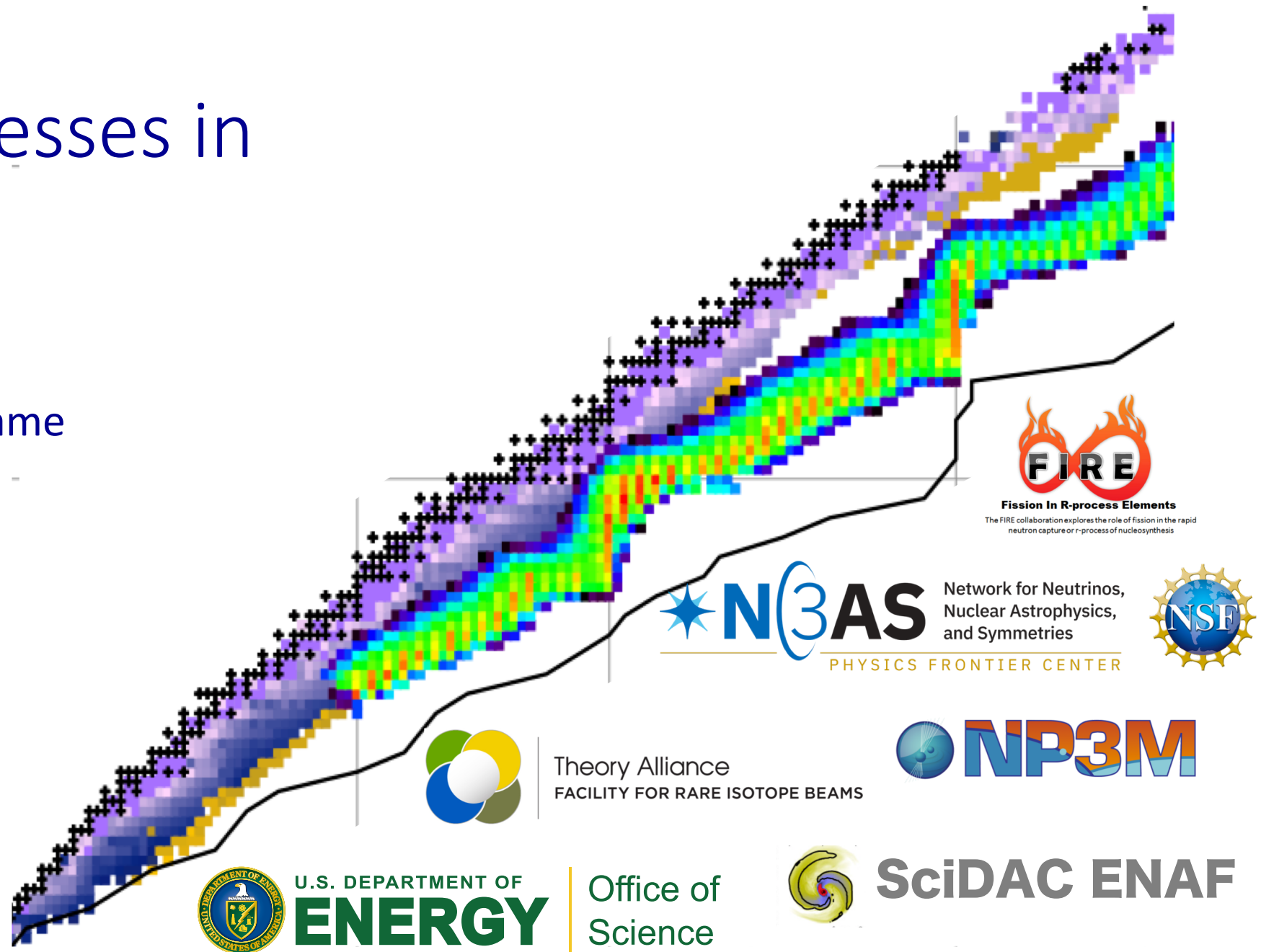


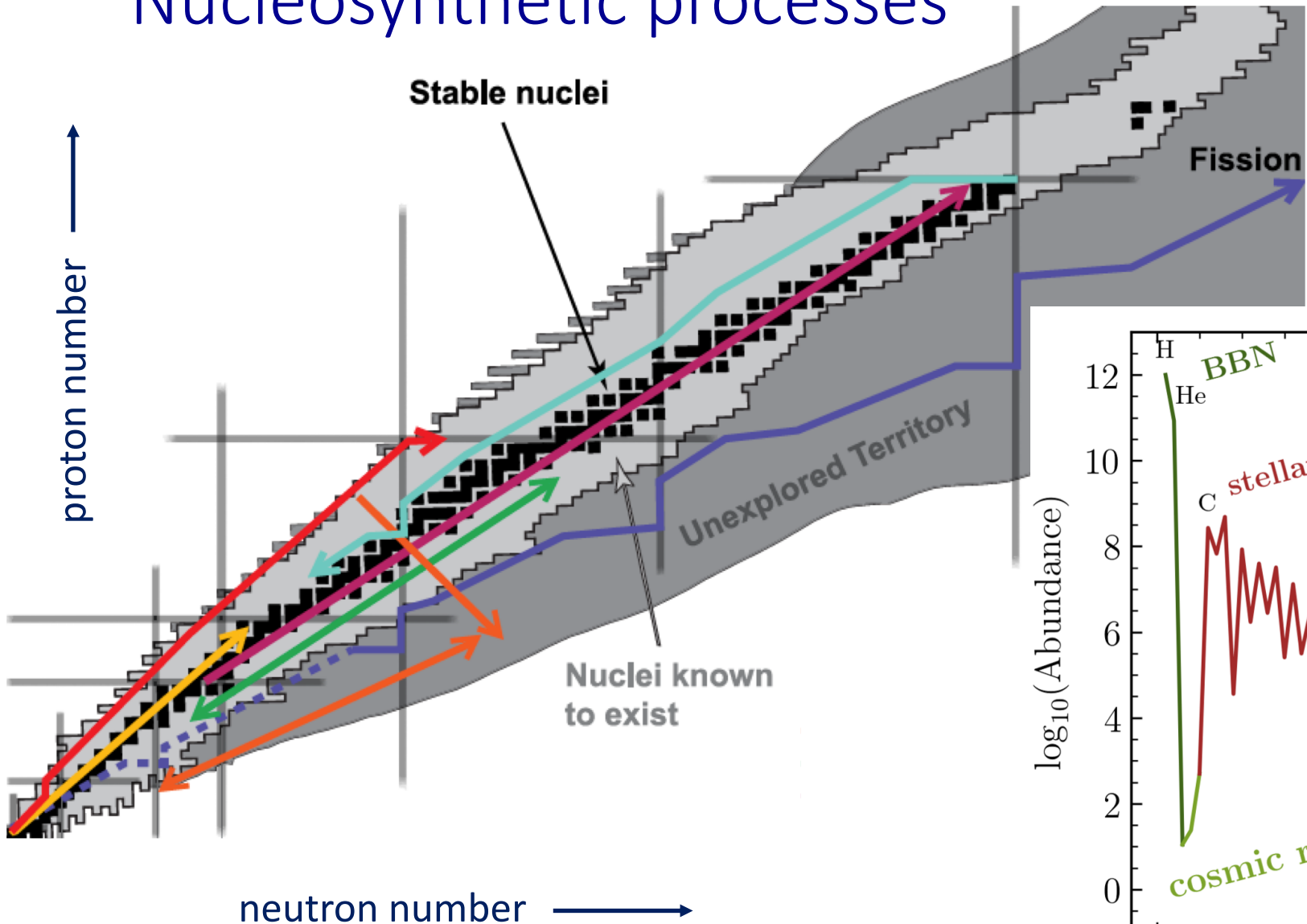
# Fission processes in astrophysics

Rebecca Surman  
University of Notre Dame

FIESTA 2024  
22 Nov 2024

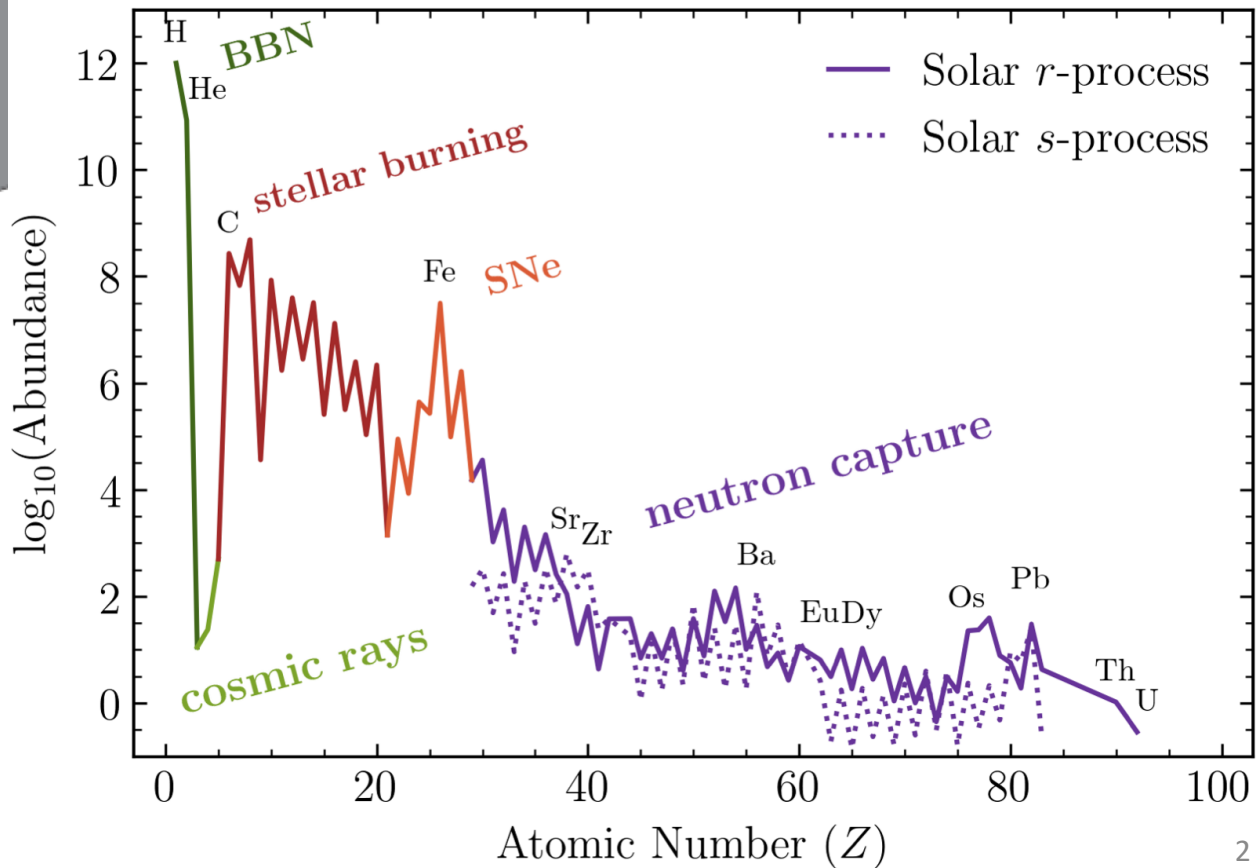


# Nucleosynthetic processes

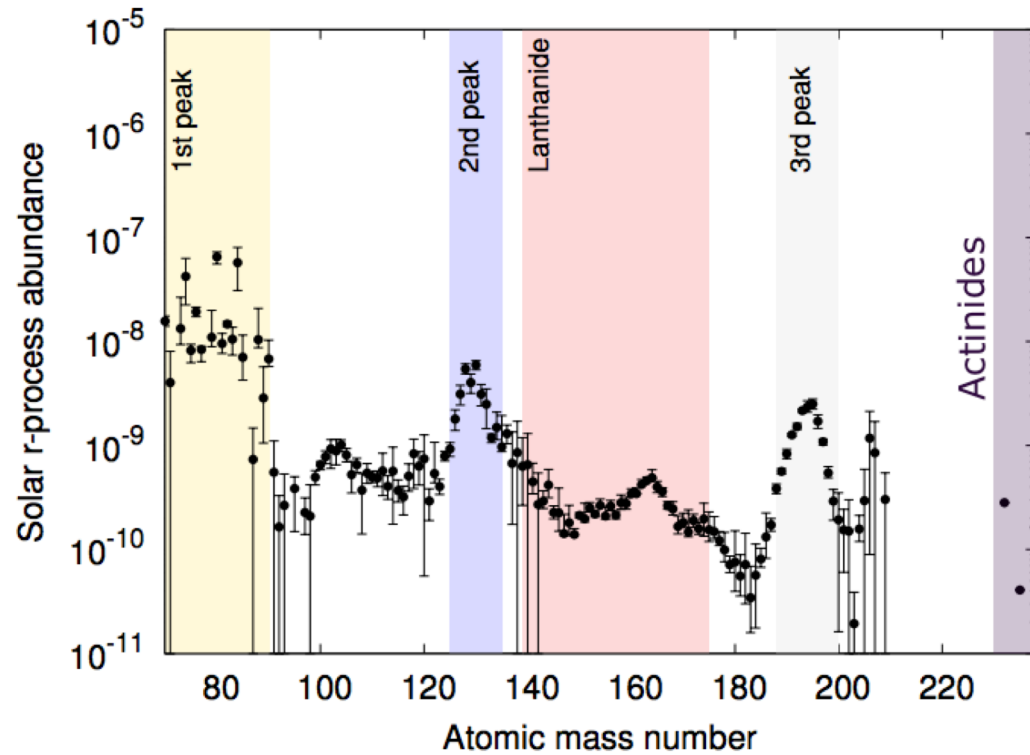


from Timmes/Schatz/Spyrou

data from Lodders 2003  
figure by E Holmbeck



# r-process nucleosynthesis



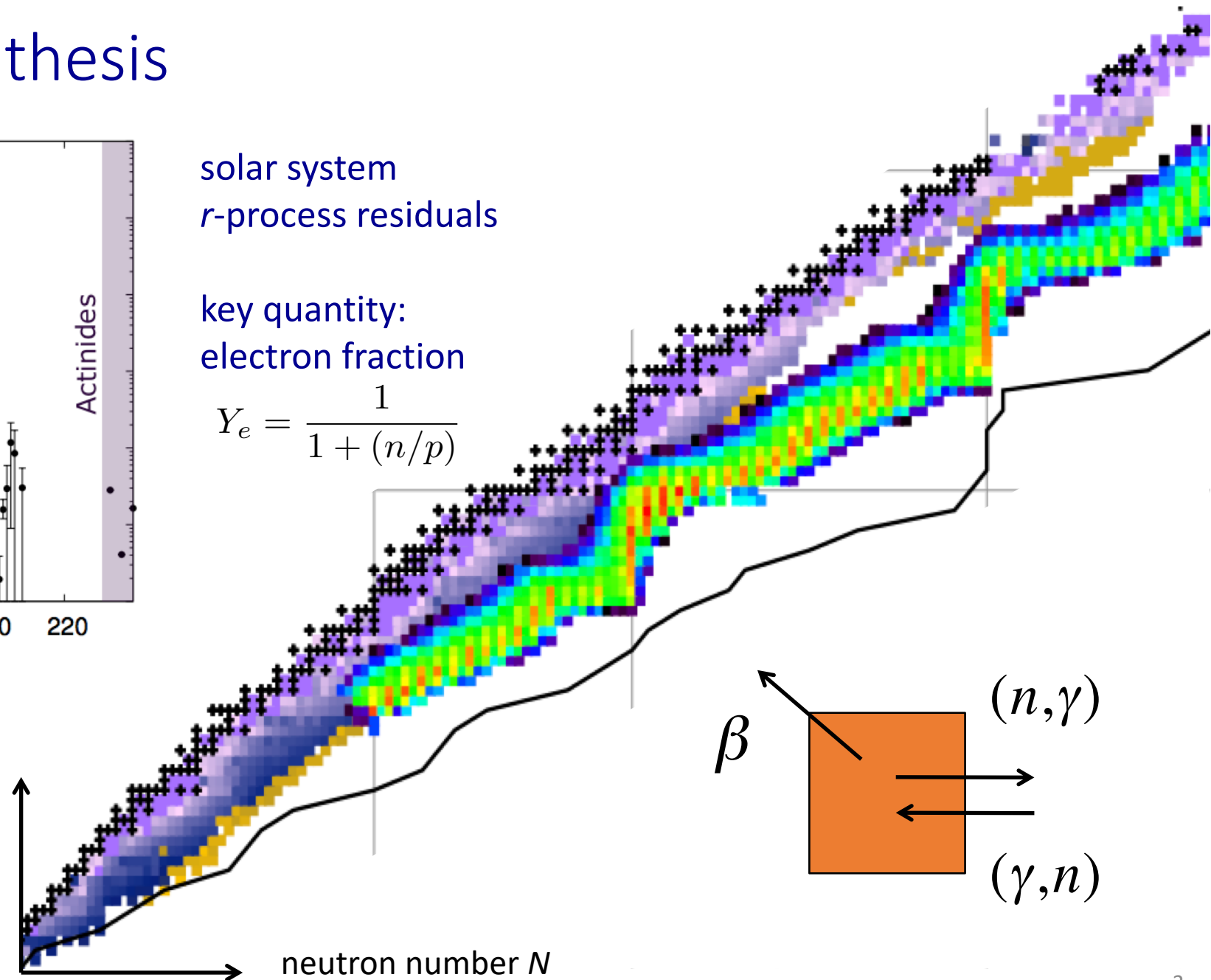
Arnould+2007, Hotokezaka+2018

solar system  
r-process residuals

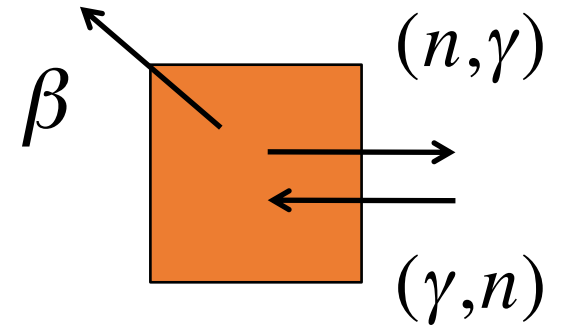
key quantity:  
electron fraction

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

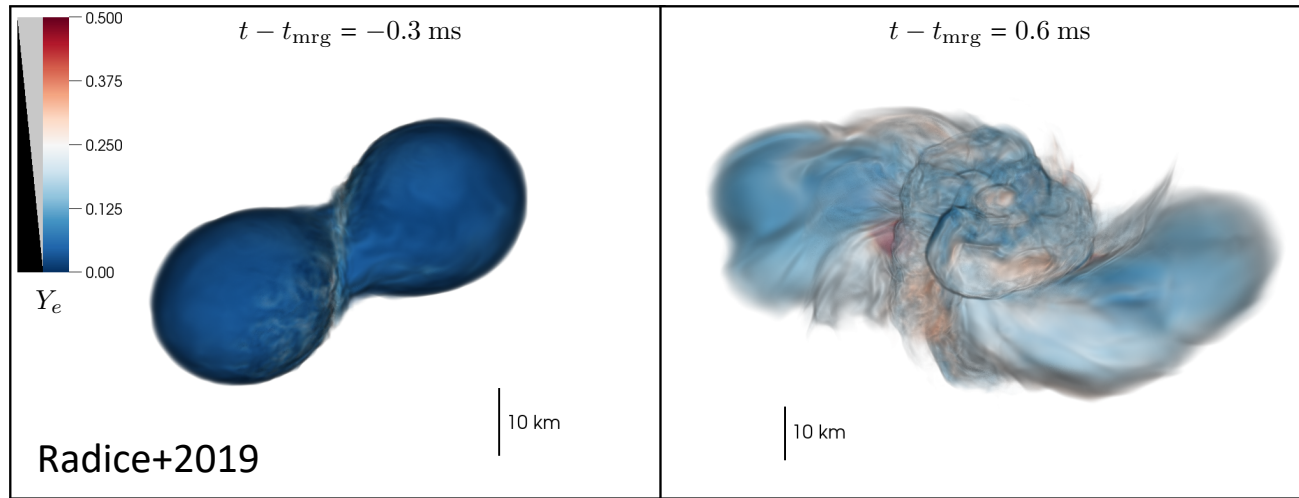
proton number  $Z$



neutron number  $N$

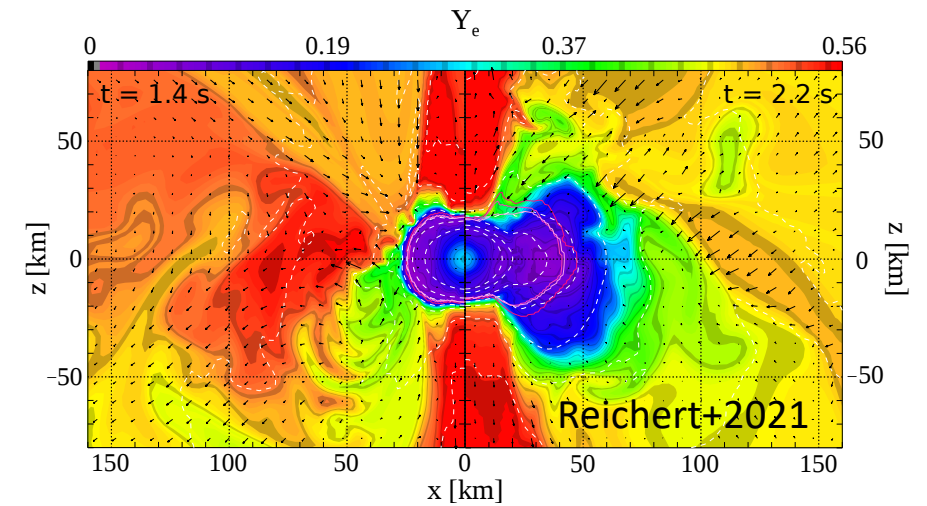
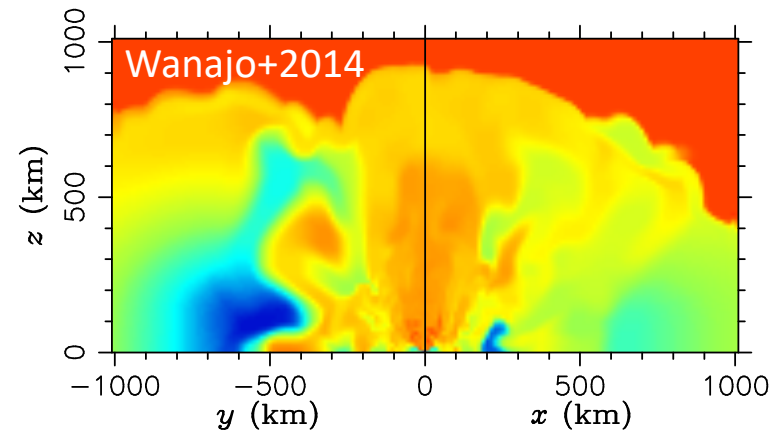


# $r$ -process astrophysical sites

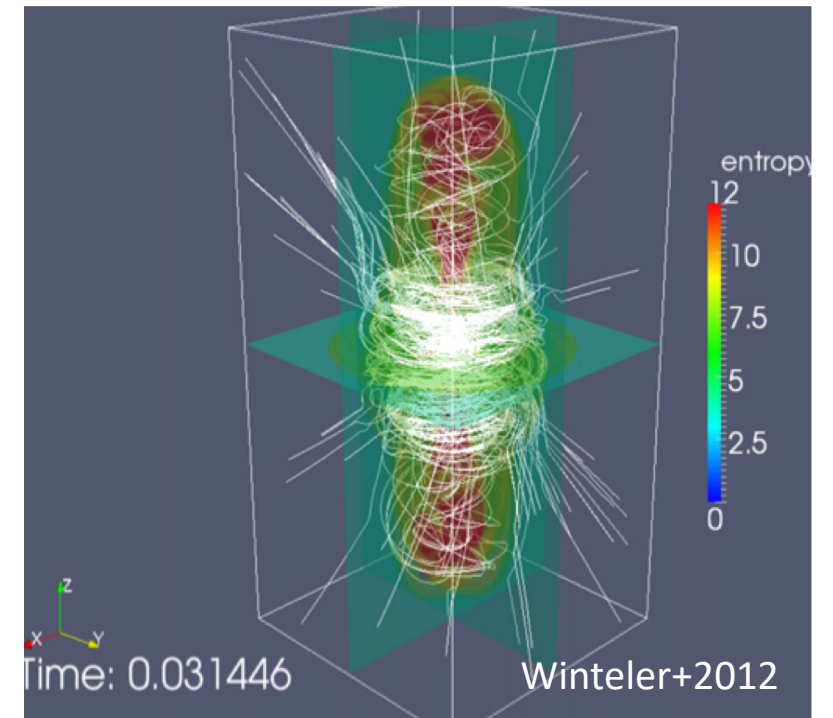


Binary neutron star  
mergers

(also neutron star-  
black hole mergers?)

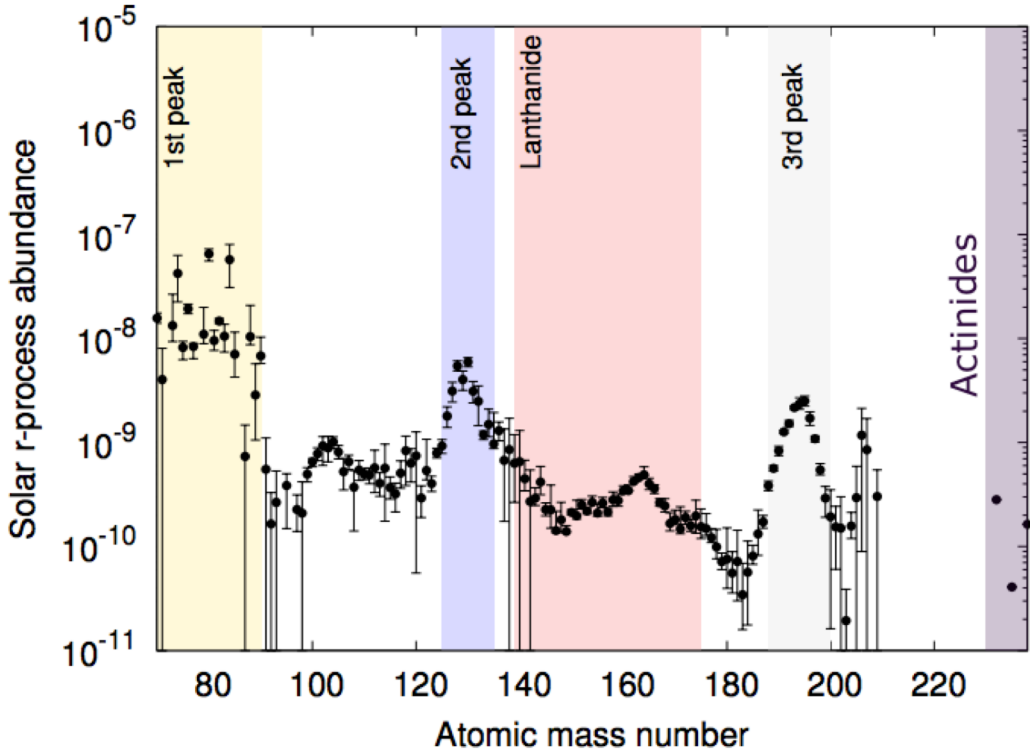


Exotic supernovae (?)



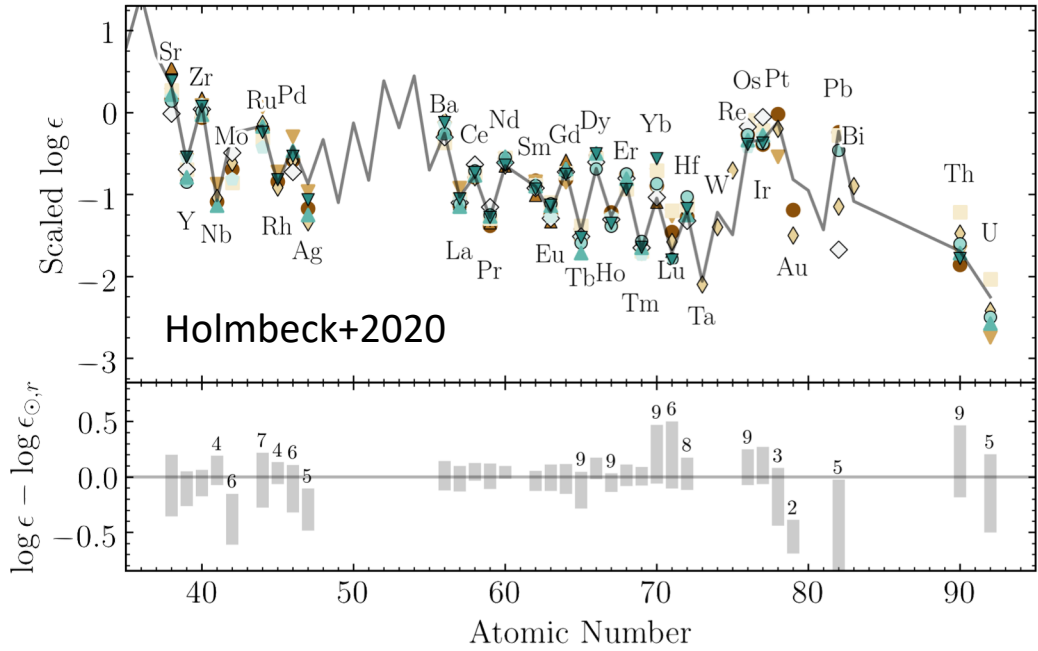


# r-process observables: abundance patterns



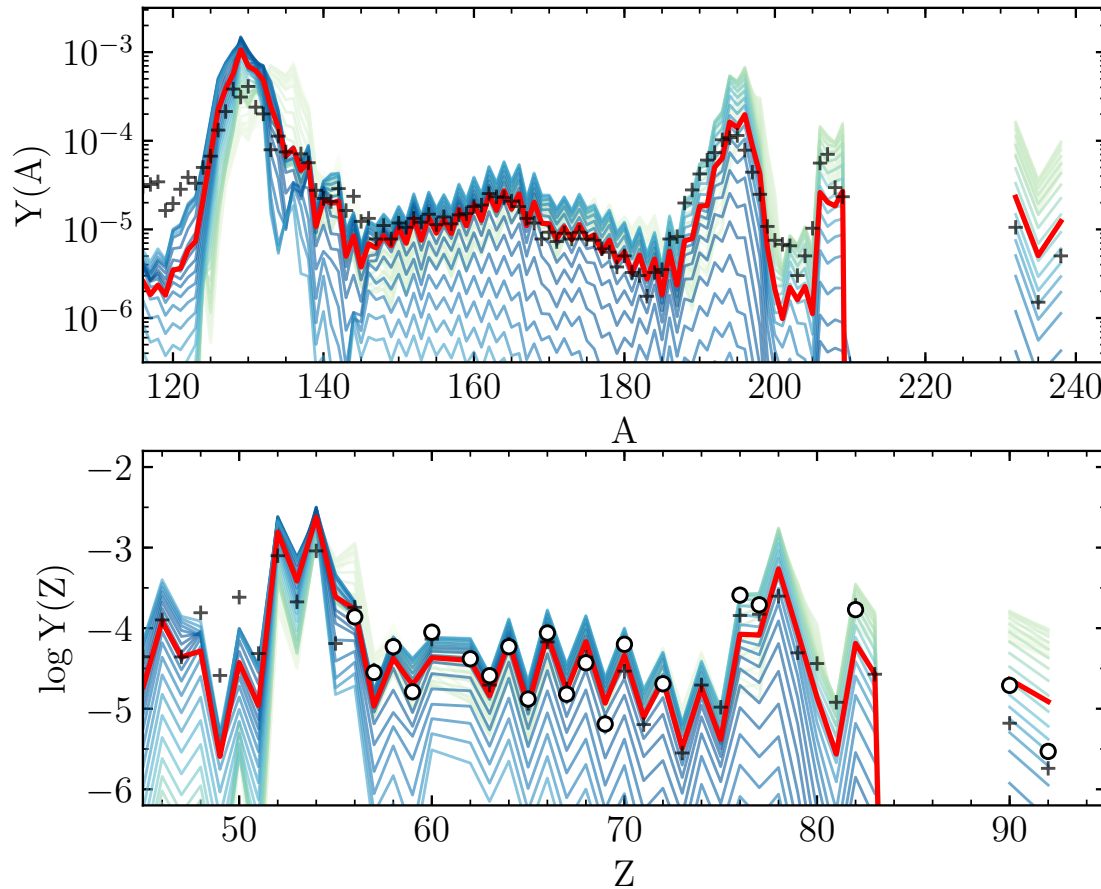
Arnould+2007, Hotokezaka+2018

solar system  
r-process residuals

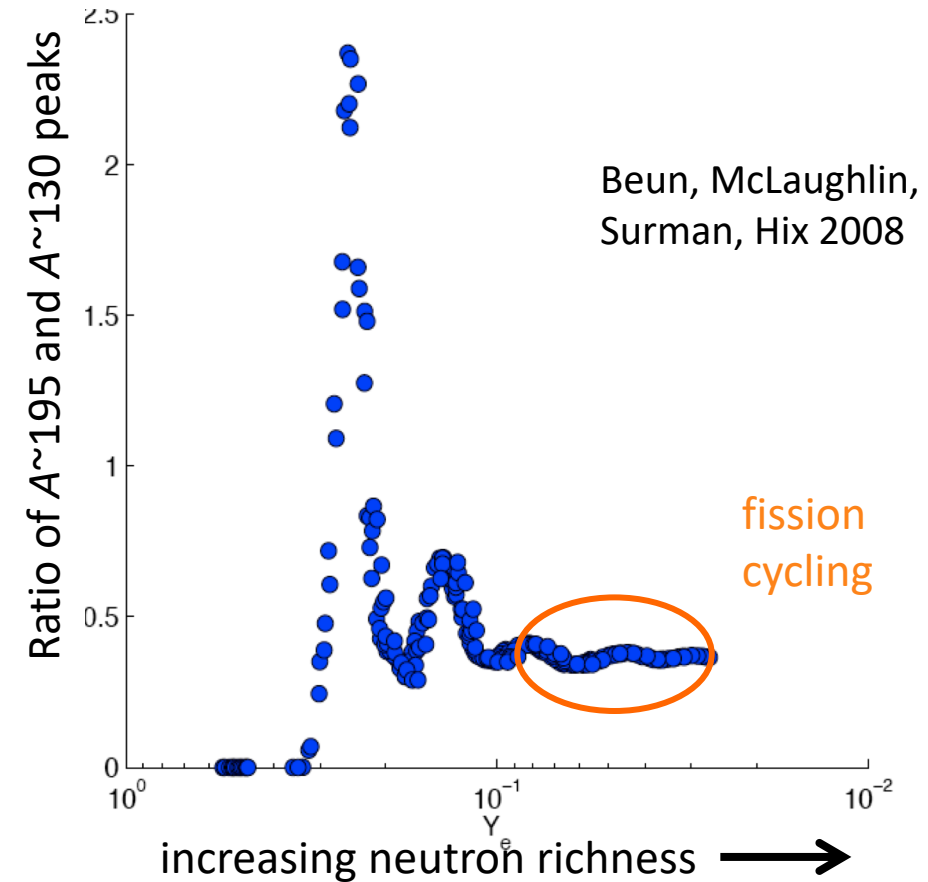


r-process elements  
in metal-poor stars

# consistent $r$ -process pattern: evidence for fission cycling?



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



# connecting fission properties to $r$ -process observables

- Can we exploit knowledge of fission and fissioning isotopes to interpret  $r$ -process observables?
- What can we learn about the fission properties of neutron-rich actinides from  $r$ -process observables?

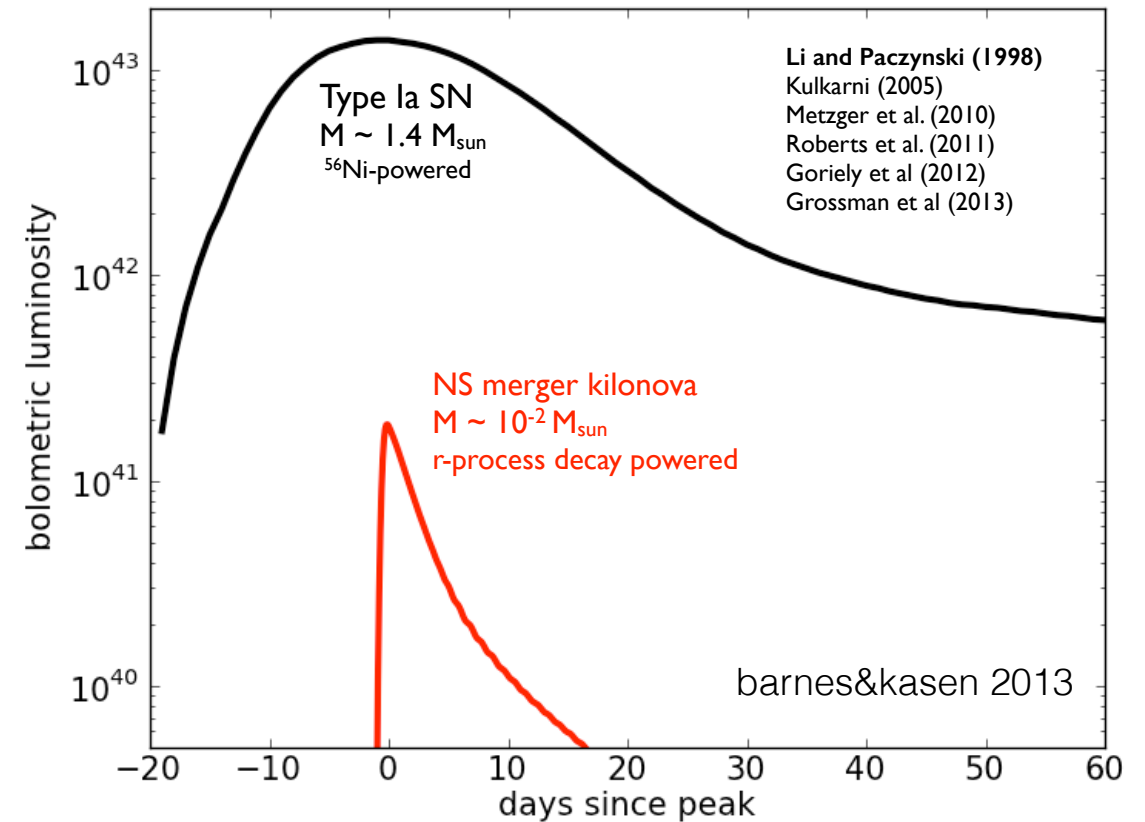
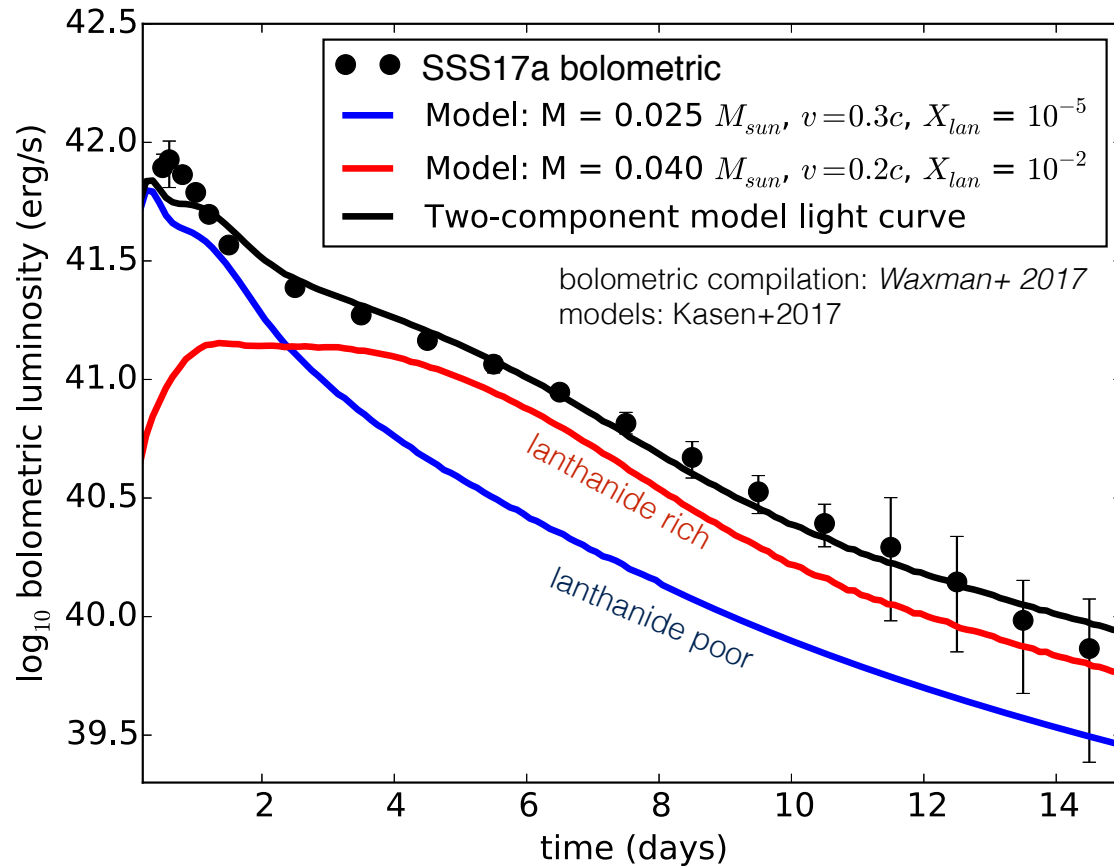
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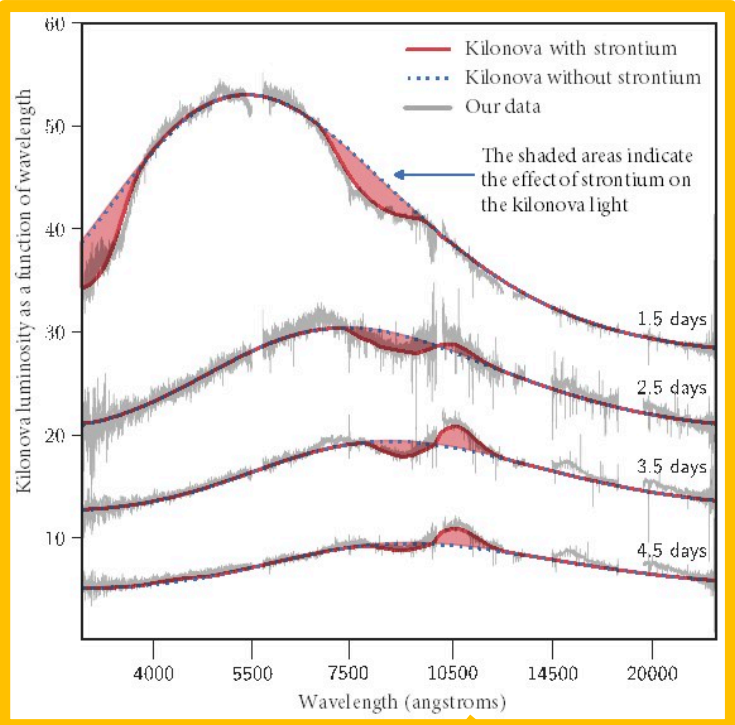


# $r$ -process observables: electromagnetic signatures

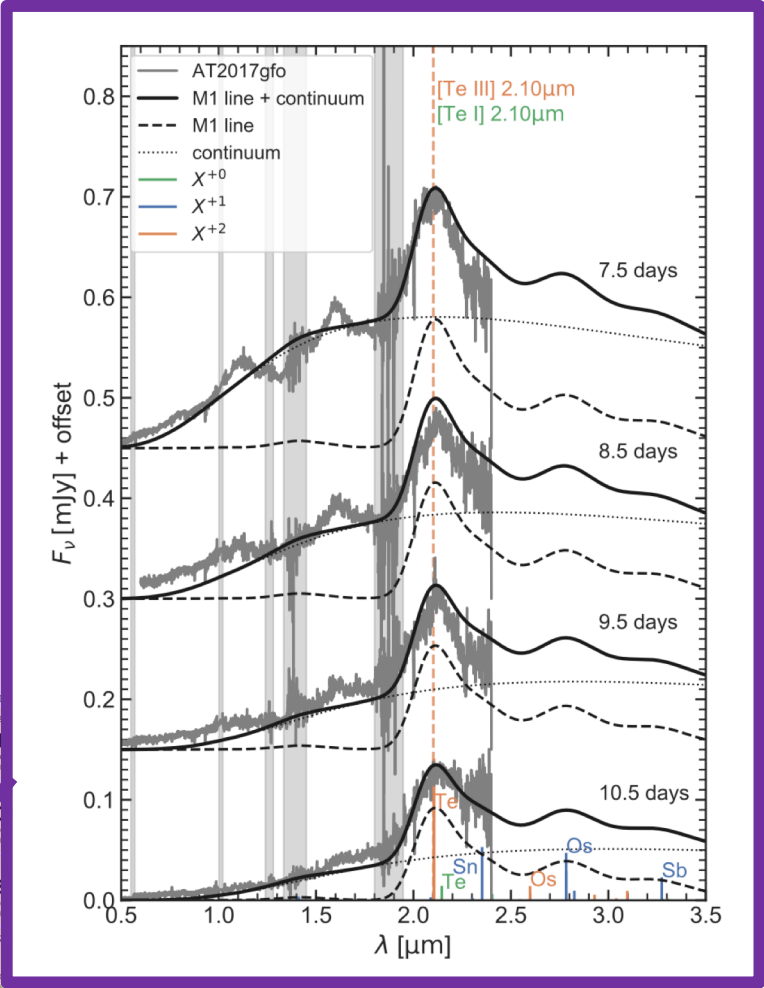
kilonova SSS17a bolometric light curve



# NSM evidence for specific elements



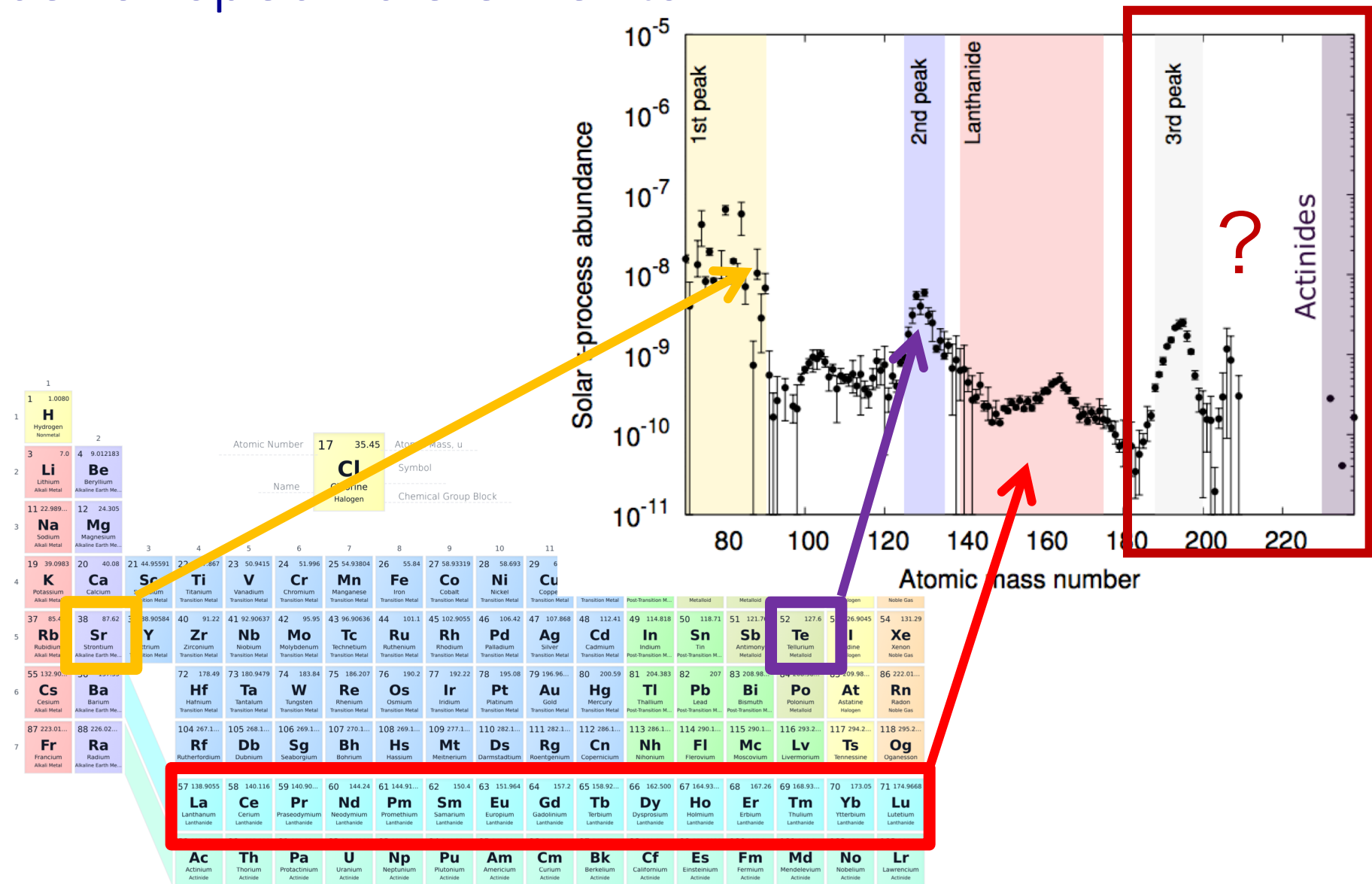
Hotokezaka+2023



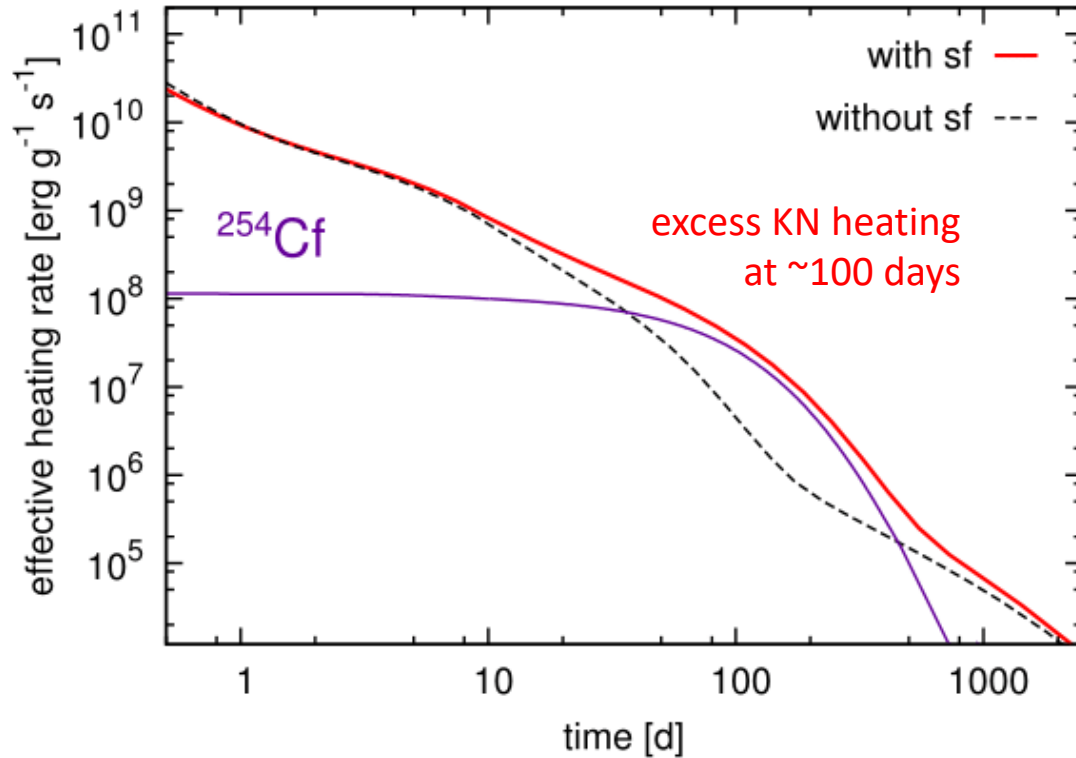
Watson+2019

Kobalt		Nickel		Copper		Zinc		Gallium		Germanium		Arsenic		Selenium		Bromine																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
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Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthanide		Lanthani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# NSM evidence for specific elements



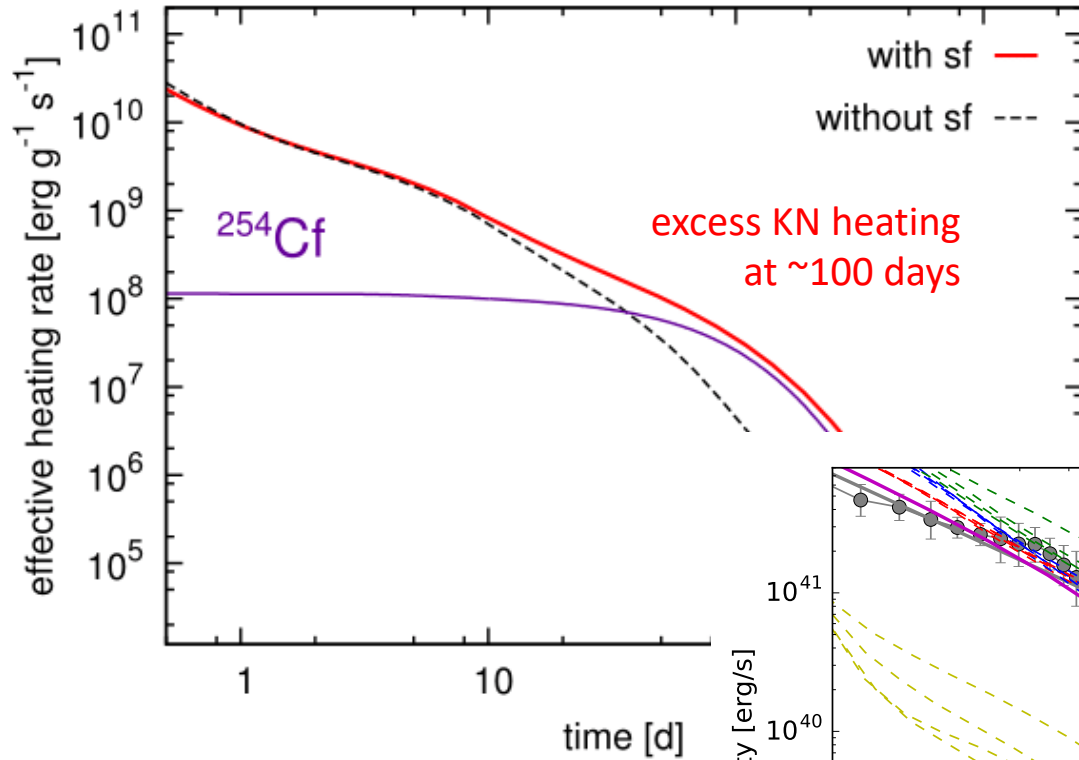
# Did the GW170817 merger produce actinides?



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

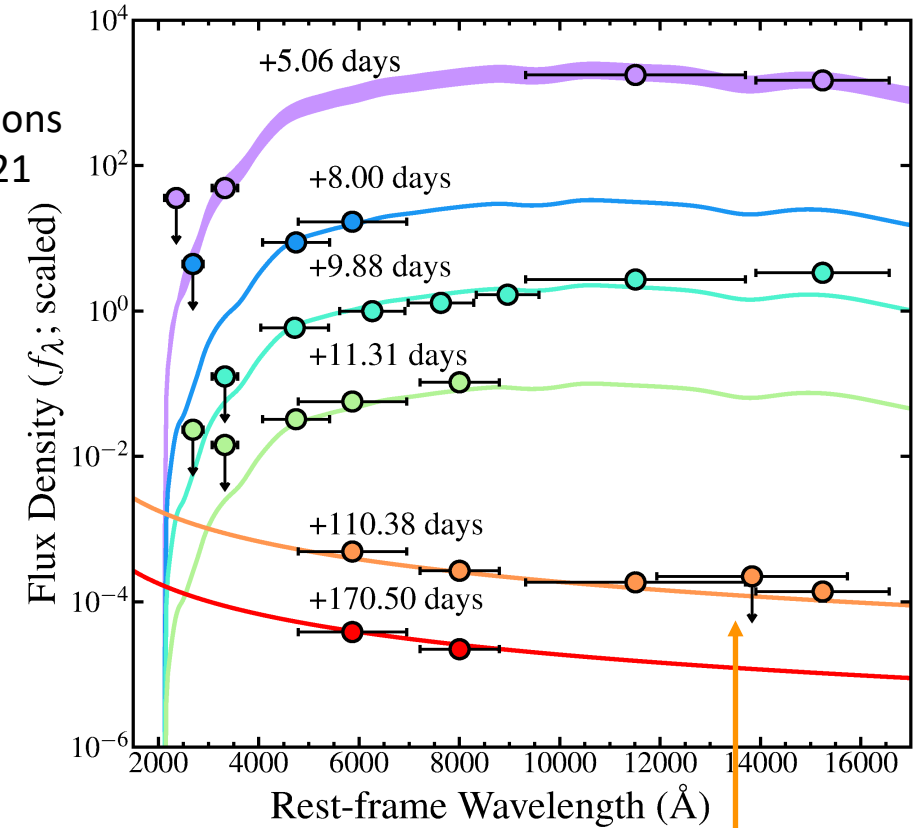


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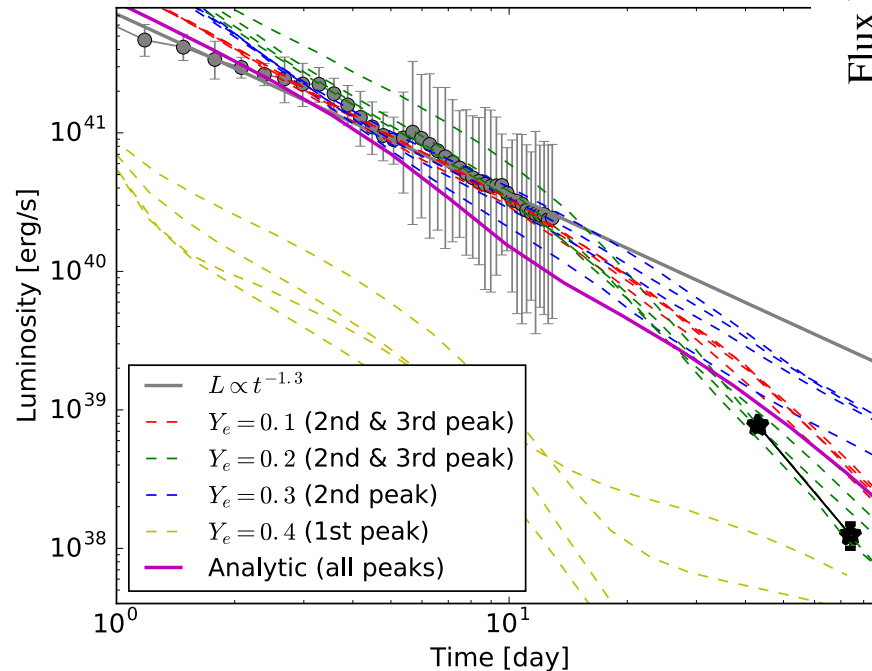


HST observations  
Kilpatrick+2021

Spitzer mid-infrared  
Kasliwal+2019

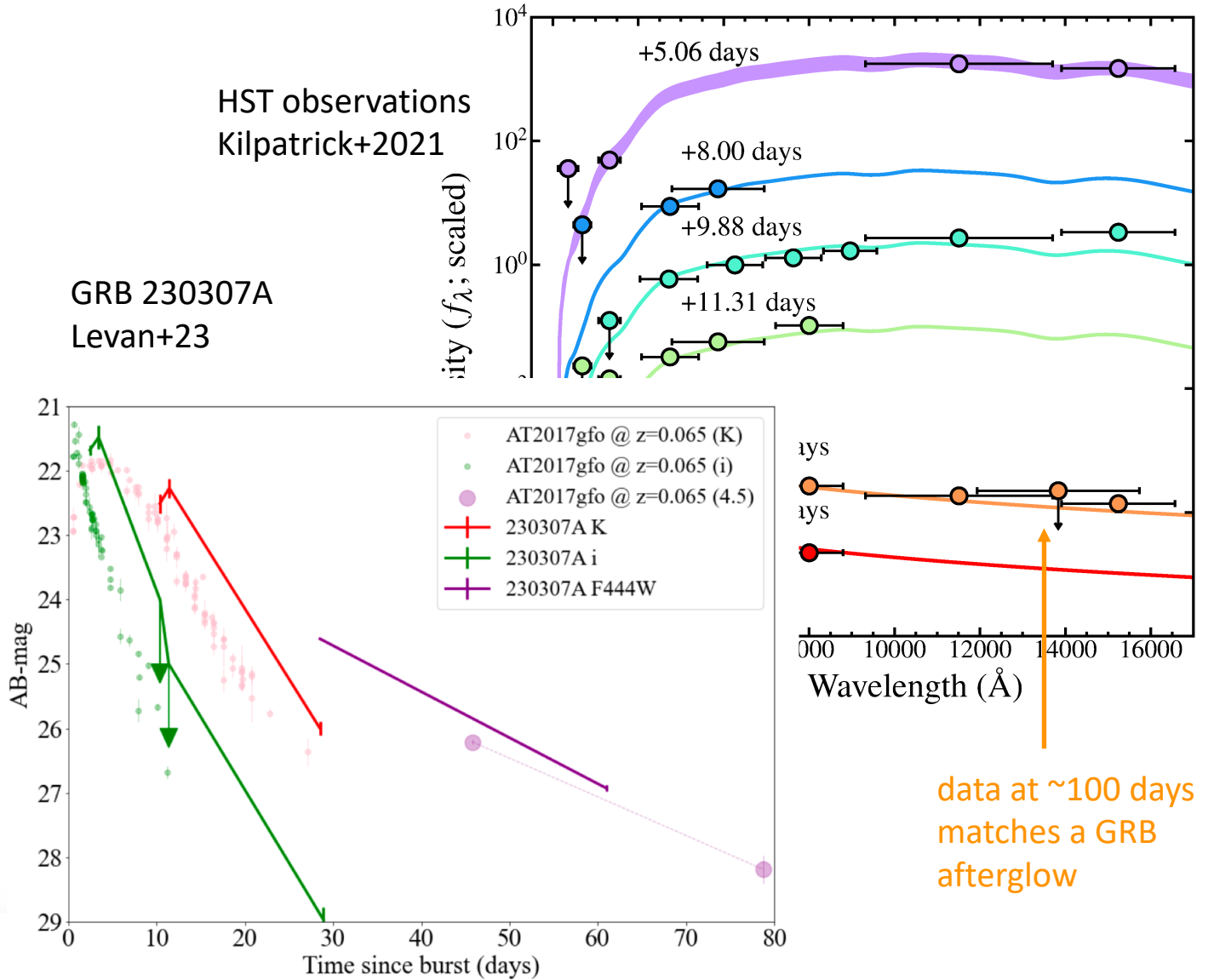
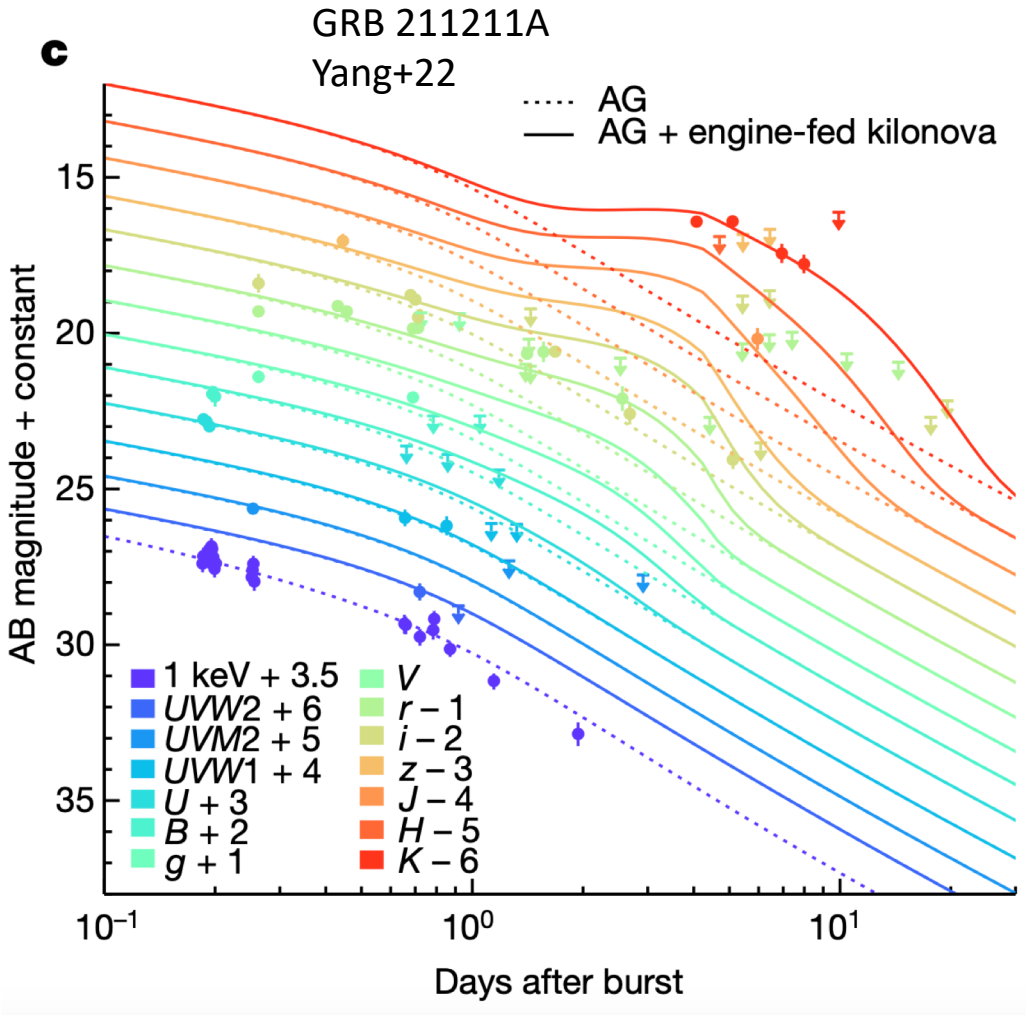


Zhu, Wollaeger, Vassh, Surman, Sprol  
Möller, McLaughlin, Korobkin, Jaffke,  
Even, Couture, Barnes, ApJL 2018

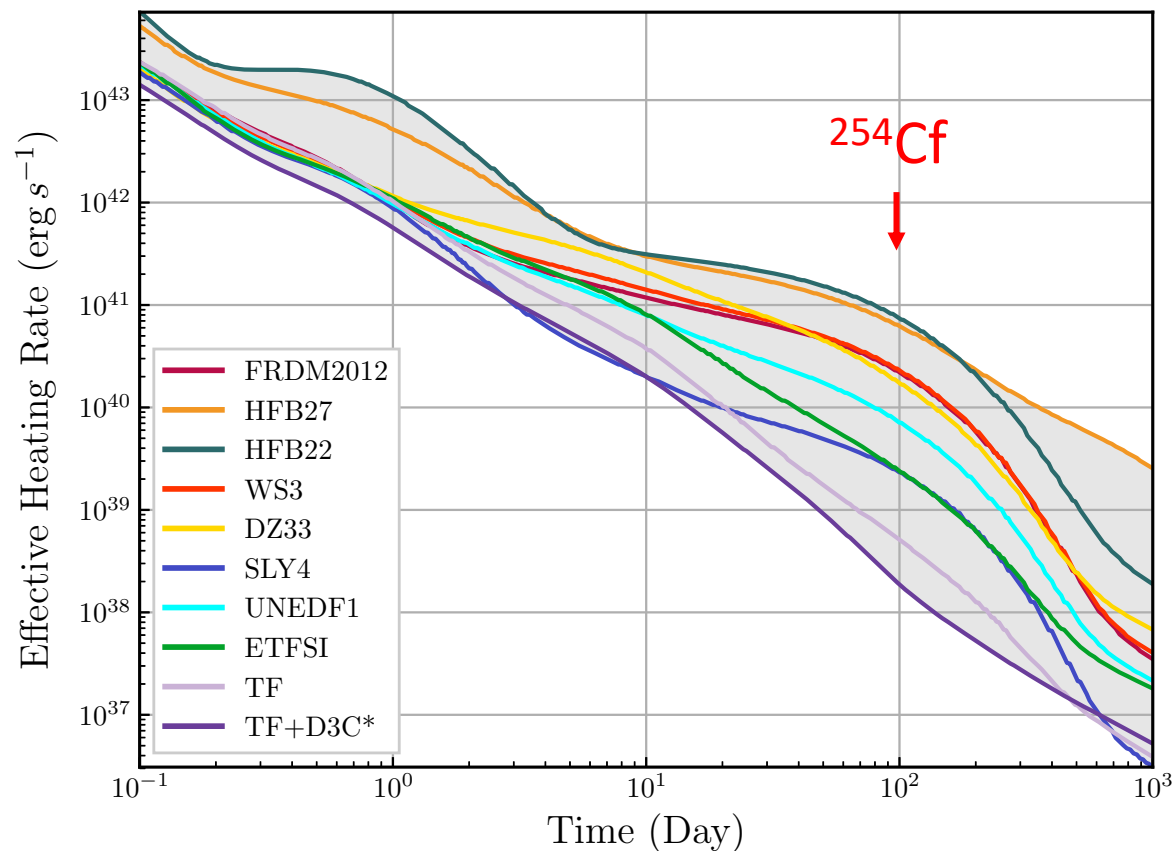


data at ~100 days  
matches a GRB  
afterglow

# Subsequent KNe show similar late time behavior

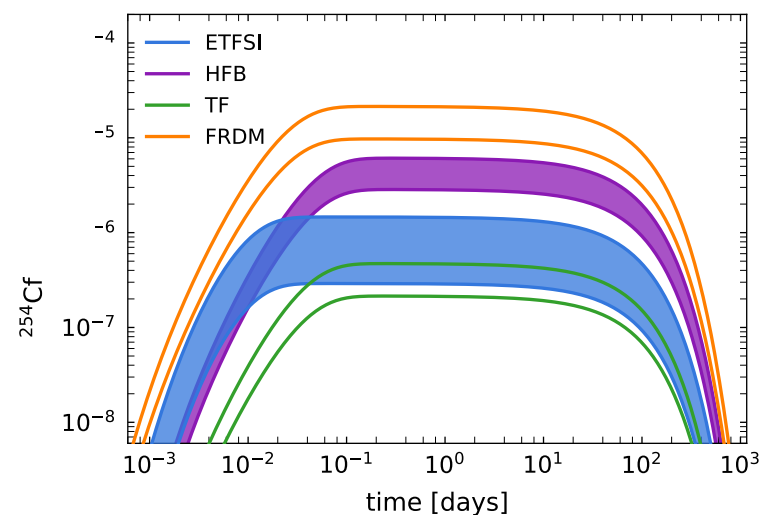
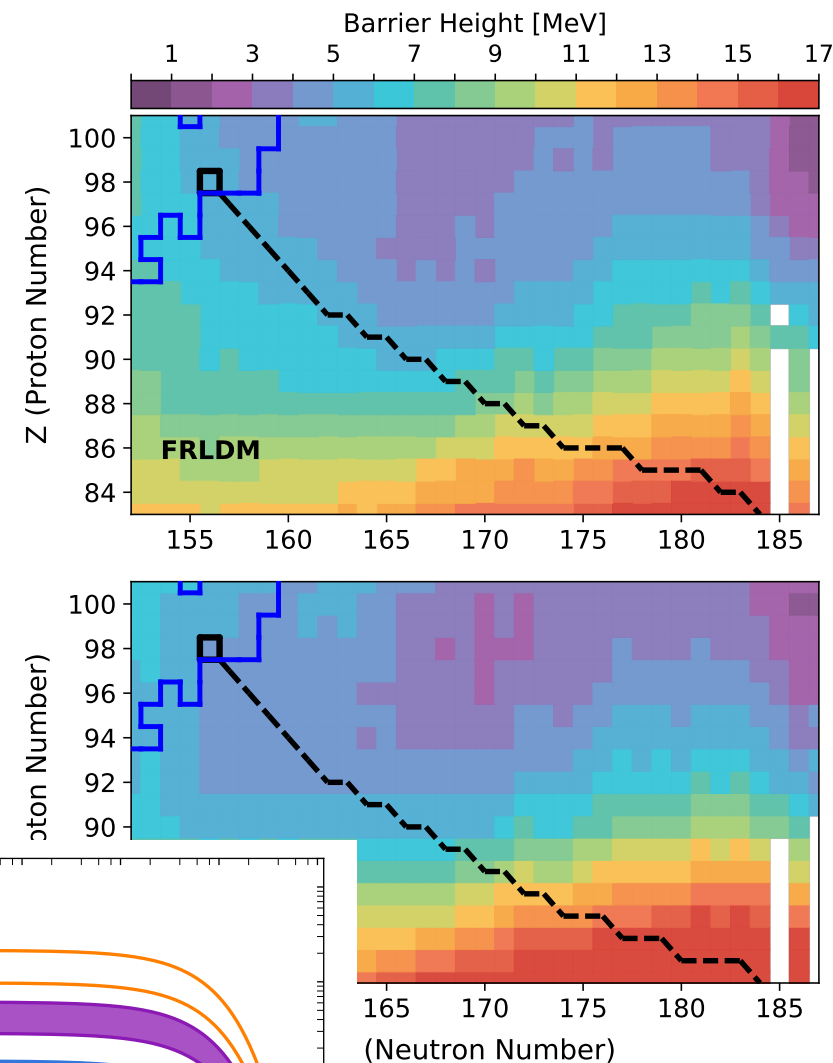


# $^{254}\text{Cf}$ : dependence on nuclear inputs

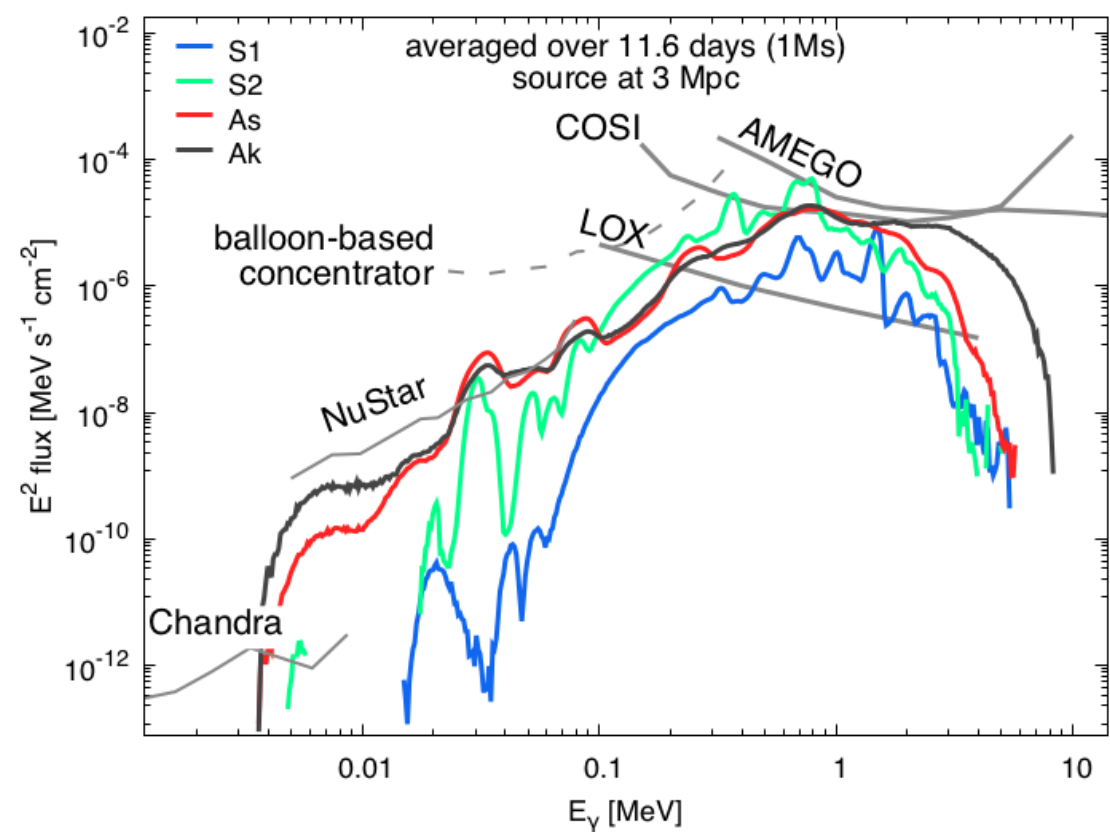


Zhu, Lund, Barnes, Sprouse, Vassh, McLaughlin, Mumpower, Surman 2021

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

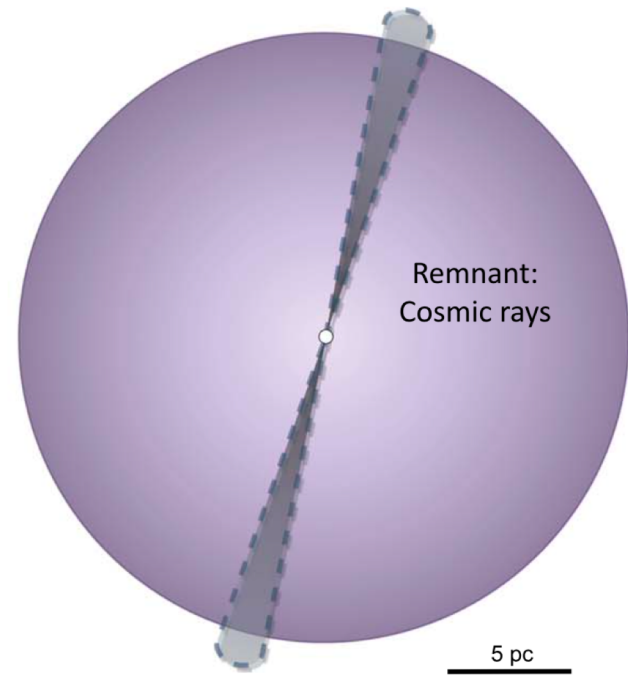
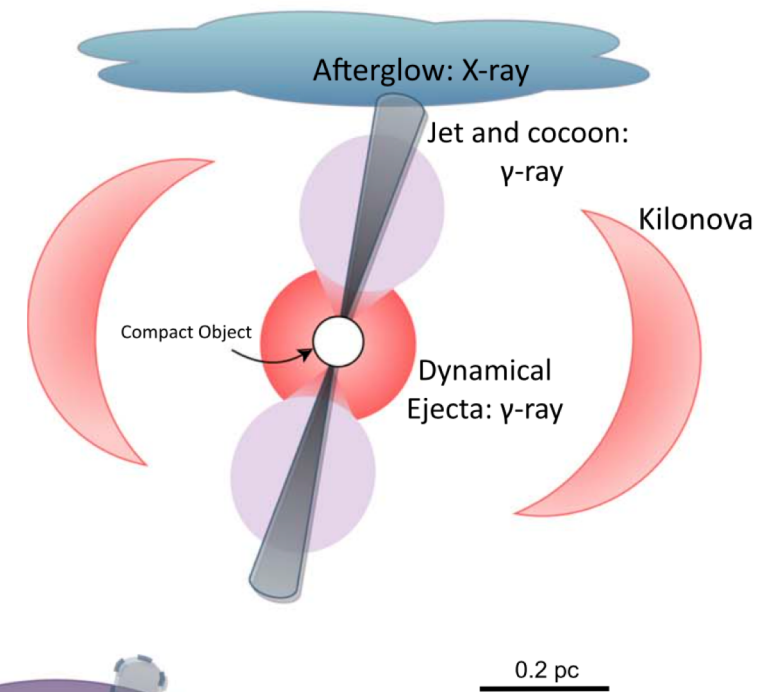


# Gamma rays from a nearby event



Korobkin, Hungerford, Fryer, Mumpower, Misch, Sprouse, Lippuner, Surman, Couture, Bloser, Shirazi, Evan, Vestrand, Miller 2020

also Hotokezaka+2016; Li 2019; Wu+2019; Ruiz-Lapuente, Korobkin 2020

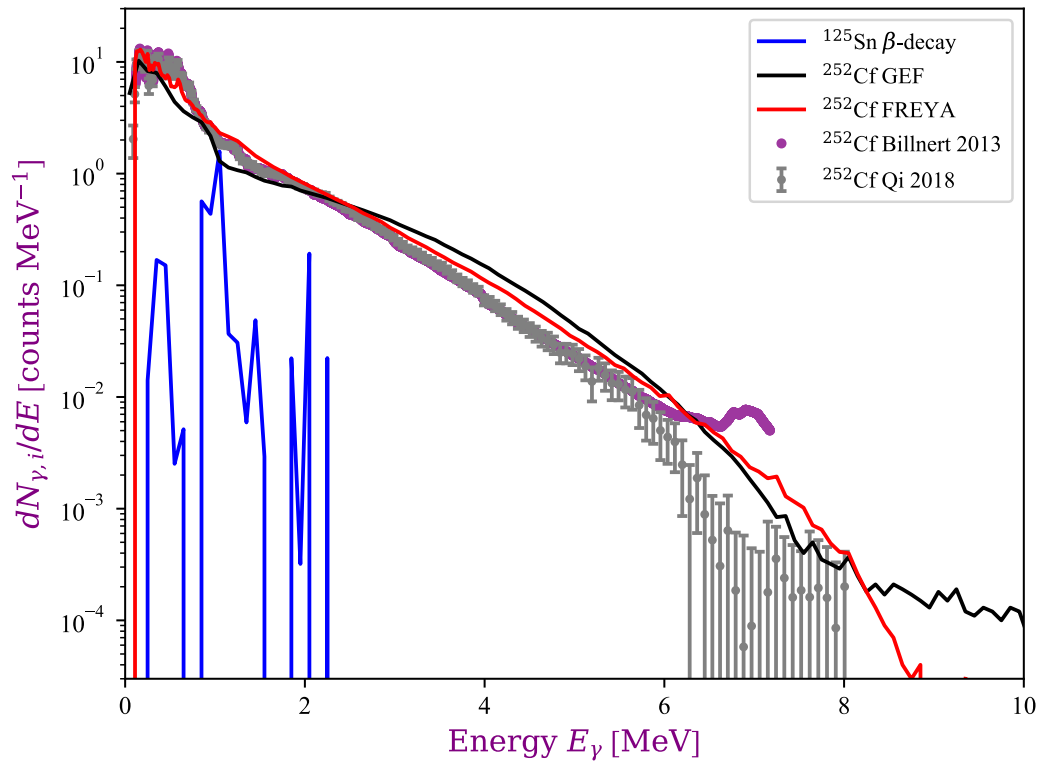


“Could a Kilonova Kill: a Threat Assessment”

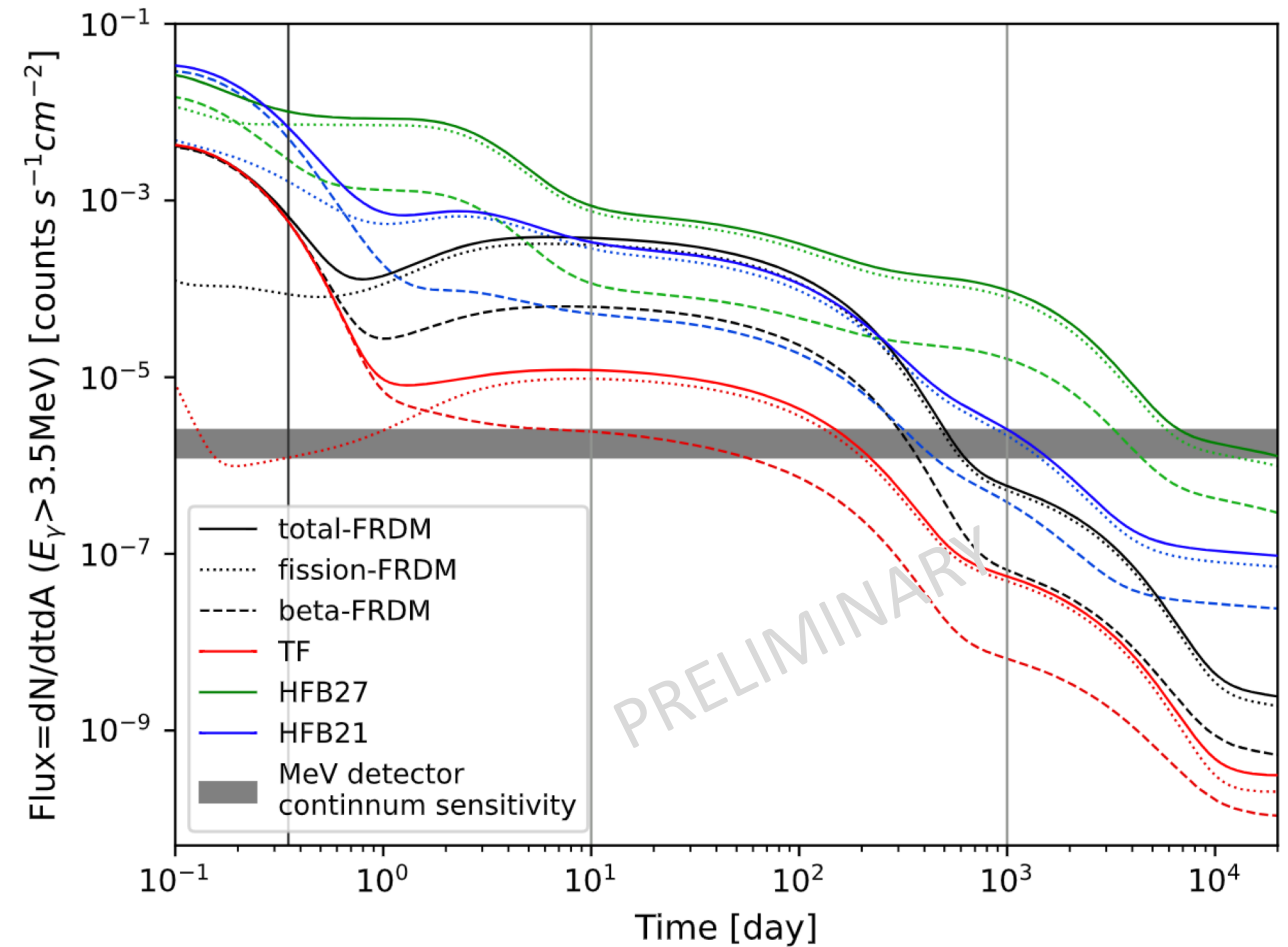
Perkins, Ellis, Fields, Hartmann, Liu, McLaughlin, Surman, Wang 2024



# Gamma rays from fission



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

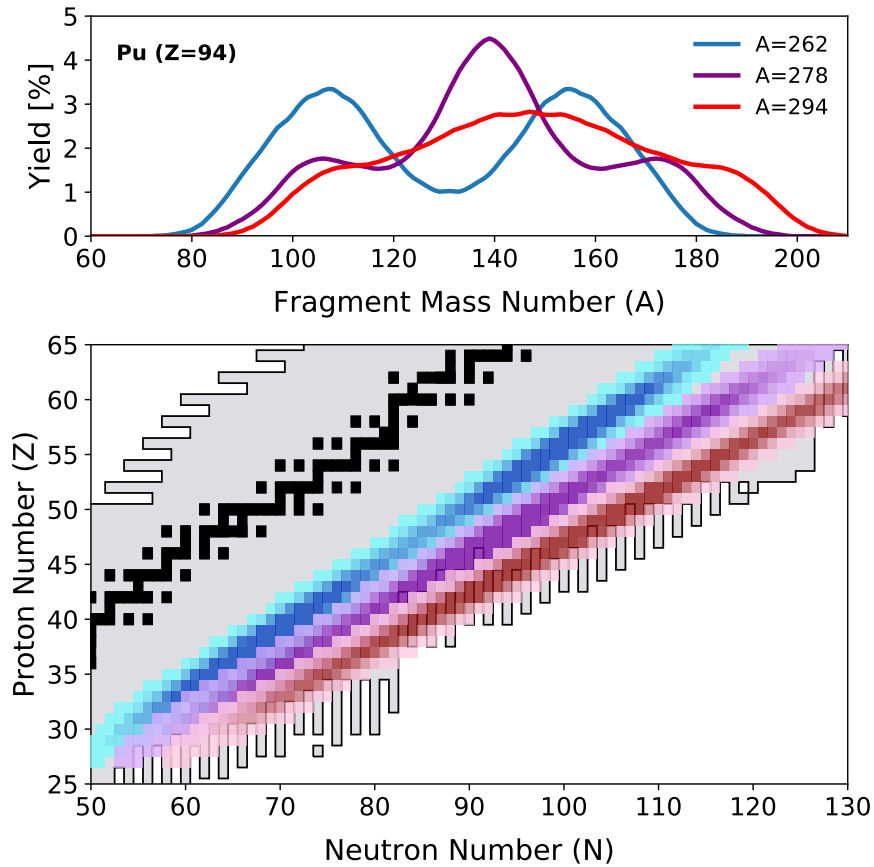


Wang, Vassh+ in preparation 2024

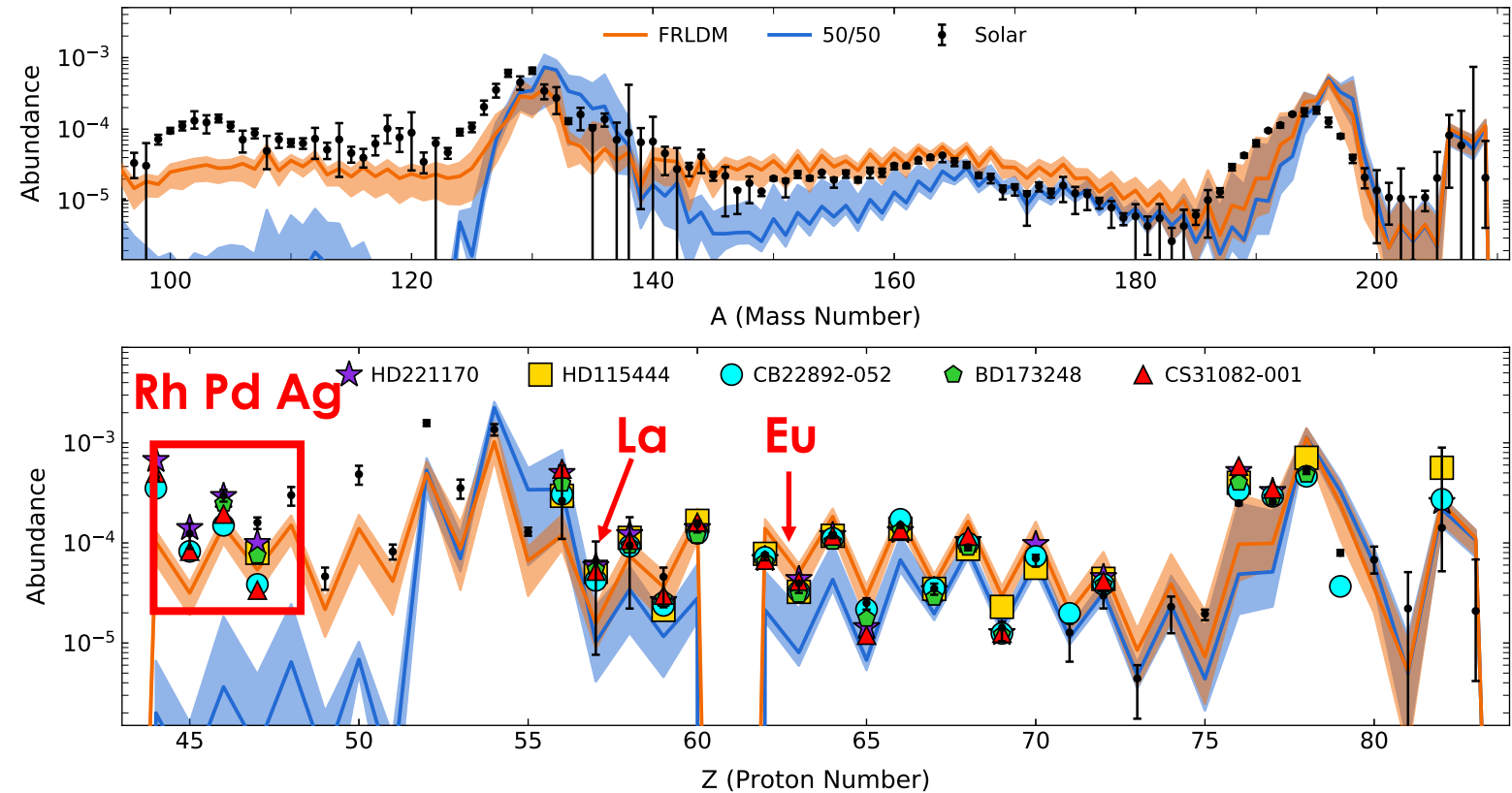
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- What can we learn about the fission properties of neutron-rich actinides from  $r$ -process observables?

# Fission yield signatures

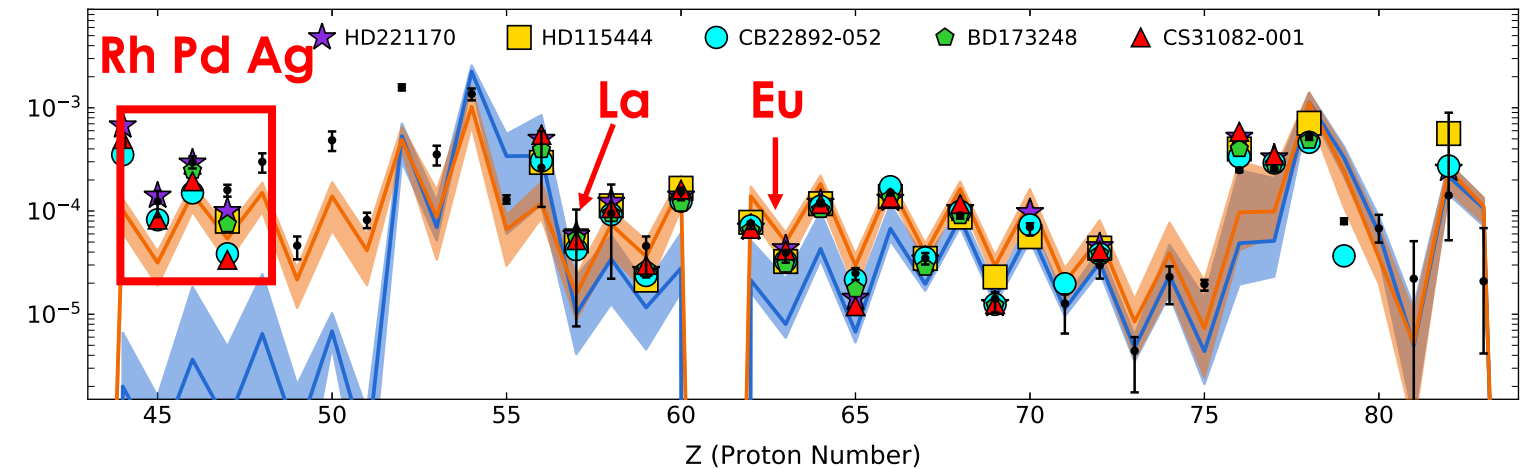
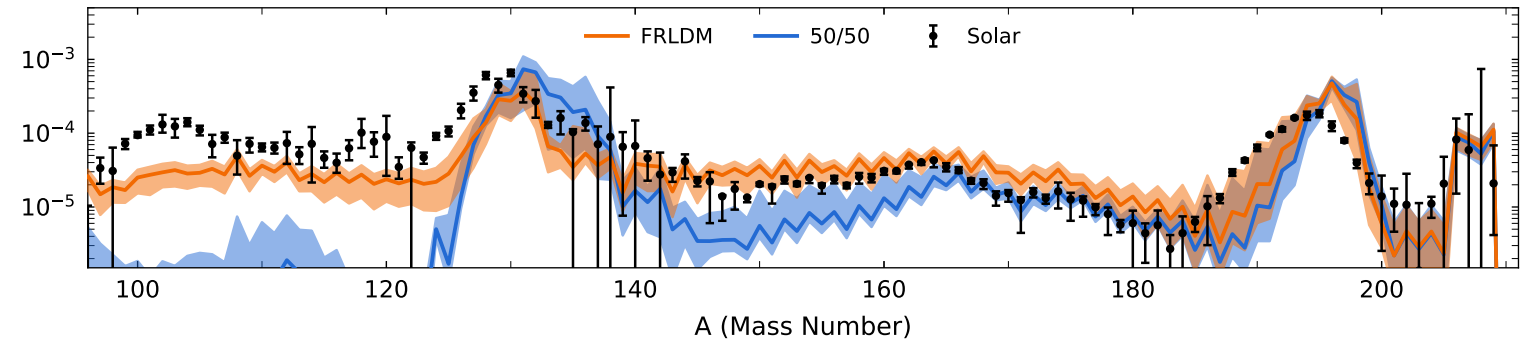
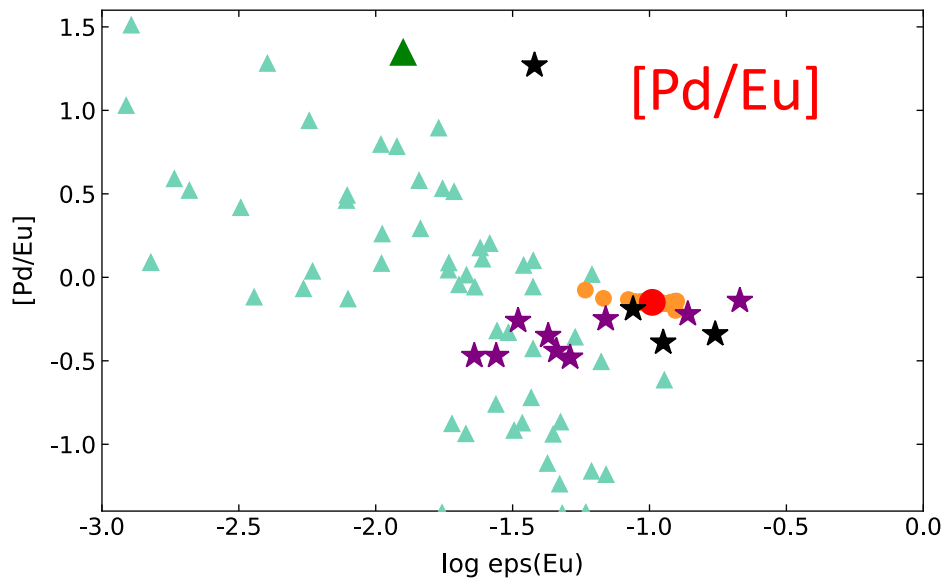
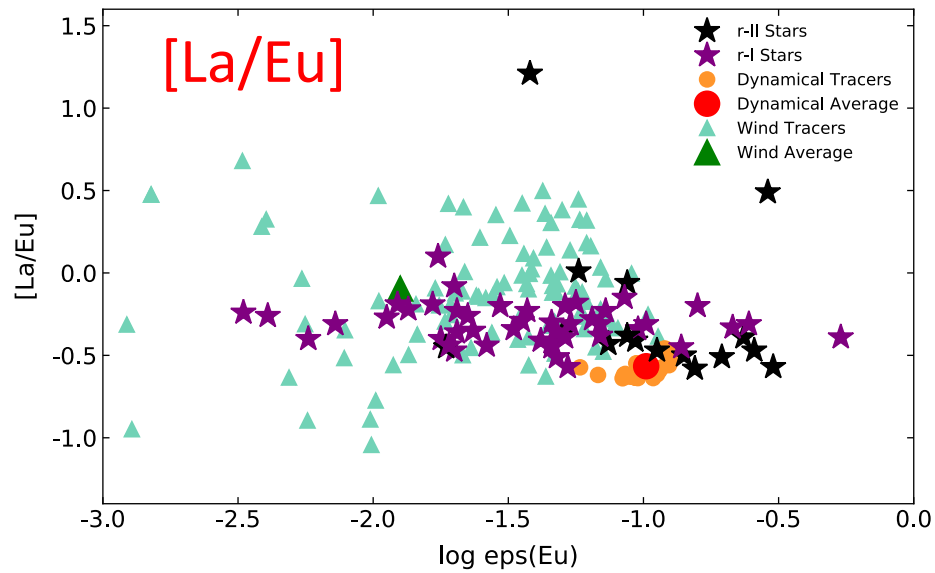


Vassh, Mumpower, McLaughlin,  
Sprouse, Surman 2020



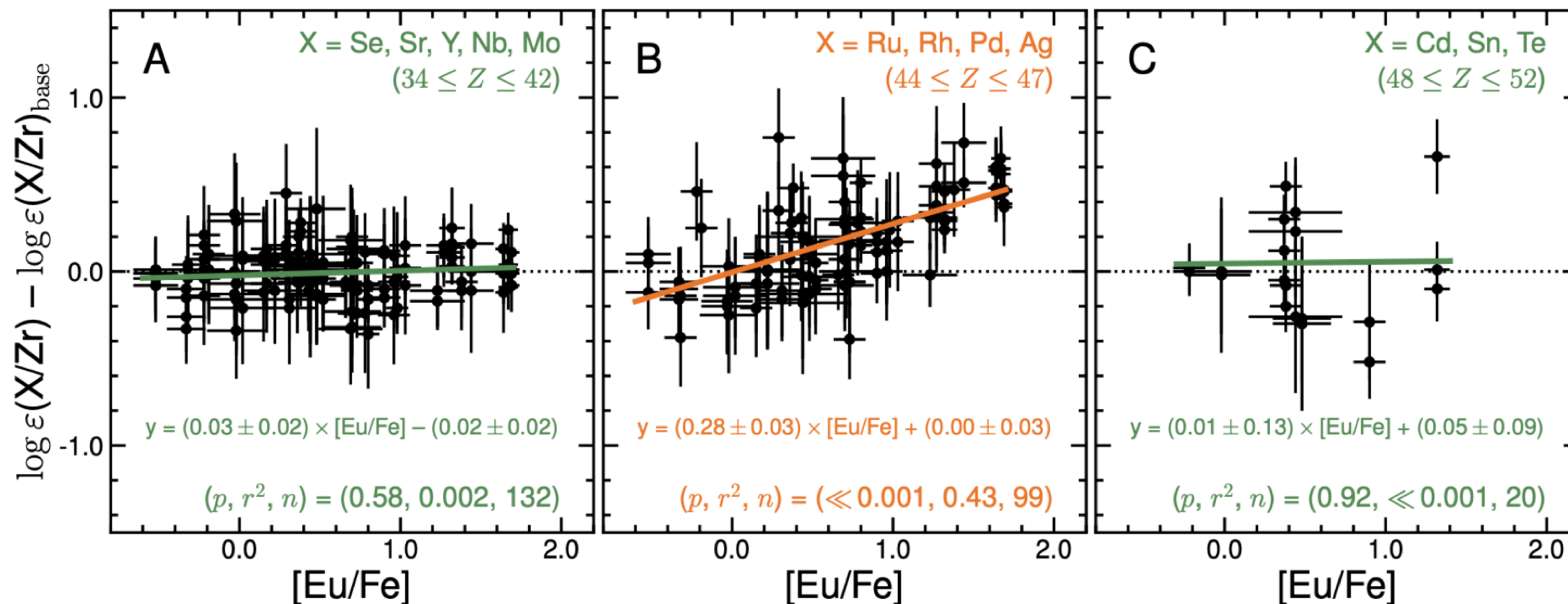
# Fission yield signatures

Vassh, Mumpower, McLaughlin,  
Sprouse, Surman 2020





# Fission yield signatures



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

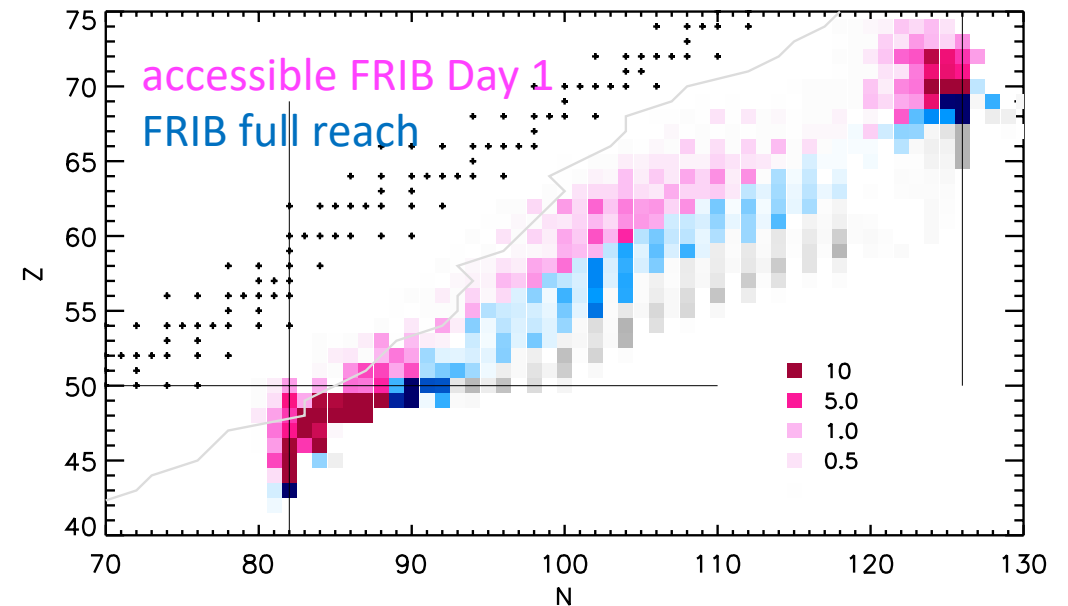
# summary

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.

**An understanding of fission is crucial** for the interpretation of  $r$ -process observables such as abundance patterns and light curves.

Additionally, as other nuclear physics uncertainties are reduced, details of fission properties of neutron-rich actinides may be extractable from  $r$ -process data.



Mumpower, Surman, McLaughlin,  
Arahamian, JPPNP 2016

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