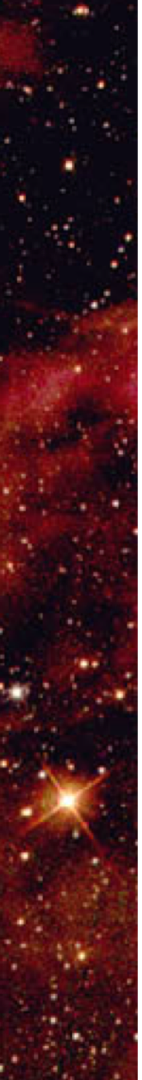
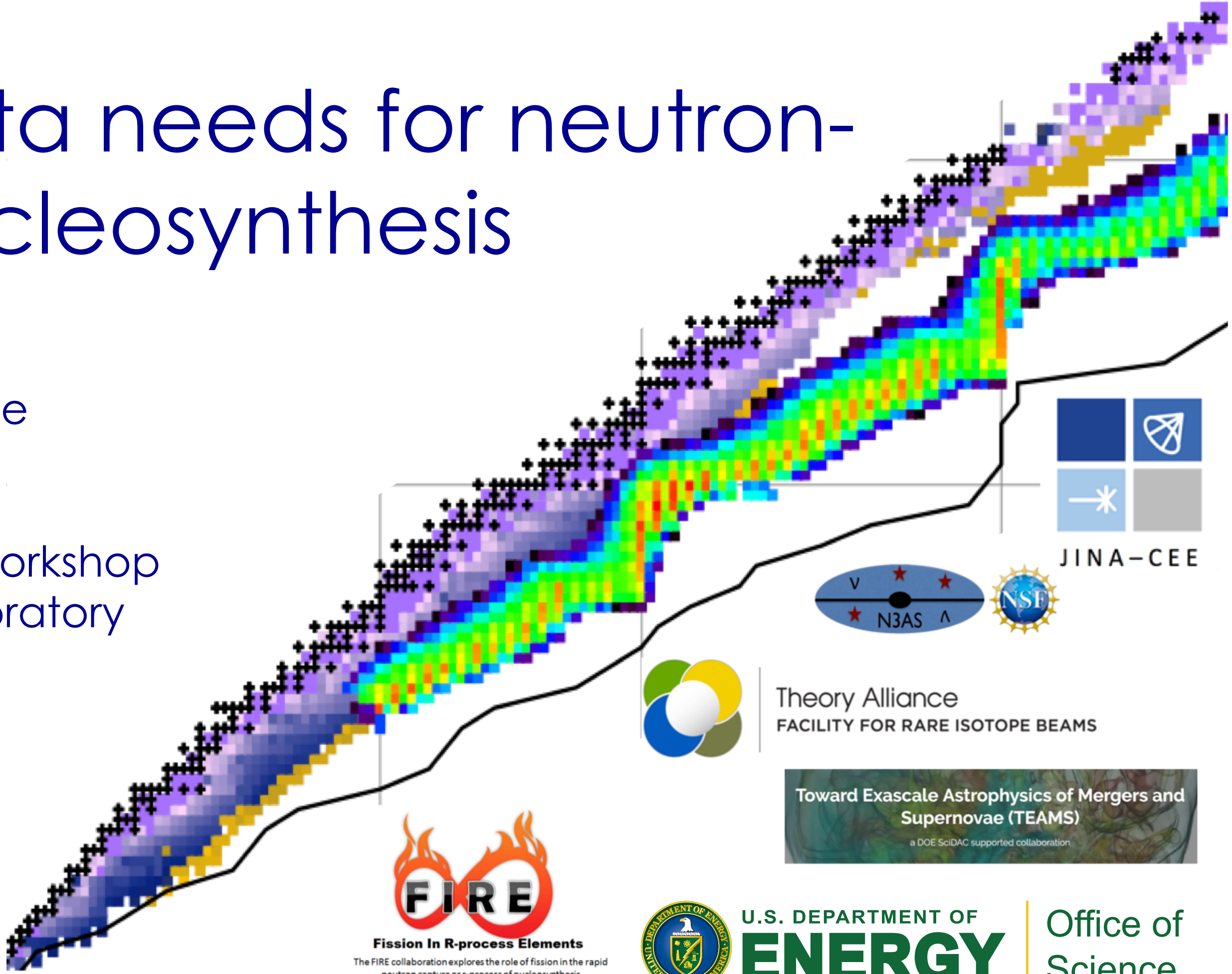


Nuclear data needs for neutron-capture nucleosynthesis

Rebecca Surman
University of Notre Dame

ATLAS/CARIBU
Nuclear Astrophysics Workshop
Argonne National Laboratory

12-13 July 2019



UNIVERSITY OF NOTRE DAME
College of Science

JINA-CEE

N3AS

NSF

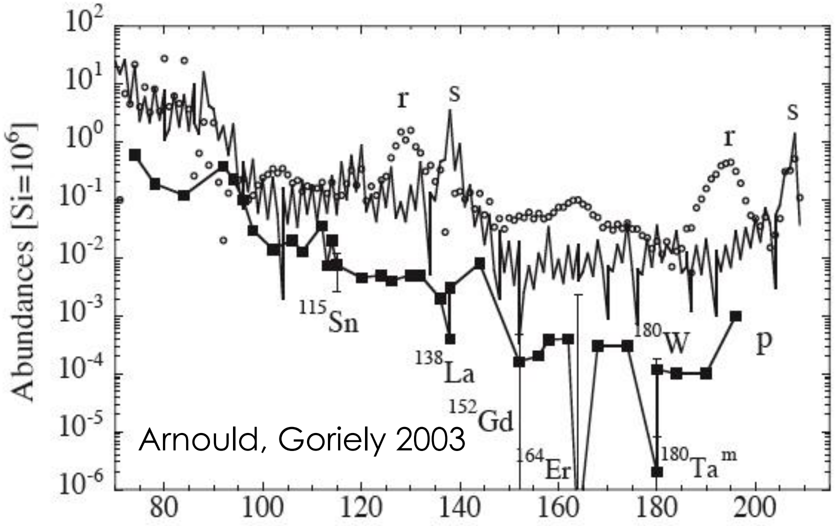
Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

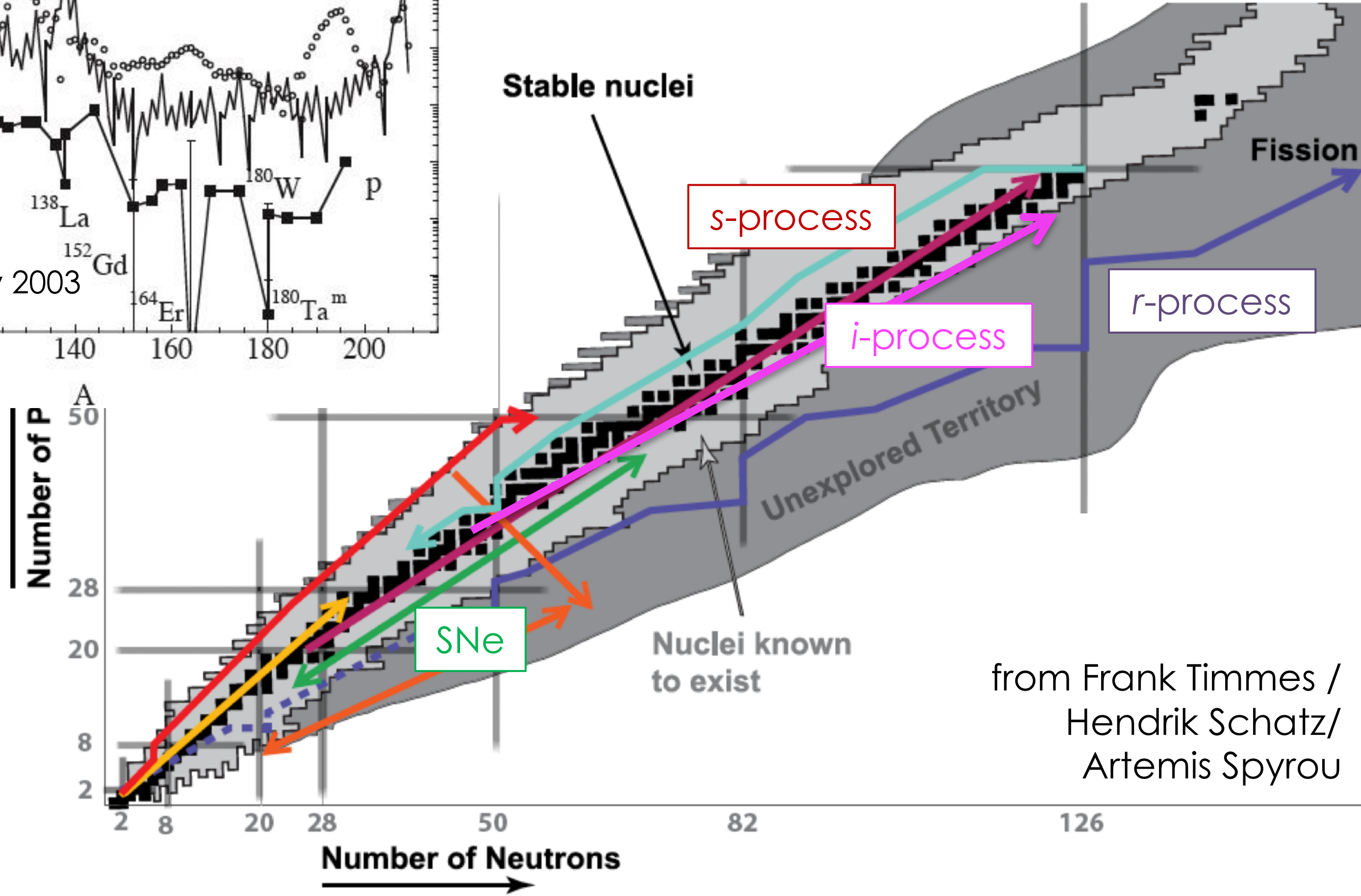
Toward Exascale Astrophysics of Mergers and Supernovae (TEAMS)
a DOE SciDAC supported collaboration

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

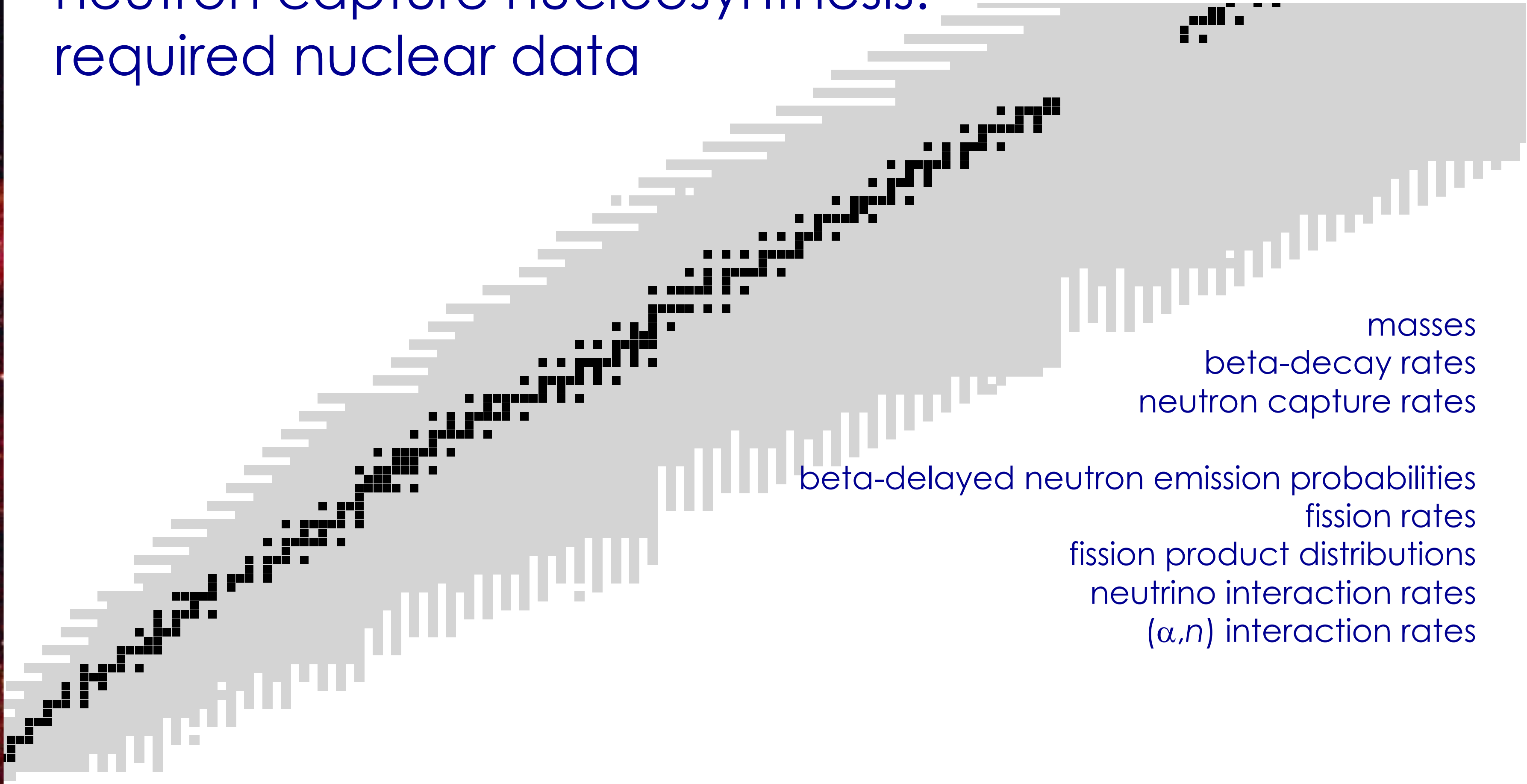
nucleosynthesis processes





from Frank Timmes / Hendrik Schatz/ Artemis Spyrou

neutron capture nucleosynthesis: required nuclear data



masses
beta-decay rates
neutron capture rates

beta-delayed neutron emission probabilities
fission rates
fission product distributions
neutrino interaction rates
(α,n) interaction rates

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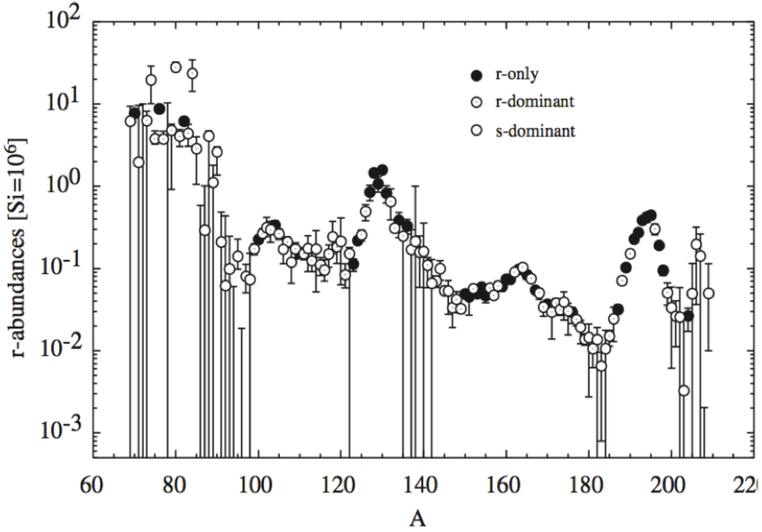
Notre Dame
ATLAS/CARIBU 12 July 2019

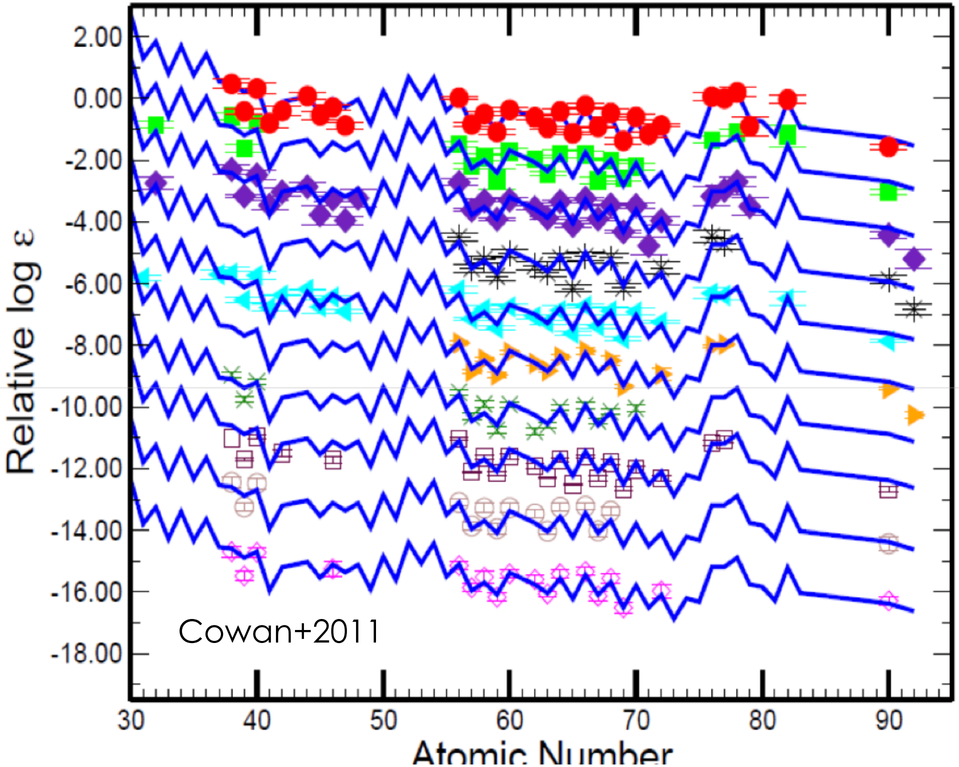
r-process elements in metal-poor stars



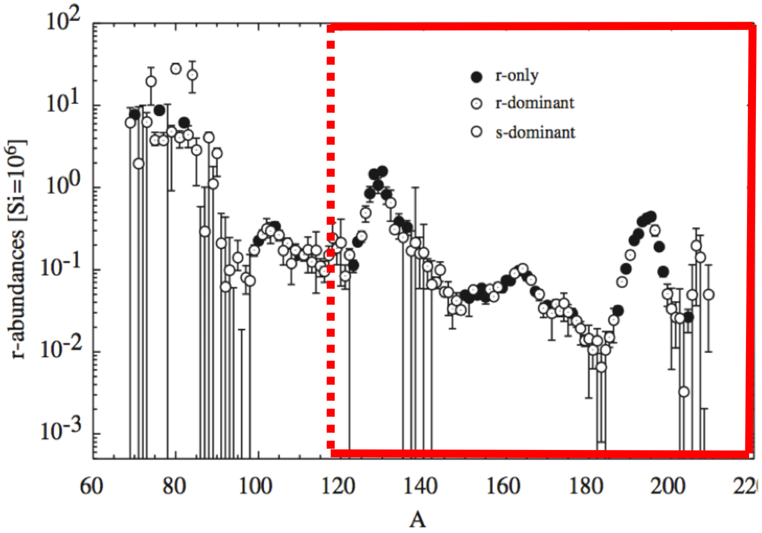
Arnould+2007

solar system
r-process residuals

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

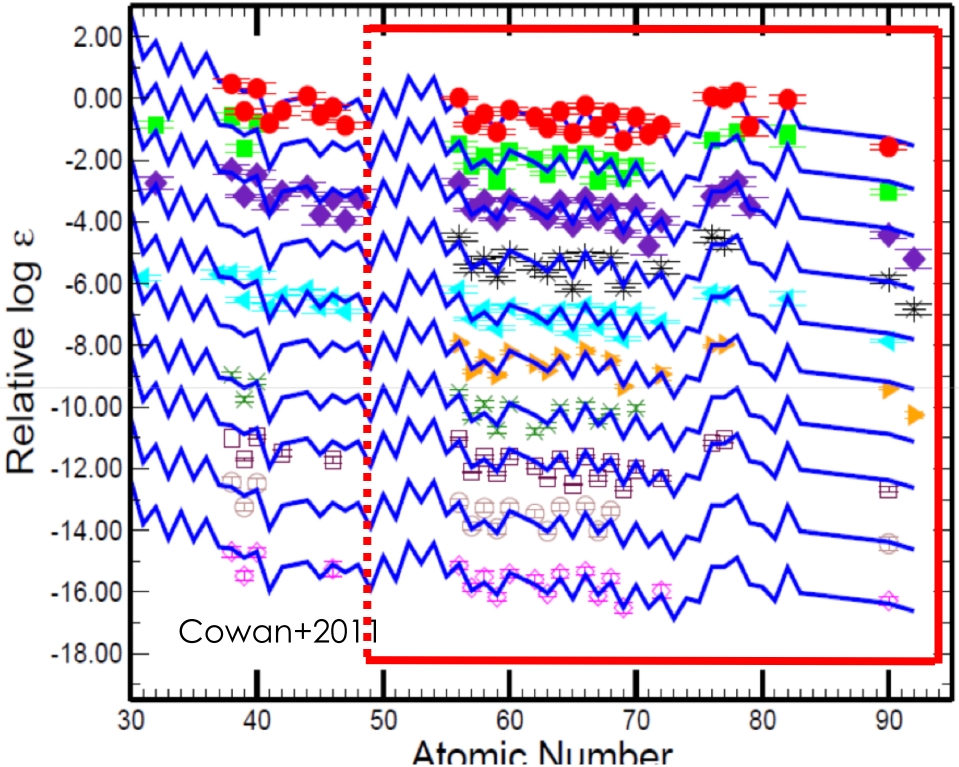


the main *r*-process



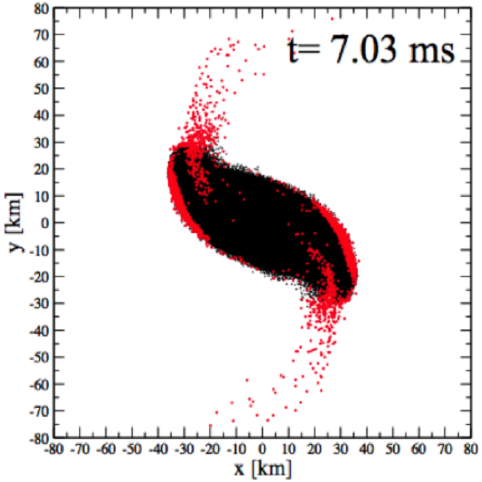
Arnould+2007

solar system
r-process residuals

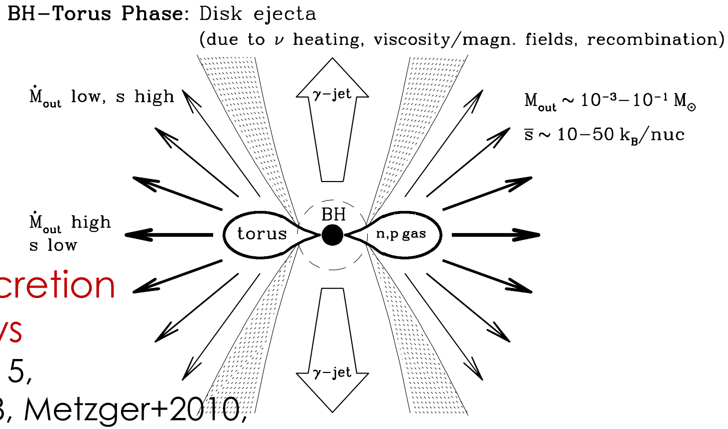


elemental abundances
from *r*-process-enhanced
metal-poor stars

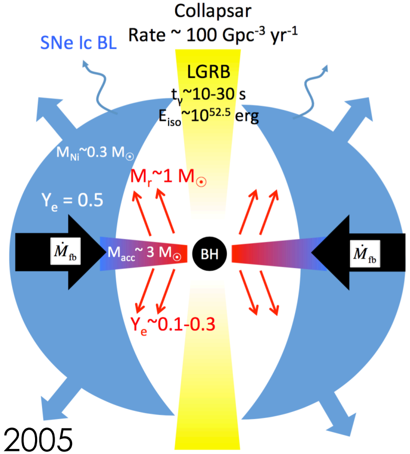
potential main *r*-process astrophysical sites



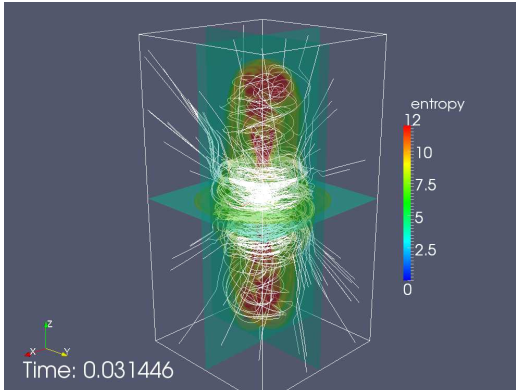
prompt nsm ejecta
e.g., Korobkin+2012, Lattimer+1973, Frieburghaus+1999, Goriely+2011, etc., etc.



merger accretion disk outflows
e.g., Just+2015, Surman+2008, Metzger+2010, Perego+2014, Wanajo+2014

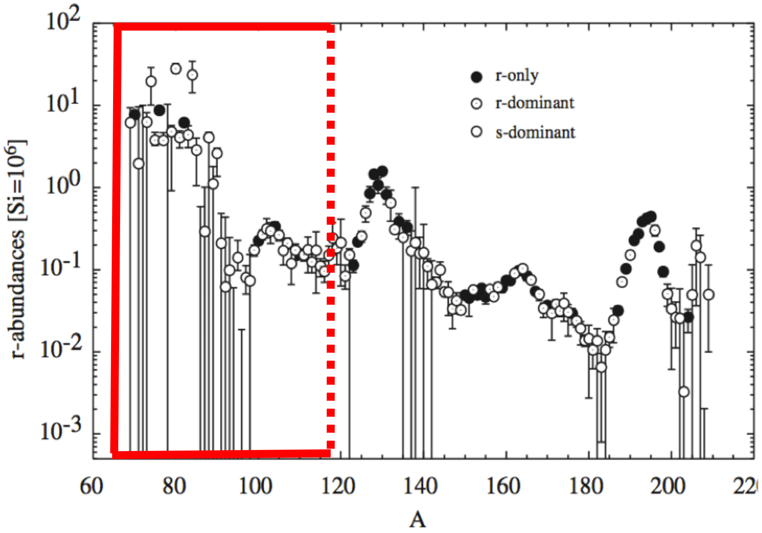


MHD supernovae
e.g., Winteler+2012



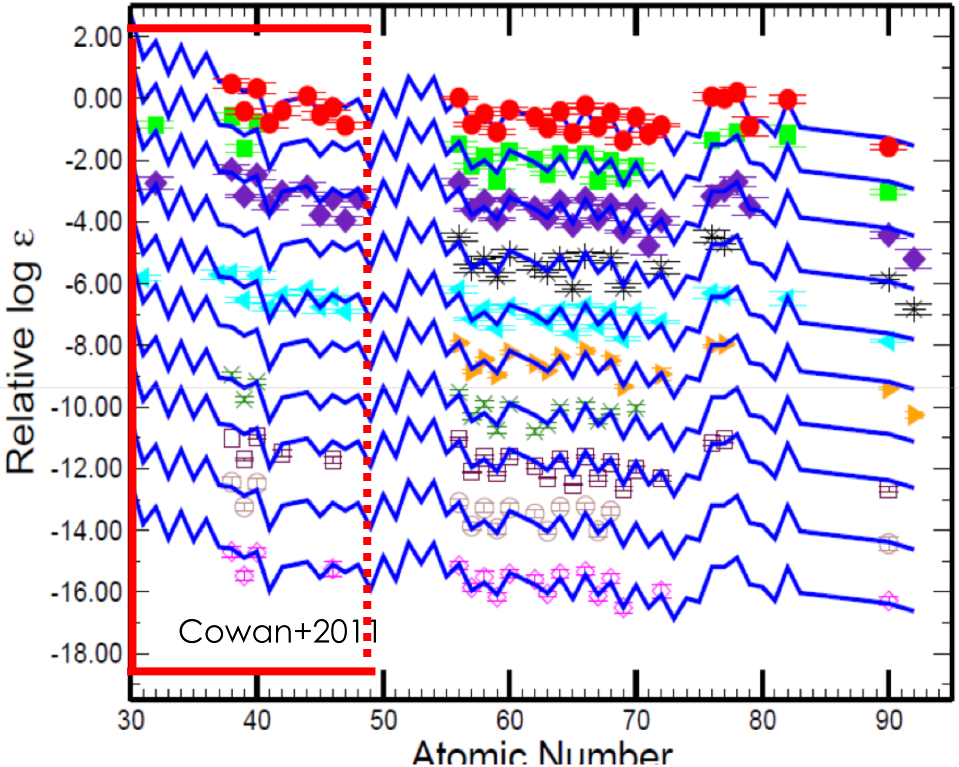
collapsars
e.g., Siegel+2018
Surman, McLaughlin 2005

the weak/limited *r*-process



Arnould+2007

solar system
r-process residuals

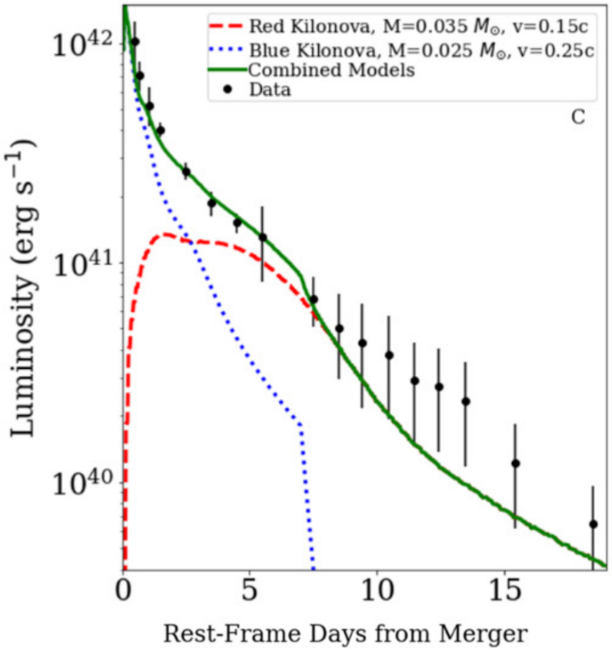


Cowan+2011

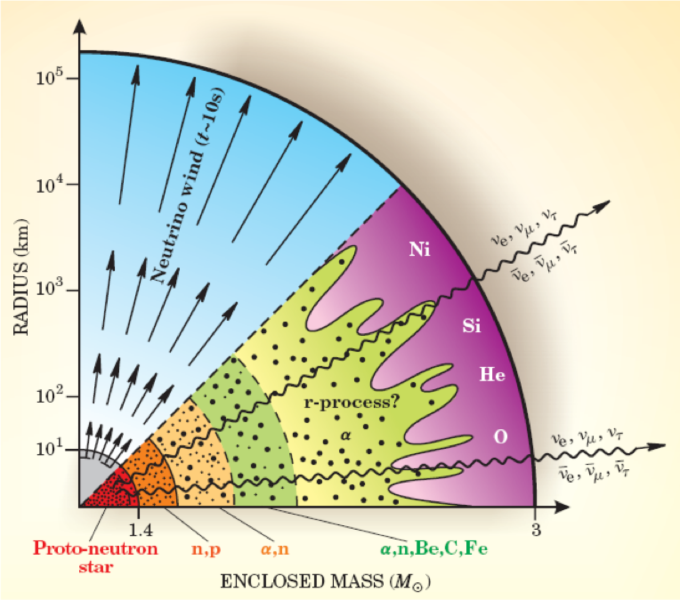
elemental abundances
from *r*-process-enhanced
metal-poor stars

potential weak/limited *r*-process astrophysical sites

All potential main r-process sites, incl. mergers:



Kilpatrick+2017
Kasen+2017



as well as additional sites, such as supernova neutrino-driven winds
e.g., Woosley, Janka 2005,
Arcones+2007

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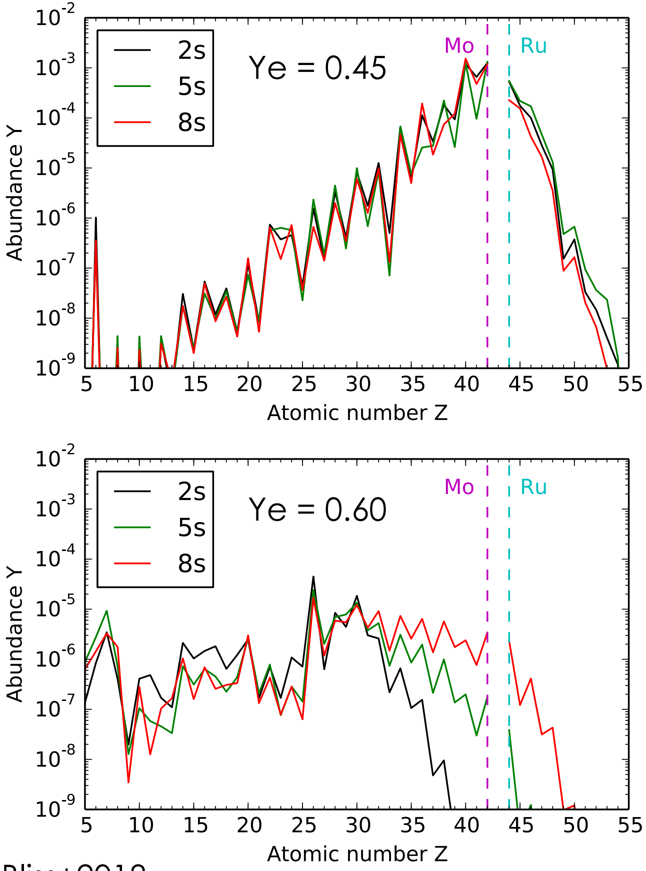
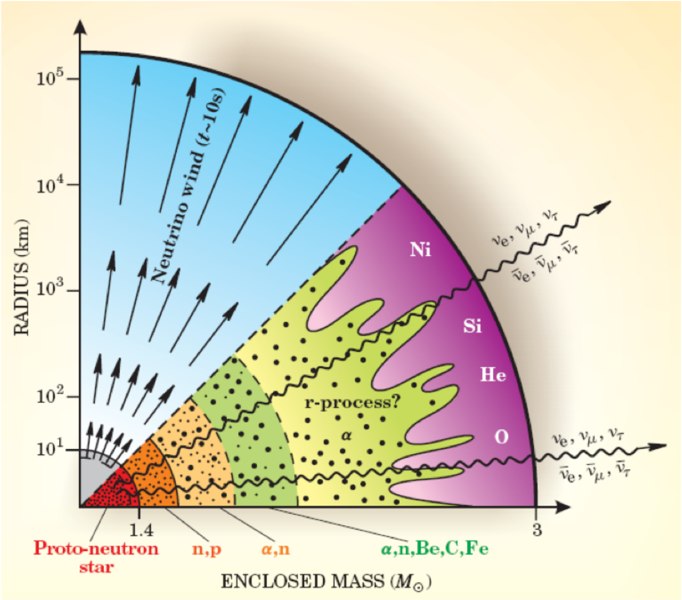
potential weak/limited *r*-process astrophysical sites



Bliss+2018



as well as additional sites, such as supernova neutrino-driven winds

e.g., Woosley, Janka 2005, Arcones+2007

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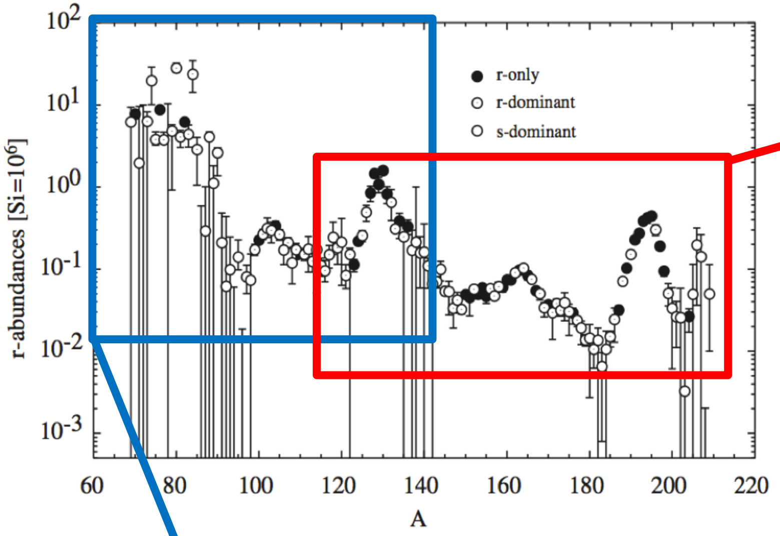
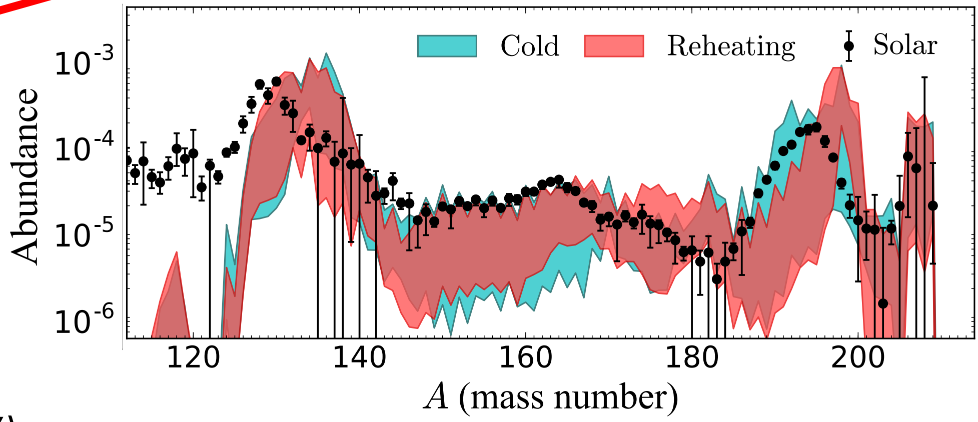
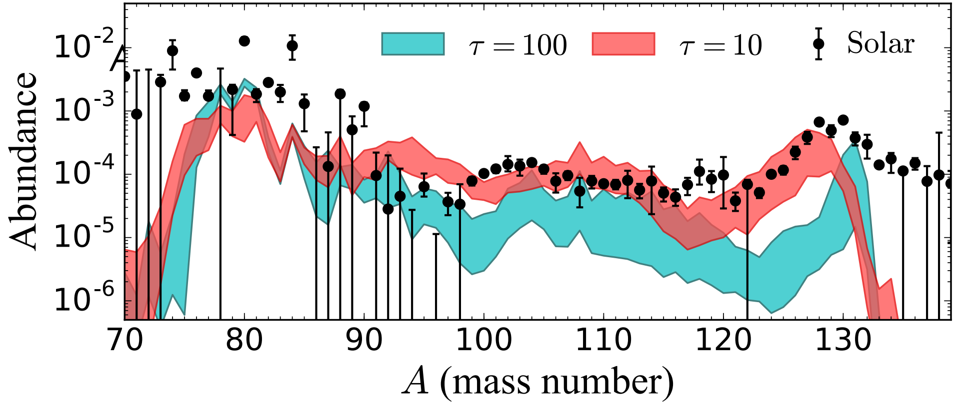


very n-rich **dynamical** ejecta



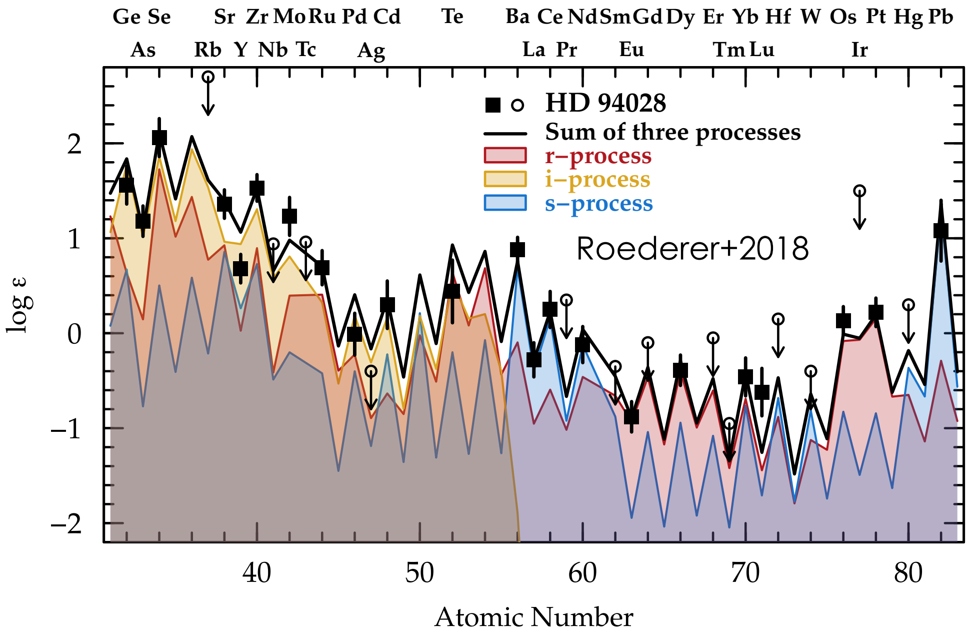
wind ejecta (s/k=10, Y_e=0.27)



r-process simulations of NSM ejecta

Côté, Fryer, Belczynski, Korobkin, Chruslinska, Vassh, Mumpower, Lippuner, Sprouse, Surman, Wollaeger 2018

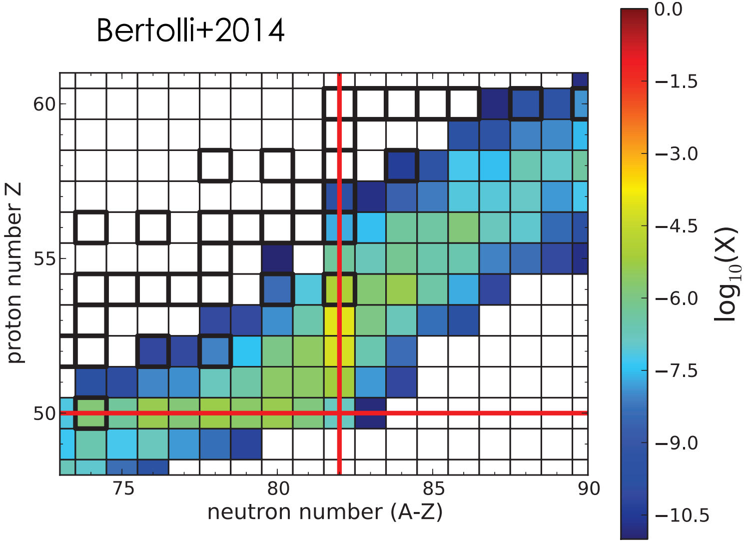
the *i* process



$^{12}C(p,\gamma)^{13}N$

$^{13}N(e^+\nu)^{13}C$

$^{13}C(\alpha,n)^{16}O$



$N_n \leq 10^{11}\,\mathrm{cm}^{-3}$ *s* process

$N_n \sim 10^{15}\,\mathrm{cm}^{-3}$ *i* process

$N_n \geq 10^{20}\,\mathrm{cm}^{-3}$ *r* process

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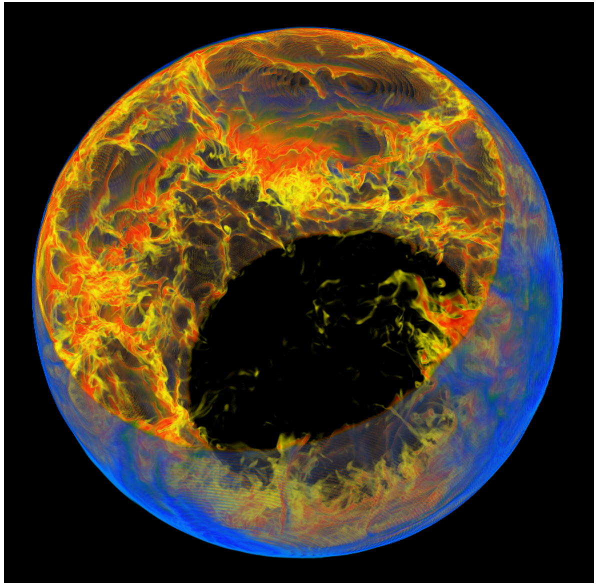
potential *i* process astrophysical sites

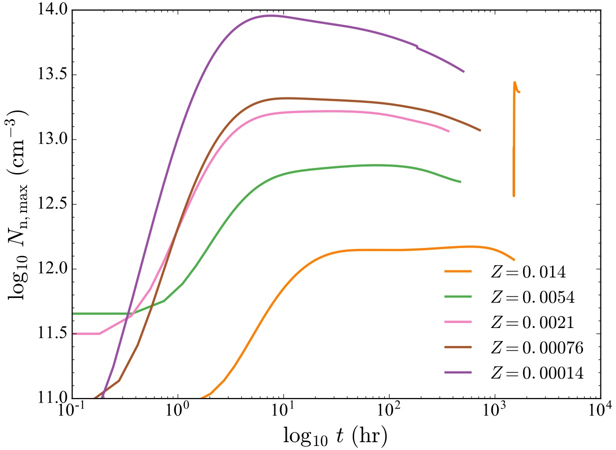


convective He burning in AGB stars

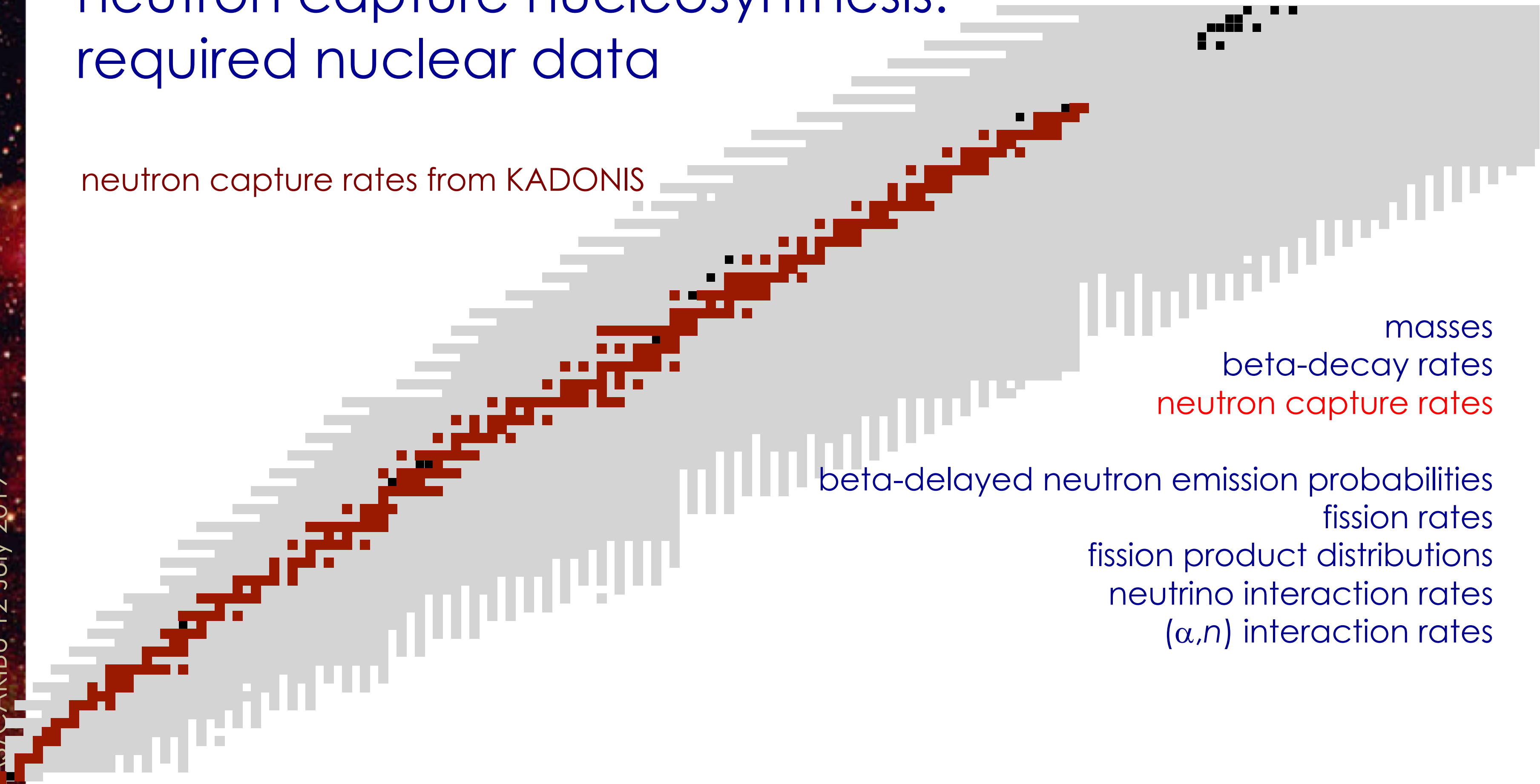
e.g., Herwig+11

rapidly accreting white dwarfs (RAWDs)

e.g., Cote+18



neutron capture nucleosynthesis: required nuclear data

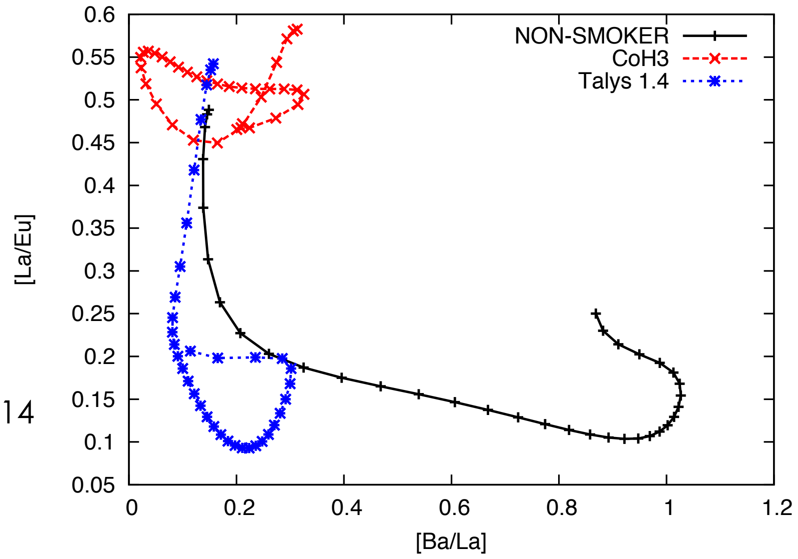


neutron capture rates from KADONIS

masses
beta-decay rates
neutron capture rates

beta-delayed neutron emission probabilities
fission rates
fission product distributions
neutrino interaction rates
(α,n) interaction rates

neutron capture rates for the *i* process

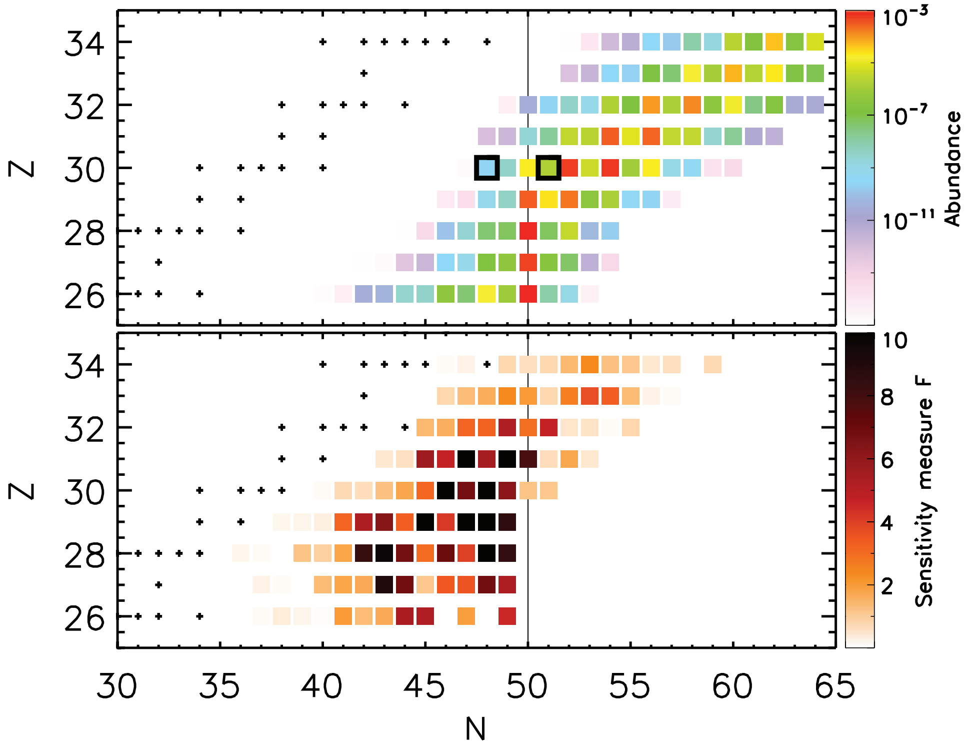


Bertolli+2014

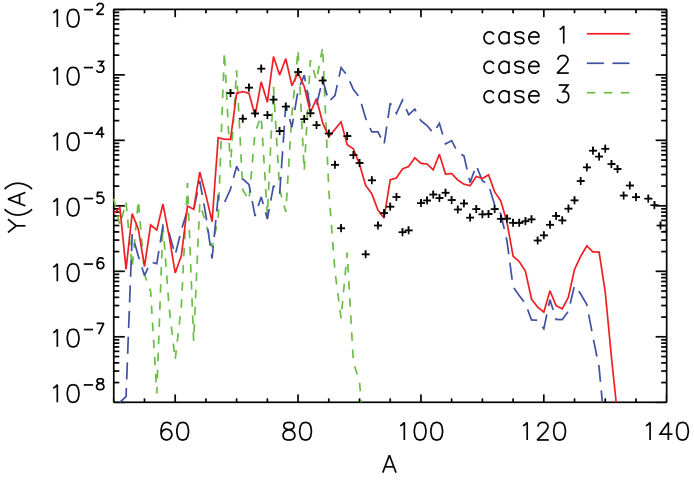
Denissenkov+2018

Reaction	Rb (up/down)	Sr (up/down)	Y (up/down)	Zr (up/down)
^{85}Br(n,γ)	$-0.102/0.028$	$0.068/-0.029$	$0.07/-0.03$	$0.071/-0.03$
^{86}Br(n,γ)	$0.034/-0.006$	$0.068/-0.014$	$0.073/-0.015$	$0.077/-0.016$
^{85}Kr(n,γ)	$-0.005/0.007$	$0.016/-0.093$	$0.016/-0.092$	$0.016/-0.094$
^{87}Kr(n,γ)	$-0.225/0.231$	$0.104/-0.28$	$0.085/-0.21$	$0.07/-0.157$
^{88}Kr(n,γ)	$0.0/0.0$	$-0.305/0.185$	$0.151/-0.269$	$0.145/-0.239$
^{89}Kr(n,γ)	$0.0/0.0$	$0.0/0.0$	$-0.276/0.066$	$0.045/-0.017$
^{89}Rb(n,γ)	$0.0/0.0$	$0.003/0.005$	$-0.226/0.241$	$0.038/-0.089$
^{89}Sr(n,γ)	$0.0/0.0$	$0.006/-0.007$	$-0.088/0.121$	$0.013/-0.027$
^{92}Sr(n,γ)	$0.0/0.0$	$0.0/0.0$	$0.0/0.0$	$-0.089/0.117$

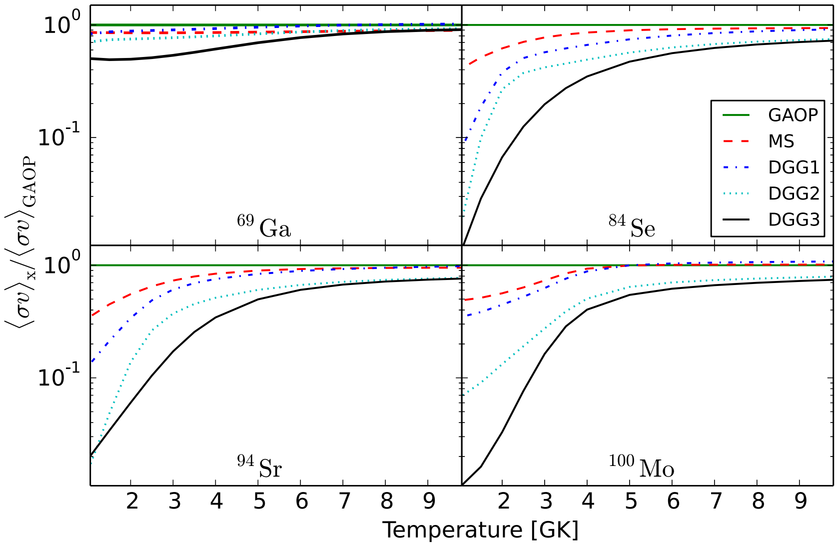
neutron capture rates for the weak/limited *r* process



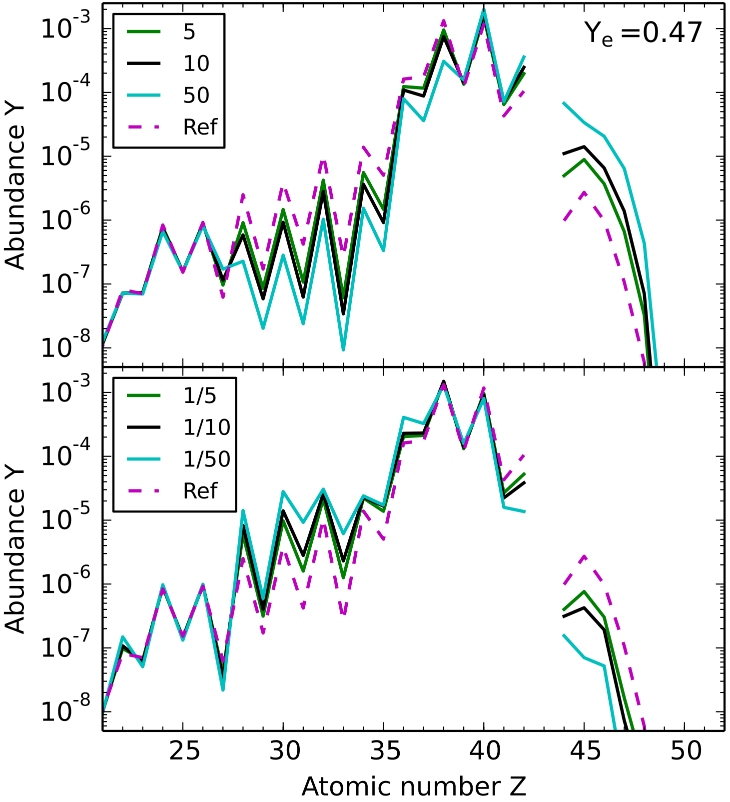
Surman, Mumpower, Sinclair, Jones, Hix, McLaughlin 2014



(α,n) rates for a SNe weak/limited *r* process



Bliss+2017, Pereira+2016



Bliss+2018

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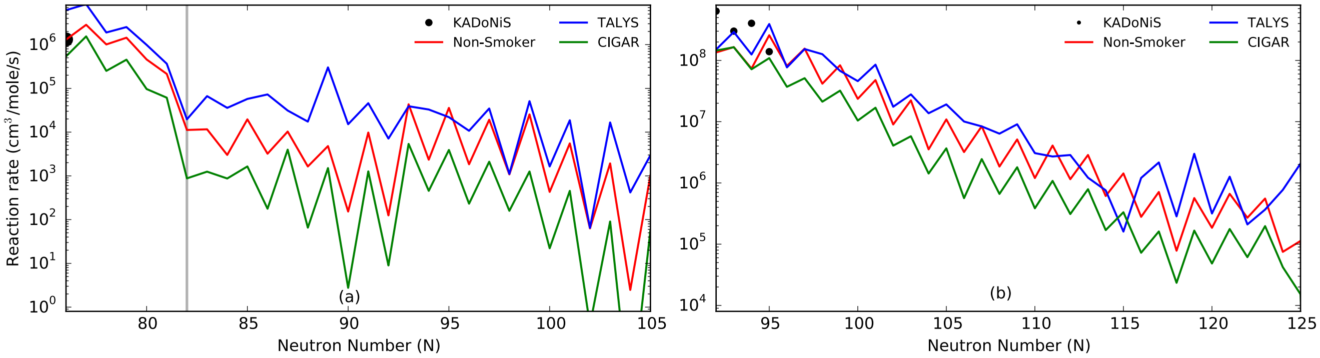
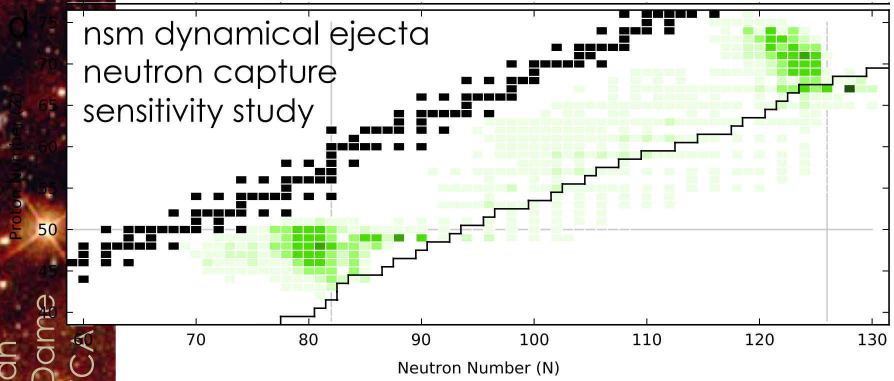
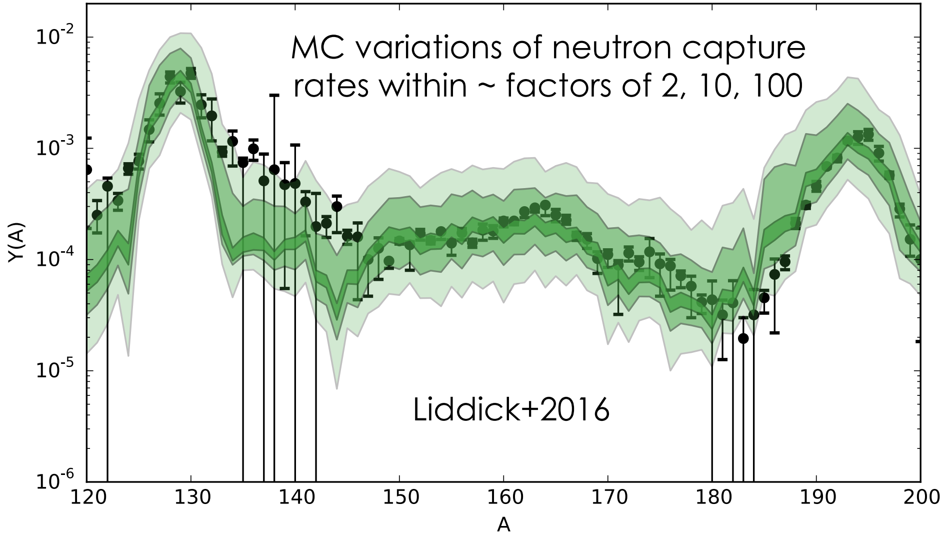
neutron capture rates for the main *r* process



Mumpower, Surman, McLaughlin, Aprahamian 2016





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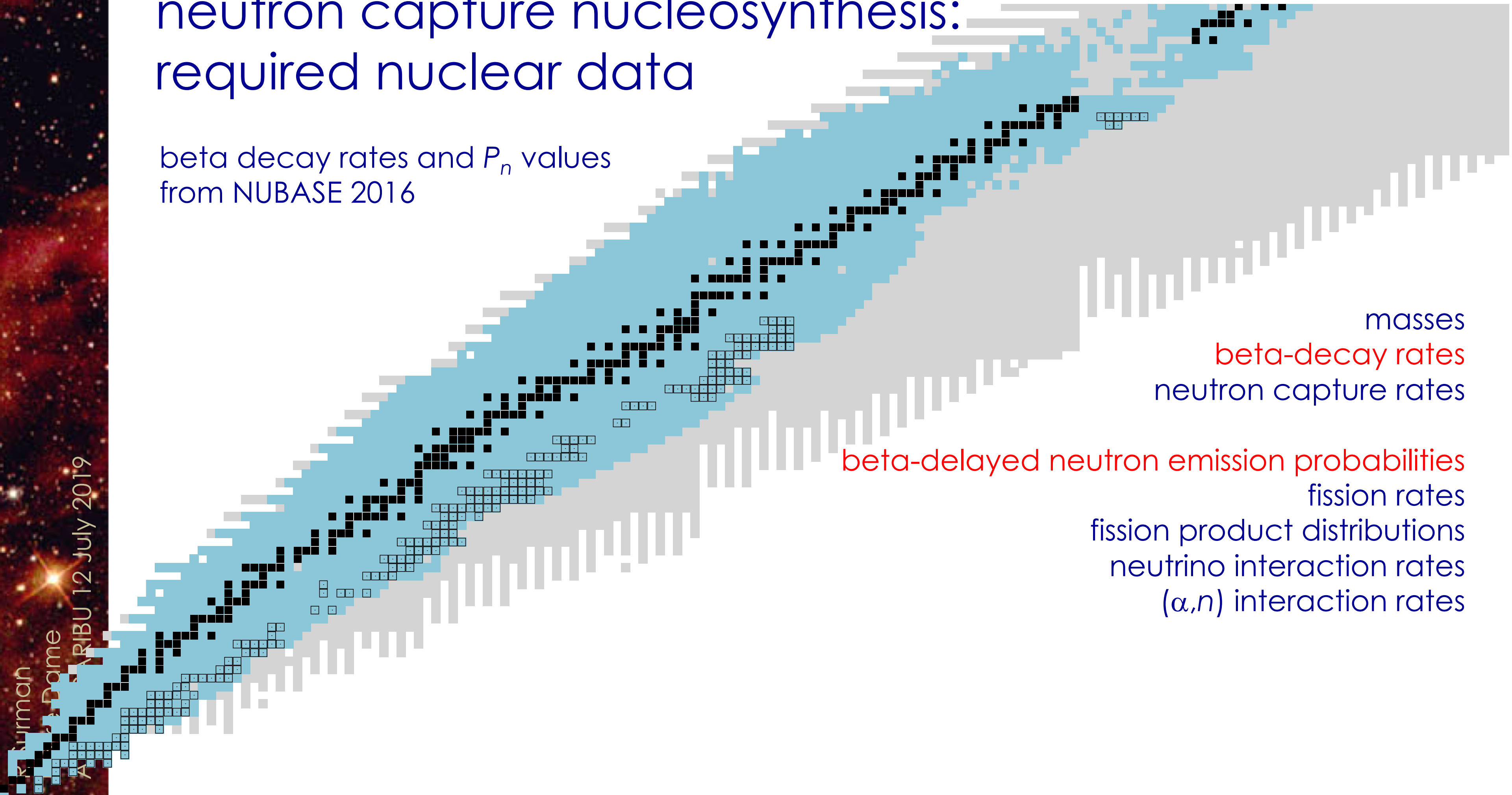
ATLAS/CA

neutron capture nucleosynthesis: required nuclear data

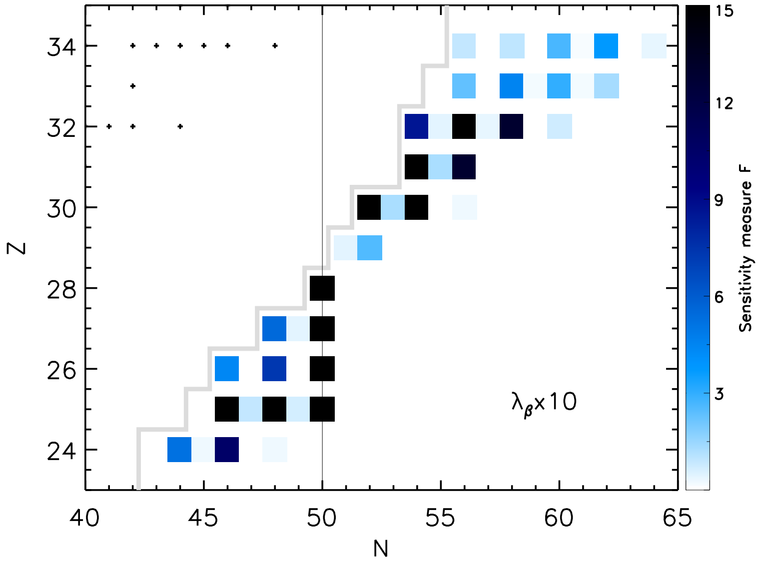
beta decay rates and P_n values
from NUBASE 2016



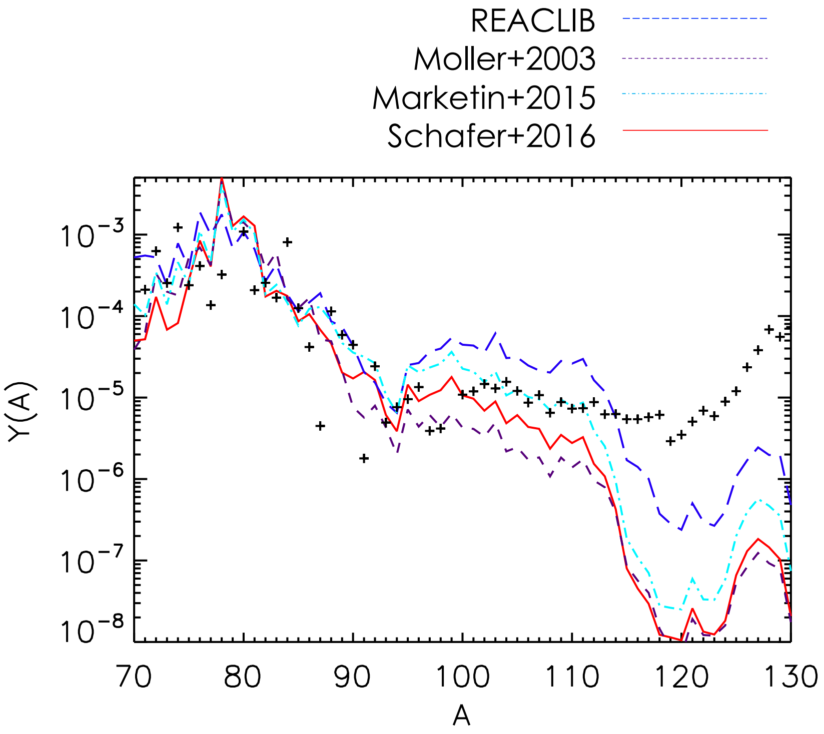
masses
beta-decay rates
neutron capture rates

beta-delayed neutron emission probabilities
fission rates
fission product distributions
neutrino interaction rates
(α,n) interaction rates

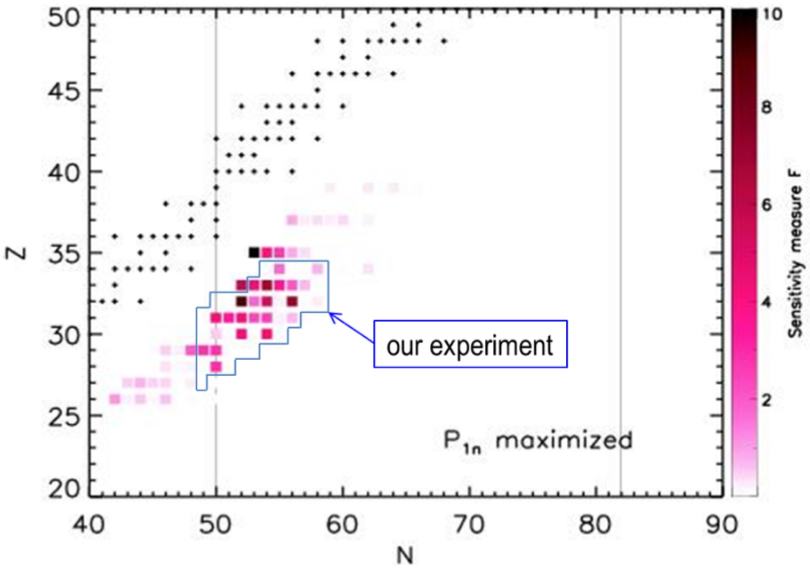
beta decay rates for the weak/limited *r* process



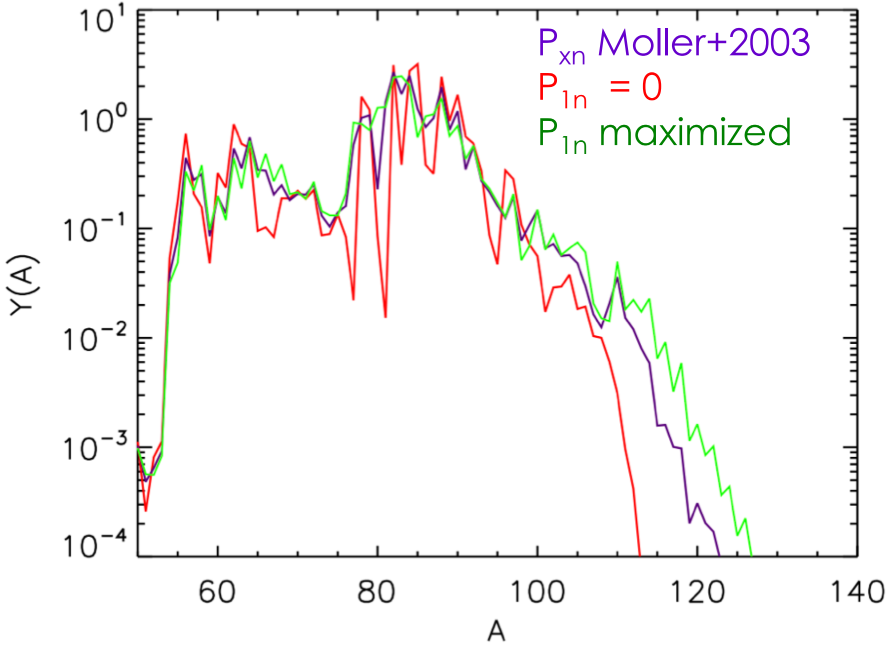
Shafer, Engel, Fröhlich,
McLaughlin, Mumpower,
Surman 2016



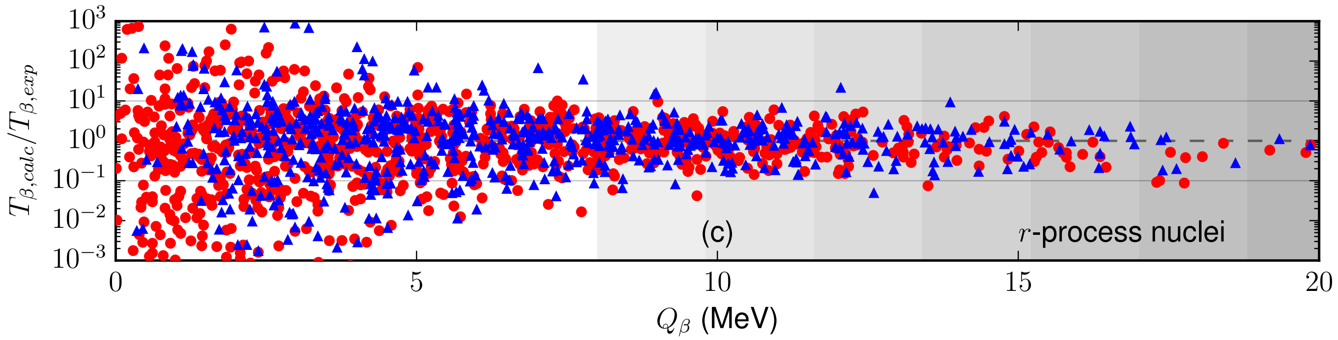
P_n values for the weak/limited *r* process



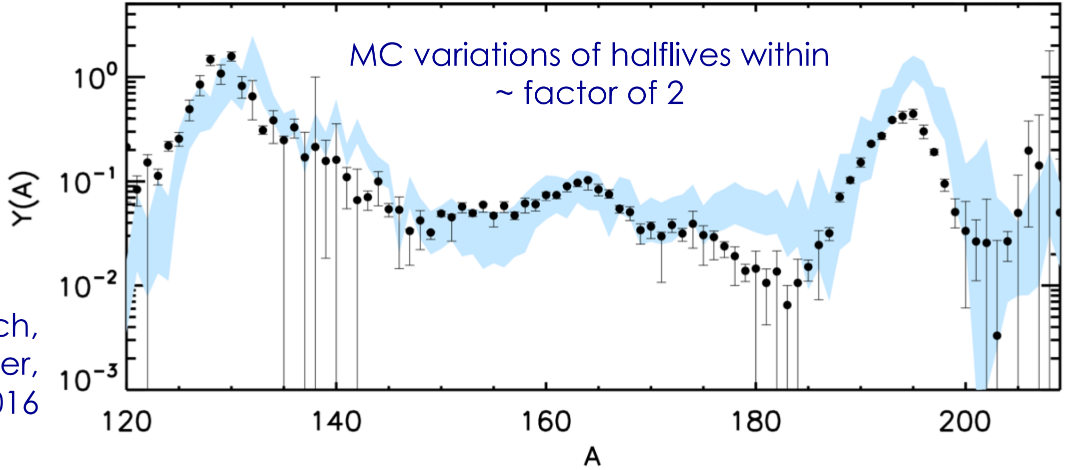
BRIKEN proposal,
Rykaczewski+2014



beta decay rates for the main *r* process

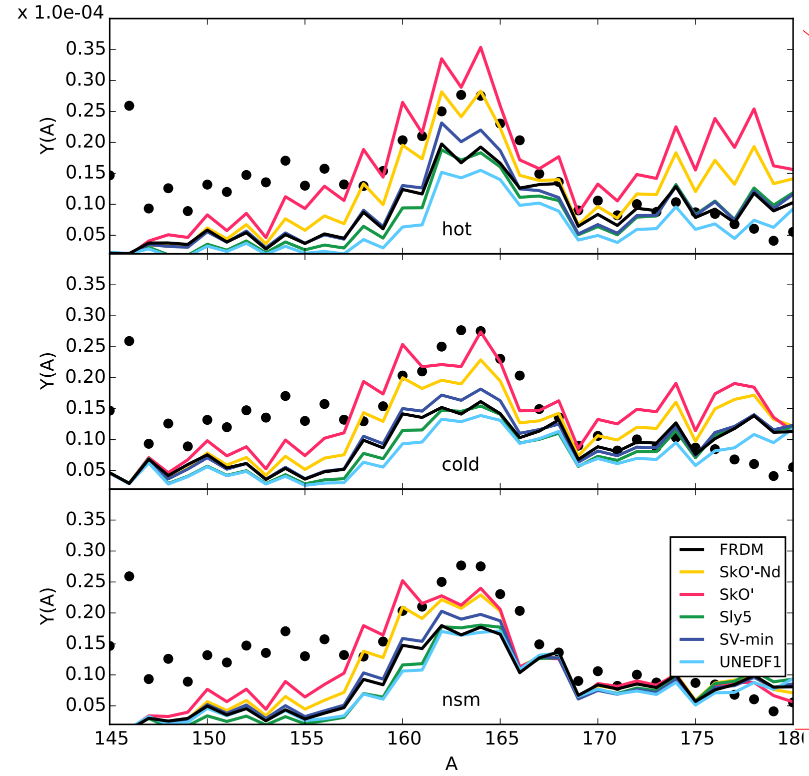


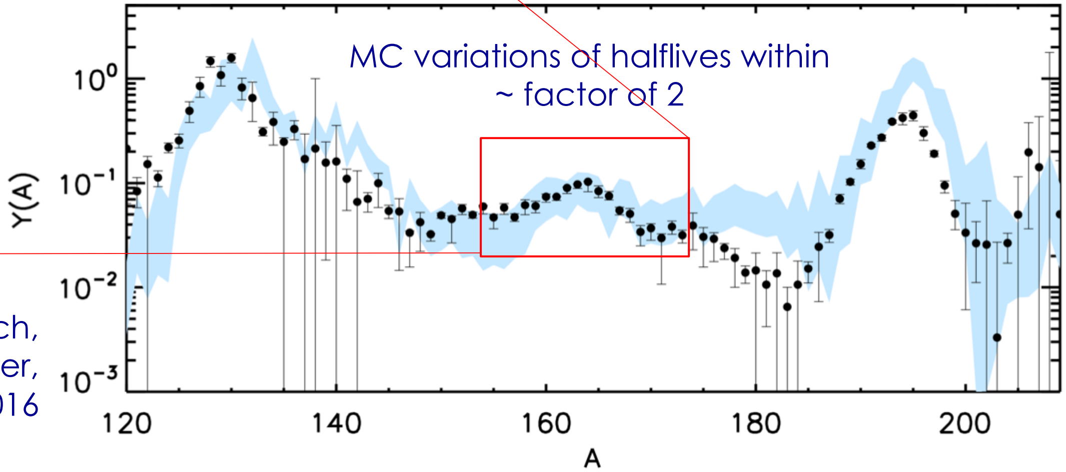
Mumpower, Surman, McLaughlin, Aprahamian 2016



Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016

beta decay rates for the main *r* process





Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016

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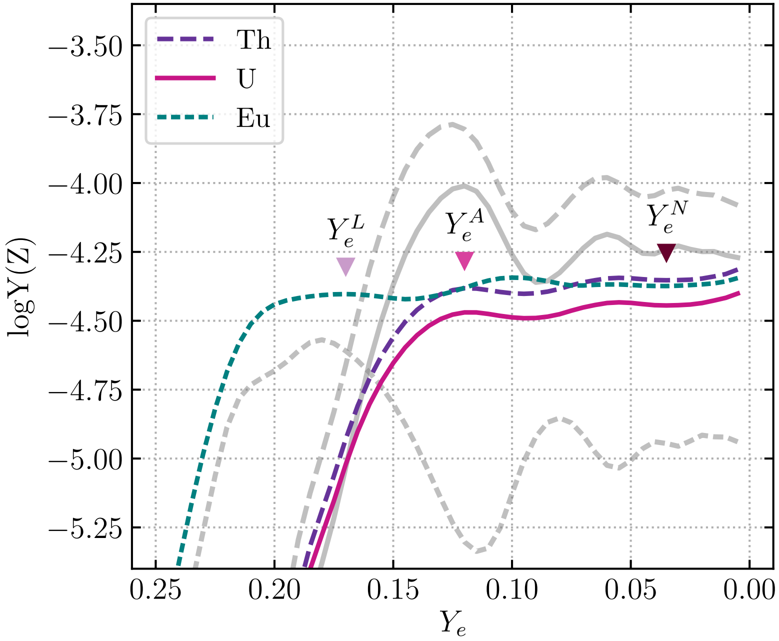
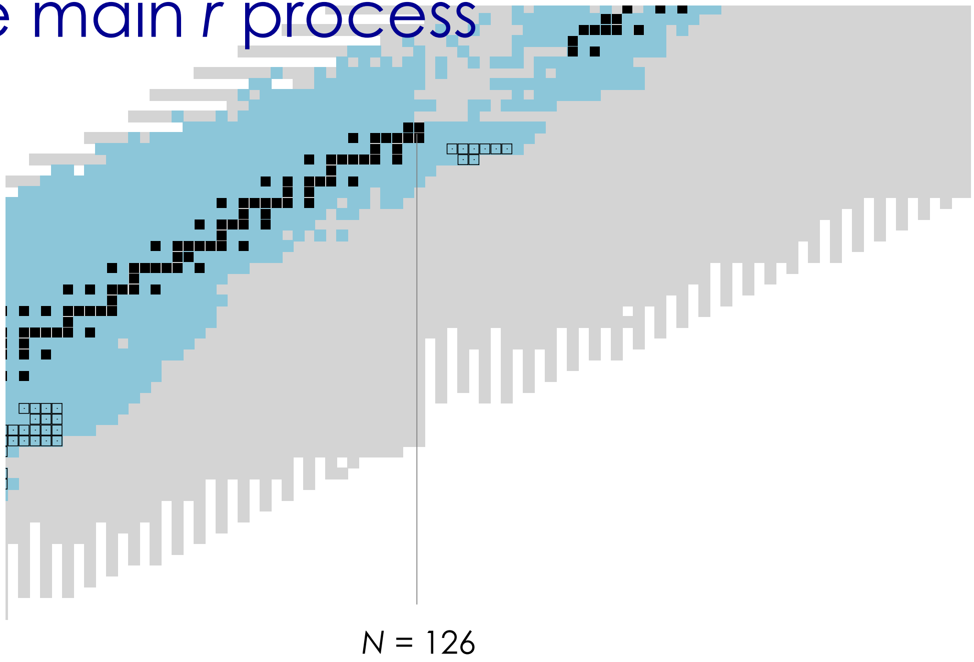
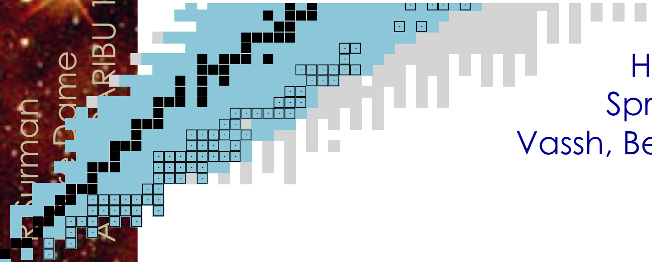
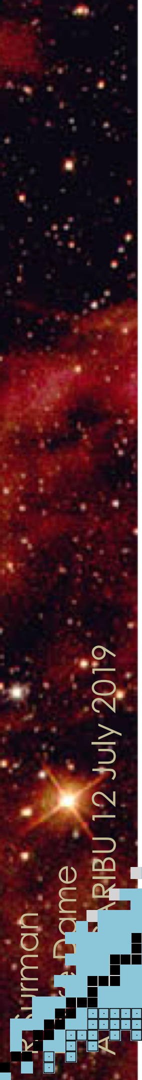
Notre Dam
ATLAS/CA

beta decay rates for the main *r* process





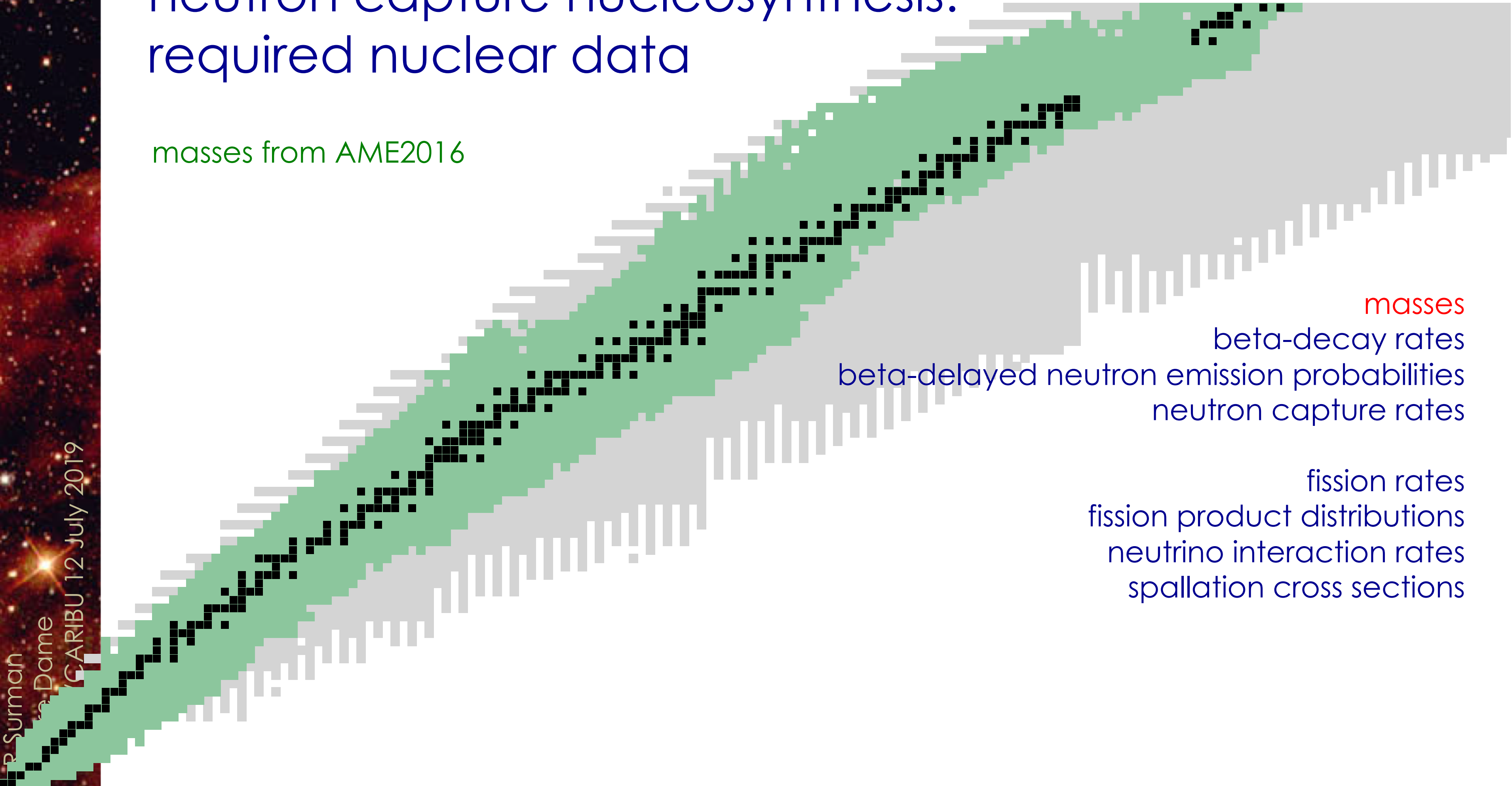




Holmbeck, Surman,
Sprouse, Mumpower,
Vassh, Beers, Kawano 2018

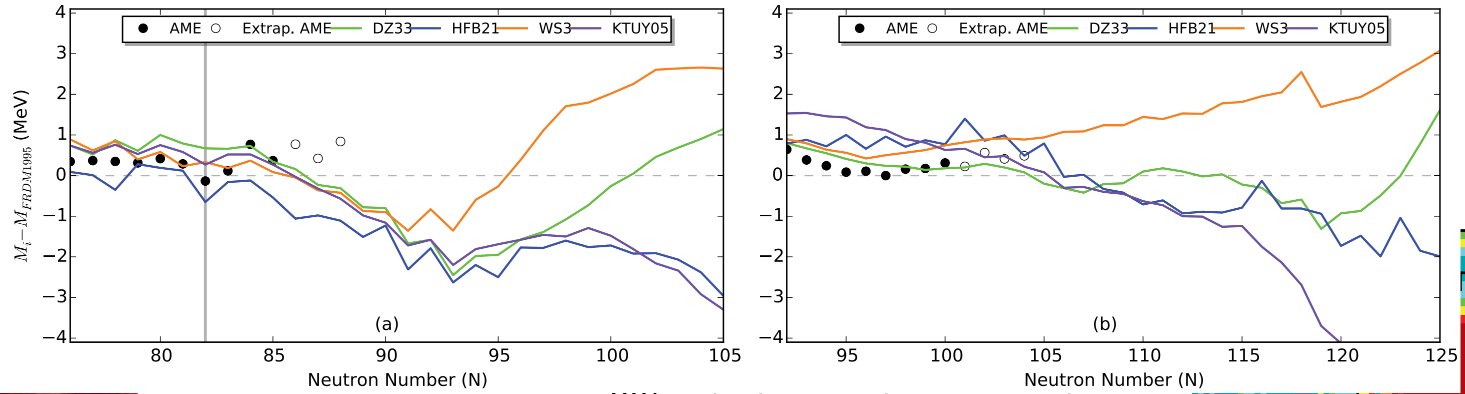
neutron capture nucleosynthesis: required nuclear data

masses from AME2016



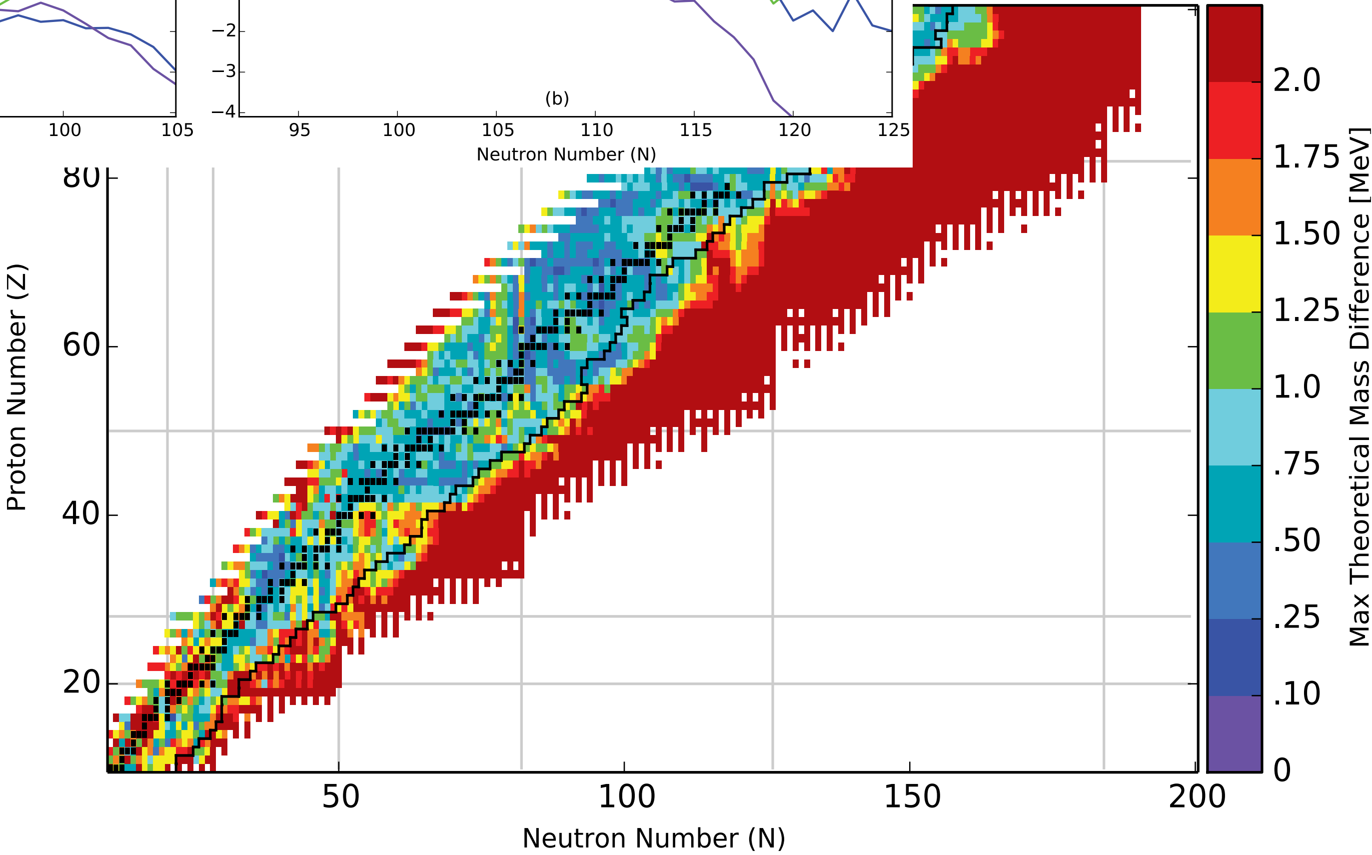
masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates

fission rates
fission product distributions
neutrino interaction rates
spallation cross sections



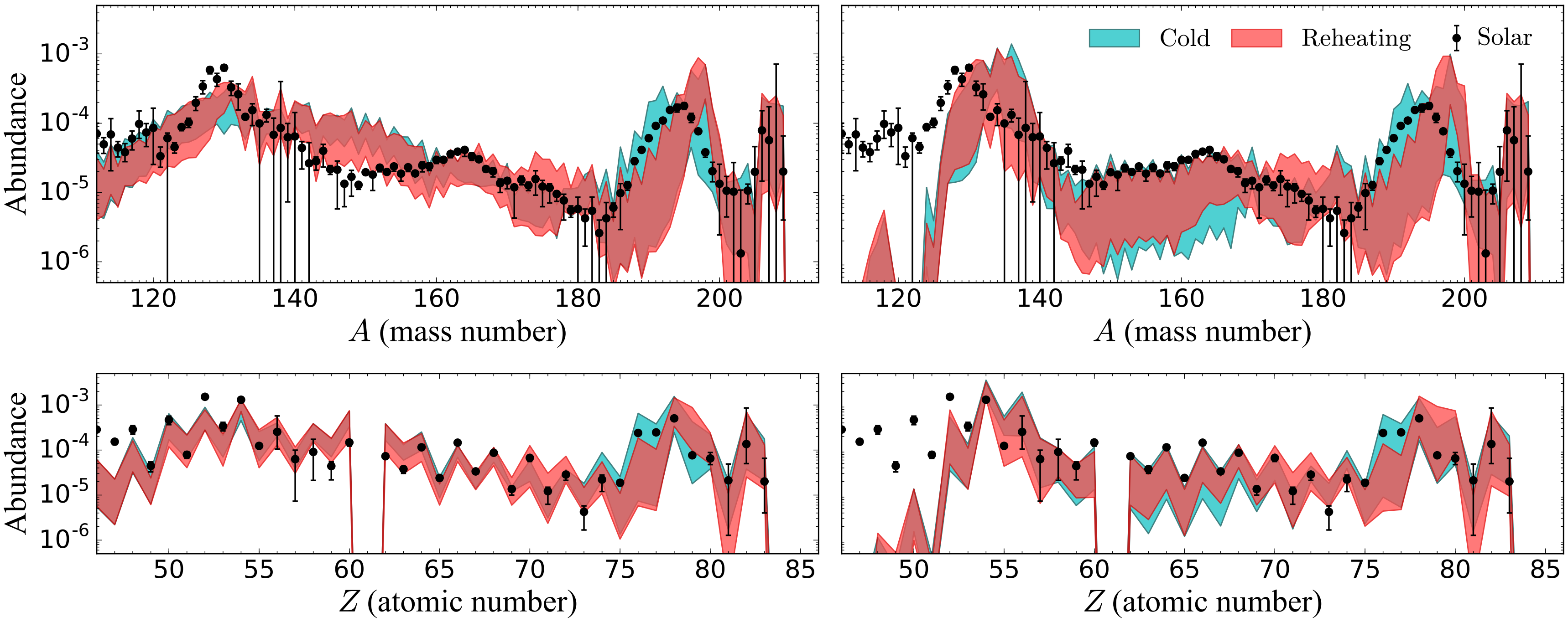
mass uncertainties

Mumpower, Surman, McLaughlin, Aprahamian 2016



impact of systematic mass uncertainties

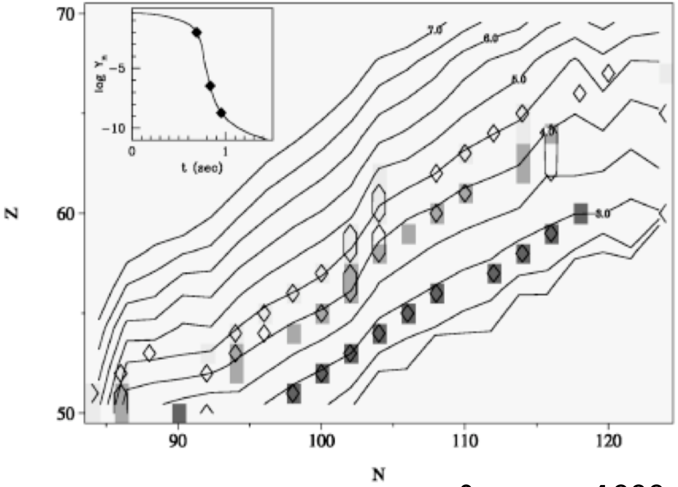
Abundance pattern ranges for 10 distinct mass models



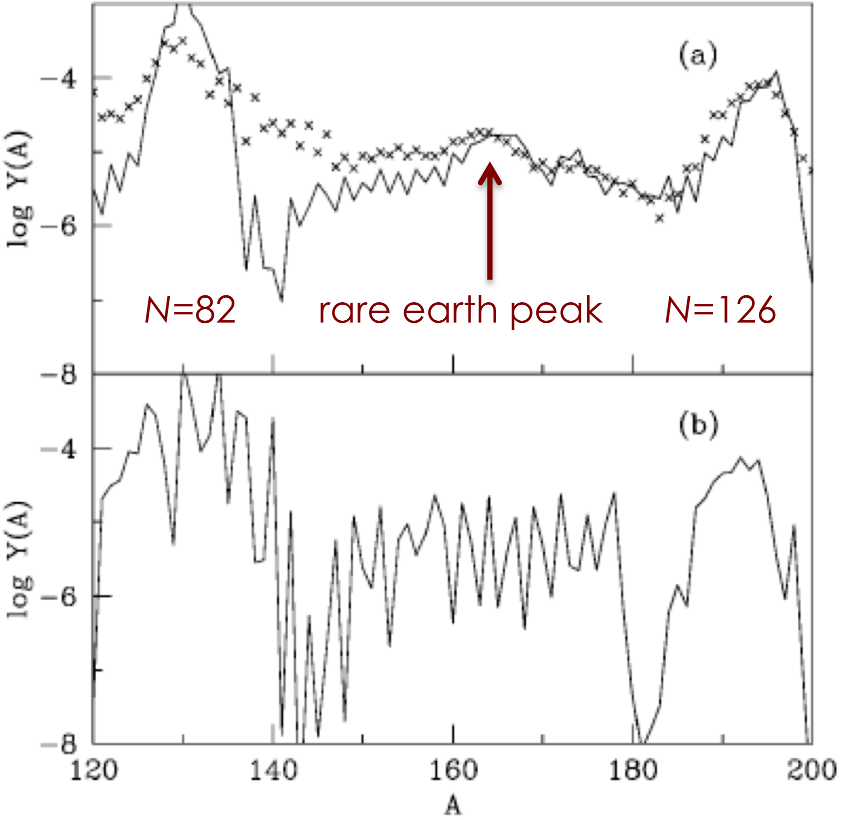
Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman, Wollaeger 2018

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



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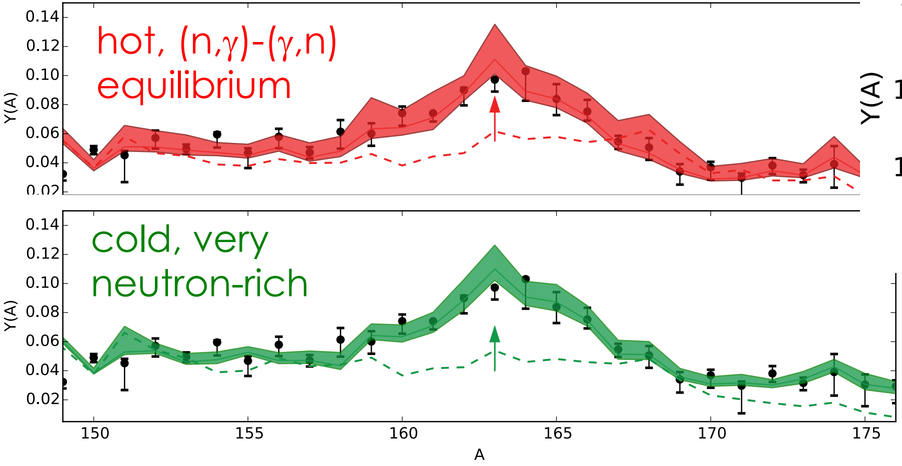
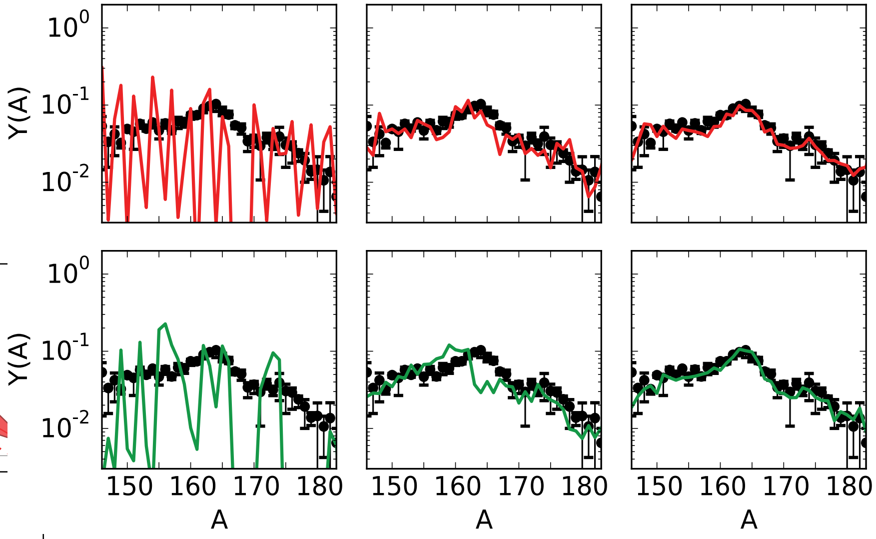
Notre Dame
ATLAS/CARIBU 12 July 2019

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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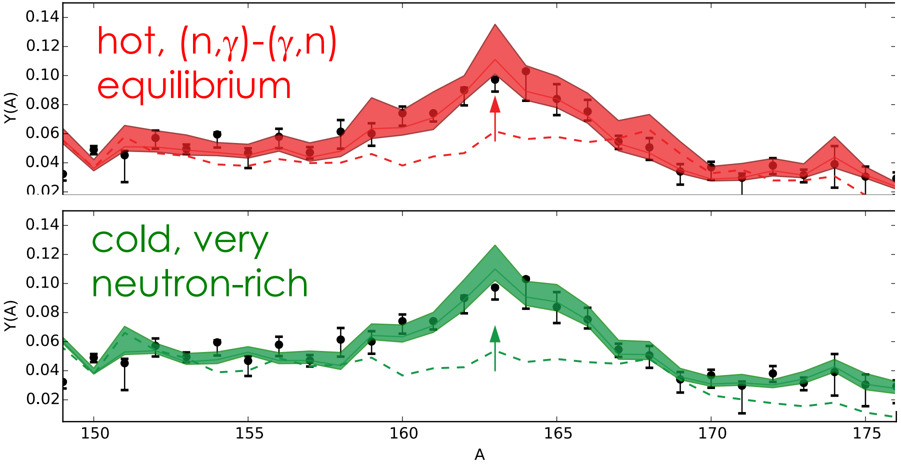
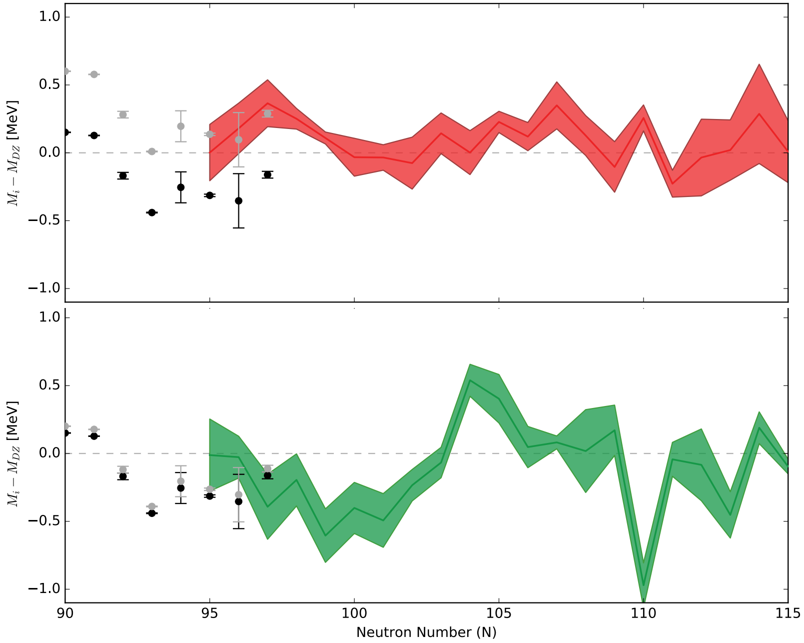
Notre Dame
ATLAS/CARIBU 12 July 2019

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

mass modification parameterization:

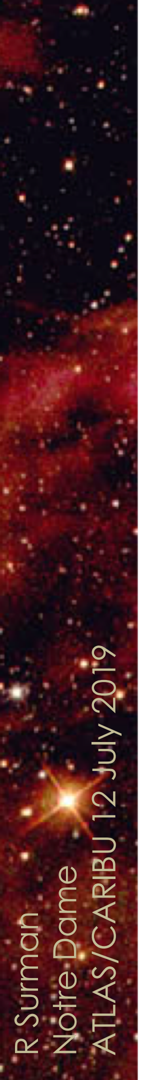
$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$



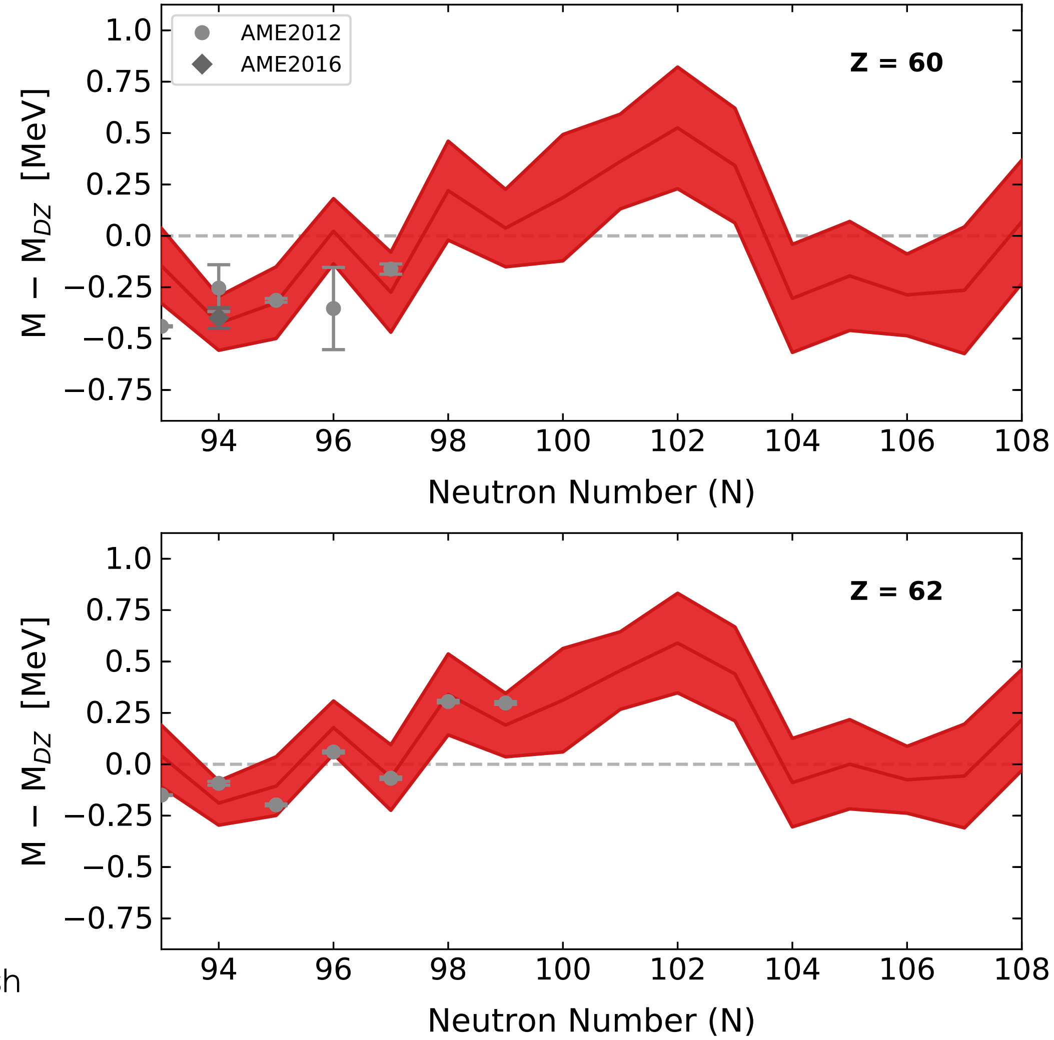


predicted mass trends for the Neodymium (Z = 60) isotopic chain

Mumpower, McLaughlin, Surman, Steiner 2016

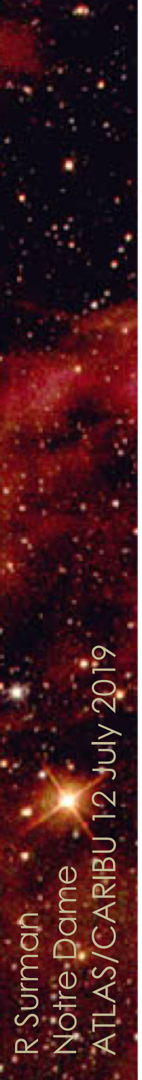


updated reverse engineering calculations



hot, (n,γ)-(γ,n) equilibrium example

figure by N Vassh

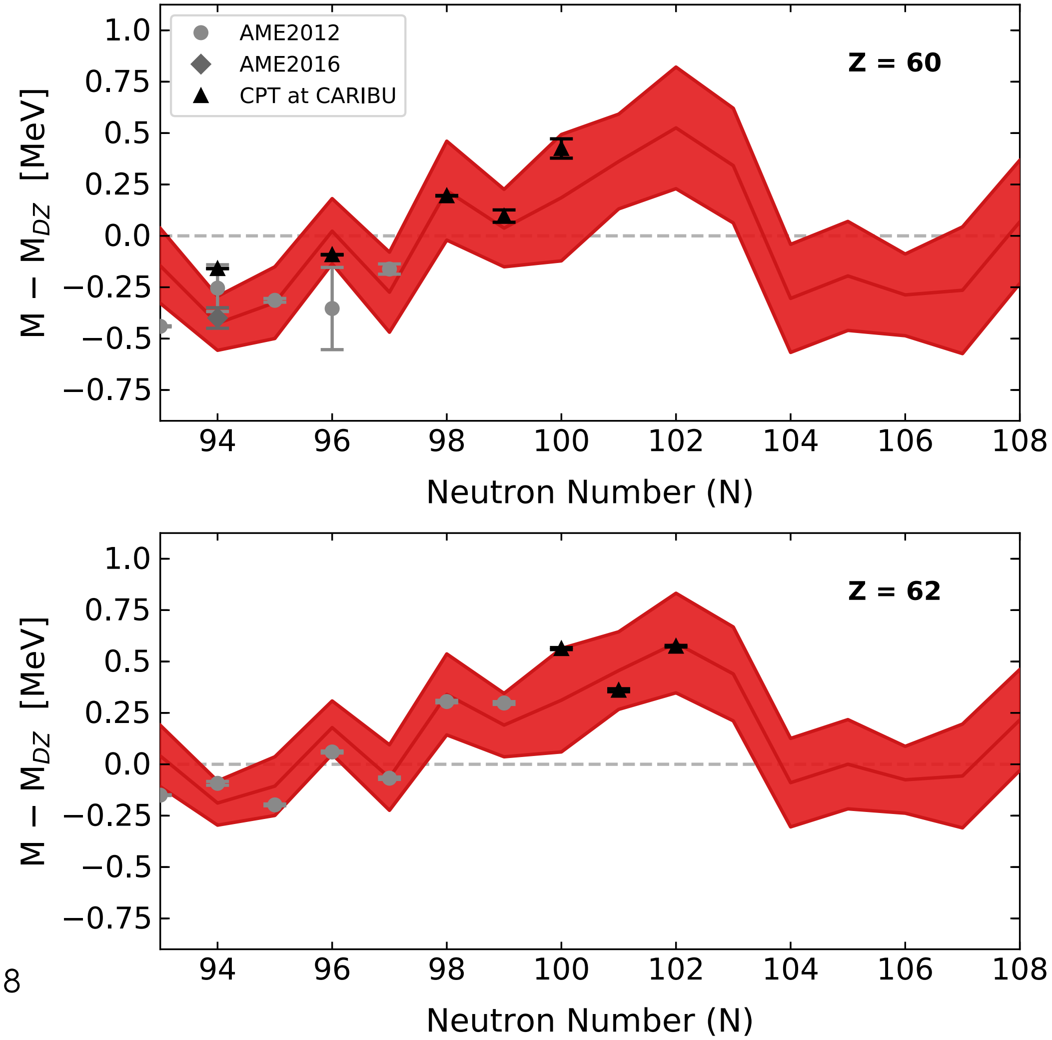


updated reverse engineering calculations + new CPT measurements

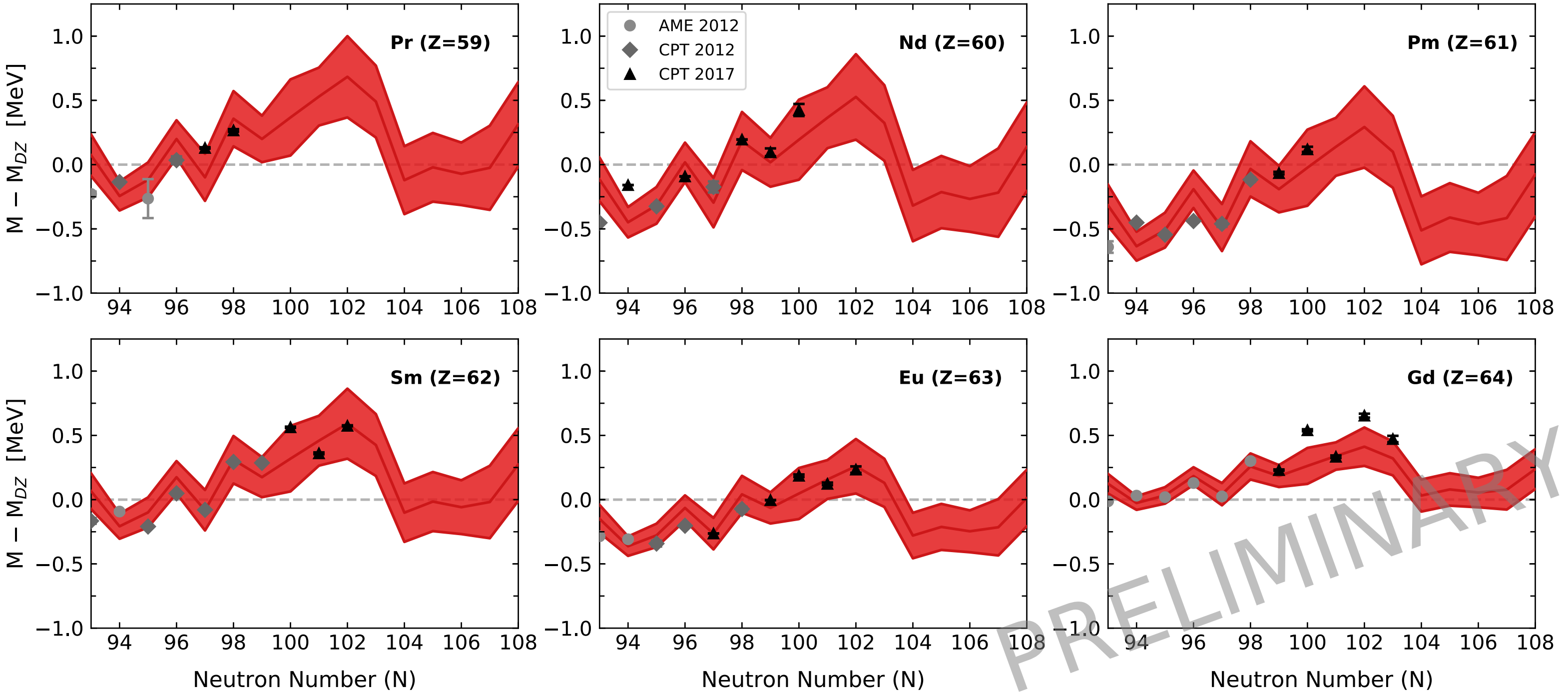
masses from CPT at CARIBU

hot, (n,γ)-(γ,n) equilibrium example

Orford+2018

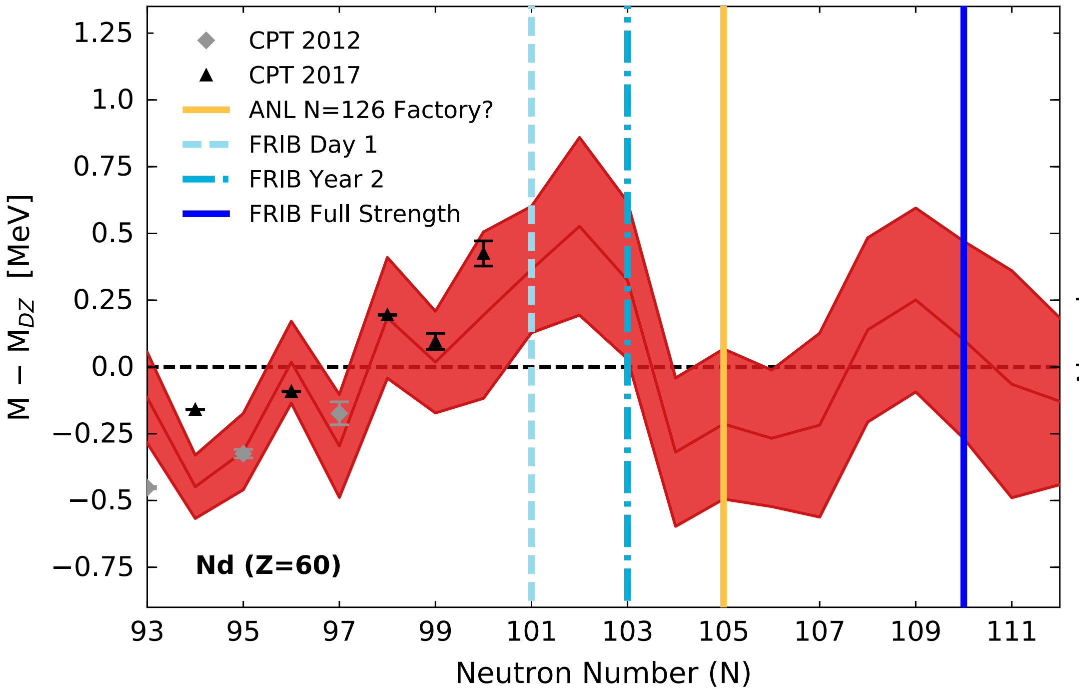


updated reverse engineering calculations + new CPT measurements

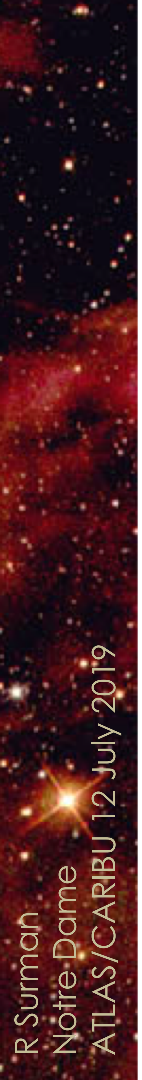


Orford+ in preparation

rare earth masses: experimental prospects



Aprahamian+18 arxiv:1809.00703

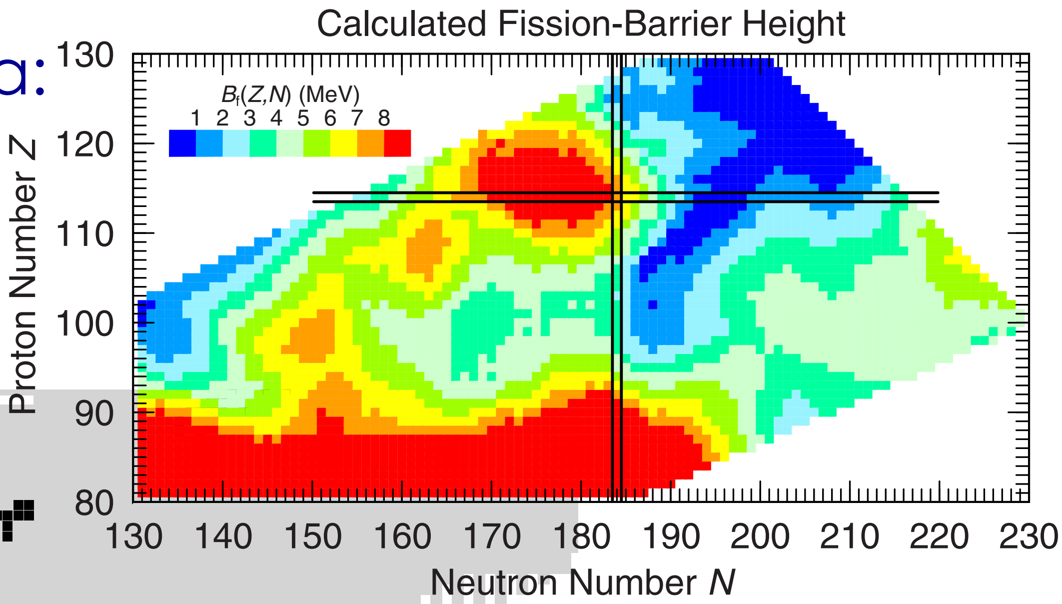


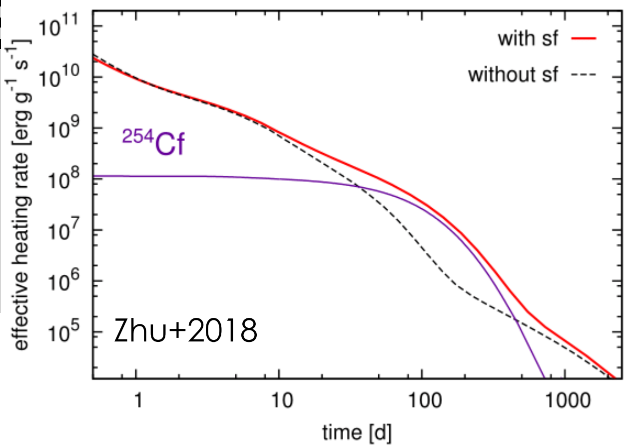
required nuclear data: fission properties

Fission In R-process Elements

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

Möller+2015





fission rates
fission product distributions
neutrino interaction rates
spallation cross sections

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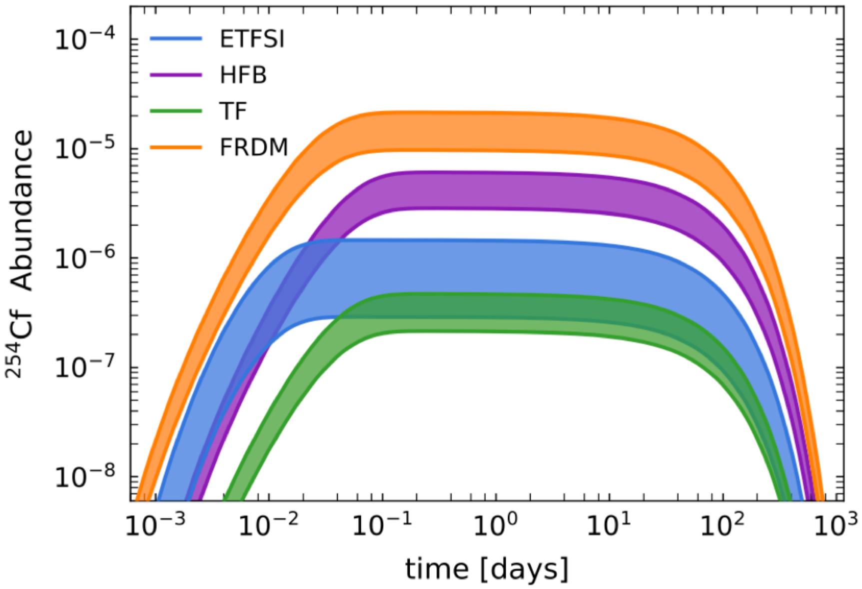
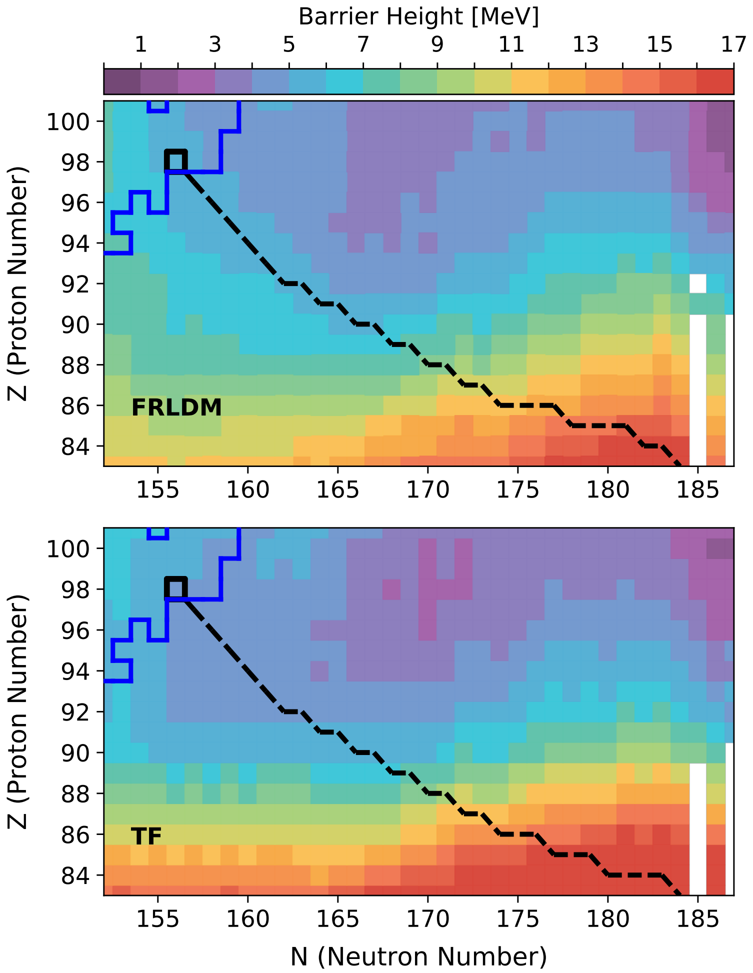
Fission barriers and ^{254}Cf production





Vassh, Vogt, Surman, Randrup, Sprouse, Mumpower, Jaffke, Shaw, Holmbeck, Zhu, McLaughlin, J Phys G 2019

summary

Detangling the origins of the heaviest elements via various neutron capture processes continues to be a key priority for nuclear astrophysics.

On the nuclear side, Argonne experiments are reaching the increasingly neutron-rich nuclei whose properties shape neutron capture nucleosynthesis and may provide key insight into the astrophysical sites of production.

We look forward to advances at CARIBU and the upcoming N=126 factory that will facilitate measurements of important masses, beta-decay properties, and indirect determinations of neutron capture rates.