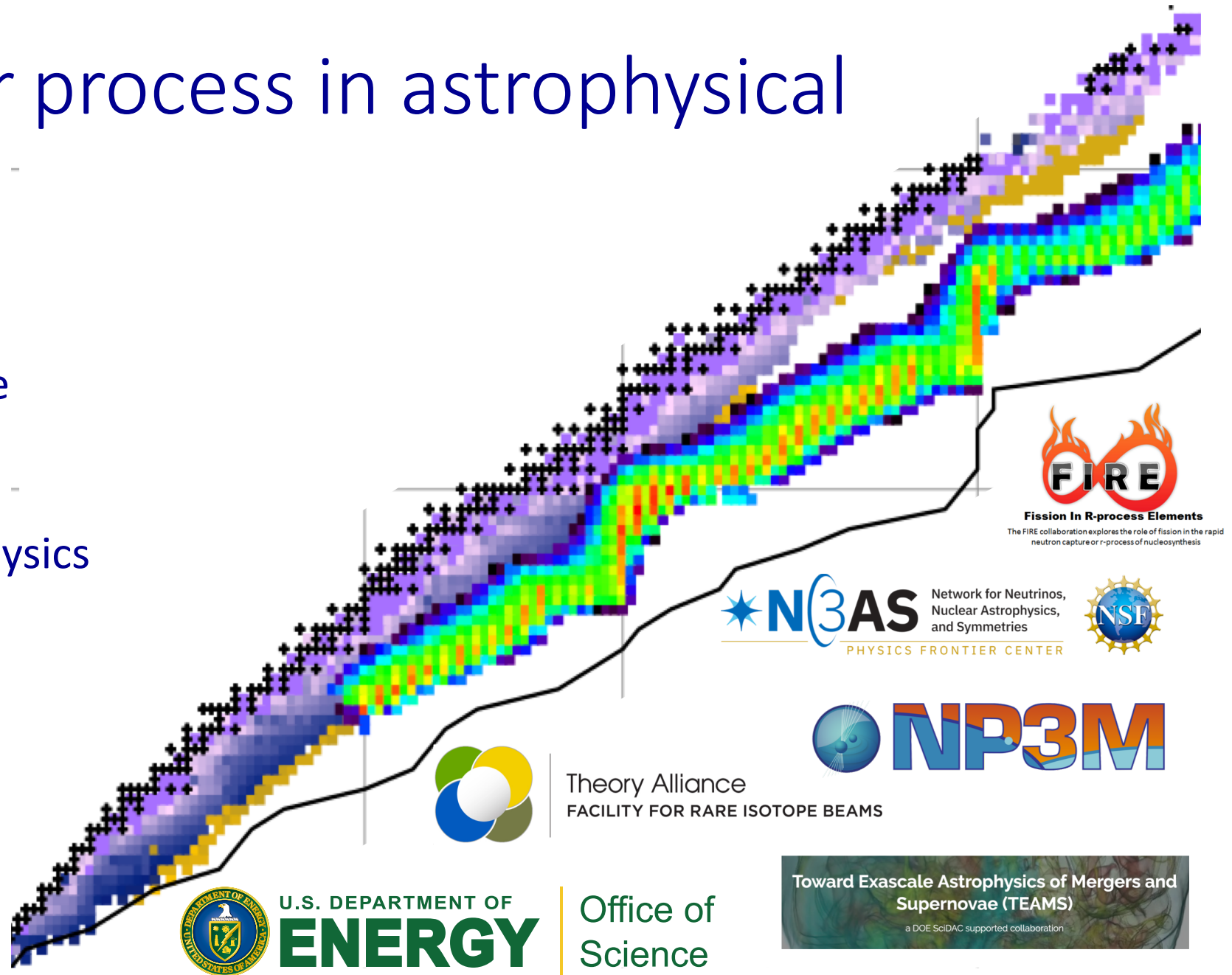


# Status of the $r$ process in astrophysical systems

Rebecca Surman  
University of Notre Dame

Neutrinos as a Portal to  
New Physics and Astrophysics  
KITP

24 March 2022



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



Theory Alliance  
FACILITY FOR RARE ISOTOPE BEAMS

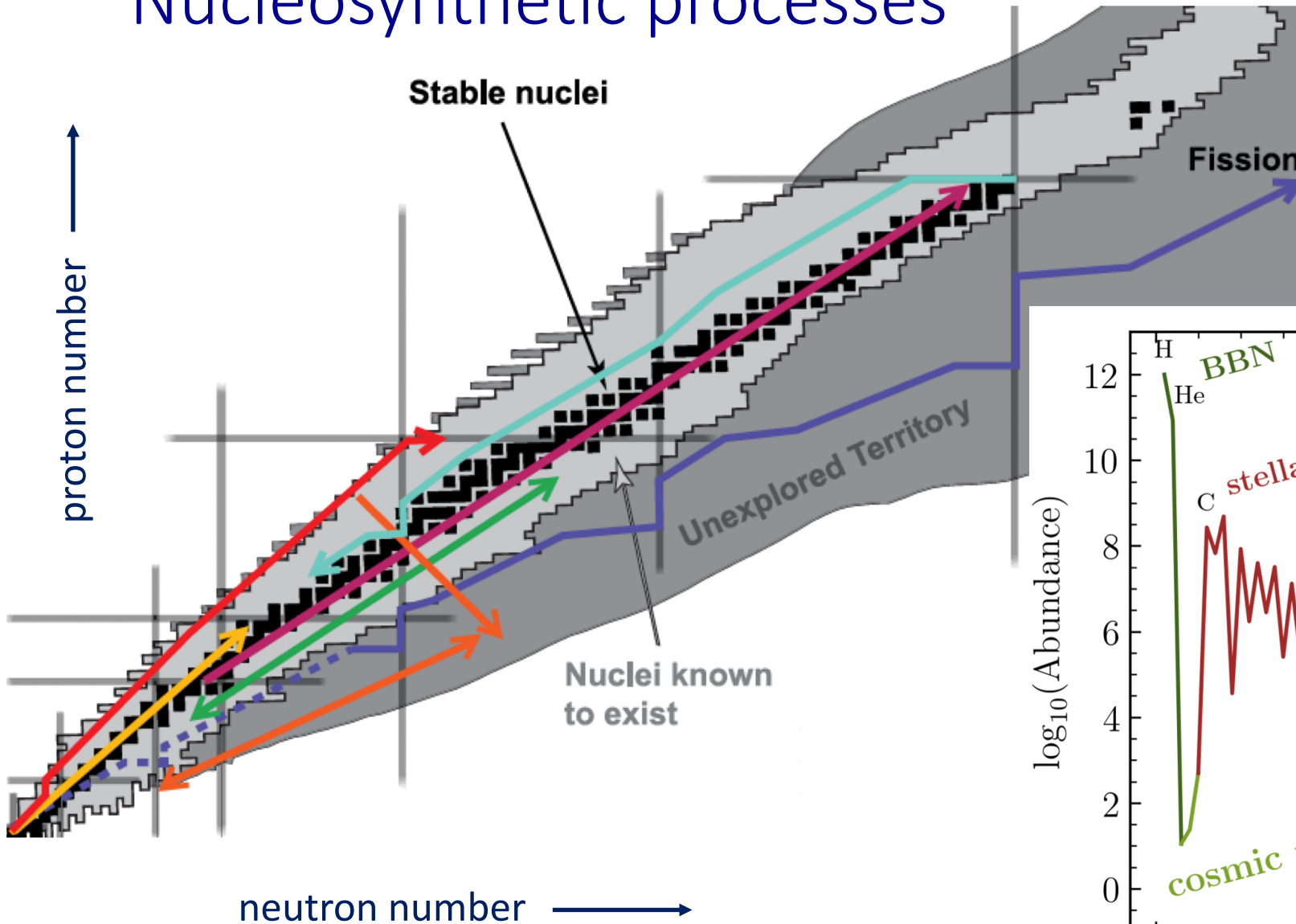


U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

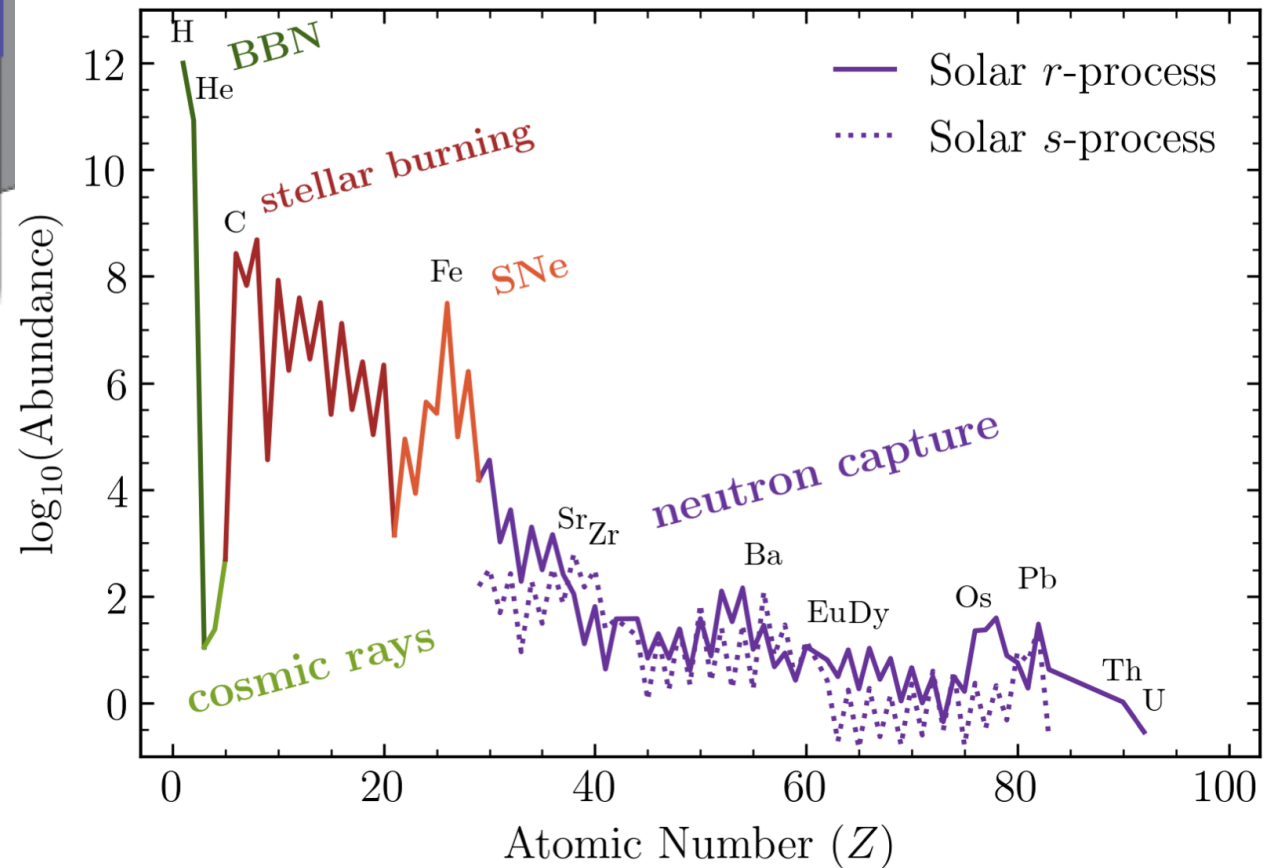
Toward Exascale Astrophysics of Mergers and  
Supernovae (TEAMS)  
a DOE SciDAC supported collaboration

# Nucleosynthetic processes



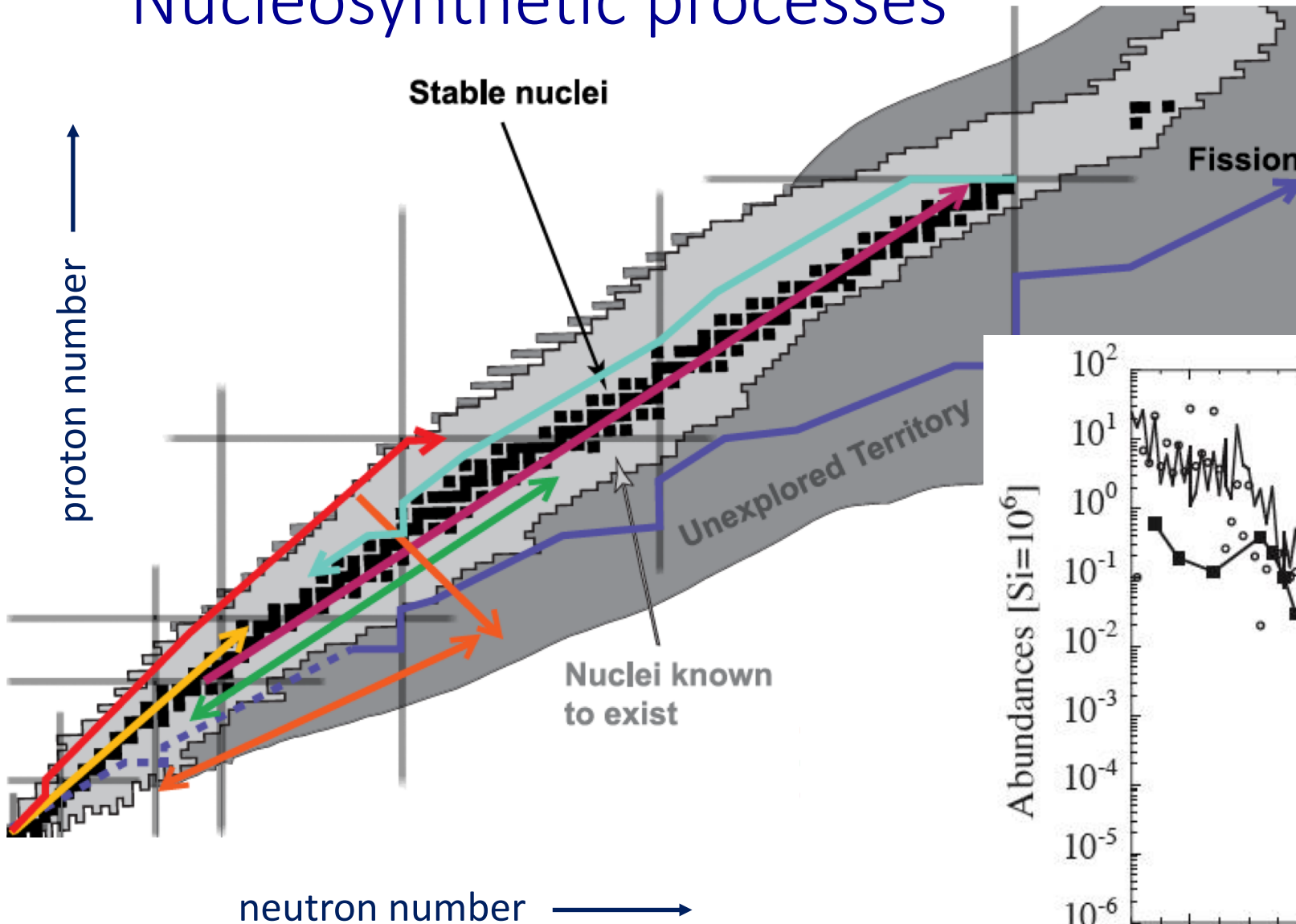
from Timmes/Schatz/Spyrou

data from Lodders 2003  
figure by E Holmbeck

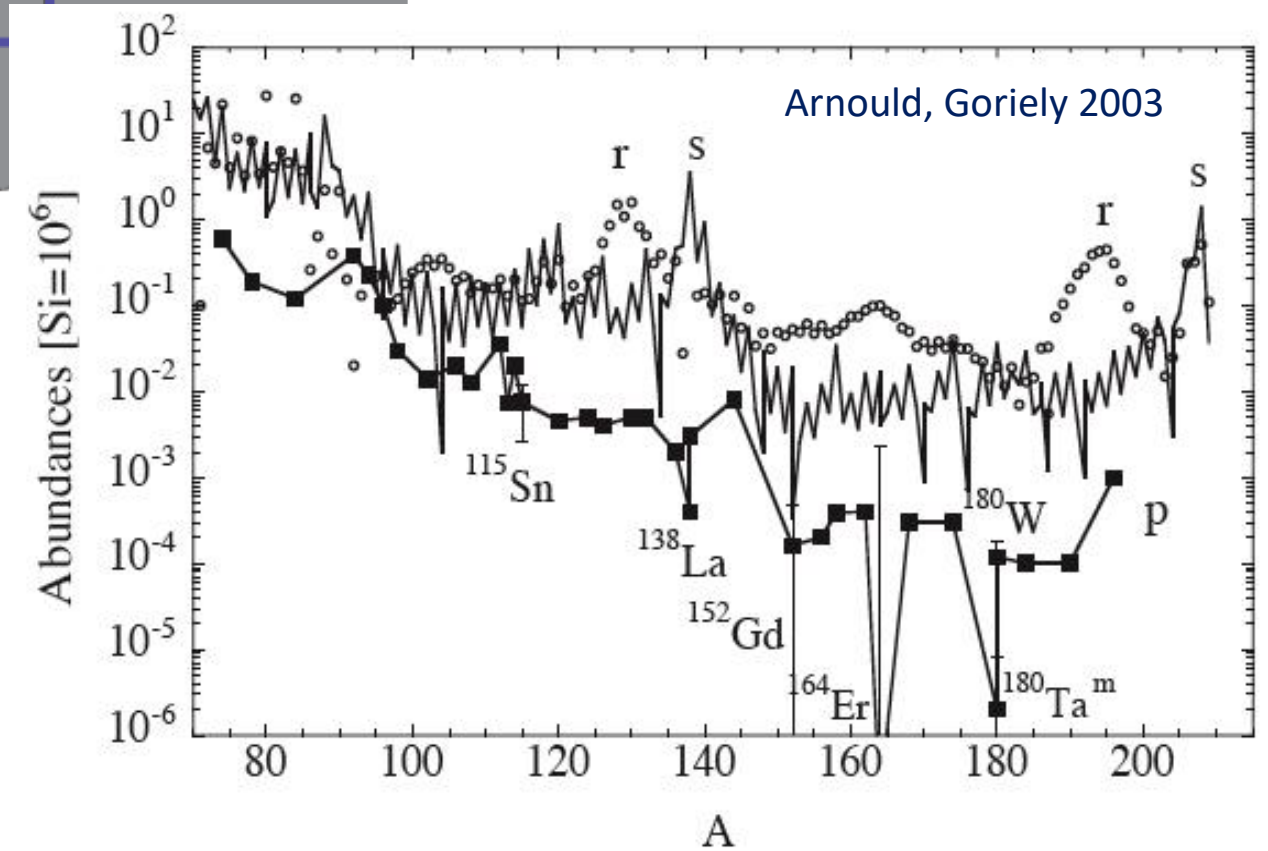




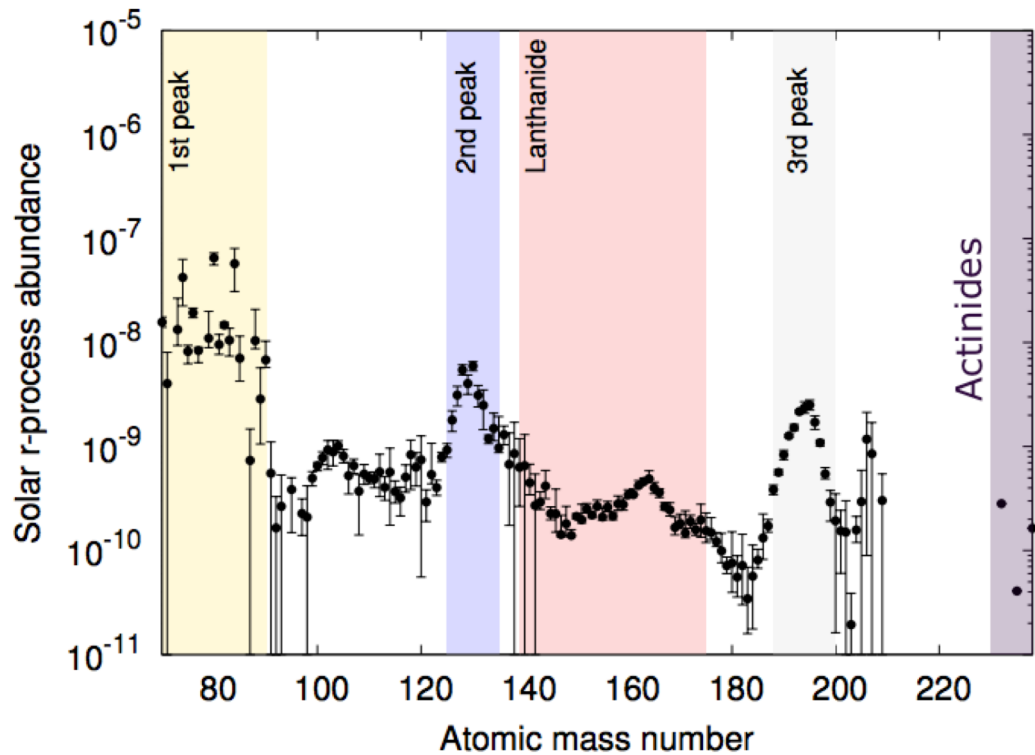
# Nucleosynthetic processes



from Timmes/Schatz/Spyrou



# r-process nucleosynthesis



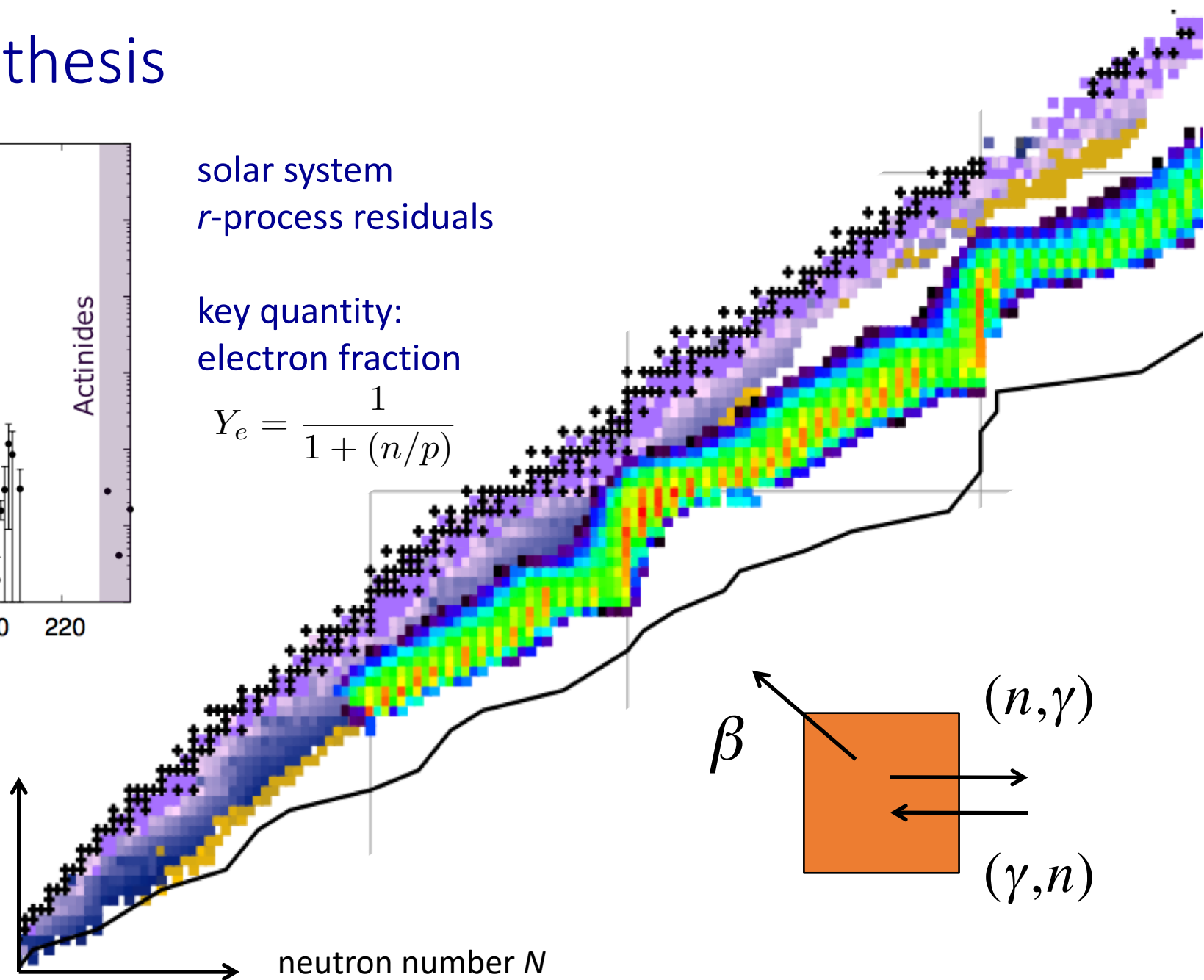
Arnould+2007, Hotokezaka+2018

solar system  
r-process residuals

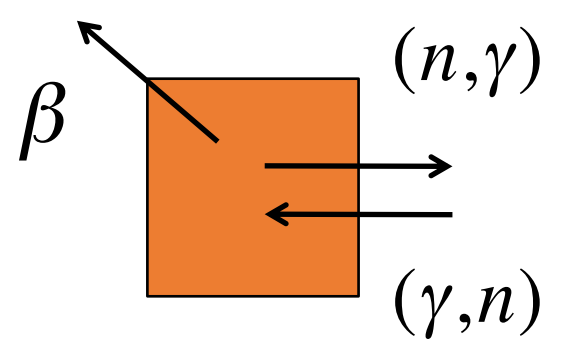
key quantity:  
electron fraction

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

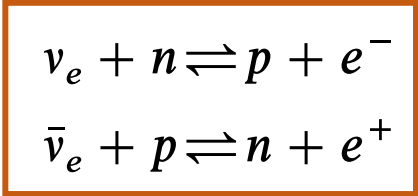
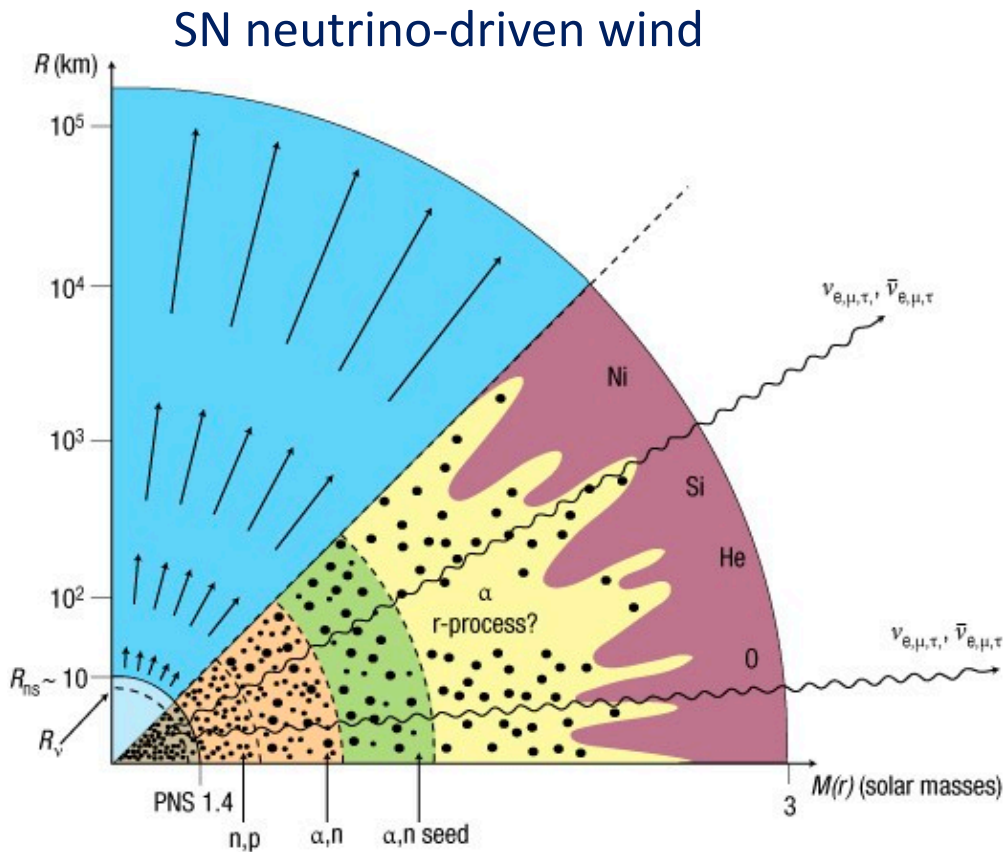
proton number  $Z$



neutron number  $N$



# r-process astrophysical sites: supernovae?



Neutrino physics shapes the

- Electron fraction

$$Y_{e,f} \approx \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}} \approx \left( 1 + \frac{L_{\bar{\nu}_e} \epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e}}{L_{\nu_e} \epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e}} \right)^{-1}$$

- Entropy per baryon

$$S_f \approx 235 C^{-1/6} L_{\bar{\nu}_e, 51}^{-1/6} \epsilon_{\bar{\nu}_e, \text{MeV}}^{-1/3} R_6^{-2/3} \left( \frac{M}{1.4 M_\odot} \right) \text{ for } S_f \gg S_N$$

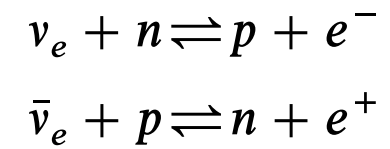
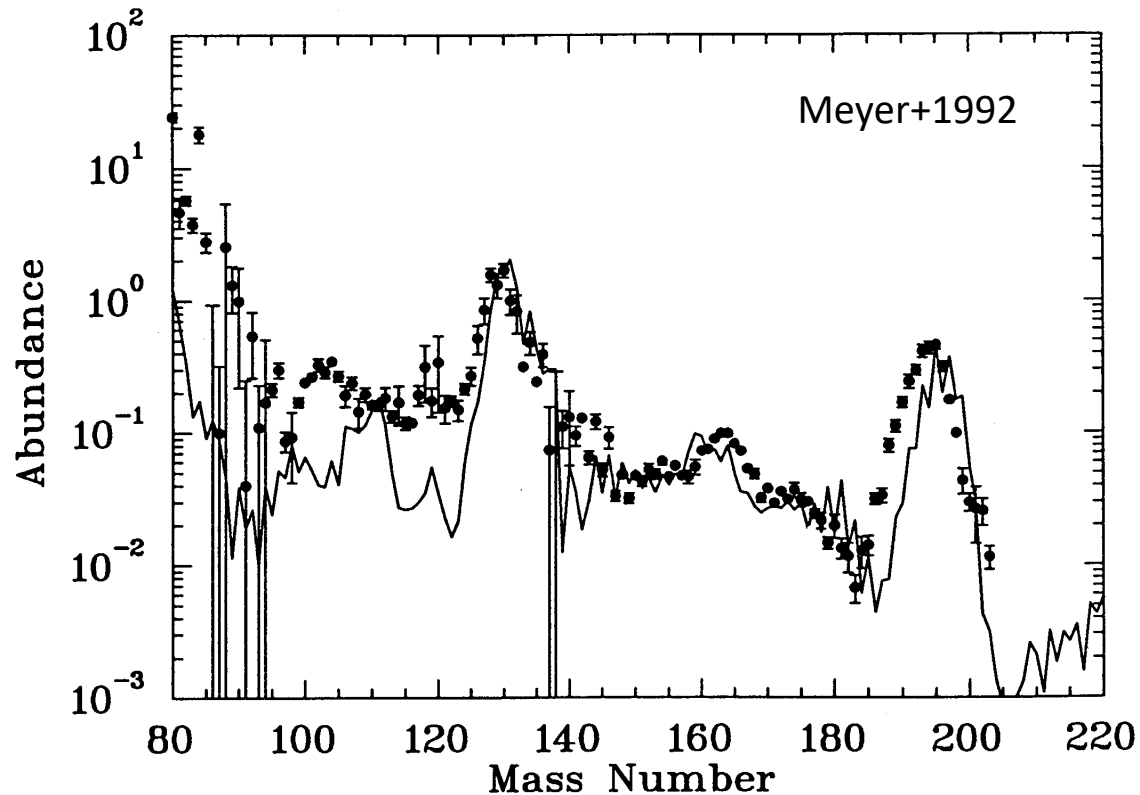
$$S_{\text{tot}} \approx S_f + S_N \approx S_f + \ln S_f + 10$$

Woosley, Janka 2005

Qian, Woosley 1996

# r-process astrophysical sites: supernovae?

SN neutrino-driven wind



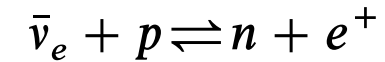
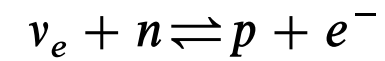
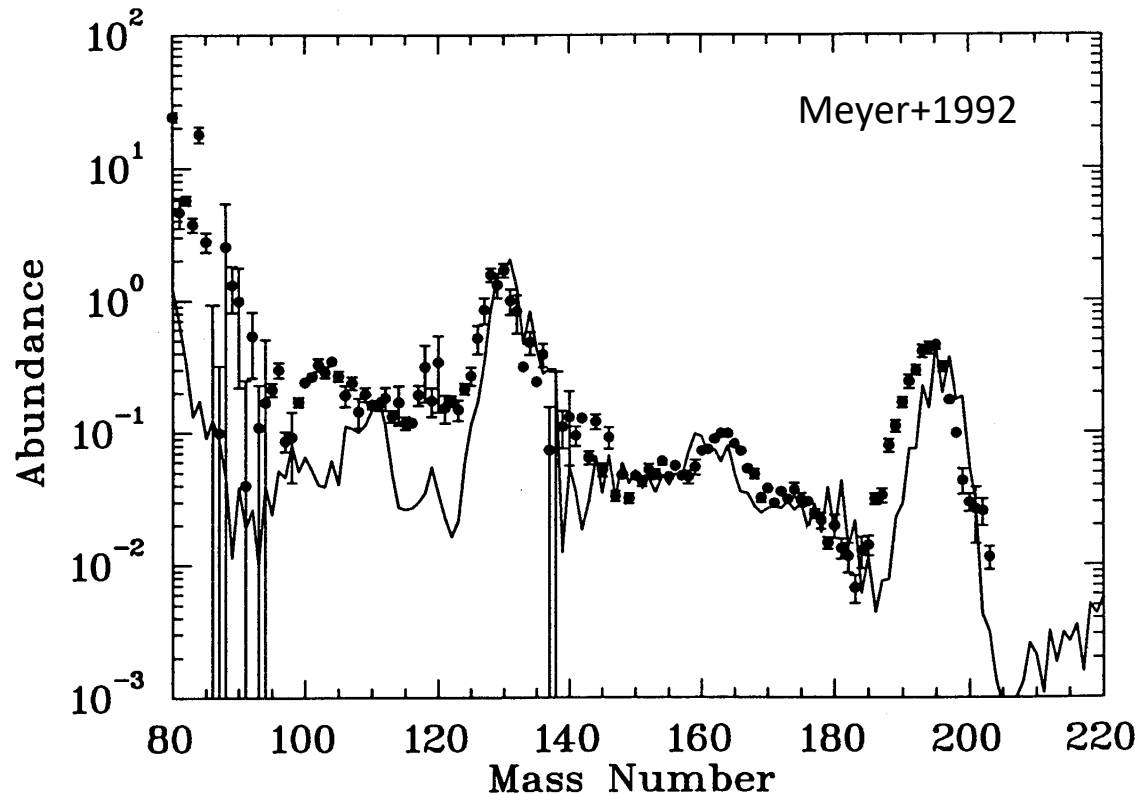
Does this work?

- Yes

Meyer+1992, Woosley+1994

# r-process astrophysical sites: supernovae?

SN neutrino-driven wind



Does this work?

- Yes

Meyer+1992, Woosley+1994

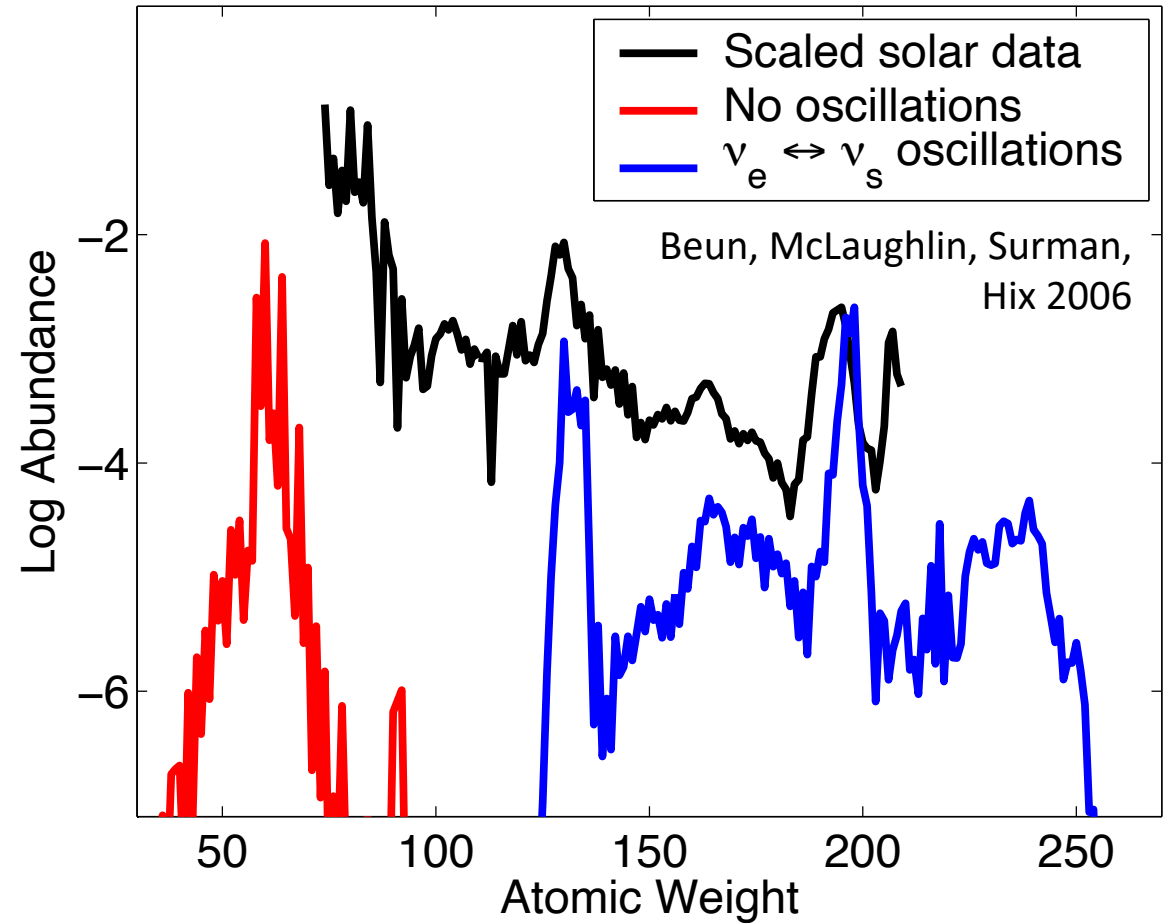
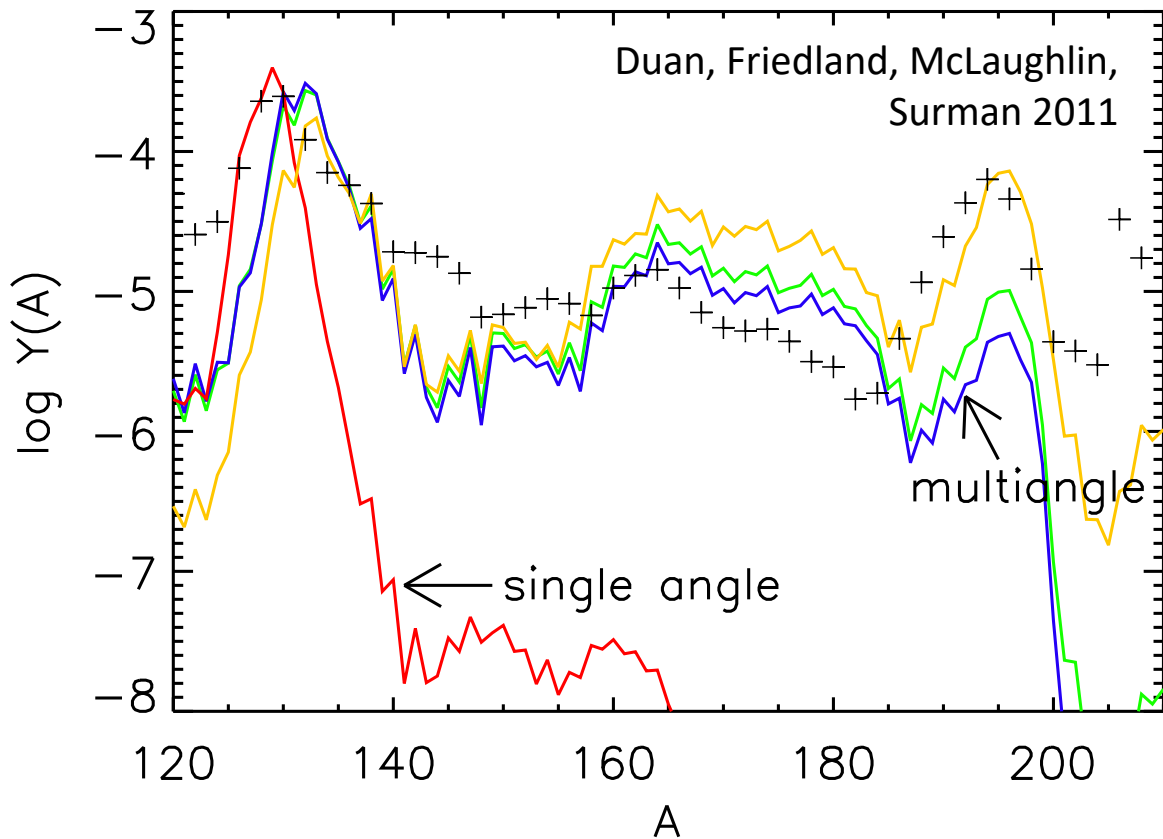
- No

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



# *r*-process astrophysical sites: supernovae?

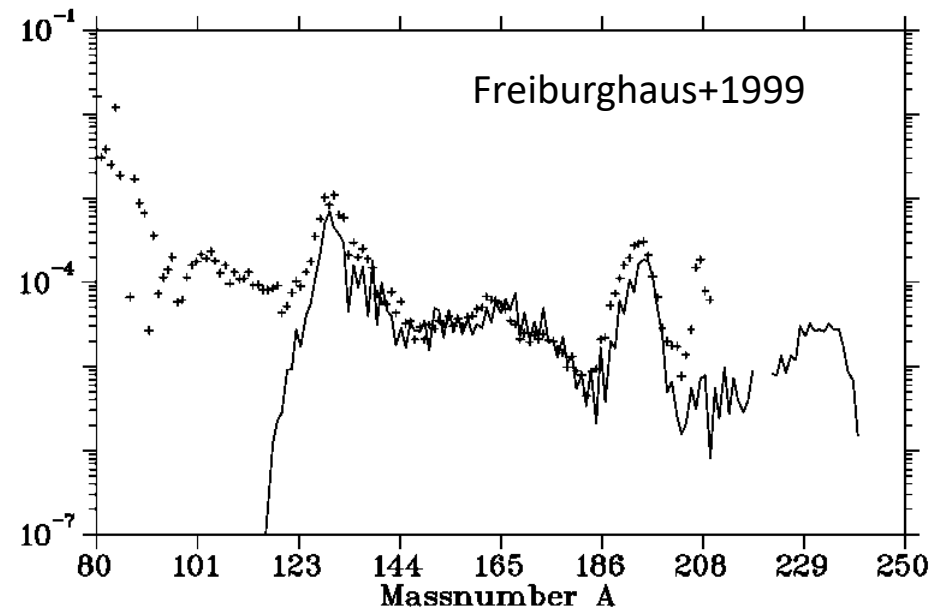
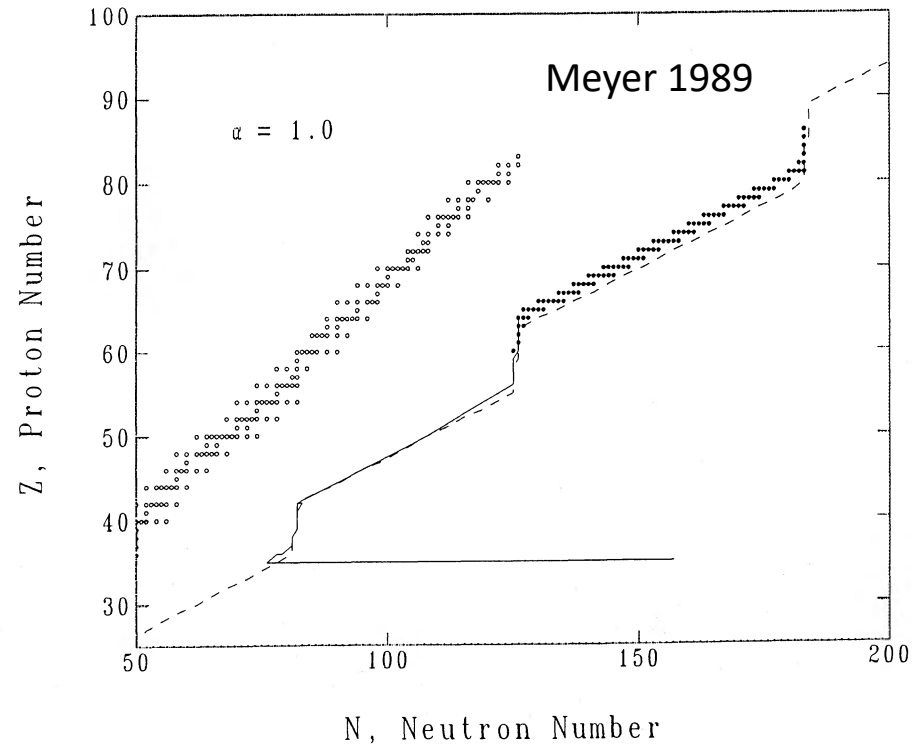
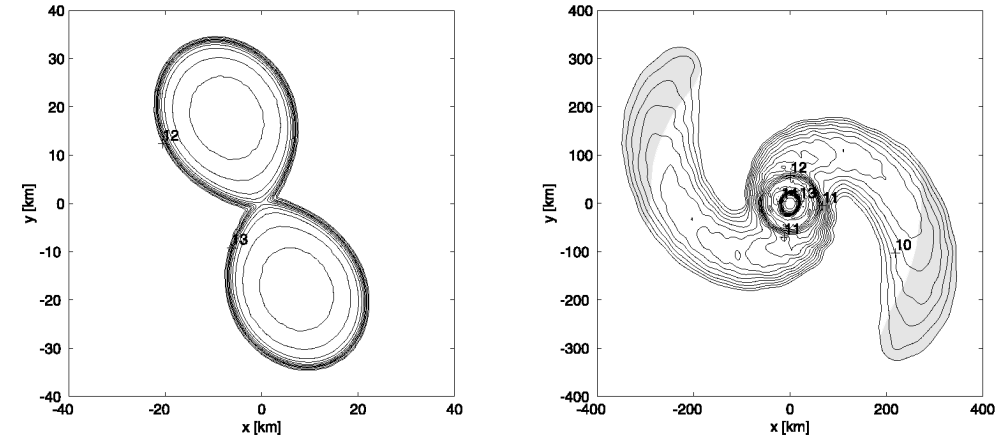
SN neutrino-driven wind: oscillations

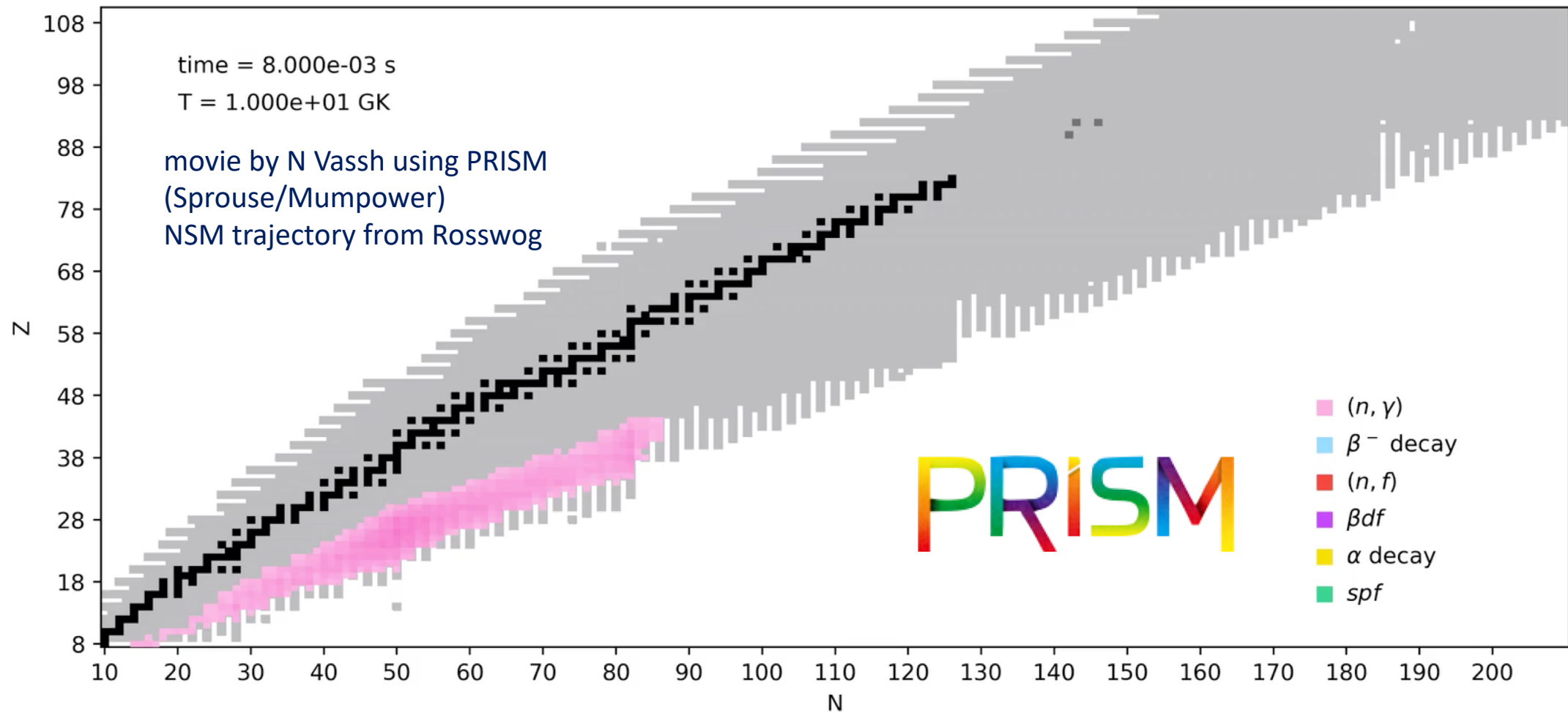
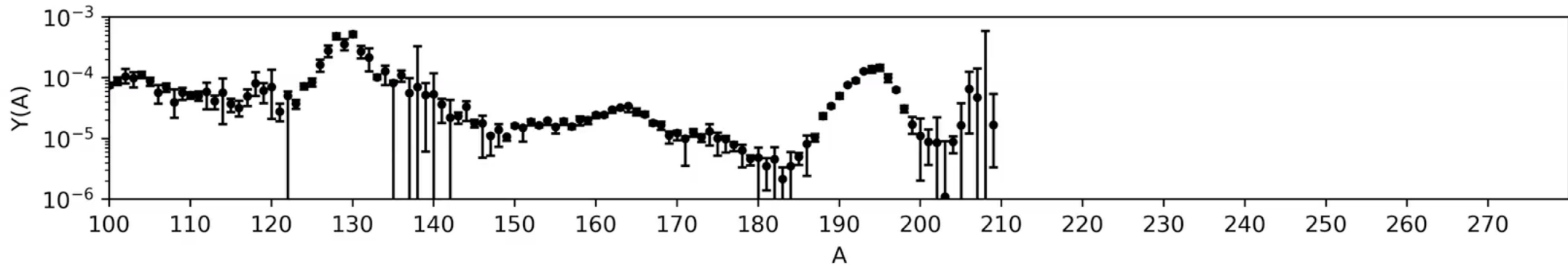


# r-process astrophysical sites: neutron star mergers?

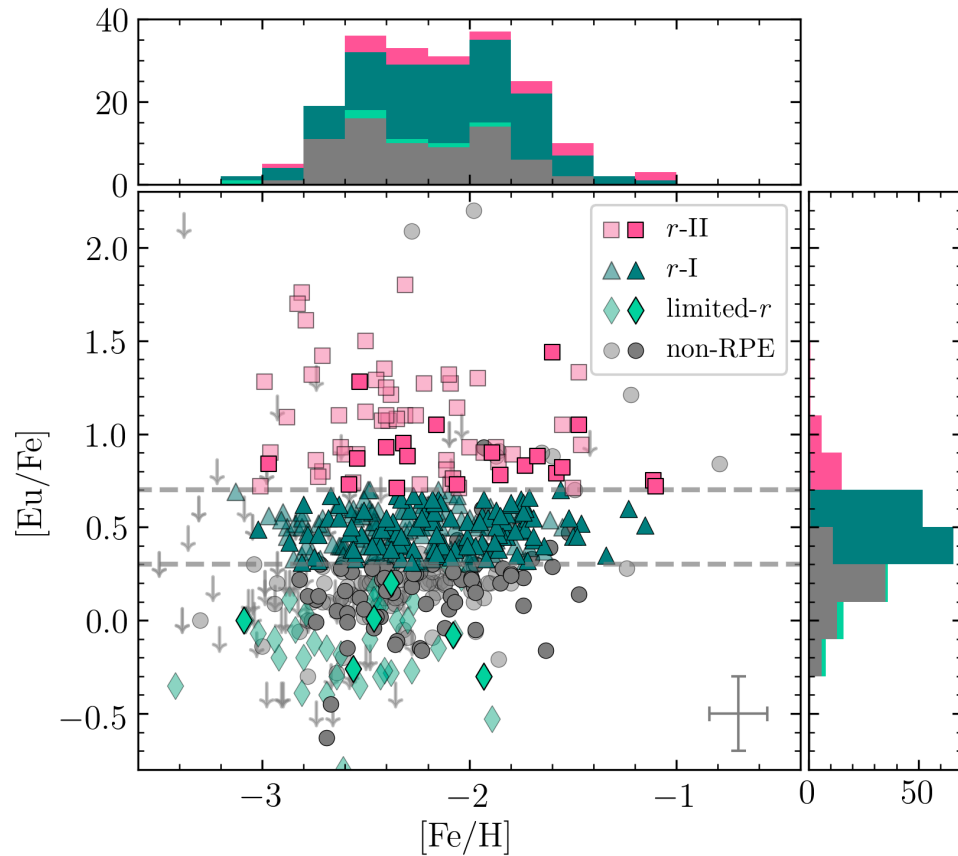
decompression of cold, neutron-rich matter

Lattimer, Schramm 1974, 1976

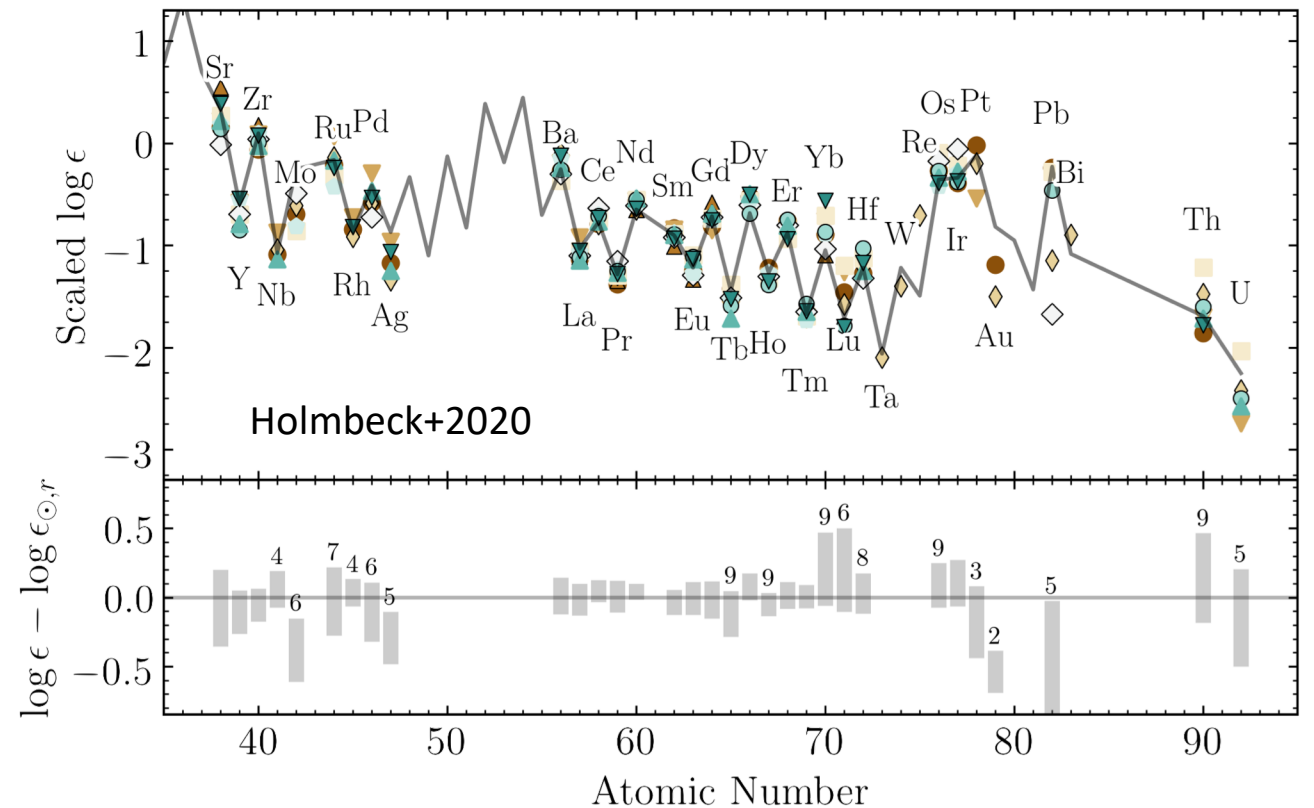




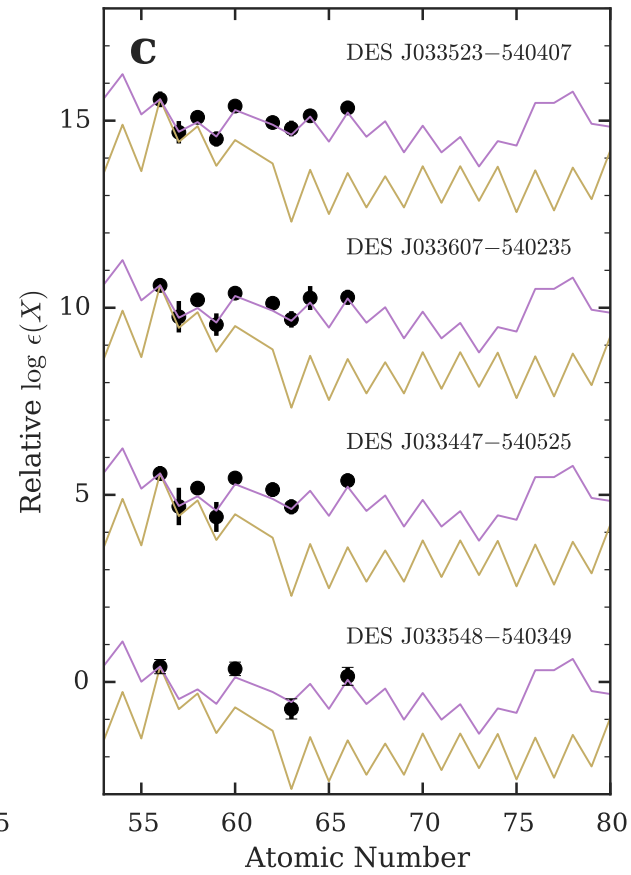
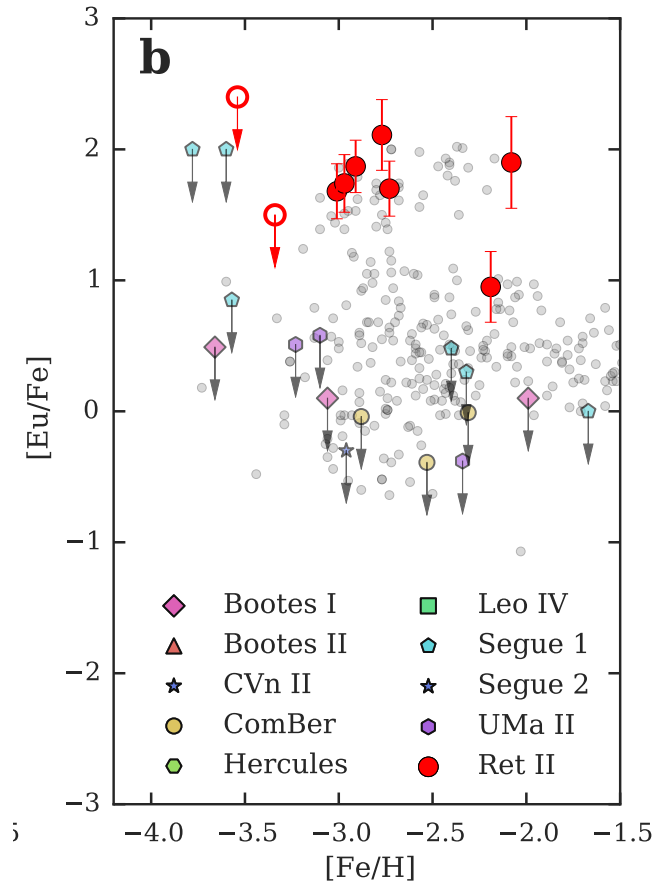
# r-process astrophysical sites: clues from stars



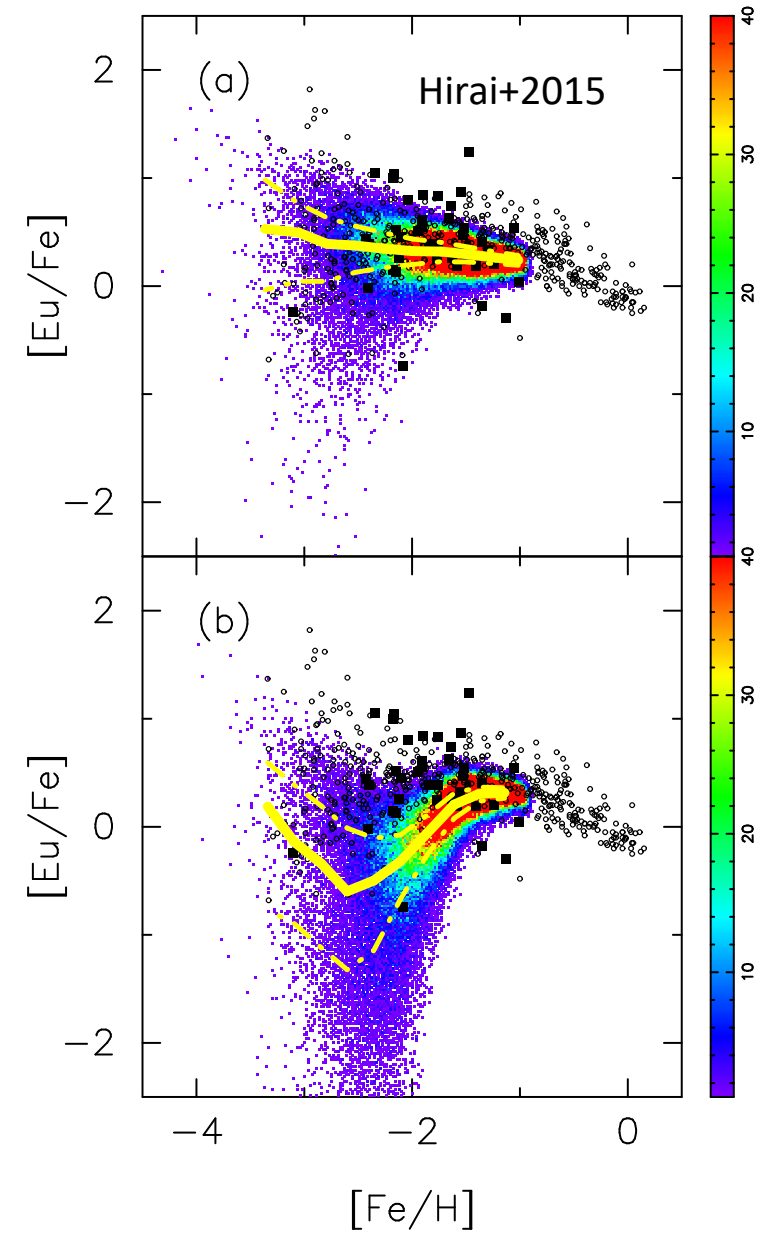
Hansen+2018, Sakari+2018, Ezzeddine+2020, Holmbeck+2020



# Dwarf galaxy Ret II



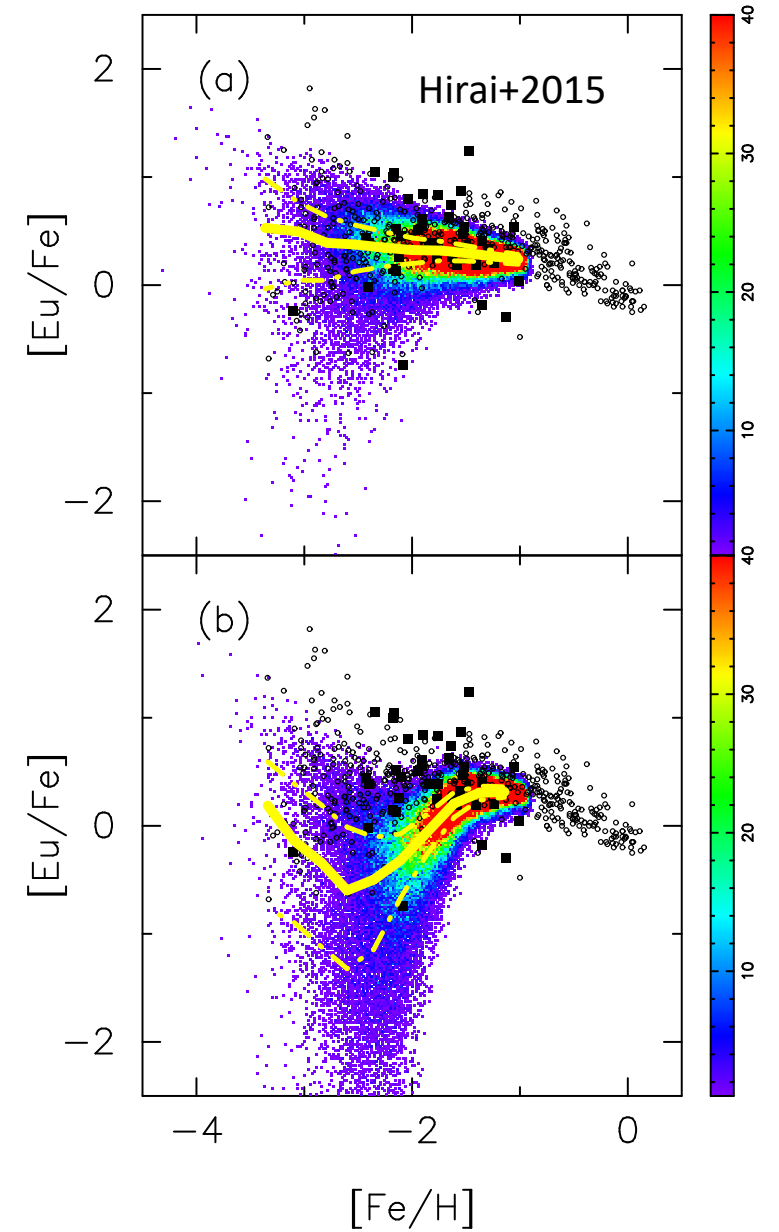
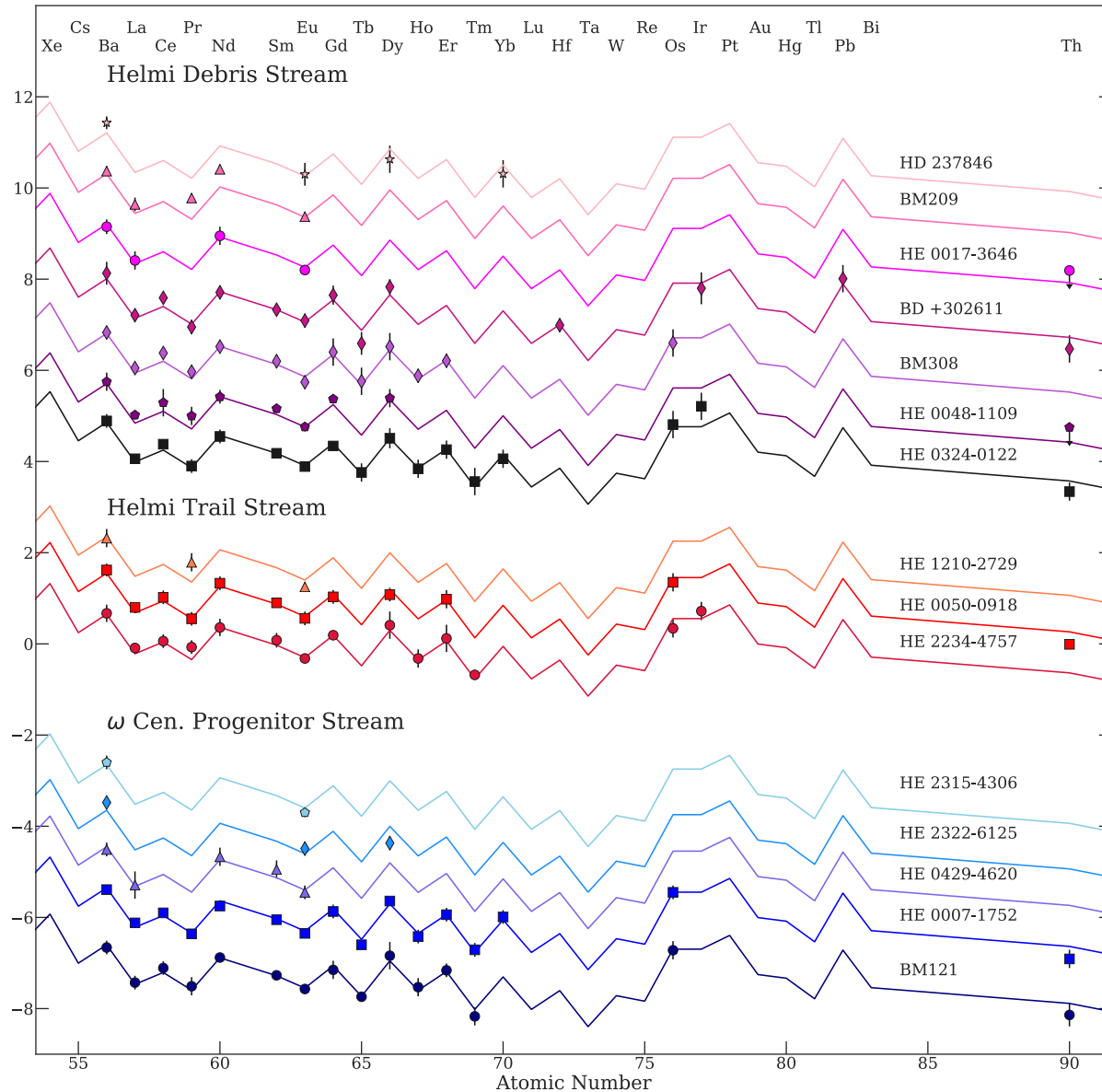
Ji+2016



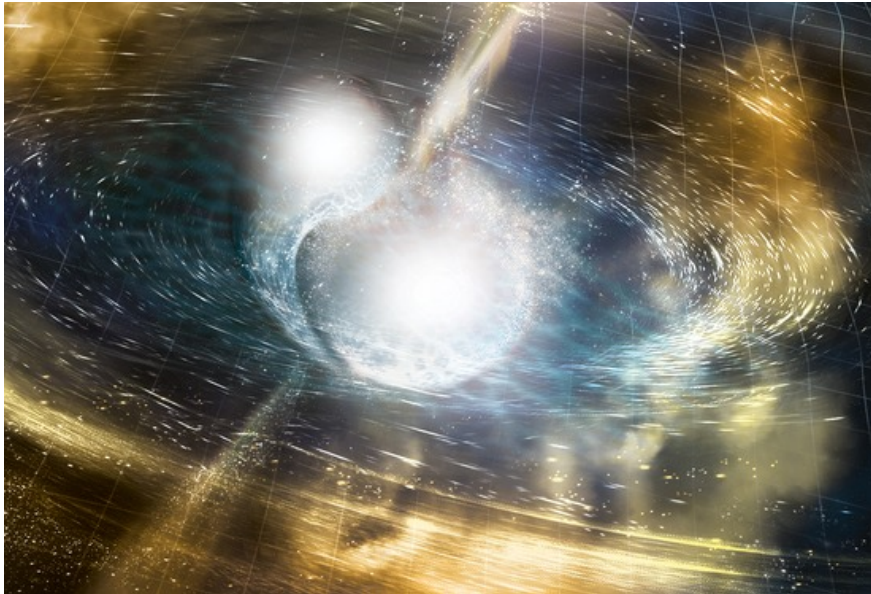


# Dwarf galaxies and stellar streams

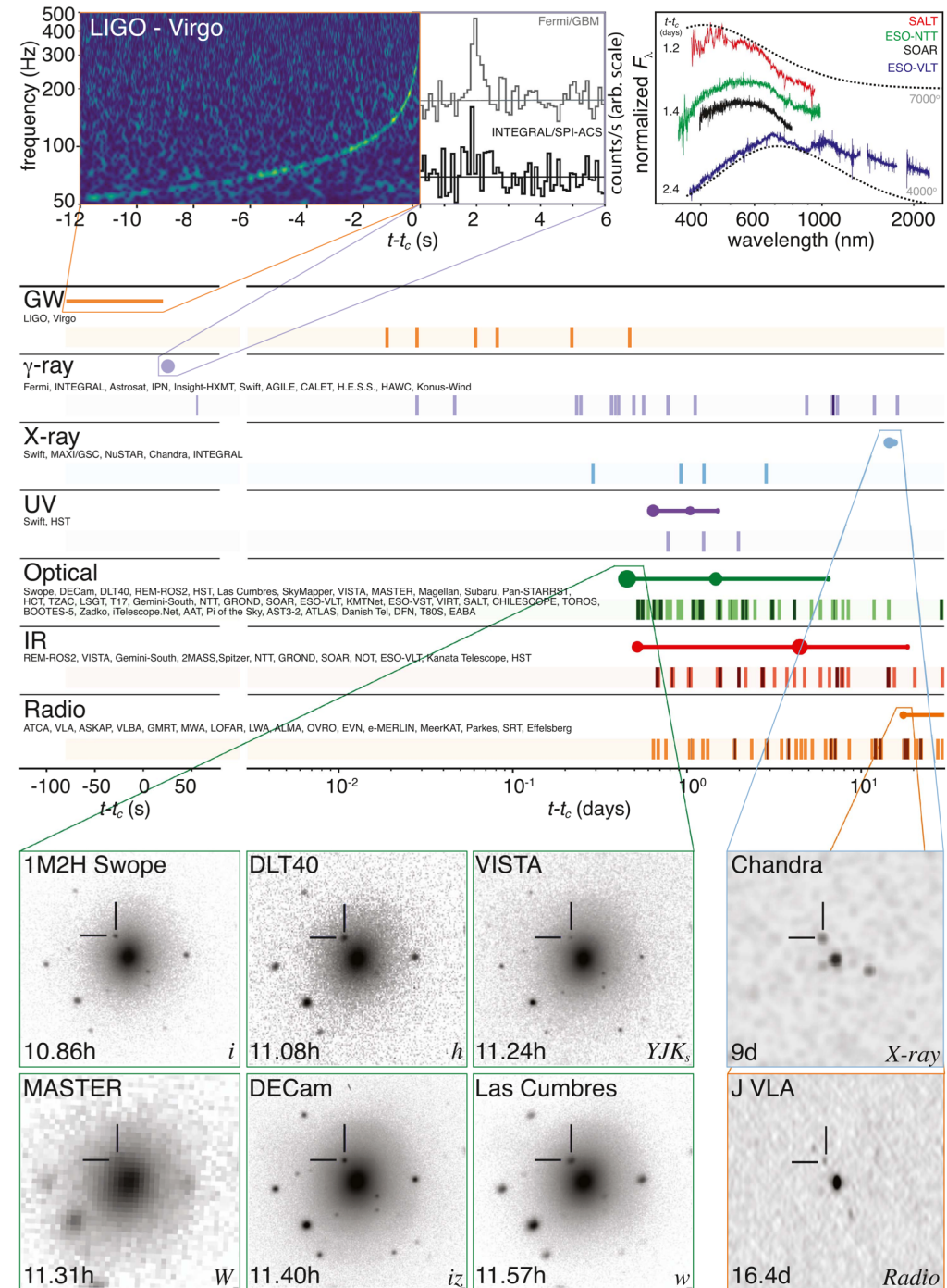
Roederer+2018  
Gull+2021



# GW170817/AT2017gfo

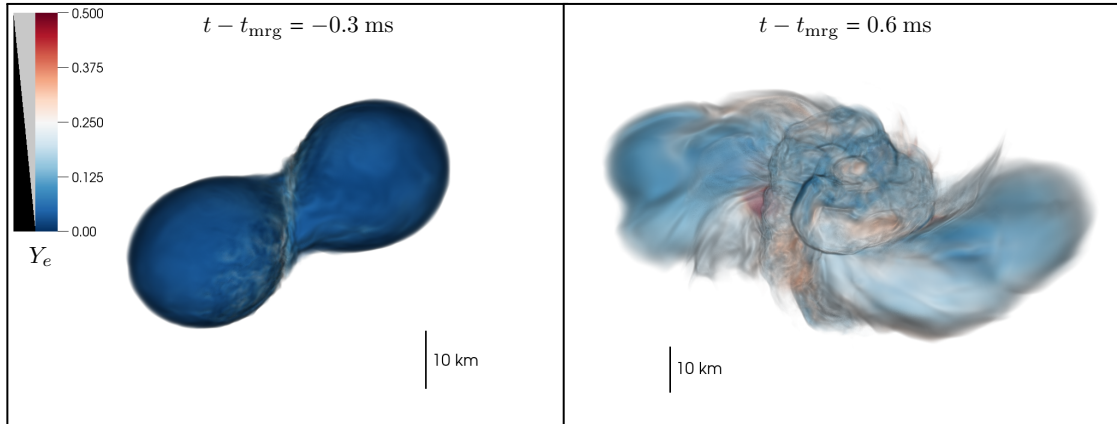


LIGO/Virgo  
+ ~70 observatories

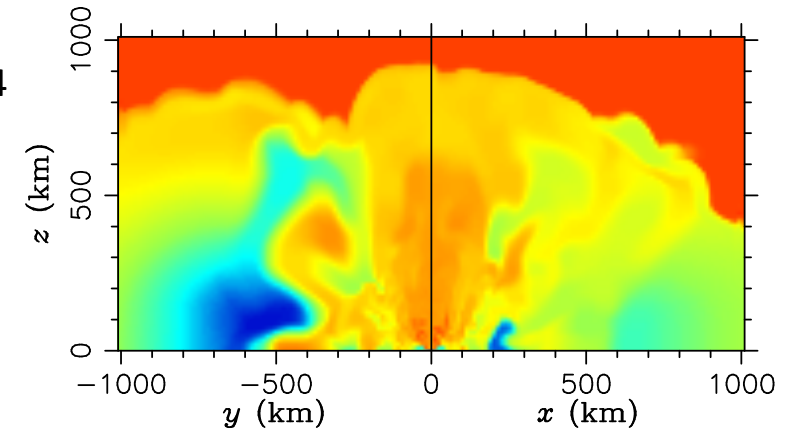


# NSM nucleosynthetic sites

prompt ejecta

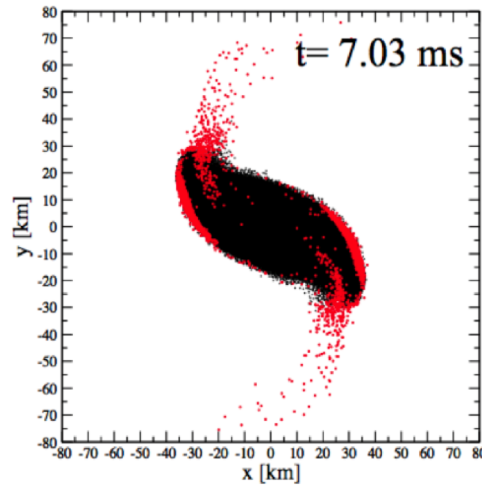


Wanajo+2014

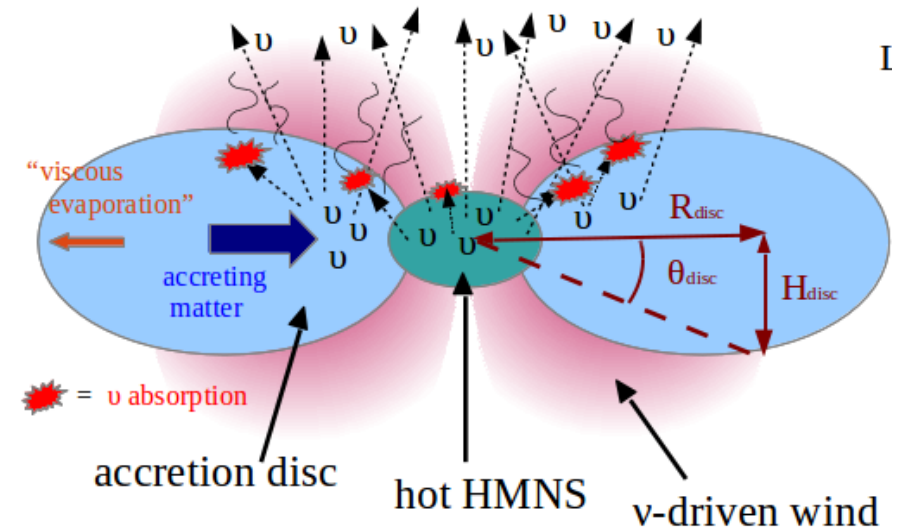


ejecta from the accretion disk

Radice+2019

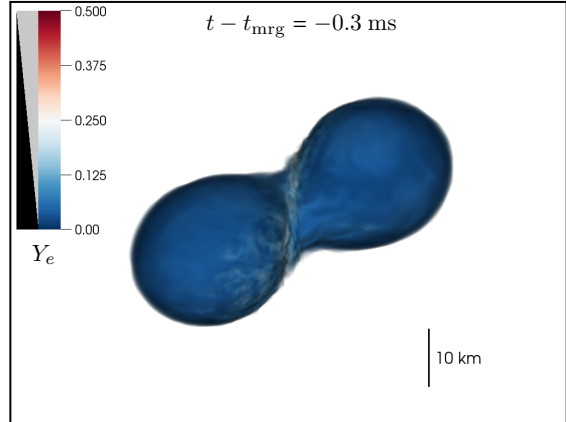


Korobkin+2012

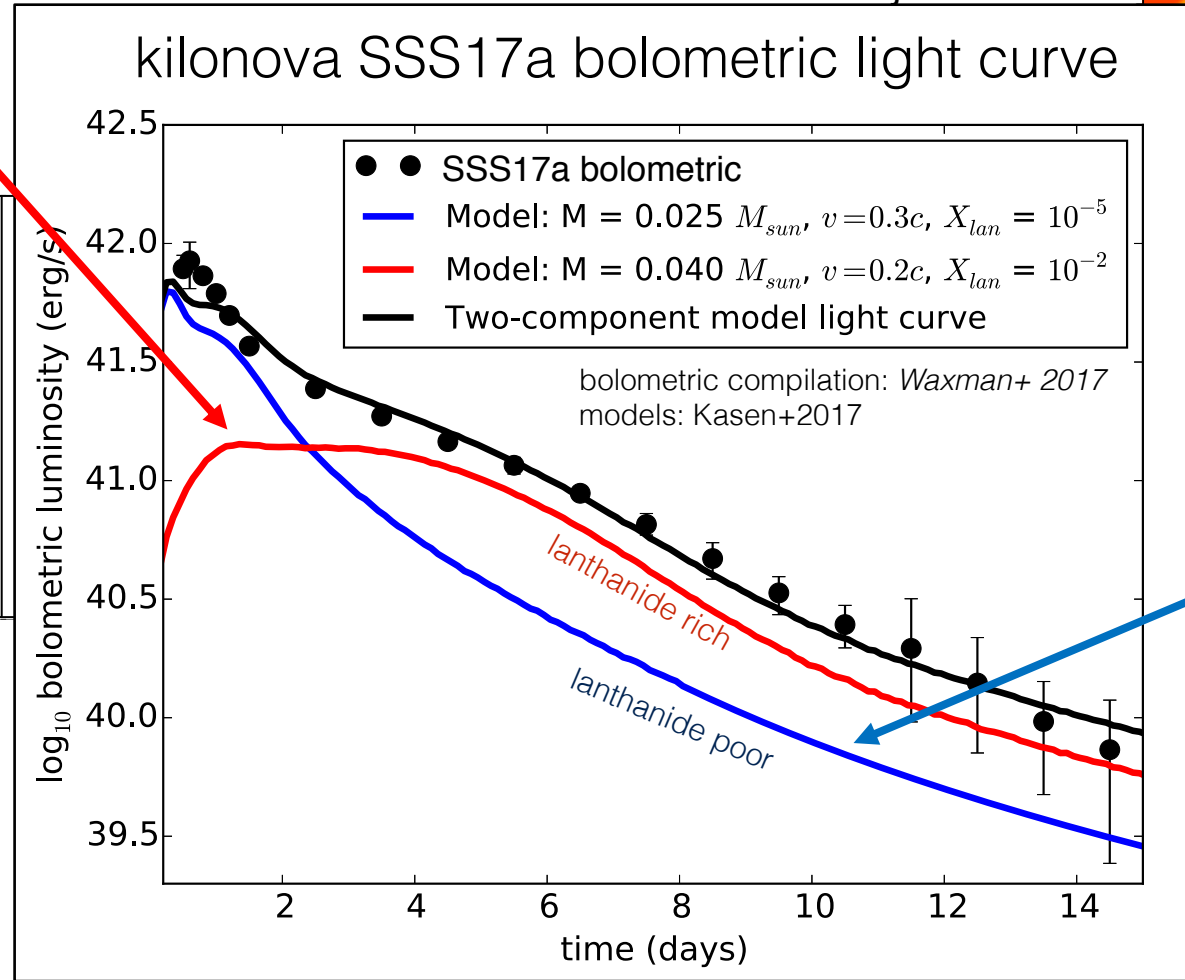


Perego+2014

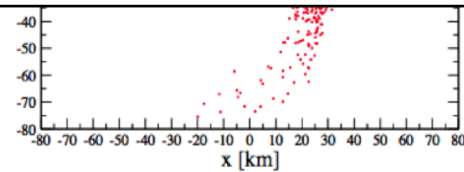
# NSM nucleosynthetic sites



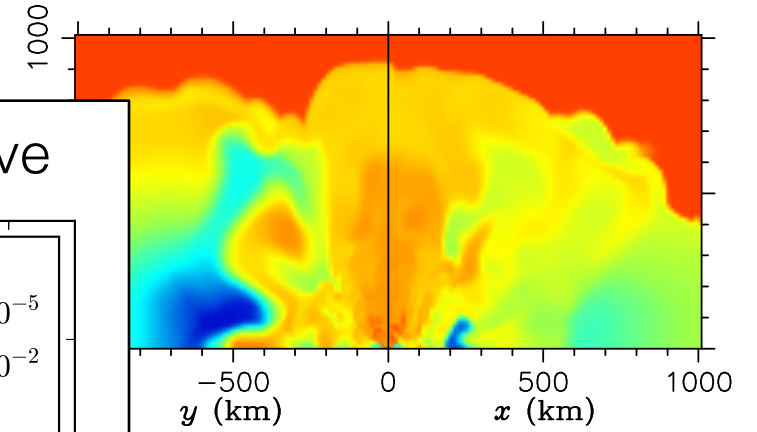
Radice+2019



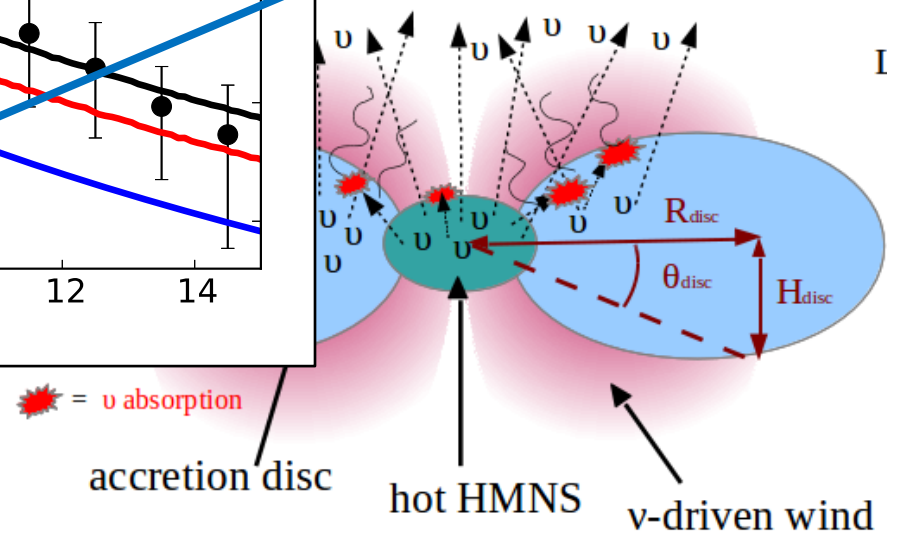
Korobkin+2012



Perego+2014

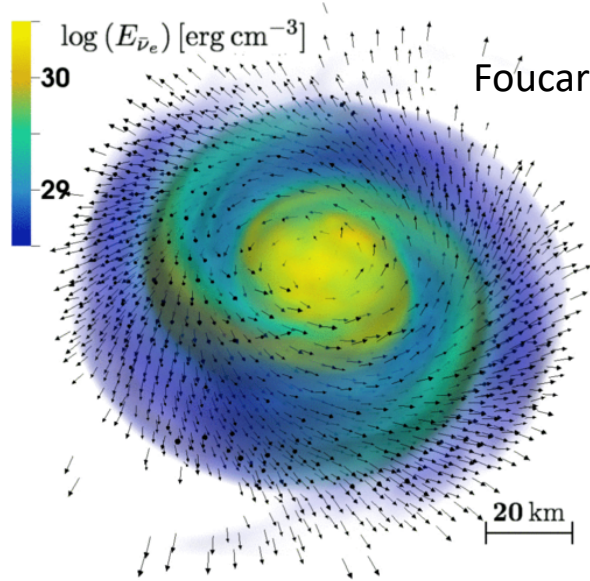


ejecta from the accretion disk

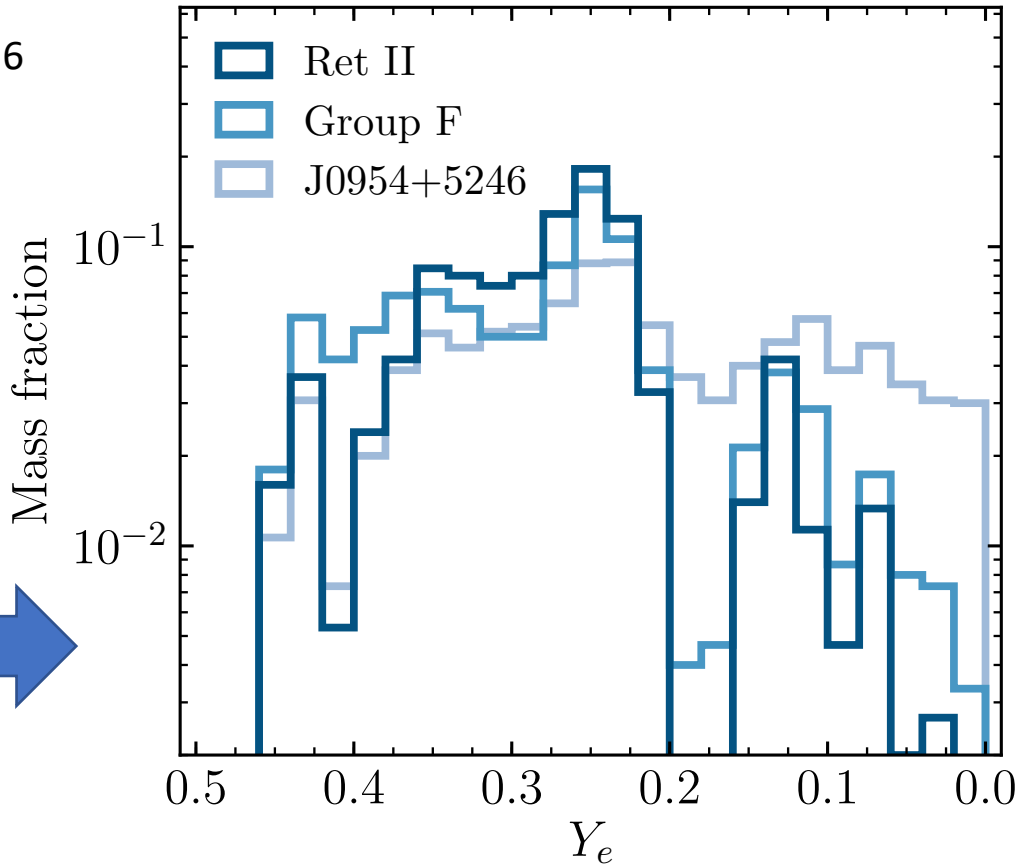




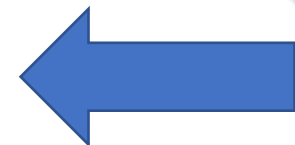
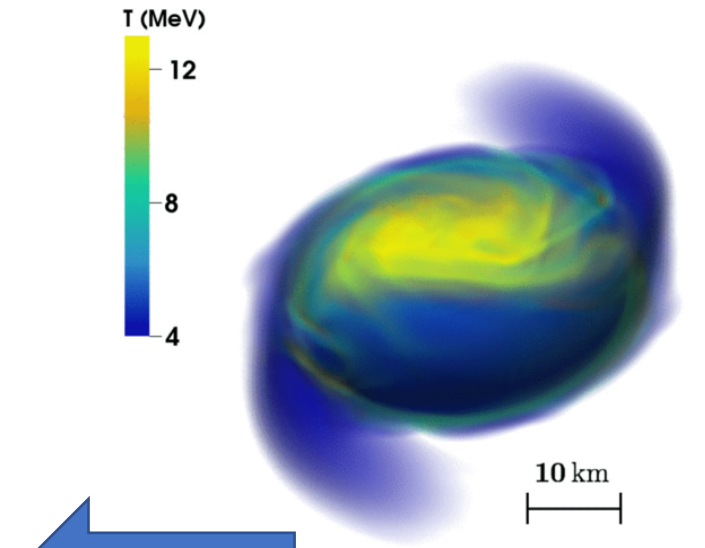
# NSMs and actinide abundances



accretion disk outflows are expected to be less neutron-rich



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

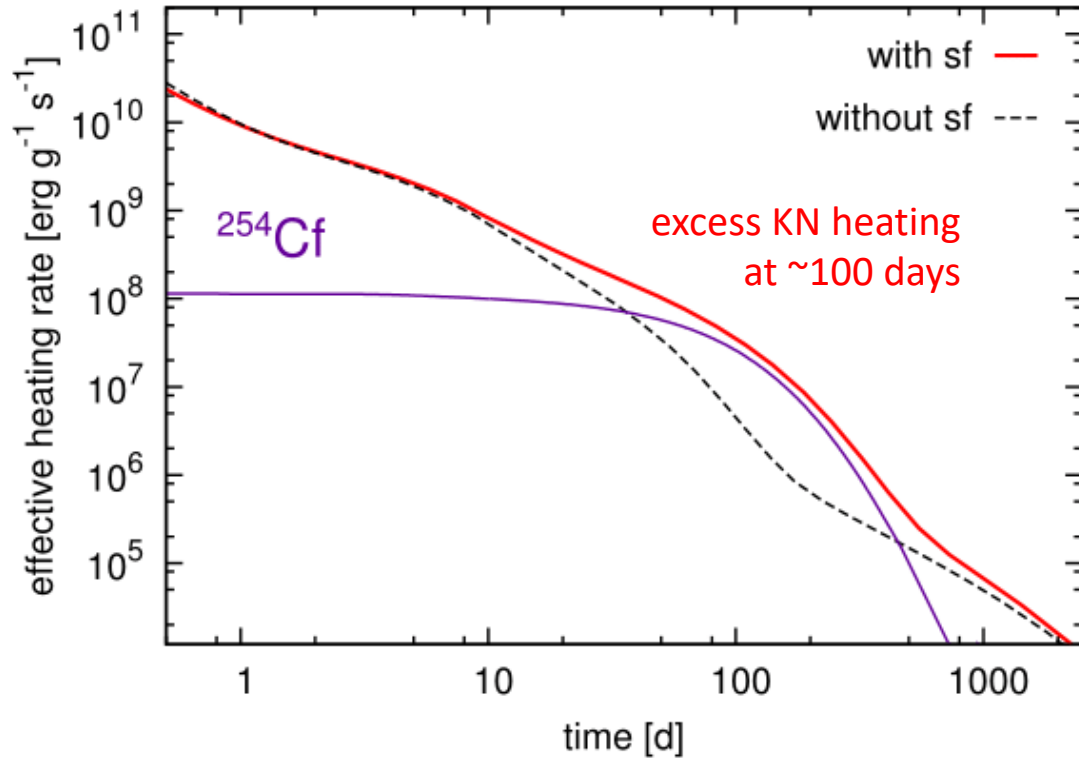


dynamical ejecta is expected to be very neutron-rich

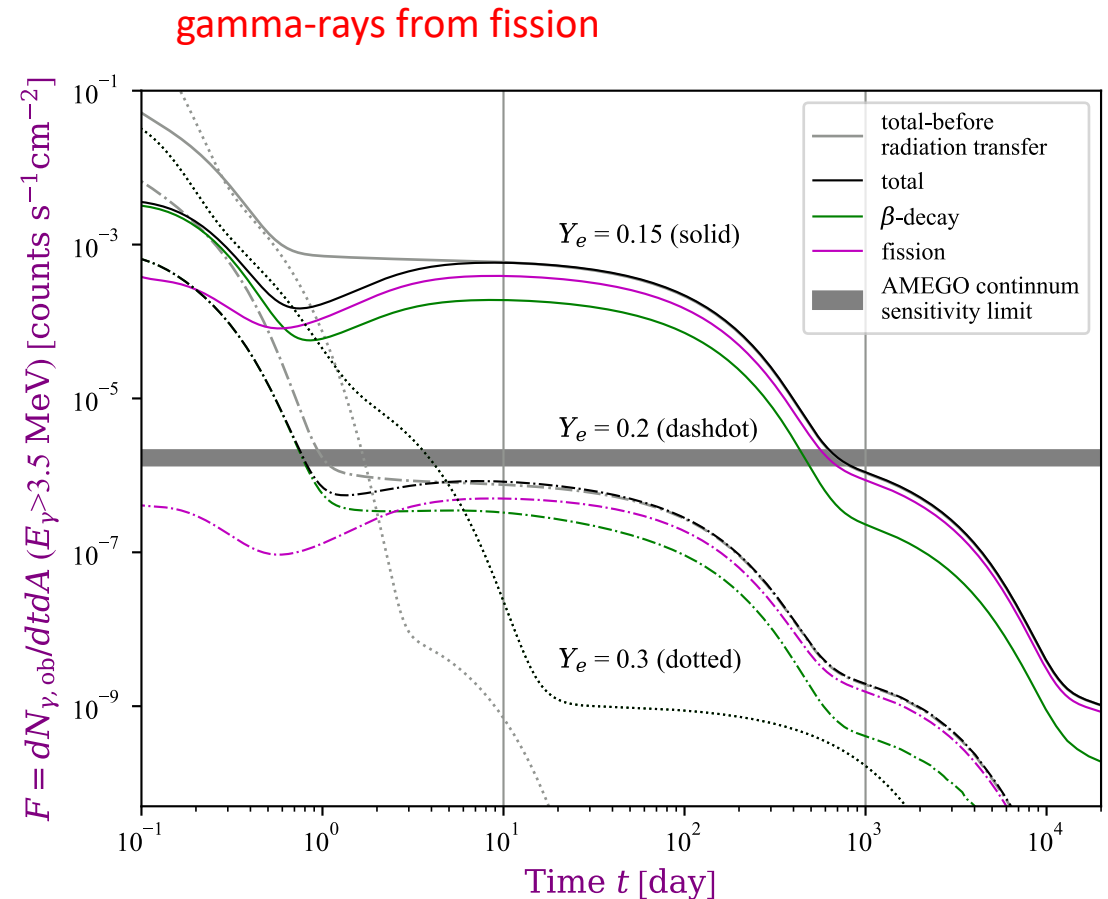
Holmbeck, Frebel, McLaughlin, Mumpower, Sprouse, Surman 2019



# Did the GW170817 merger produce actinides?

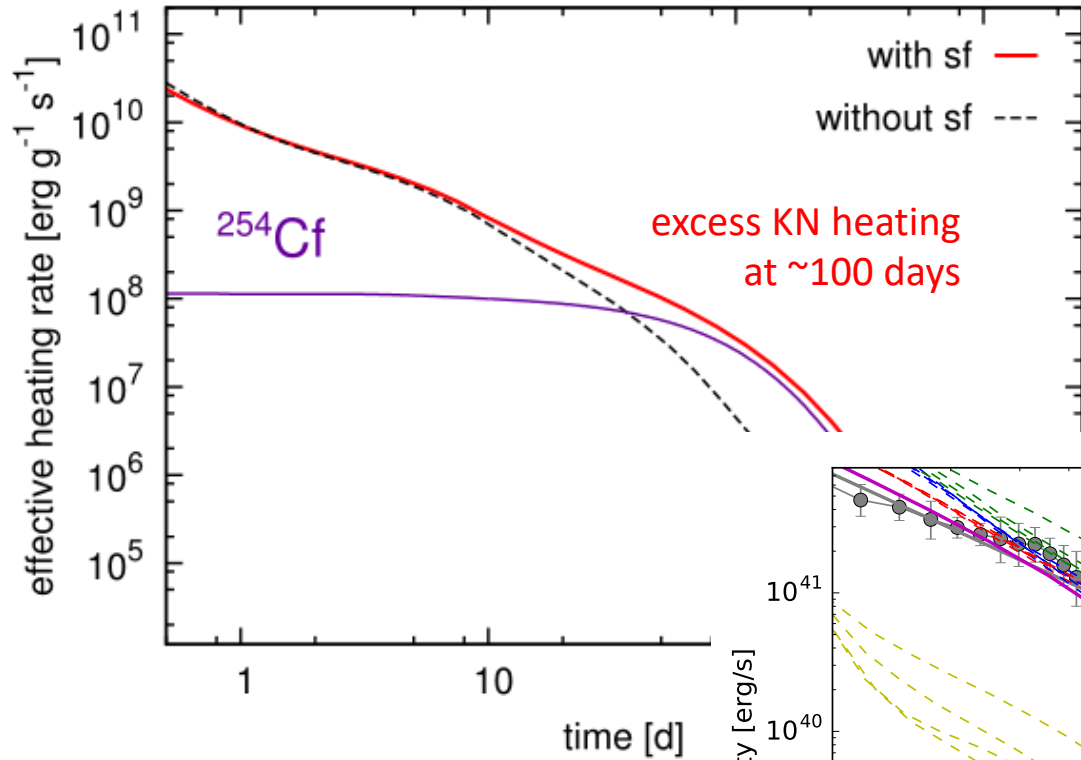


Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, ApJL 2018



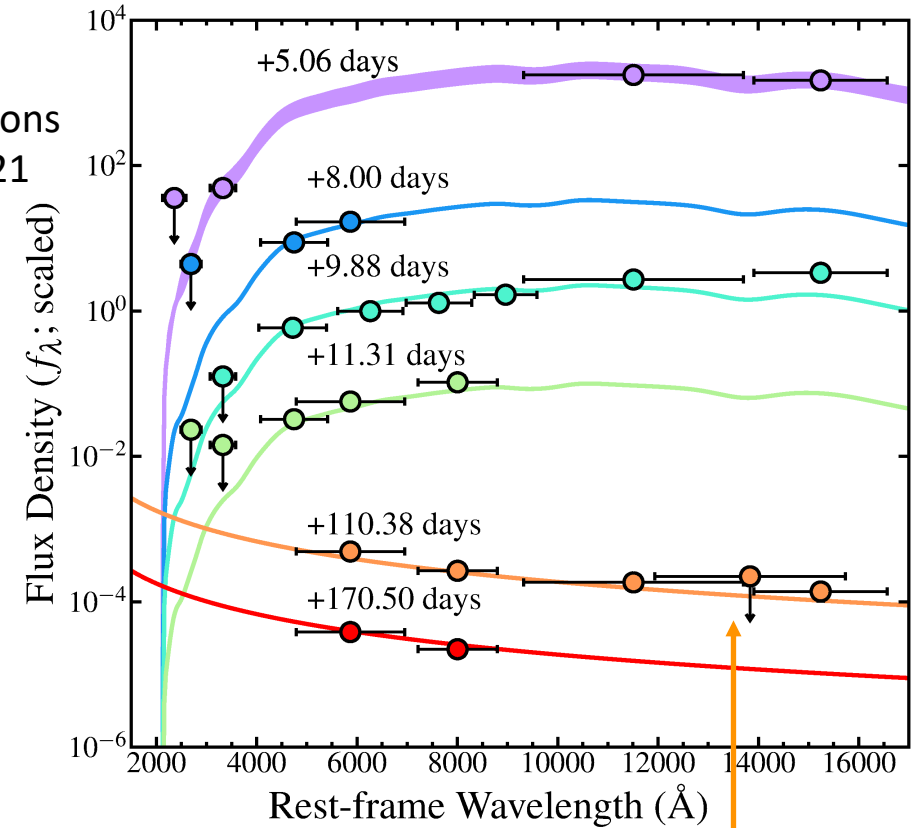
Wang, Vassh, Sprouse, Mumpower, Vogt, Randrup, Surman ApJL 2020

# Did the GW170817 merger produce actinides?



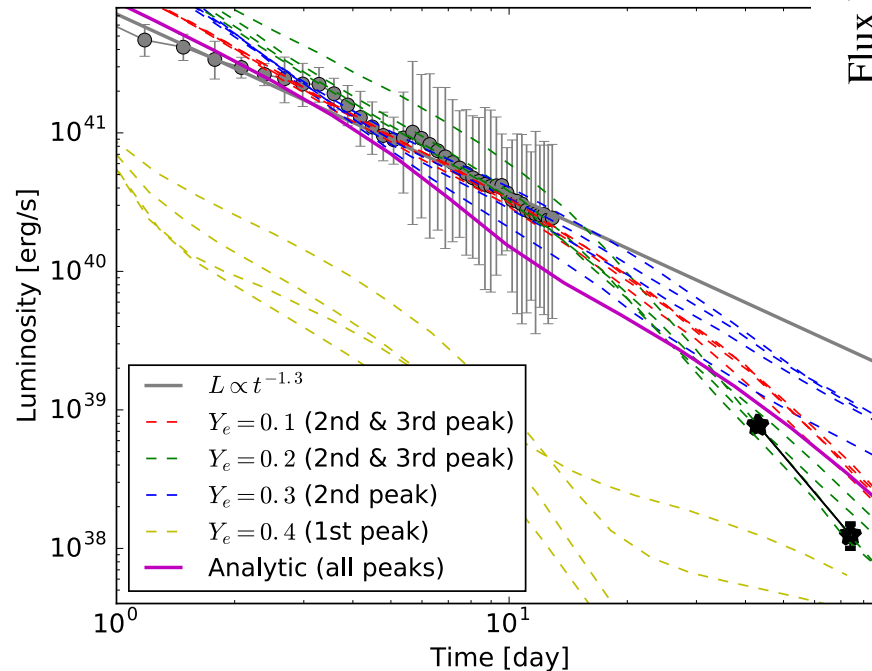
HST observations  
Kilpatrick+2021

Spitzer mid-infrared  
Kasliwal+2019



data at ~100 days  
matches a GRB  
afterglow

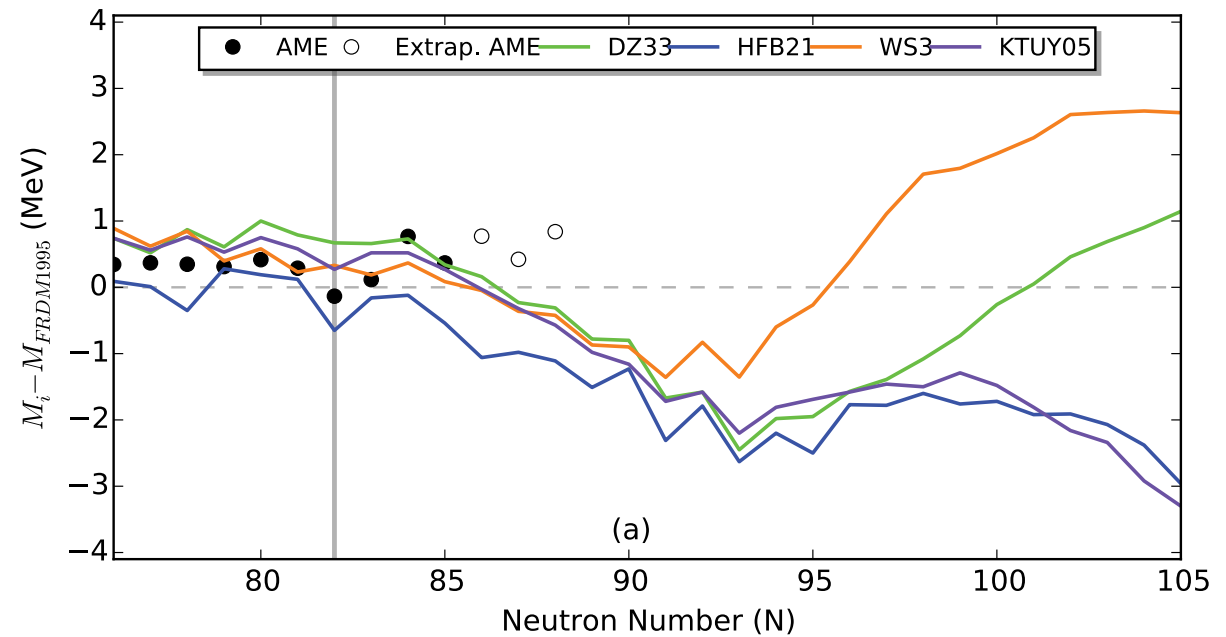
Zhu, Wollaeger, Vassh, Surman, Sproll, Möller, McLaughlin, Korobkin, Jaffke, Even, Couture, Barnes, ApJL 2018



# Nuclear data for the $r$ -process

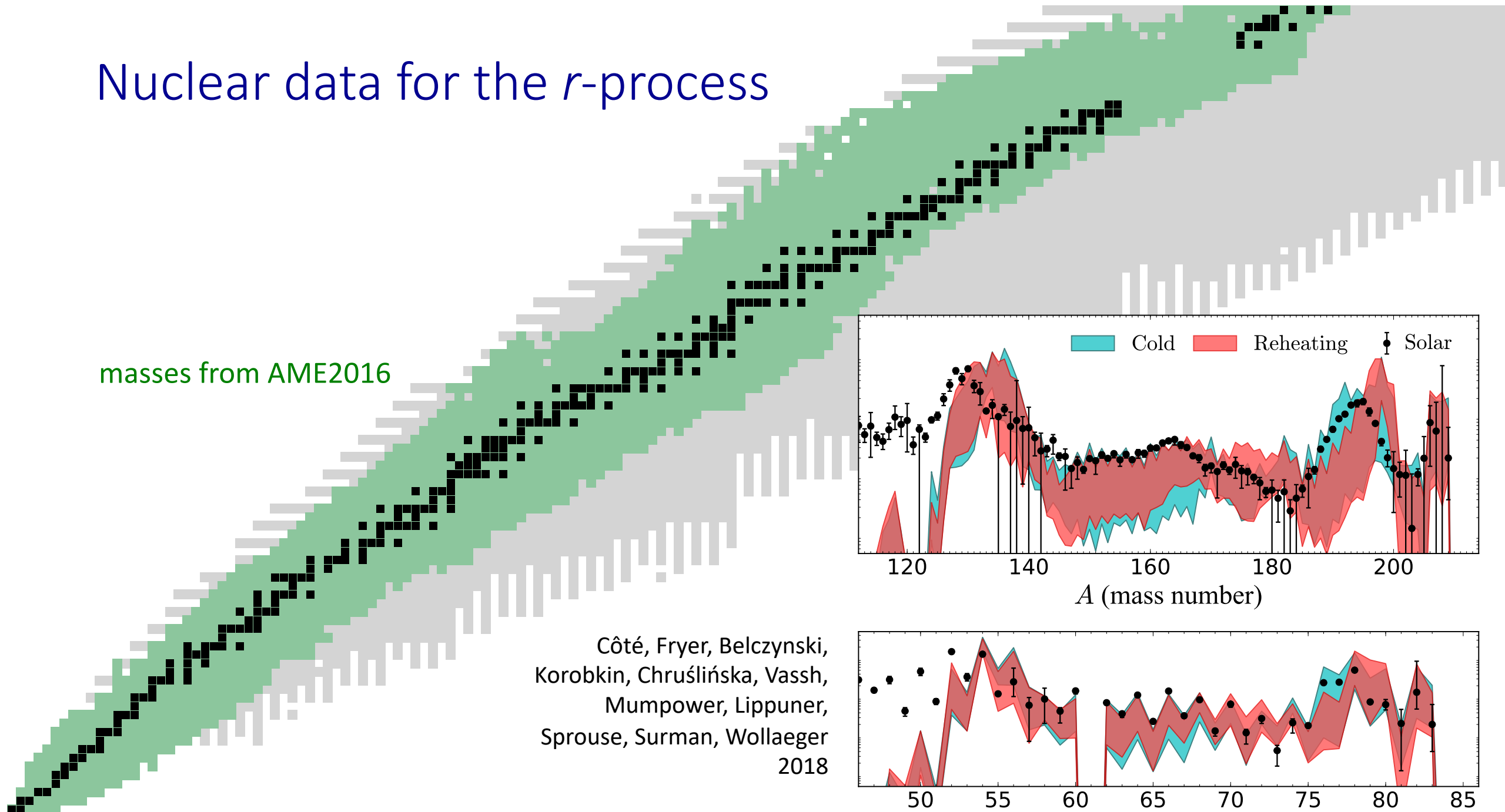
masses from AME2016

Mumpower, Surman,  
McLaughlin, Aprahamian 2016

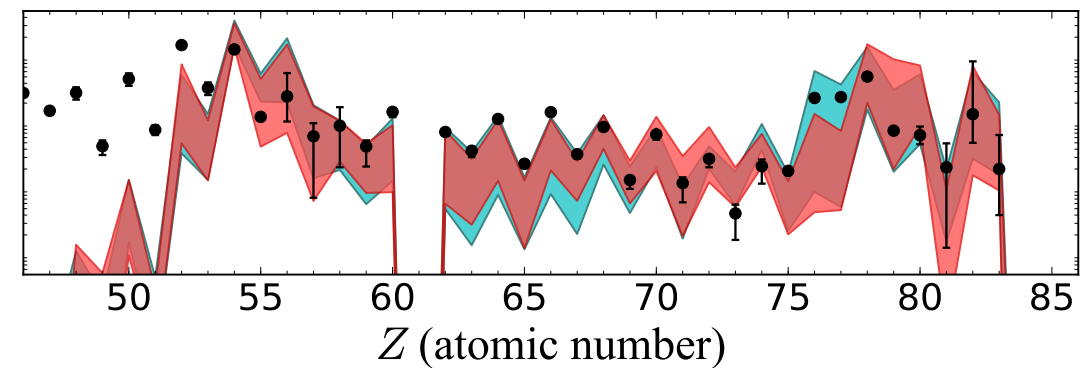
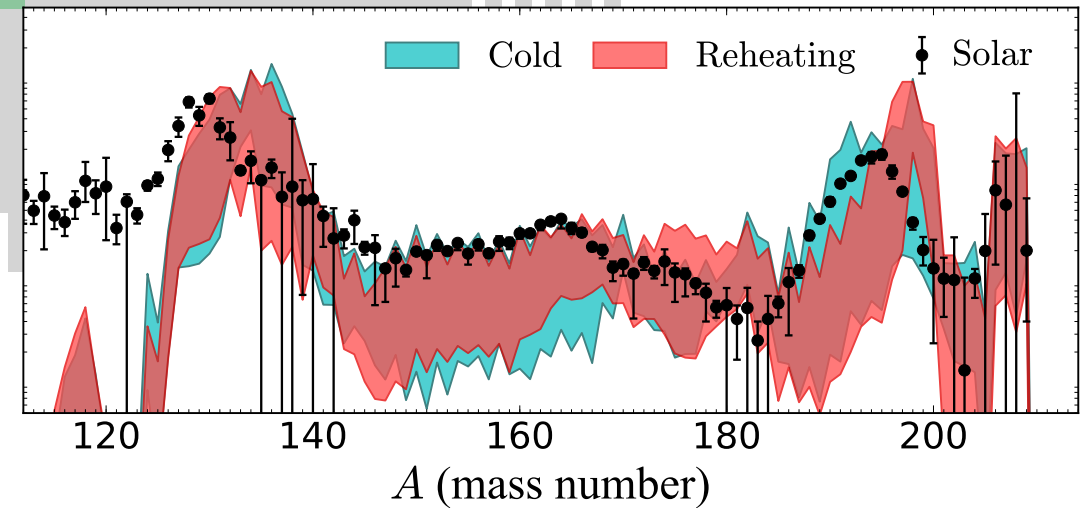


# Nuclear data for the $r$ -process

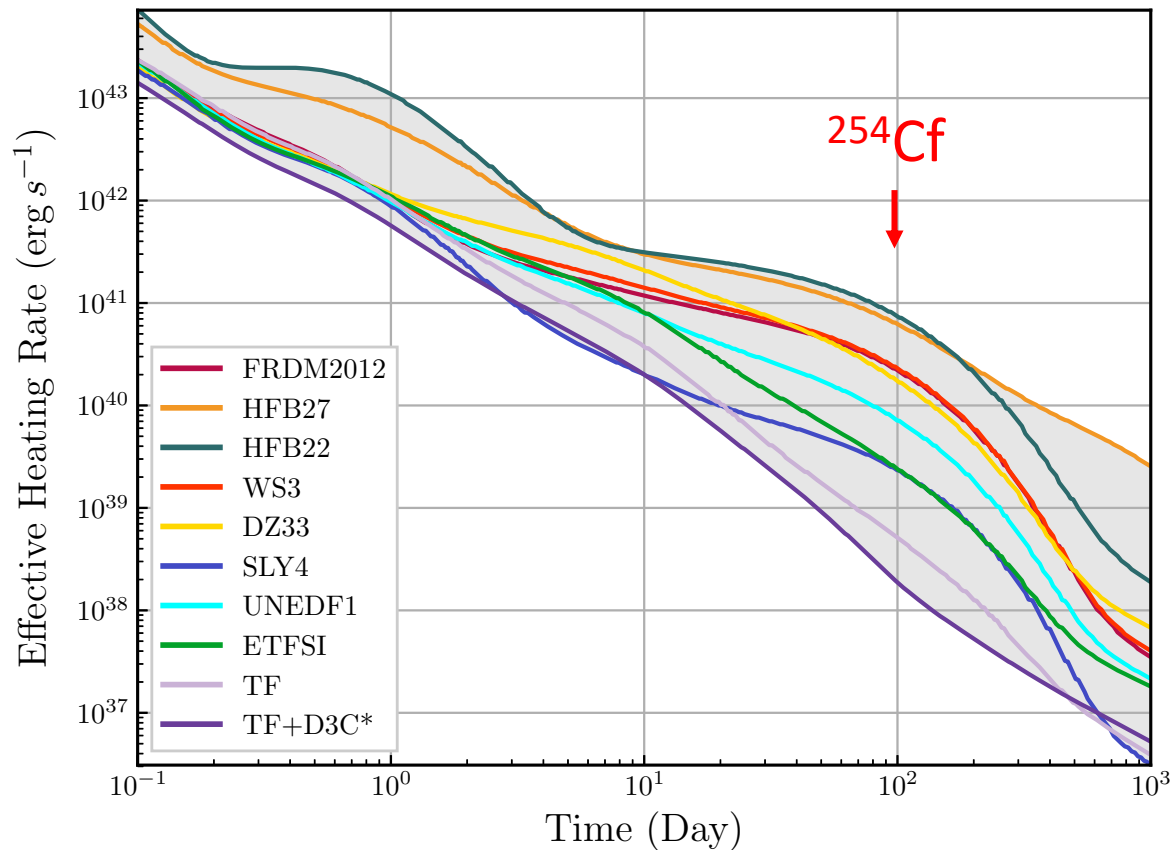
masses from AME2016



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

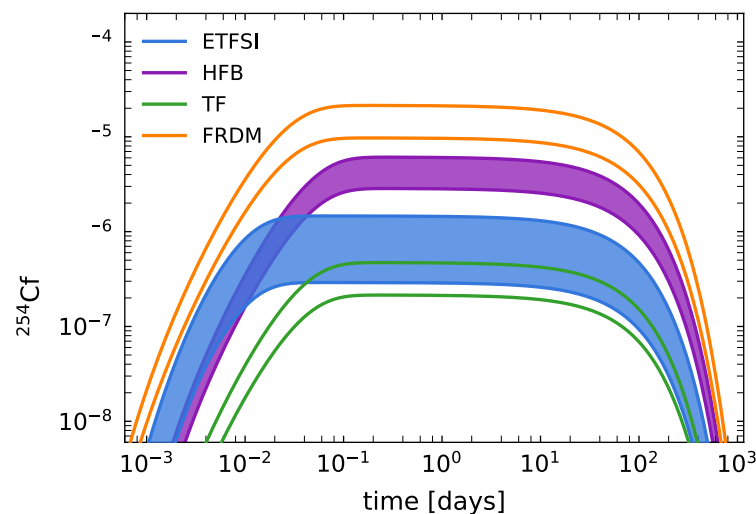
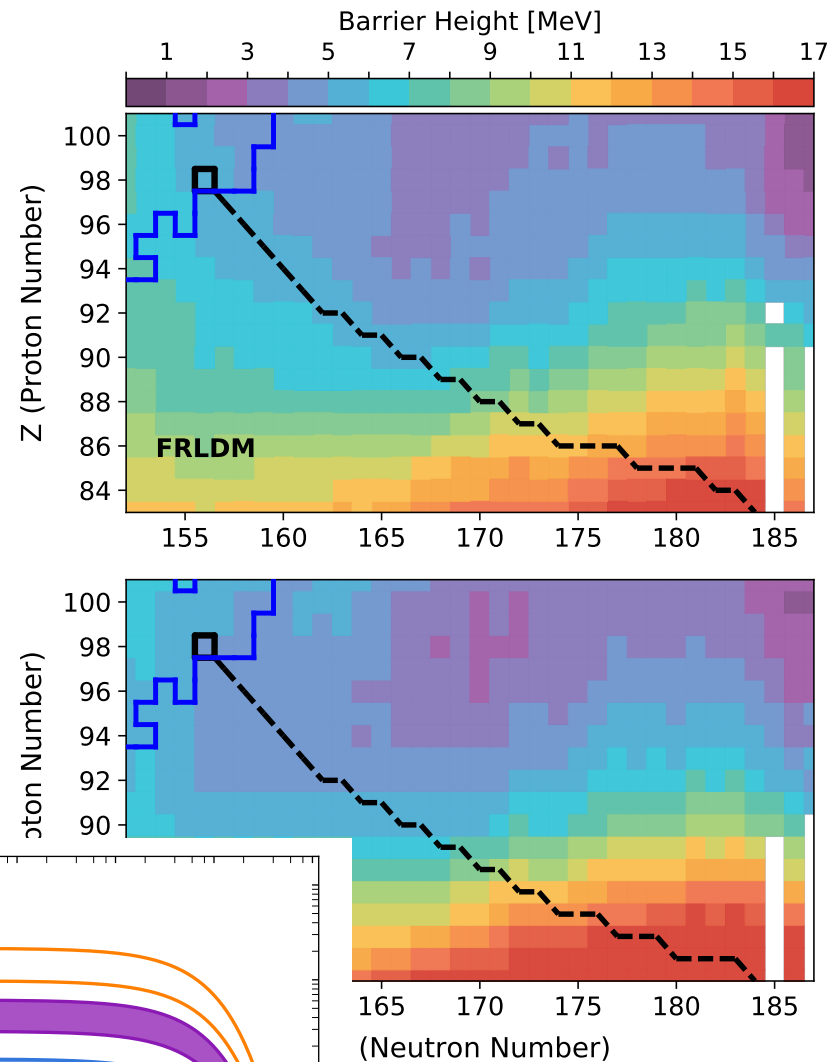


# $^{254}\text{Cf}$ : dependence on nuclear inputs



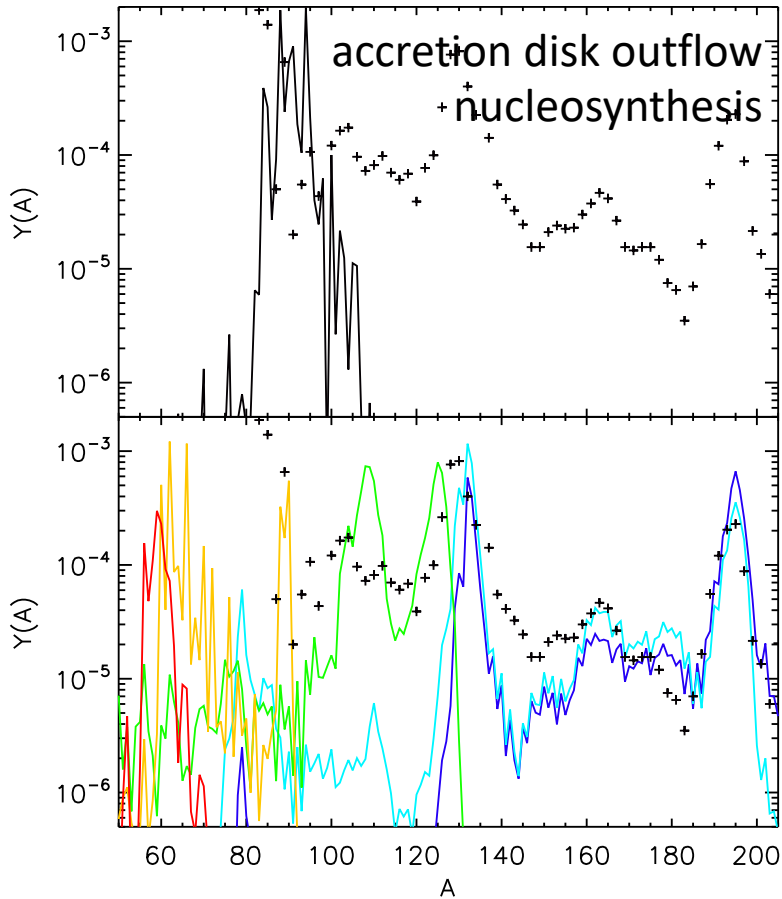
Zhu, Lund, Barnes, Sprouse, Vassh, McLaughlin, Mumpower, Surman 2021

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



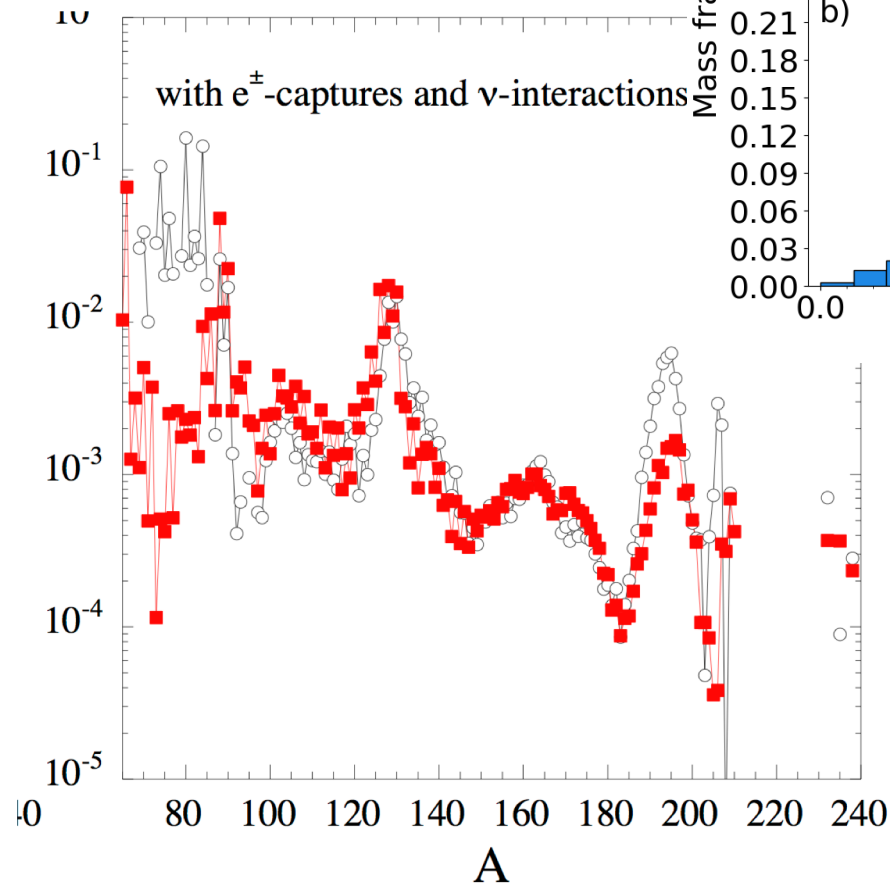


# Neutrinos and NSM nucleosynthesis

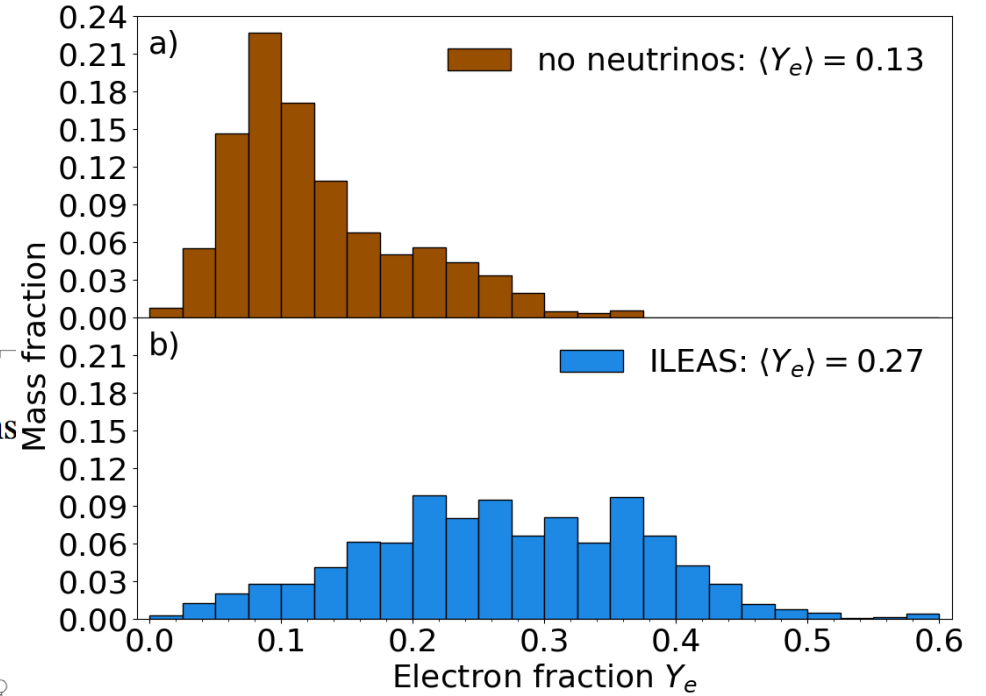


Malkus, McLaughlin, Surman 2016

dynamical ejecta  
nucleosynthesis



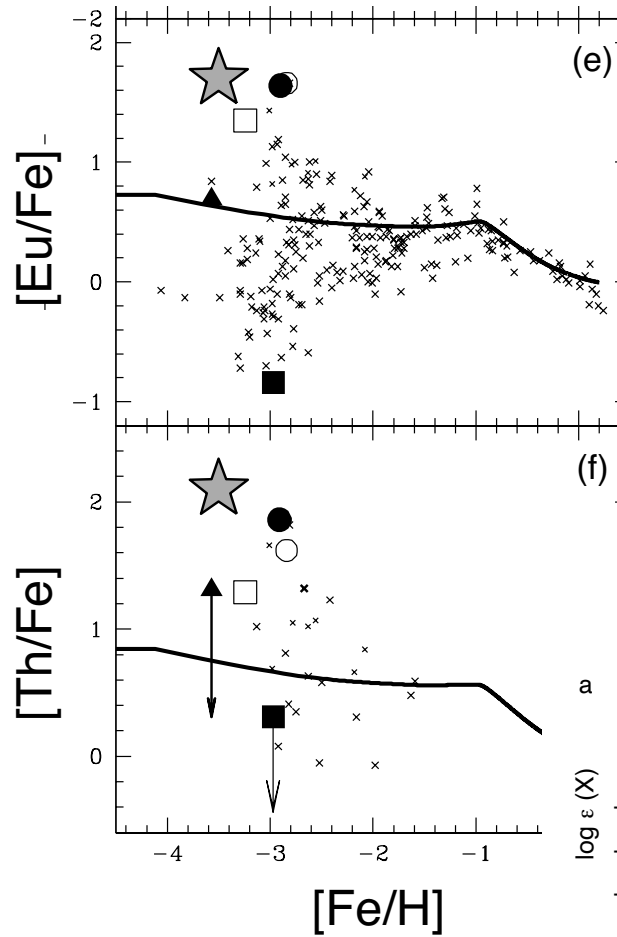
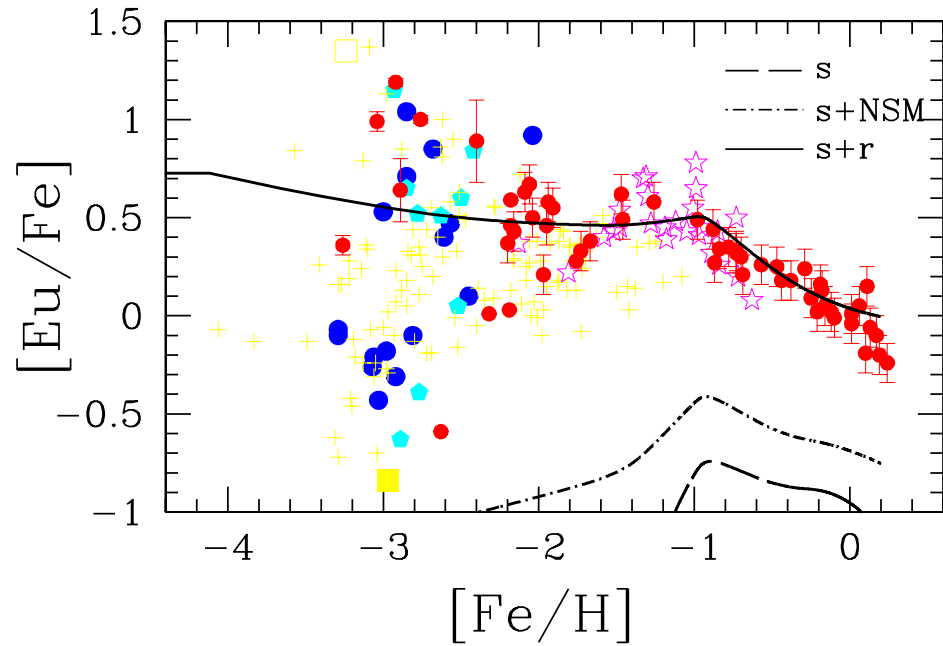
Goriely+2015



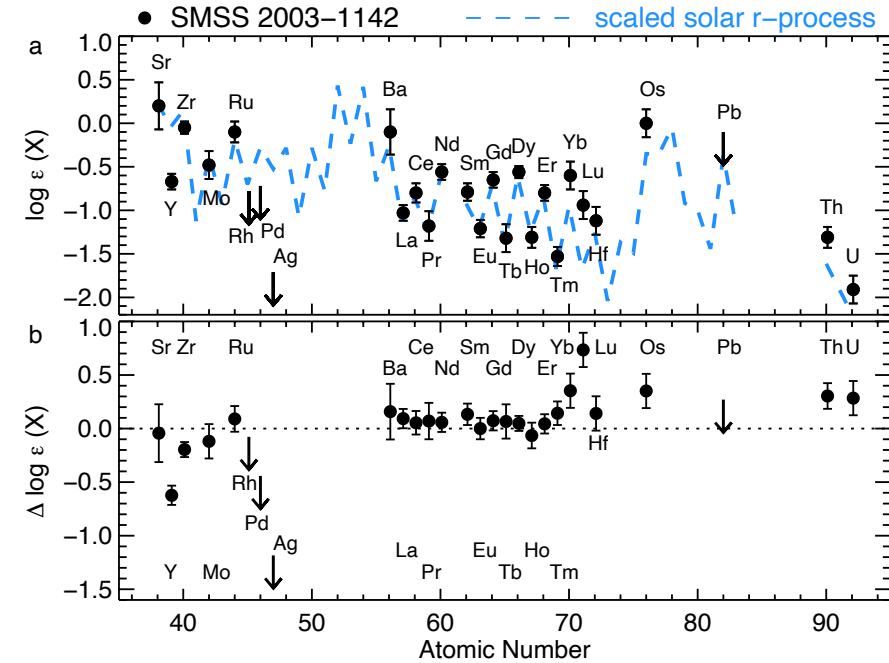
Kullmann+2021

# r-process astrophysical sites: exotic supernovae?

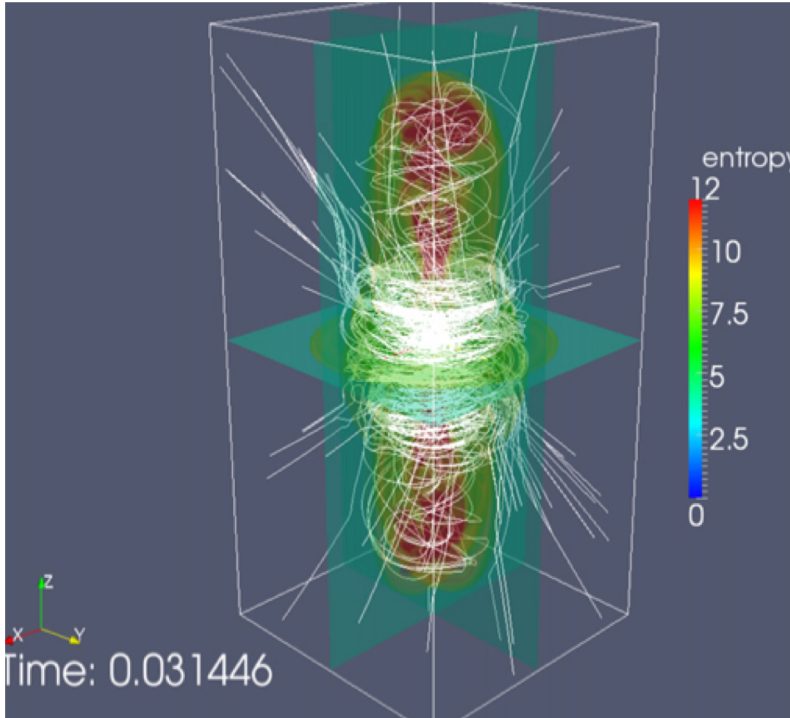
Kobayashi+2020



Yong+2021

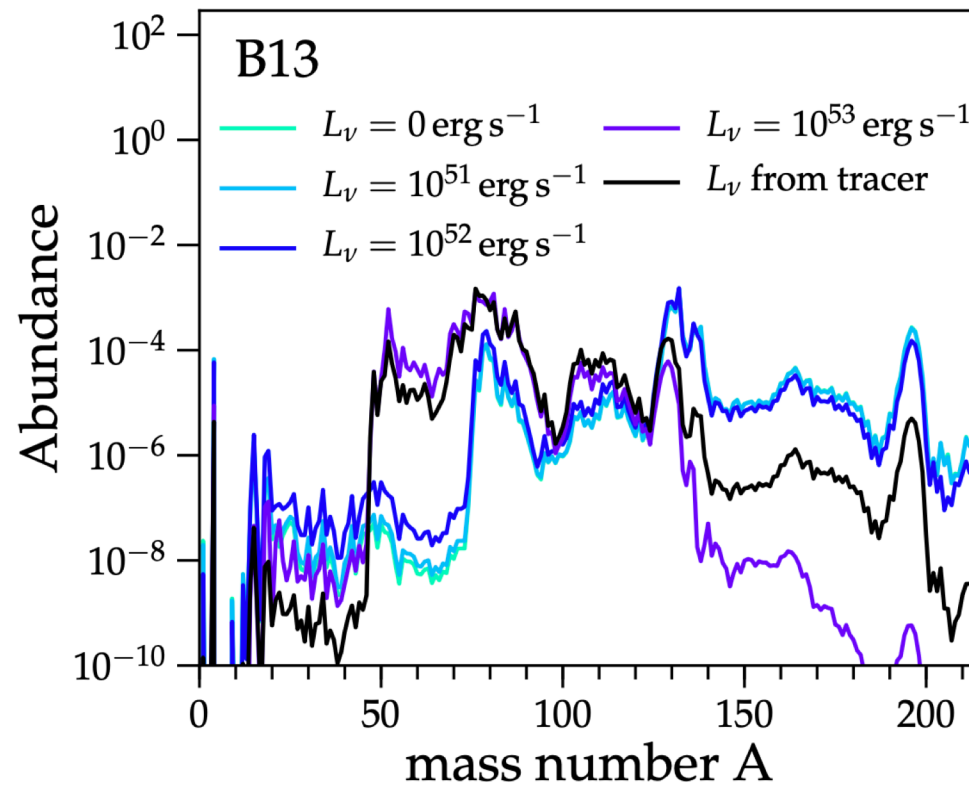
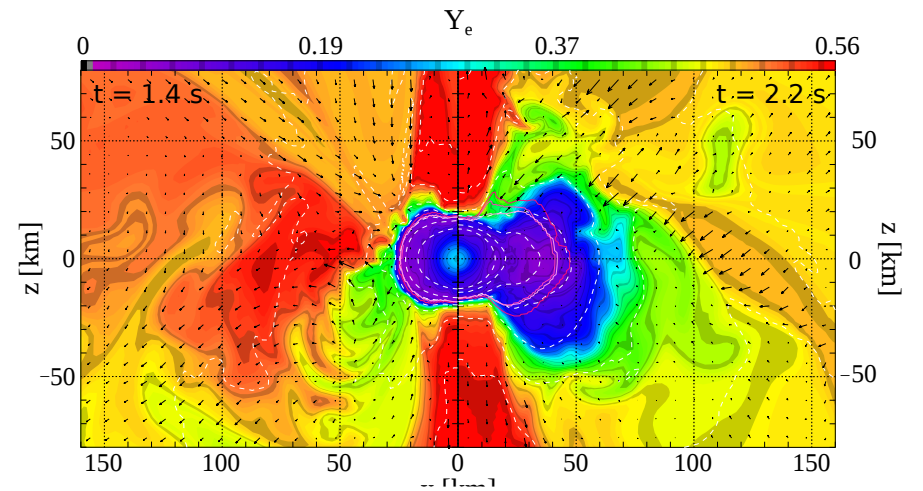


# MHD supernovae?



Winteler+2012  
Nishimura+2015, 2017

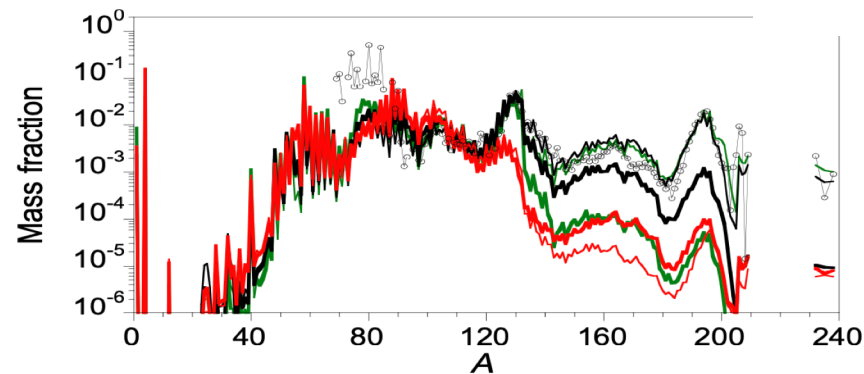
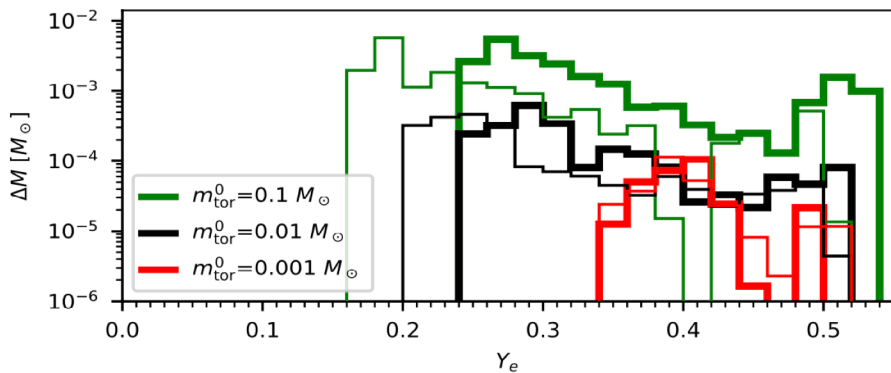
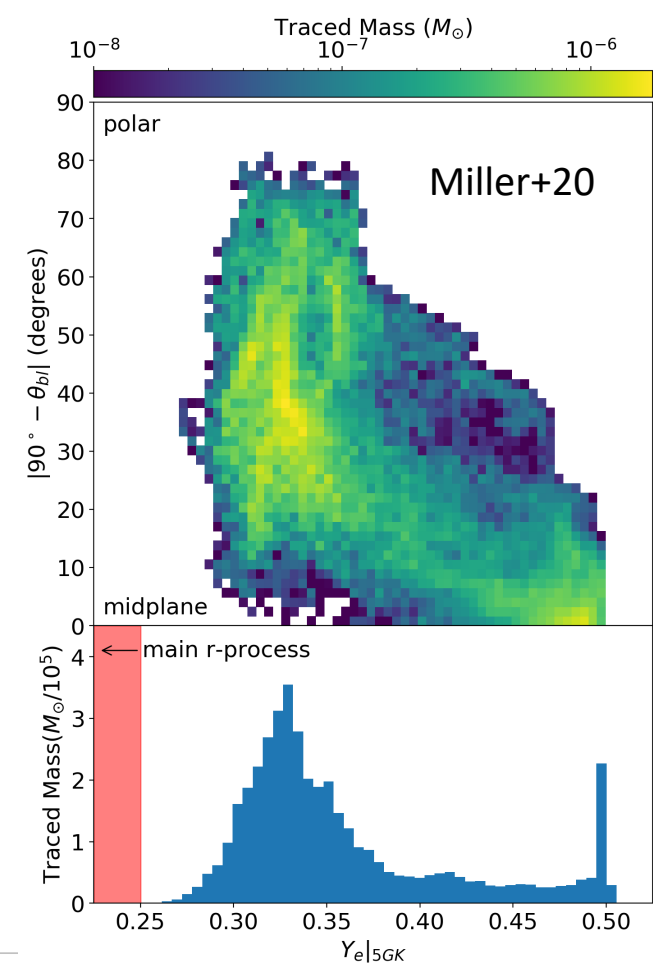
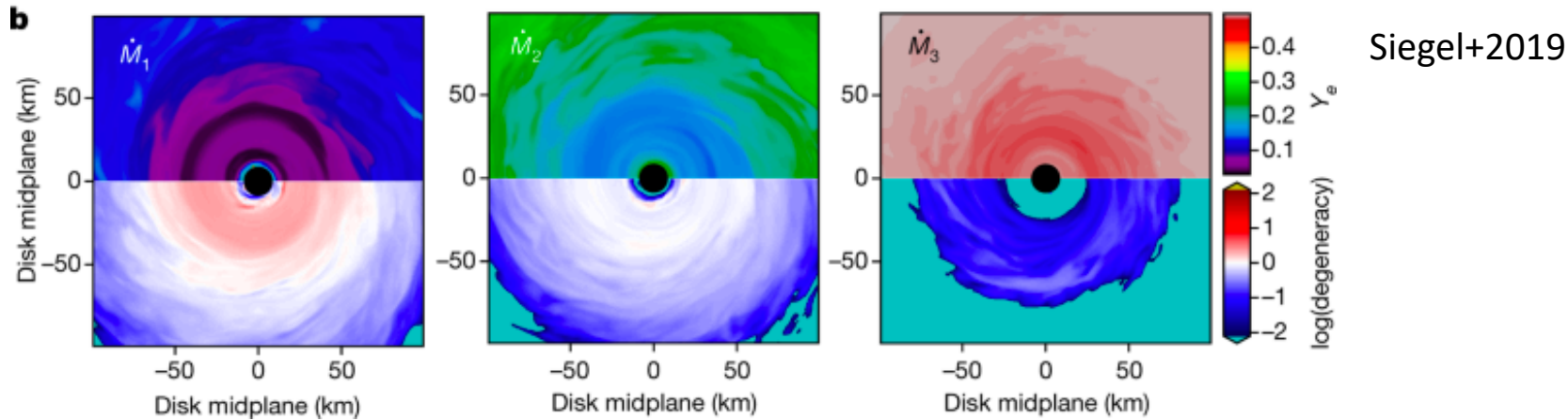
Reichert+2021



Mösta+2018

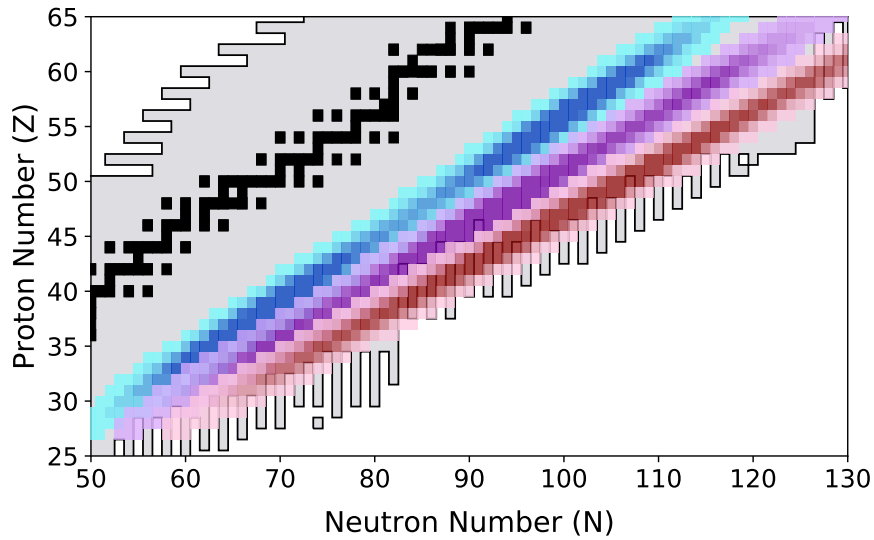
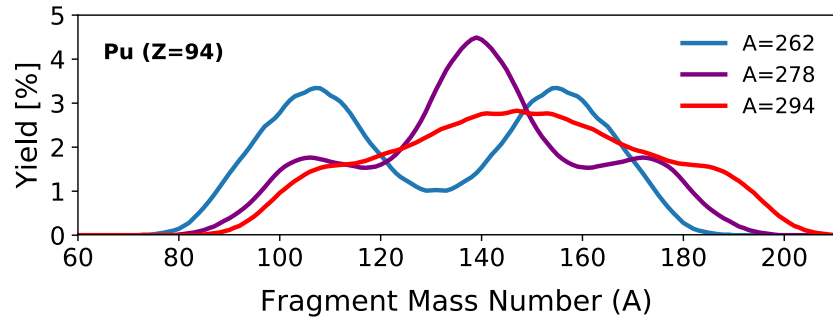
# Collapsars?

Beloborodov 2003, Nagataki+2003, Surman, McLaughlin 2005, Nagataki+2006, Fryer+2006, Fujimoto+2007, Fujimoto+2008, Tominaga 2009, Maeda,Tominaga 2009, Nomoto+2010, Horiuchi +2012, Shibata, Tominaga 2012, Malkus+2012, Nakamura+2013...

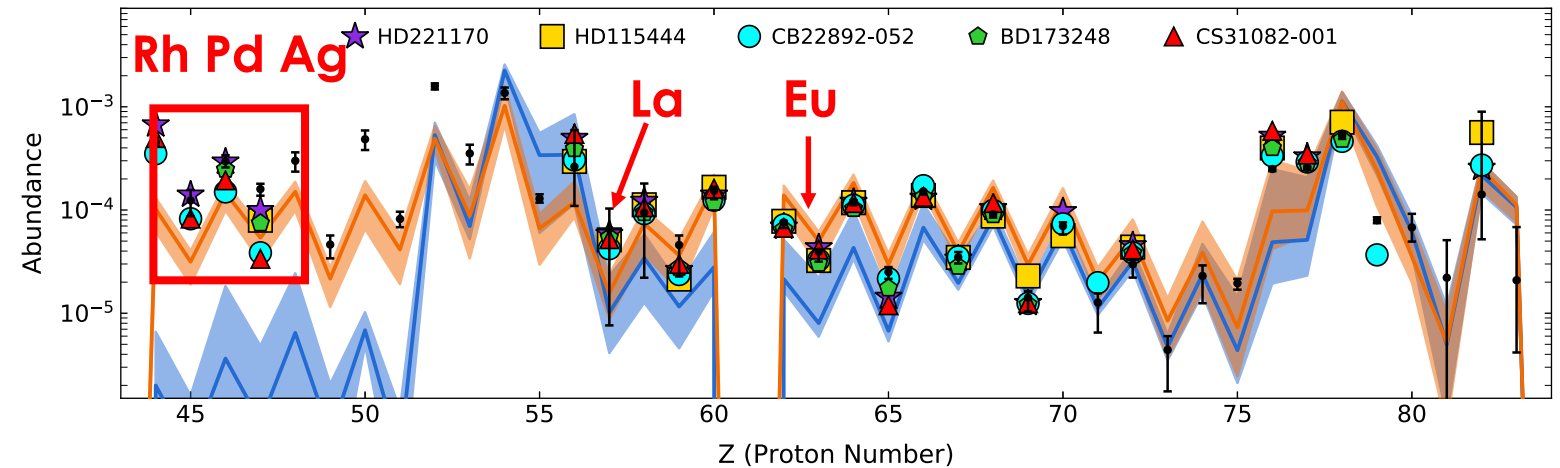
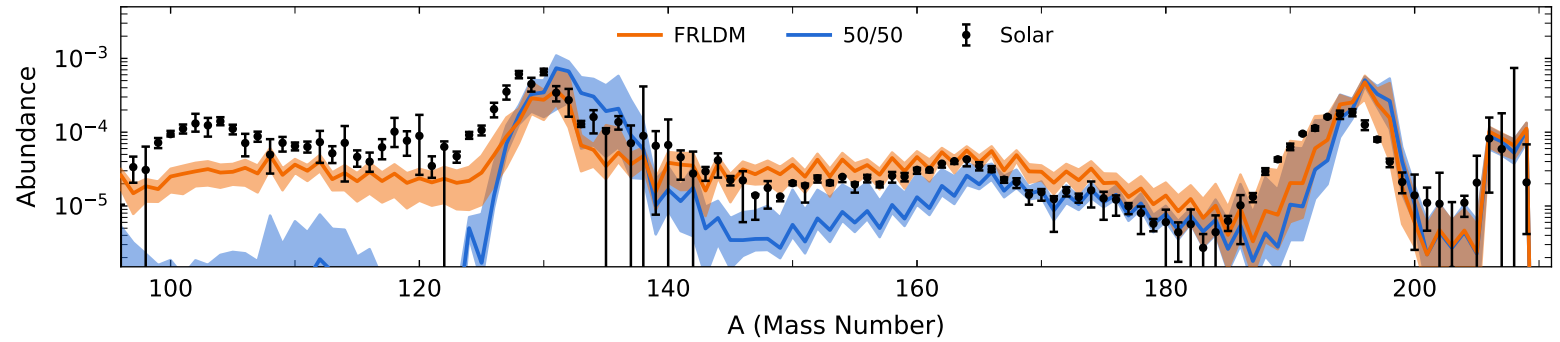


Just+2020

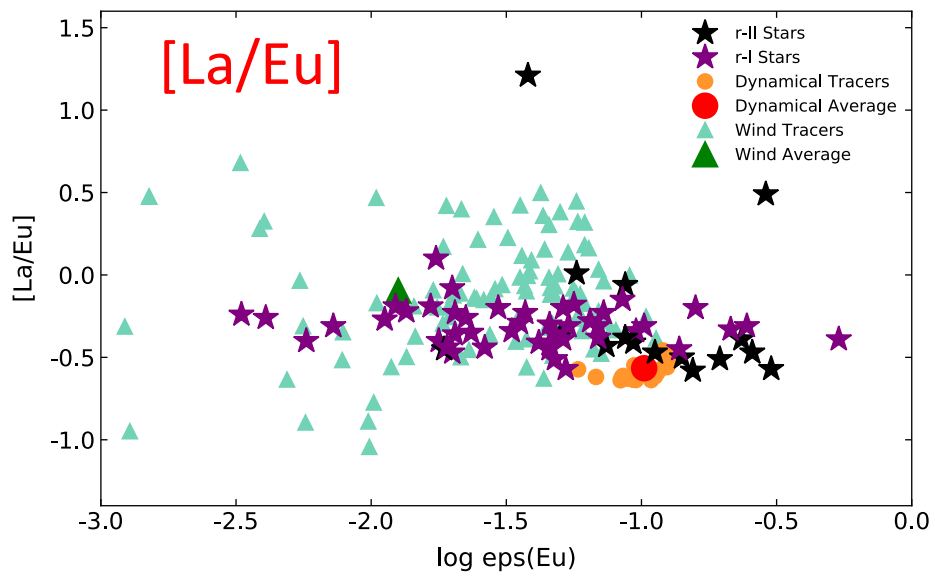
# Actinide observables: fission yield signatures



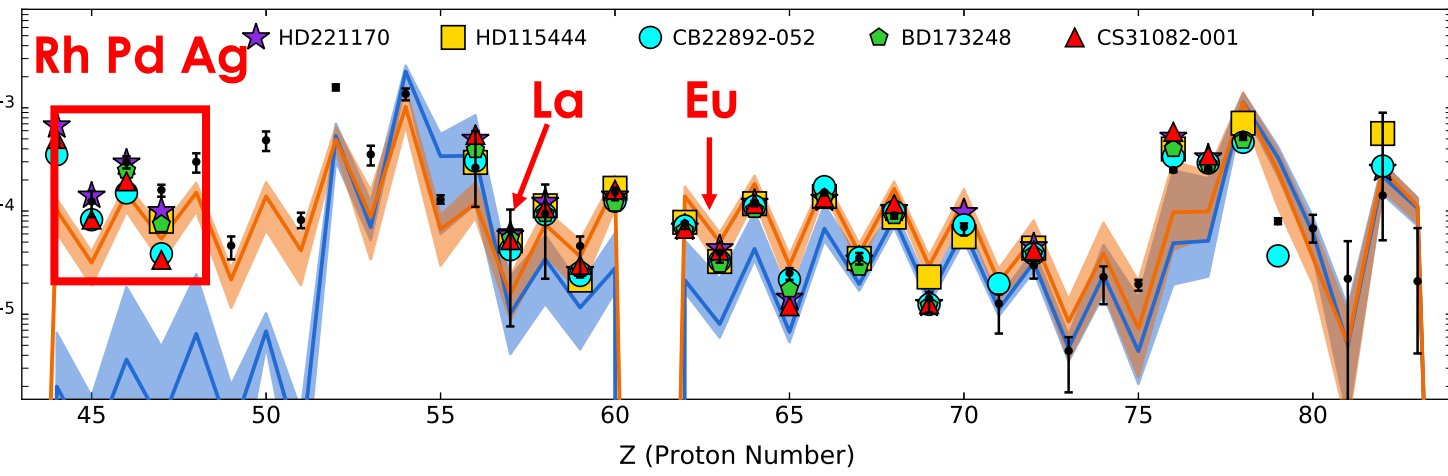
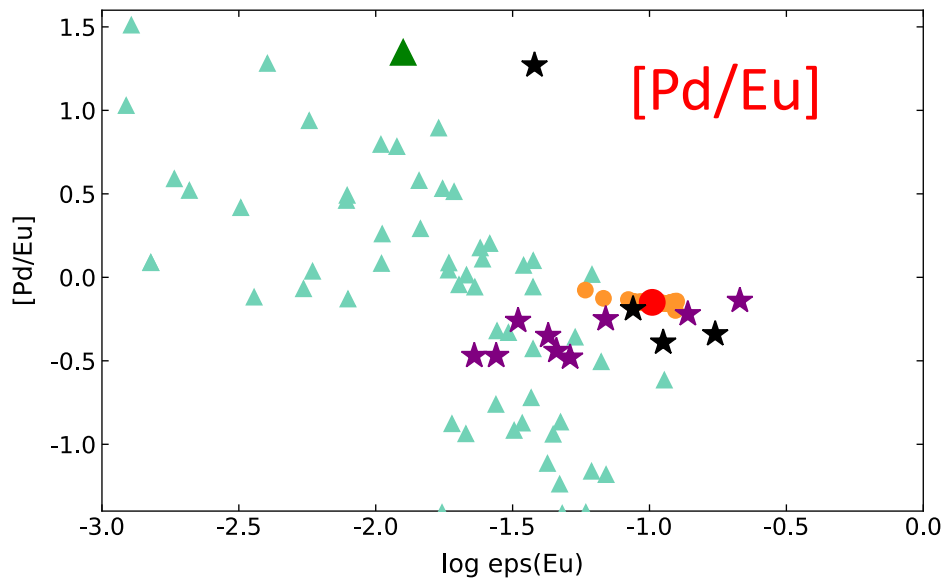
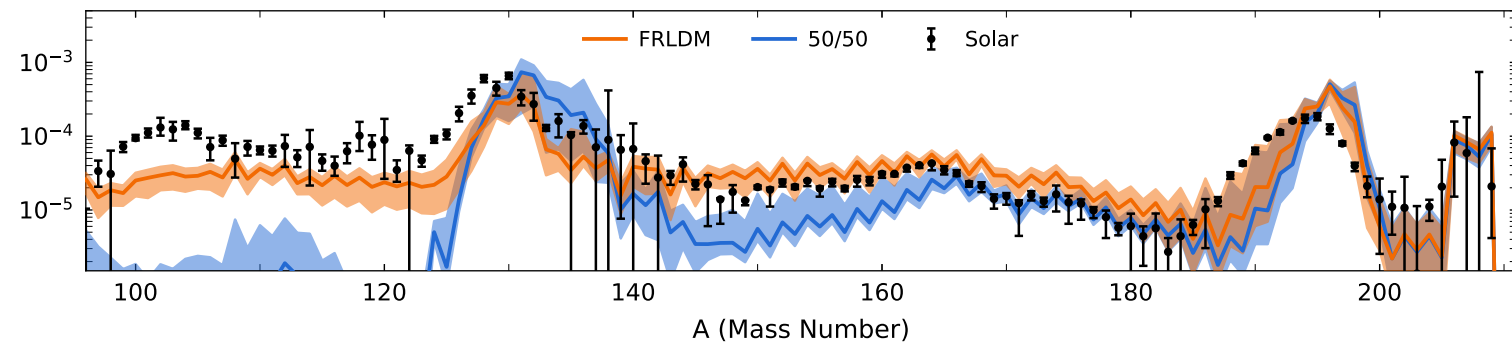
Vassh, Mumpower, McLaughlin,  
Sprouse, Surman 2020



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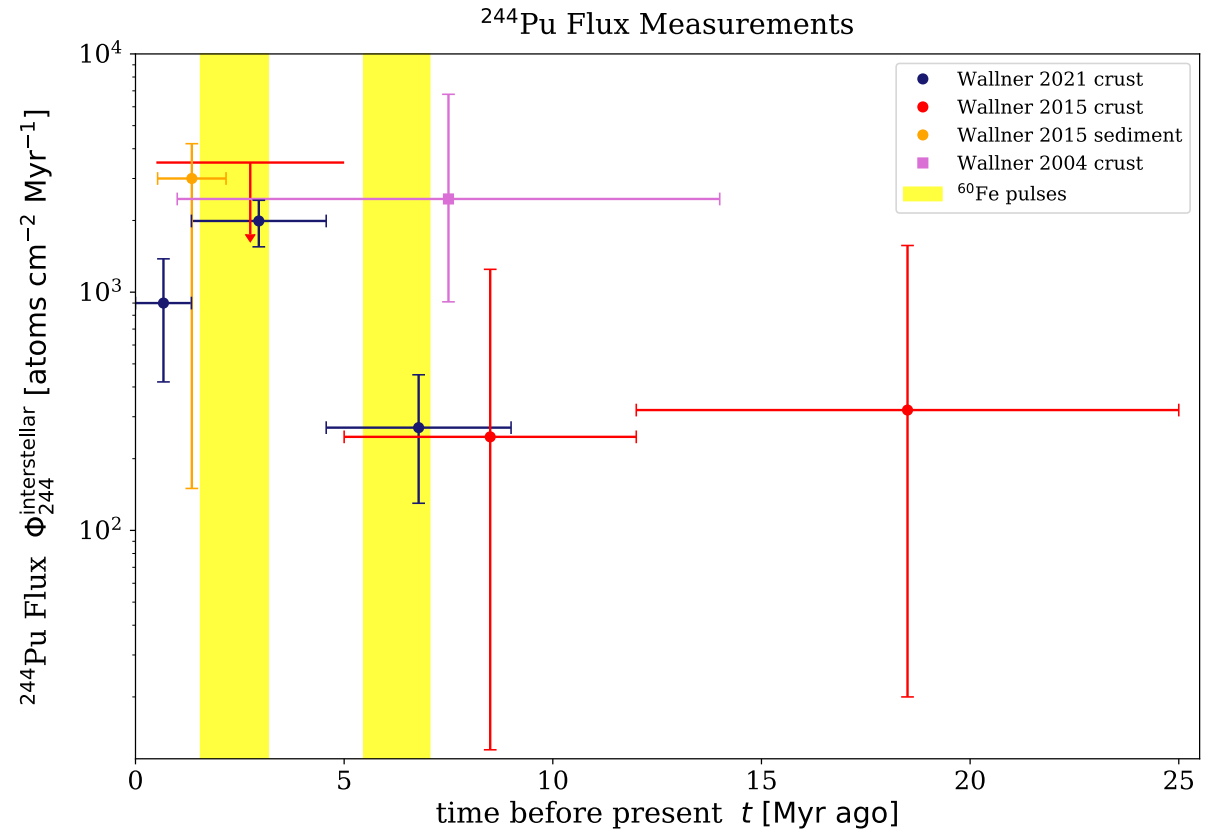
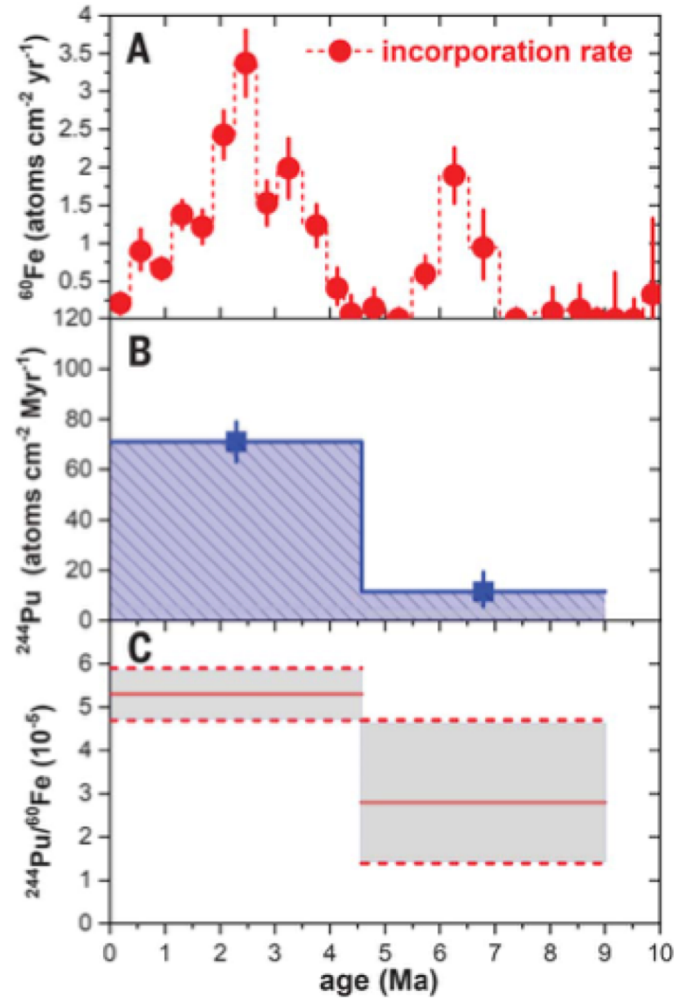
Vassh, Mumpower, McLaughlin,  
Sprouse, Surman 2020





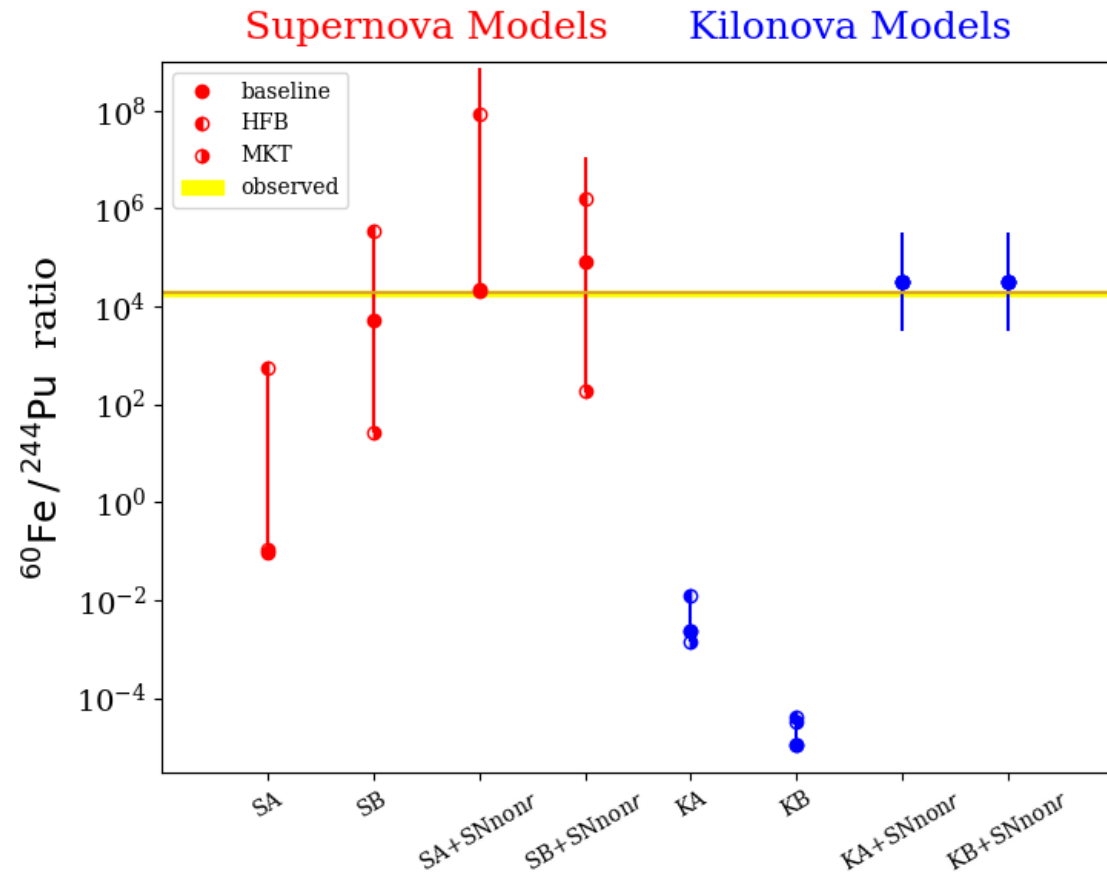
# Actinide observables: $^{60}\text{Fe}$ and $^{244}\text{Pu}$ in Fe-Mn crusts

Wallner+2021



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

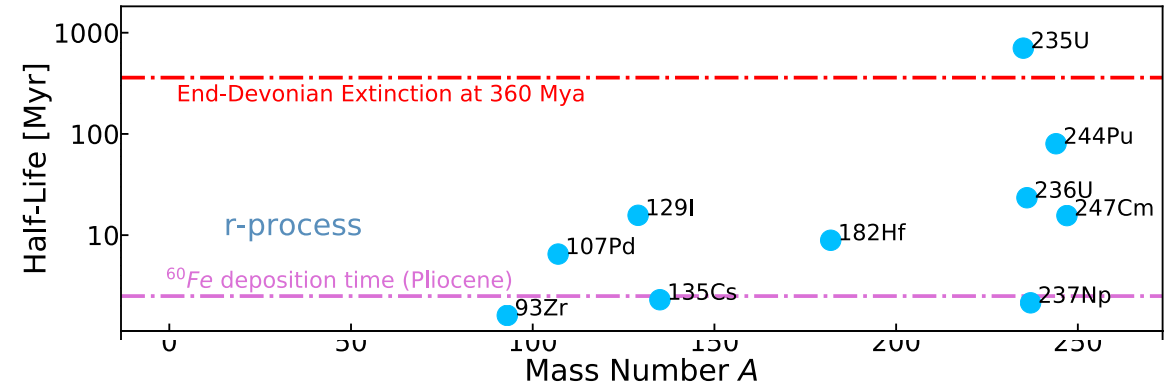
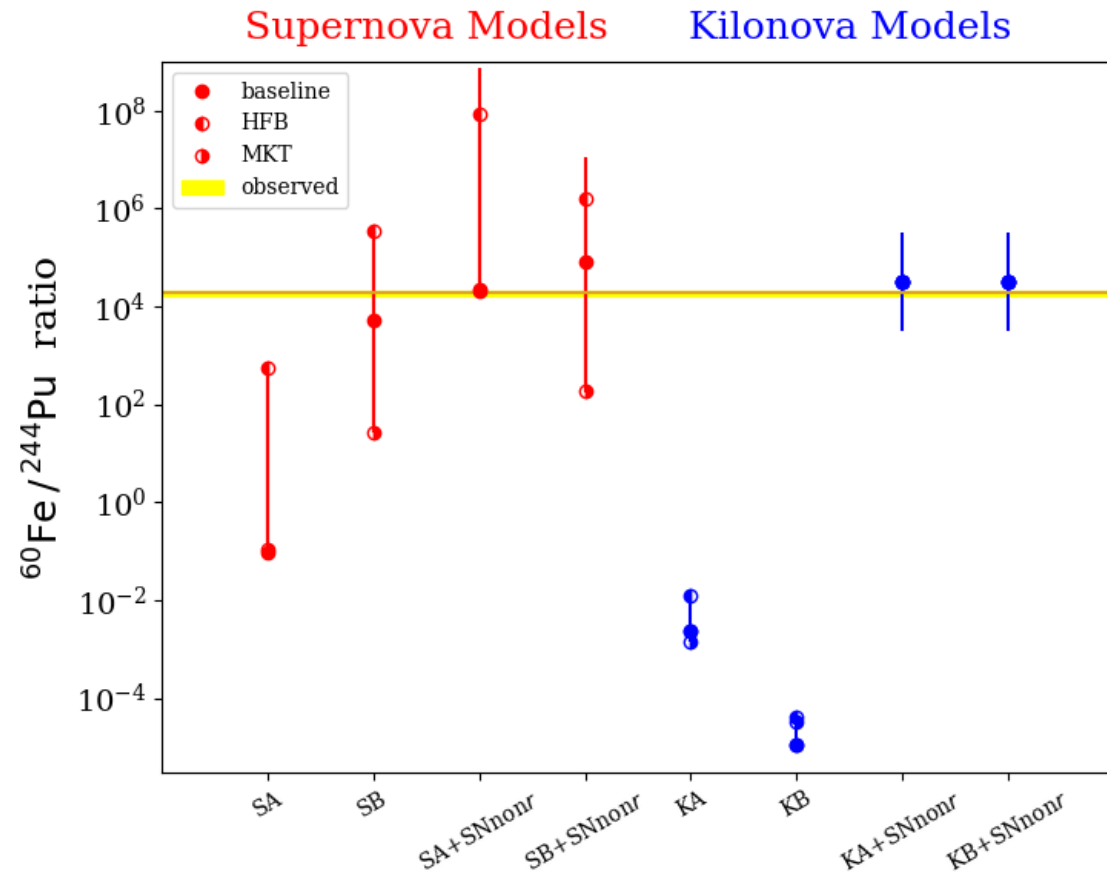
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Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;

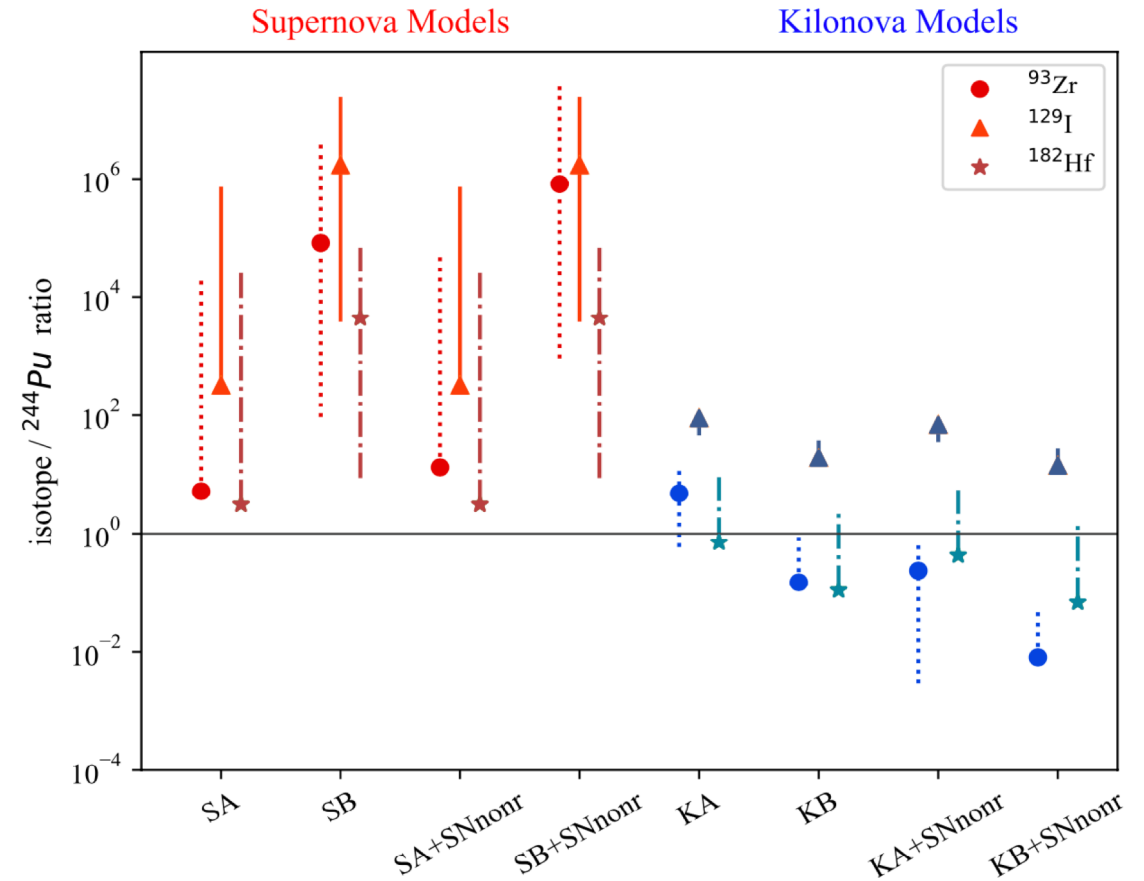
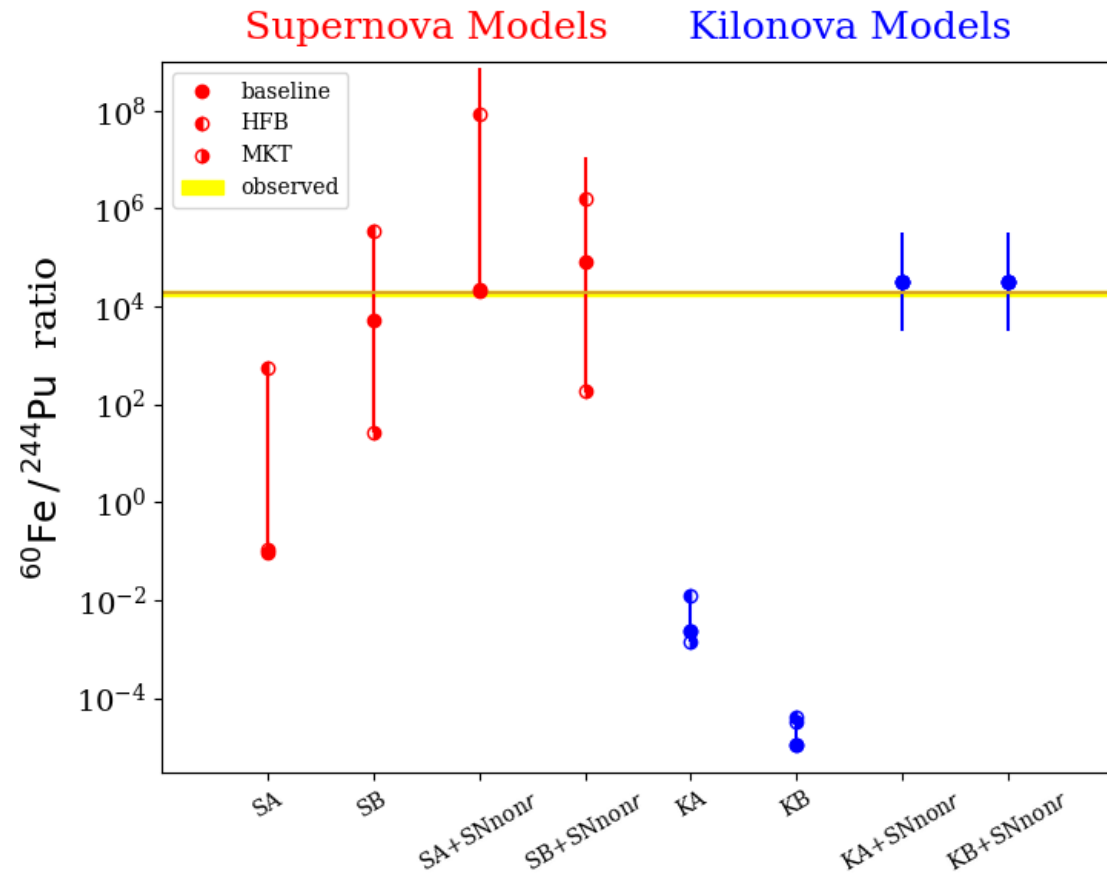
Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, arxiv:2112.09607

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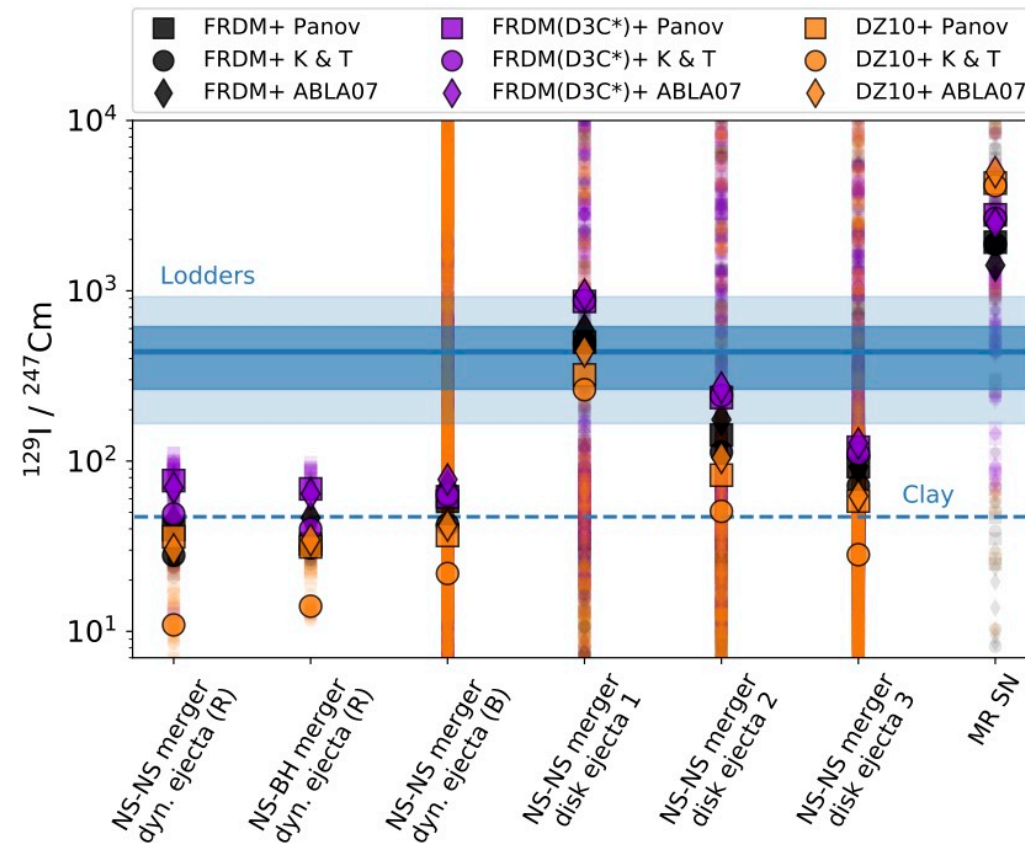
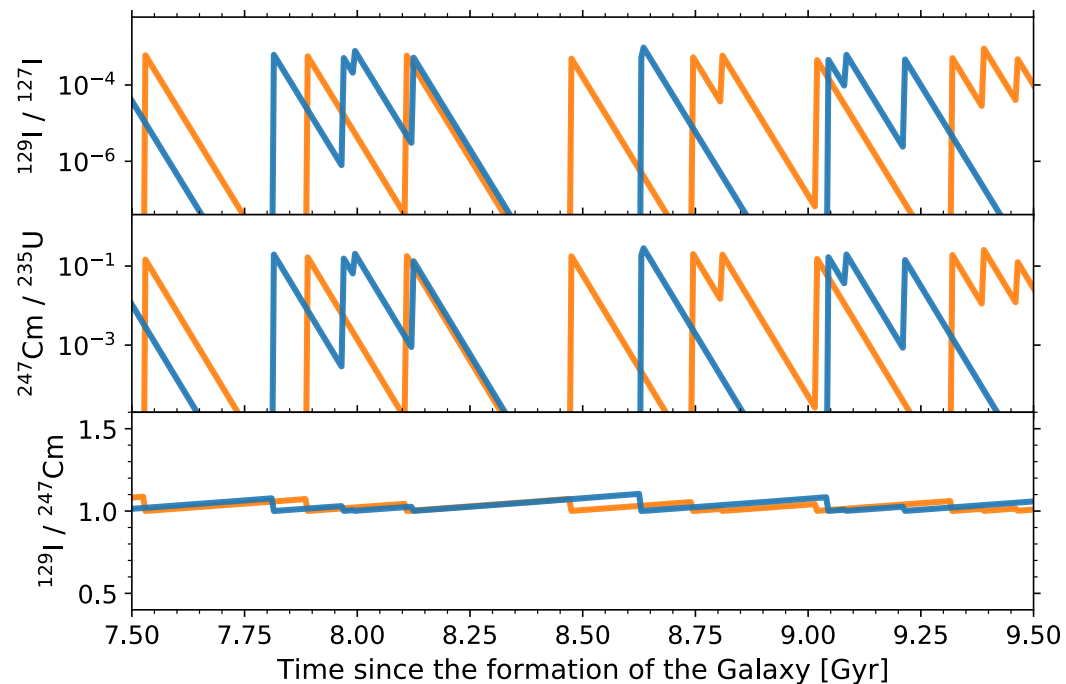
Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;  
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Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, ApJ 2021;  
 Wang, Clark, Ellis, Ertel, Fields, Fry, Liu, Miller, Surman, arxiv:2112.09607

# Actinide observables: $^{129}\text{I}/^{247}\text{Cm}$ ratio



## RESEARCH


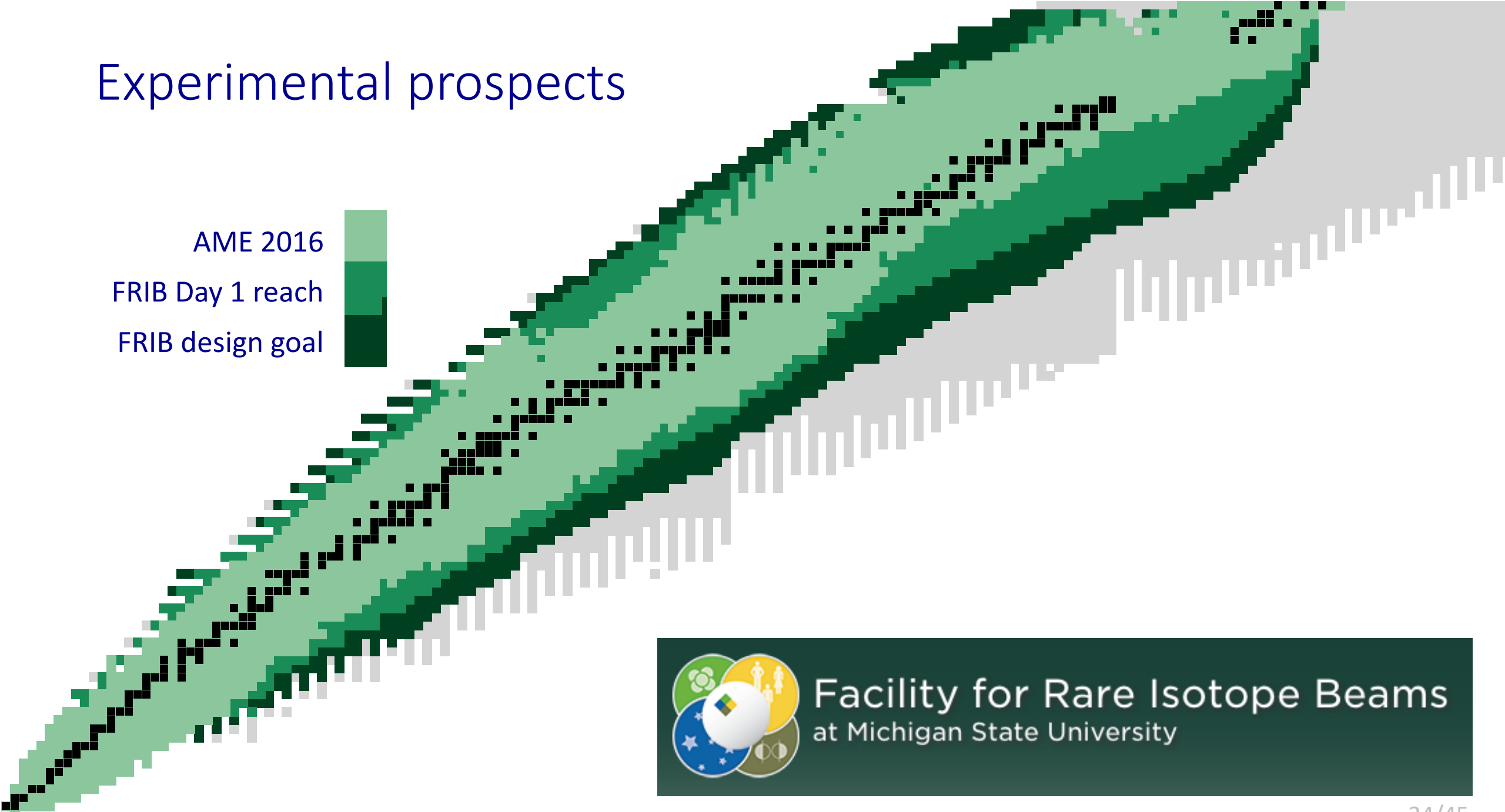
### NUCLEAR ASTROPHYSICS

$^{129}\text{I}$  and  $^{247}\text{Cm}$  in meteorites constrain the last astrophysical source of solar r-process elements

Benoit Côté<sup>1,2,3\*</sup>, Marius Eichler<sup>4</sup>, Andrés Yagüe López<sup>1</sup>, Nicole Vassh<sup>5</sup>, Matthew R. Mumpower<sup>6,7</sup>, Blanka Világos<sup>1,2</sup>, Benjámín Soós<sup>1,2</sup>, Almudena Arcones<sup>4,8</sup>, Trevor M. Sprouse<sup>5,6</sup>, Rebecca Surman<sup>5</sup>, Marco Pignatari<sup>9,1</sup>, Mária K. Pető<sup>1</sup>, Benjamin Wehmeyer<sup>1,10</sup>, Thomas Rauscher<sup>10,11</sup>, Maria Lugaro<sup>1,2,12</sup>

# Experimental prospects

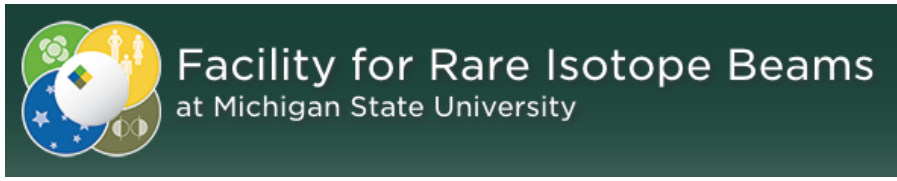
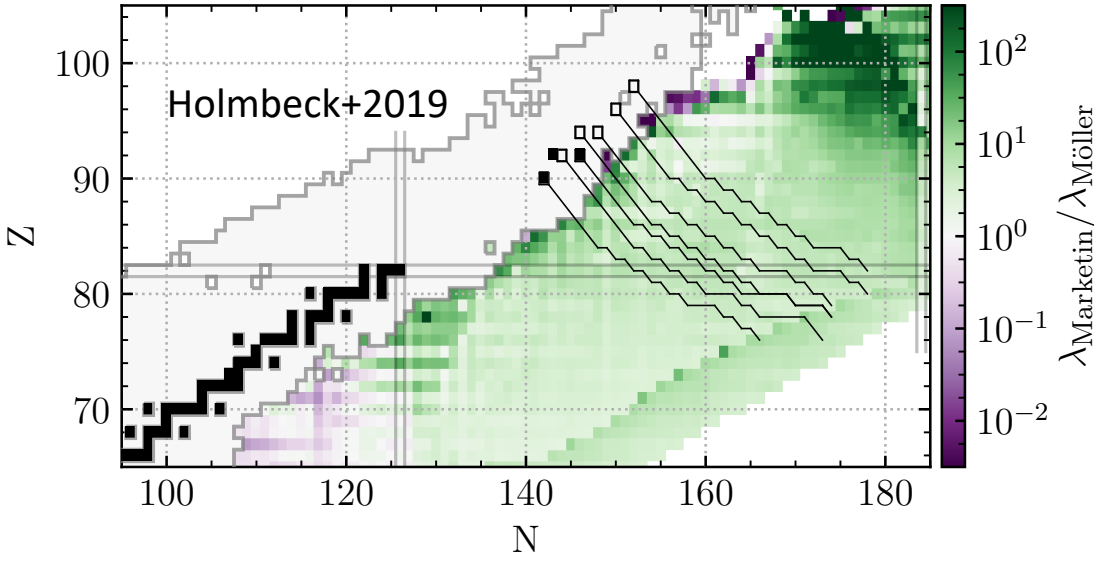
AME 2016  
FRIB Day 1 reach  
FRIB design goal



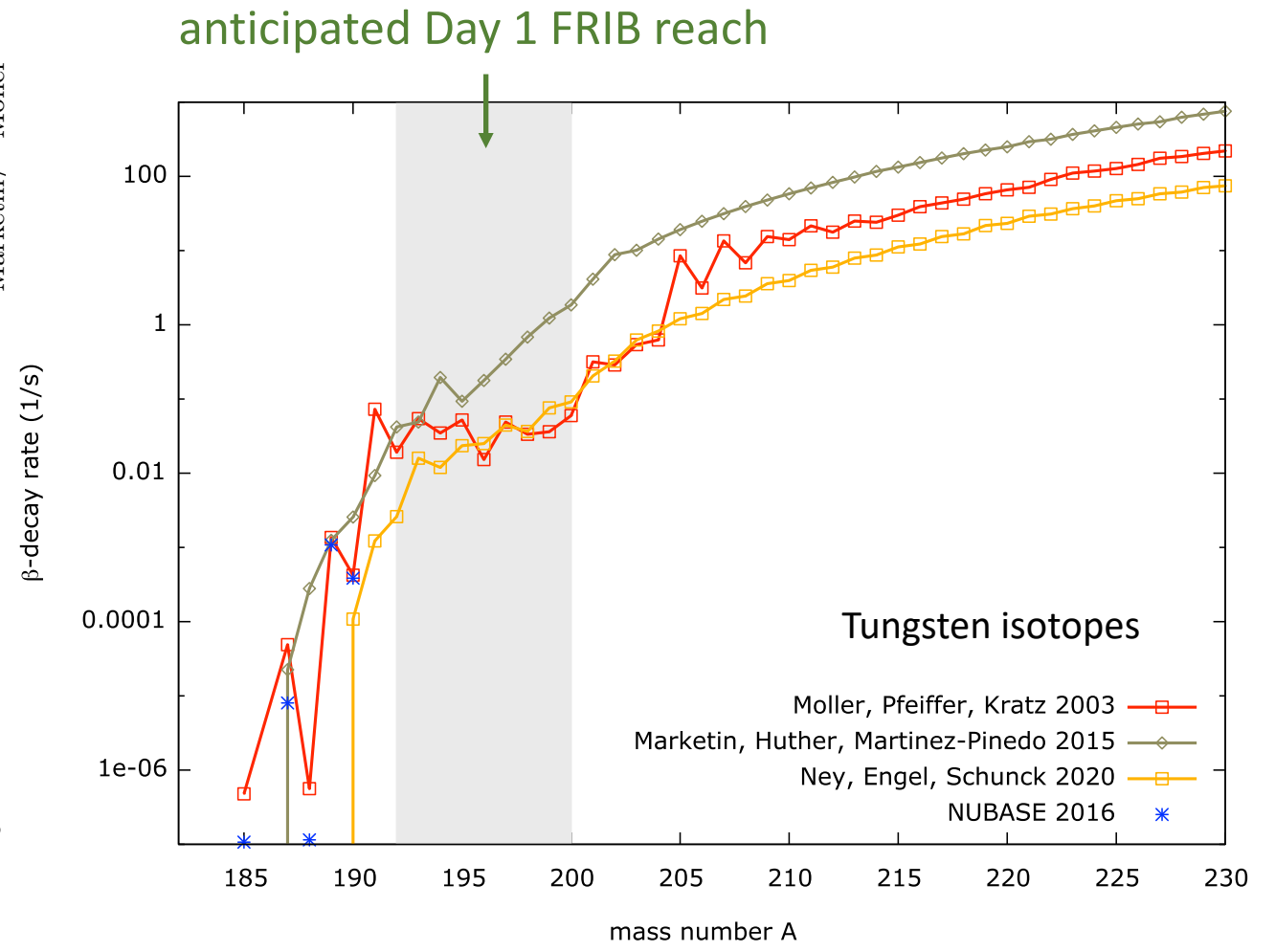
Facility for Rare Isotope Beams  
at Michigan State University



# $N \sim 126$ region measurement prospects



FRIB FDSi Day 1 proposal  
 $N = 126$  region half-lives  
 Estrade+2021

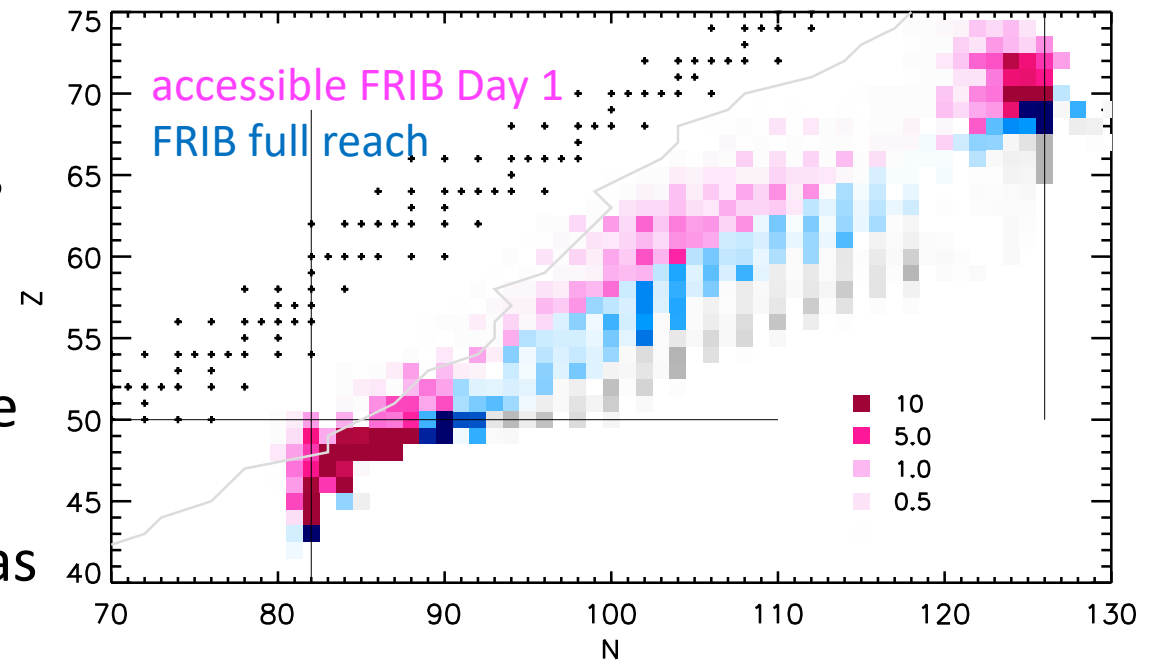


# summary

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. Accurate interpretation of  $r$ -process observables such as elemental and isotopic ratios, abundance patterns, and light curves require advances in these areas.



Mumpower, Surman, McLaughlin,  
Arahamian, JPPNP 2016