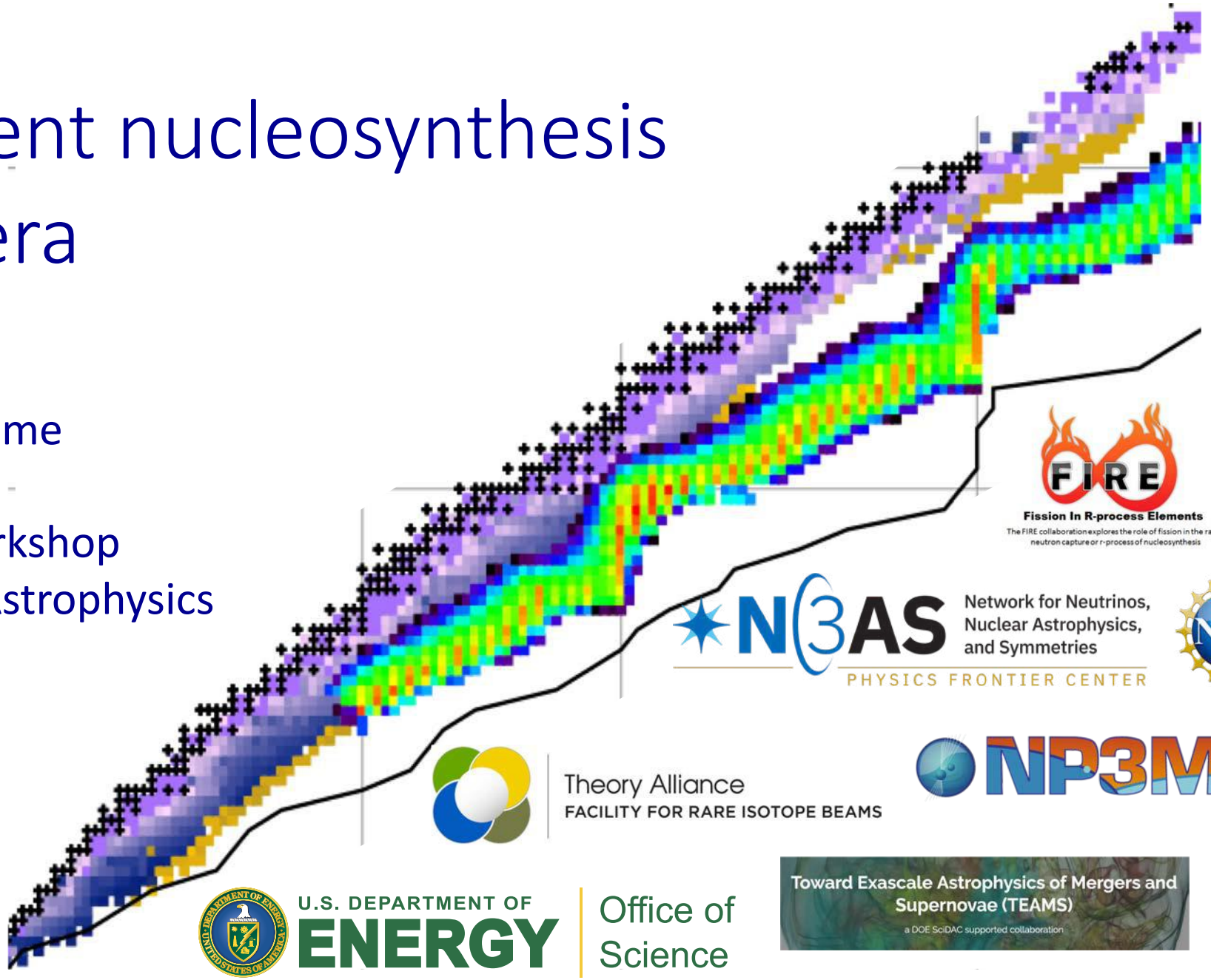
Heavy element nucleosynthesis in the FRIB era

Rebecca Surman
University of Notre Dame

Joint RIKEN/N3AS Workshop
on Multi-Messenger Astrophysics
26 Nov 2023



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College of Science

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

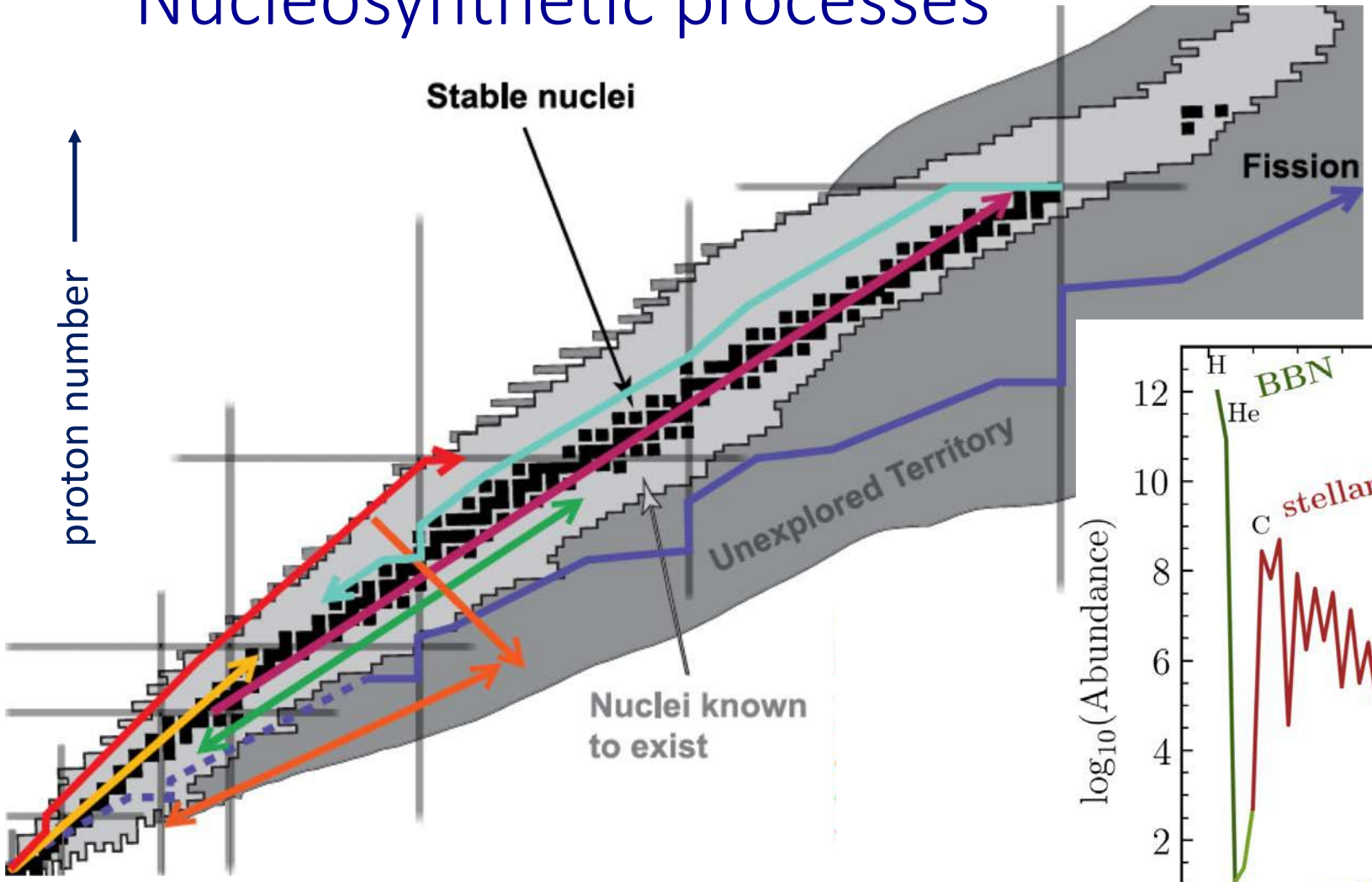
Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

NP3M

U.S. DEPARTMENT OF ENERGY | Office of Science

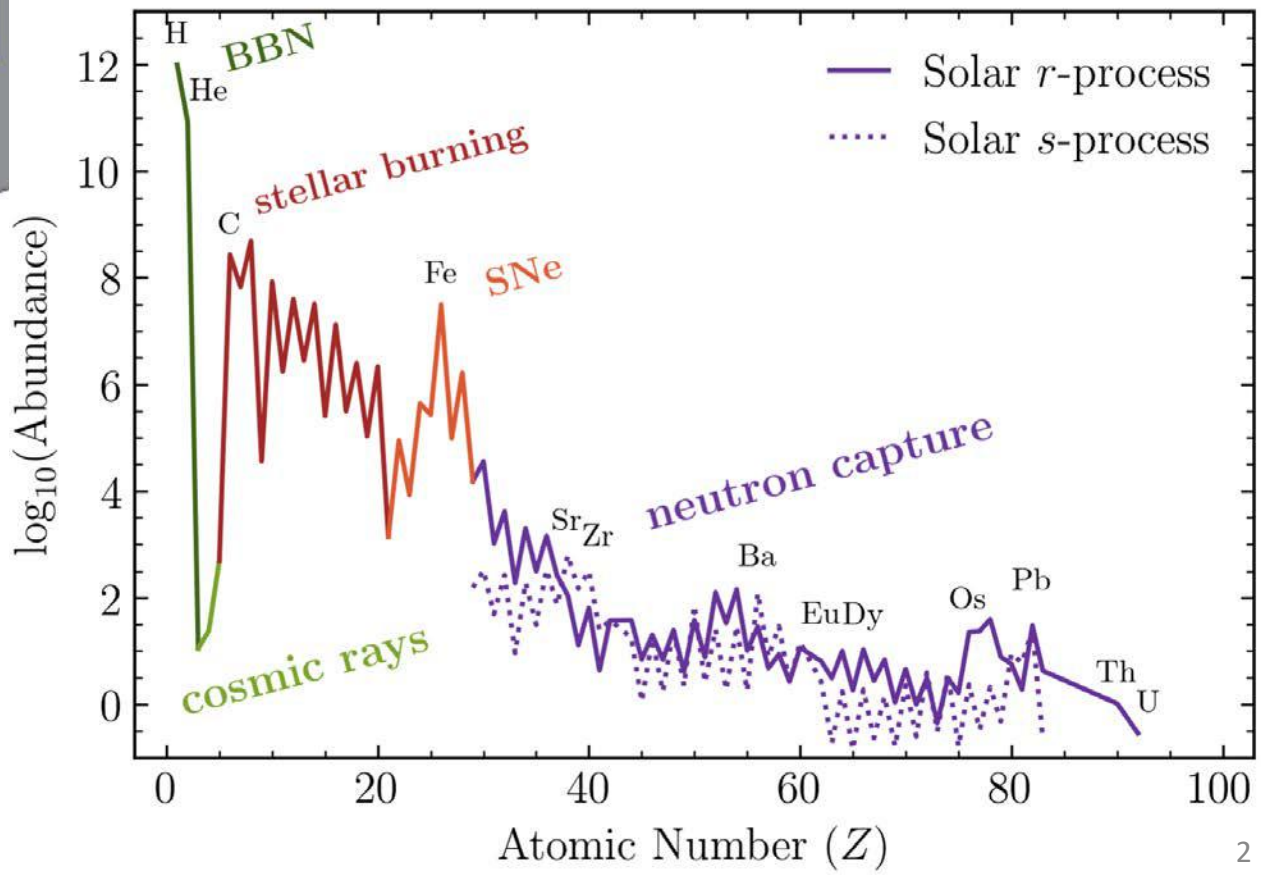
Toward Exascale Astrophysics of Mergers and Supernovae (TEAMS)
a DOE SciDAC supported collaboration

Nucleosynthetic processes



from Timmes/Schatz/Spyrou

data from Lodders 2003
figure by E Holmbeck



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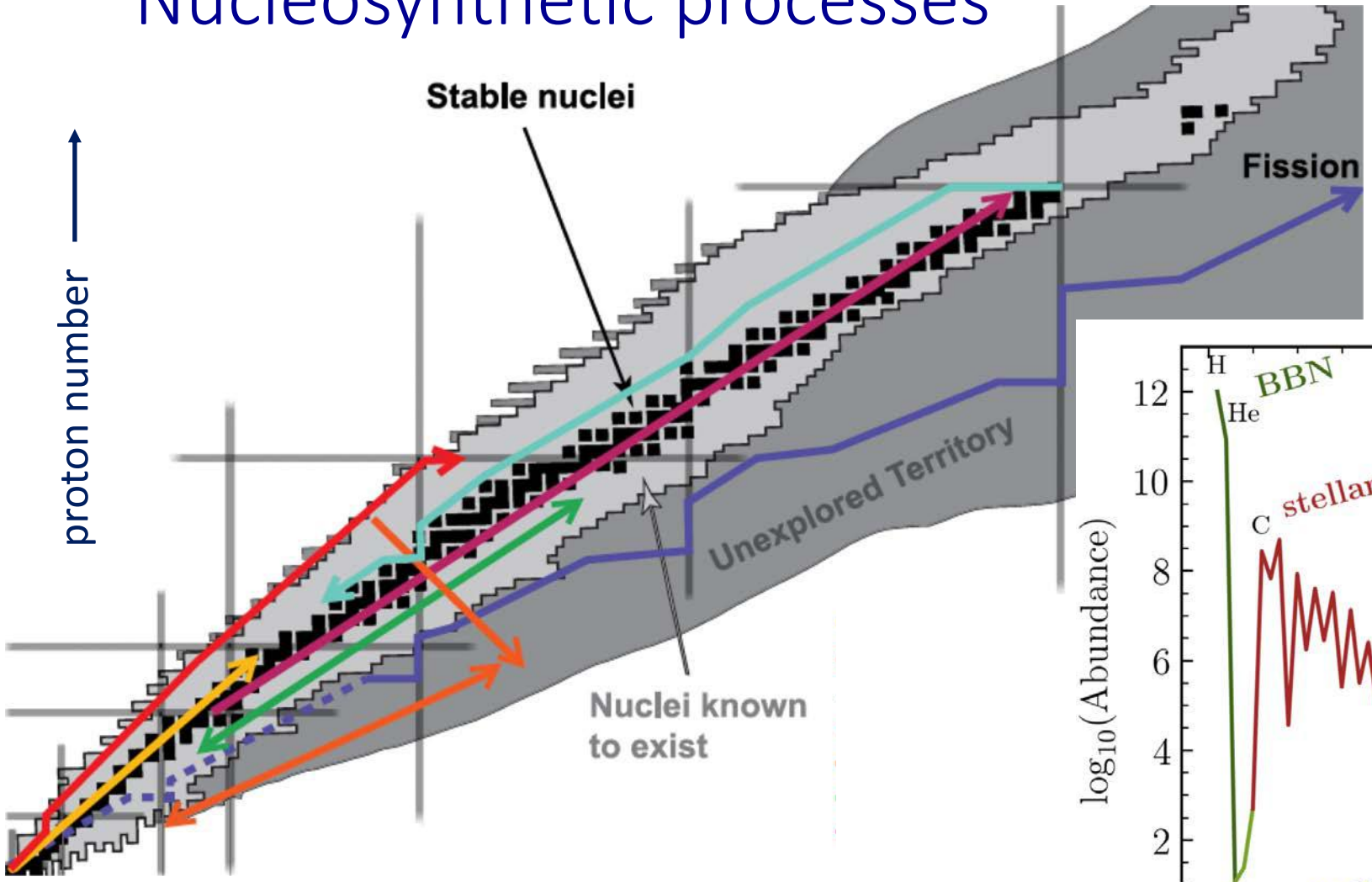
Nucleosynthetic processes



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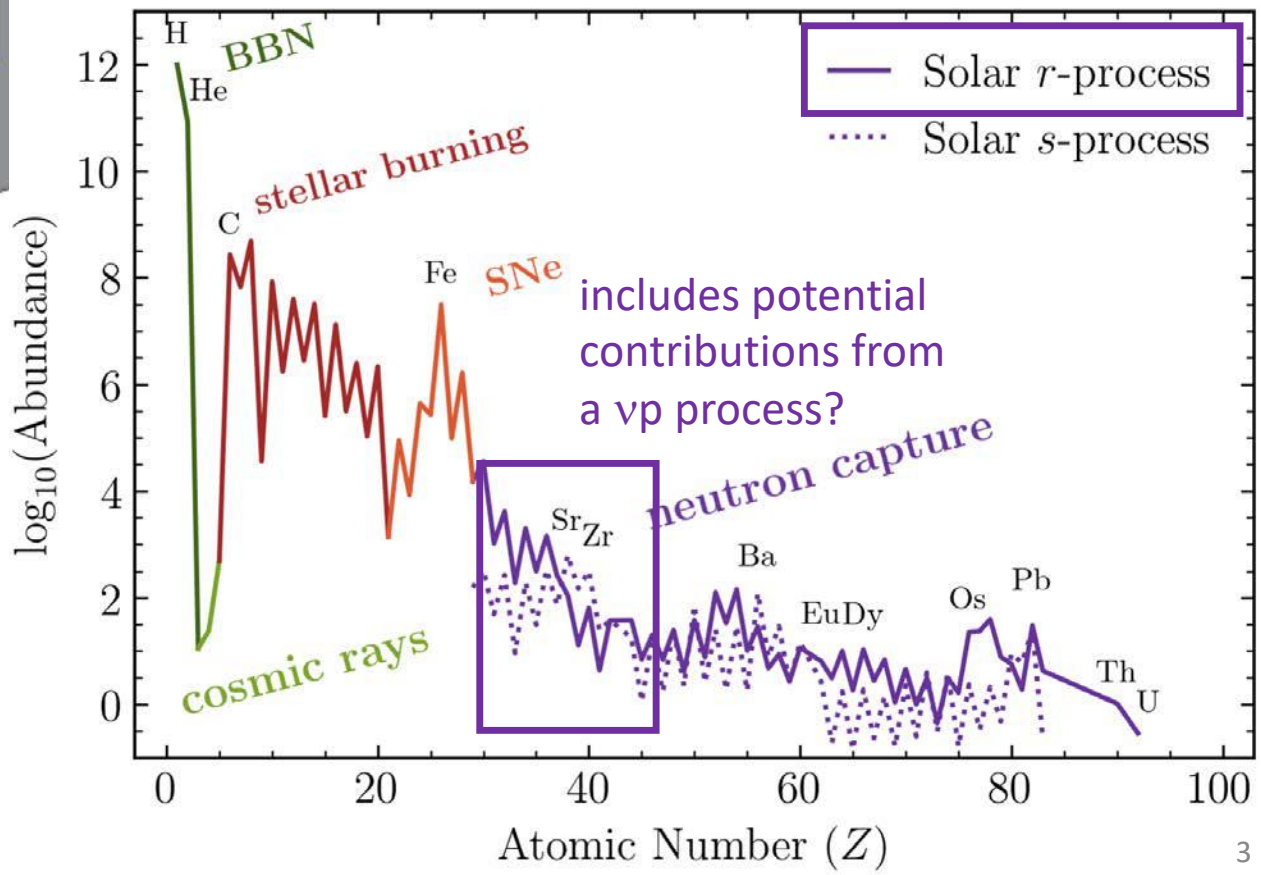
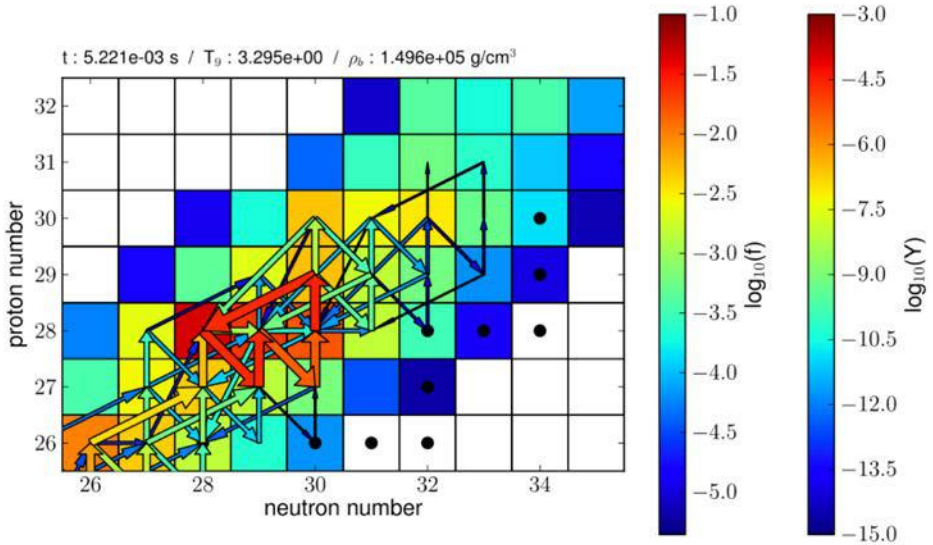
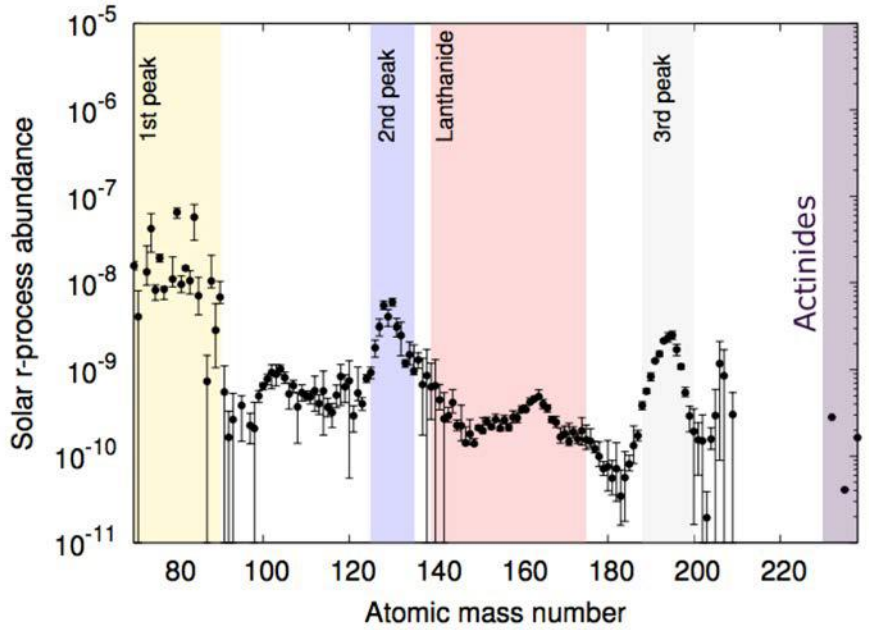


r and *νp* processes

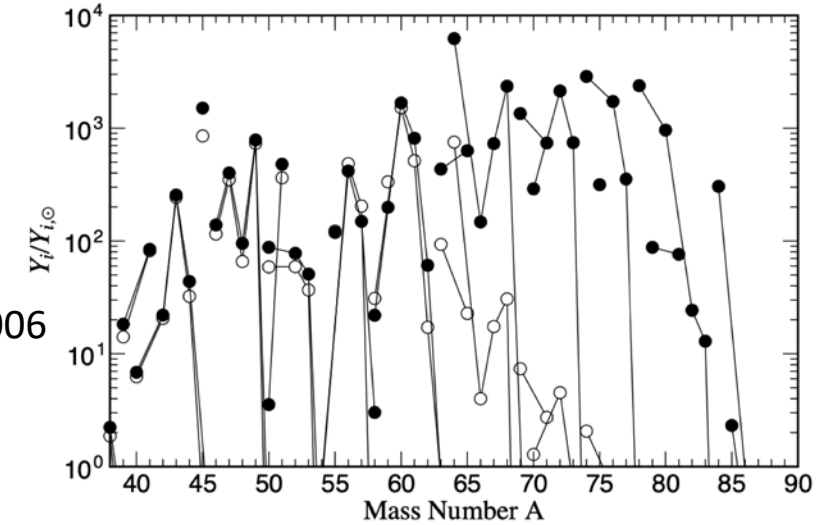


Arcones+2012

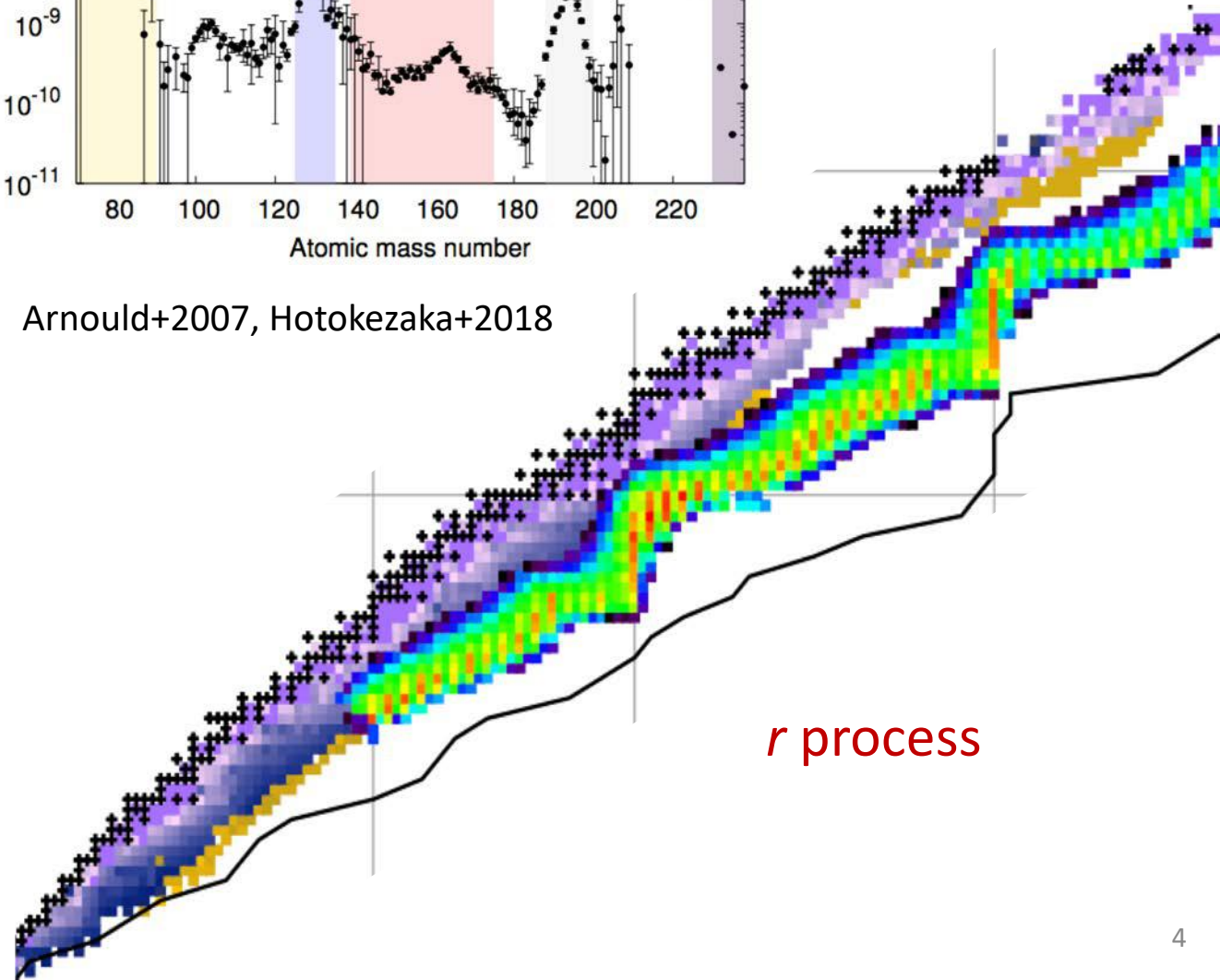


Arnould+2007, Hotokezaka+2018

νp process



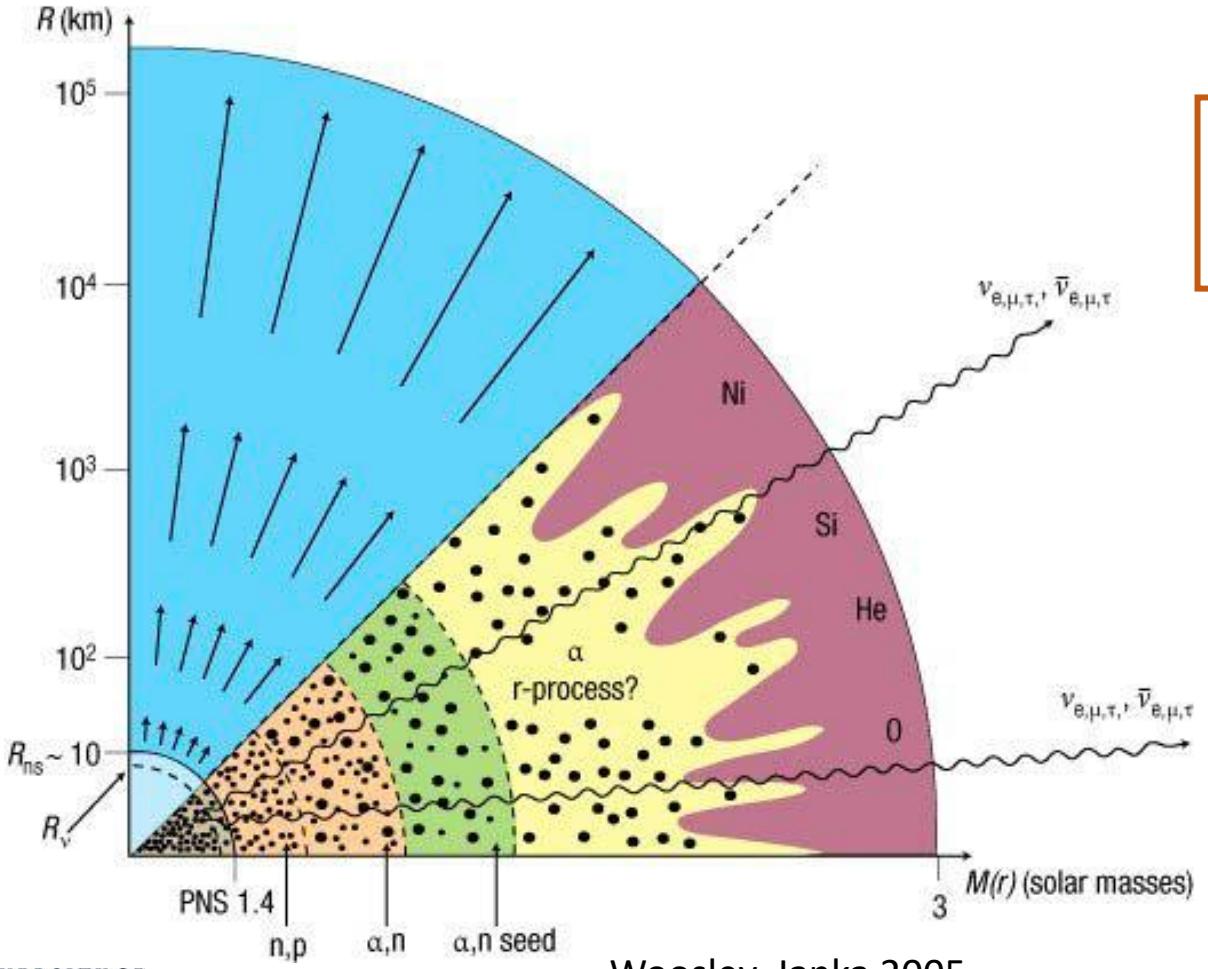
Frohlich+2006



r process

Astrophysical sites of heavy element synthesis: supernovae

SN neutrino-driven wind

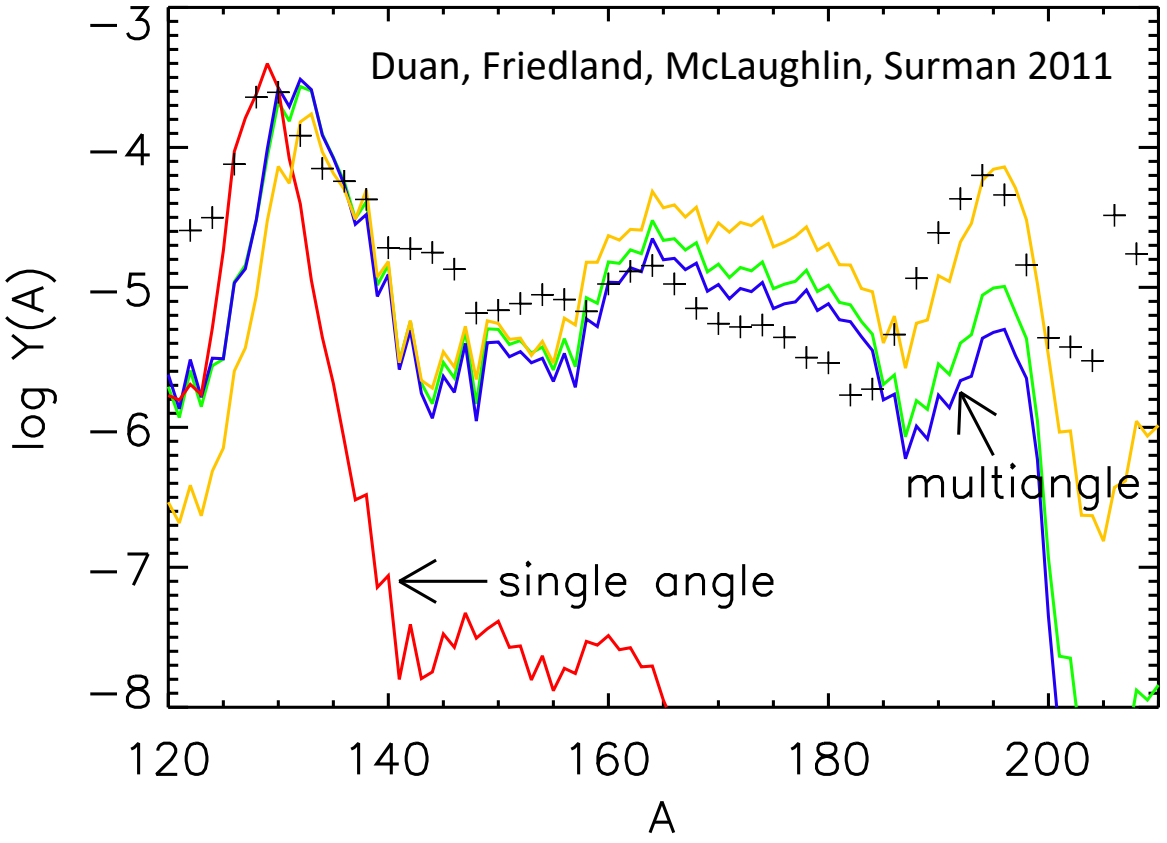


Woosley, Janka 2005

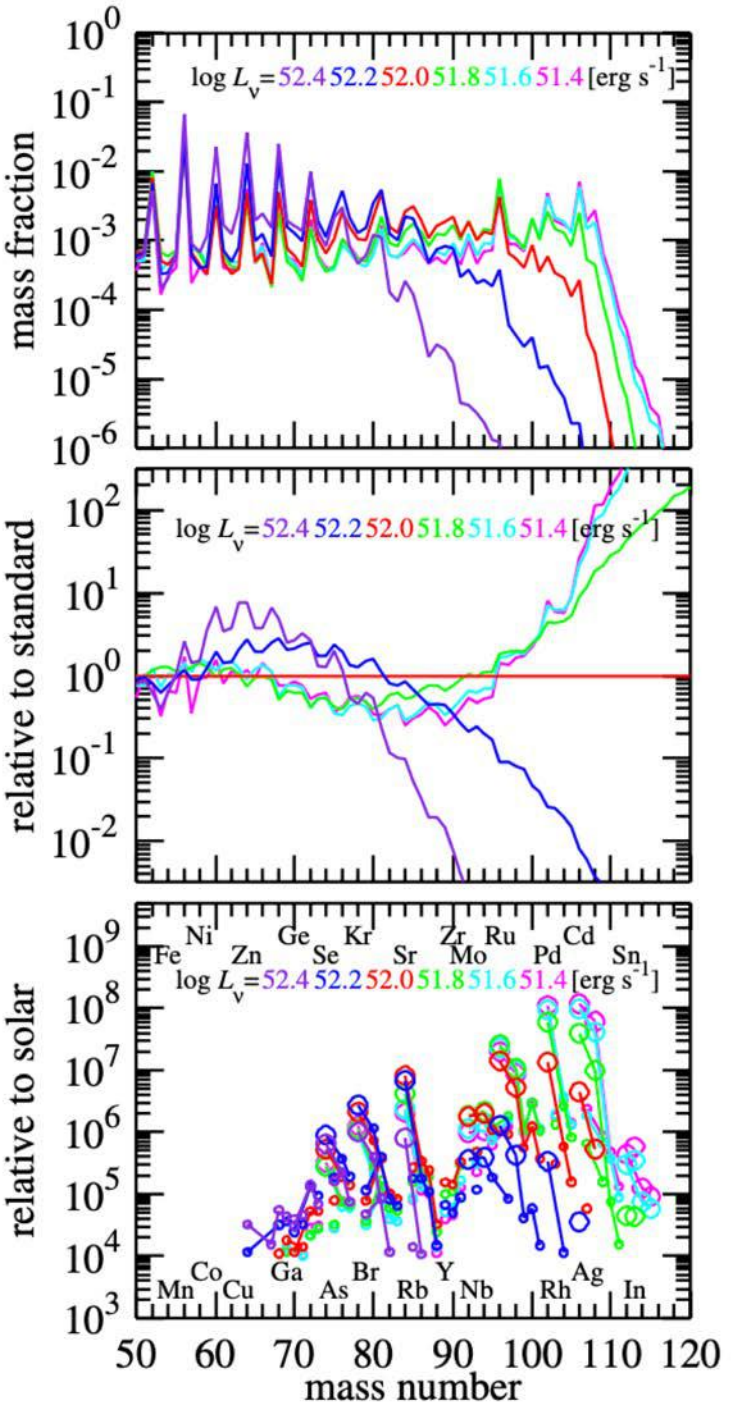
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

Meyer+1992, Woosley+1994, Takahashi+1994, Witti+1994, Fuller, Meyer 1995, McLaughlin+1996, Qian & Woosley 1996, Hoffman+1997, Otsuki+2000, Thompson+2001, Terasawa+2002, Liebendorfer+2005, Frohlich+2005, Wanajo 2006, Arcones+2007, Huedepohl+2010, Fischer+2010, Roberts, Reddy 2012, Martinez-Pinedo+2014, Chakraborty+ 2015, Goriely, Janka 2016, etc., etc.

Neutrinos and SN nucleosynthesis



Higher neutrino capture rates -> **less** robust *r* process

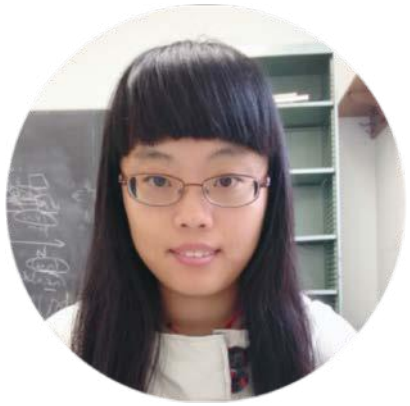


Higher neutrino capture rates -> **more** robust *νp* process

Wanajo+2011

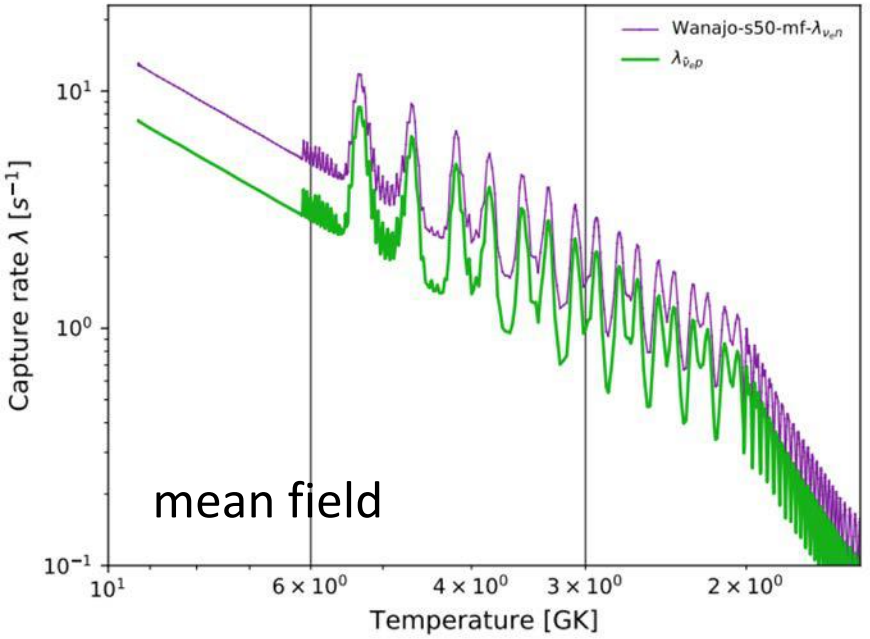
Neutrinos and SN nucleosynthesis

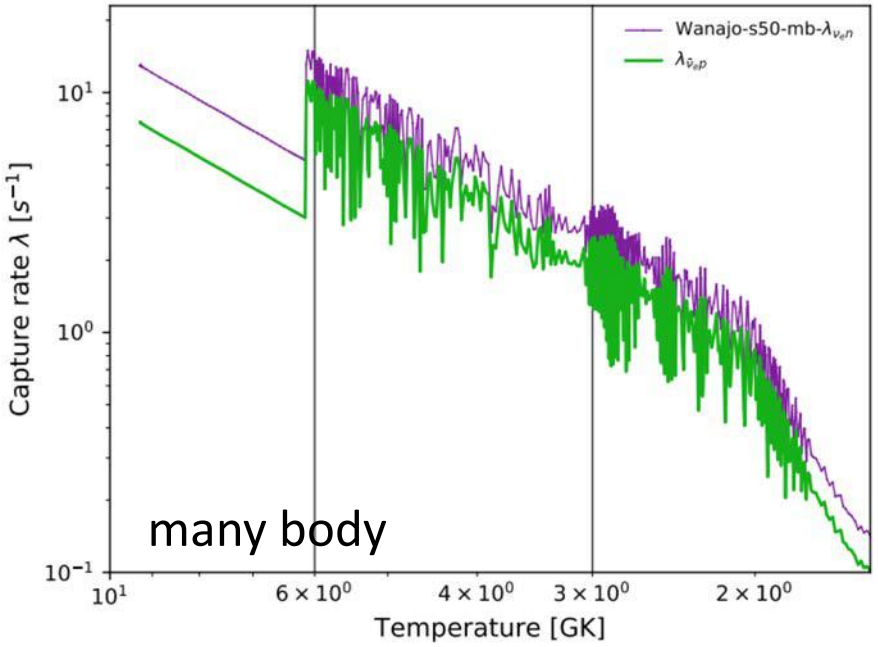
Amol Patwardhan



Xilu Wang

See earlier talk by Baha Balantekin





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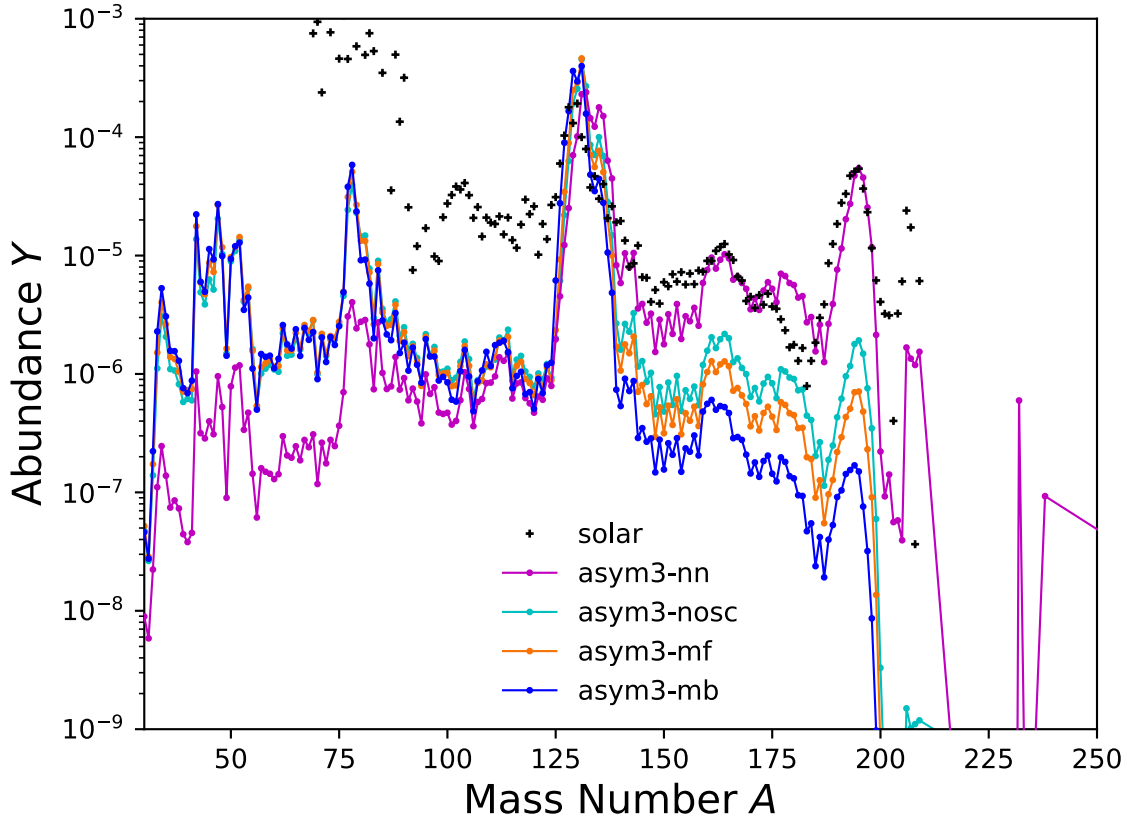
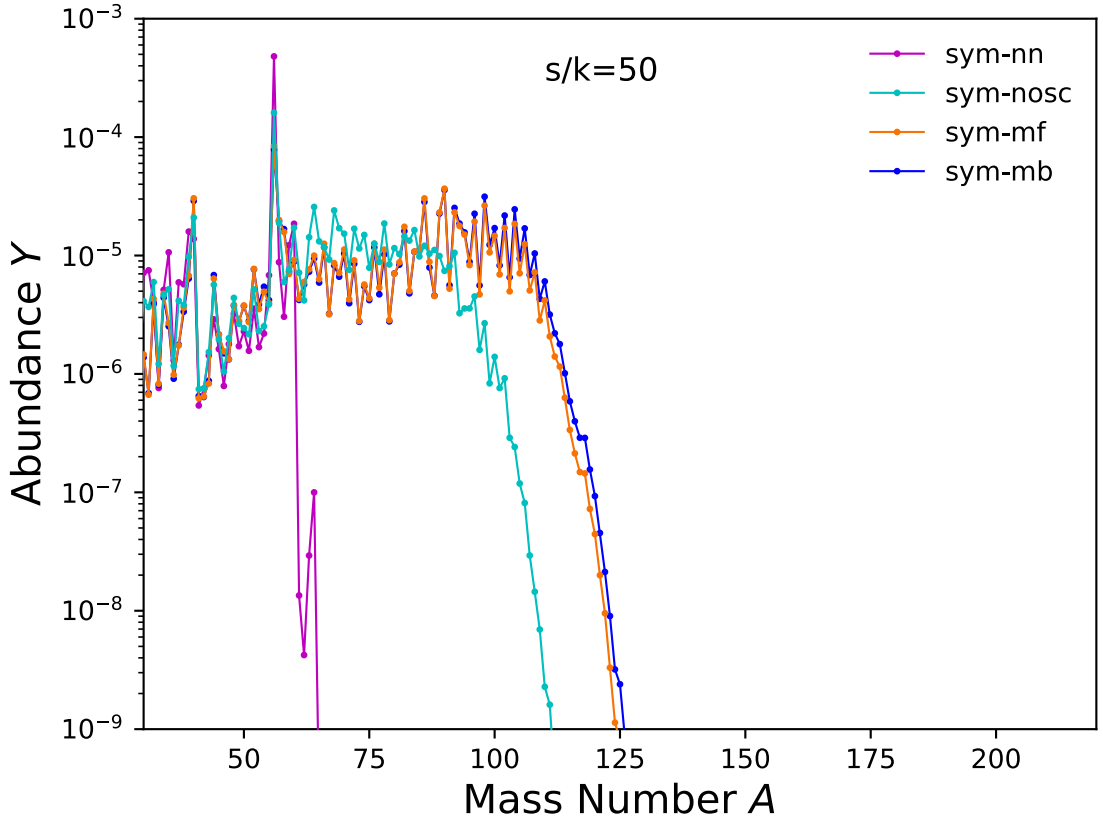
Neutrinos and SN nucleosynthesis: *r* and νp processes





Balantekin, Cervia, Patwardhan, Surman, Wang, arXiv:2311.02562

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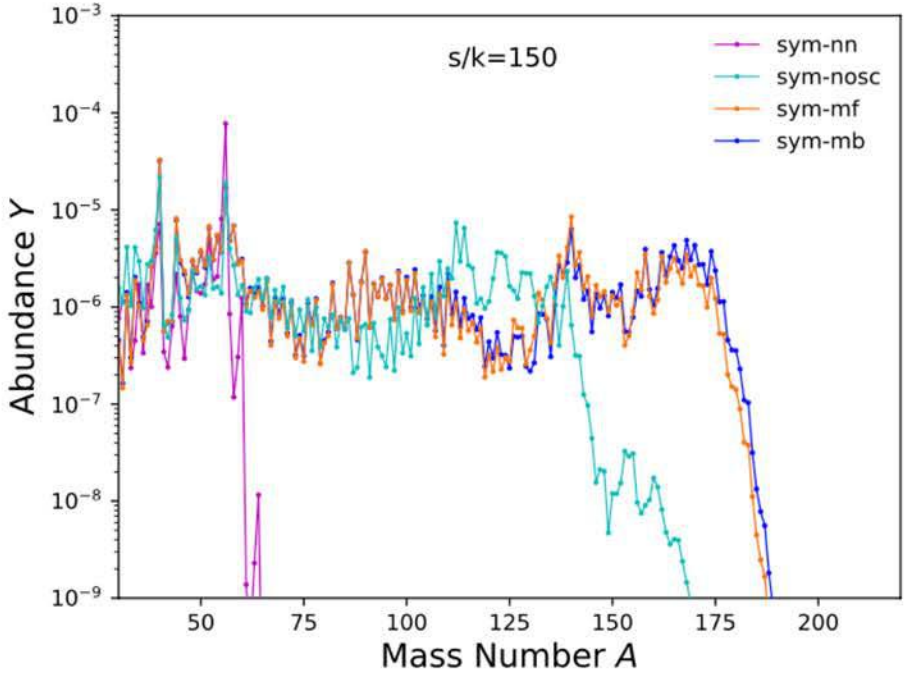
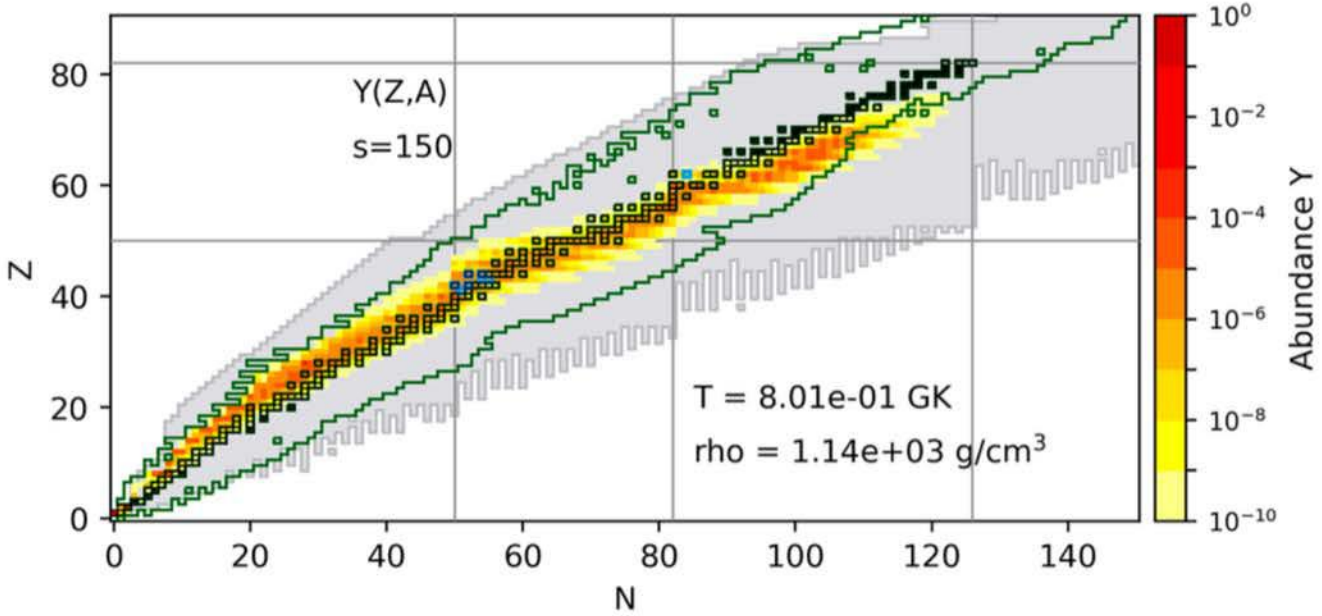
Neutrinos and SN nucleosynthesis: the *νi* process



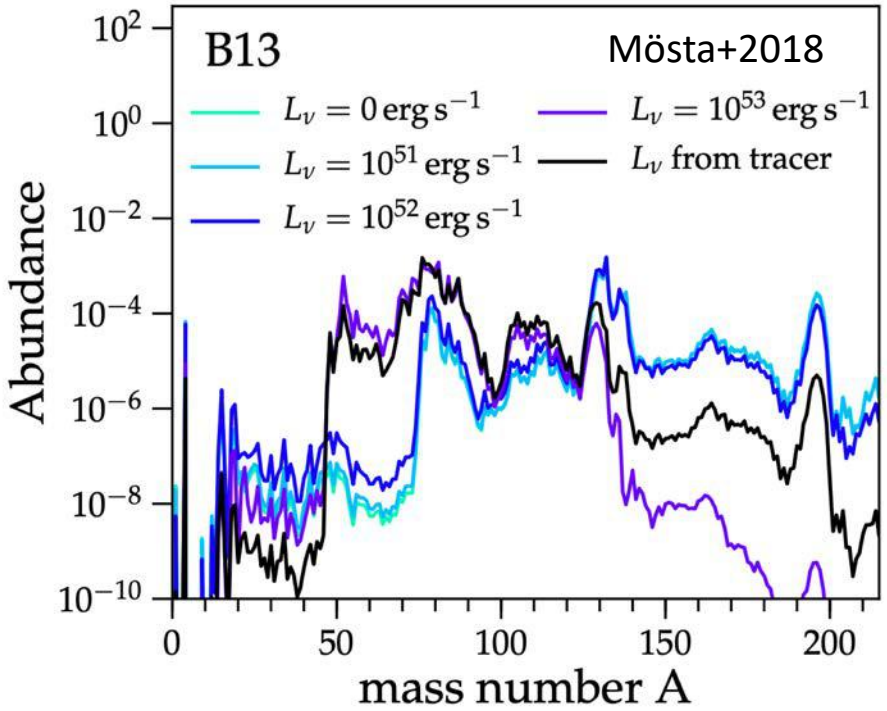


Balantekin, Cervia, Patwardhan, Surman, Wang, arXiv:2311.02562

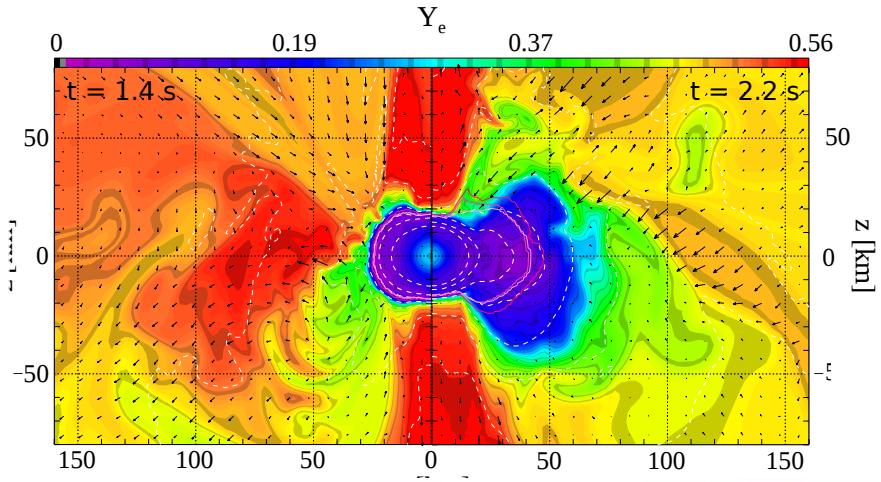
See also, e.g., Wanajo+2011, Arcones+2012, Fujibayashi+2015

Astrophysical sites of heavy element synthesis: supernovae

MHD supernovae

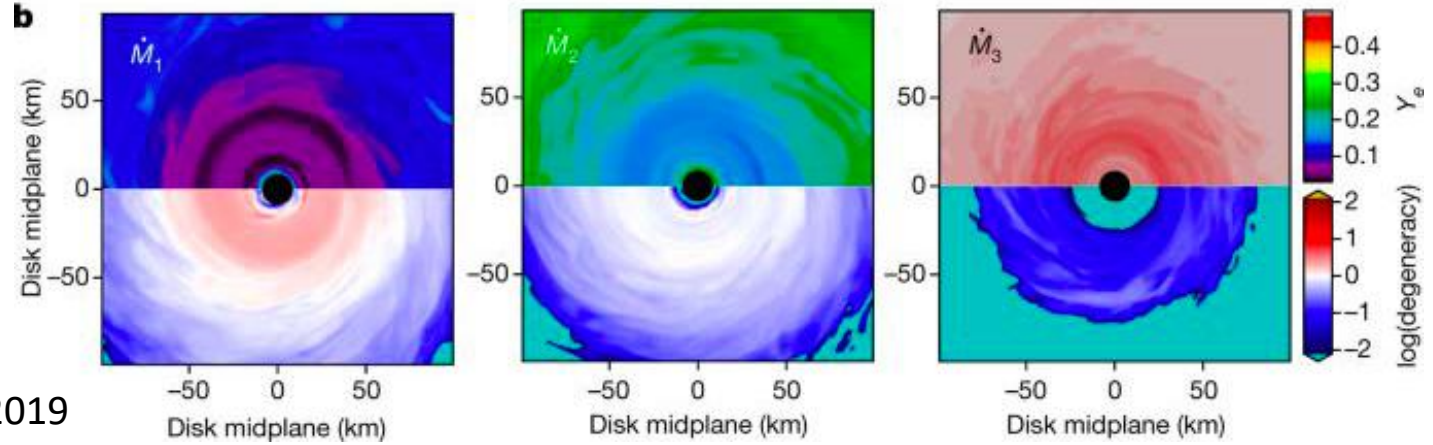


See also, e.g., Winteler+2012, Nishimura+2015, 2017



Reichert+2021

collapsars

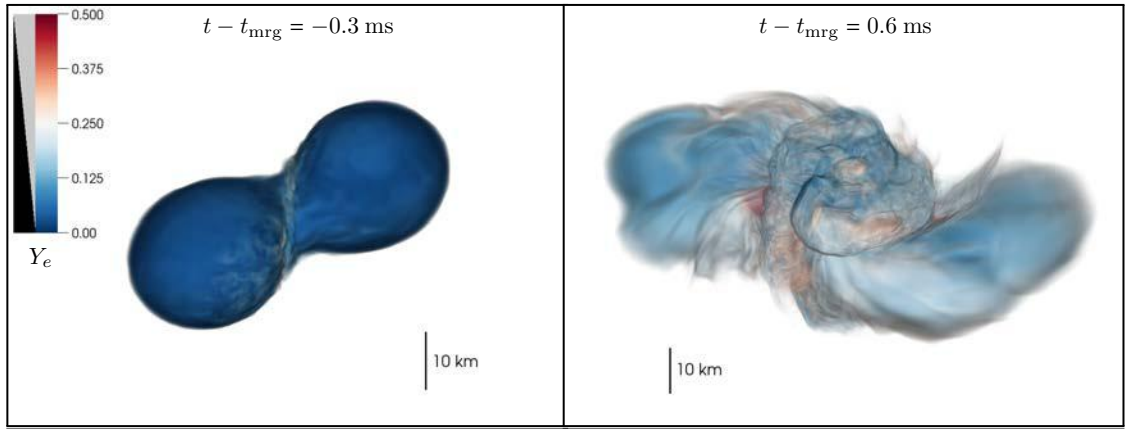


Siegel+2019

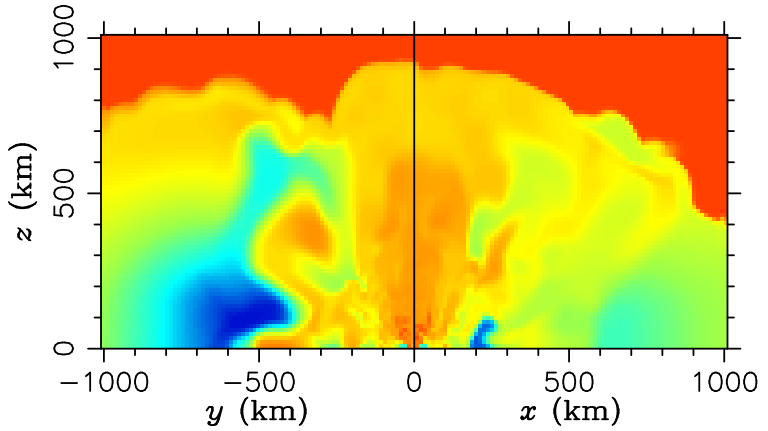
See also, e.g., Beloborodov 2003, Surman, McLaughlin 2005, Nagataki+2006, Fryer+2006, Fujimoto+2008, Maeda, Tominaga 2009, Nomoto+2010, Horiuchi +2012, Malkus+2012, Nakamura+2013, Just+2020, Miller+2020

Astrophysical sites of heavy element synthesis: mergers

NSM prompt ejecta



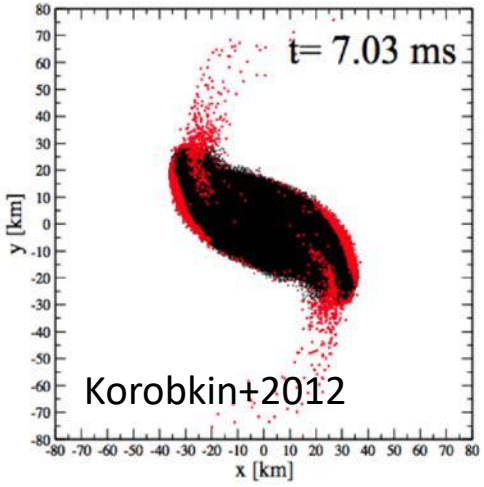
Radice+2019



Wanajo+2014

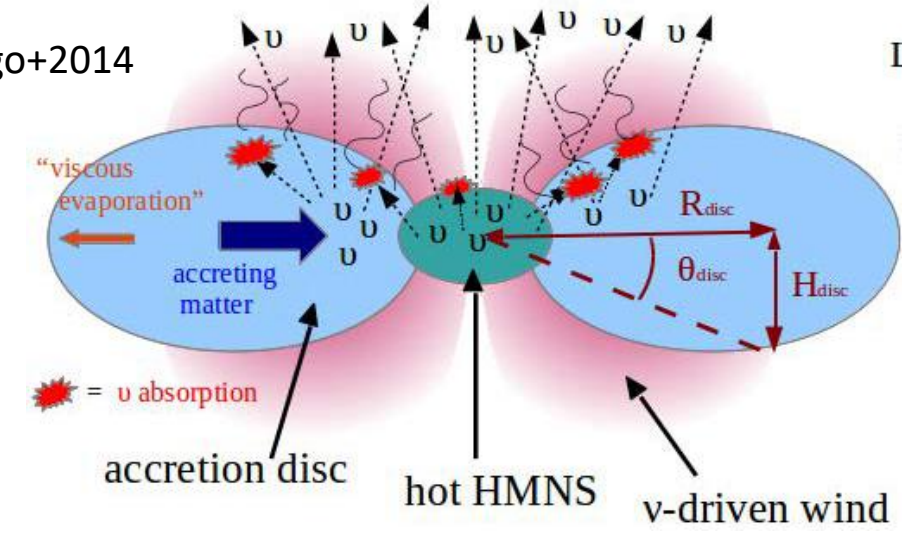
ejecta from the merger accretion disk

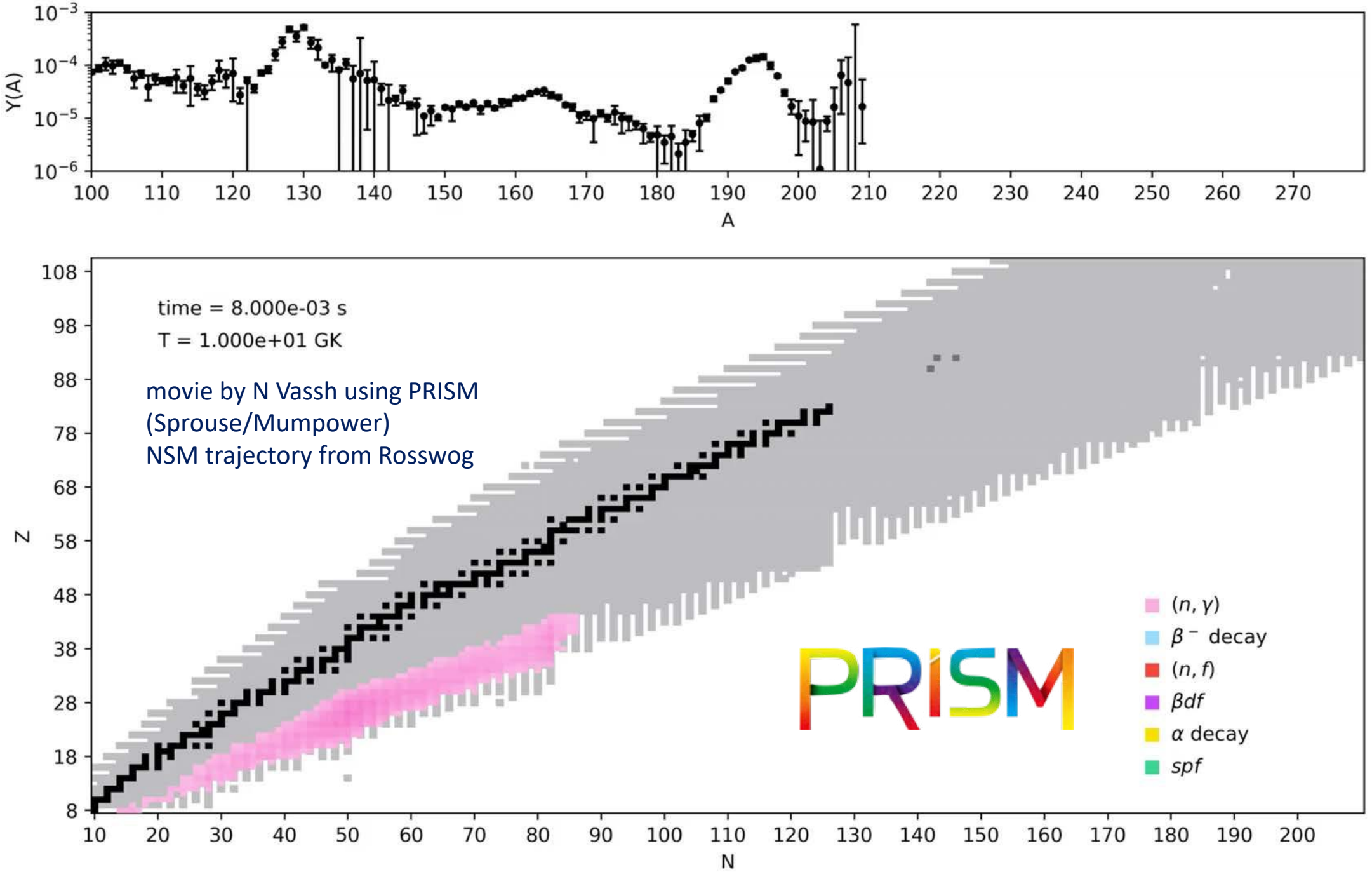
Lattimer, Schramm 1974, 1976, Meyer 1989, Freiburghaus+1999



Korobkin+2012

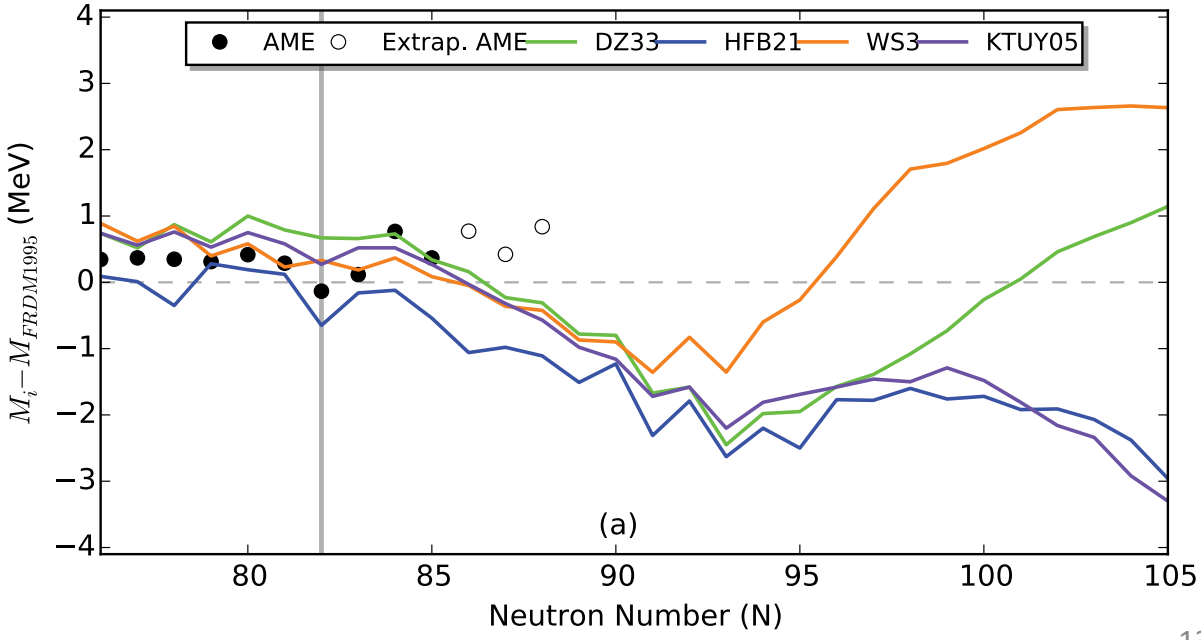
Perego+2014




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
PRISM
(n, γ)
β⁻ decay
(n, f)
βdf
α decay
spf
Z
N

Nuclear data for the *r*-process

masses from AME2016

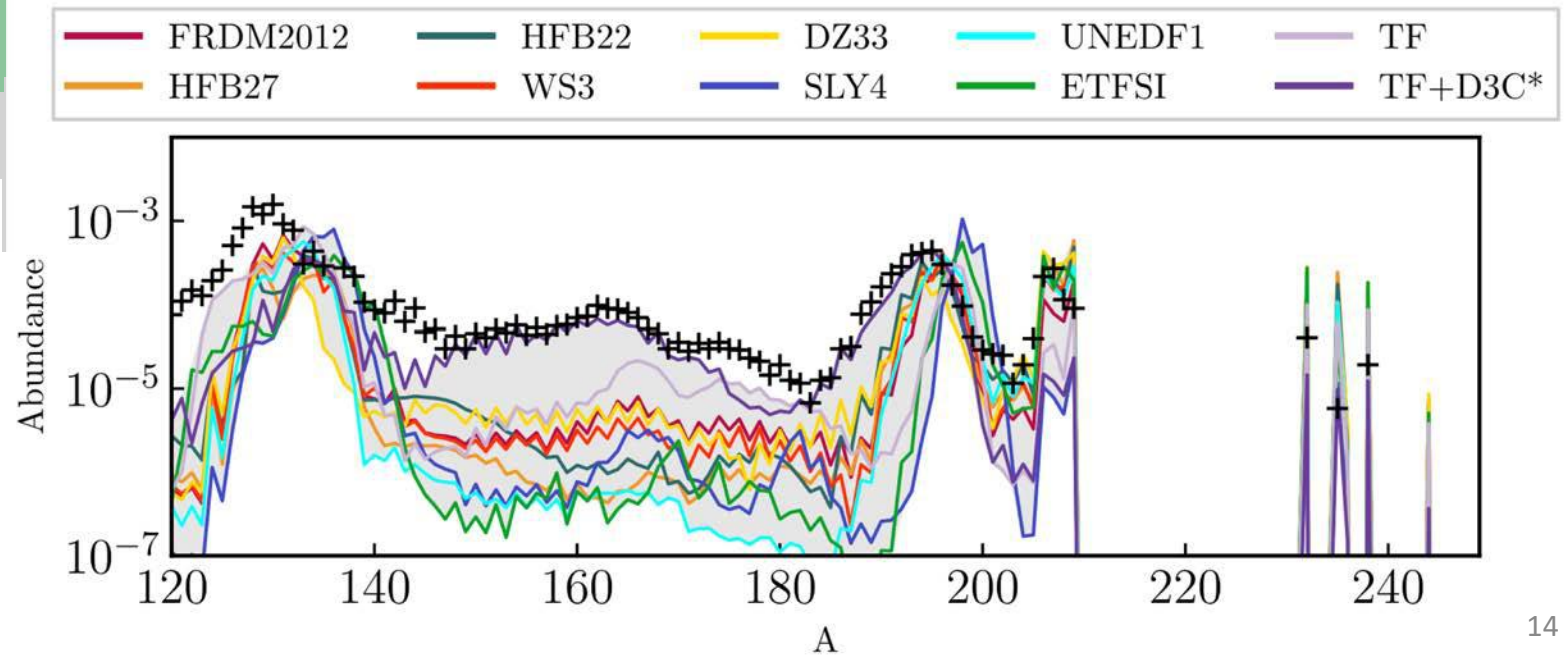


Mumpower, Surman,
McLaughlin, Aprahamian 2016

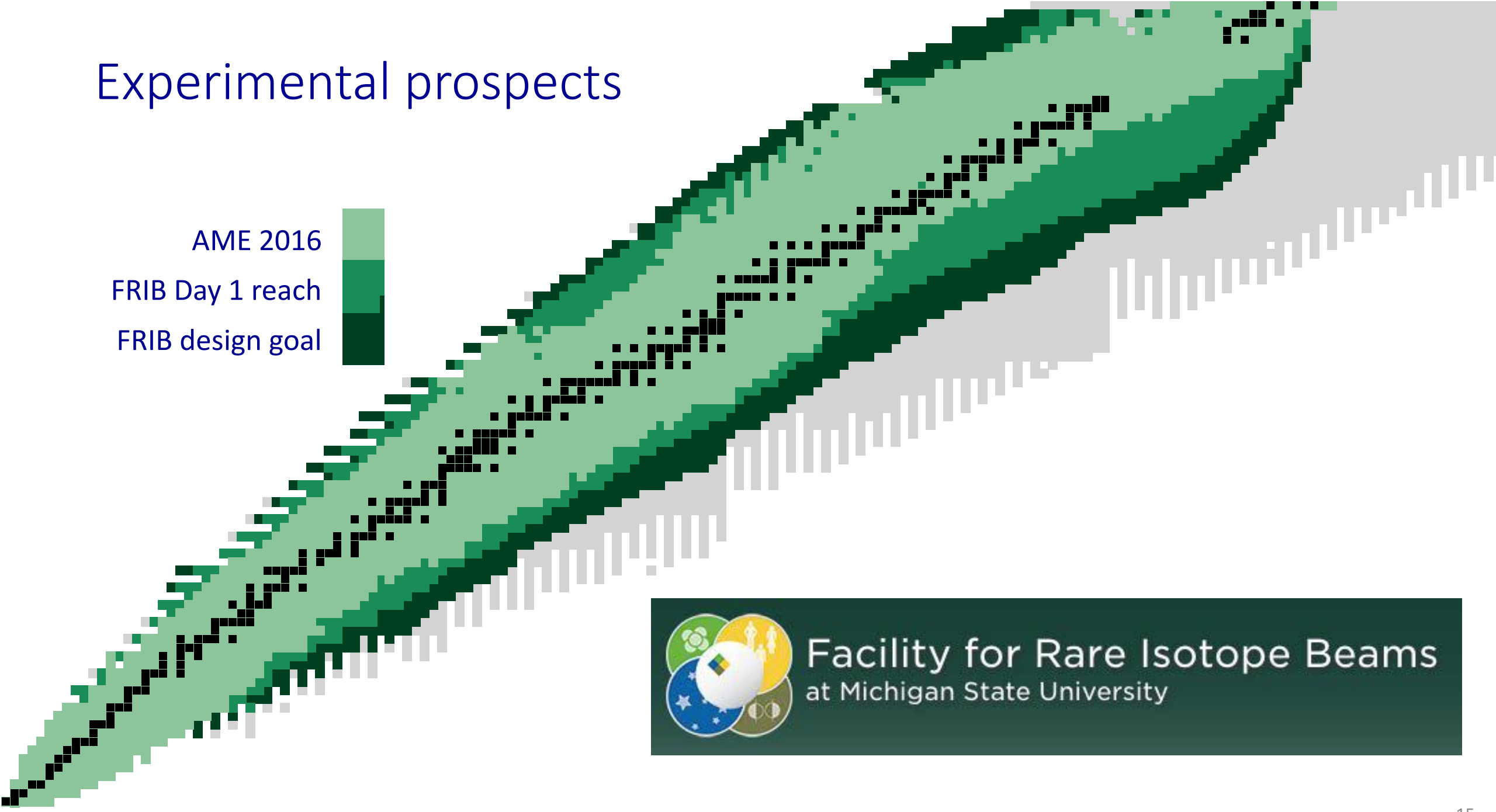
Nuclear data for the *r*-process

masses from AME2016

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



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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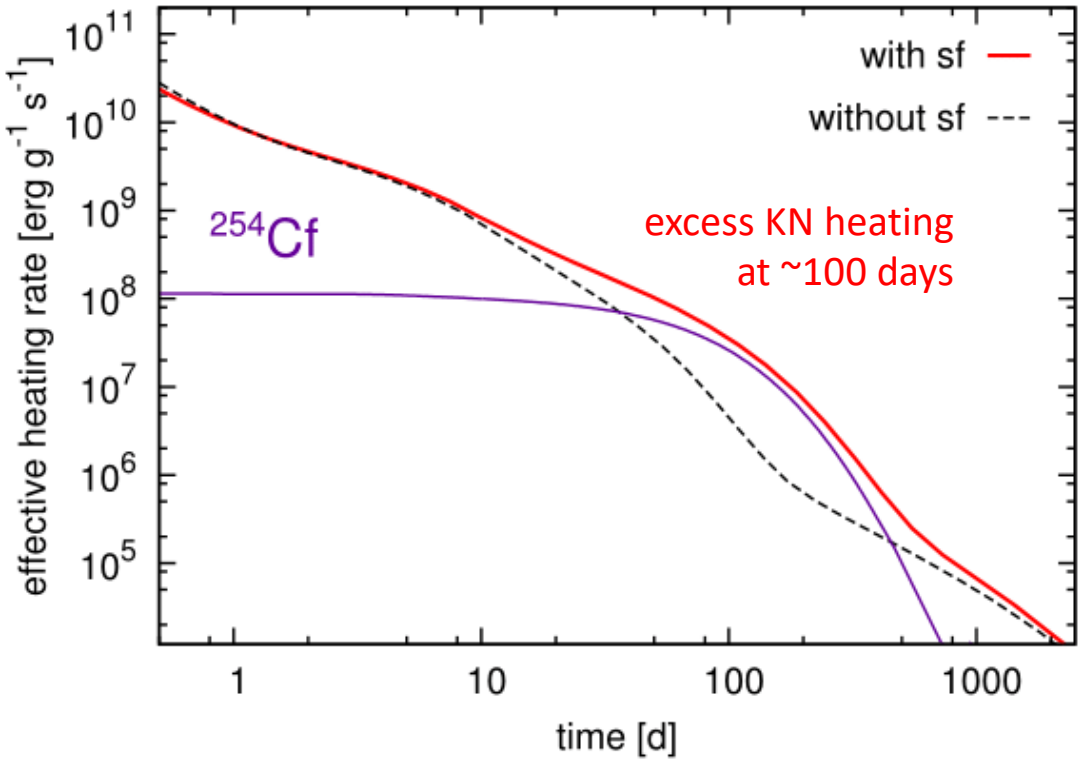
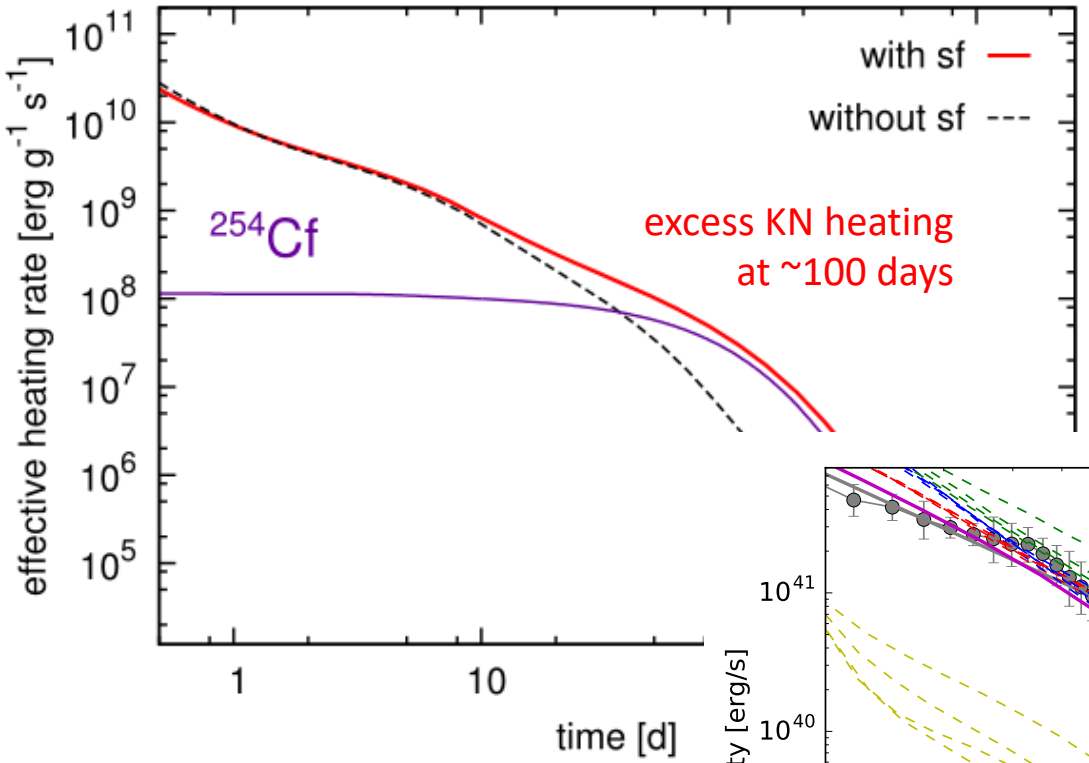
Did the GW170817 merger produce actinides?



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

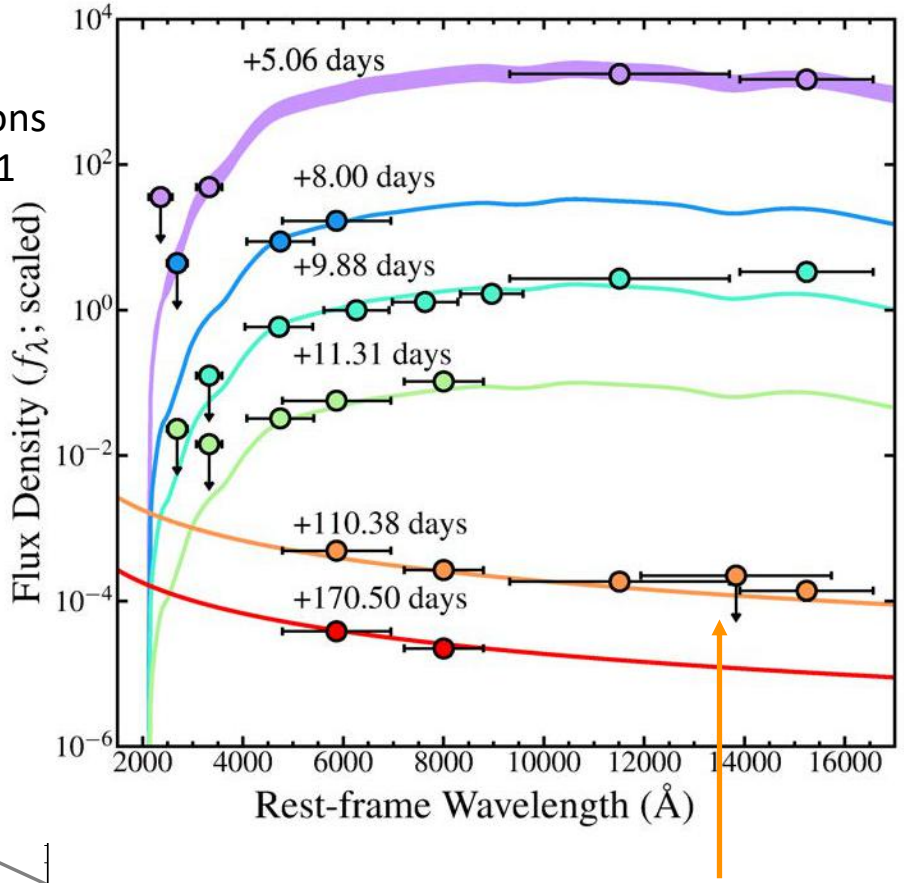
Did the GW170817 merger produce actinides?



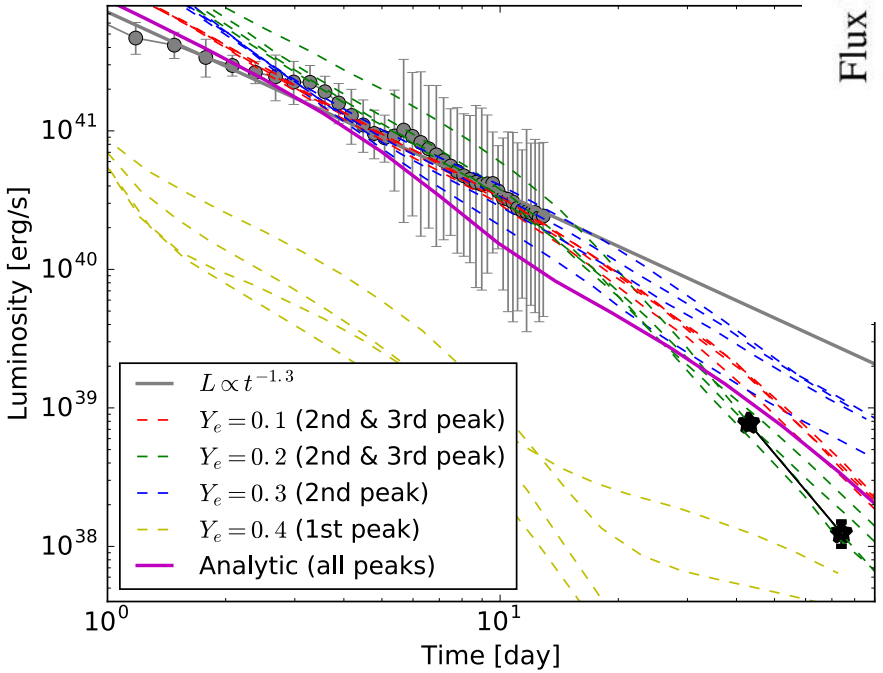
excess KN heating
at ~100 days

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

HST observations
Kilpatrick+2021

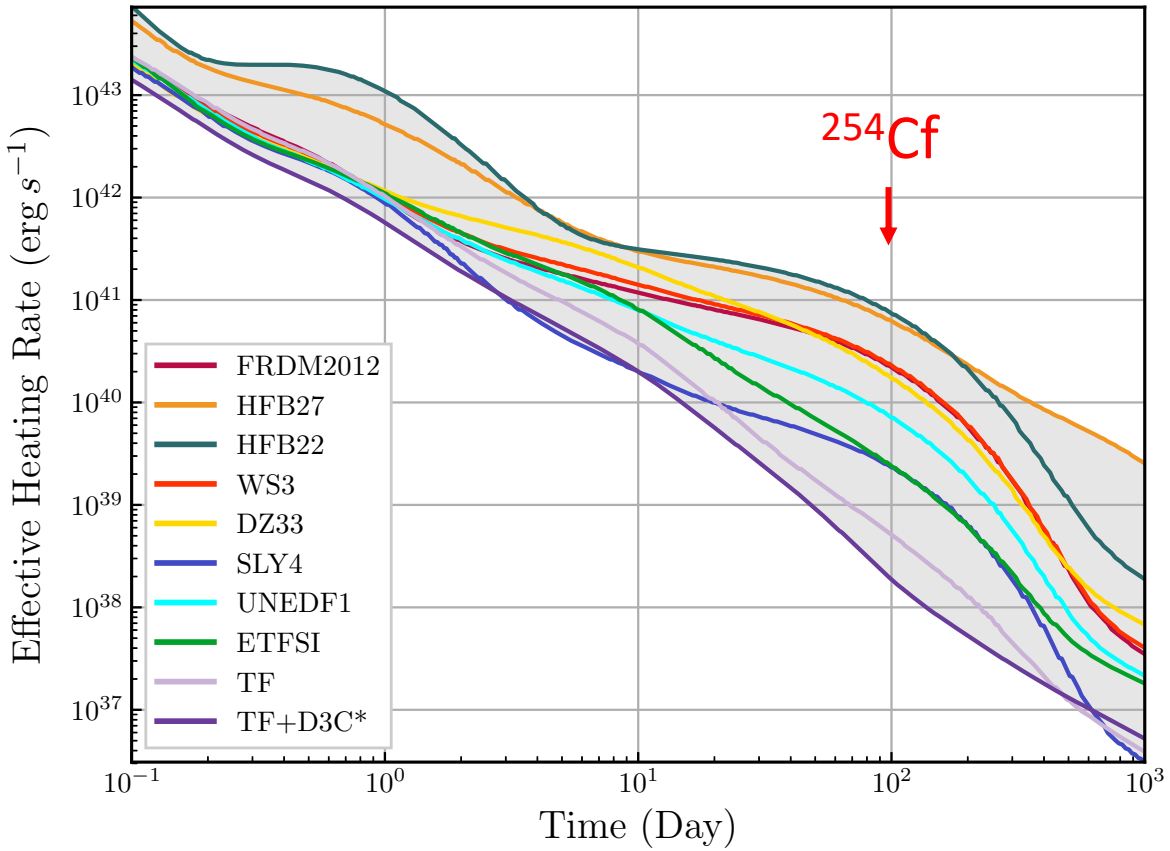


Spitzer mid-infrared
Kasliwal+2019

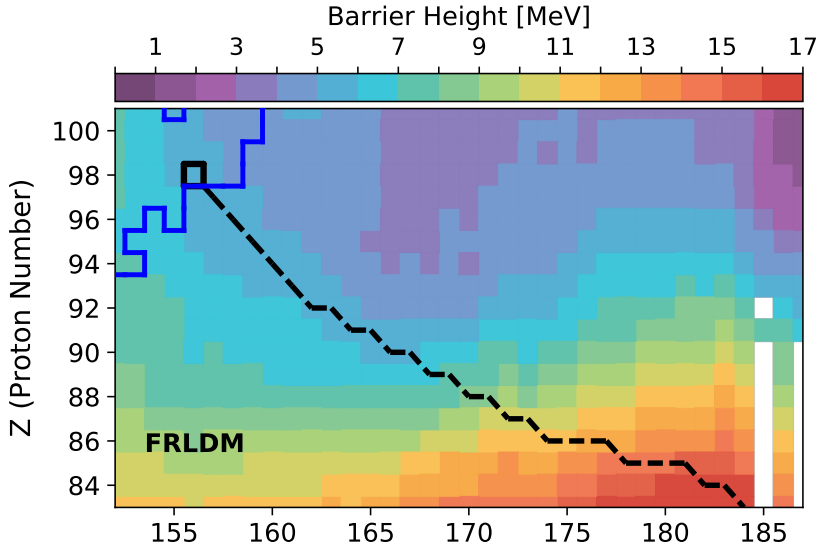


data at ~100 days
matches a GRB
afterglow

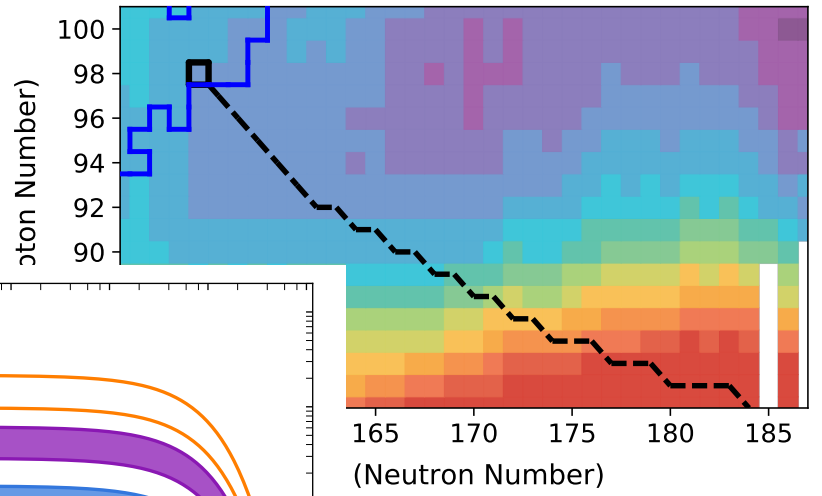
^{254}Cf: dependence on nuclear inputs

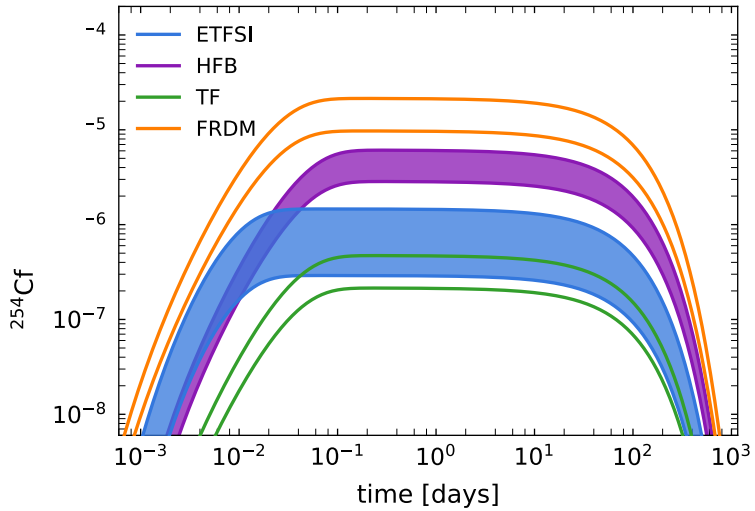


Zhu, Lund, Barnes, Sprouse, Vassh, McLaughlin, Mumpower, Surman 2021



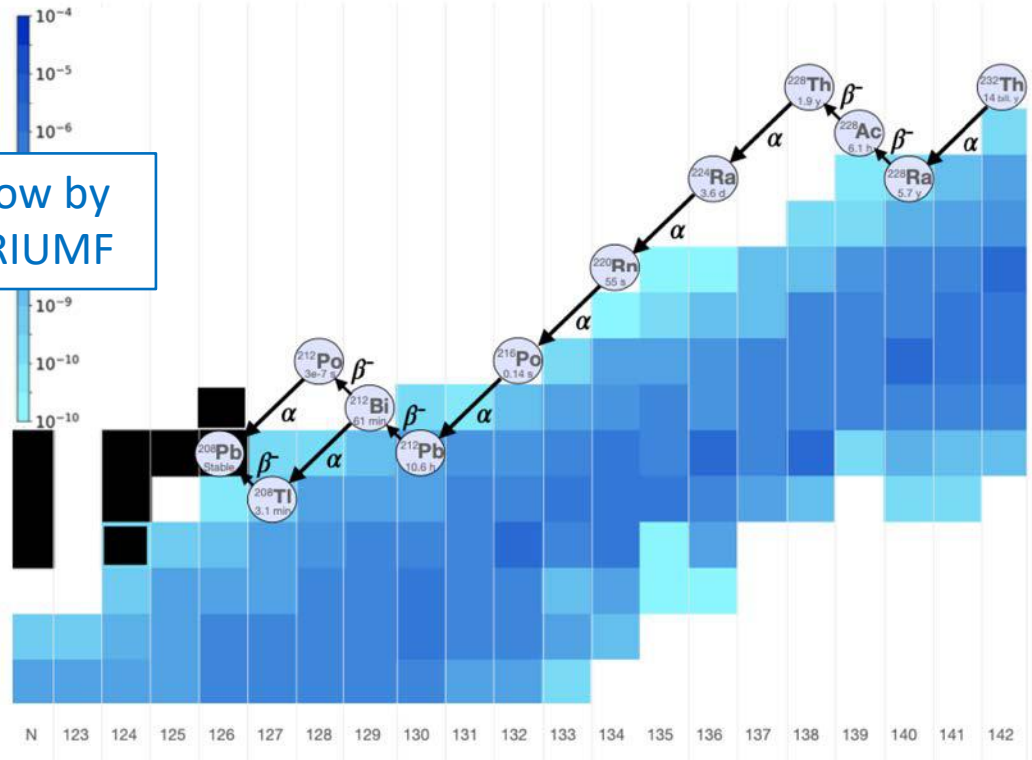
Vassh, Vogt, Surman, Randrup, Sprouse, Mumpower, Jaffke, Shaw, Holmbeck, Zhu, McLaughlin, 2018

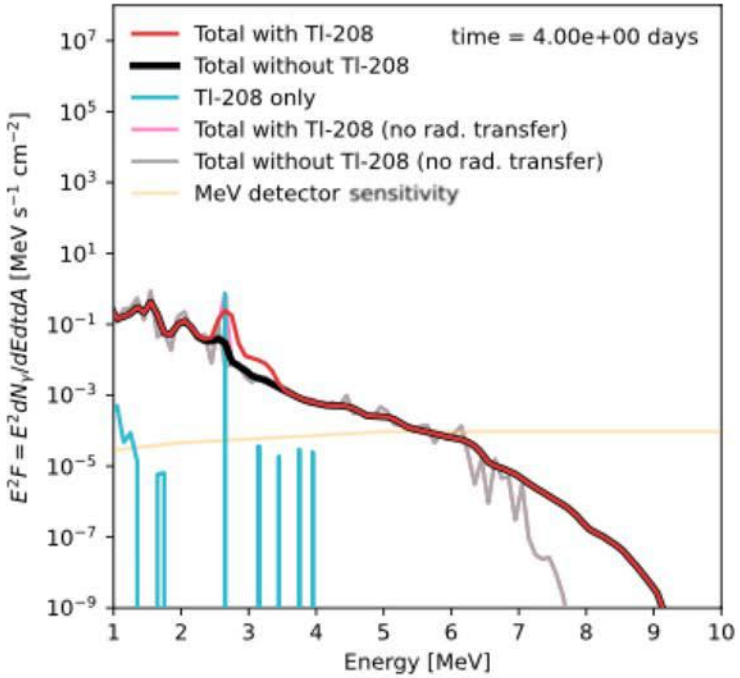


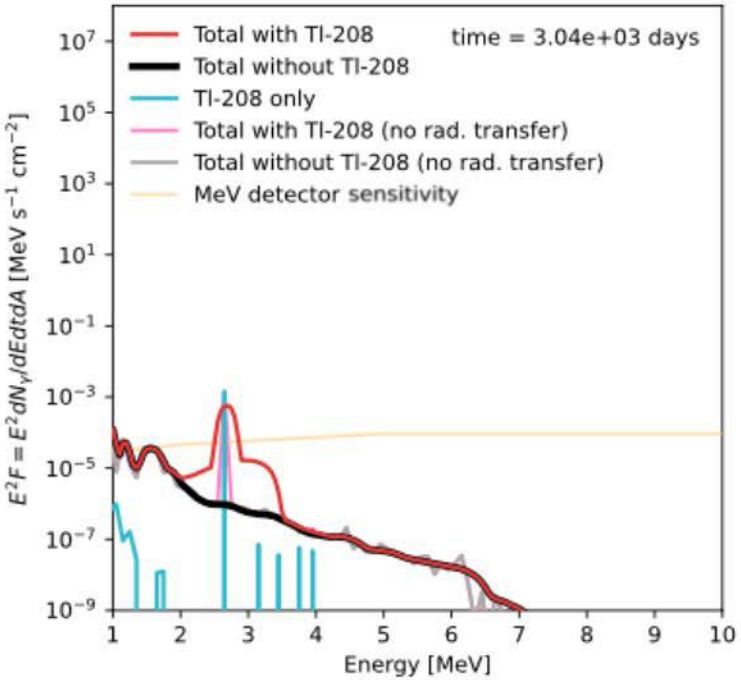


^{208}Tl: a potential actinide signature in gamma rays

See talk tomorrow by Nicole Vassh, TRIUMF



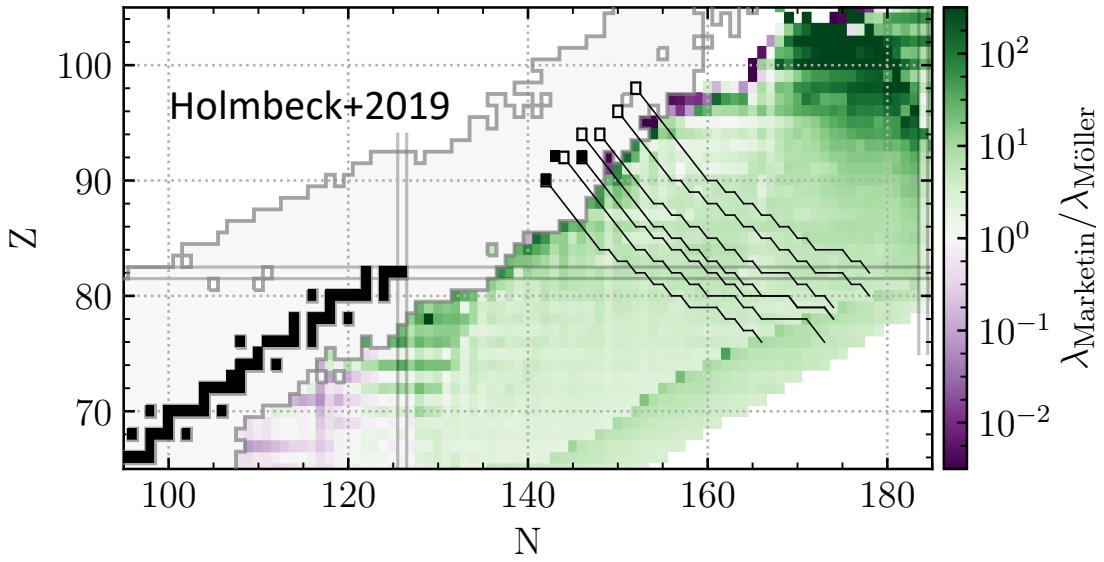




Vassh, Wang, Lariviere, Sprouse, Mumpower, Surman, Liu, McLaughlin, Denissenkov, Herwig, arXiv:2311.10895
accepted in *PRL* 2023

Beta decay and actinide production

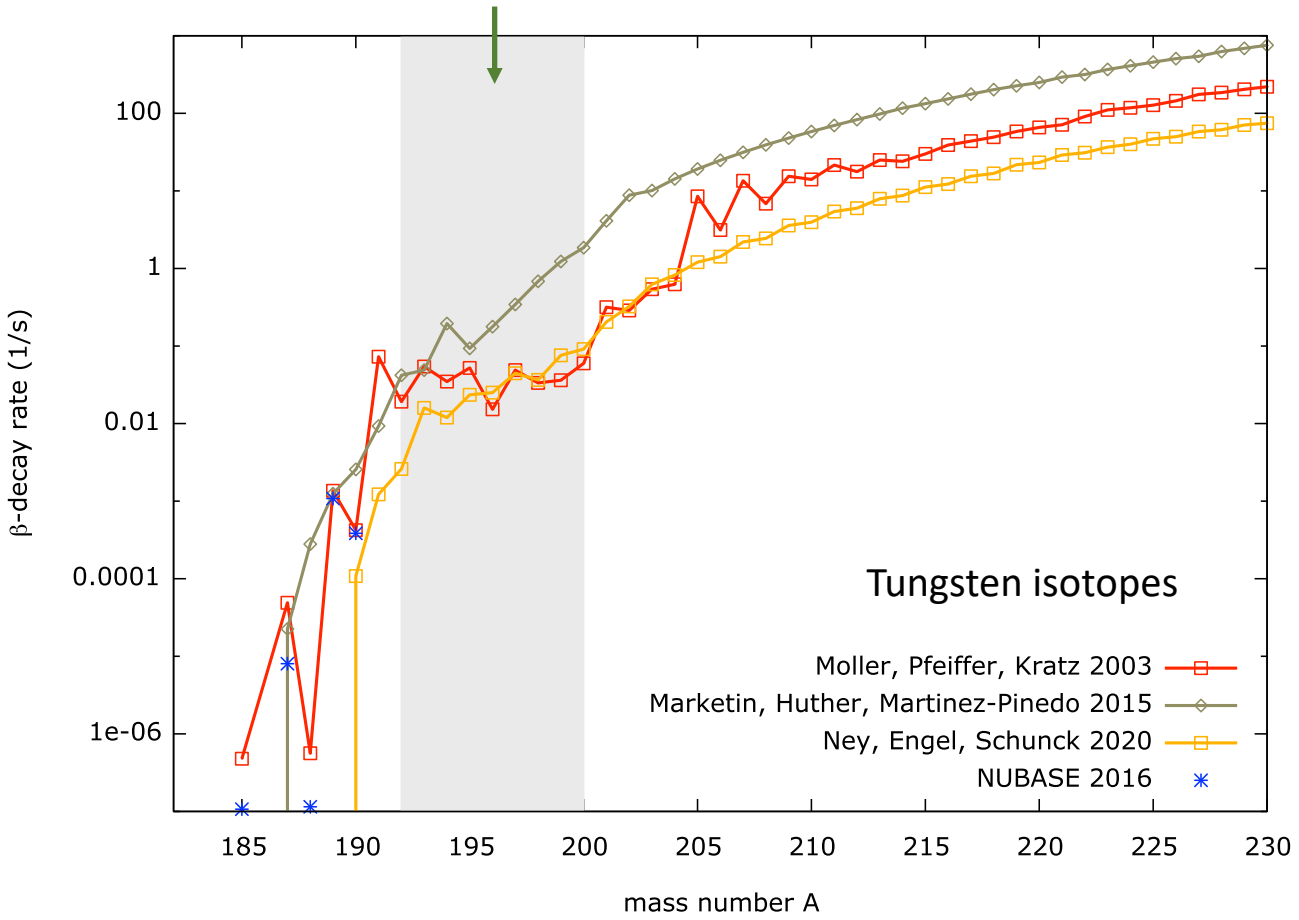
See my talk tomorrow in FDS workshop session



Facility for Rare Isotope Beams
at Michigan State University

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

anticipated Day 1 FRIB reach



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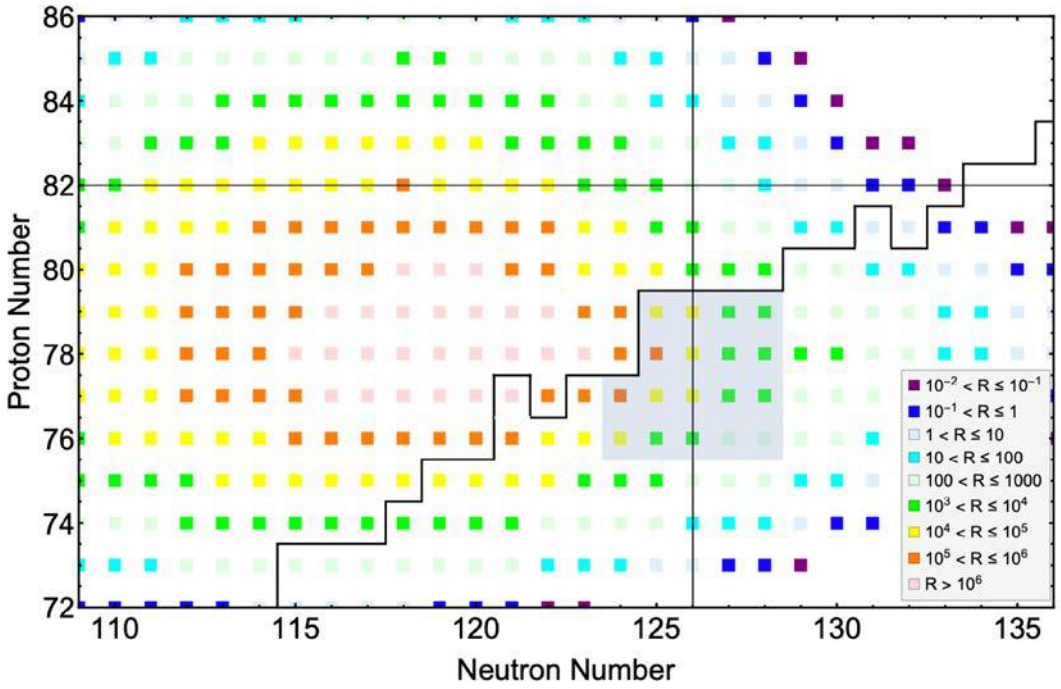
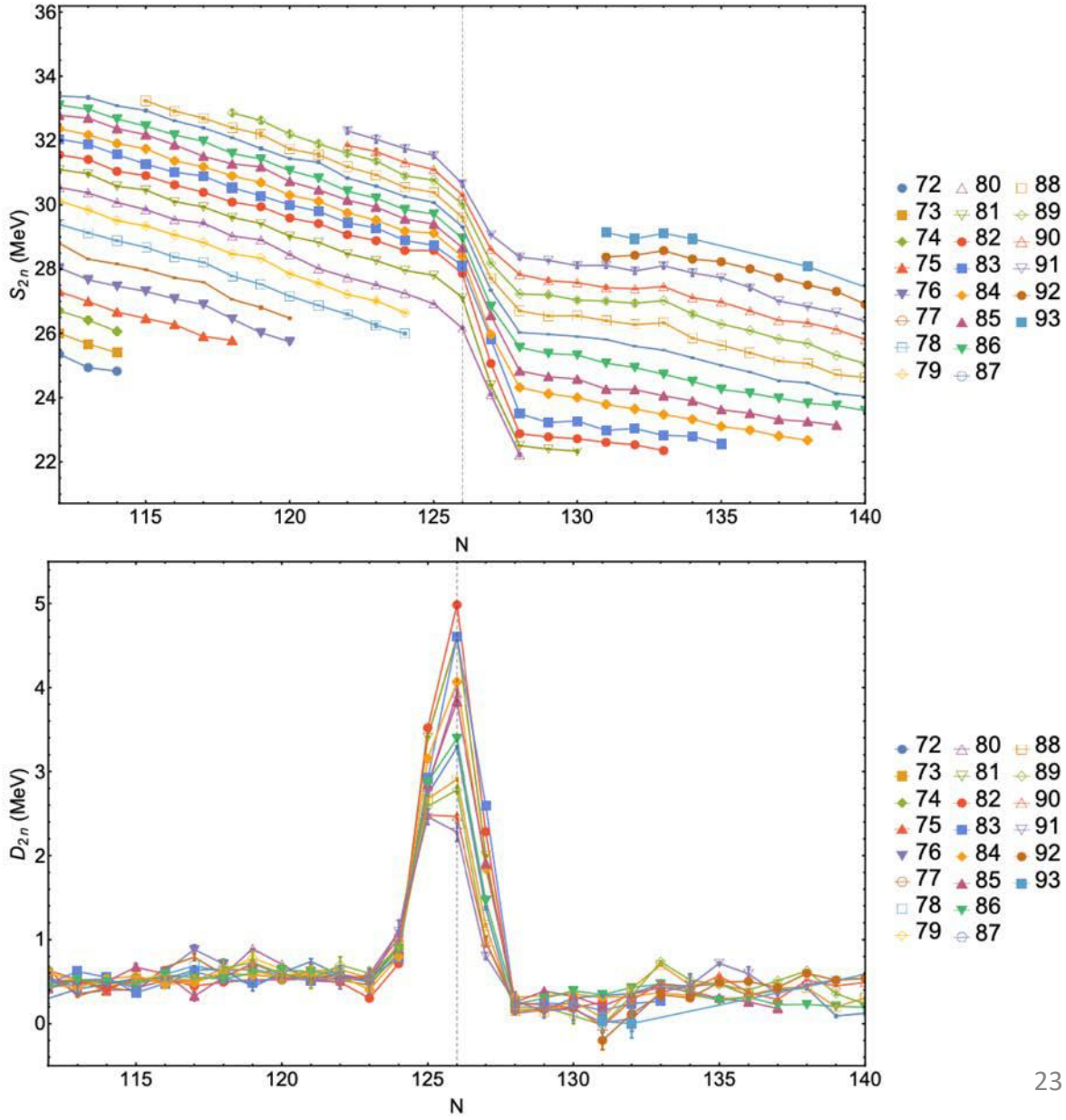
Nuclear masses and actinide production





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

Interpreting observables of *r*-process nucleosynthesis

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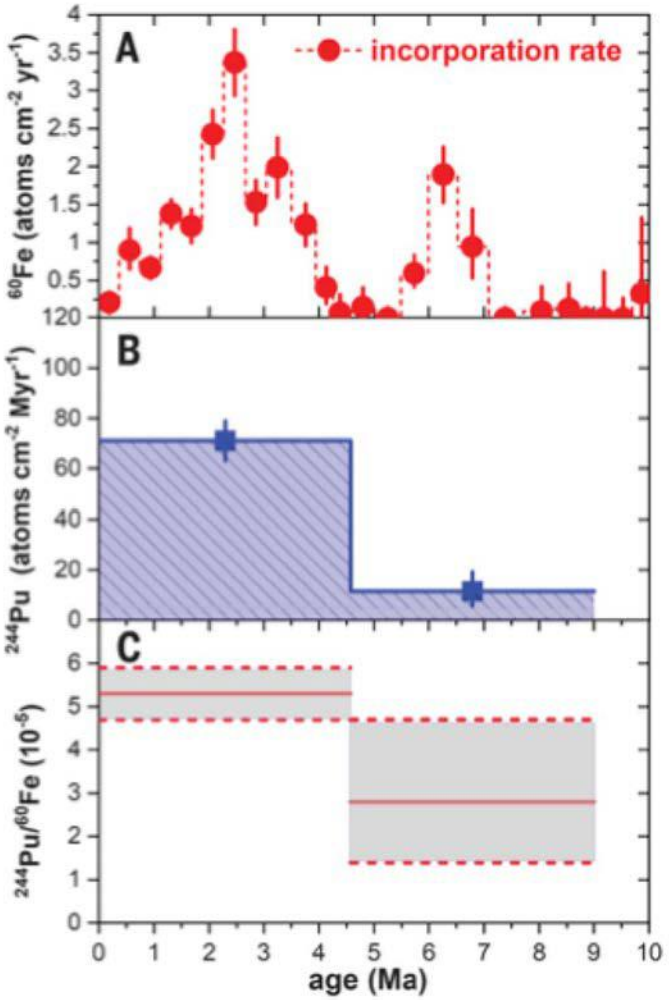
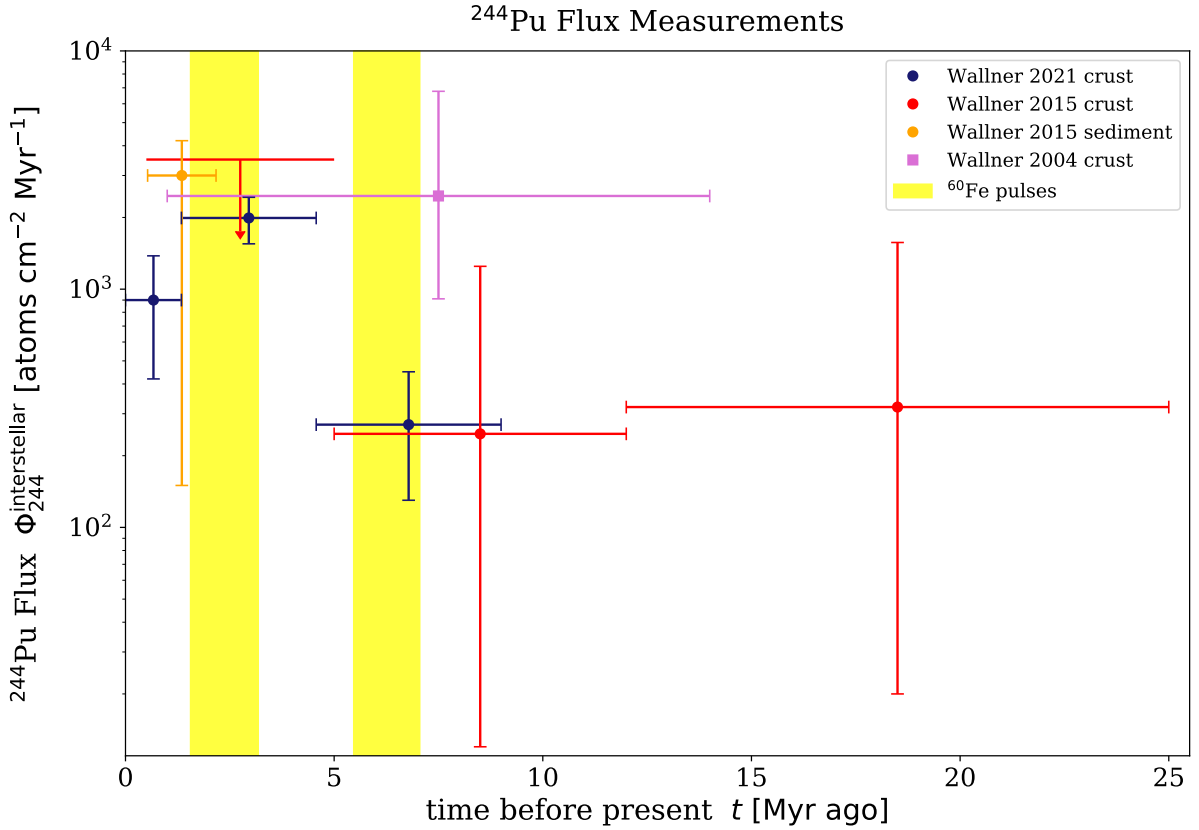
Actinide observables: ^{60}Fe and ^{244}Pu in Fe-Mn crusts

Wallner+2021





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

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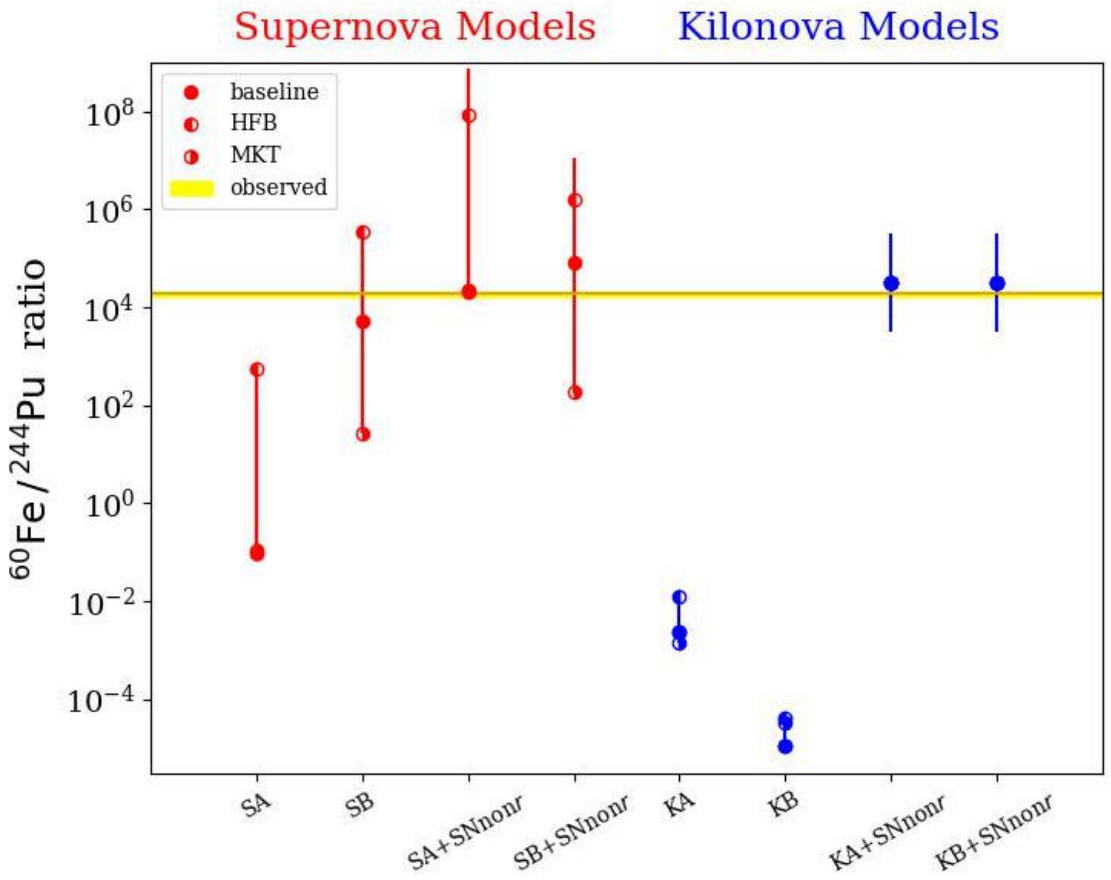
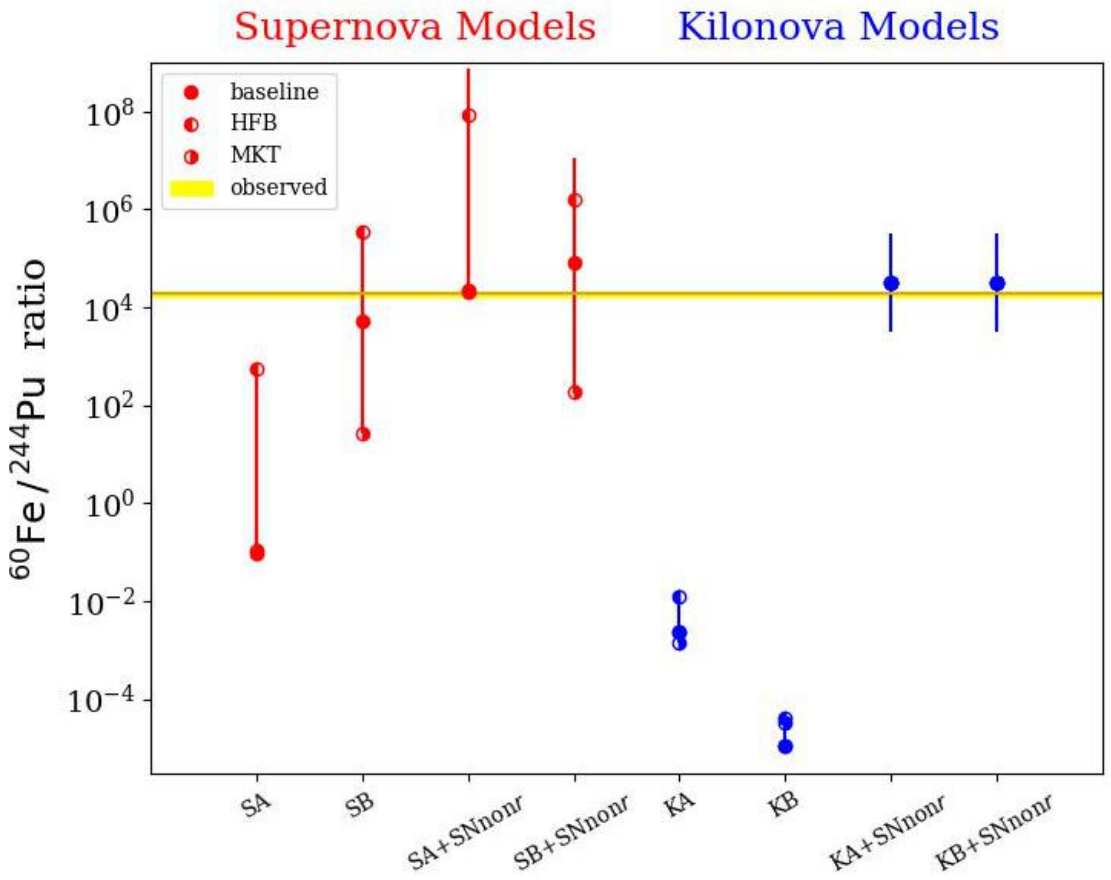
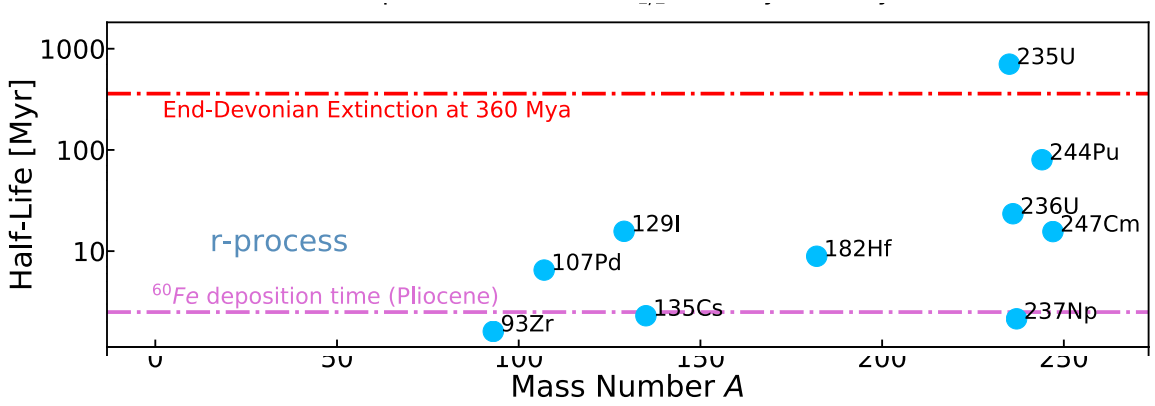
Actinide observables: ^{60}Fe and ^{244}Pu in Fe-Mn crusts



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

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





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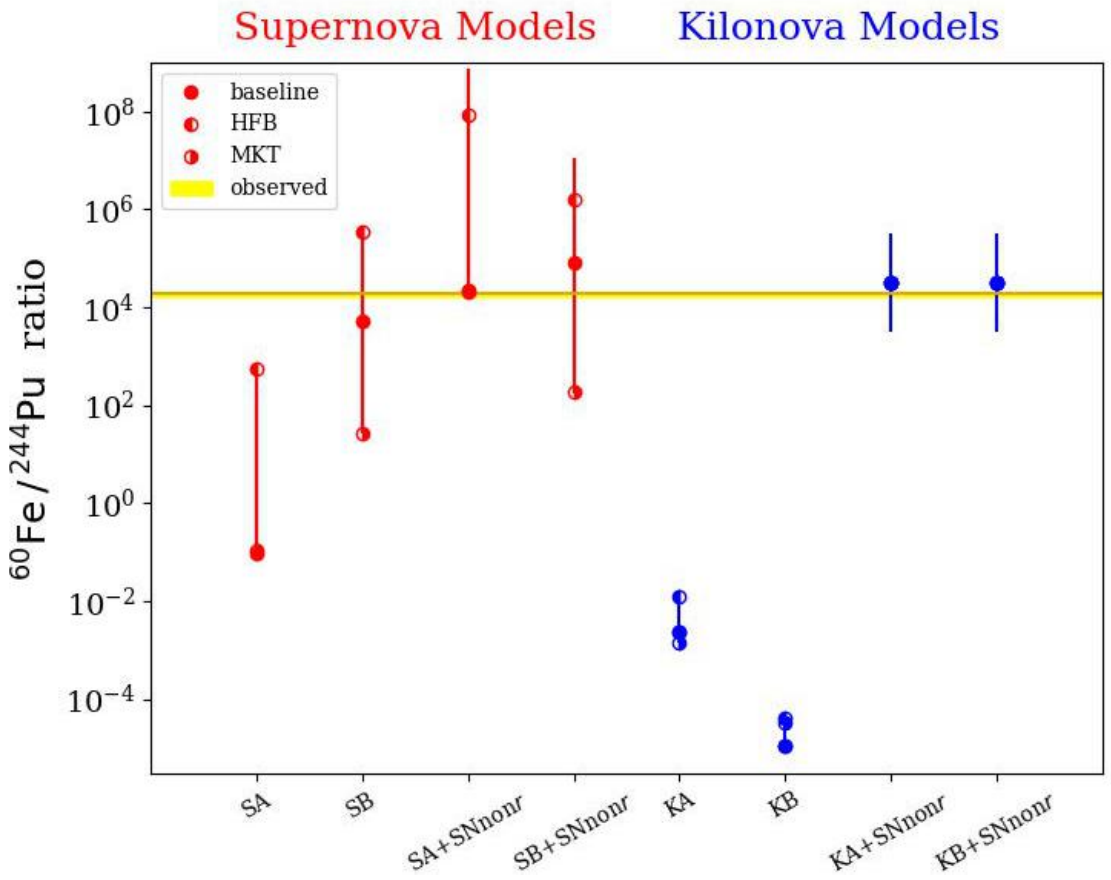
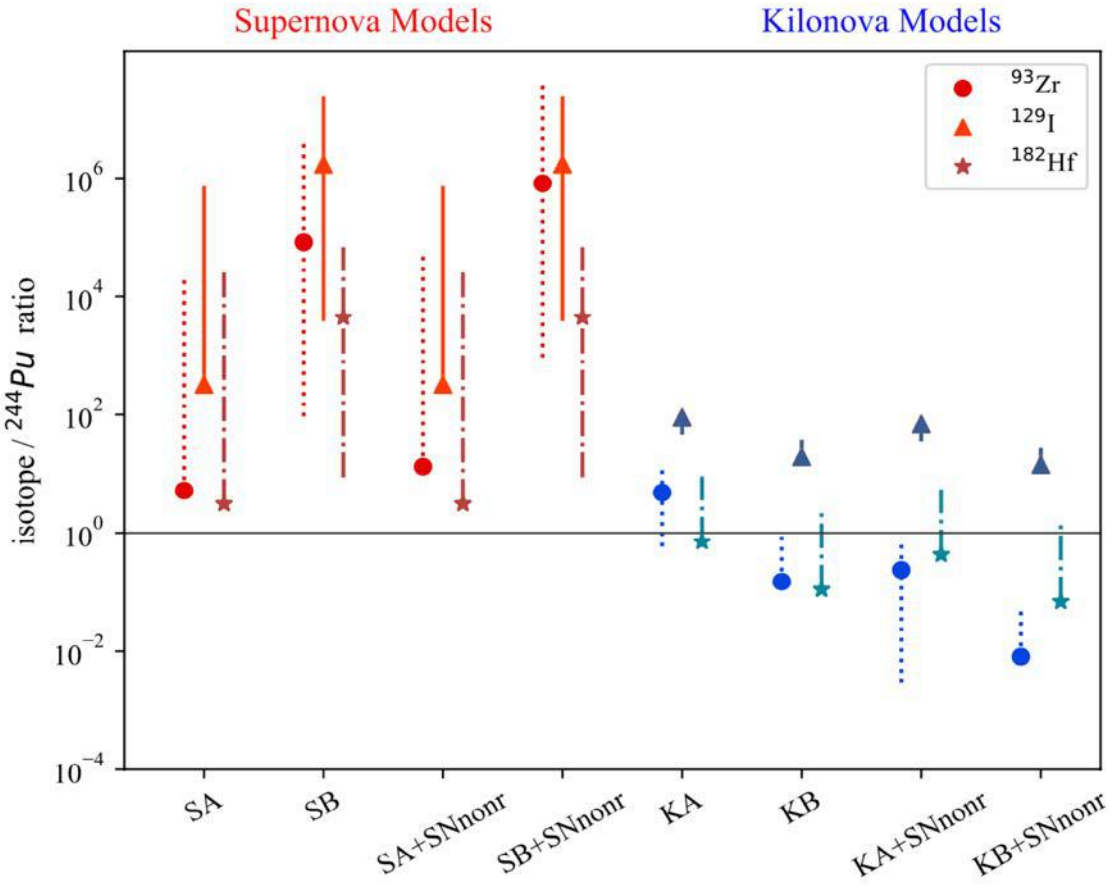
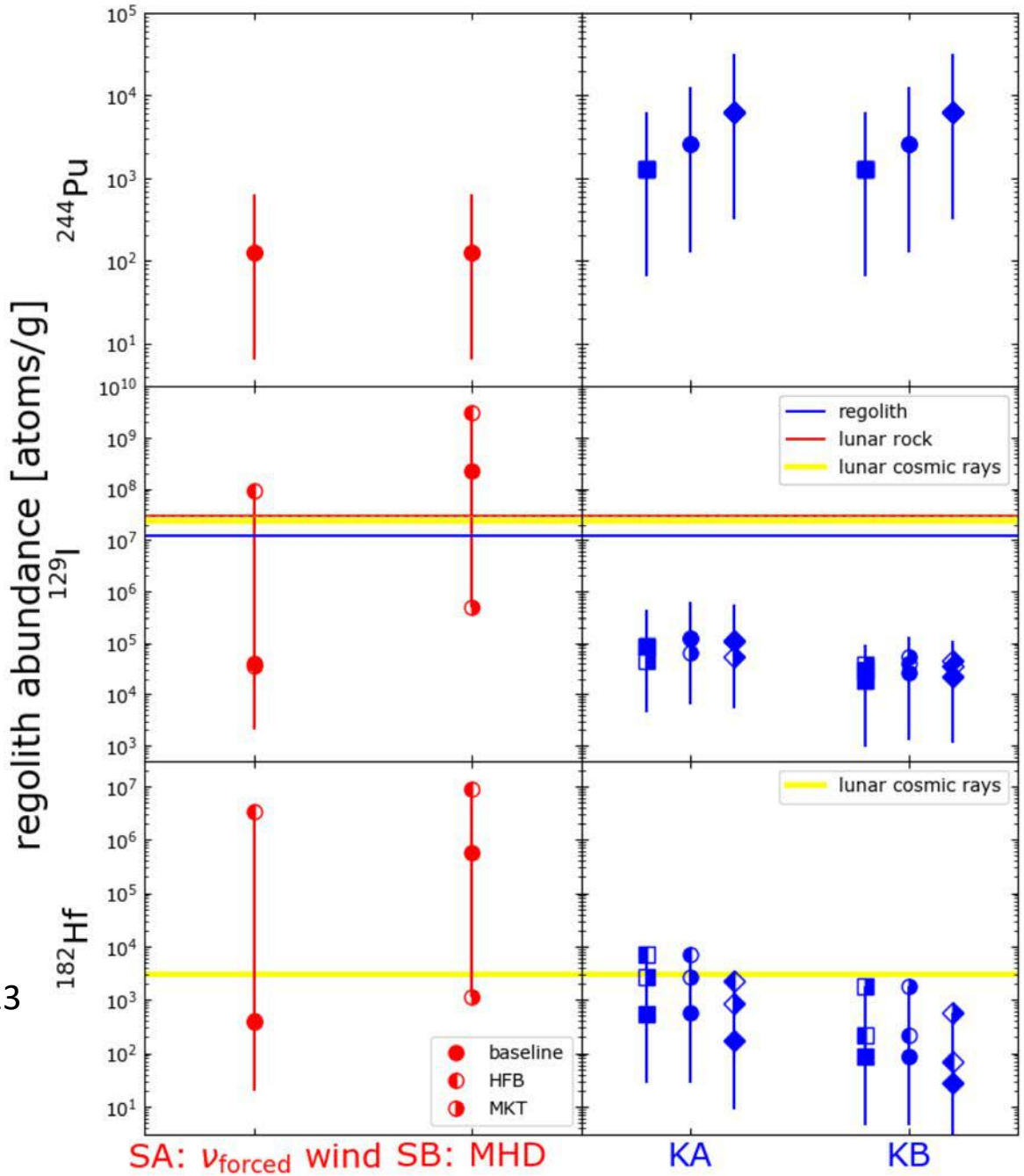




Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;
Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2023

Actinide observables: lunar regolith

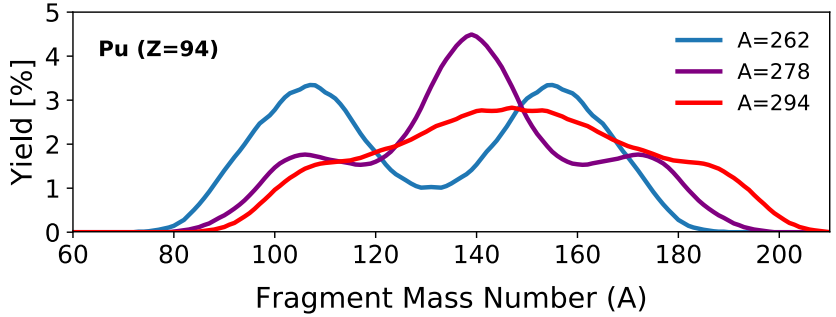


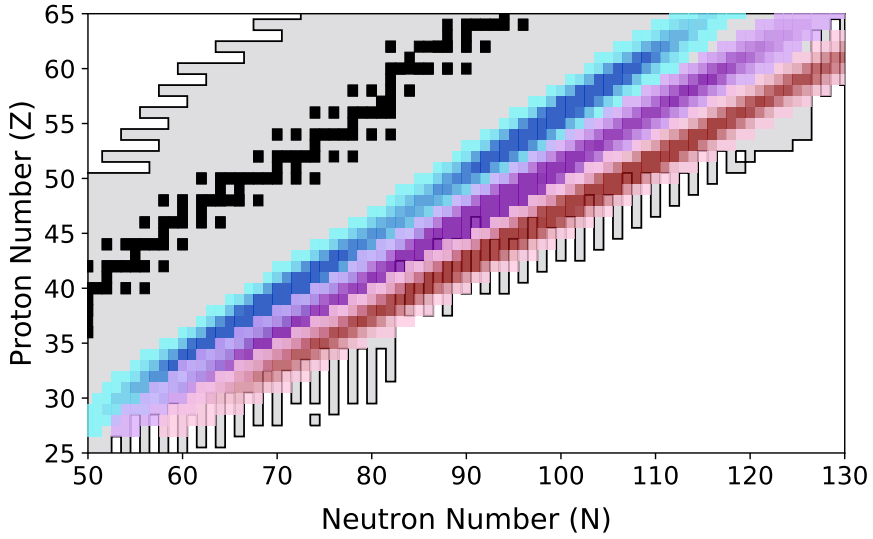
Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2023

Interpreting observables of *r*-process nucleosynthesis

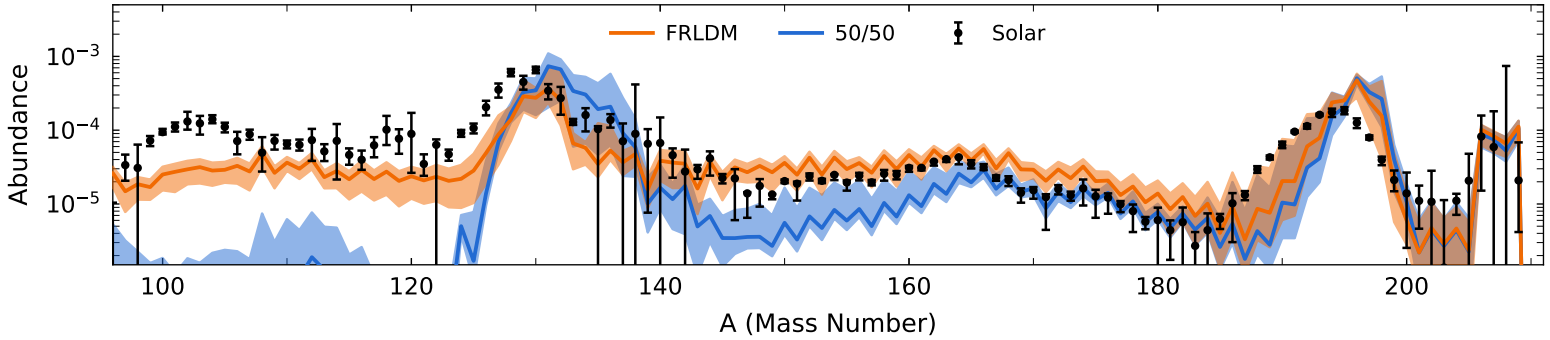
- What observables are currently limited by nuclear uncertainties that could be addressed in the FRIB era?
- Are there distinguishing observables that rise above nuclear uncertainties?
- What can we learn about nuclear physics far from stability from *r*-process observables?

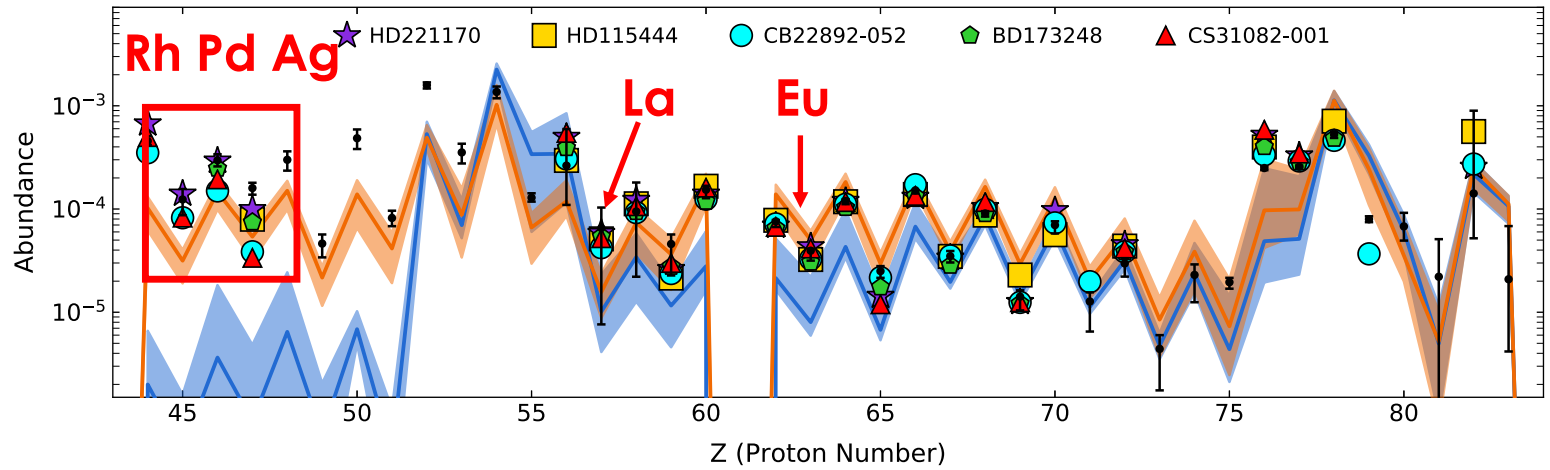
Fission yield signatures



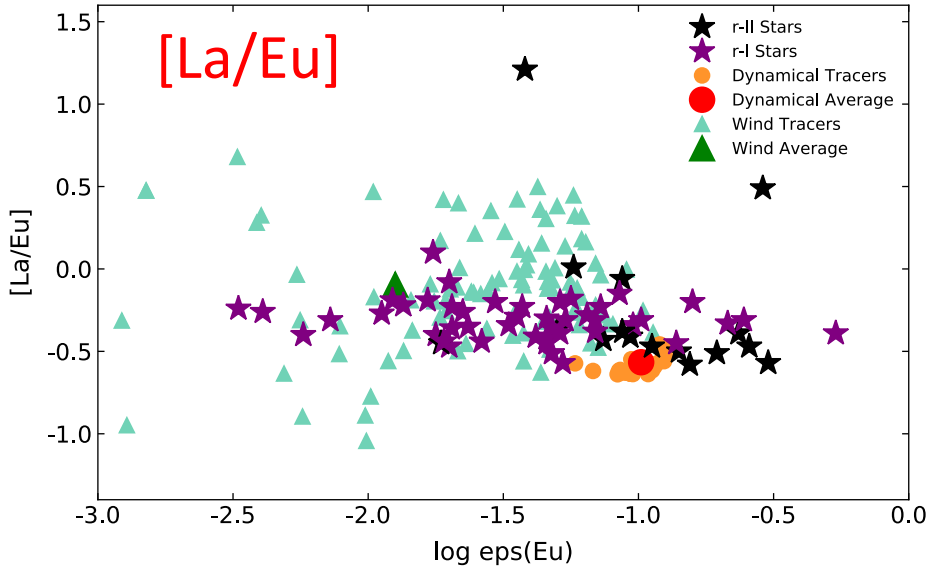


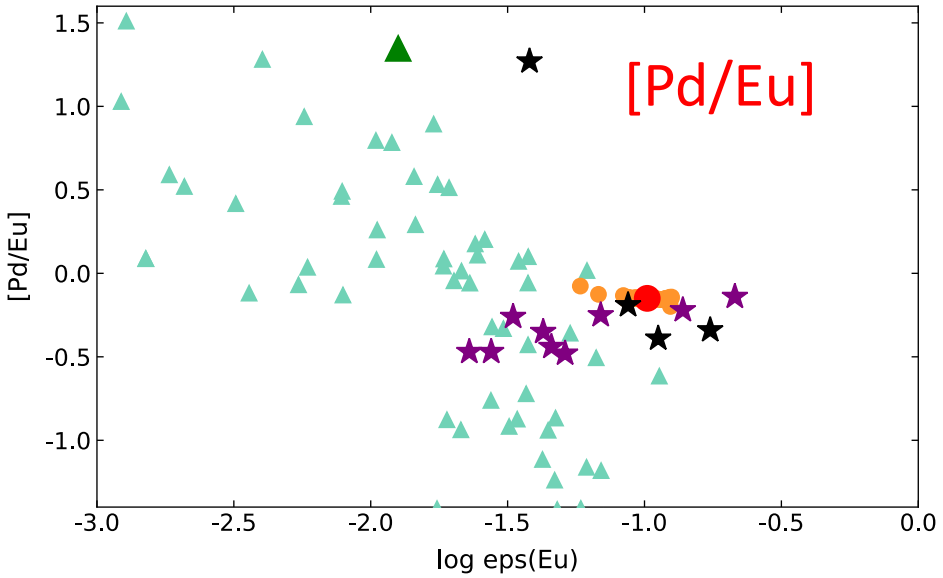
Vassh, Mumpower, McLaughlin, Sprouse, Surman 2020



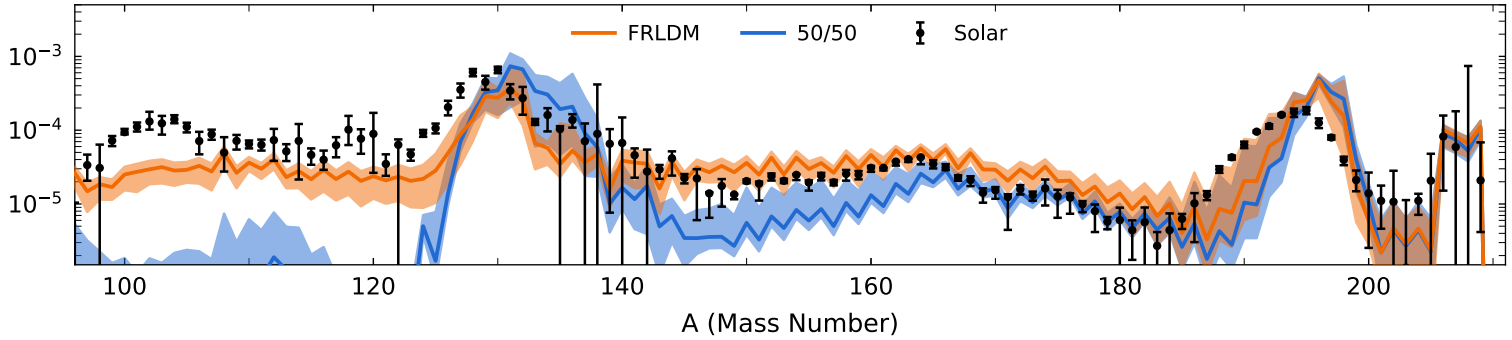


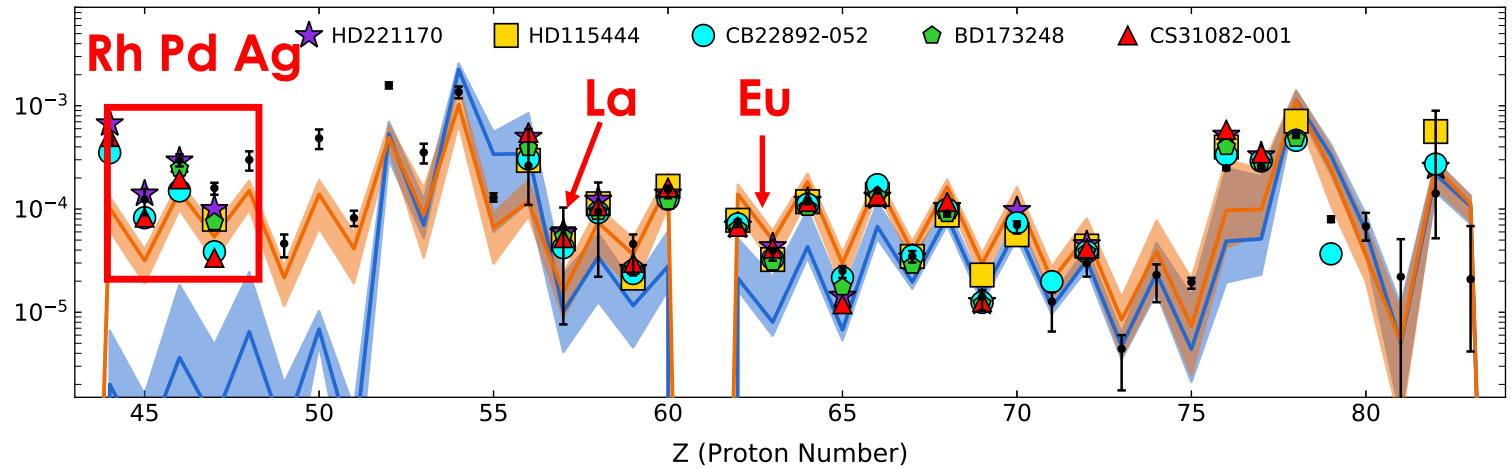
Fission yield signatures





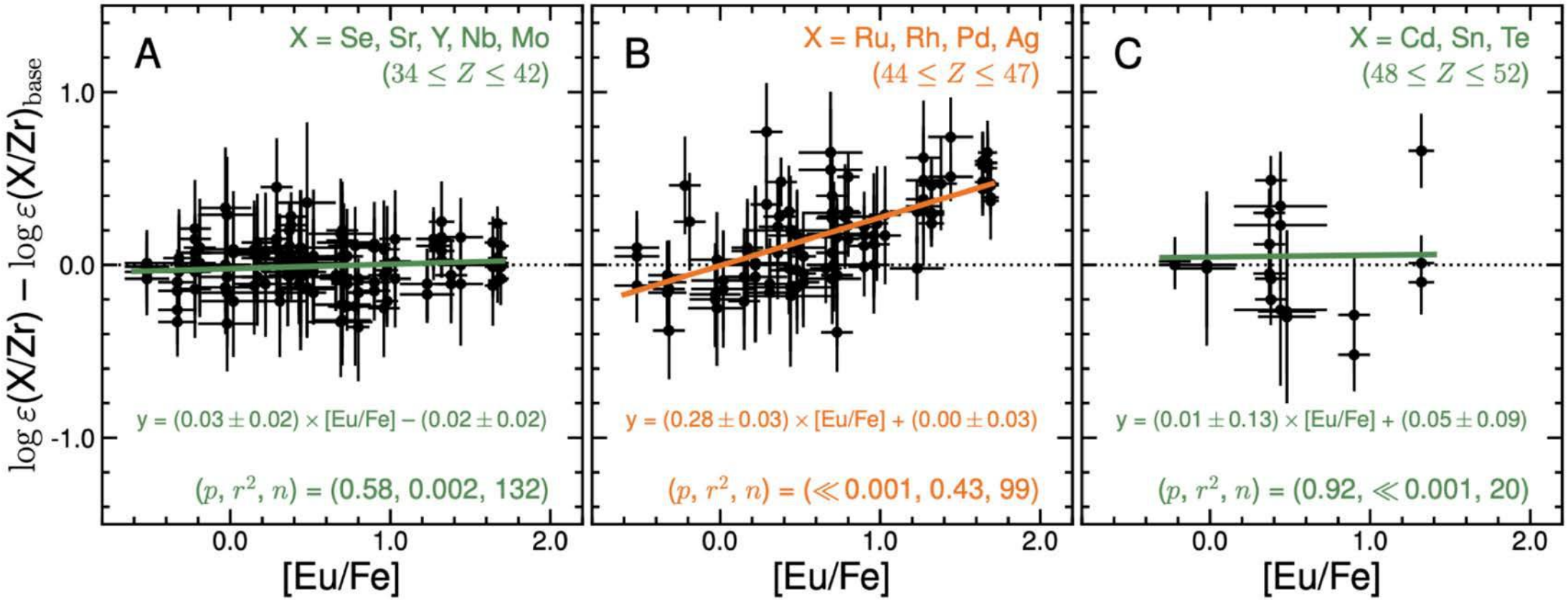
Vassh, Mumpower, McLaughlin, Sprouse, Surman 2020





See talk tomorrow by Ian Roederer, NCSU

Fission yield signatures



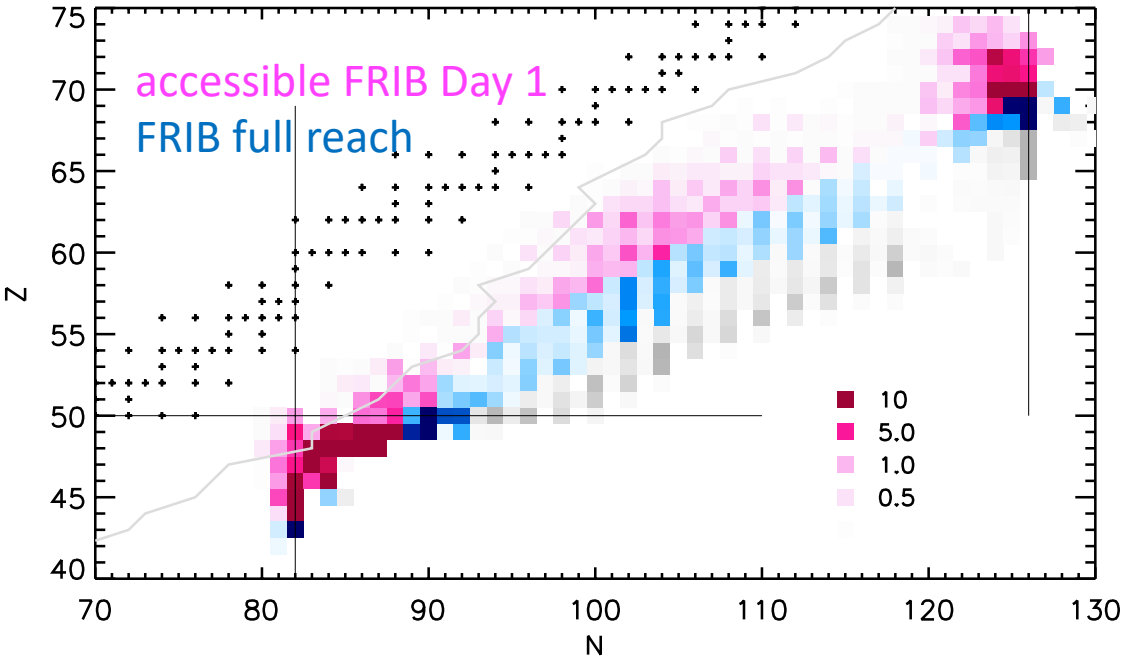
Roederer, Vassh, Holmbeck, Mumpower, Surman, Cowan, Beers, Ezzeddine, Frebel, Hansen, Placco, Sakari, accepted in *Science* 2023

summary

The origins of the heaviest elements have 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 role of the *νp* process in galactic chemical evolution is even less clear.

The neutrino and nuclear physics of candidate events remains poorly understood. FRIB has the potential to reduce key nuclear uncertainties, facilitating accurate interpretations of nucleosynthetic observables.



Mumpower, Surman, McLaughlin, Aprahamian, JPPNP 2016