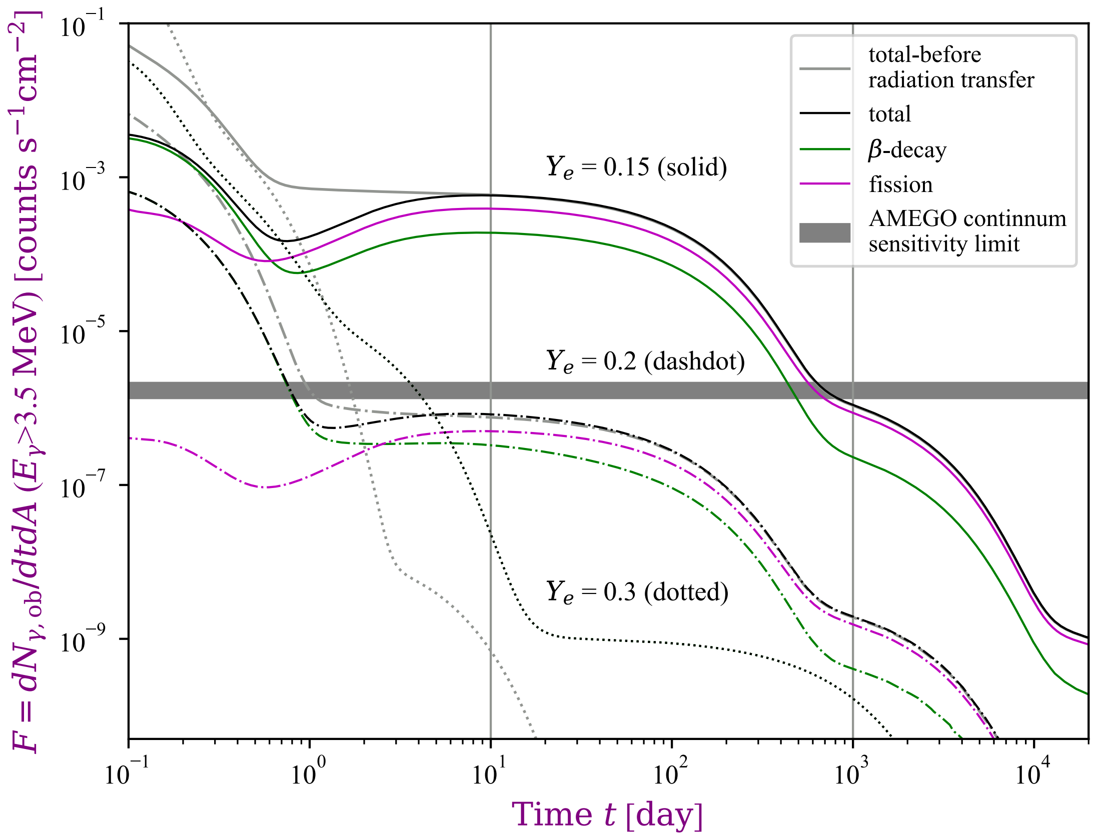

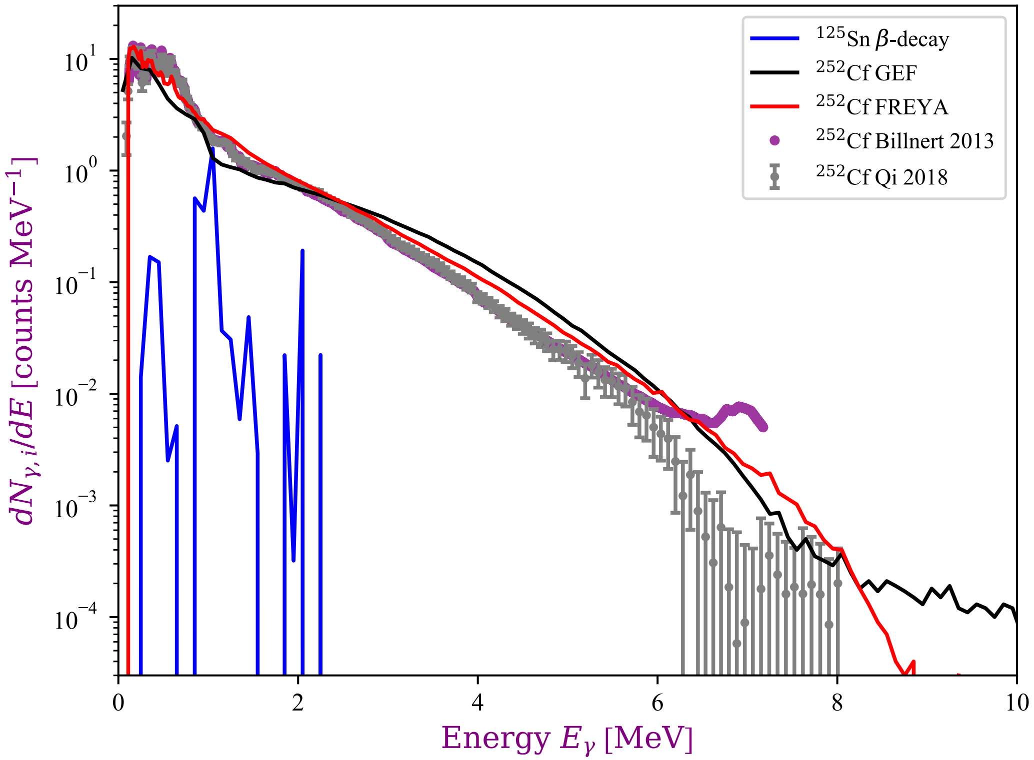

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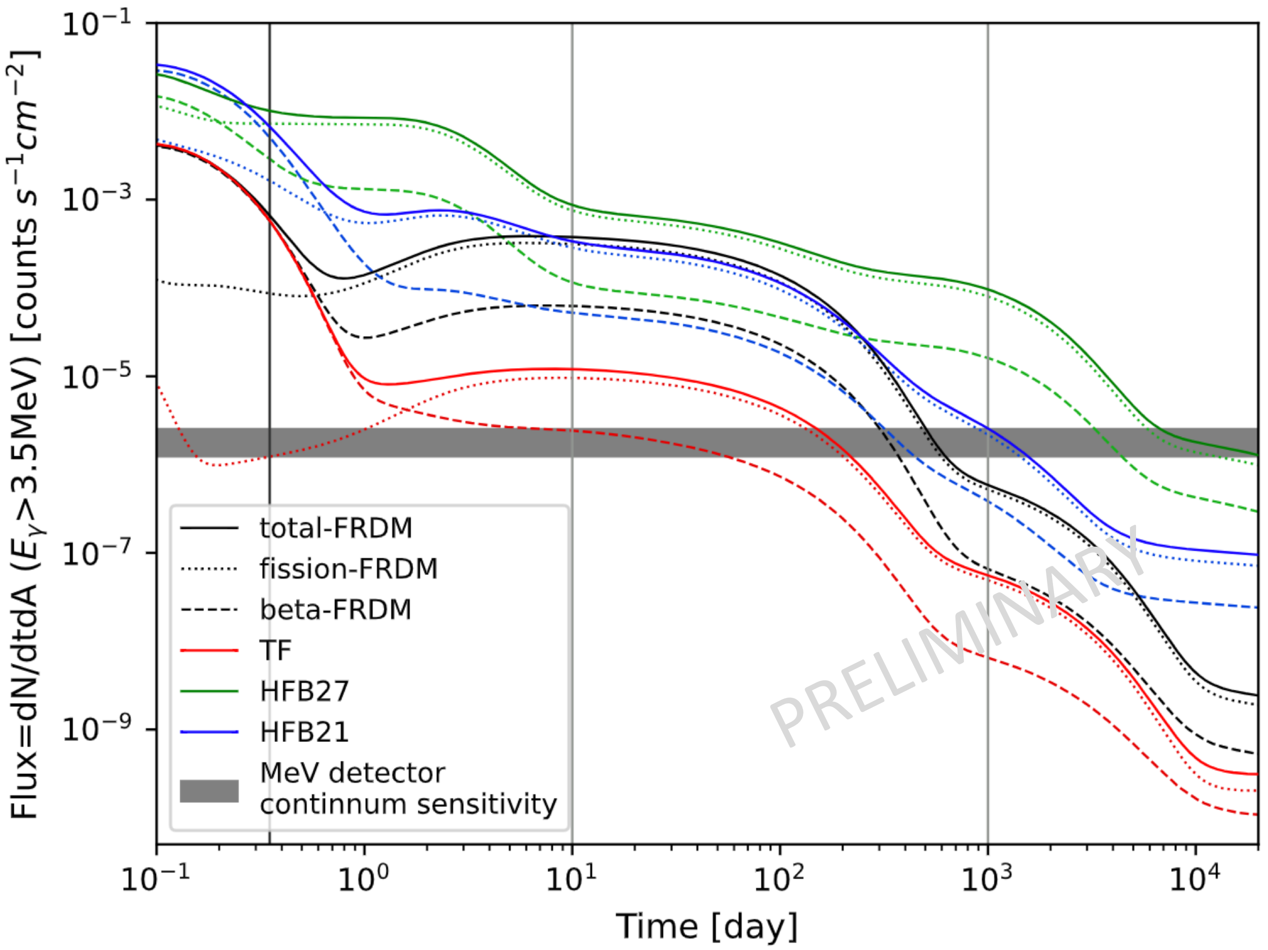
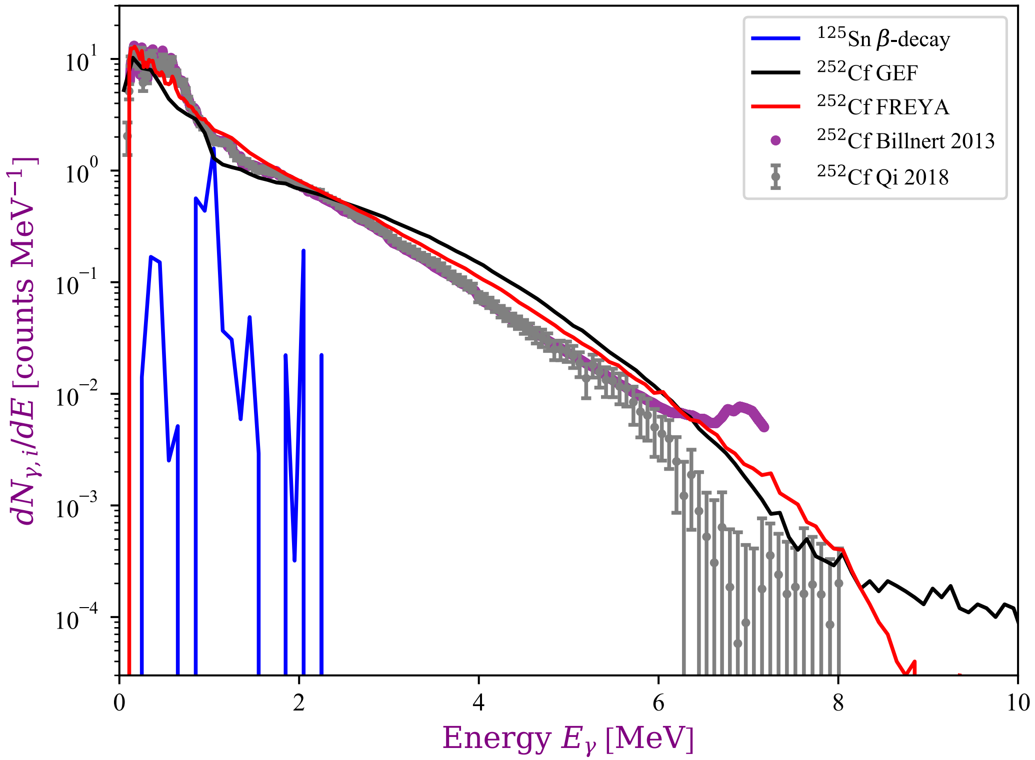


Wang+ in preparation 2023



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

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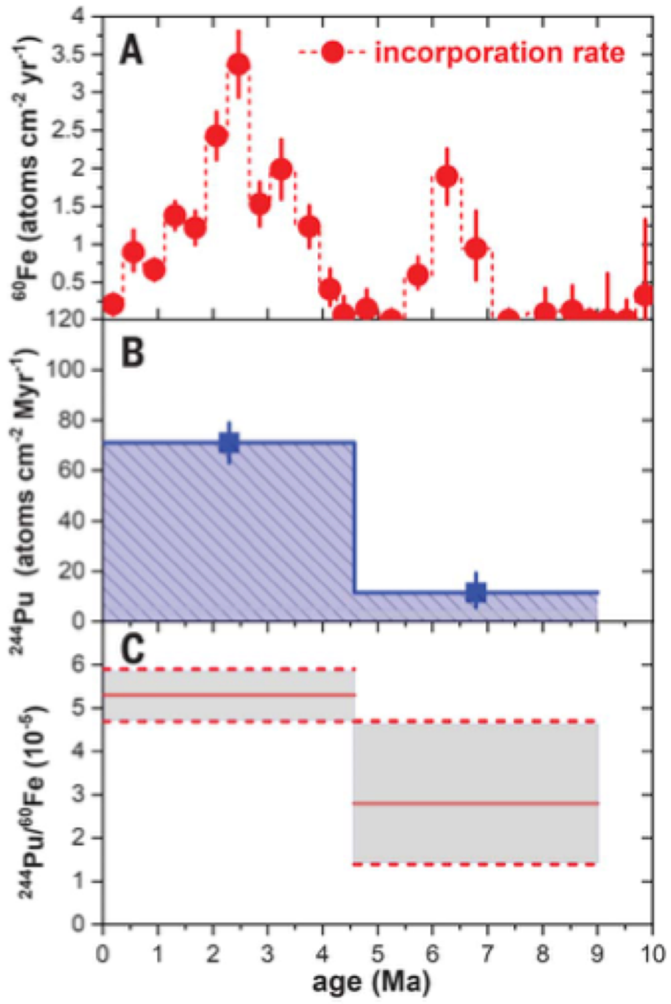
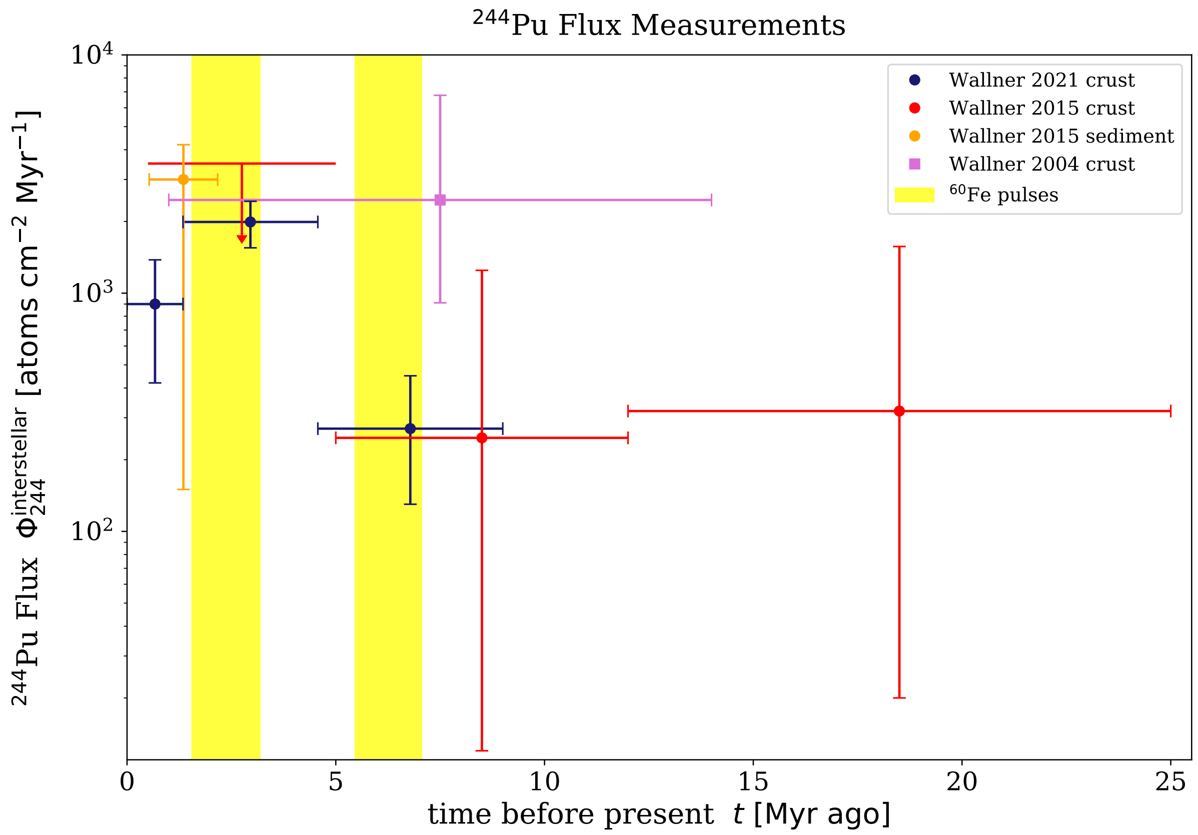
Actinide observables: ^{60}Fe and ^{244}Pu in Fe-Mn crusts

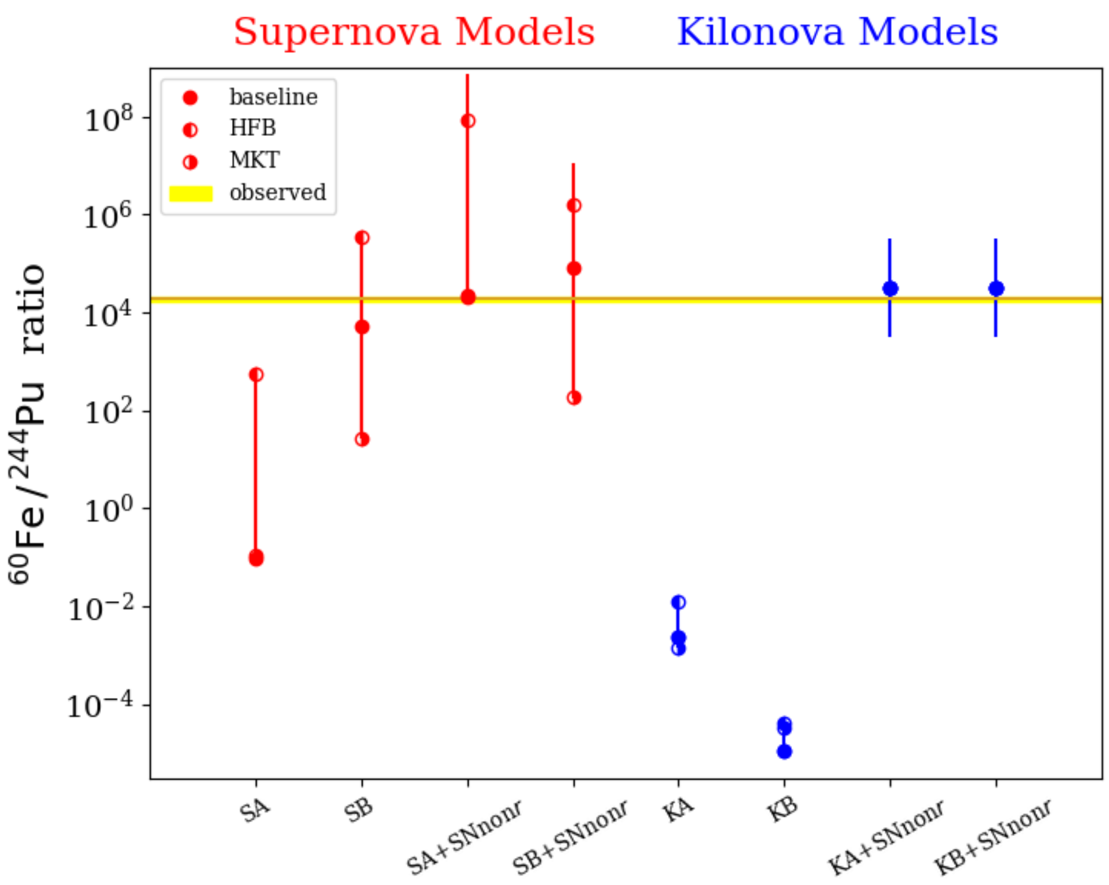
Wallner+2021





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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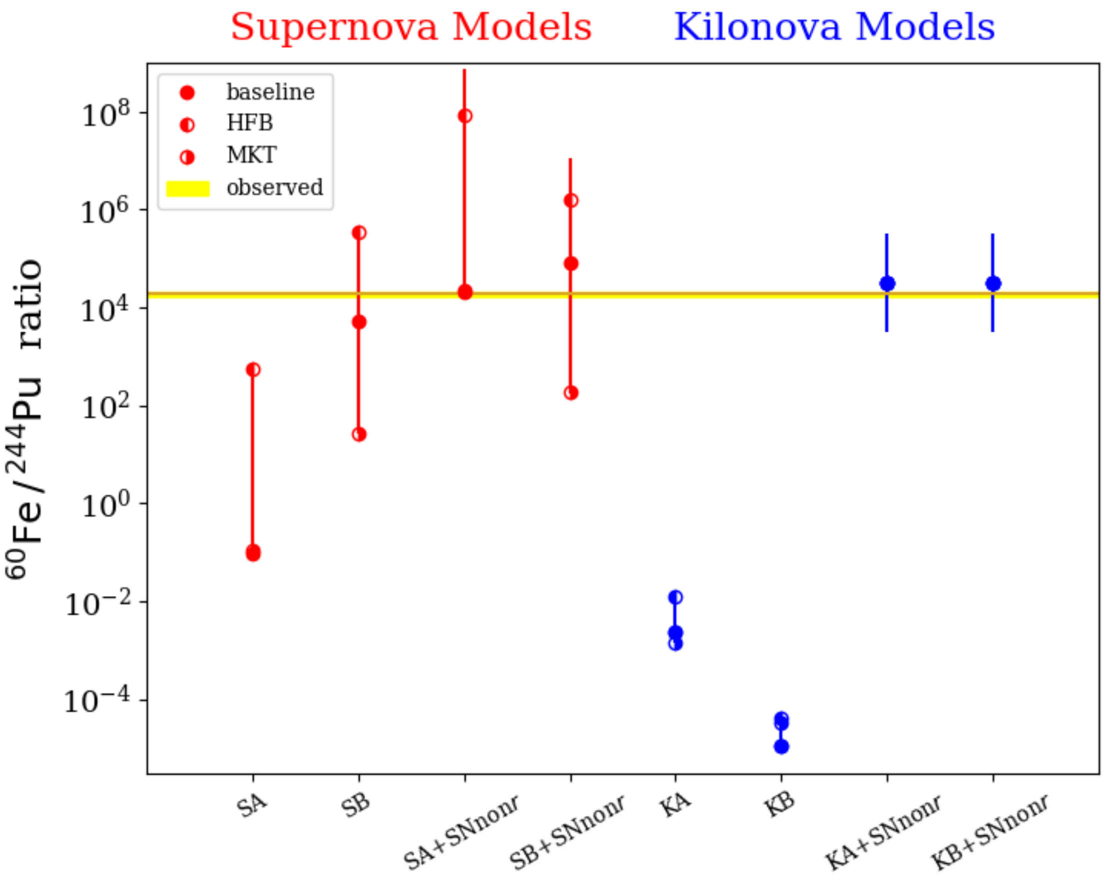

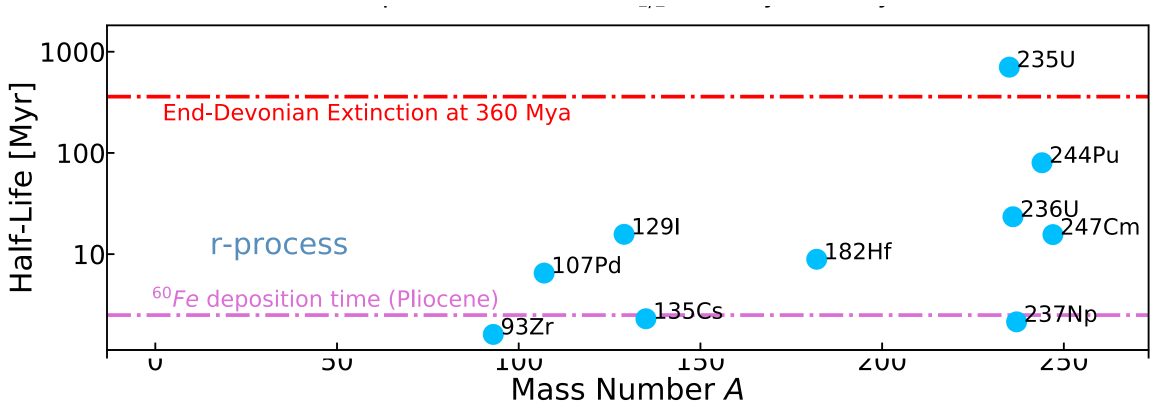

Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;
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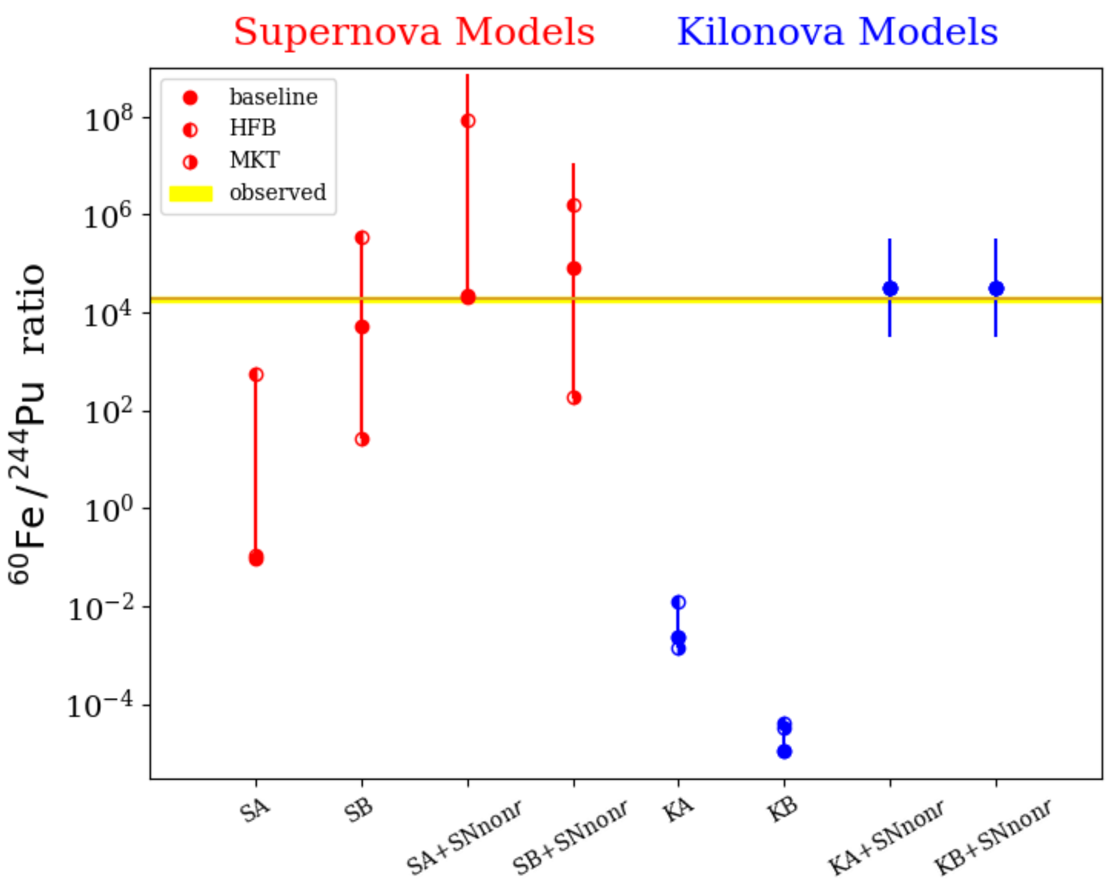

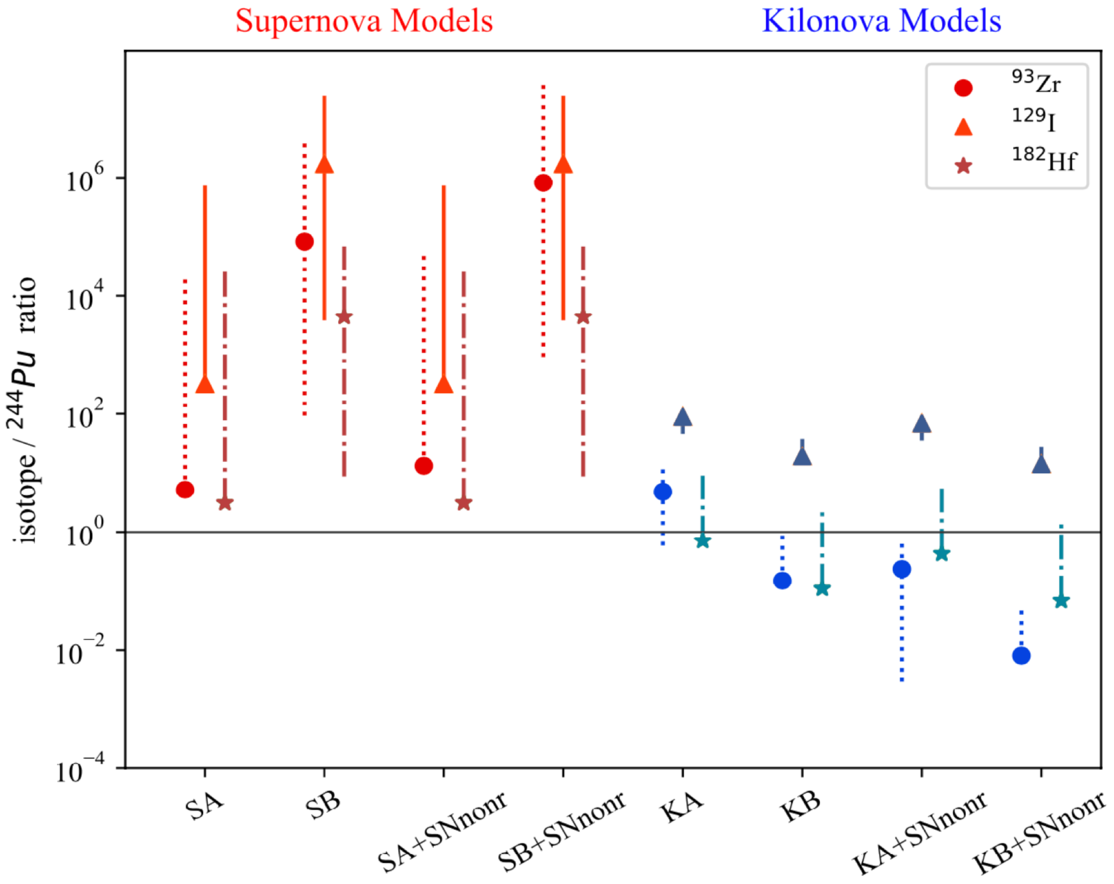

Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;
Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2023

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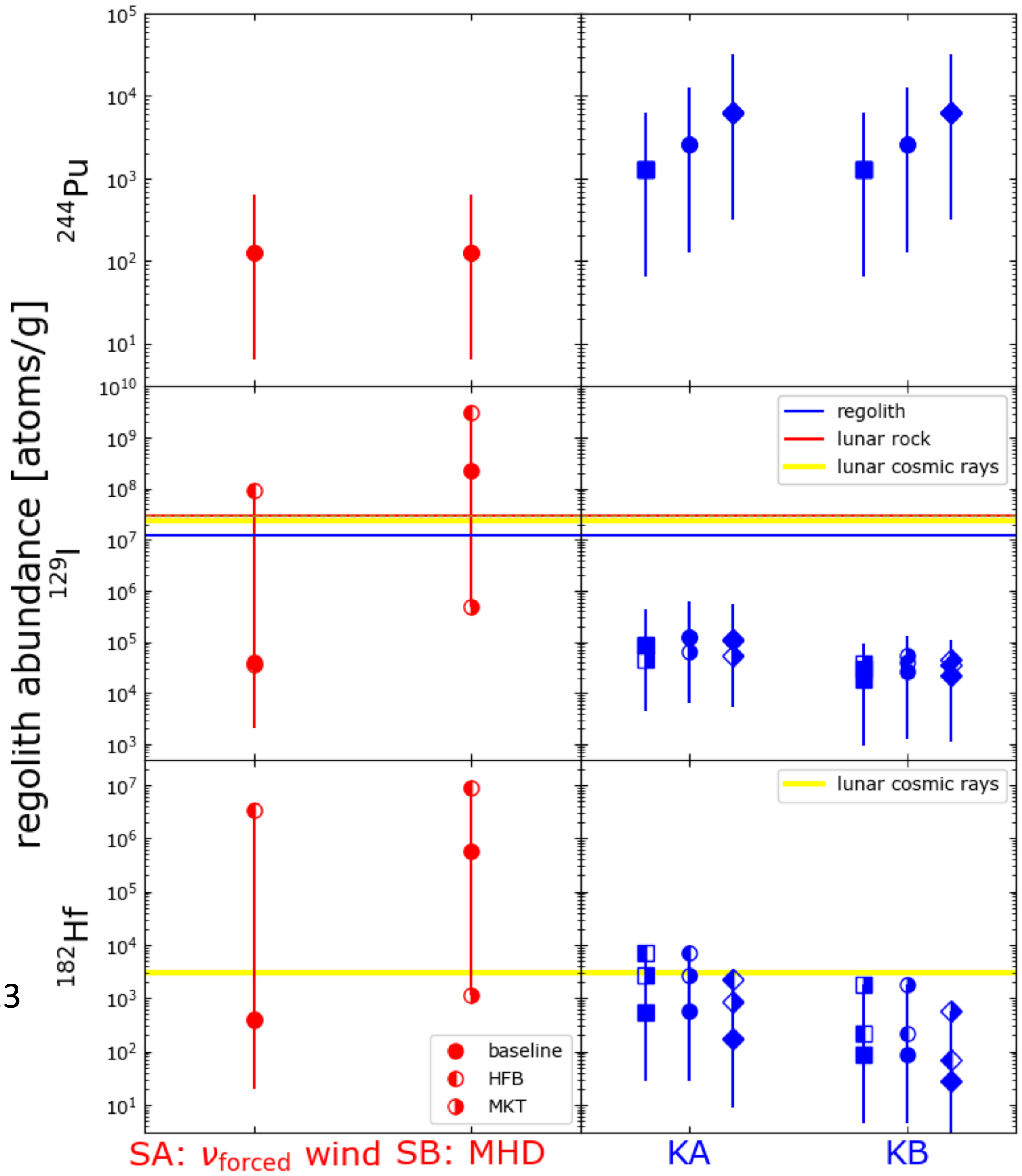
Actinide observables: lunar regolith



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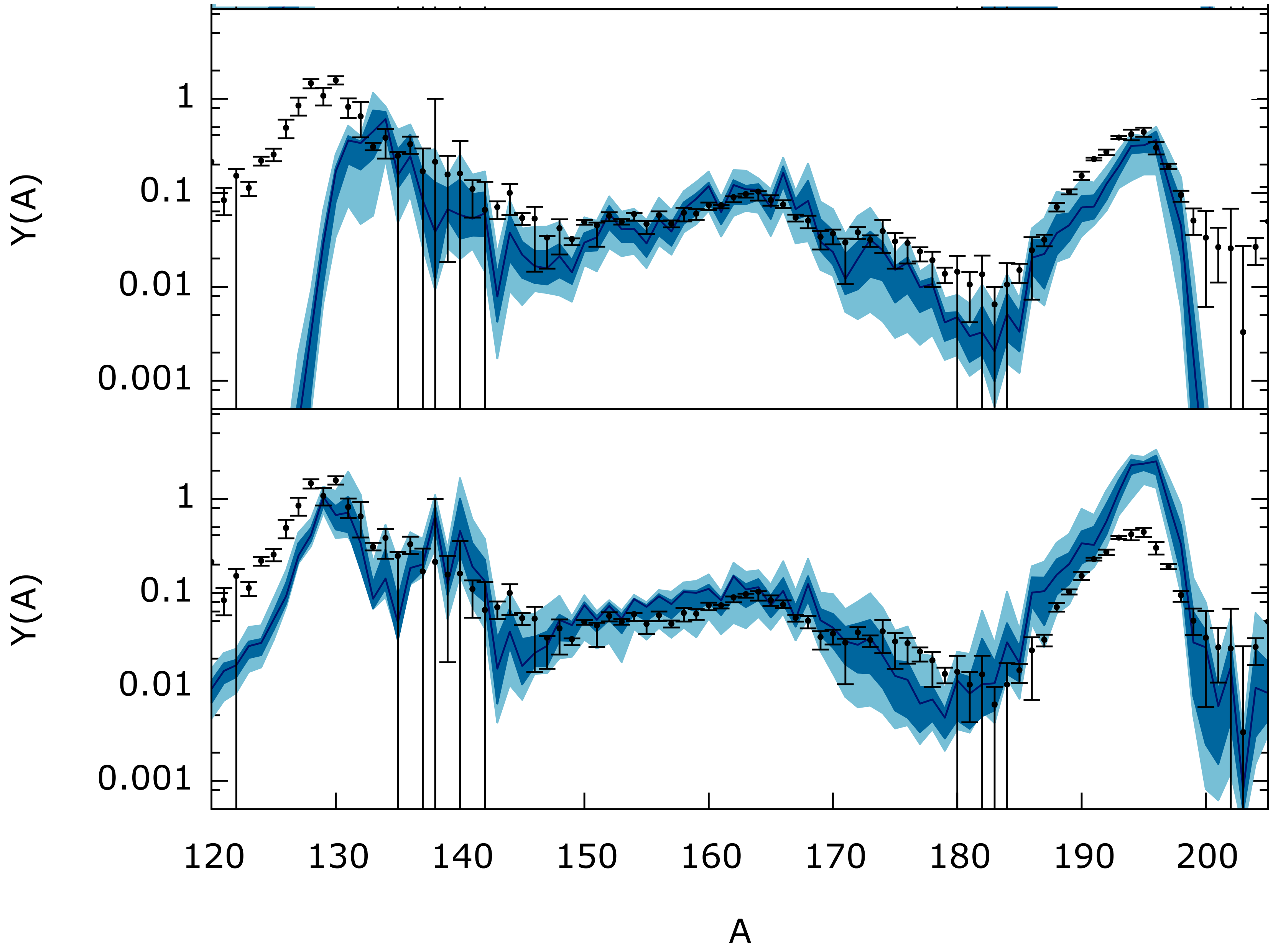
UNEDF1 masses



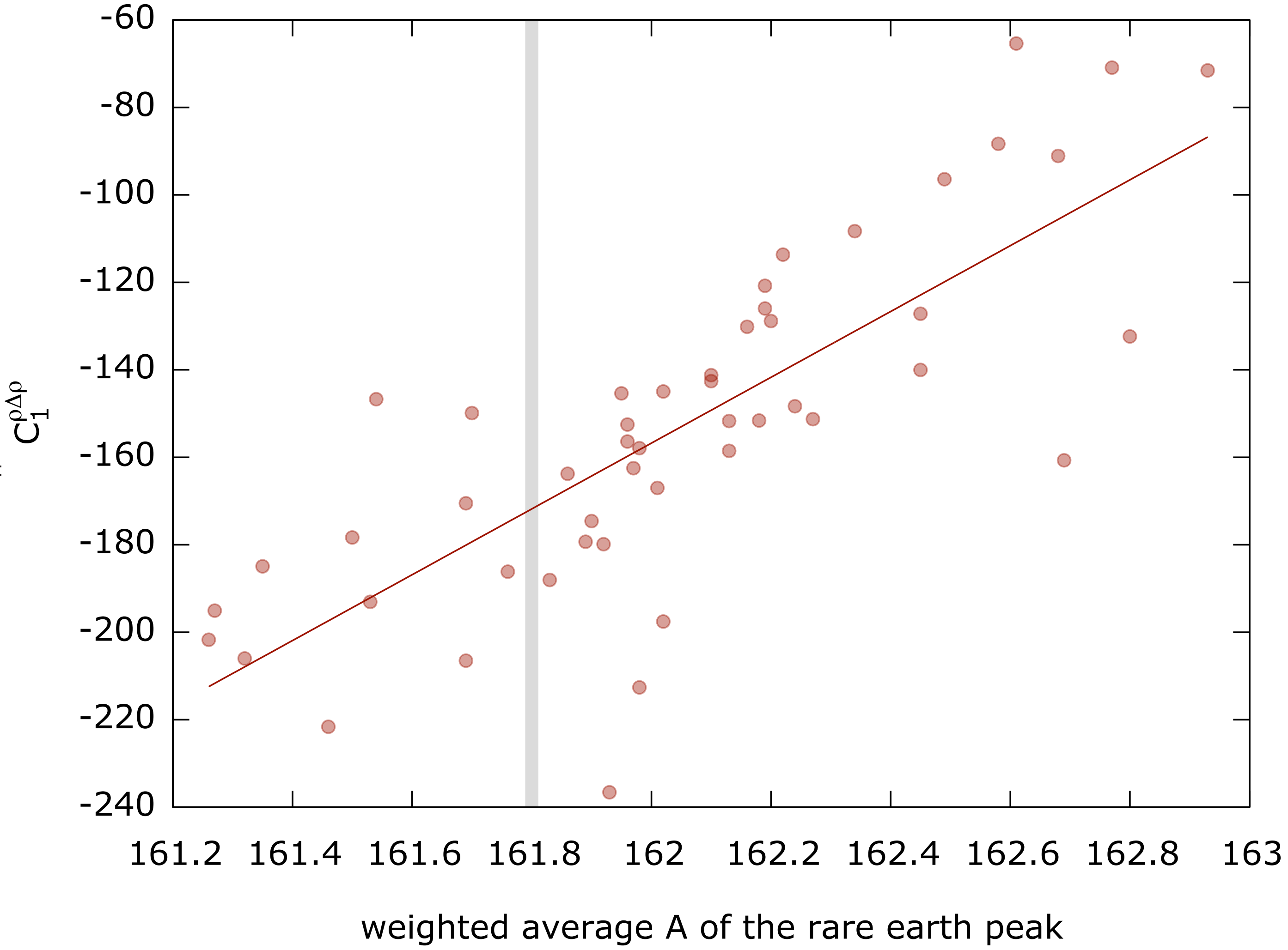
Sprouse, Navarro Perez, Surman, Mumpower, McLaughlin, Schunck 2020

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



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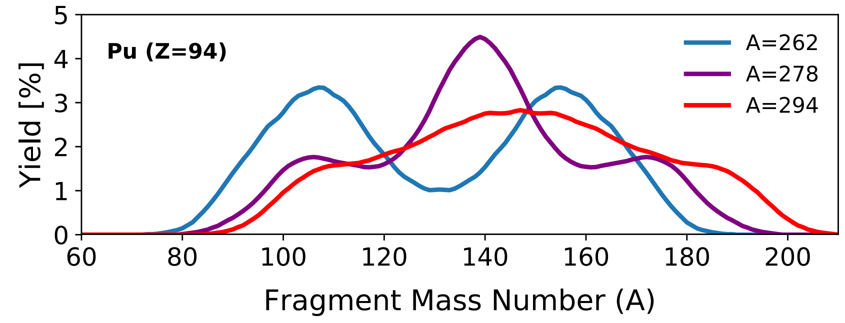
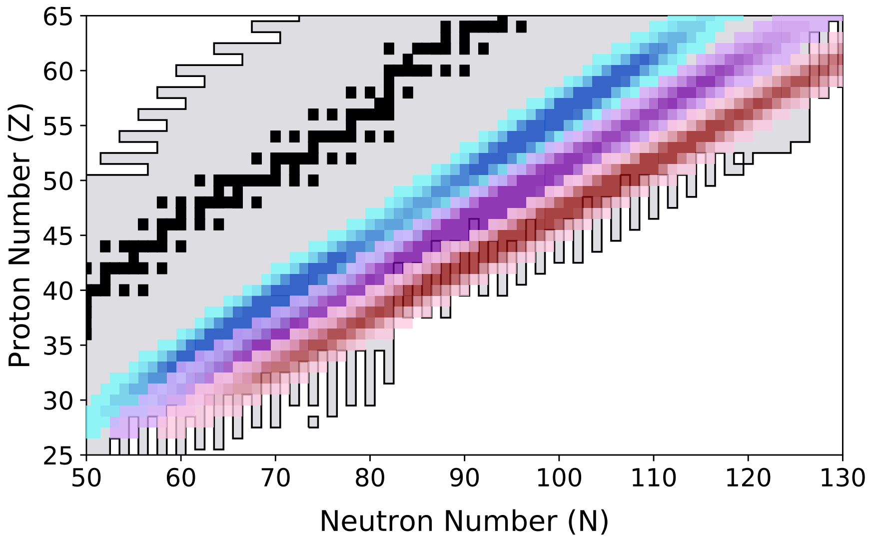
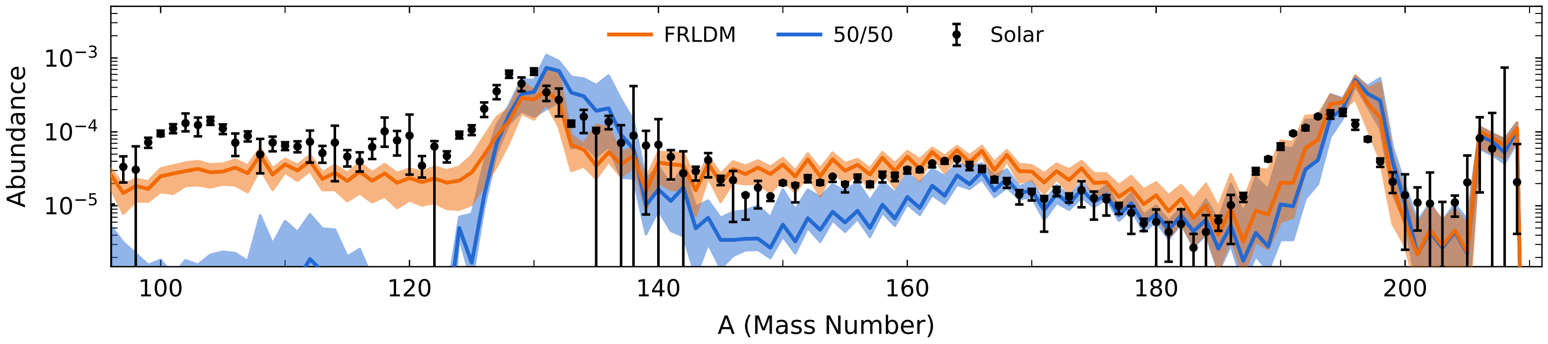
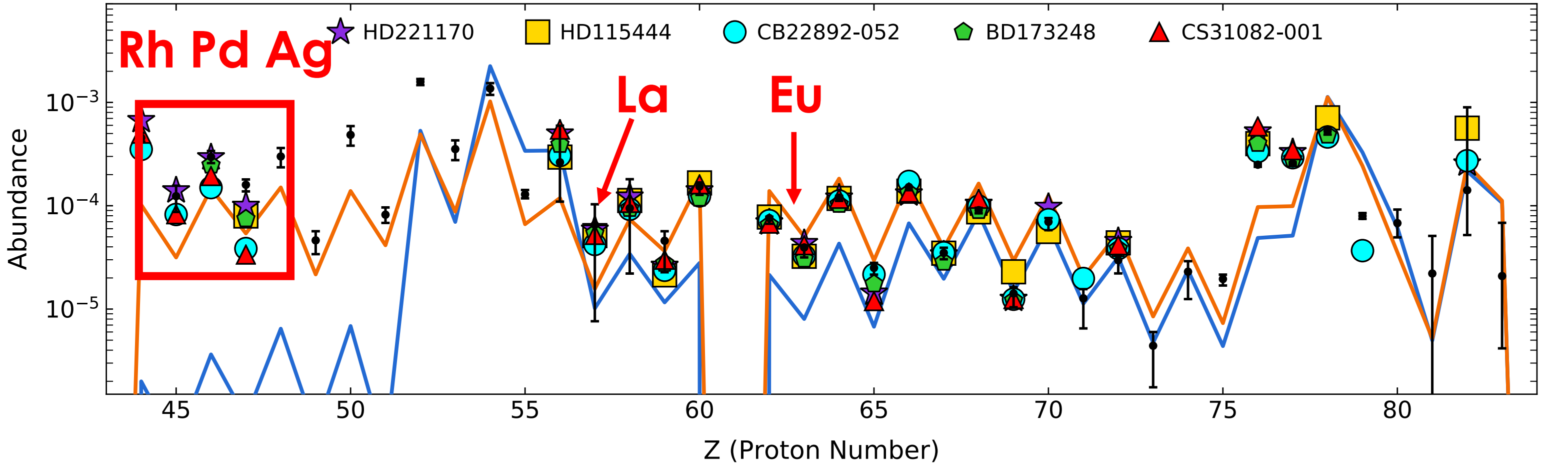
Fission yield signatures

Vassh, Mumpower, McLaughlin, Sprouse, Surman 2020





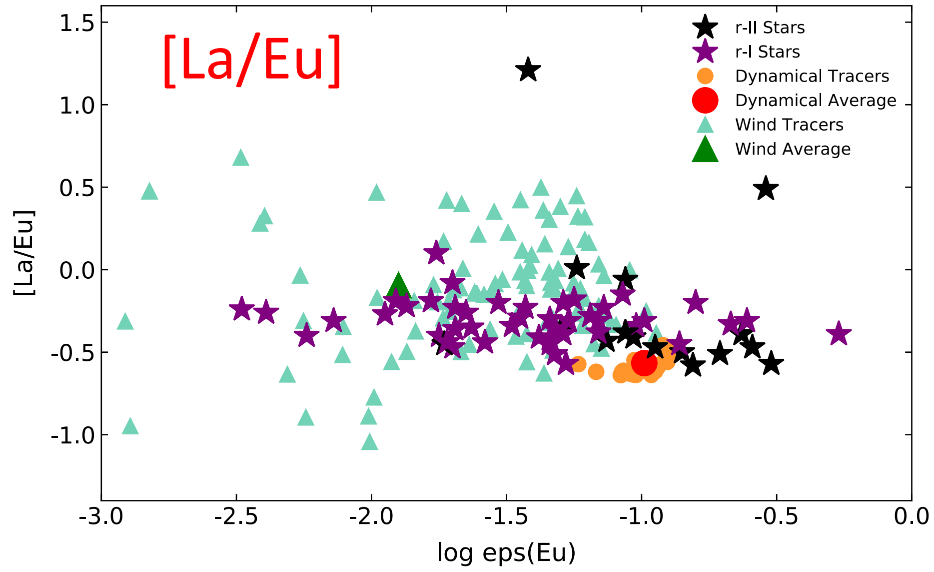


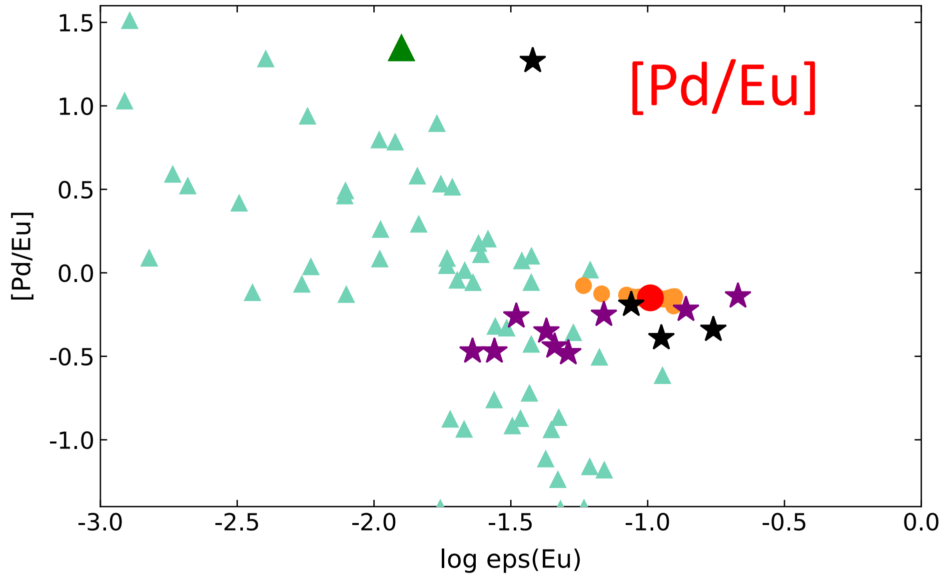


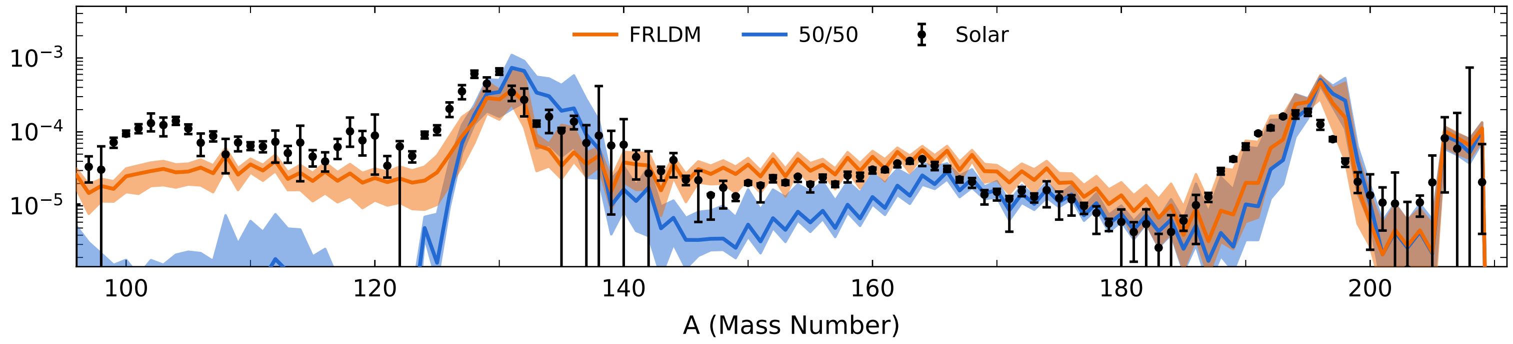
UNIVERSITY OF NOTRE DAME
College of Science

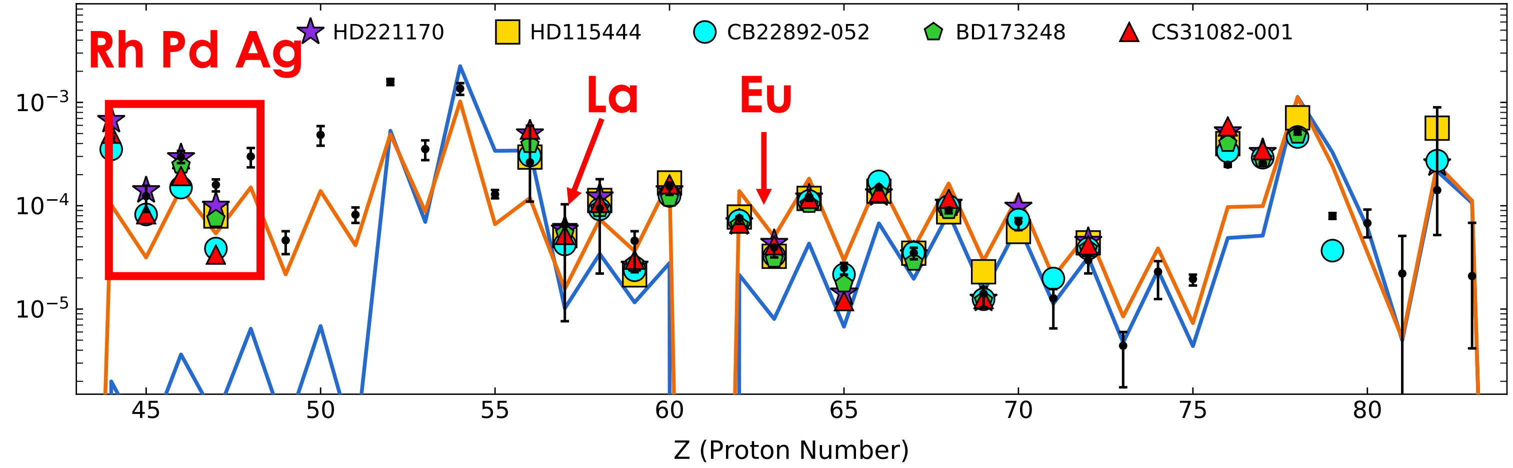
Fission yield signatures

Vassh, Mumpower, McLaughlin, Sprouse, Surman 2020

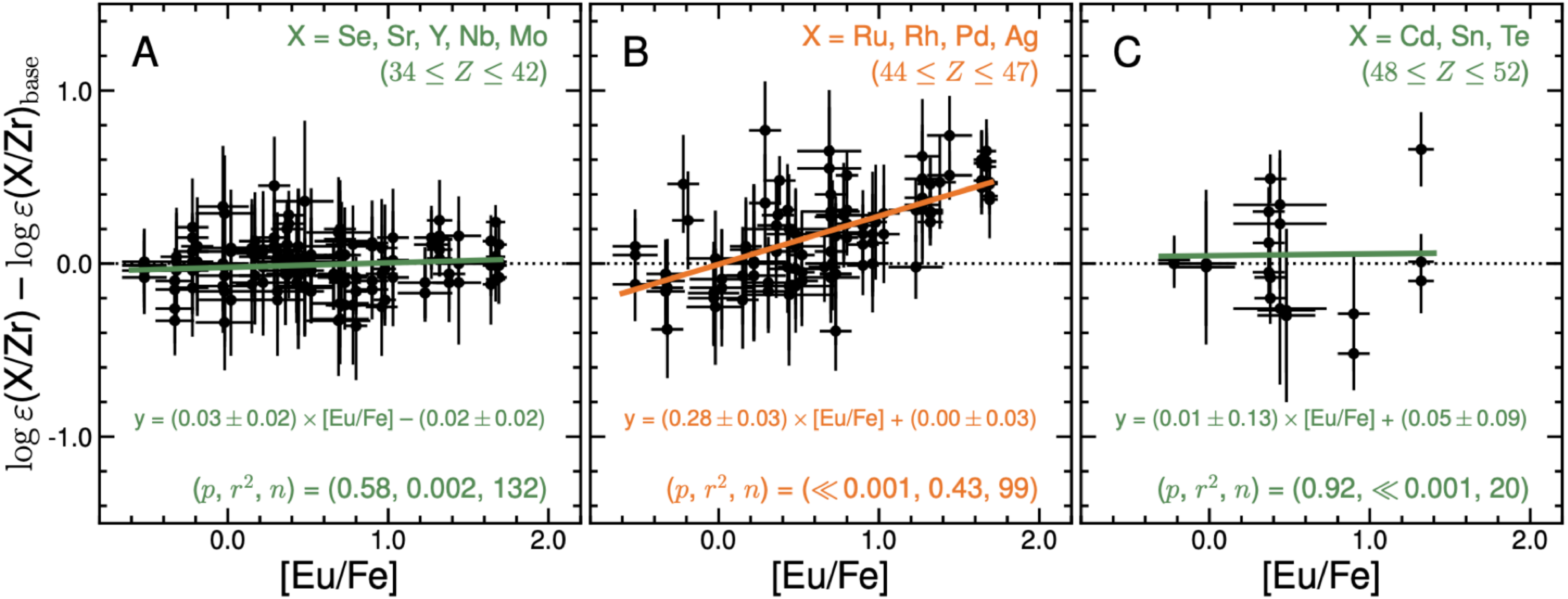








Fission yield signatures



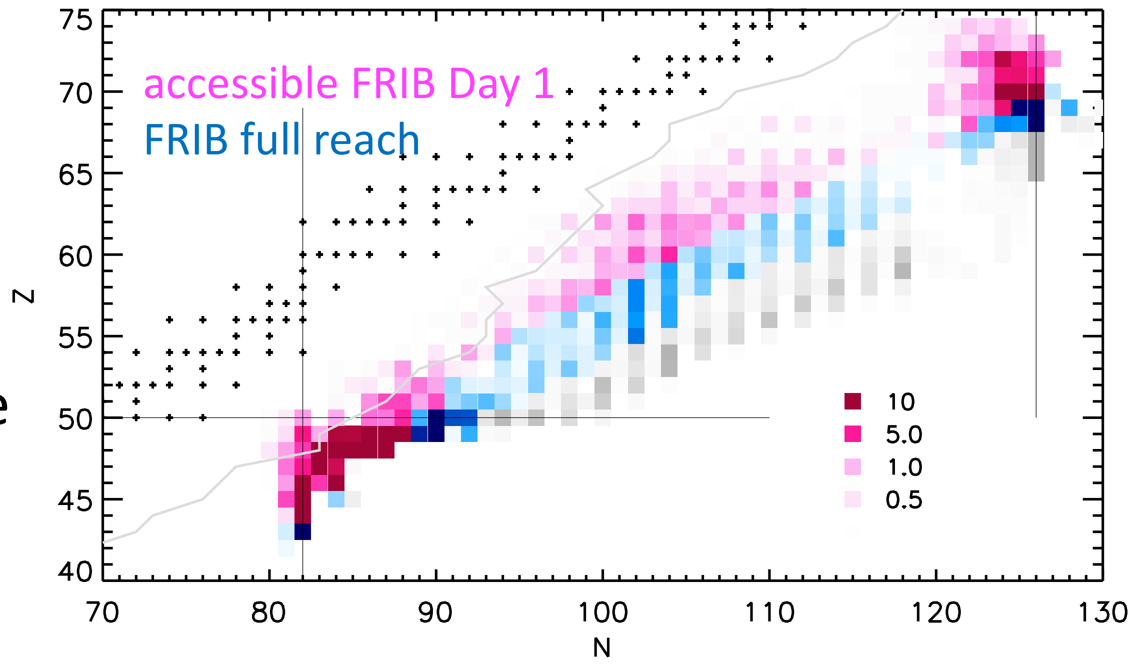
Roederer+ submitted 2023

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