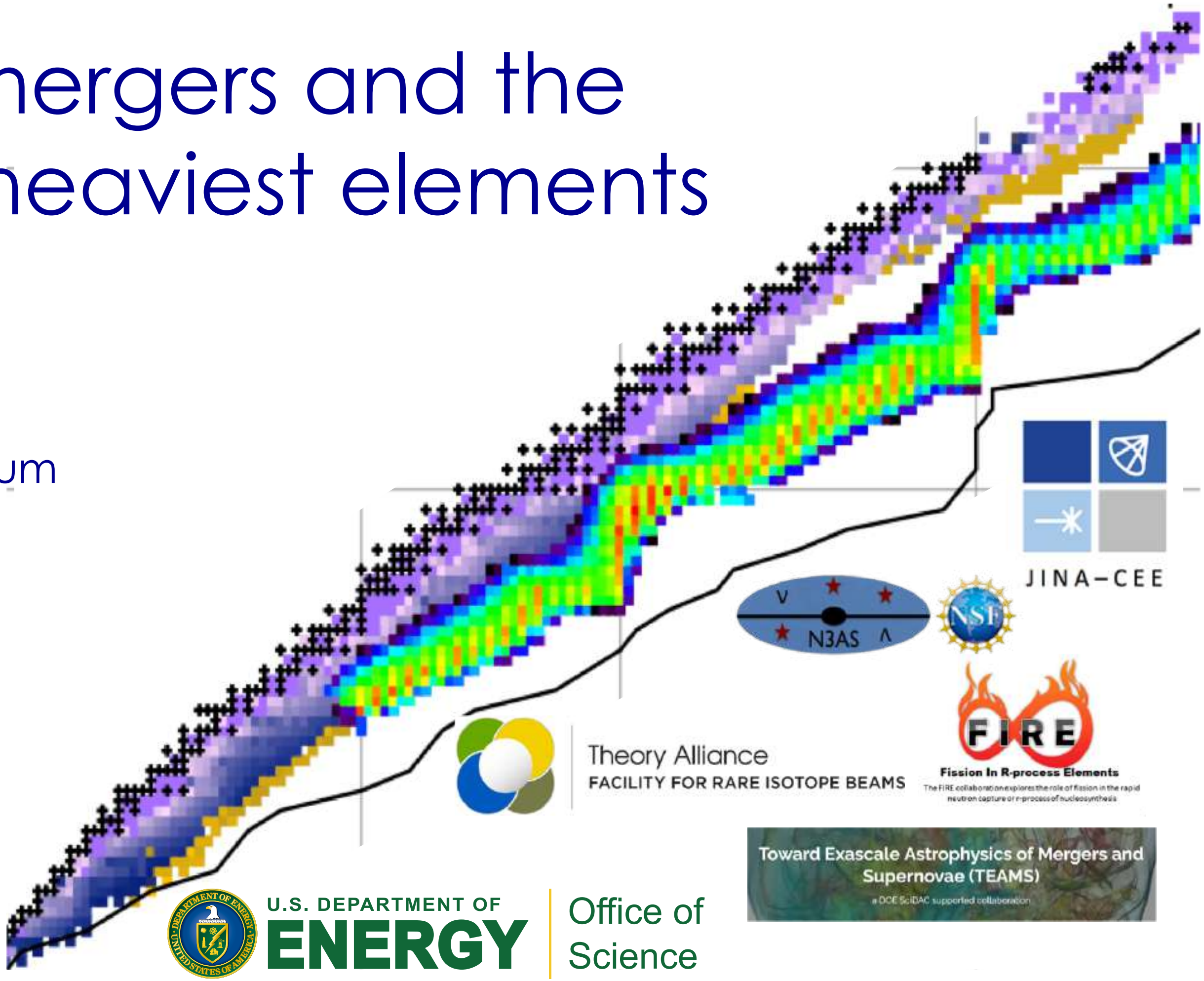
Neutron star mergers and the origins of the heaviest elements

Rebecca Surman
University of Notre Dame

Theoretical Physics Colloquium
Arizona State University

15 April 2020



UNIVERSITY OF NOTRE DAME
College of Science

JINA-CEE

N3AS

NSF

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

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

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

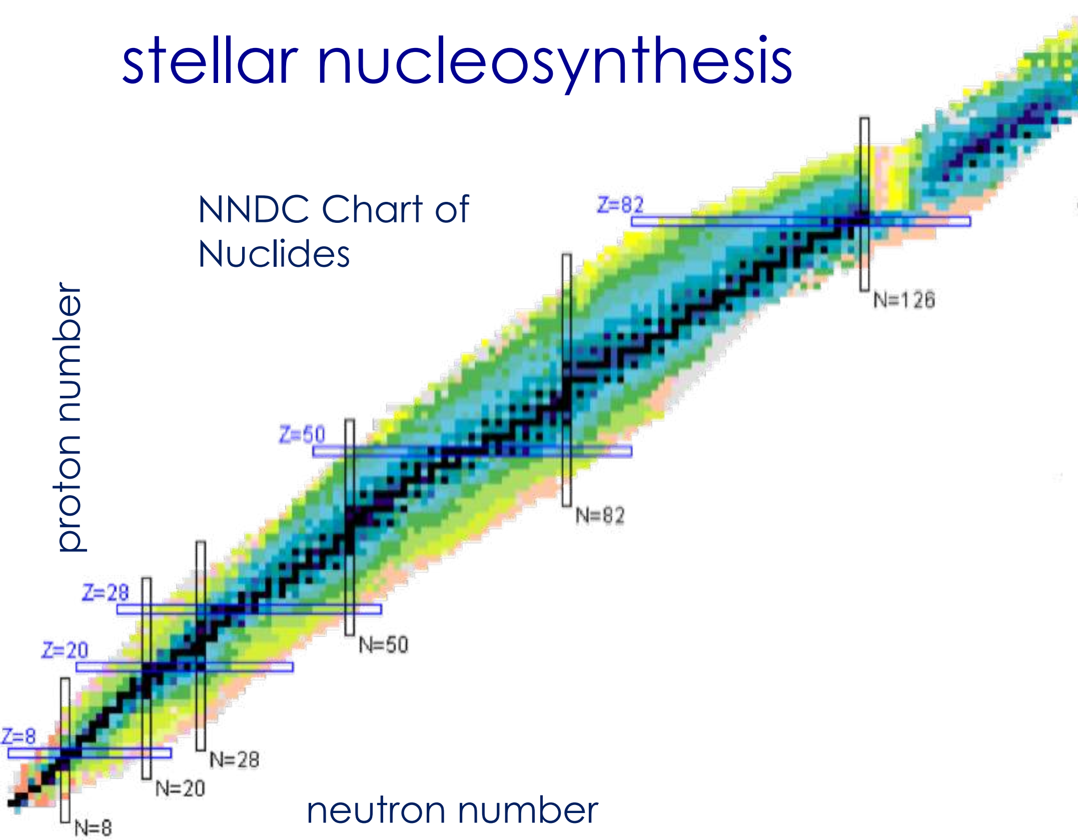
U.S. DEPARTMENT OF ENERGY | Office of Science

stellar nucleosynthesis

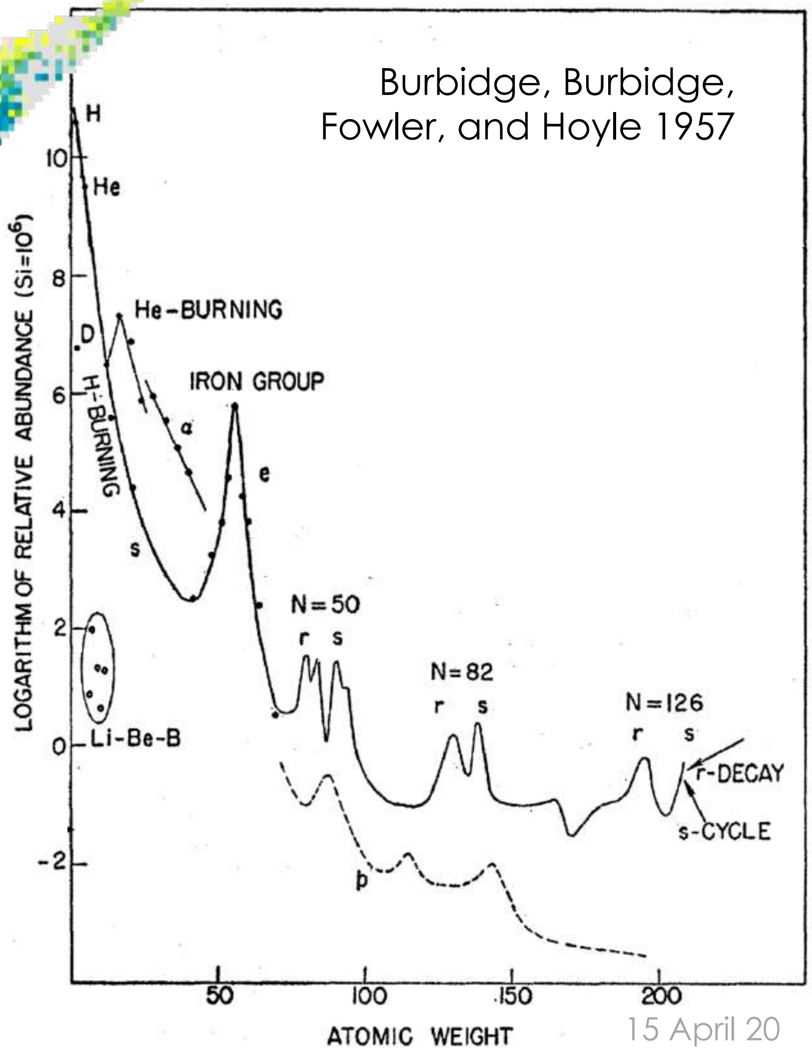
NNDC Chart of Nuclides

proton number

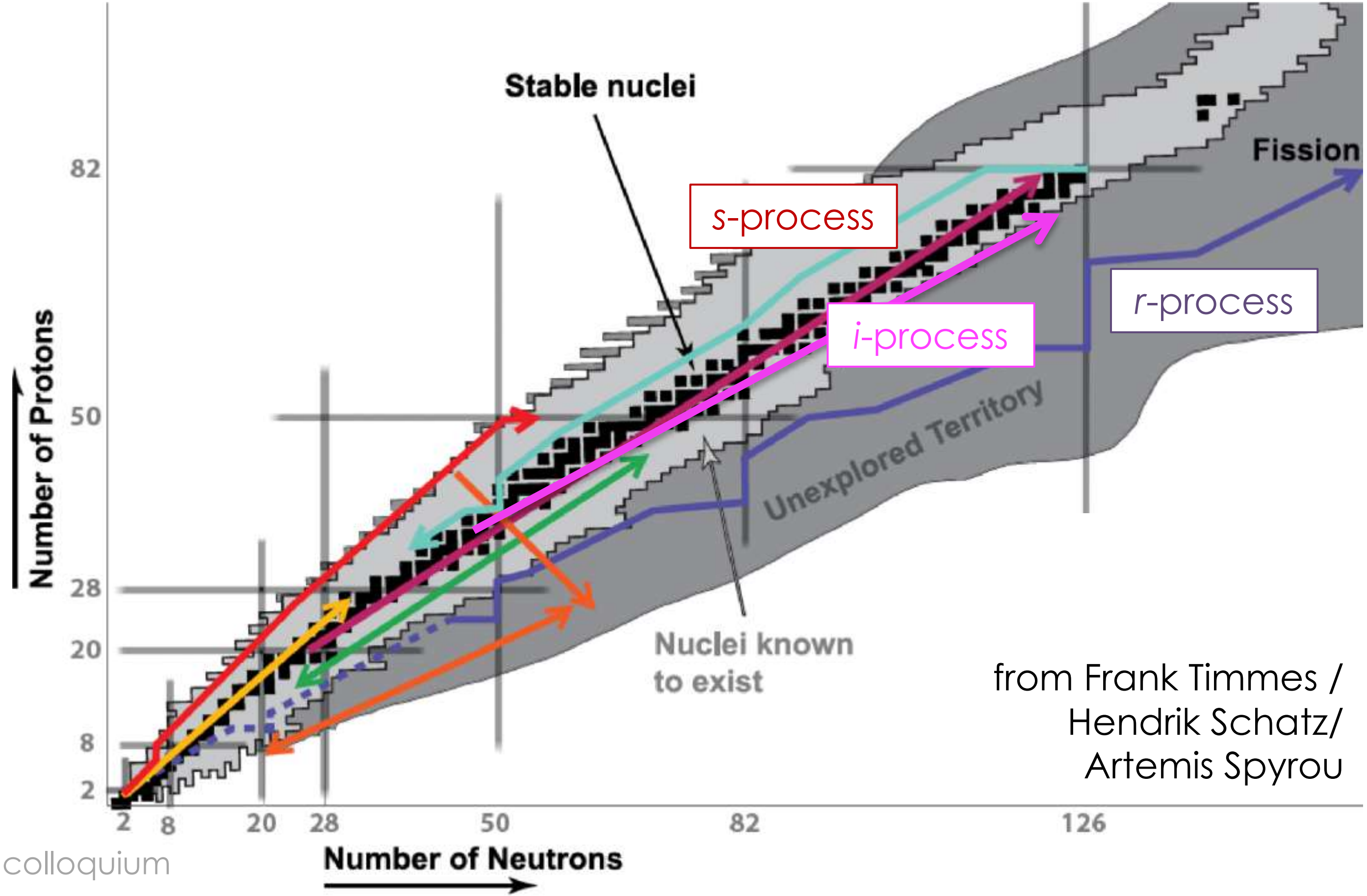
neutron number



Burbidge, Burbidge, Fowler, and Hoyle 1957

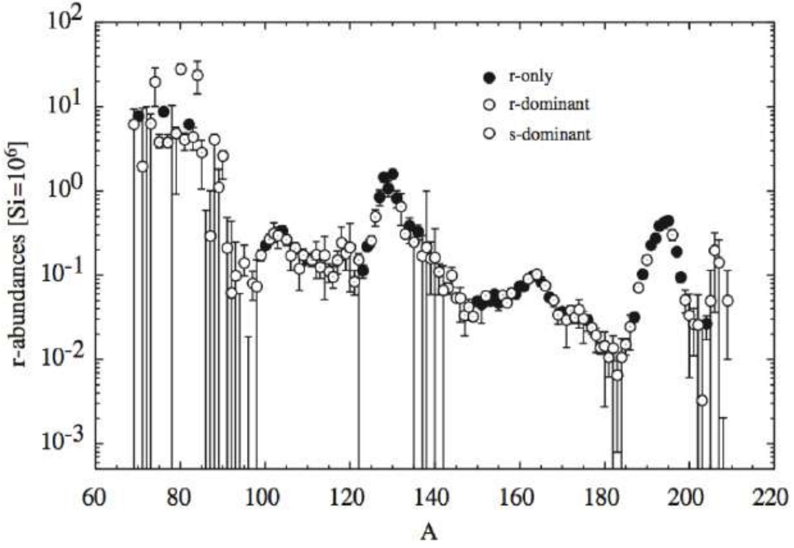


heavy element nucleosynthesis processes



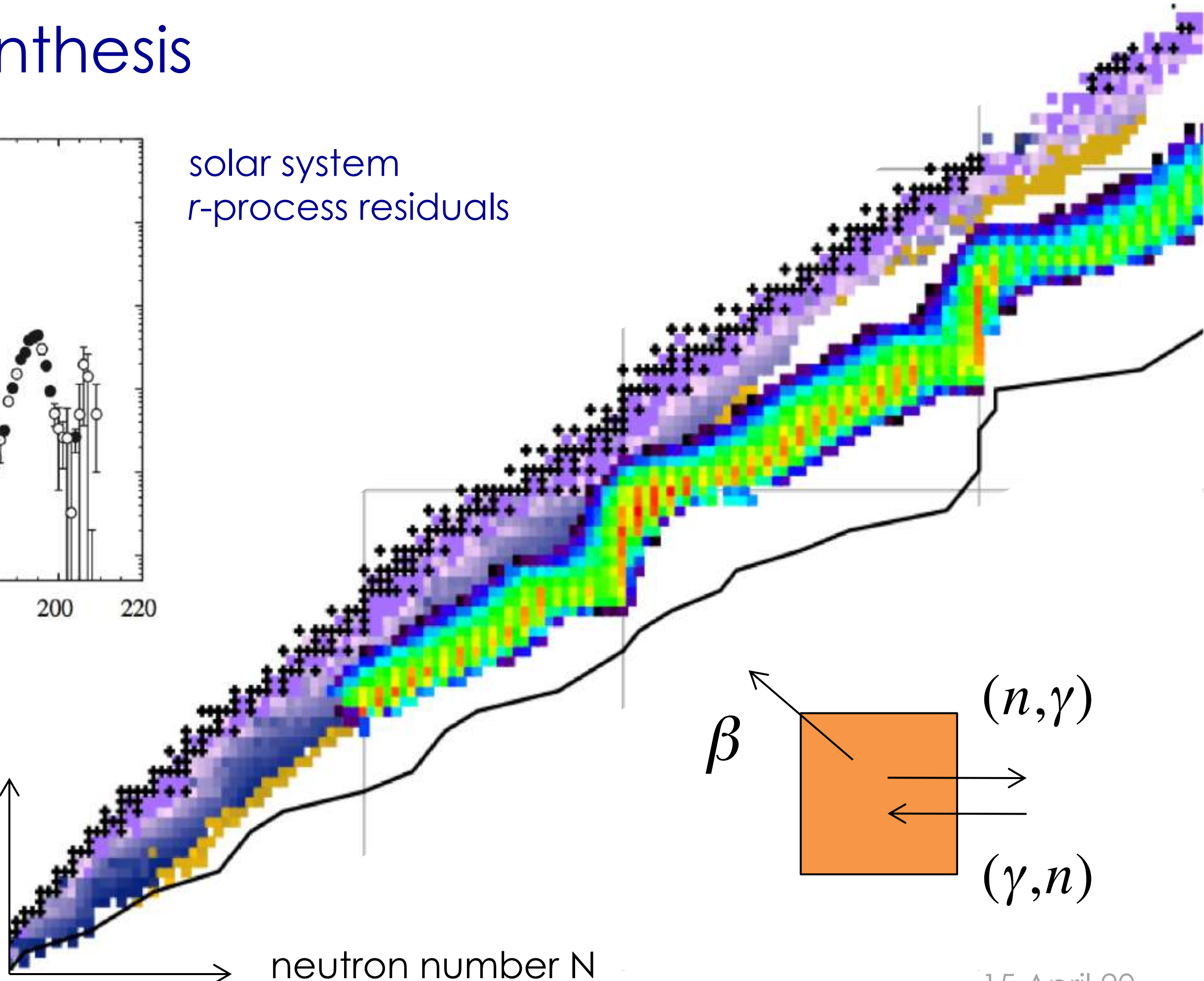
from Frank Timmes / Hendrik Schatz/ Artemis Spyrou

r-process nucleosynthesis

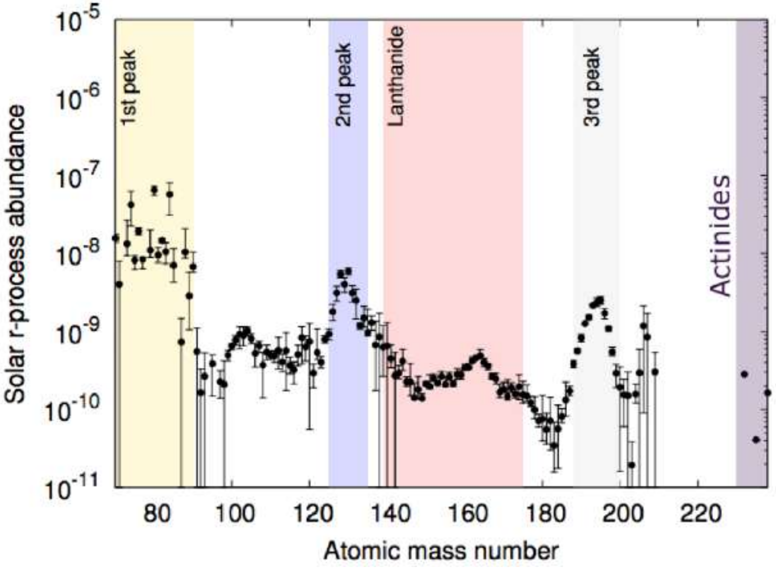


solar system
r-process residuals

Arnould+2007



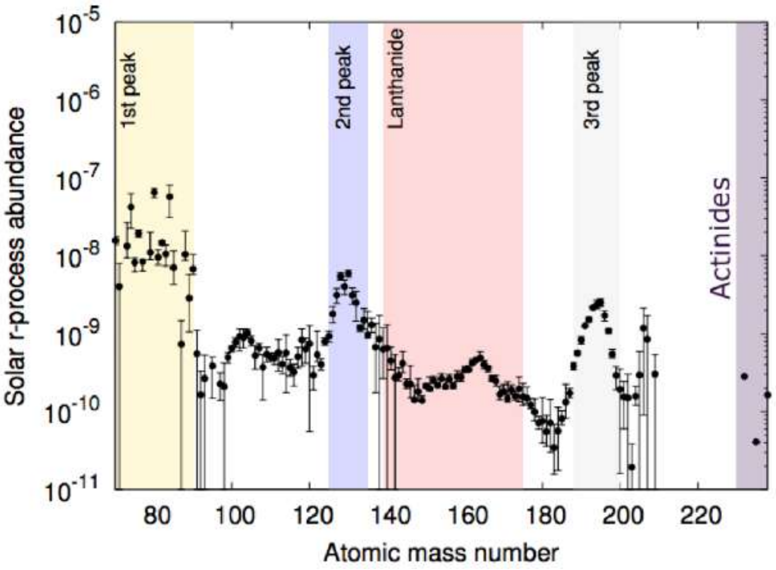
r-process observables: abundance patterns



solar system
r-process residuals

Arnould+2007,
Hotokezaka+2018

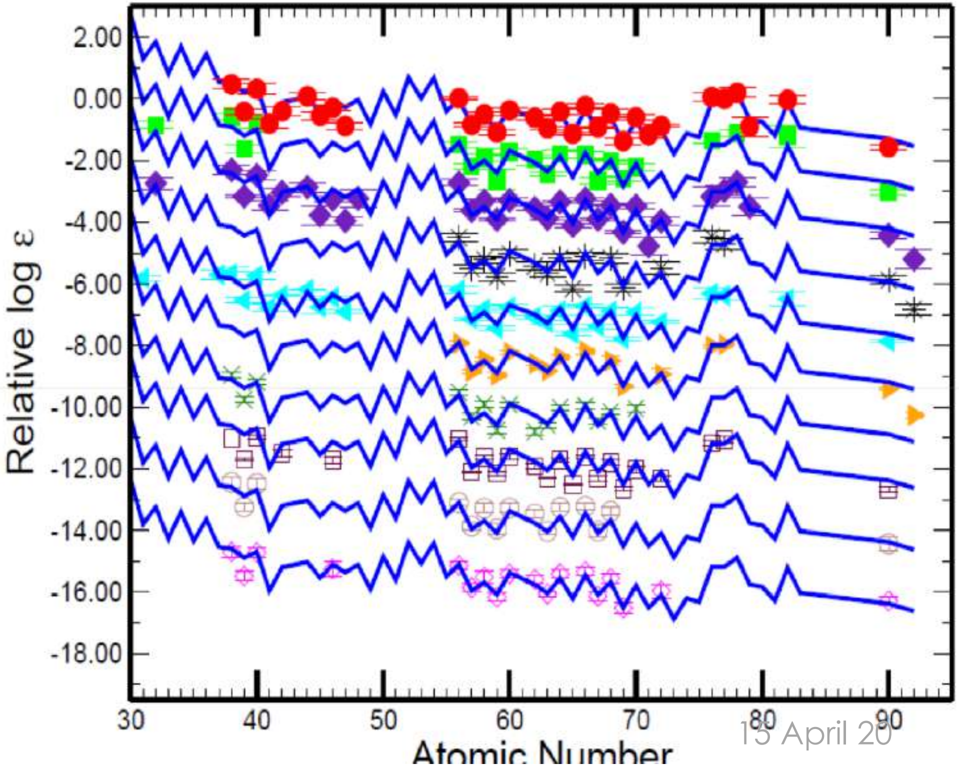
r-process observables: abundance patterns



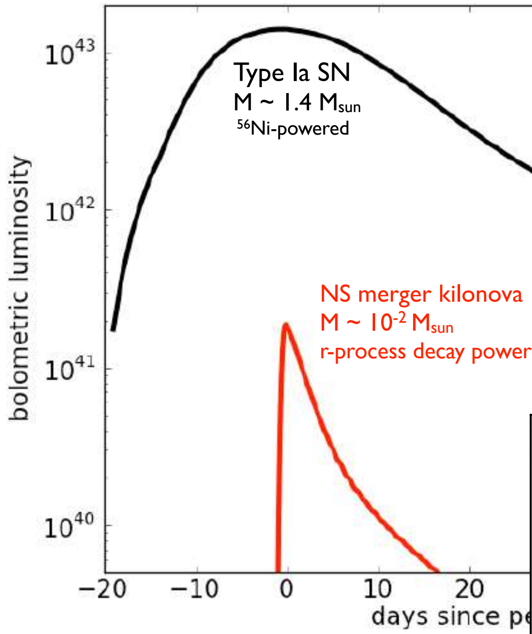
Arnould+2007,
Hotokezaka+2018

solar system
r-process residuals

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

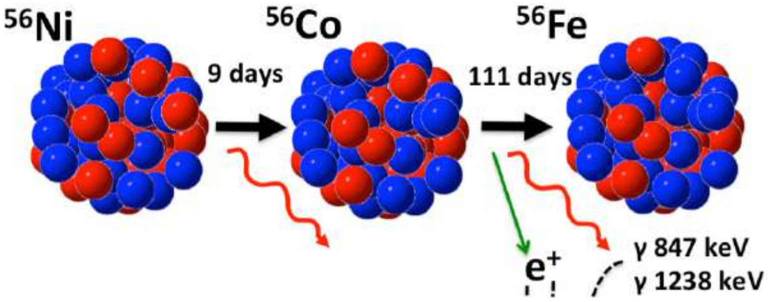


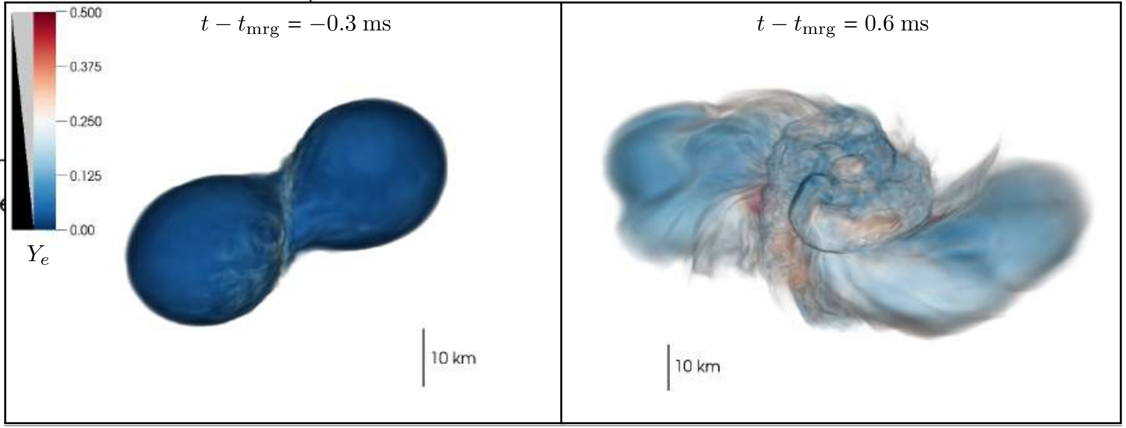
r-process observables: electromagnetic signatures



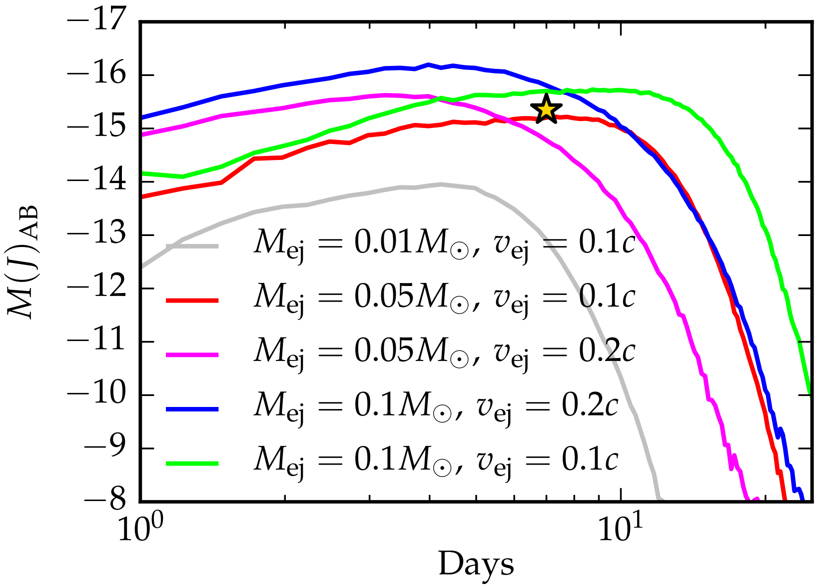
Li and Paczynski (1998)
Kulkarni (2005)
Metzger et al. (2010)
Roberts et al. (2011)
Goriely et al (2012)
Grossman et al (2013)

Barnes, Kasen 2013



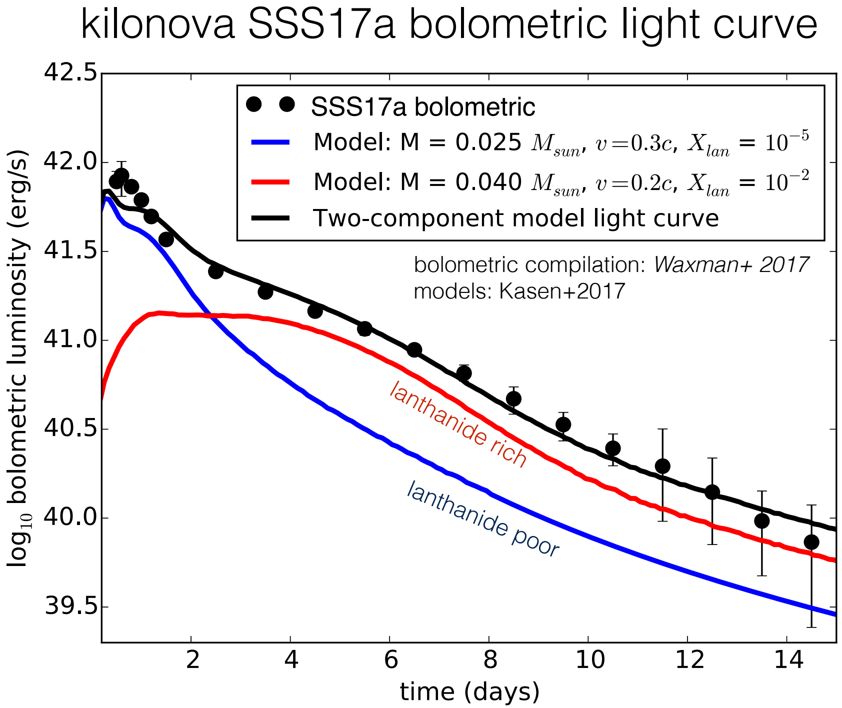


r-process observables: electromagnetic signatures

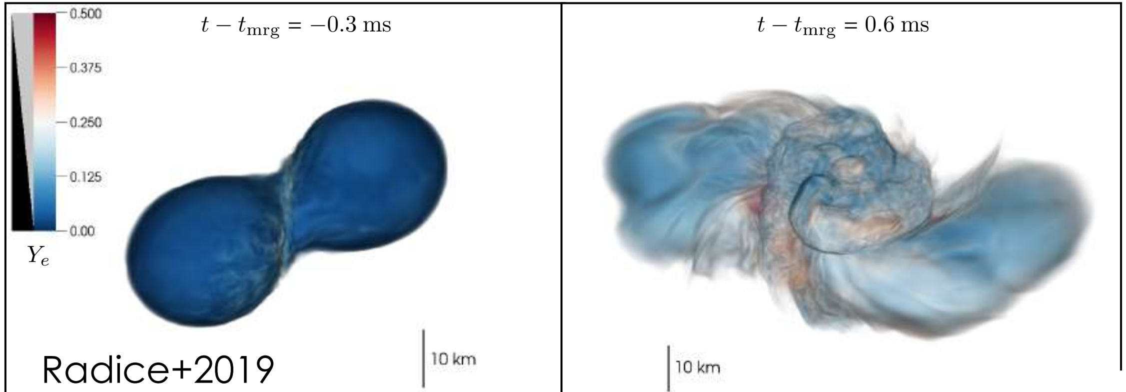


Barnes+2016
sGRB 130603B: Tanvir+2013

Kilpatrick+2017, Kasen+2017, etc.
GW170817



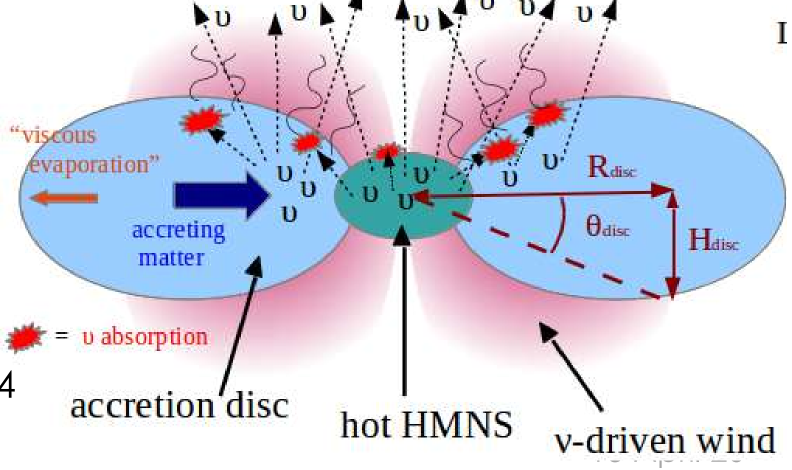
neutron star merger *r*-process environments



Radice+2019

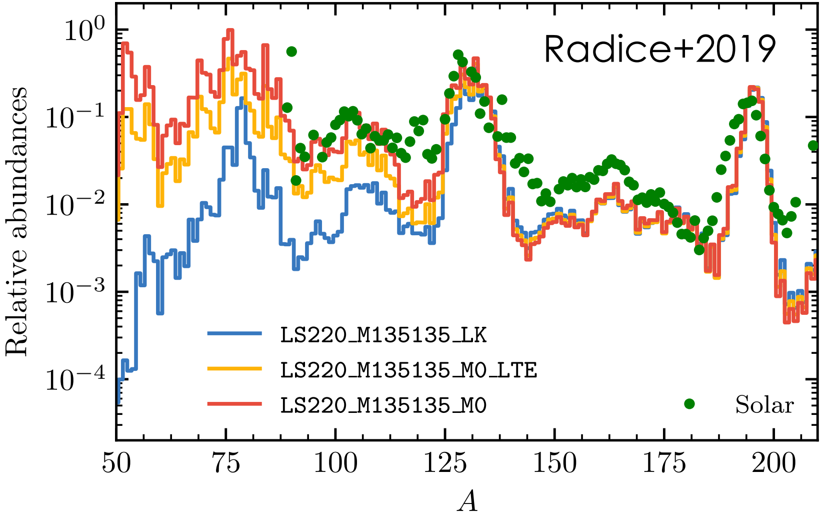
prompt ejecta

ejecta from the accretion disk



Perego+2014

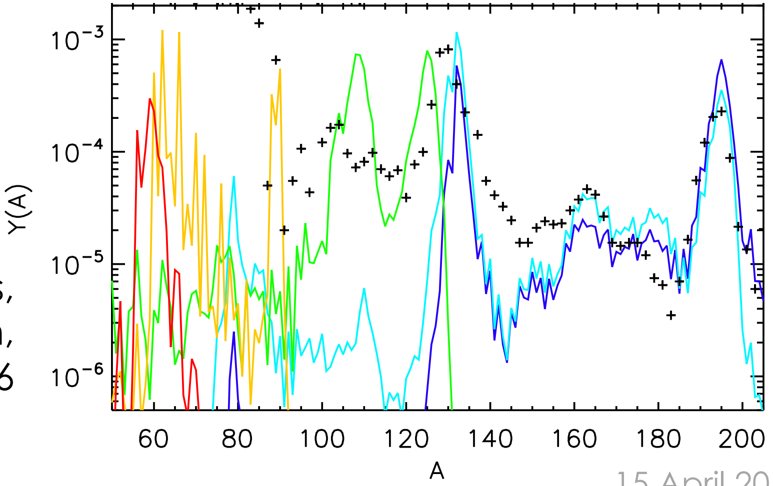
neutron star merger *r*-process environments



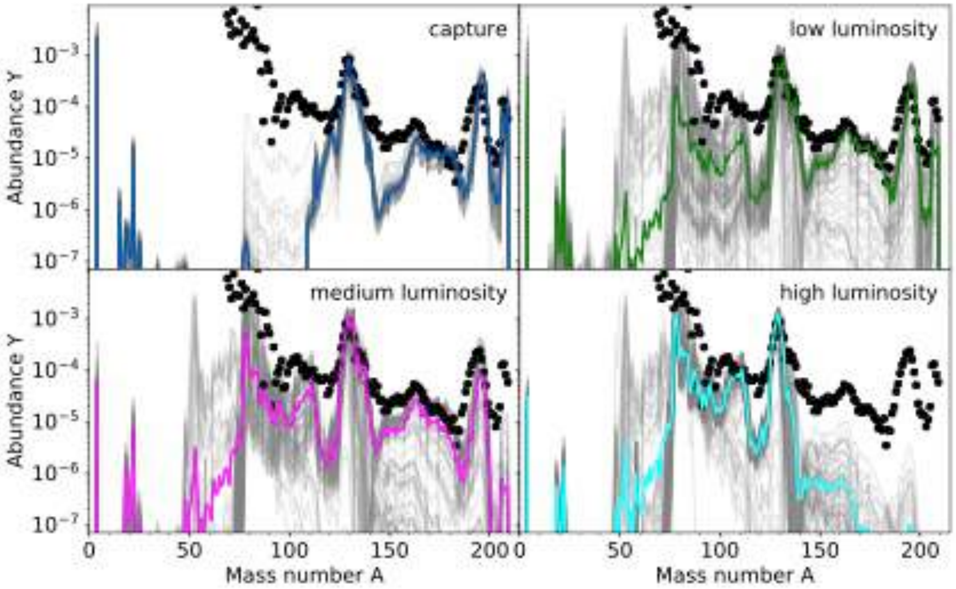
ejecta from the accretion disk

prompt ejecta

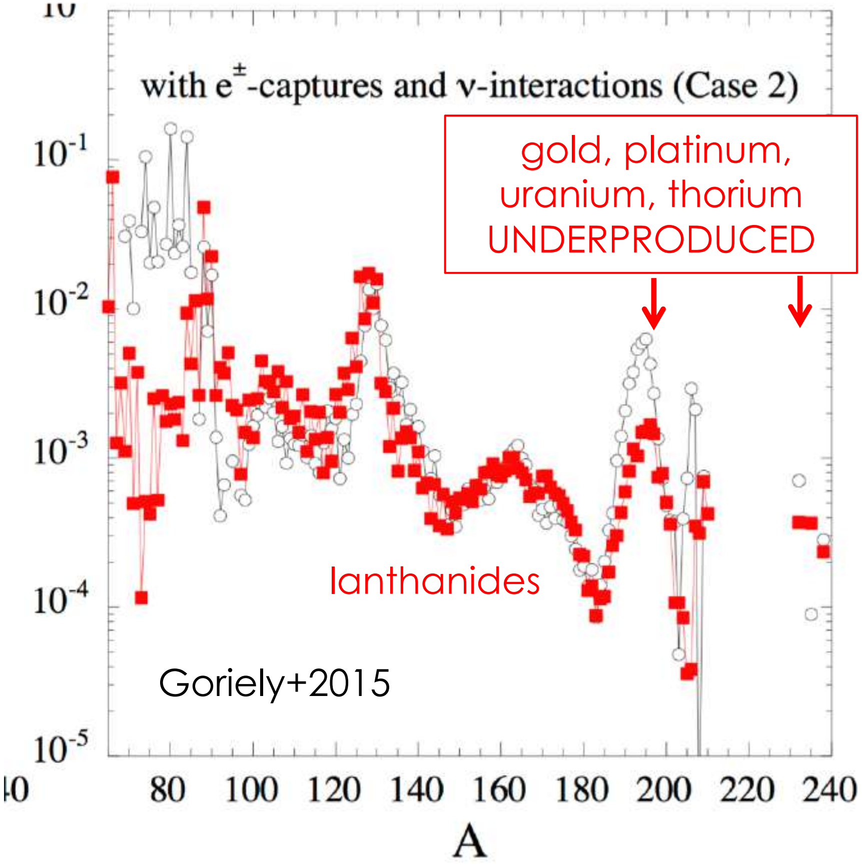
Malkus, McLaughlin, Surman 2016



nsm integrated nucleosynthesis yields



Martin+2018



gold, platinum,
uranium, thorium
UNDERPRODUCED

lanthanides

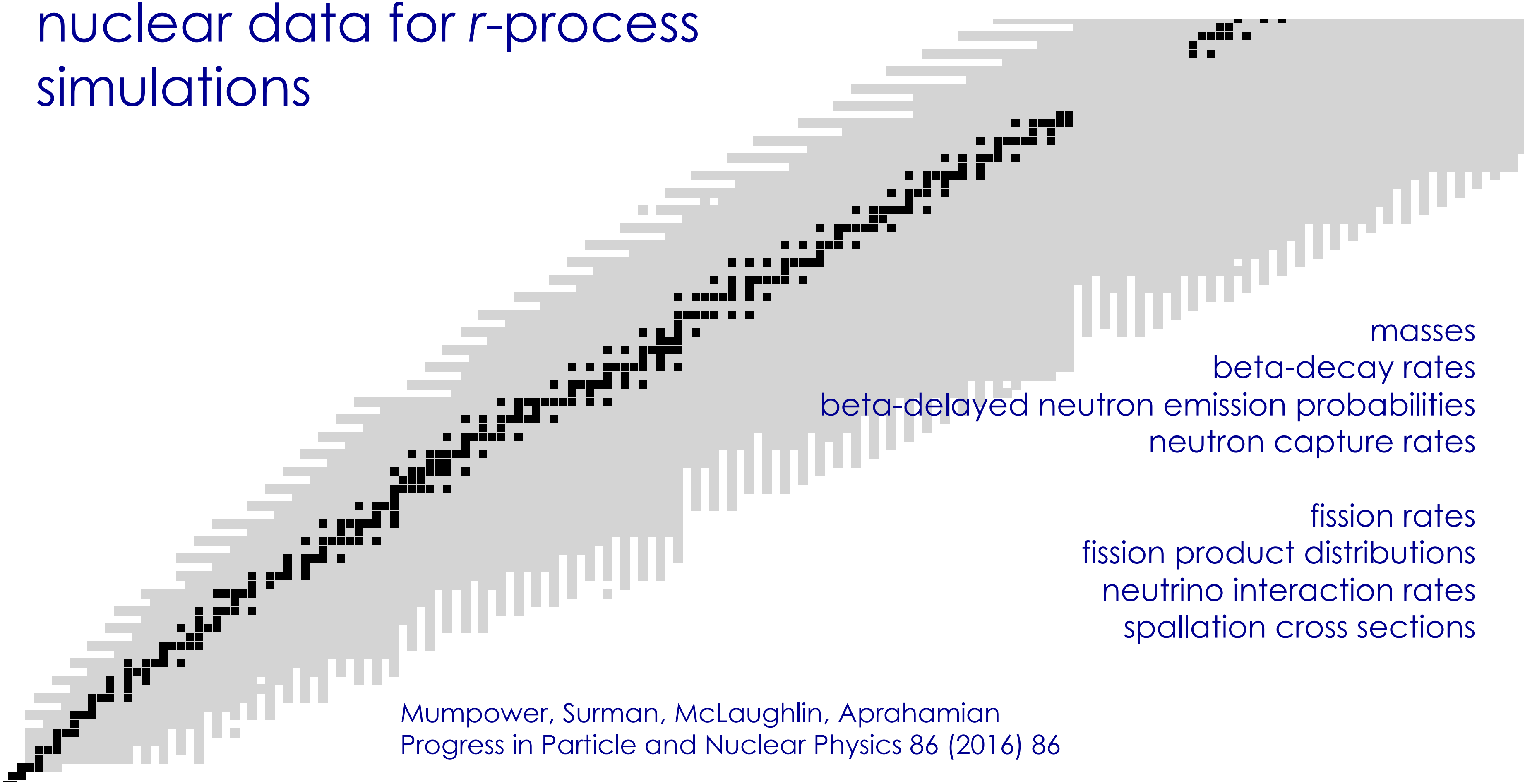
Goriely+2015

open questions in nsm/*r*-process nucleosynthesis

Can we understand neutron star merger nucleosynthesis from first principles?

Are neutron star mergers responsible for the production of all *r*-process elements, or do multiple distinct sites contribute?

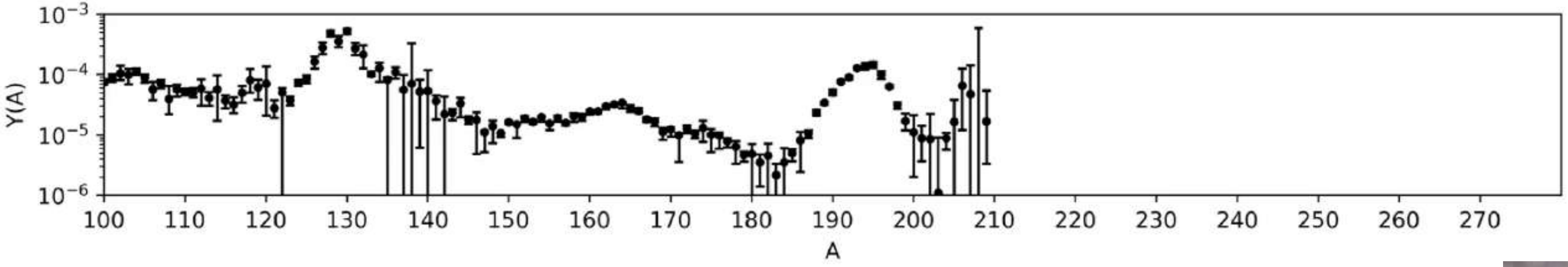
nuclear data for *r*-process simulations

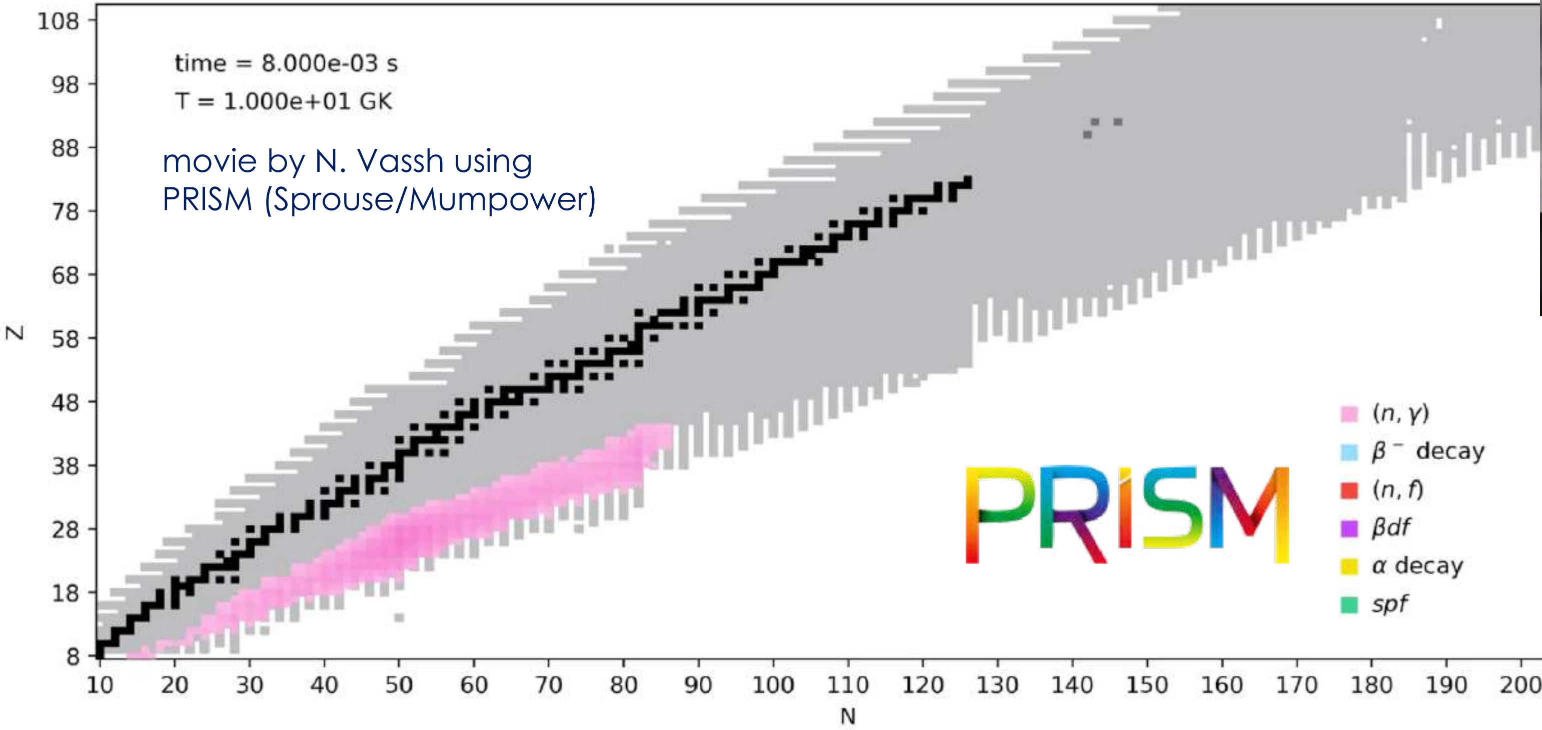


masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates

fission rates
fission product distributions
neutrino interaction rates
spallation cross sections

Mumpower, Surman, McLaughlin, Aprahamian
Progress in Particle and Nuclear Physics 86 (2016) 86



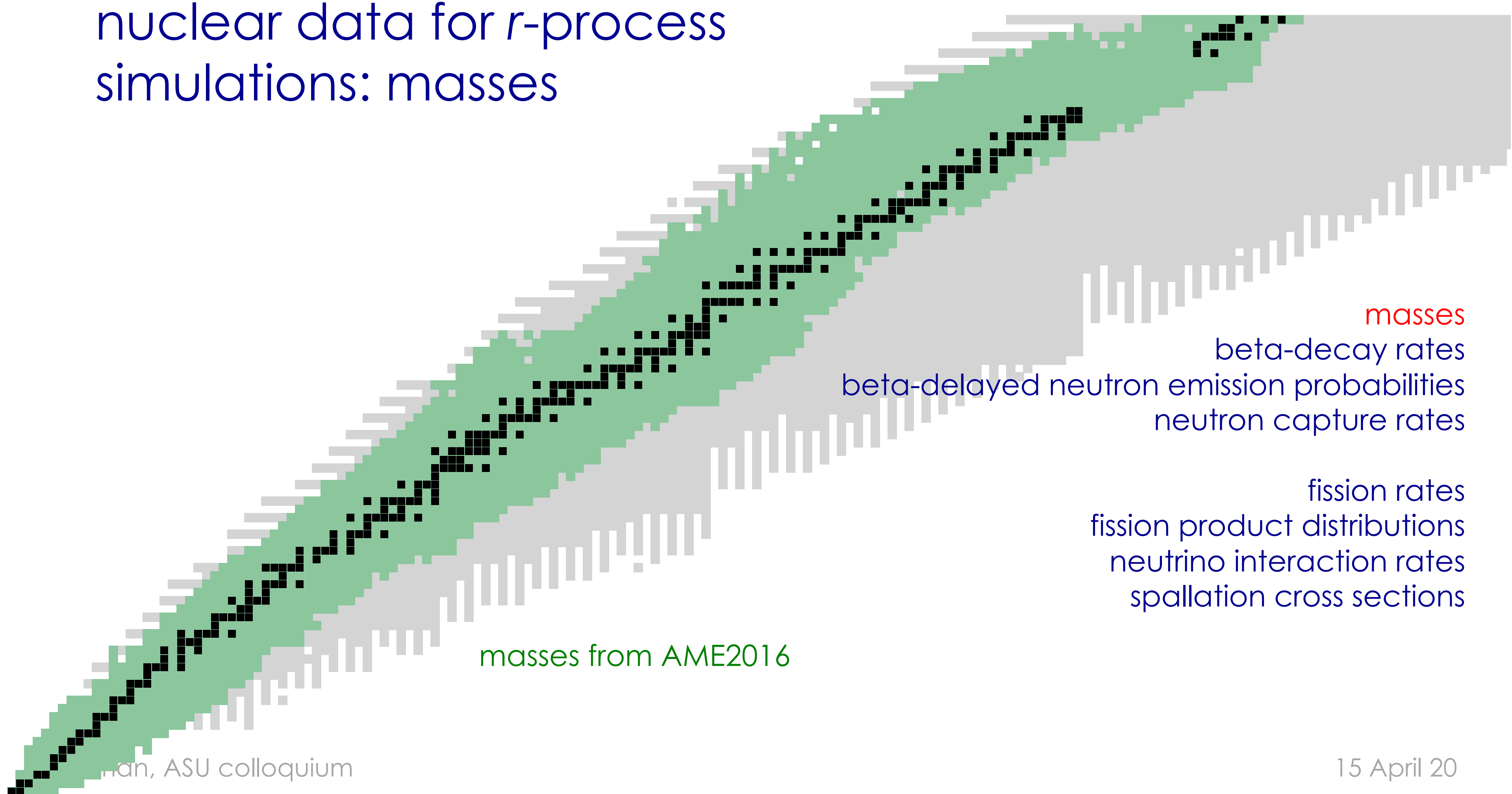


movie by N. Vassh using
PRISM (Sprouse/Mumpower)

PRISM

Trevor
Sprouse,
TEAMS/ND
grad student

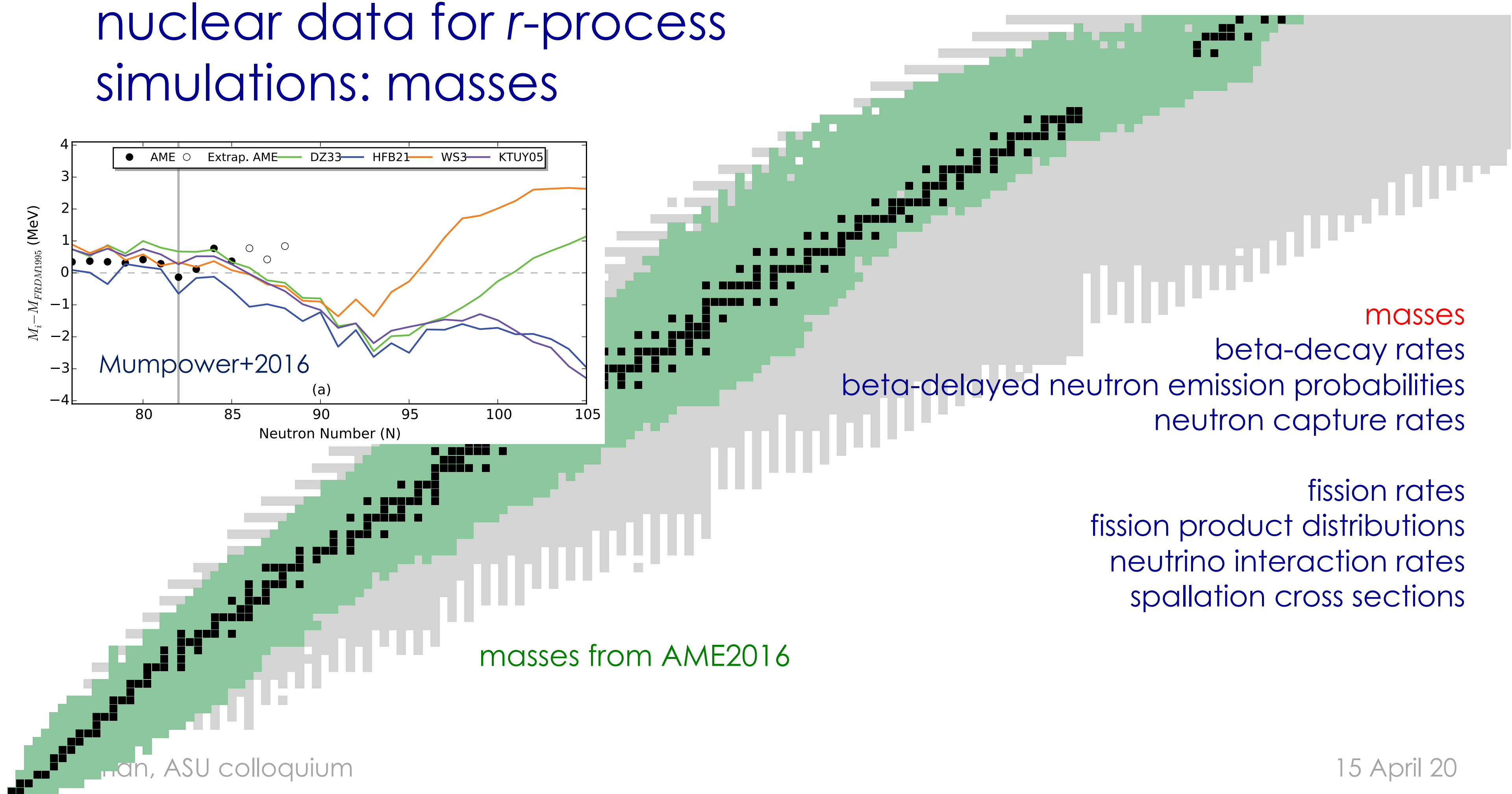
nuclear data for *r*-process simulations: masses



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

fission rates
fission product distributions
neutrino interaction rates
spallation cross sections

nuclear data for *r*-process simulations: masses



Mumpower+2016

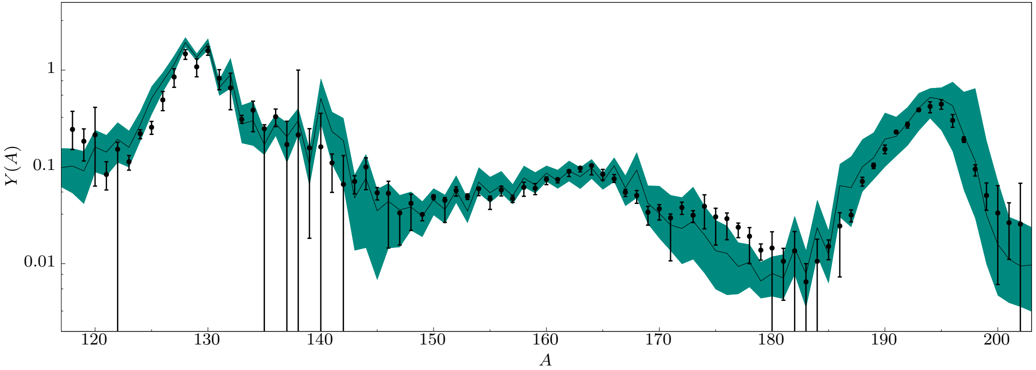
masses from AME2016

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

fission rates
fission product distributions
neutrino interaction rates
spallation cross sections

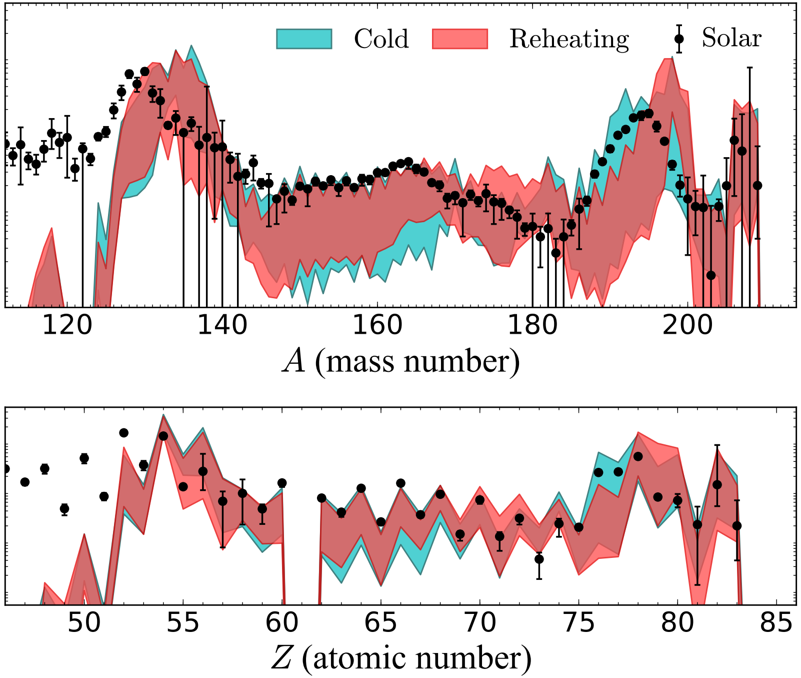
impact of mass uncertainties on abundance patterns

Abundance pattern ranges for 50 sets of masses calculated with the UNEDF1 functional



Sprouse, Navarro Perez, Surman, McLaughlin, Mumpower, Schunk
arXiv:1901.10337, accepted in PRC

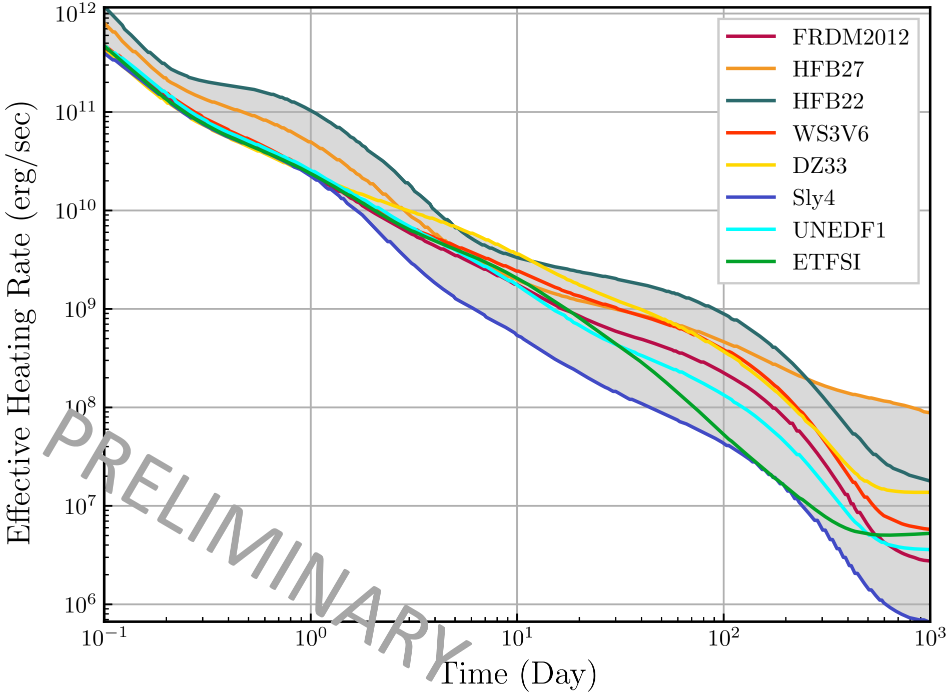
Abundance pattern ranges for 10 distinct mass models



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

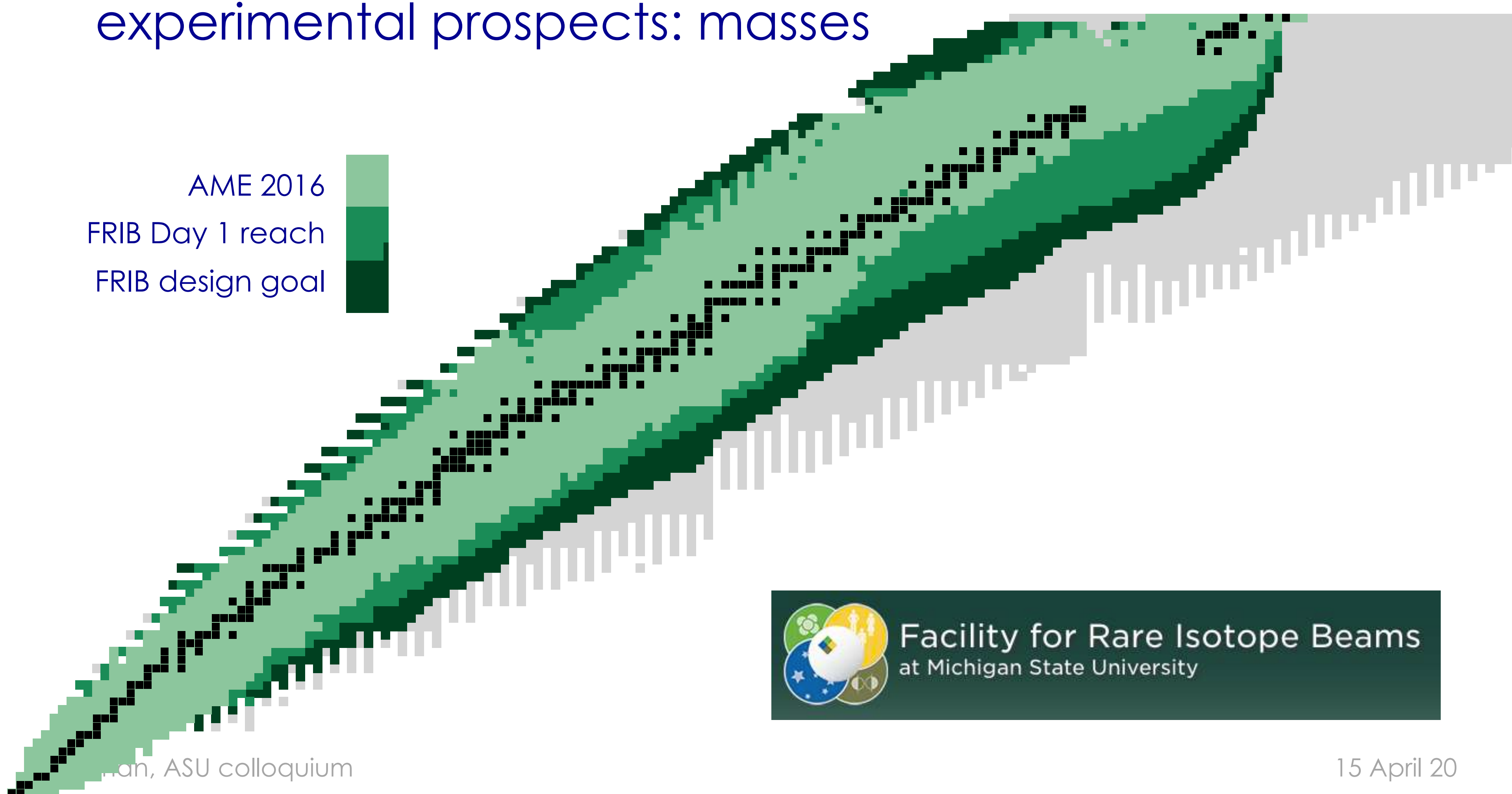
impact of mass uncertainties on kilonova heating rates

Yonglin Zhu,
FIRE/NCSU
grad student



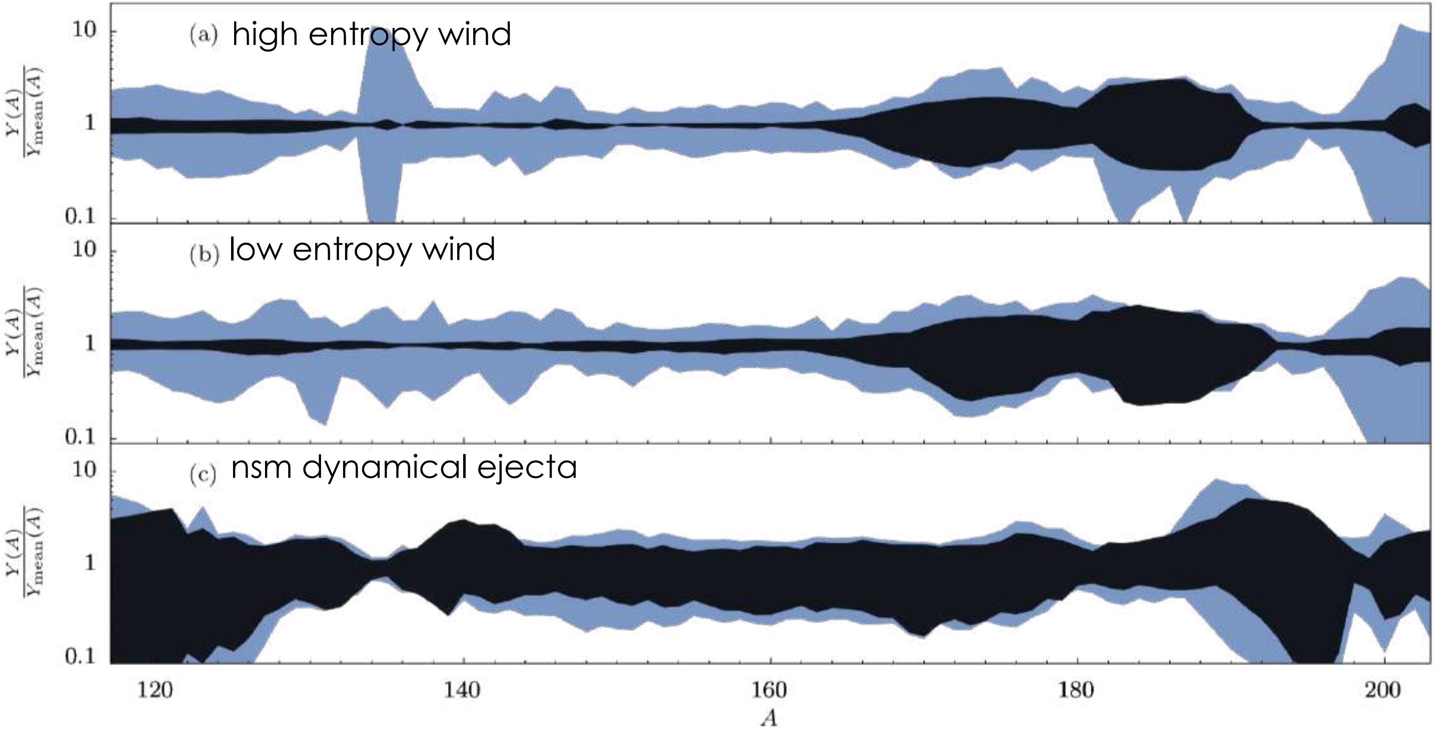
Zhu+ in preparation

experimental prospects: masses



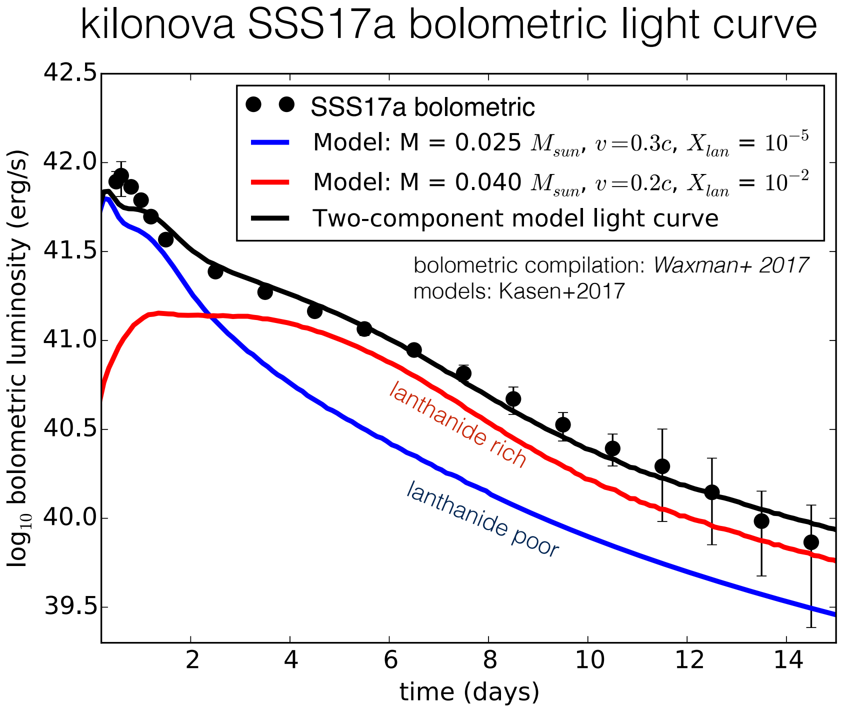
Facility for Rare Isotope Beams
at Michigan State University

experimental prospects: masses

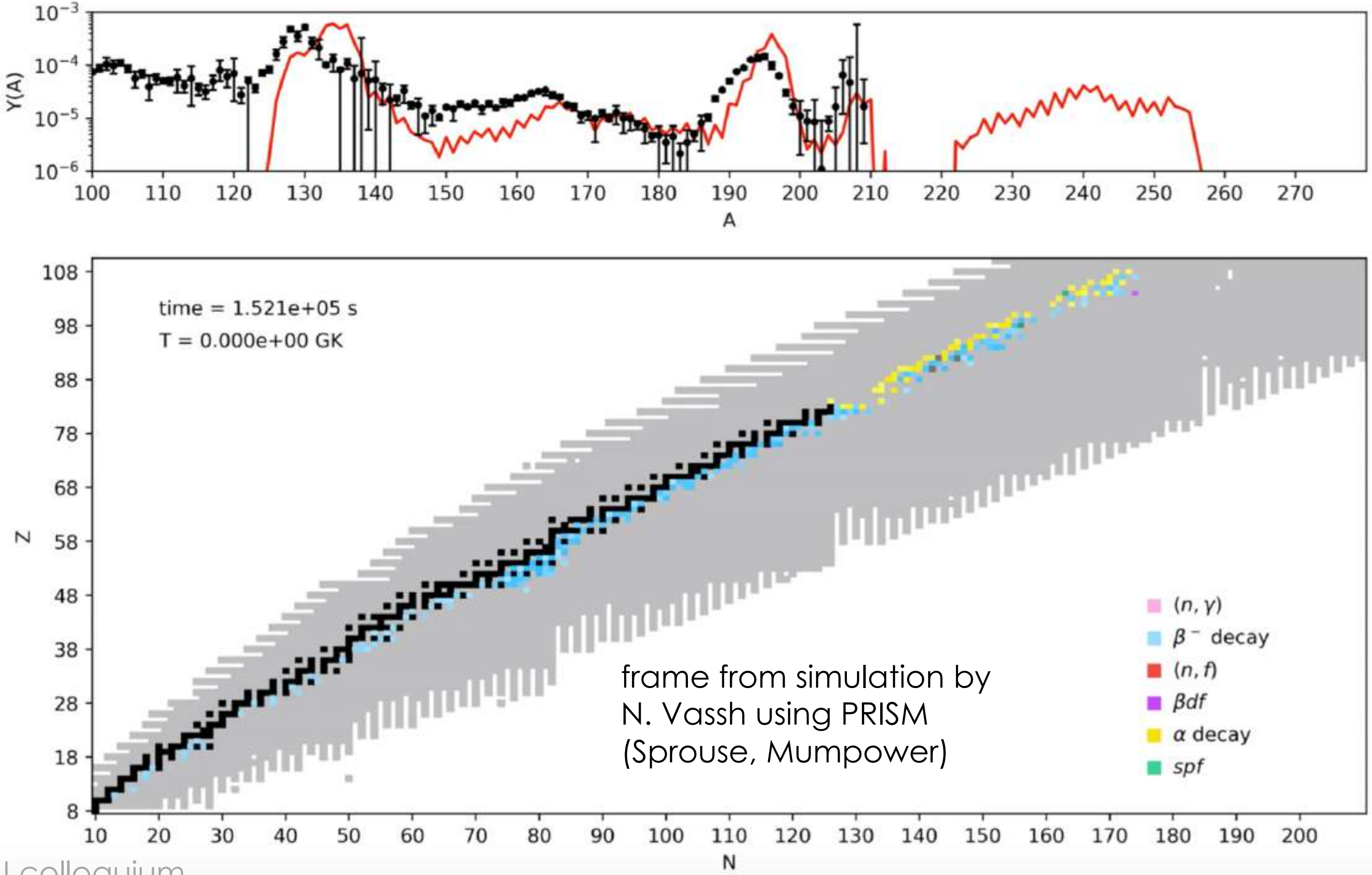


Sprouse, Navarro Perez, Surman, McLaughlin, Mumpower, Schunk
arXiv:1901.10337, accepted in PRC

kilonova signatures

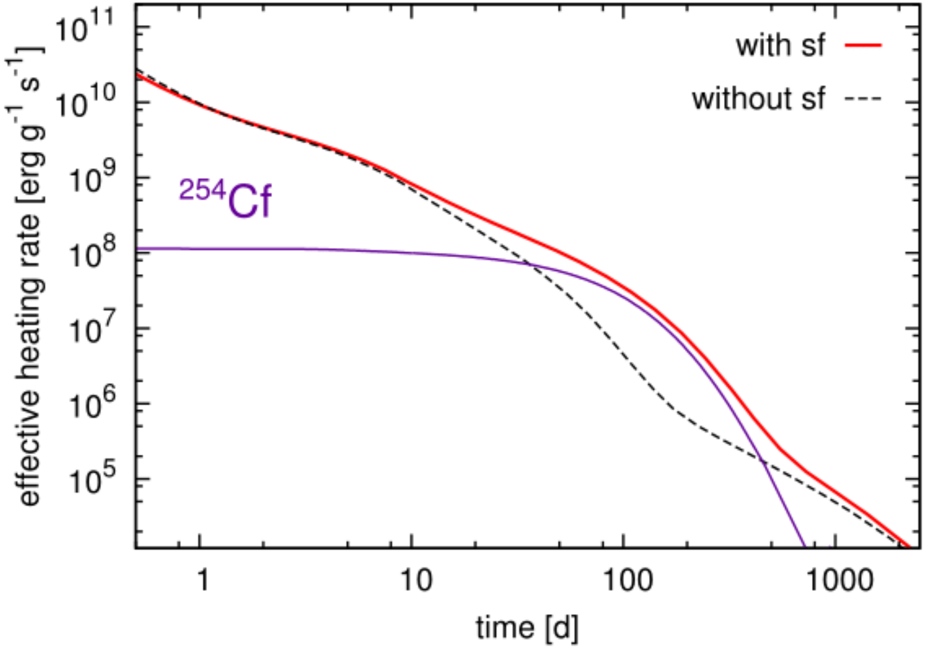


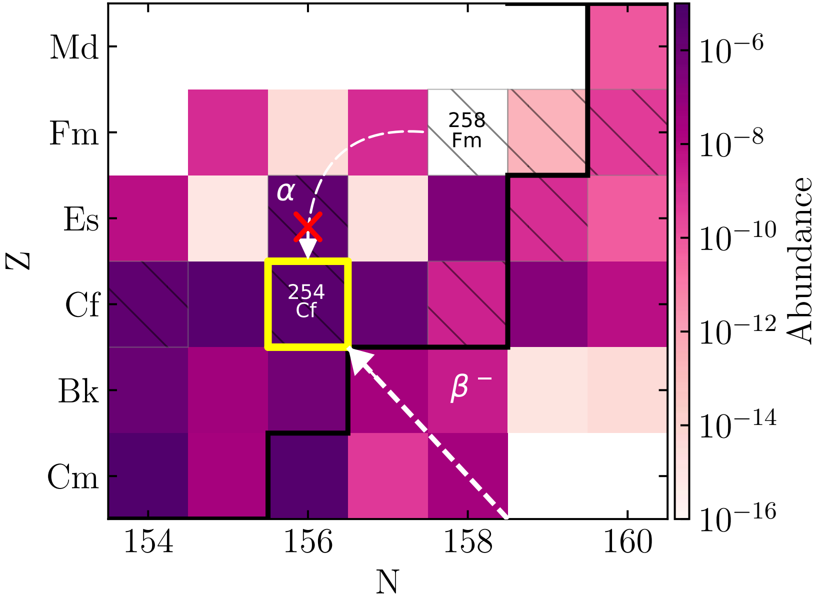
signature of actinide production?



frame from simulation by N. Vassh using PRISM (Sprouse, Mumpower)

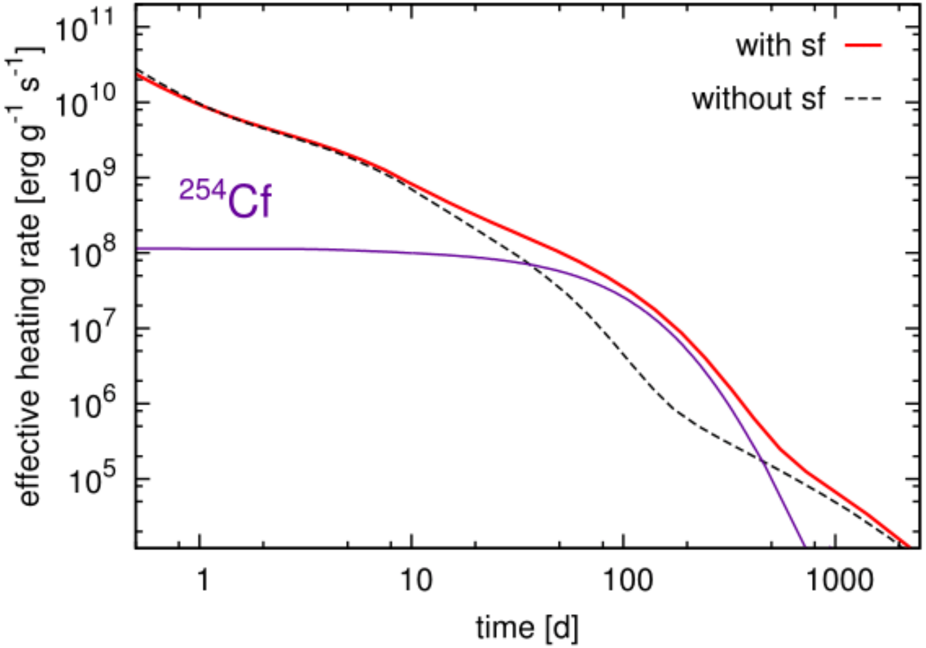
^{254}Cf and late-time radioactive heating

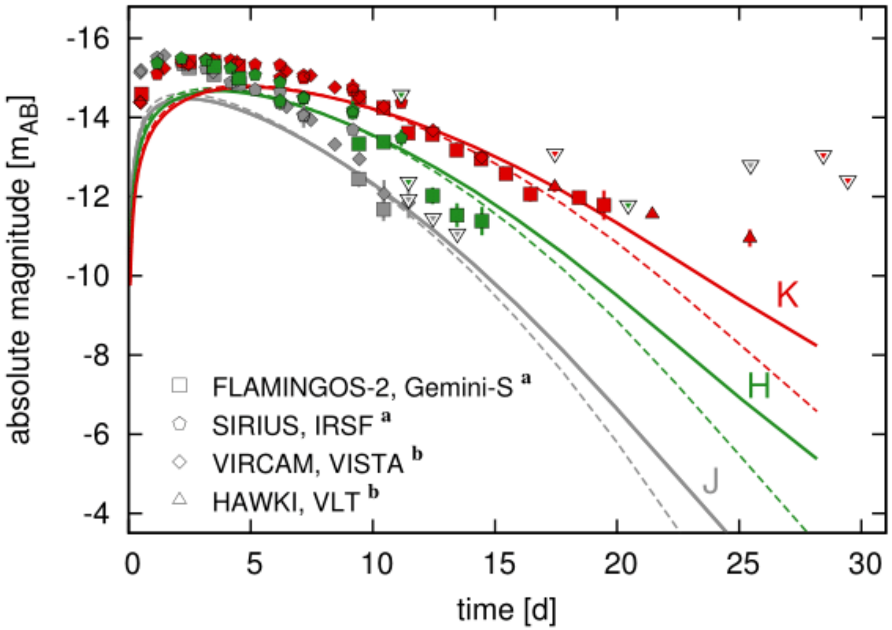




Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, ApJL 2018

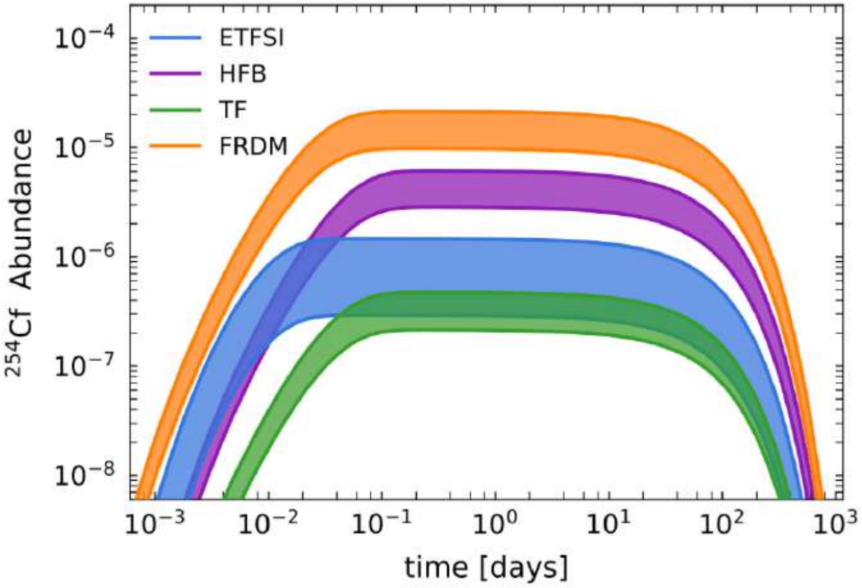
^{254}Cf and late-time radioactive heating

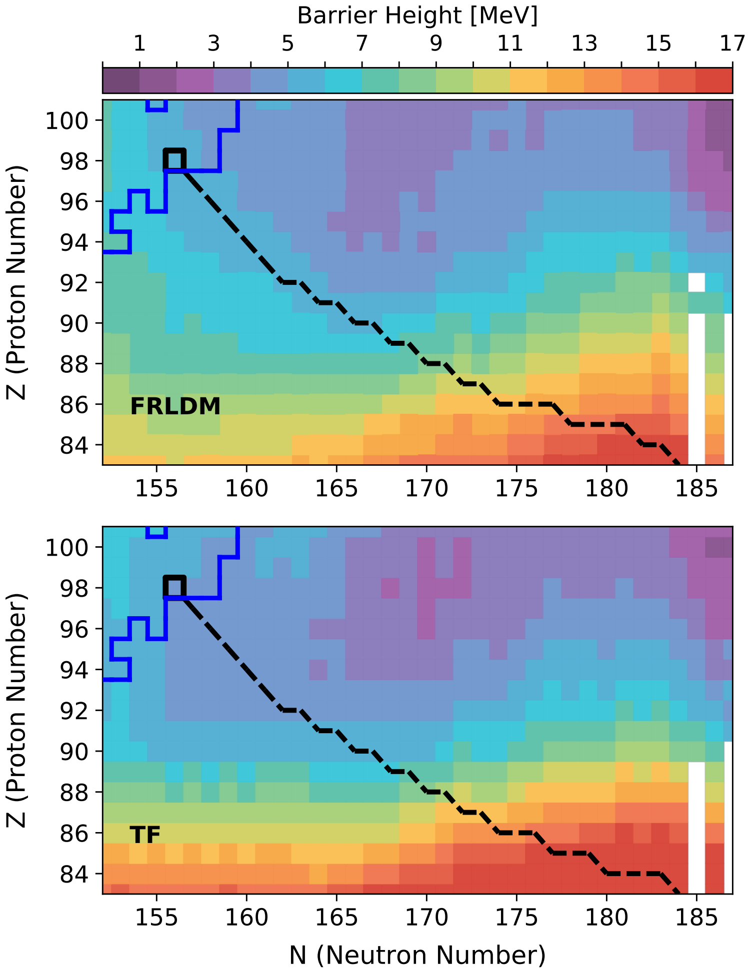




Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, ApJL 2018

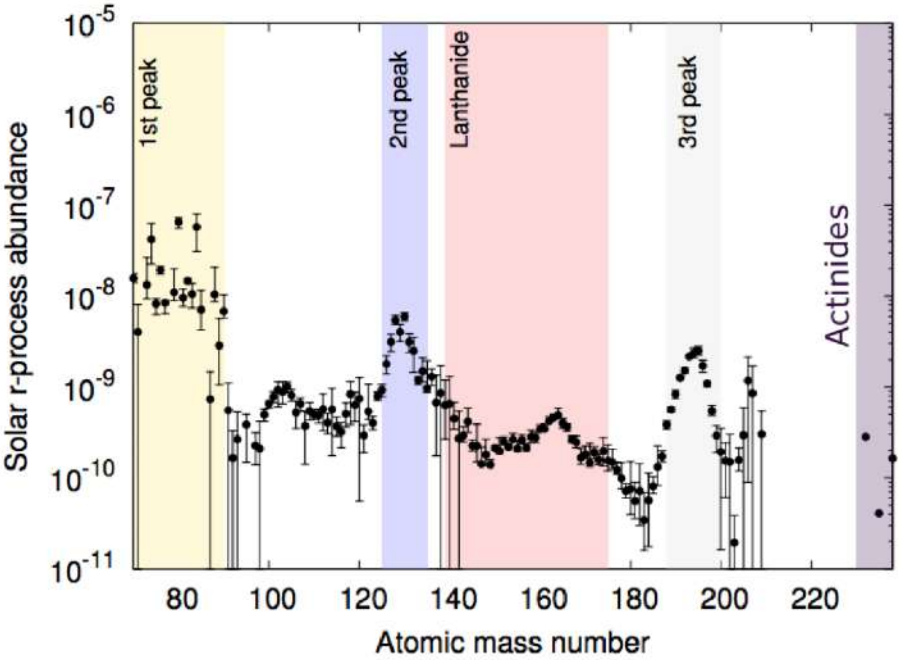
^{254}Cf: nuclear uncertainties





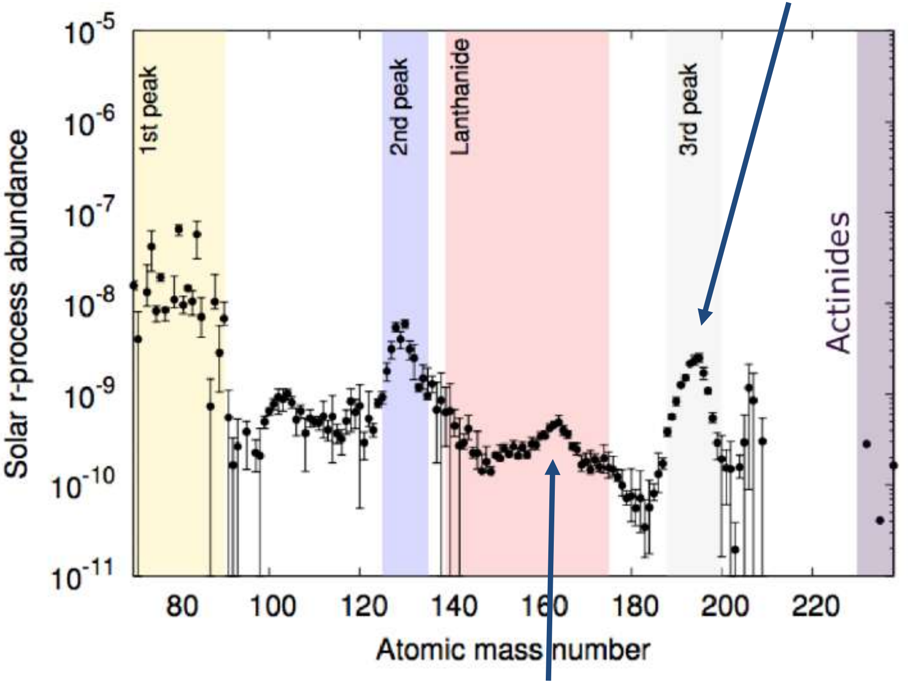
Vassh, Vogt, Surman, Randrup, Sprouse,
Mumpower, Jaffke, Shaw, Holmbeck, Zhu,
McLaughlin, J Phys G 2019

abundance pattern signatures



Arnould+2007,
Hotokezaka+2018

abundance pattern signatures



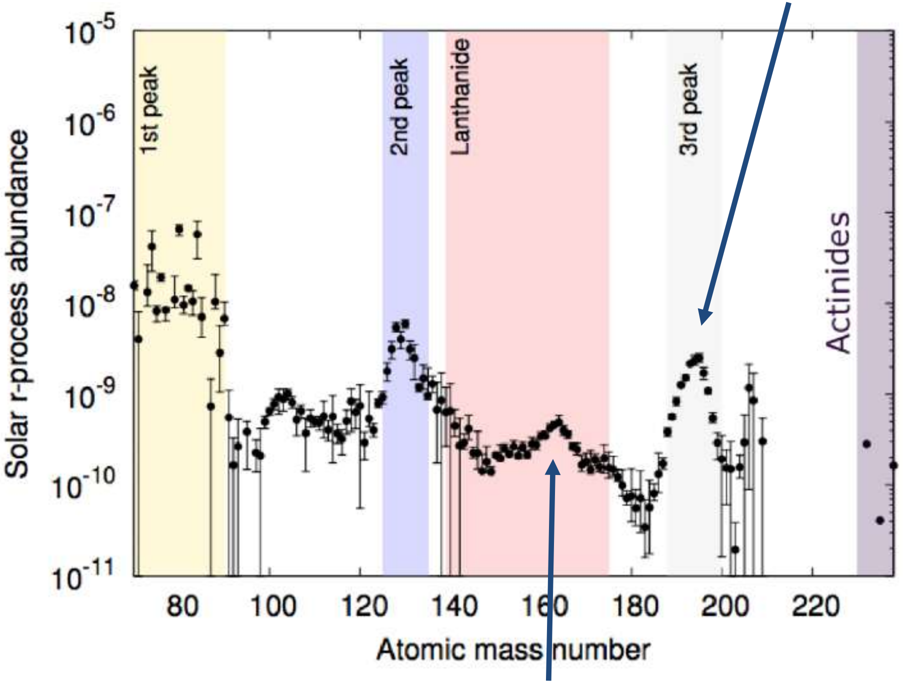
spallation and the 3rd peak

actinide boost

mass model reverse engineering
for rare earth peak formation

Arnould+2007,
Hotokezaka+2018

abundance pattern signatures



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Arnould+2007,
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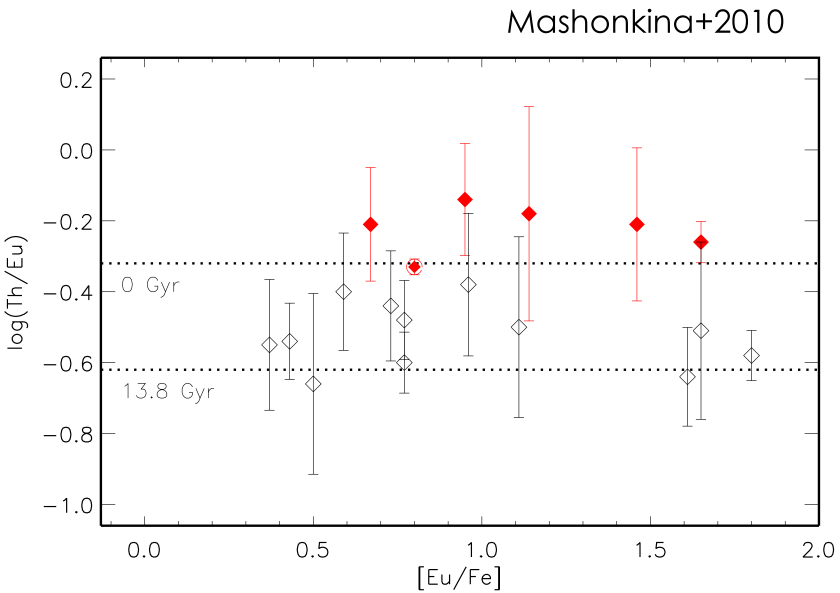
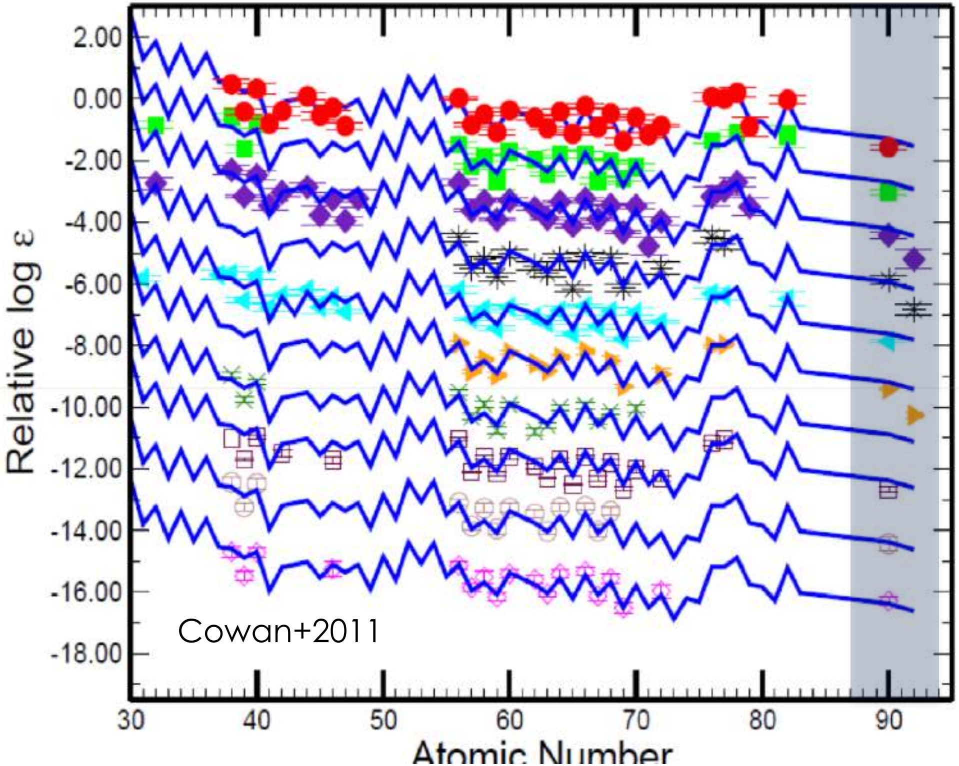
actinide production: clues from metal-poor stars

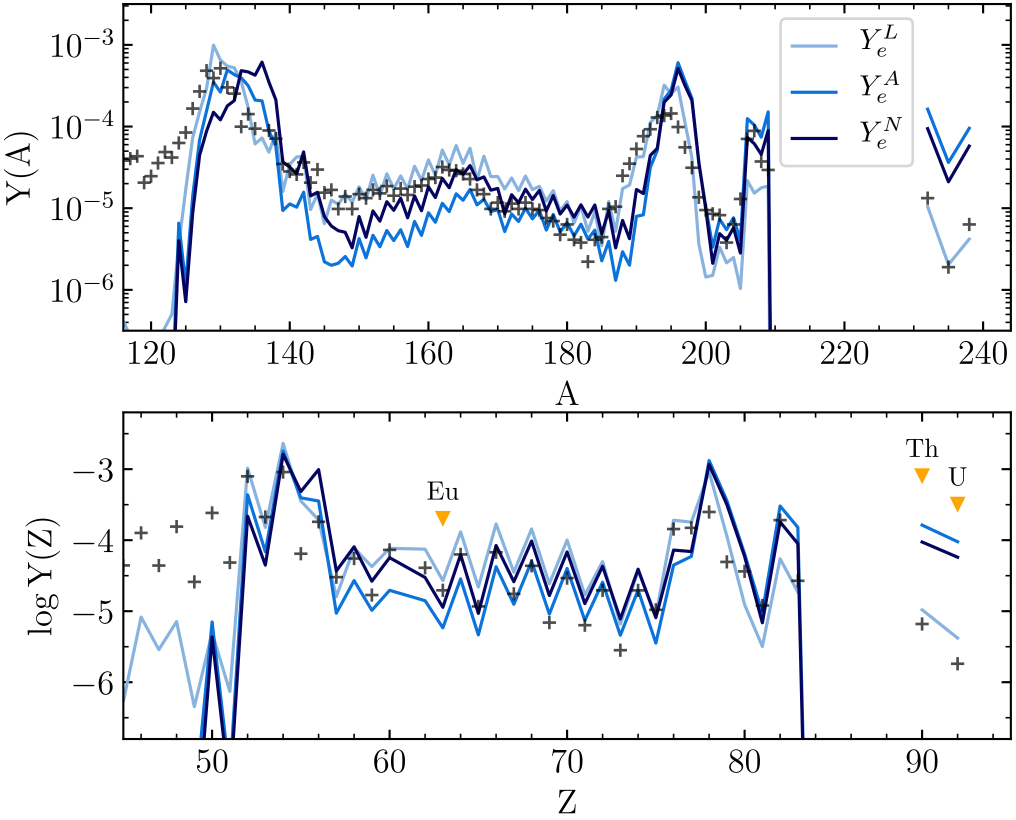


actinide boost?



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

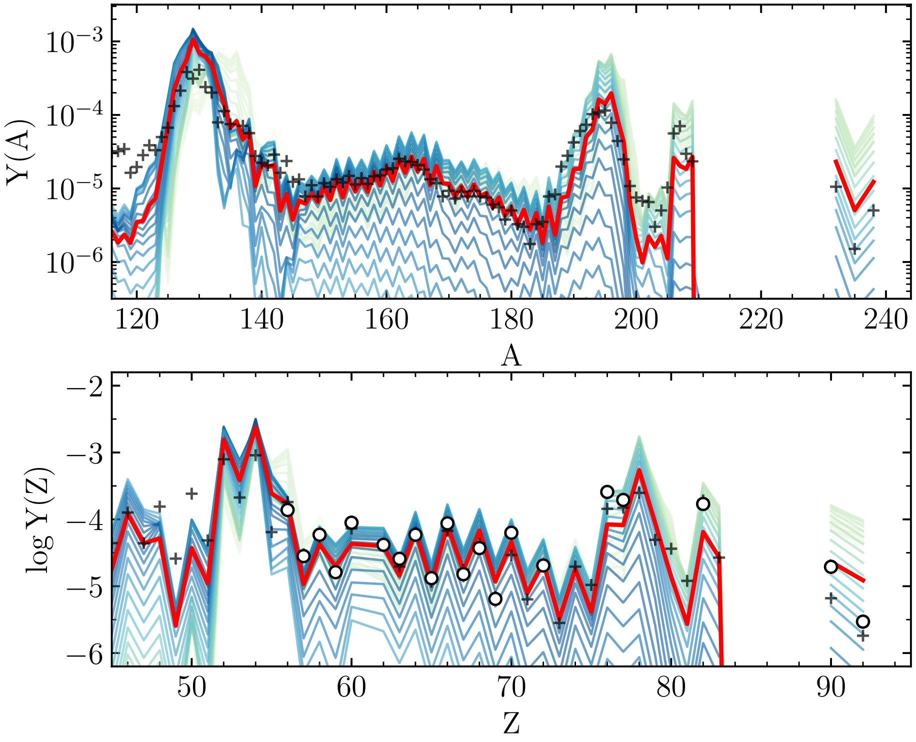
actinide production in *r*-process simulations

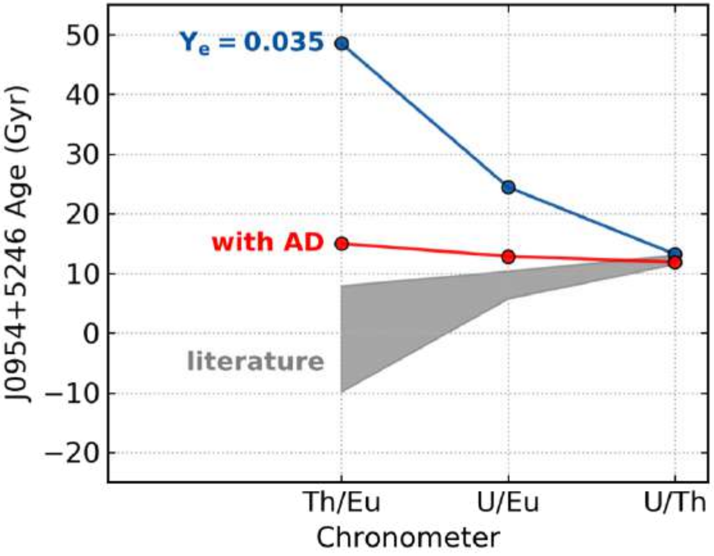


Erika Holmbeck,
JINA-CEE/ND grad student

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

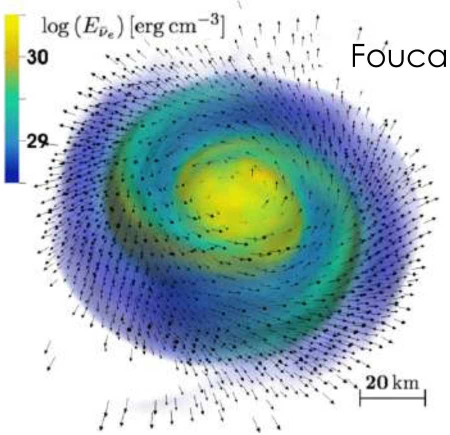
actinide dilution model





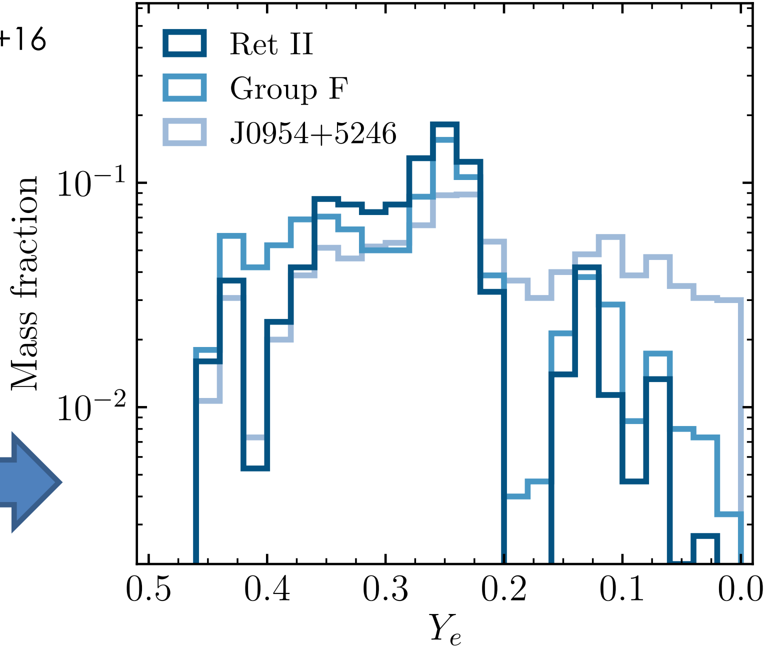
Holmbeck, Sprouse, Mumpower,
Vassh, Surman, Beers, Kawano 2019

actinide dilution + matching model

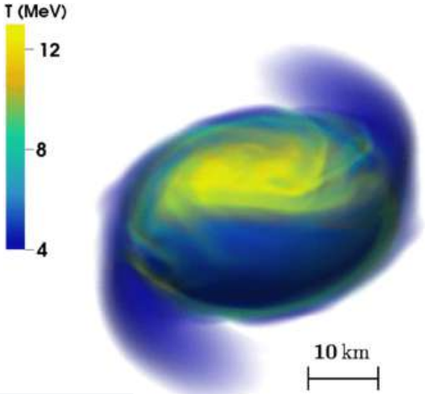


Foucart+16

accretion disk outflows are expected to be less neutron-rich



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

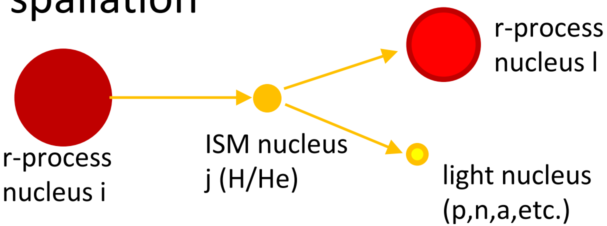


dynamical ejecta is expected to be very neutron-rich

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

spallation of *r*-process nuclei

spallation

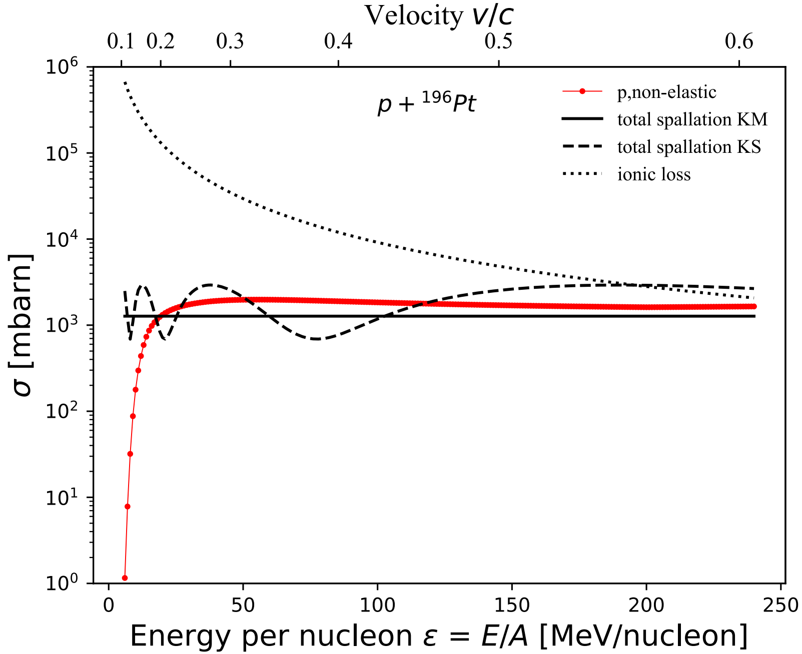


r-process nucleus i

ISM nucleus j (H/He)

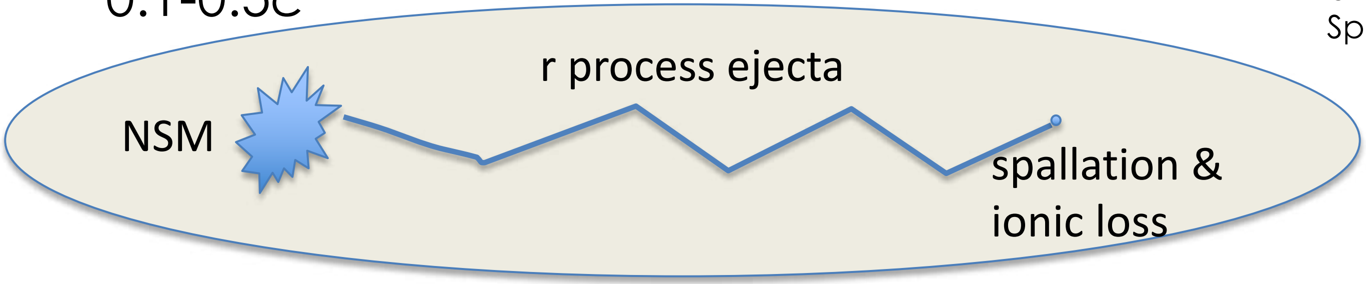
r-process nucleus l

light nucleus (p,n,a,etc.)



Wang, Fields, Mumpower, Sprouse, Surman, Vassh, arXiv:1909.12889 accepted in ApJ

NSM outflows ~ 0.1-0.5*c*

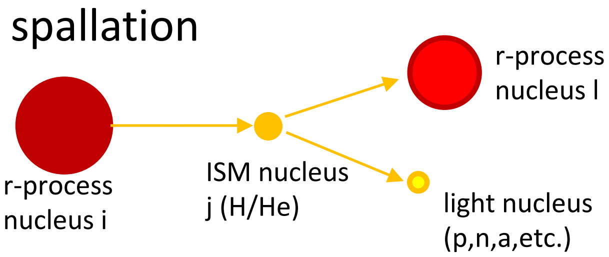


r process ejecta

NSM

spallation & ionic loss

spallation of *r*-process nuclei


spallation

r-process nucleus i

ISM nucleus j (H/He)

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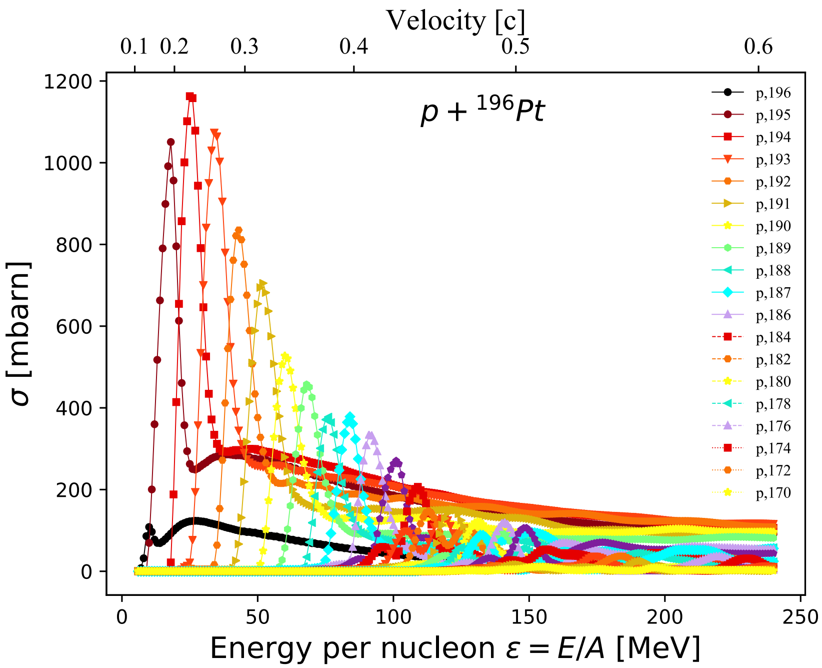
light nucleus (p,n,a,etc.)



Wang, Fields, Mumpower,
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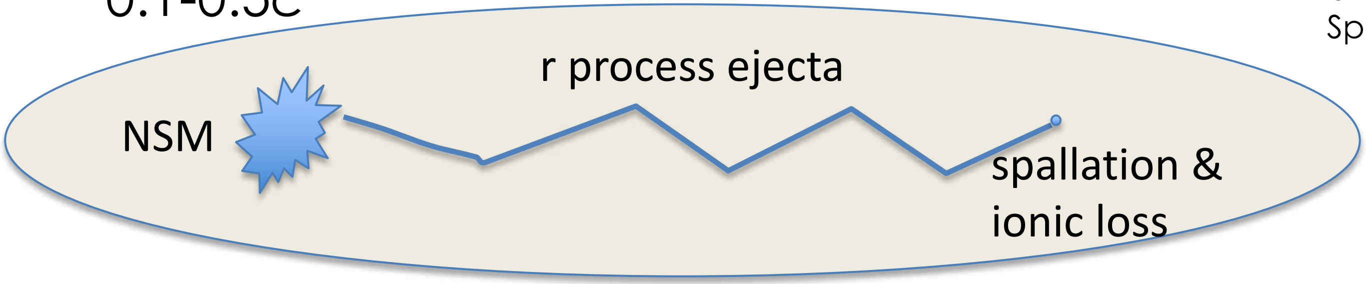
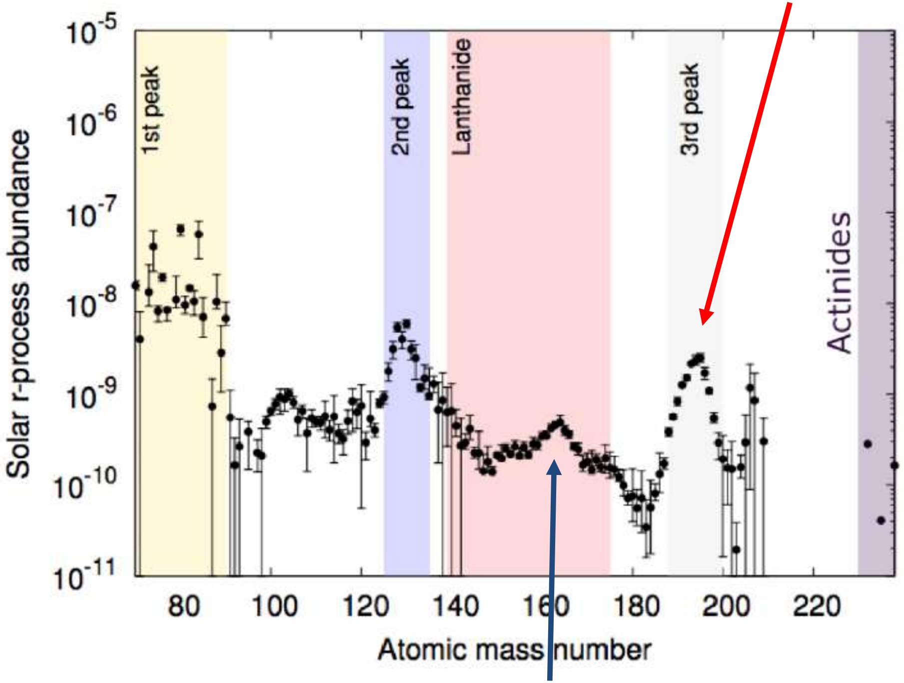

NSM

r process ejecta

spallation &
ionic loss

abundance pattern signatures



spallation and the 3rd peak

actinide boost

mass model reverse engineering
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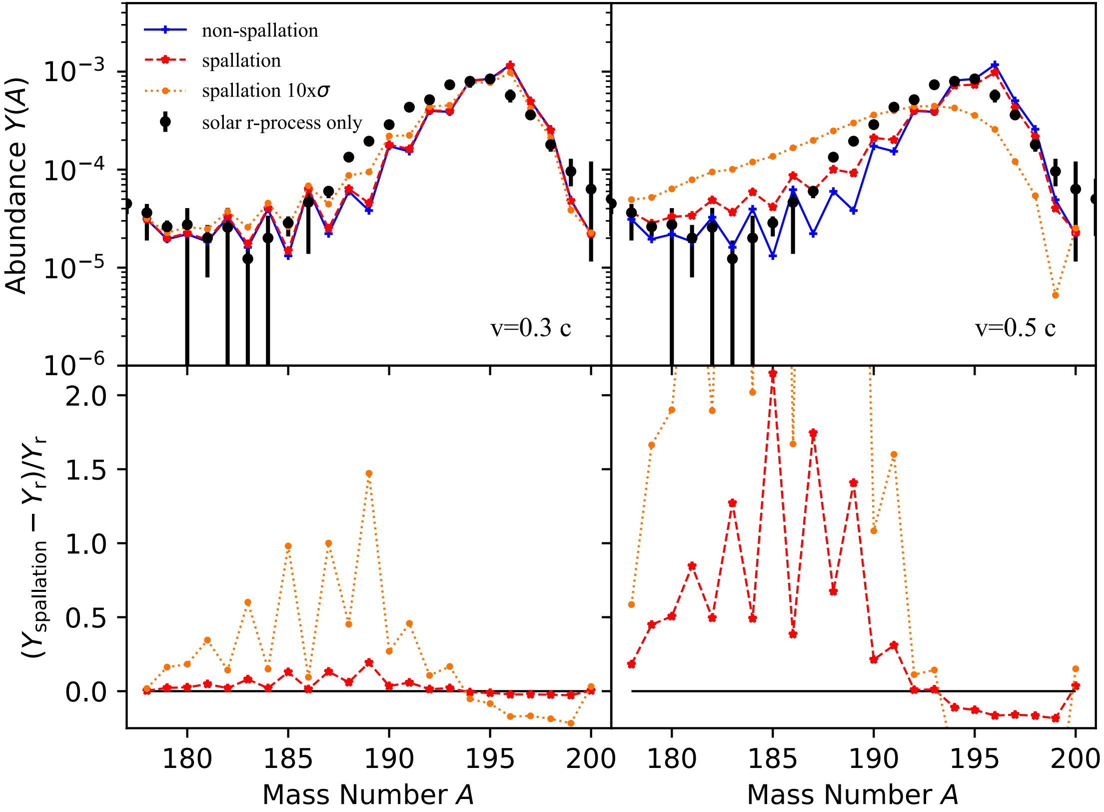
Arnould+2007,
Hotokezaka+2018

spallation and the *A* ~ 195 peak

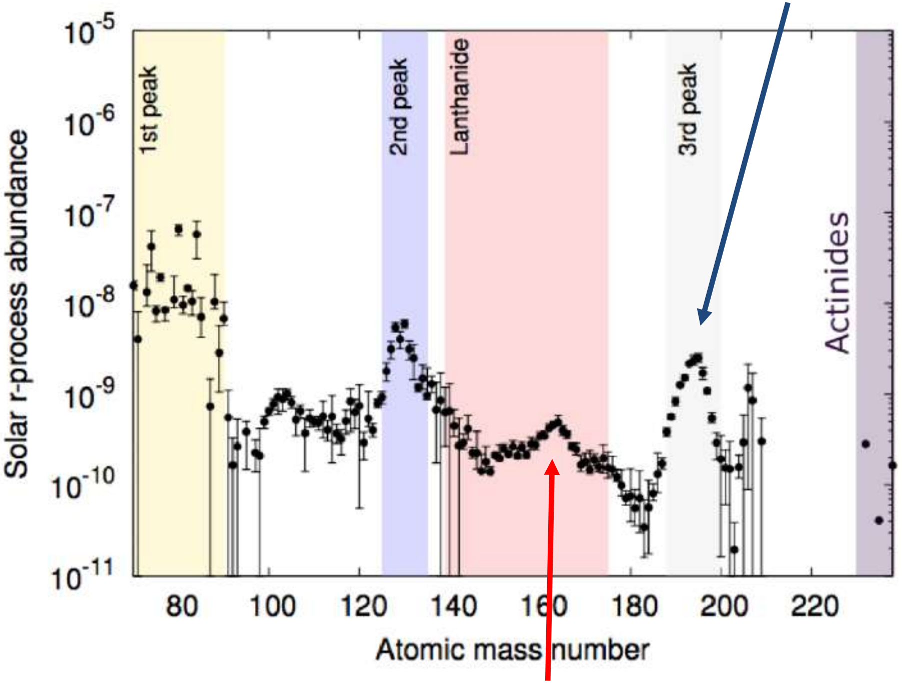
Xilu Wang,
N3AS/ND postdoc

Wang, Fields, Mumpower,
Sprouse, Surman, Vassh,
arXiv:1909.12889
accepted in ApJ



abundance pattern signatures

spallation and the 3rd peak



actinide boost

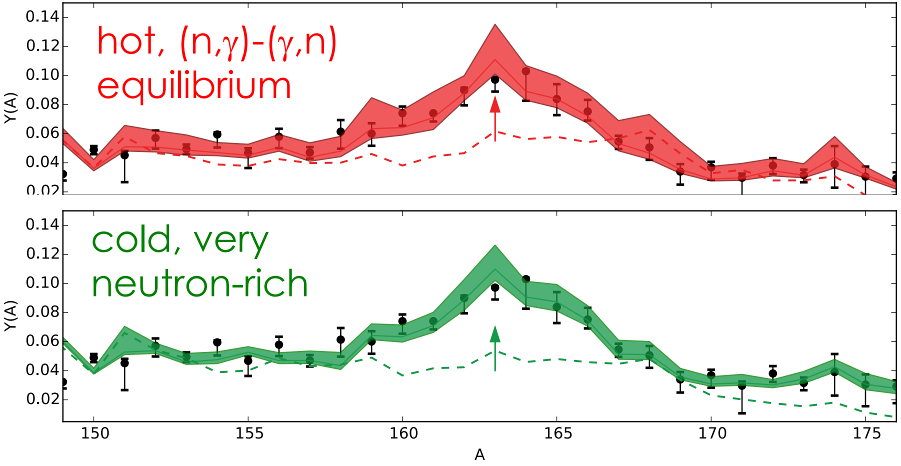
Arnould+2007,
Hotokezaka+2018

mass model reverse engineering
for rare earth peak formation

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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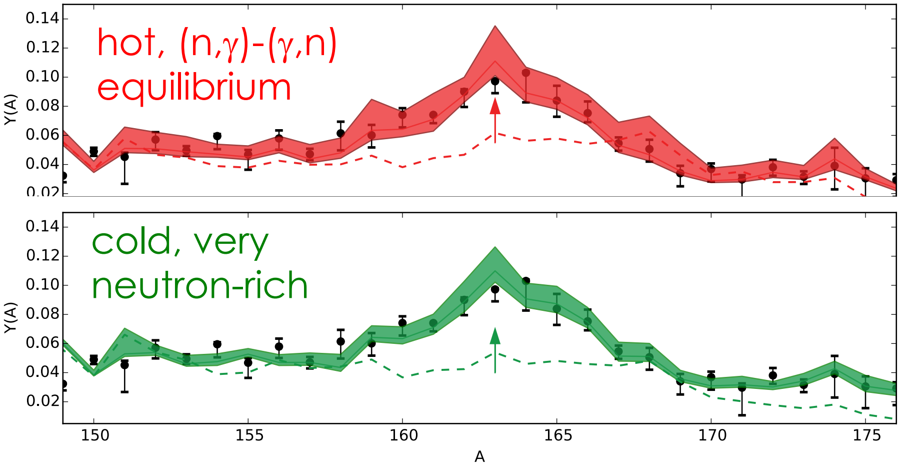
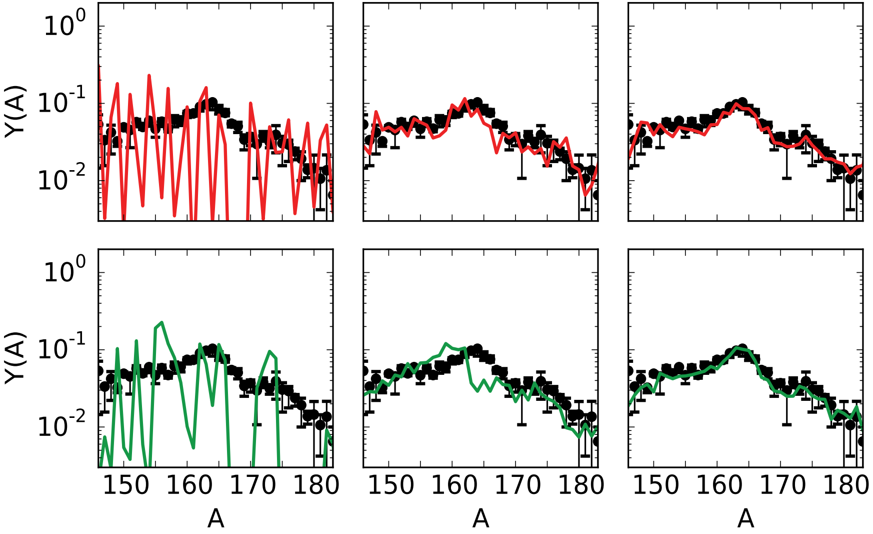
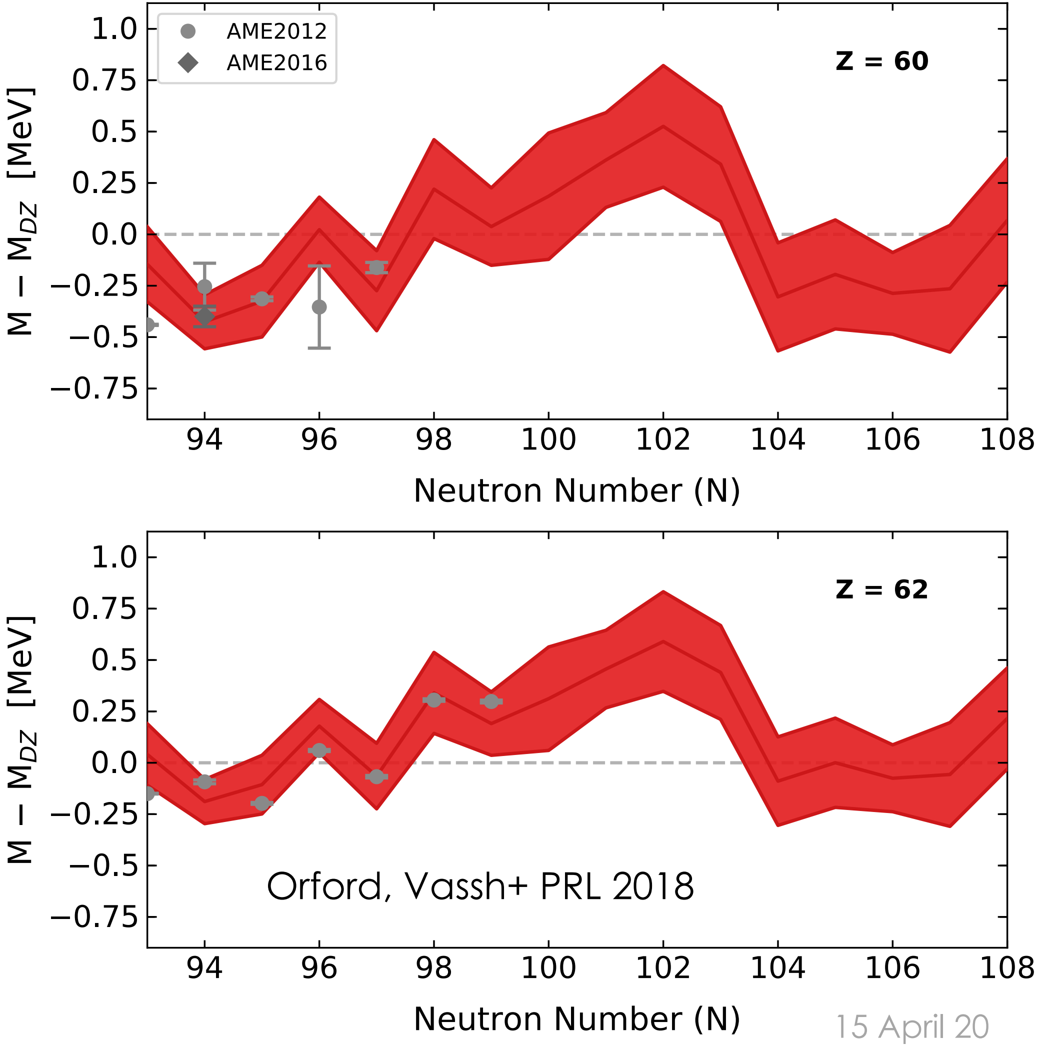




Mumpower, McLaughlin, Surman, Steiner, 2016

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

Nicole Vassh,
FIRE/ND postdoc

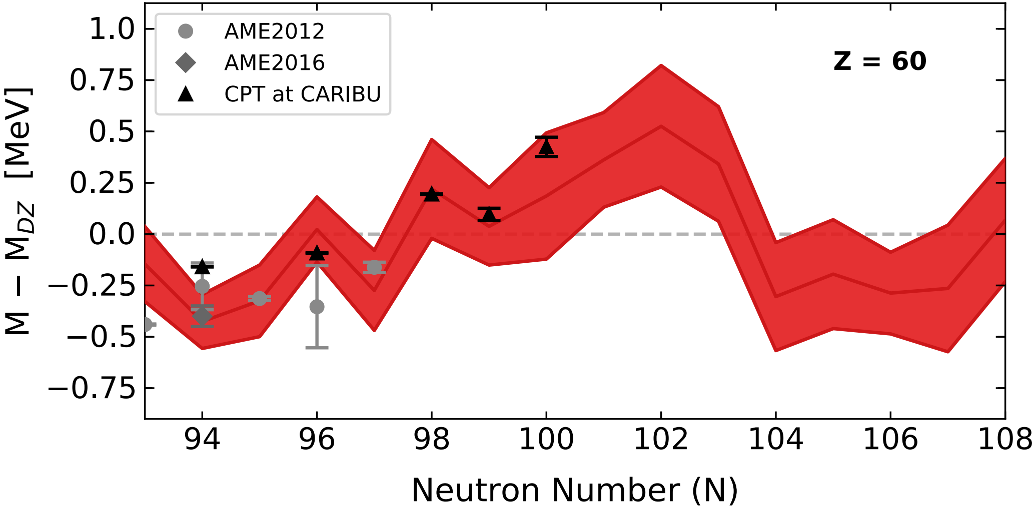


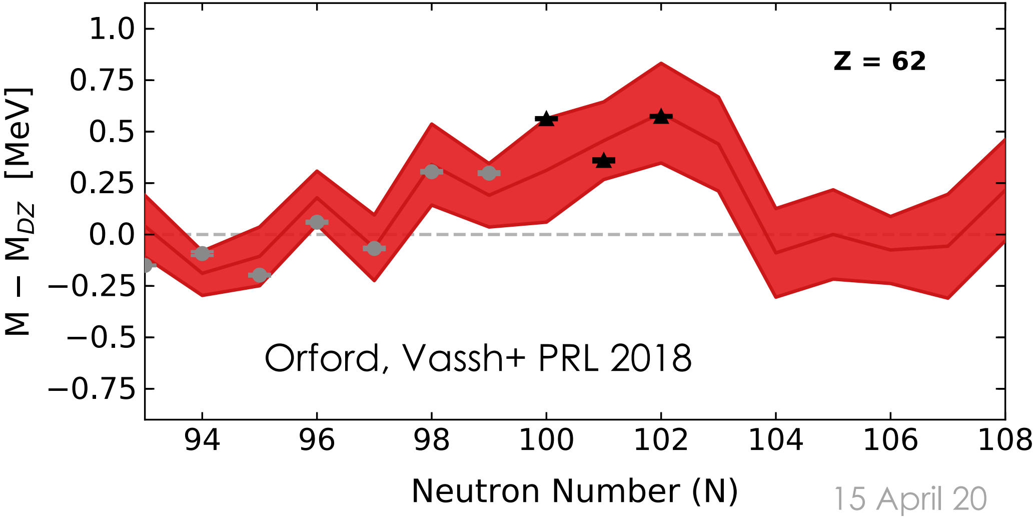
Orford, Vassh+ PRL 2018

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

masses from CPT at CARIBU

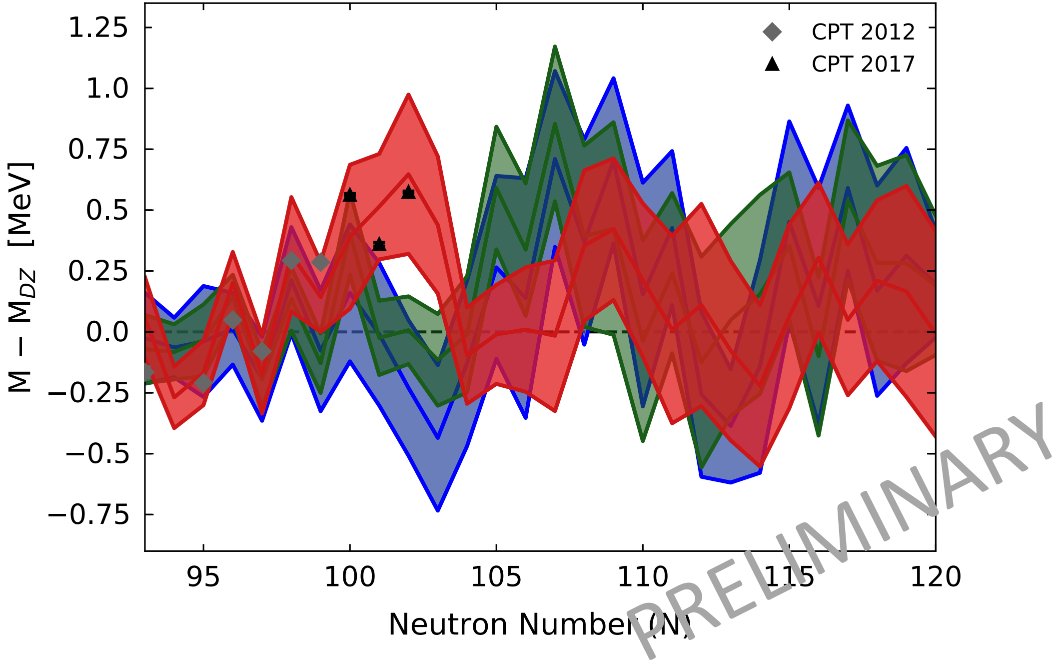
astrophysical conditions of a hot, (n,γ)-(γ,n) equilibrium wind





Orford, Vassh+ PRL 2018

reverse-engineering results for three distinct scenarios



Vassh+ in preparation

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.

Evidence from a variety of directions increasingly points to neutron star mergers as an important source of *r*-process elements, but more work is needed, e.g., advances in astrophysical modeling, neutrino physics, and nuclear theory and experiment.

On the nuclear side, the next generation of radioactive beam facilities offers great promise to reach the increasingly neutron-rich nuclei whose properties may provide key insight into the astrophysical conditions of *r*-process production.