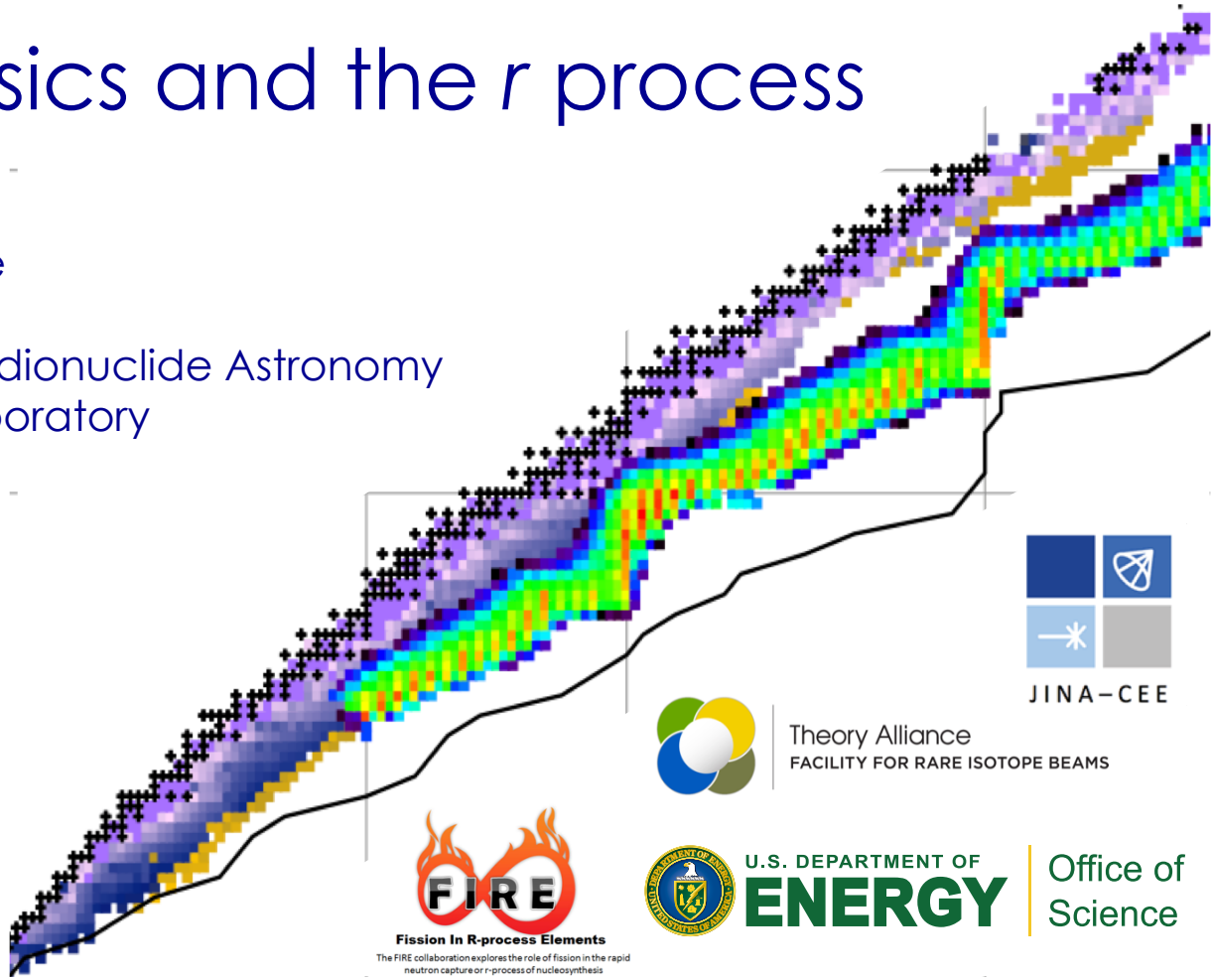
nuclear physics and the *r* process

Rebecca Surman
University of Notre Dame

To 2020 and Beyond: Radionuclide Astronomy
Los Alamos National Laboratory

20-22 August 2018



JINA–CEE

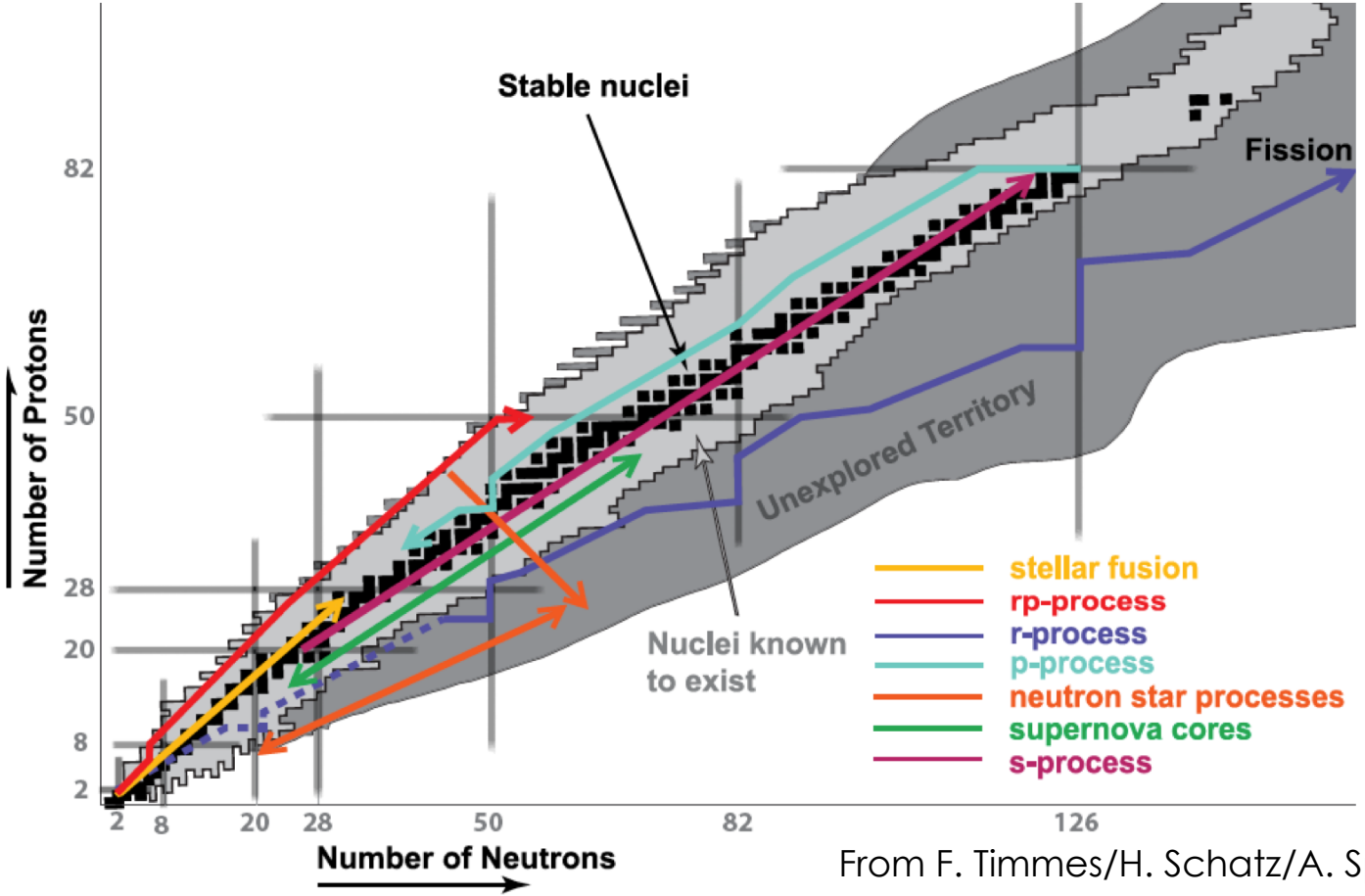
Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

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

U.S. DEPARTMENT OF ENERGY | Office of Science

UNIVERSITY OF NOTRE DAME
College of Science

overview of astrophysical processes



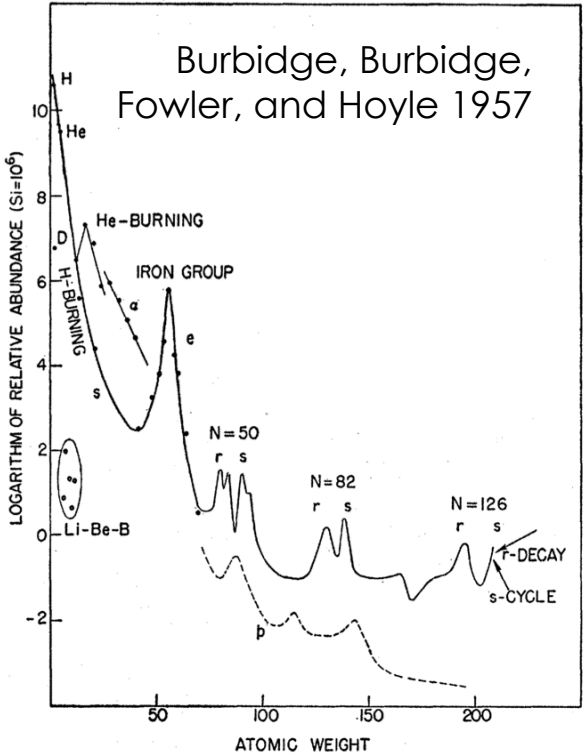
From F. Timmes/H. Schatz/A. Spyrou

summary: gamma-rays from *r*-process nuclei?

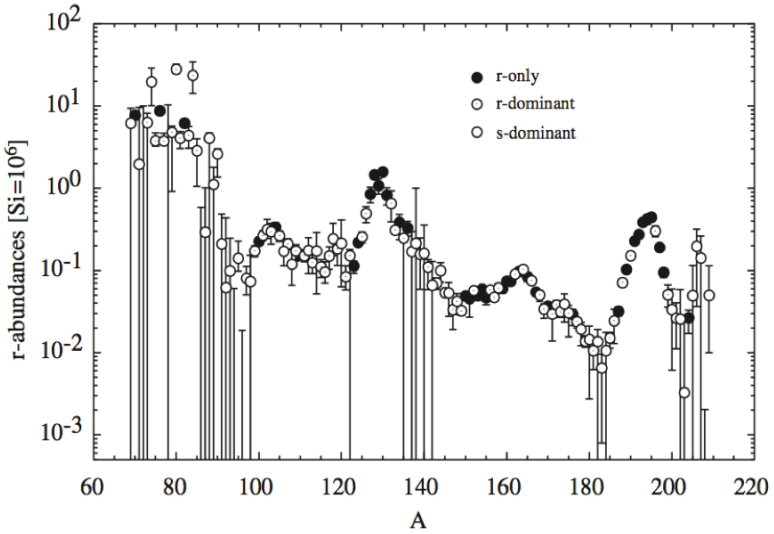
The origin of the heaviest elements in the *r*-process of nucleosynthesis has been one of the greatest mysteries in nuclear astrophysics for decades. Can gamma-ray astronomy contribute to its resolution?

The abundances of *r*-process isotopes in the galaxy are too low for general observations. However, if an *r*-process event occurs close enough, we can potentially see gammas from the transient.

Exactly which isotopes are the best candidates for such observations depends on (largely unknown) nuclear physics far from stability. Upcoming radioactive beam facilities such as FRIB can potentially dramatically reduce these uncertainties and facilitate the development of precision *r*-process predictions.

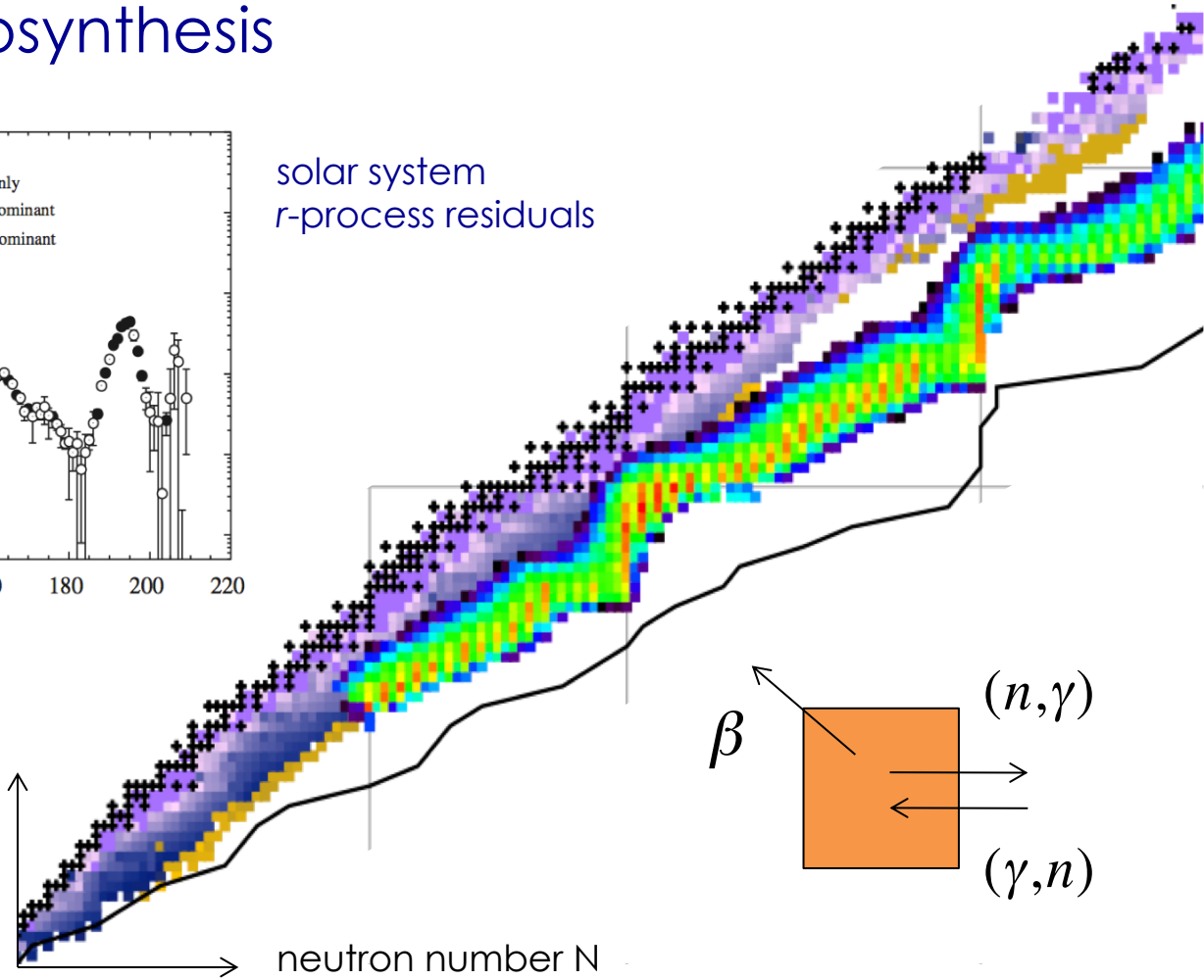


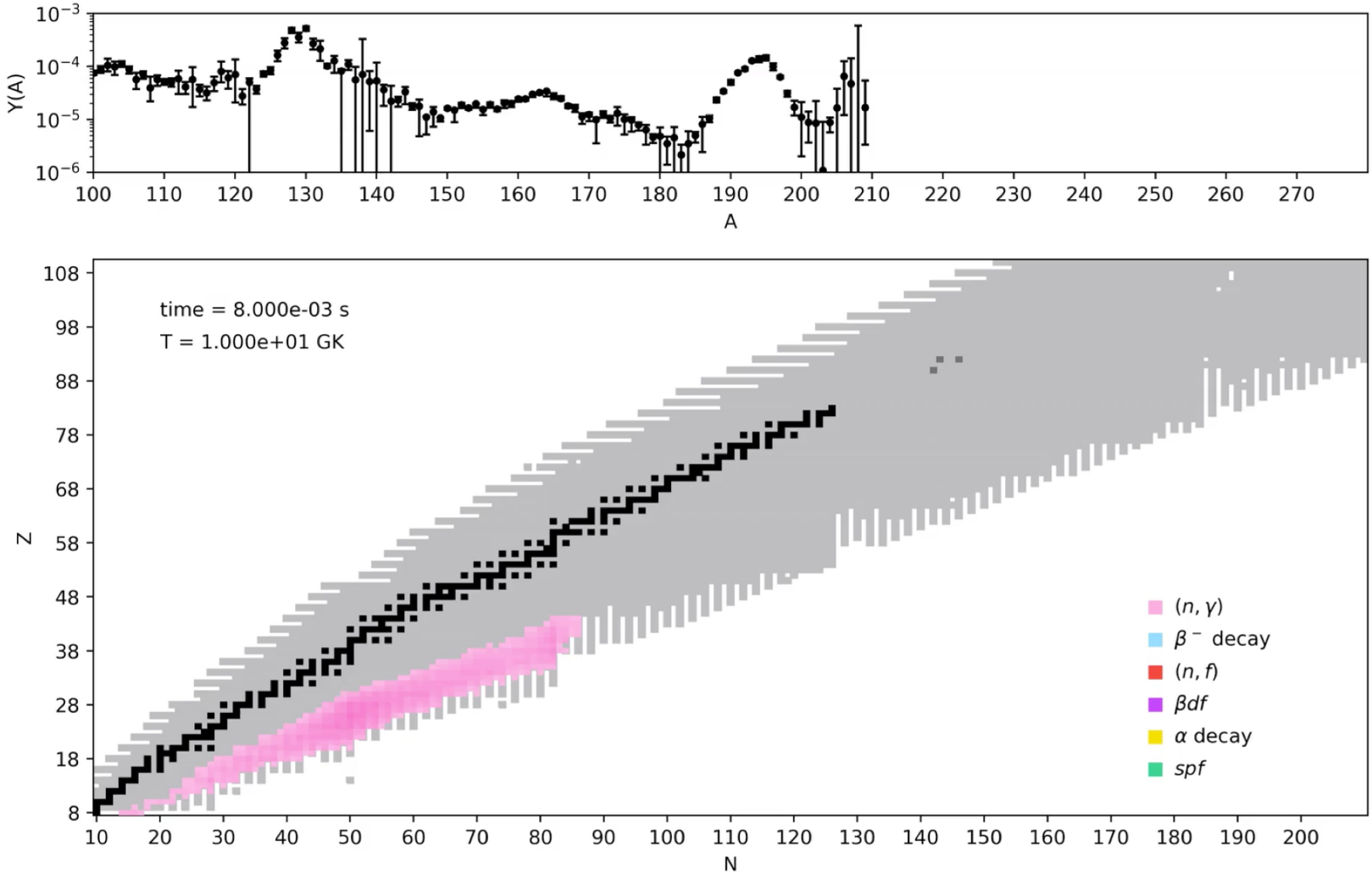
r-process nucleosynthesis



Arnould+2007

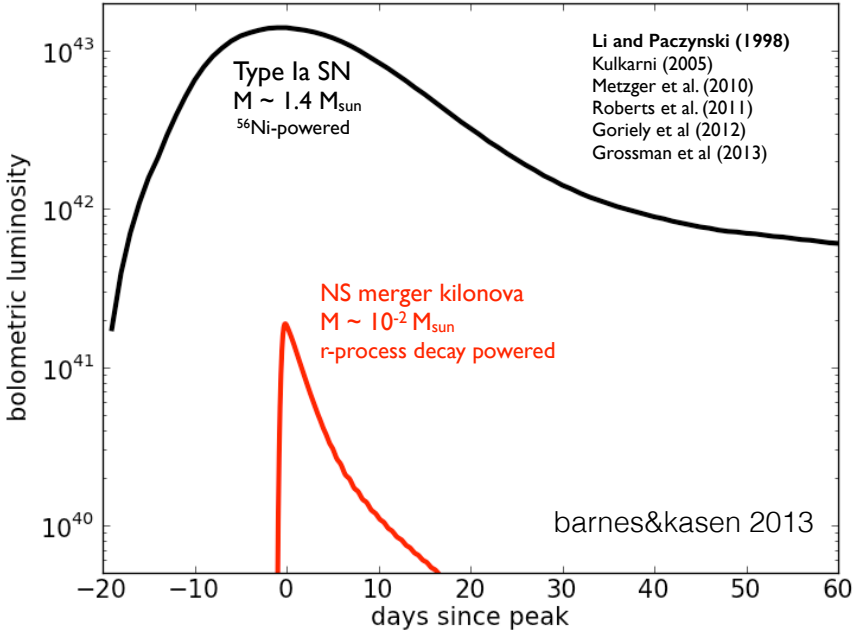
solar system
r-process residuals



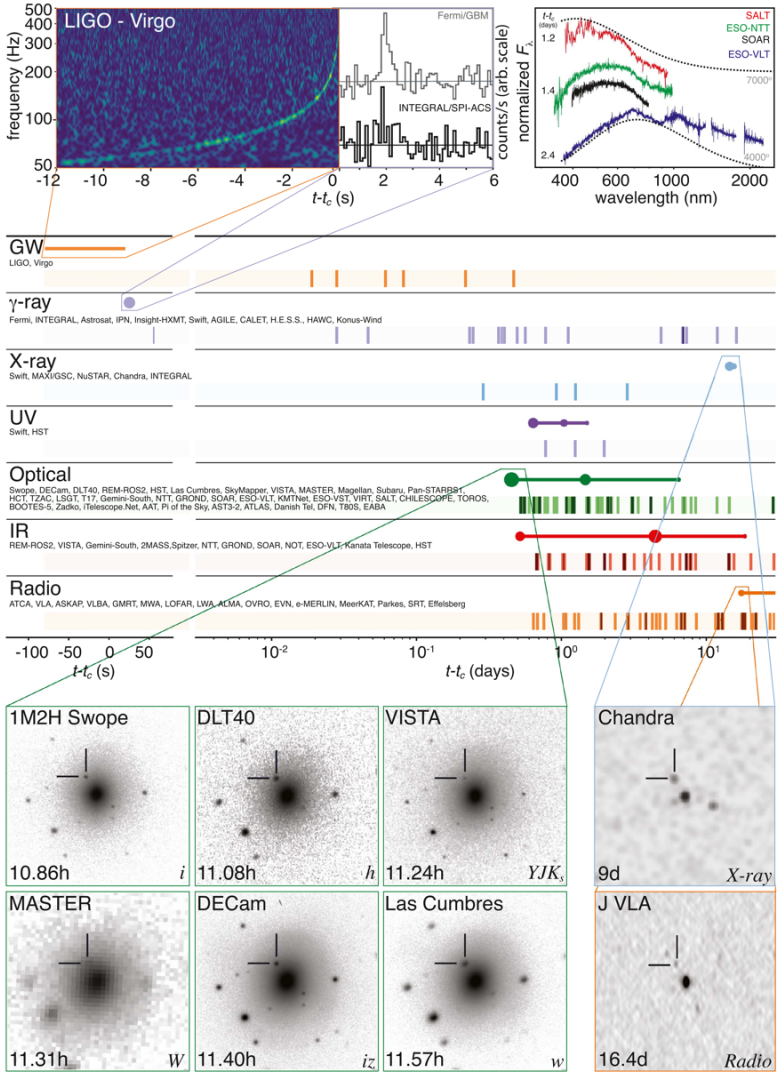


movie by N. Vassh using PRISM (Sprouse/Mumpower)

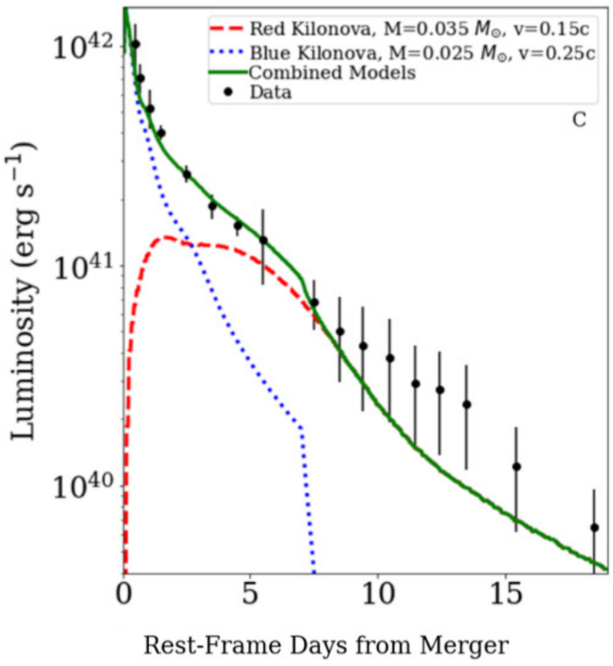
GW170817



LIGO/Virgo +
70 observatories



GW170817 kilonova



Kilpatrick+2017
Kasen+2017

Reference	$m_{\rm dyn}$ $[M_\odot]$	$m_{\rm w}$ $[M_\odot]$
Abbott et al. (2017a)	0.001 – 0.01	–
Arcavi et al. (2017)	–	0.02 – 0.025
Cowperthwaite et al. (2017)	0.04	0.01
Chornock et al. (2017)	0.035	0.02
Evans et al. (2017)	0.002 – 0.03	0.03 – 0.1
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Kasliwal et al. (2017b)	> 0.02	> 0.03
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Smartt et al. (2017)	0.03 – 0.05	0.018
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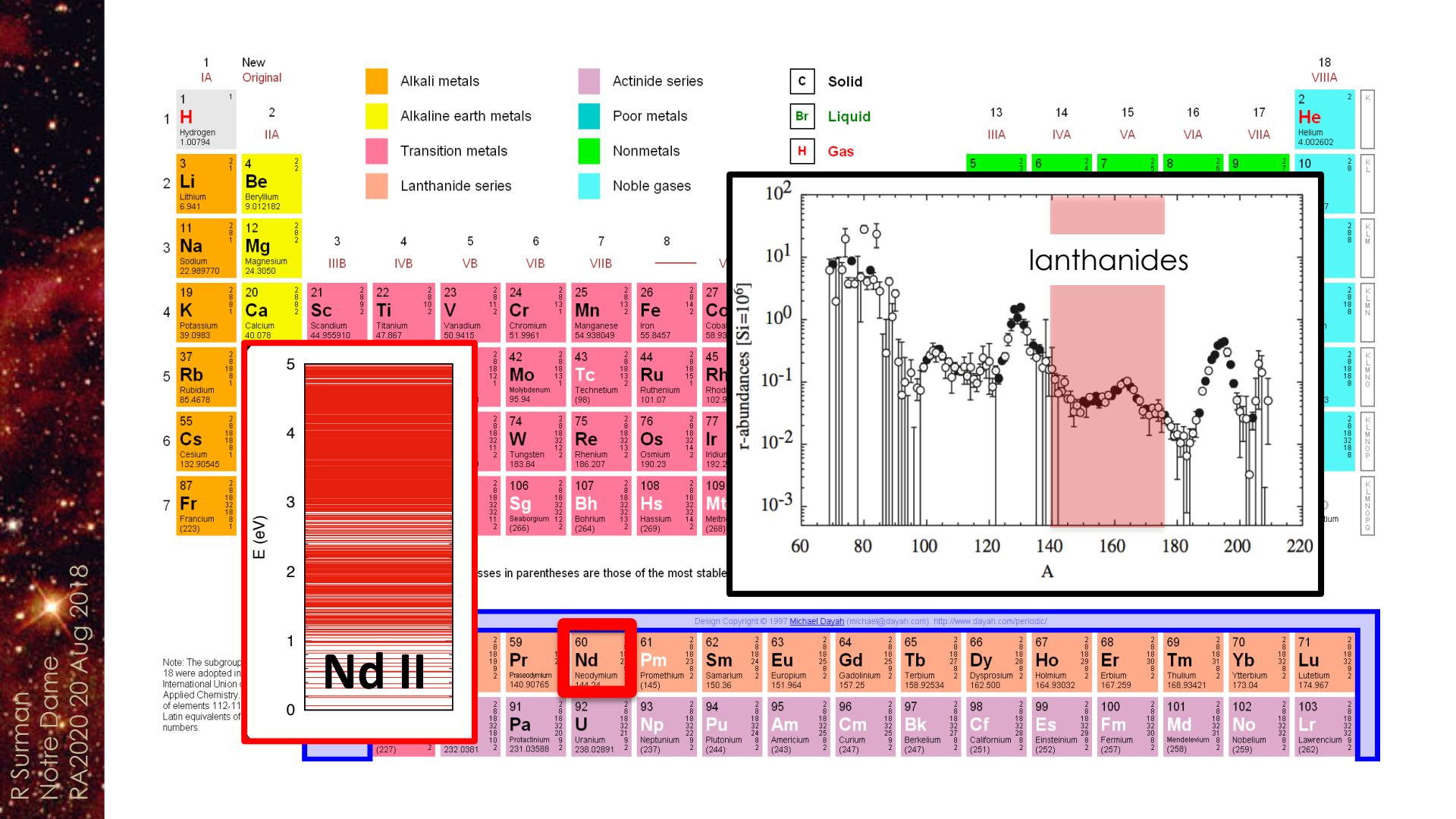
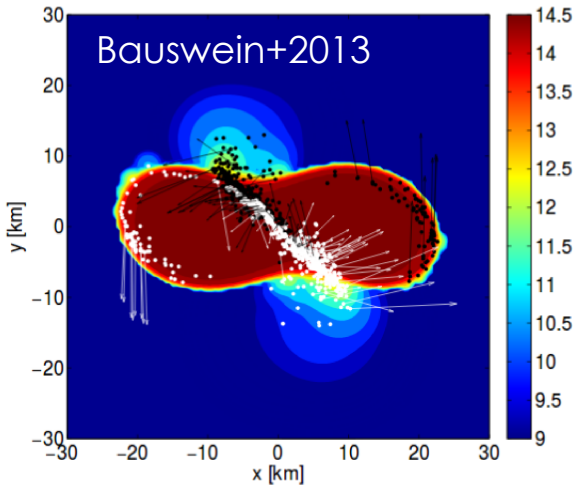
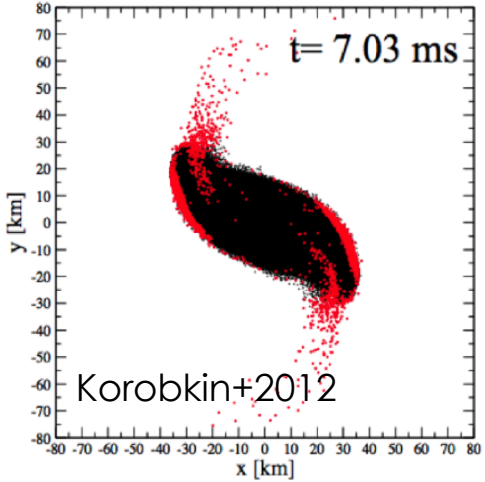
Troja et al. (2017)	0.001 – 0.01	0.015 – 0.03

Côté+2018 high opacity low opacity


Alkali metals
Alkaline earth metals
Transition metals
Lanthanide series
Actinide series
Poor metals
Nonmetals
Noble gases
Solid
Liquid
Gas
lanthanides
r-abundances [Si=10^6]
A
E (eV)
Nd II
Design Copyright © 1997 Michael Dayah (michael@dayah.com). http://www.dayah.com/periodic/
R Surman
Notre Dame
RA2020 20 Aug 2018

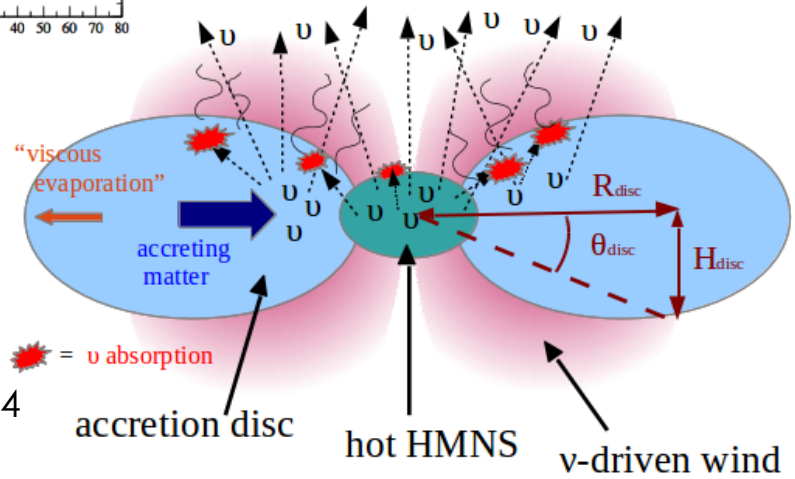
NSM environments for element synthesis





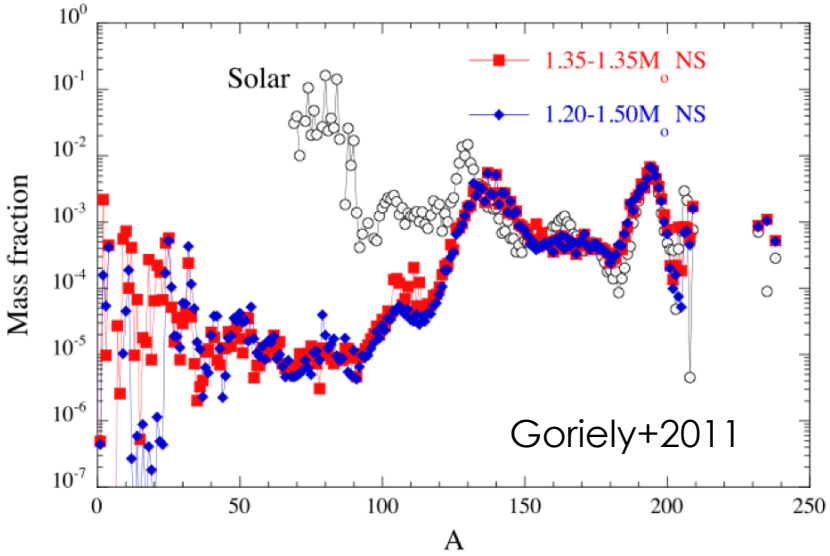
prompt ejecta

ejecta from the accretion disk



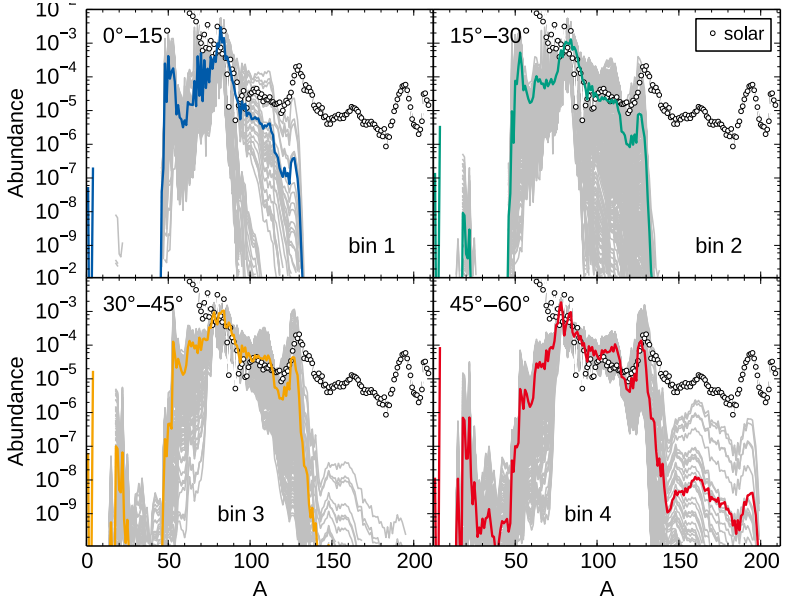
Perego+2014

NSM environments for element synthesis



prompt ejecta

→ fission recycling = consistent pattern?



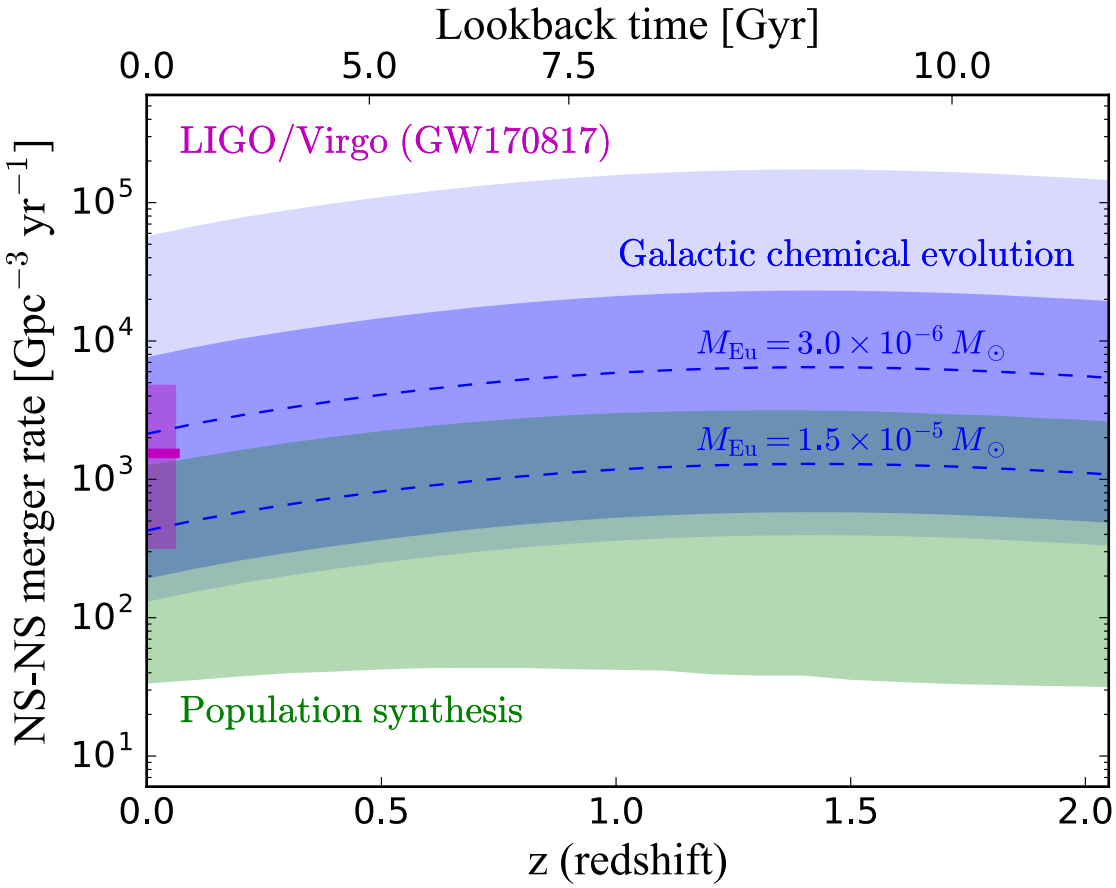
ejecta from the accretion disk

→ dependent on outflow conditions, neutrino physics, etc.

Martin+2015

GRB170817 + galactic chemical evolution

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



GW170817 kilonova: gold?

Astronomers just proved the incredible origin of nearly all gold, platinum, and silver in the universe

Dave Mosher
Oct. 16, 2017, 10:35 AM 54,916

FACEBOOK LINKEDIN TWITTER

Science News *from research organizations*

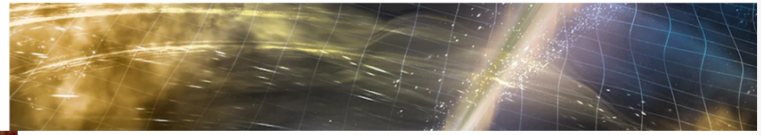
Astronomers strike cosmic gold, confirm origin of precious metals in neutron star mergers

First observation of light from neutron star merger reveals new cosmic phenomenon, opens new field

TECHNOLOGY > SPACE

Neutron collision tells us about how gold is made - and possibly the secrets of the universe

Ben O'Shea | The West Australian
Sunday, 22 October 2017 2:32AM



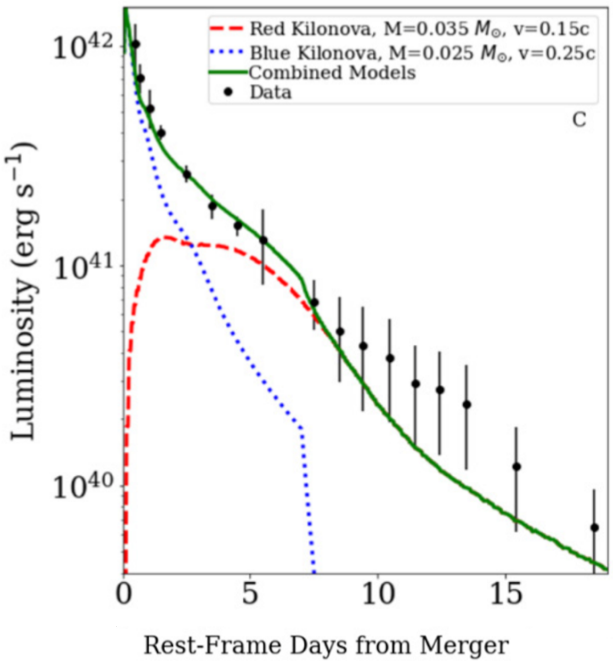
LIVESCIENCE NEWS TECH HEALTH PLANET EARTH

Live Science > Space.com

Neutron-Star Collision Reveals Origin of Gold, Astronomers Say

By Jesse Emspak, Live Science Contributor | October 17, 2017 11:51am ET

GW170817 kilonova interpretation



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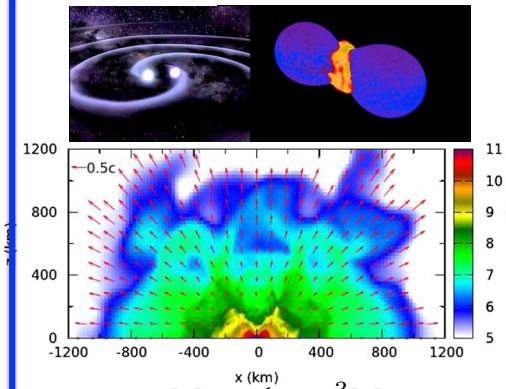
Côté+2018

high opacity
prompt?

low opacity
disk?

GW170817 kilonova interpretation

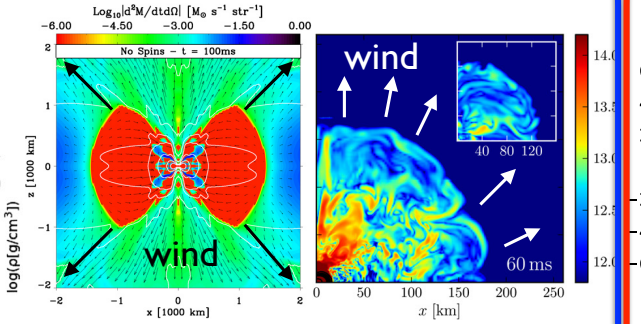
dynamical ejecta (~ms)



$M_{\rm tot} \lesssim 10^{-3} M_\odot$

$v \gtrsim 0.2c$

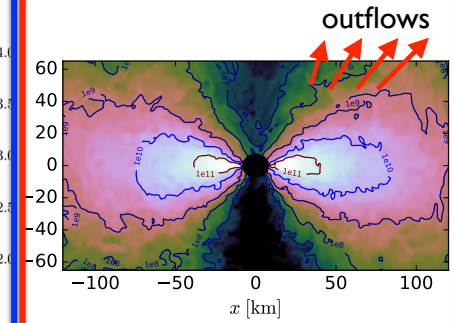
winds from NS remnant (~ms-1s)



$\dot{M}_{\rm in} \sim (10^{-3} - 10^{-2}) M_\odot s^{-1}$

$v \lesssim 0.1c$

accretion disk (~10ms-1s)



$M_{\rm tot} \gtrsim 10^{-2} M_\odot$

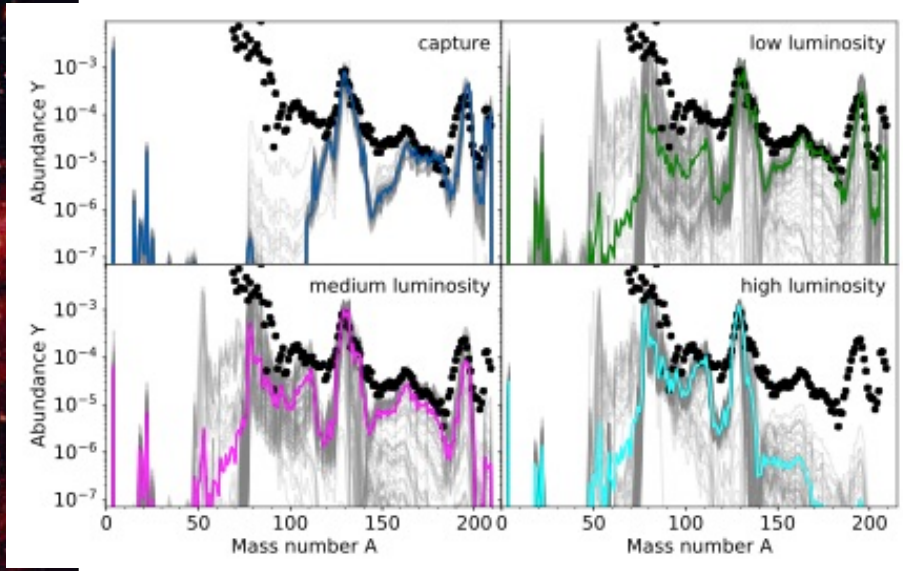
$v \sim 0.1c$

blue KN in GW170817

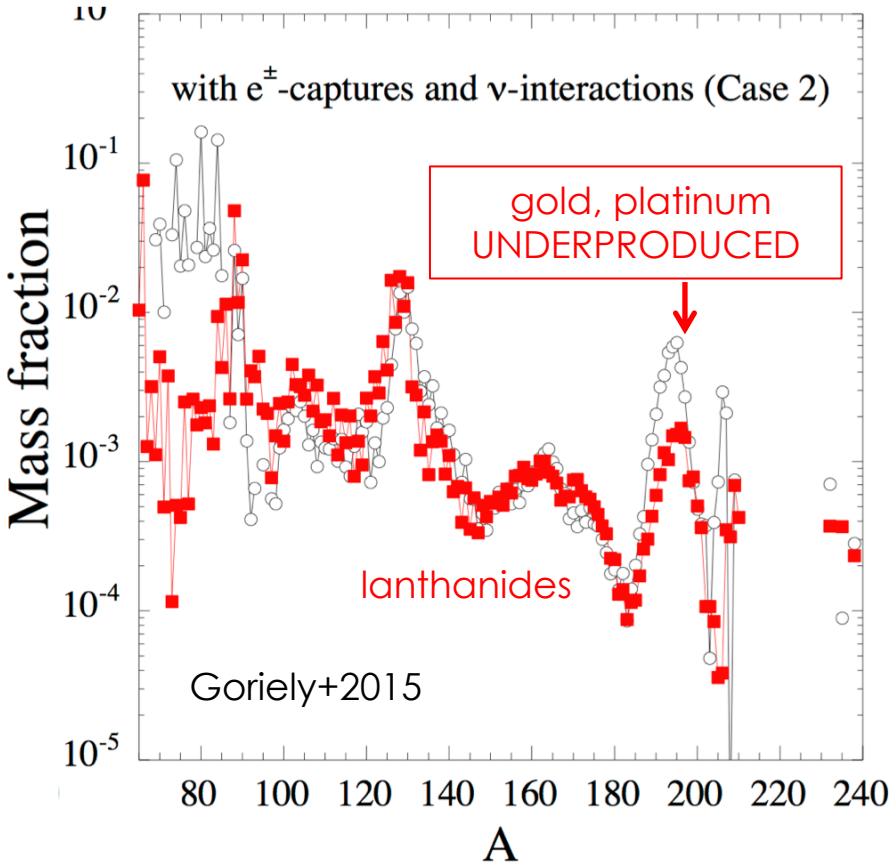
red KN in GW170817

slide from D. Siegel
Siegel & Metzger 2017, 2018

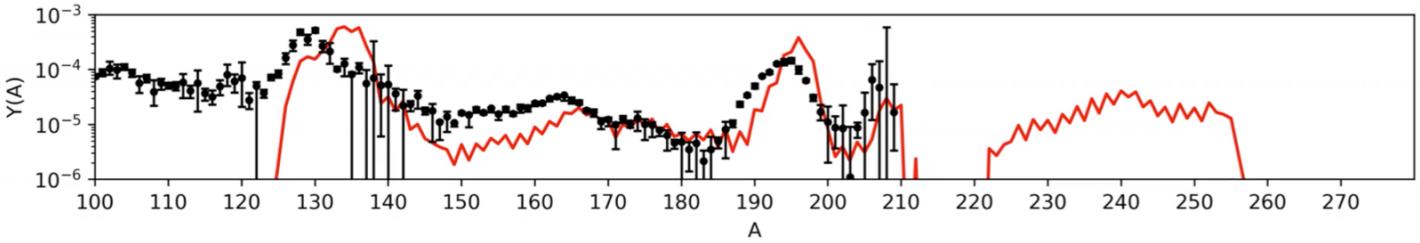
integrated nucleosynthesis with neutrinos

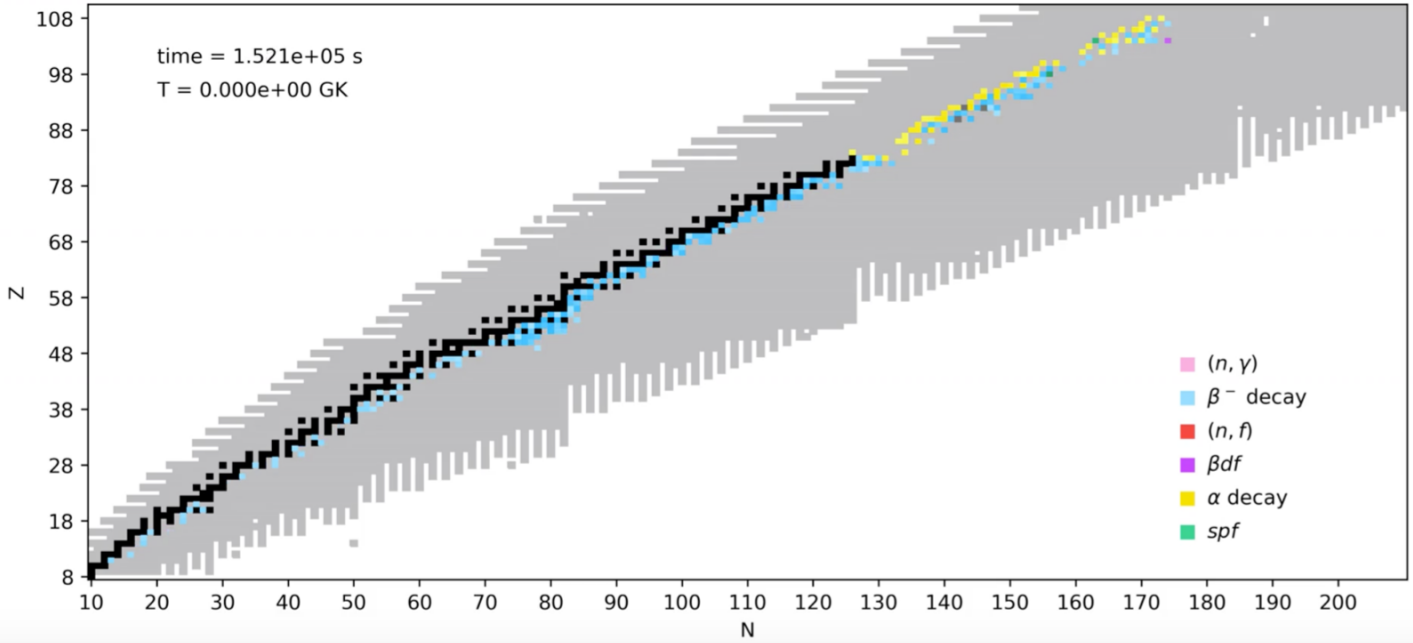


Martin+2018

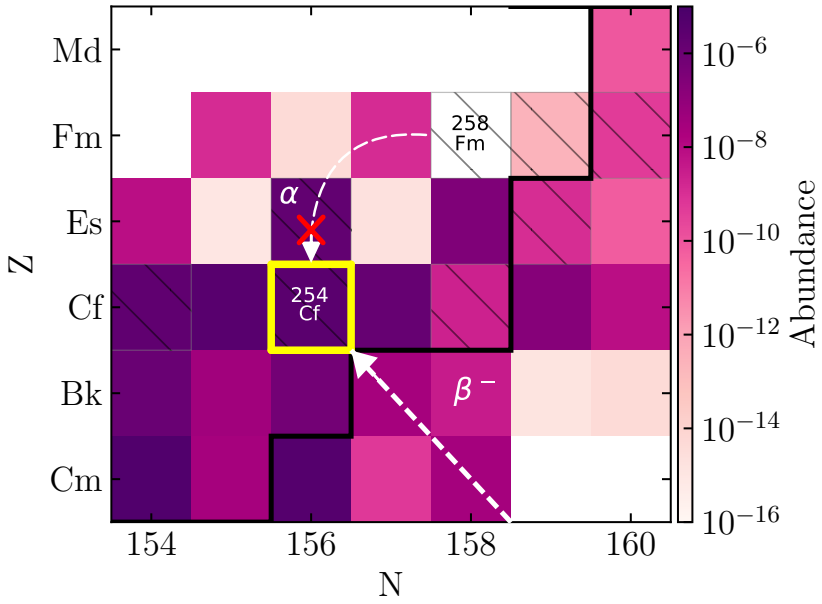


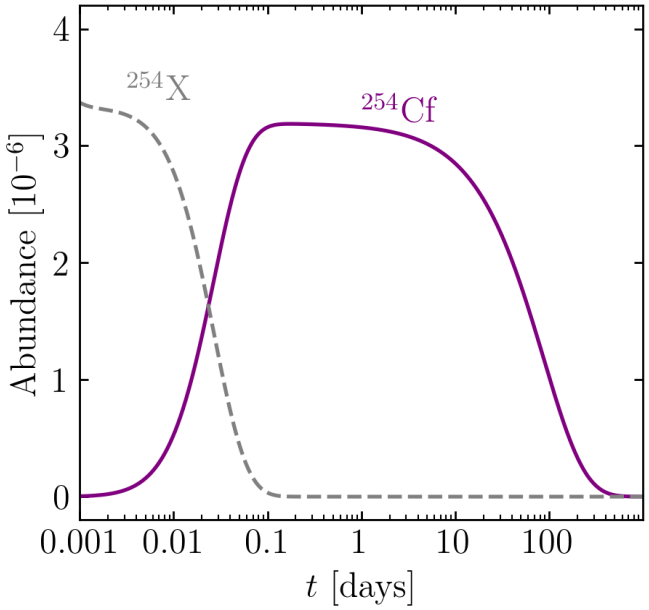
signature of actinide production?





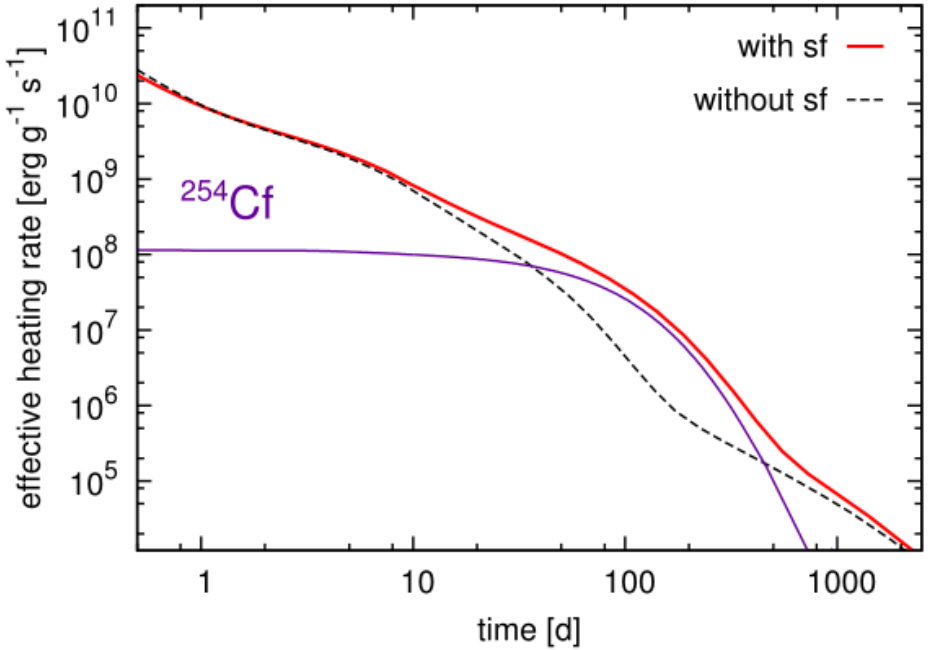
^{254}Cf and late-time radioactive heating



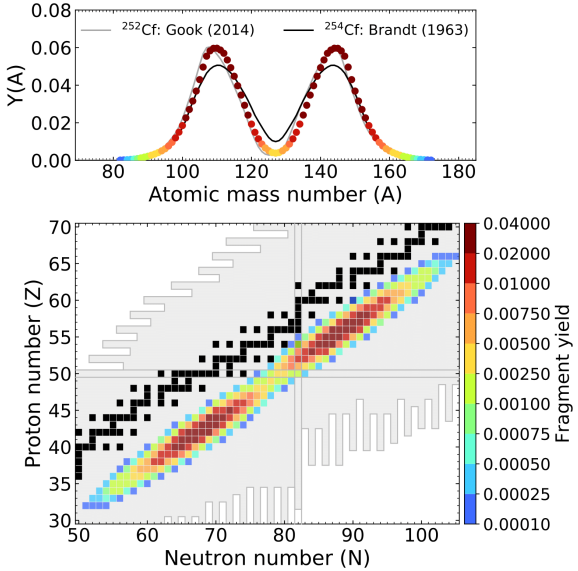


Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, ApJL 2018

^{254}Cf and late-time radioactive heating

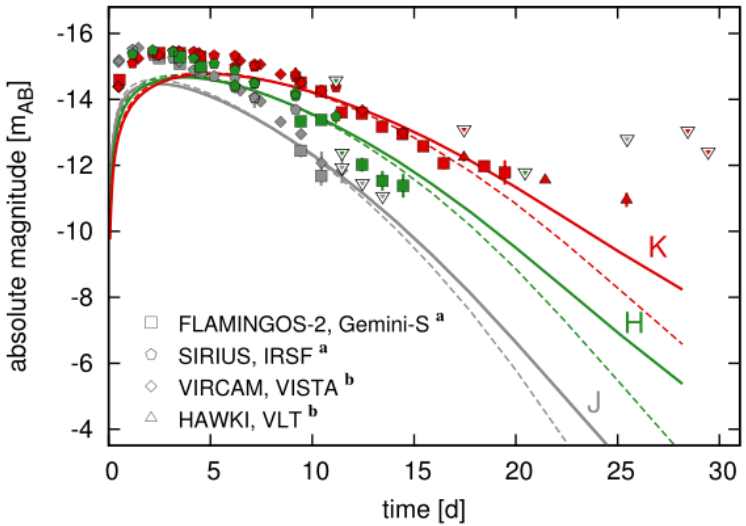


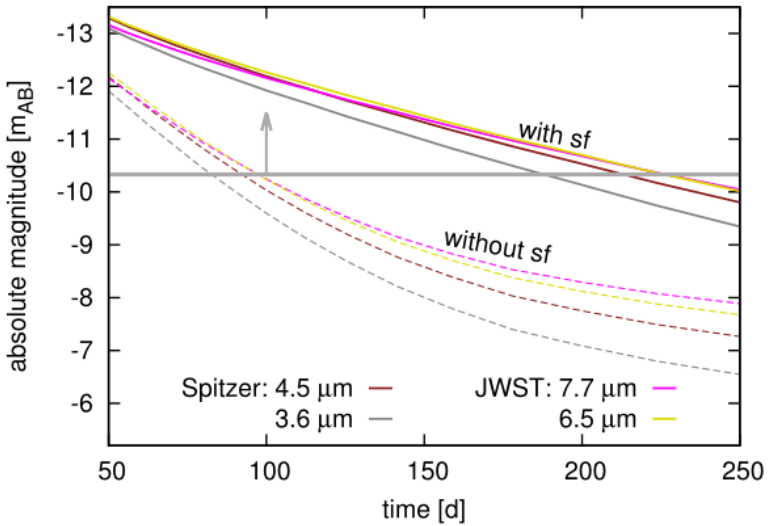
^{254}Cf yield calculation



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

^{254}Cf: observational impact





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

merger outflow nucleosynthesis: required nuclear data

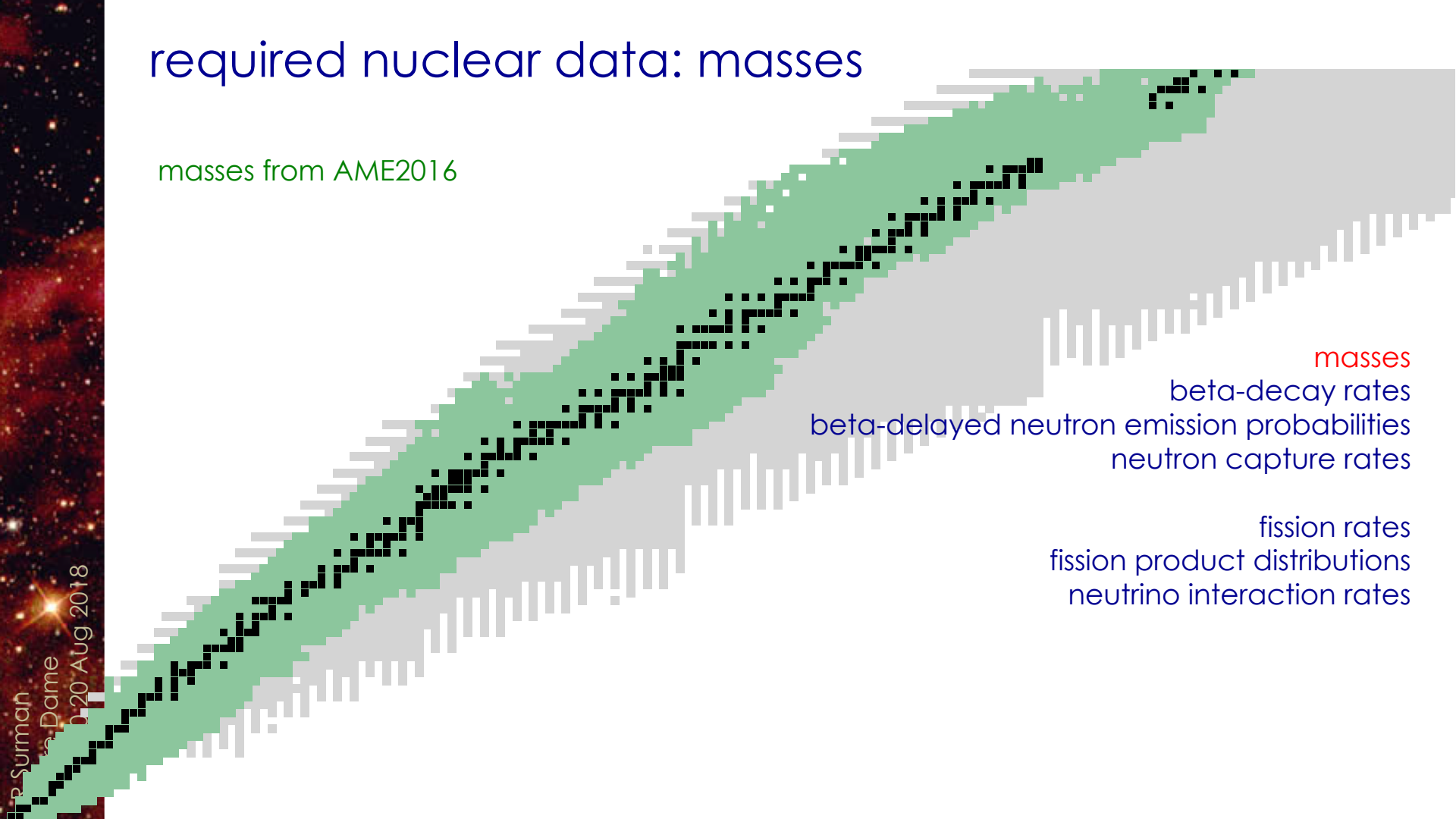
masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates

fission rates
fission product distributions
neutrino interaction rates

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

required nuclear data: masses

masses from AME2016



masses
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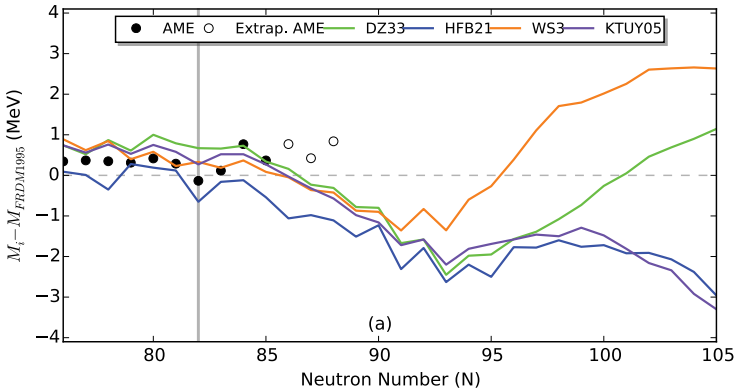
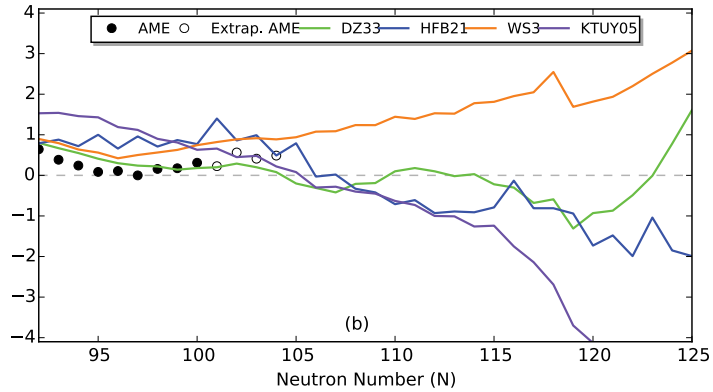
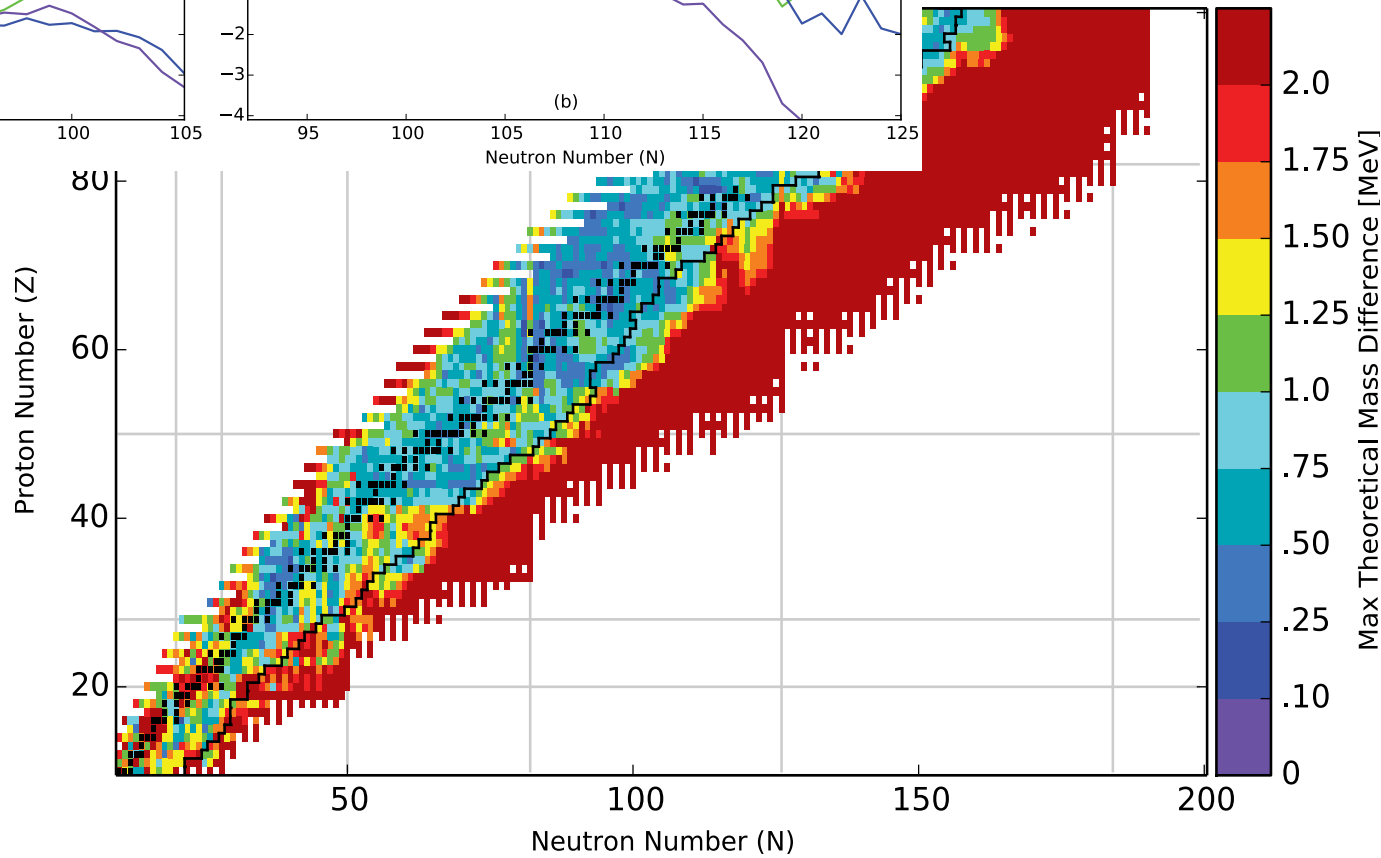


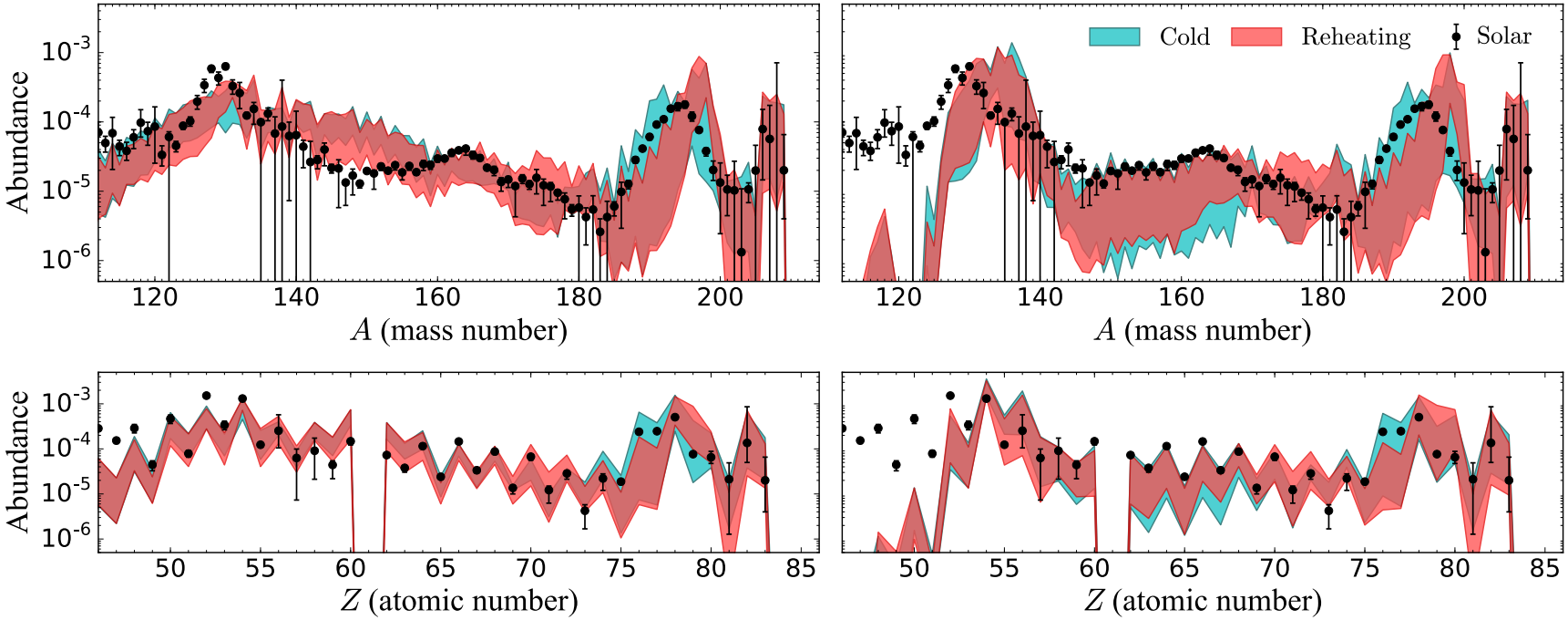


mass uncertainties

Mumpower, Surman, McLaughlin, Aprahamian 2016

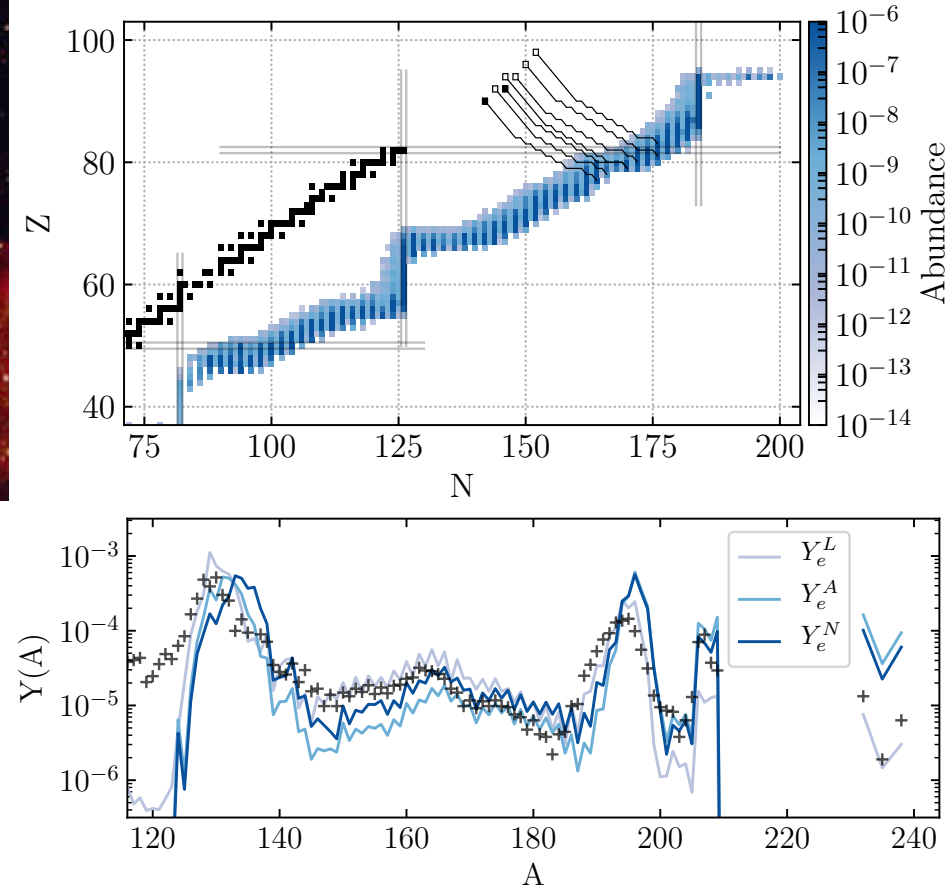


impact of mass uncertainties

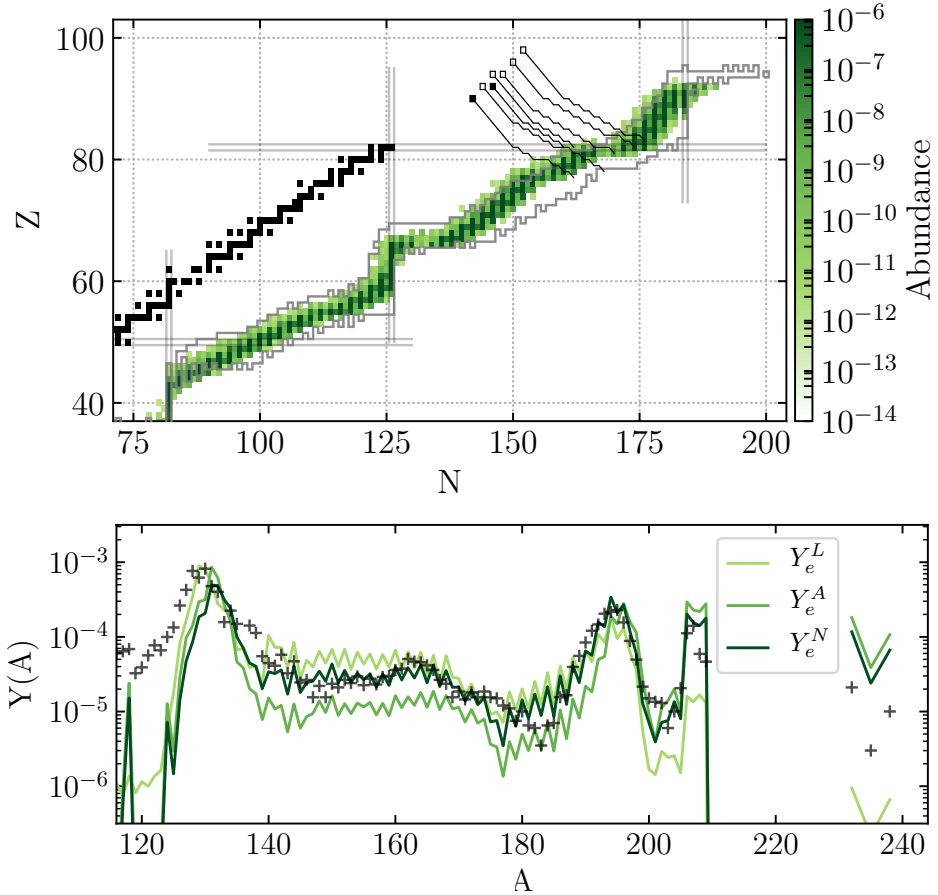


Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman, Wollaeger 2018

FRDM

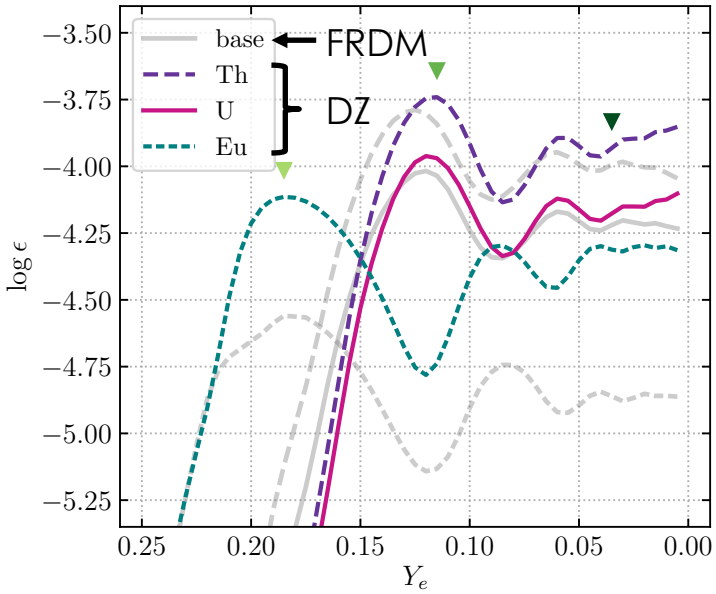


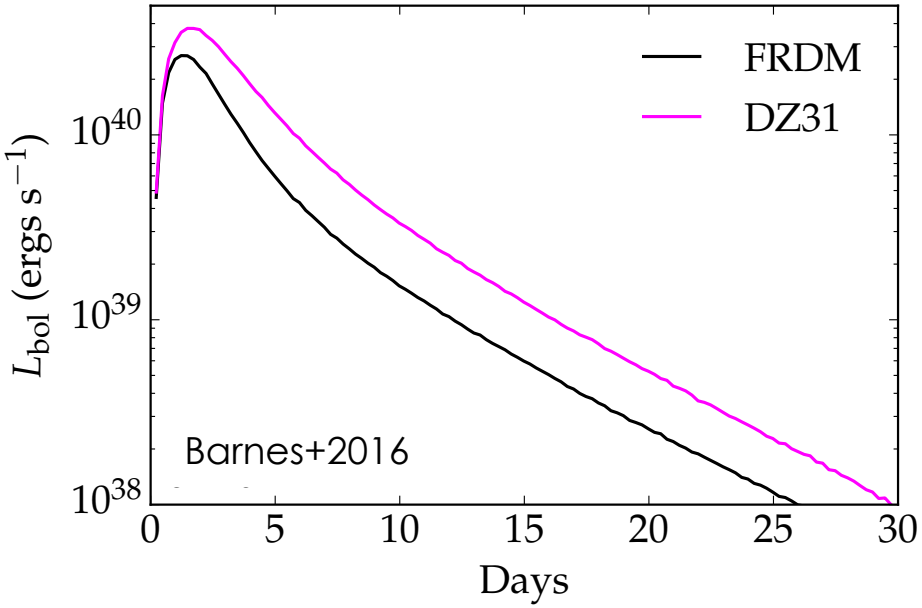
Duflo-Zuker



Holmbeck, Surman, Sprouse, Mumpower, Vassh, Beers arXiv: 1807.06662

impact of mass uncertainties





Holmbeck, Surman, Sprouse, Mumpower, Vassh, Beers
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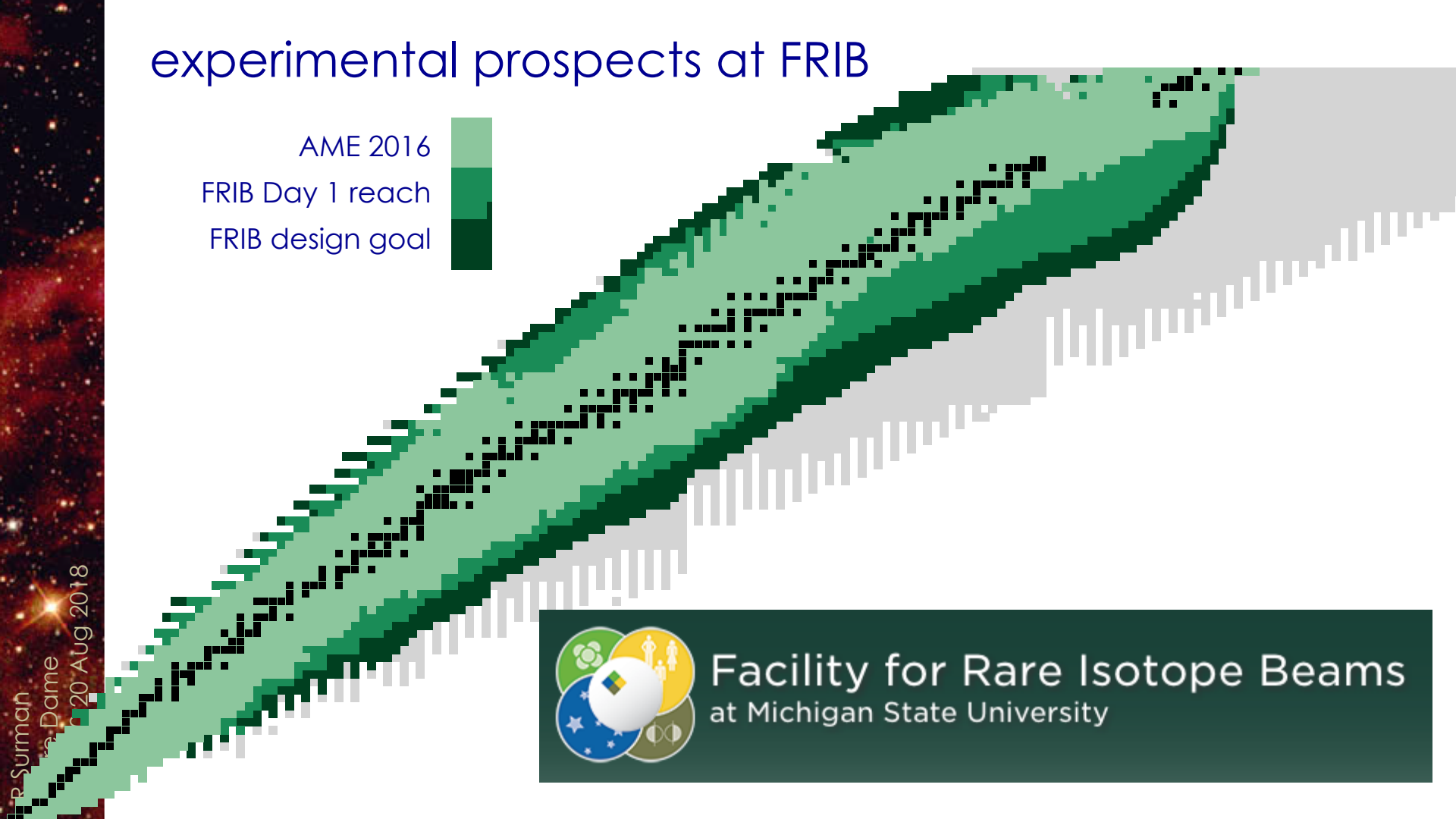
experimental prospects at FRIB



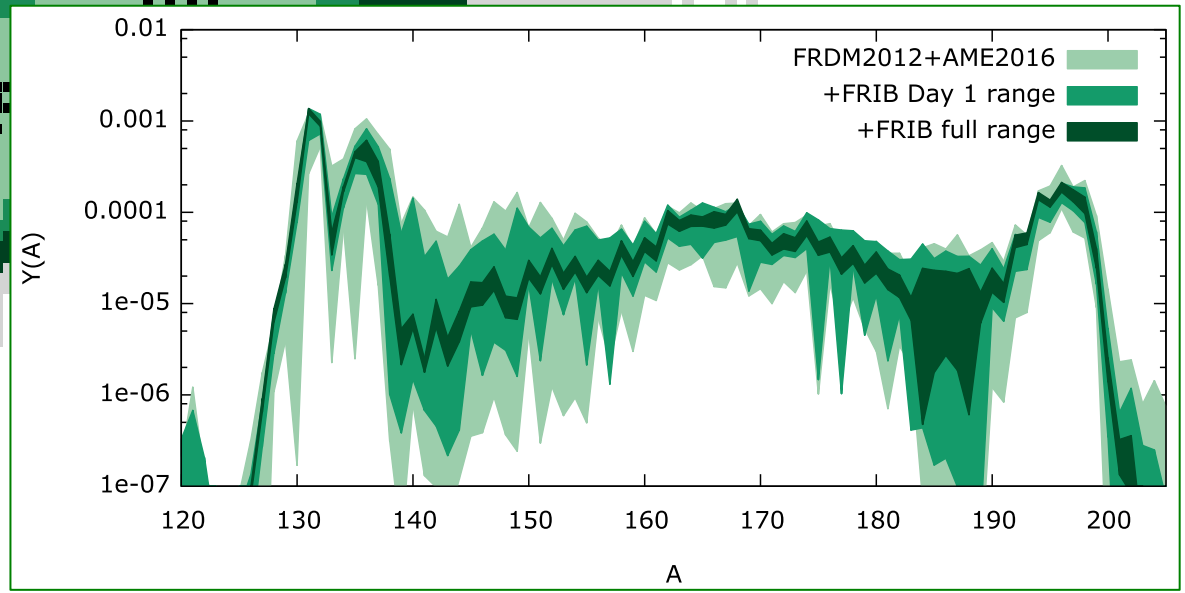
Facility for Rare Isotope Beams
at Michigan State University

experimental prospects at FRIB

AME 2016

FRIB Day 1 reach

FRIB design goal



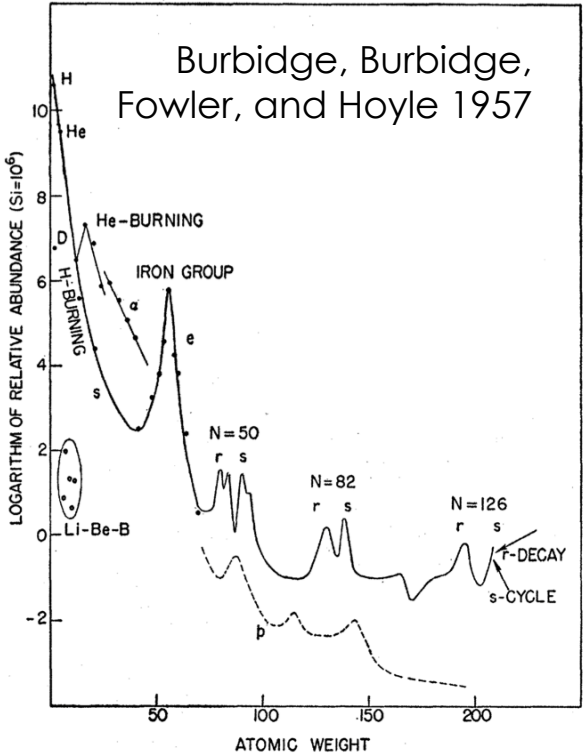
Surman and Mumpower 2018

summary: gamma-rays from *r*-process nuclei?

The origin of the heaviest elements in the *r*-process of nucleosynthesis has been one of the greatest mysteries in nuclear astrophysics for decades. Can gamma-ray astronomy contribute to its resolution?

The abundances of *r*-process isotopes in the galaxy are too low for general observations. However, if an *r*-process event occurs close enough, we can potentially see gammas from the transient.

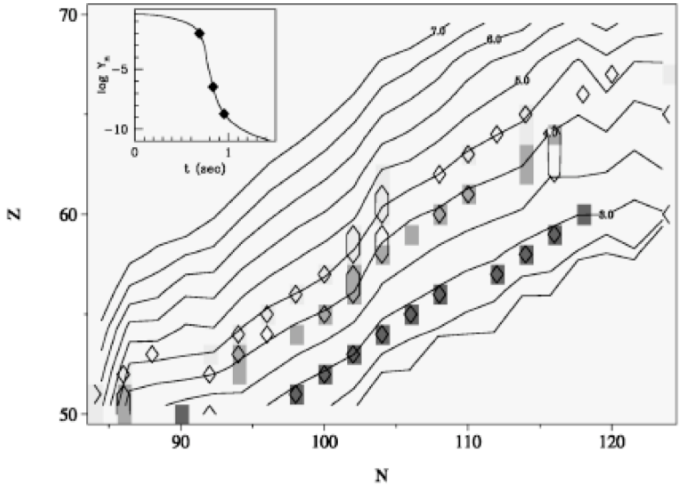
Exactly which isotopes are the best candidates for such observations depends on (largely unknown) nuclear physics far from stability. Upcoming radioactive beam facilities such as FRIB can potentially dramatically reduce these uncertainties and facilitate the development of precision *r*-process predictions.



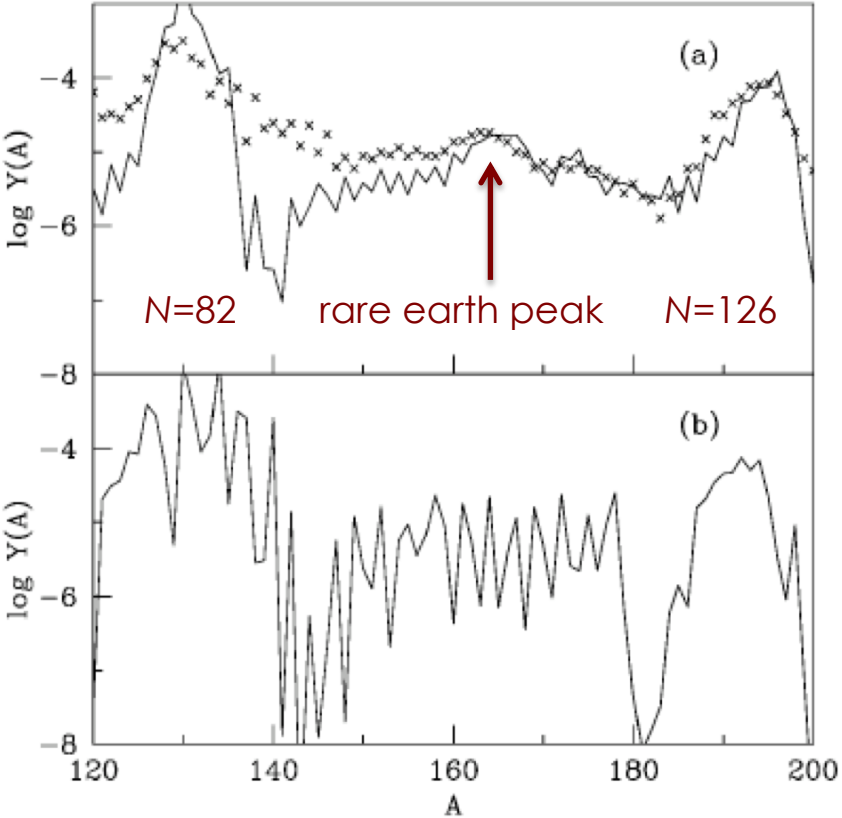
additional slides

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



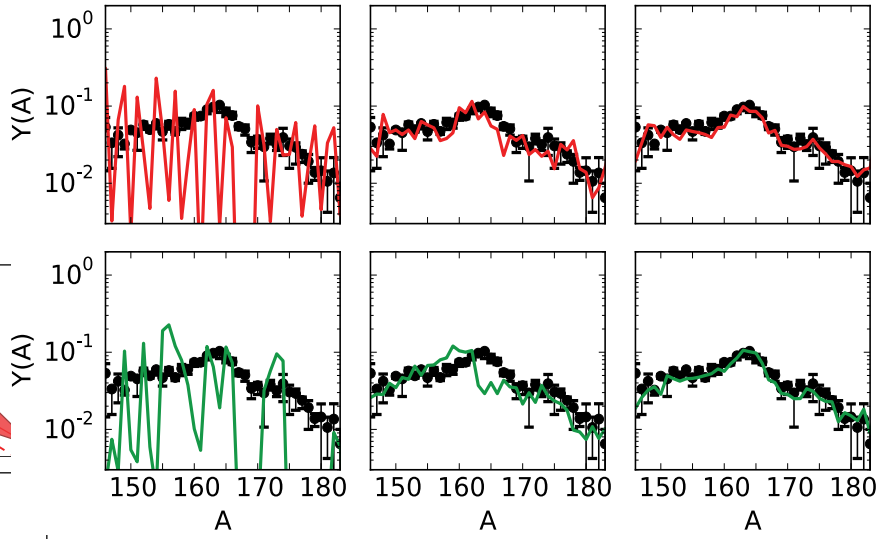
Surman+1998

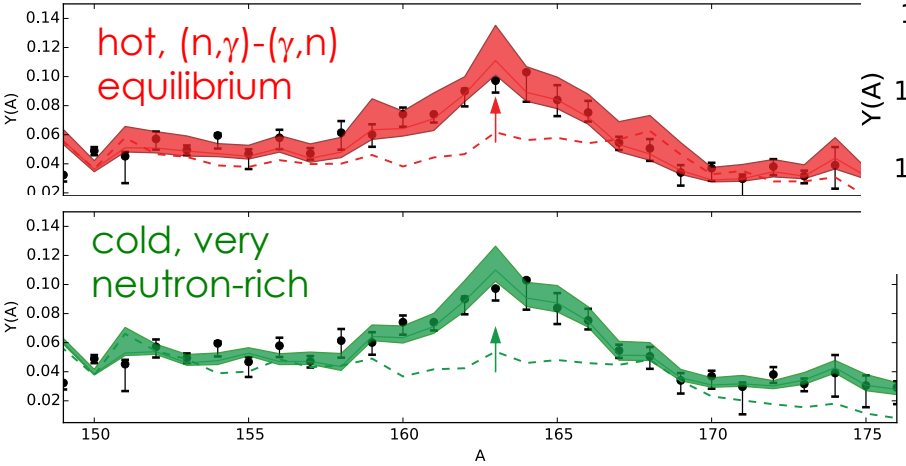


deducing *r*-process conditions from abundance pattern details: the rare earth peak

mass modification parameterization:

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





Mumpower, McLaughlin, Surman, Steiner 2016

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

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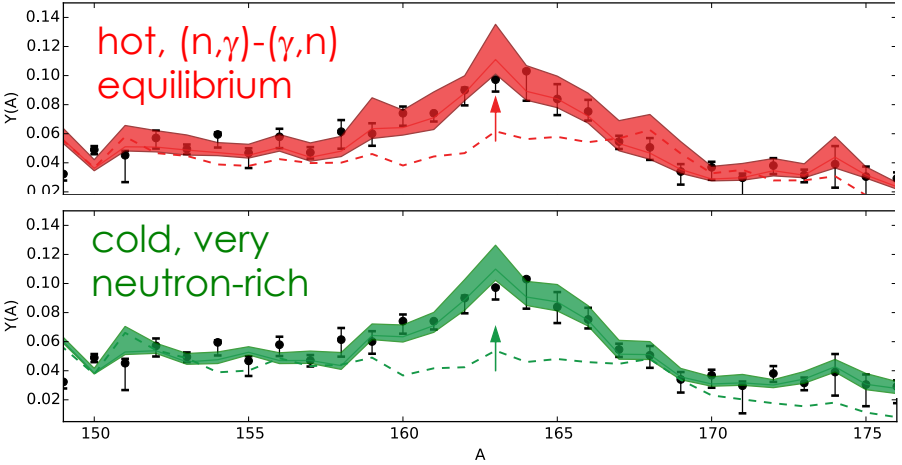
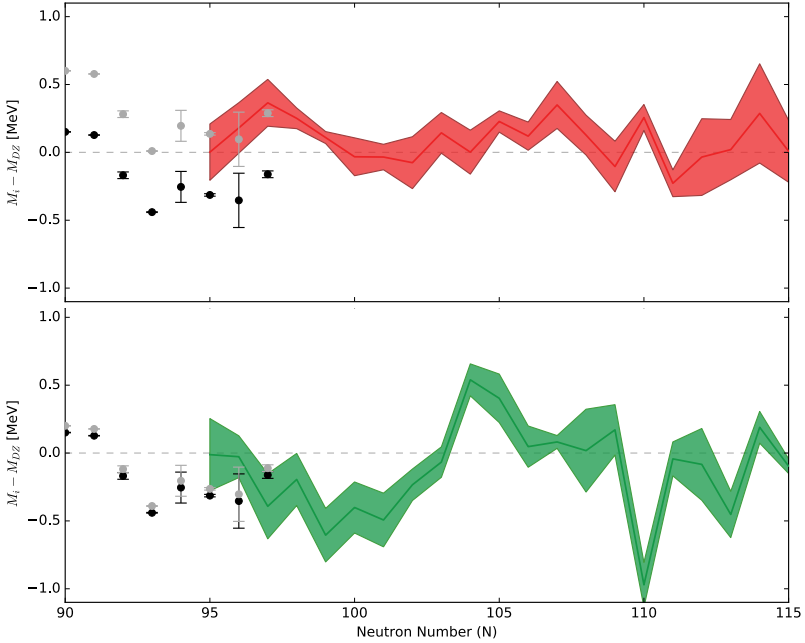
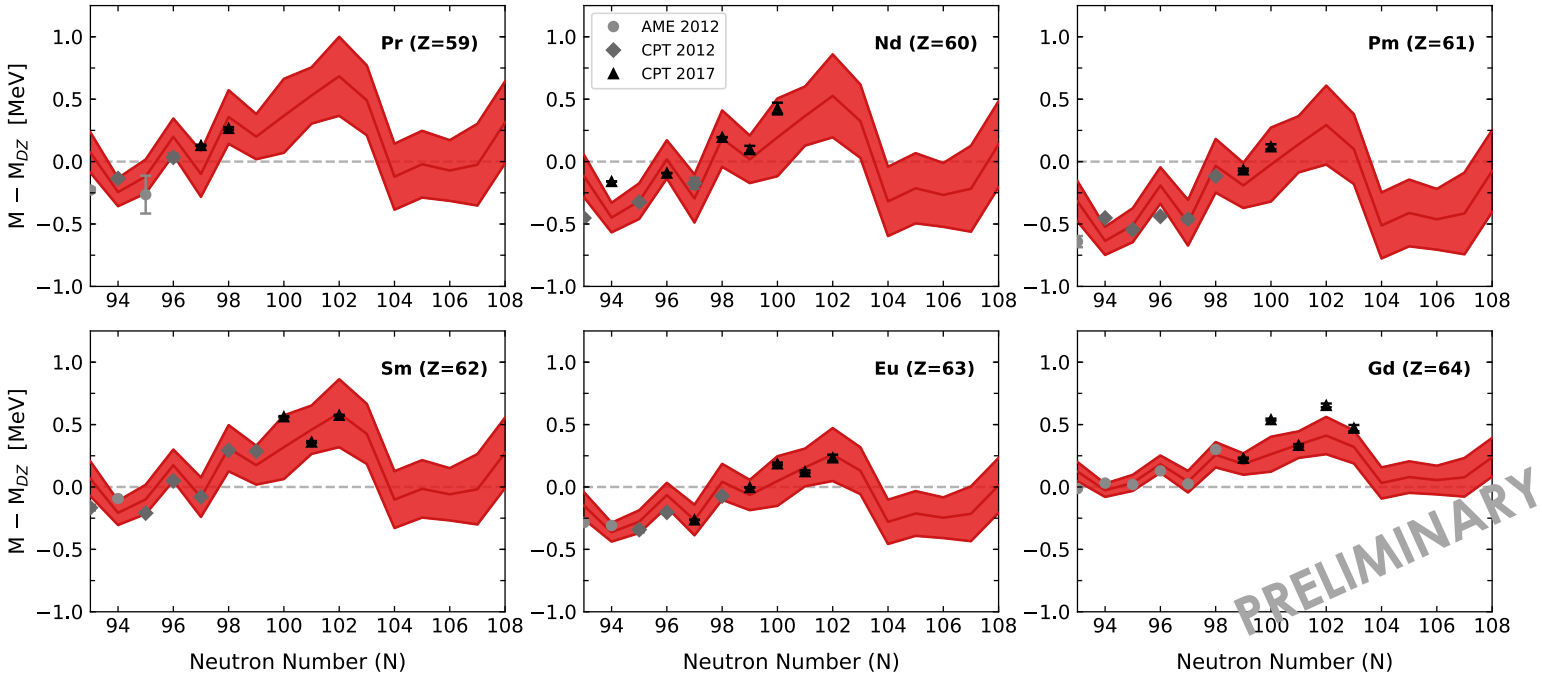




predicted mass trends for the Neodymium (Z = 60) isotopic chain

Mumpower, McLaughlin, Surman, Steiner 2016

updated reverse engineering calculations



reverse engineering calcs led by Nicole Vassh + masses from CPT at CARIBU

Orford, Vassh, et al, PRL 2018; Orford et al in prep; Vassh et al in prep

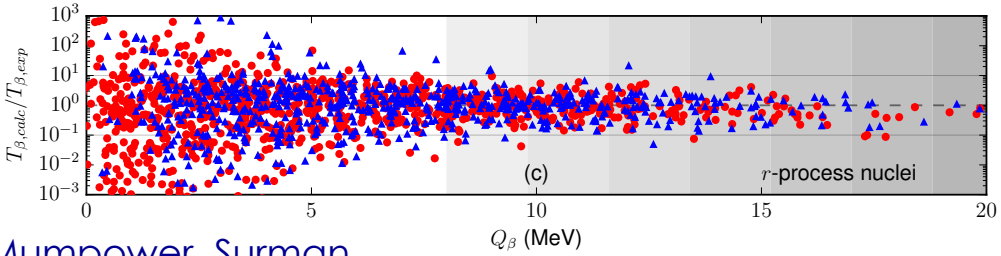
required nuclear data: beta decay

beta decay rates from NUBASE 2016

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

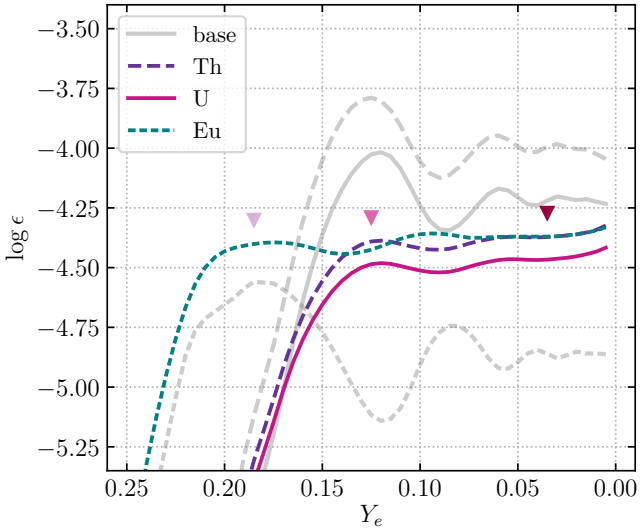
fission rates
fission product distributions
neutrino interaction rates

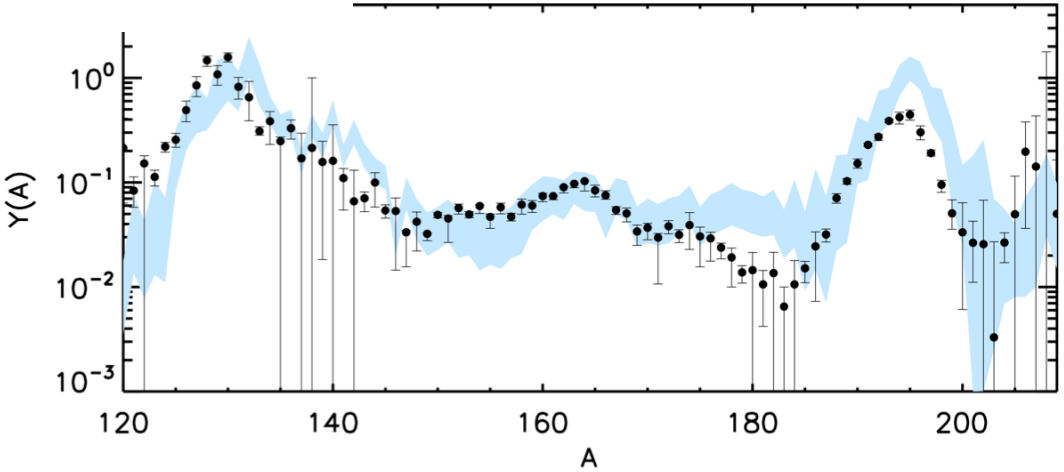
beta decay uncertainties and impact



Mumpower, Surman, McLaughlin, Aprahamian 2016

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



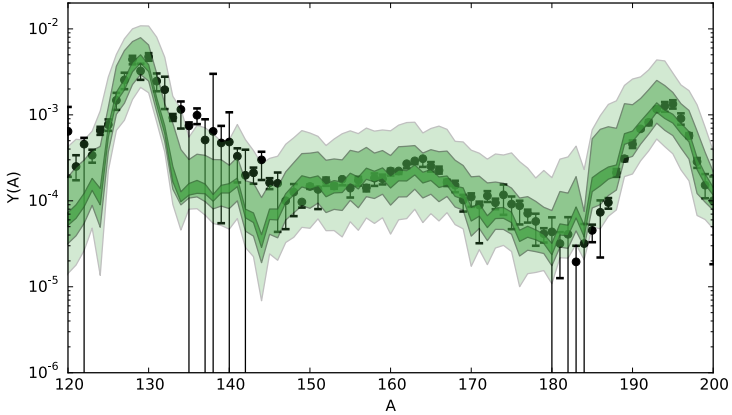


Holmbeck, Surman, Sprouse, Mumpower, Vassh, Beers
arXiv: 1807.06662

required nuclear data: neutron capture

neutron capture rates from KADONIS

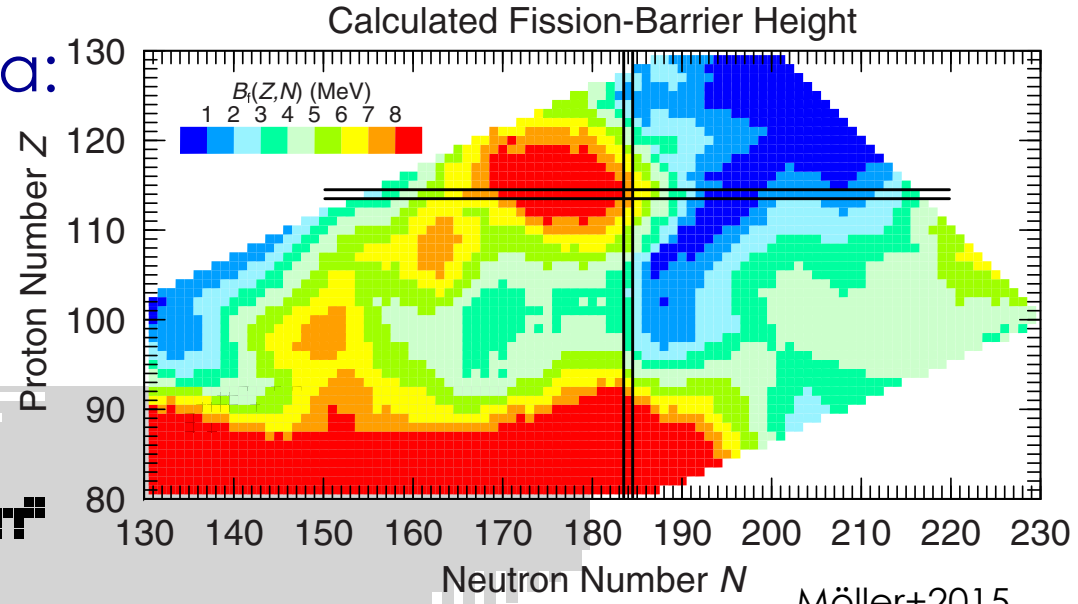
masses
beta-decay rates
beta-delayed neutron emission probabilities
neutron capture rates



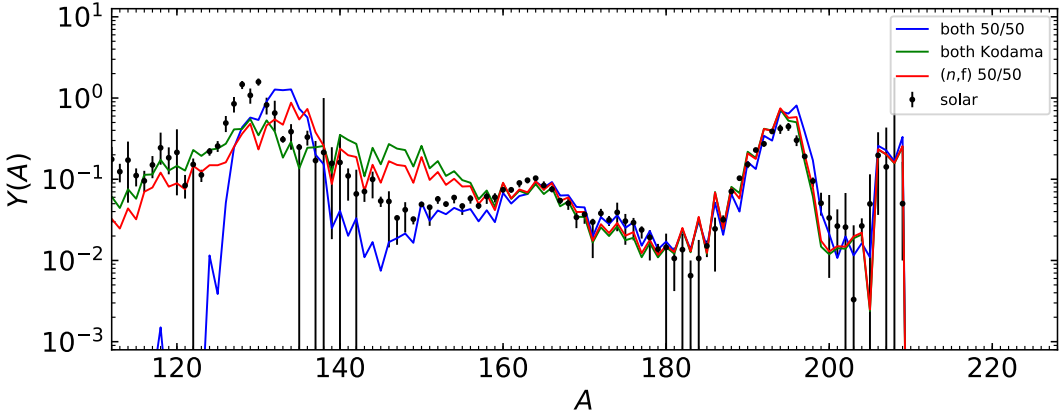
Liddick+2016

required nuclear data: fission properties

FIRE: Fission In R-process Elements
US DOE/NNSA
Topical Collaboration



Möller+2015



Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, Möller, submitted