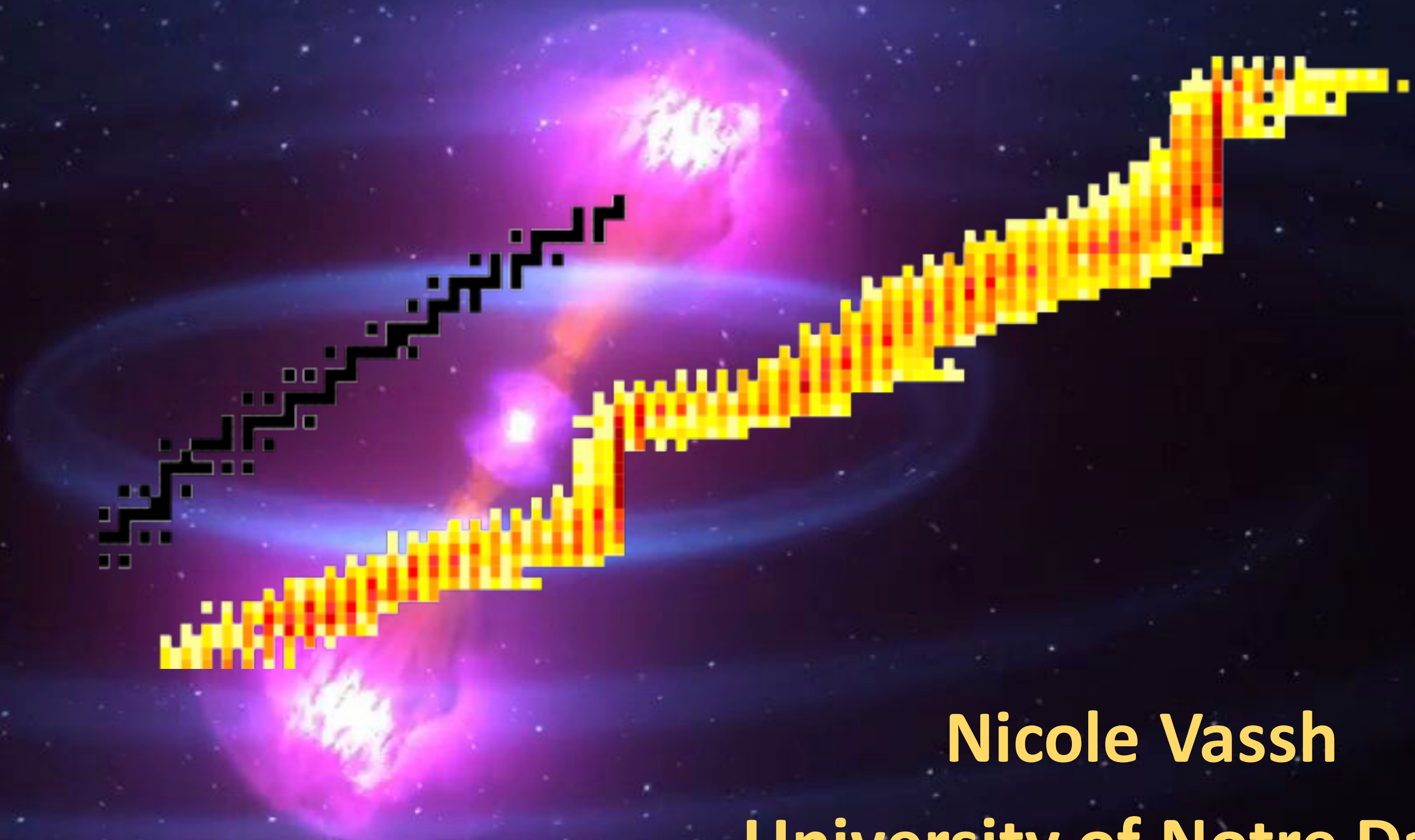
# Fission and lanthanide production in *r*-process nucleosynthesis



**Nicole Vassh**

**University of Notre Dame**

FRIB and the GW170817 Kilonova, MSU
7/18/18

Fission In R-process Elements

FIRE

**Fission In R-process Elements**

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

BROOKHAVEN NATIONAL LABORATORY

McCutchan and Sonzogni

Lawrence Livermore National Laboratory

Vogt and Schunck

NORTH CAROLINA STATE UNIVERSITY FOUNDED MARCH 7, 1887

McLaughlin and Zhu

UNIVERSITY OF NOTRE DAME

Vassh and Surman

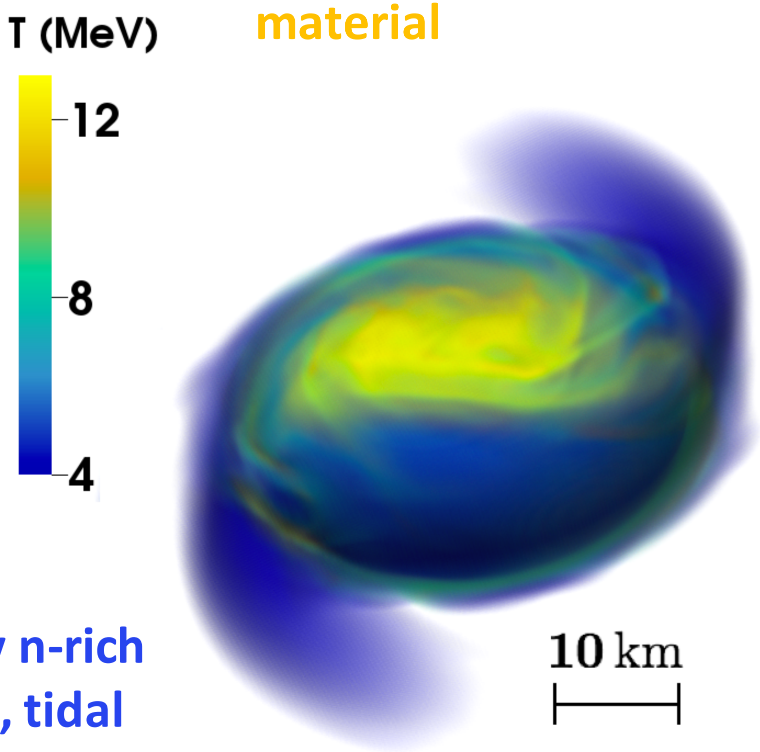
Los Alamos NATIONAL LABORATORY EST. 1943

Mumpower, Jaffke, Verriere, Kawano, Talou, and Hayes-Sterbenz

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

# *r*-process sites within a Neutron Star Merger

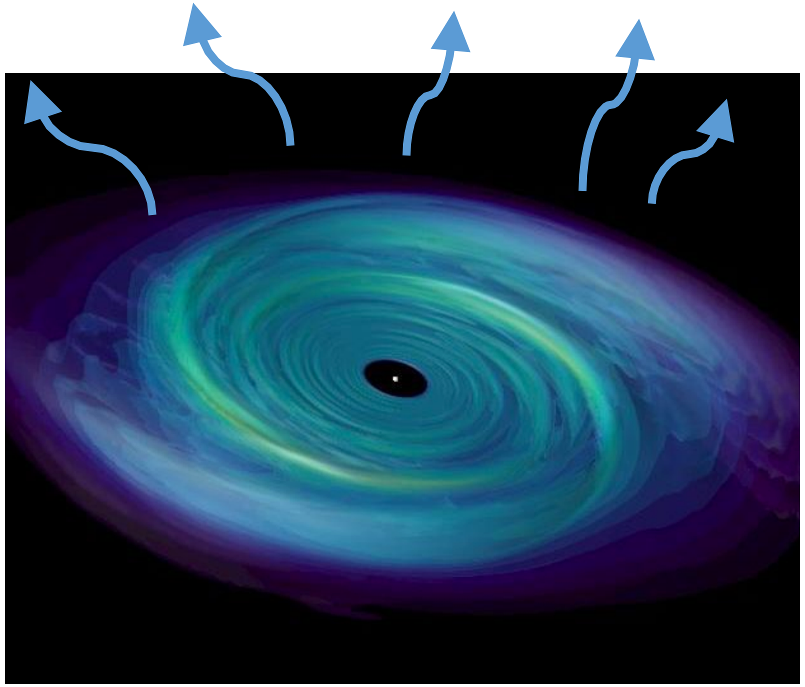
Hot, shocked material




Very n-rich cold, tidal outflows

Foucart et al (2016)

Accretion disk winds – exact driving mechanism and neutron richness varies

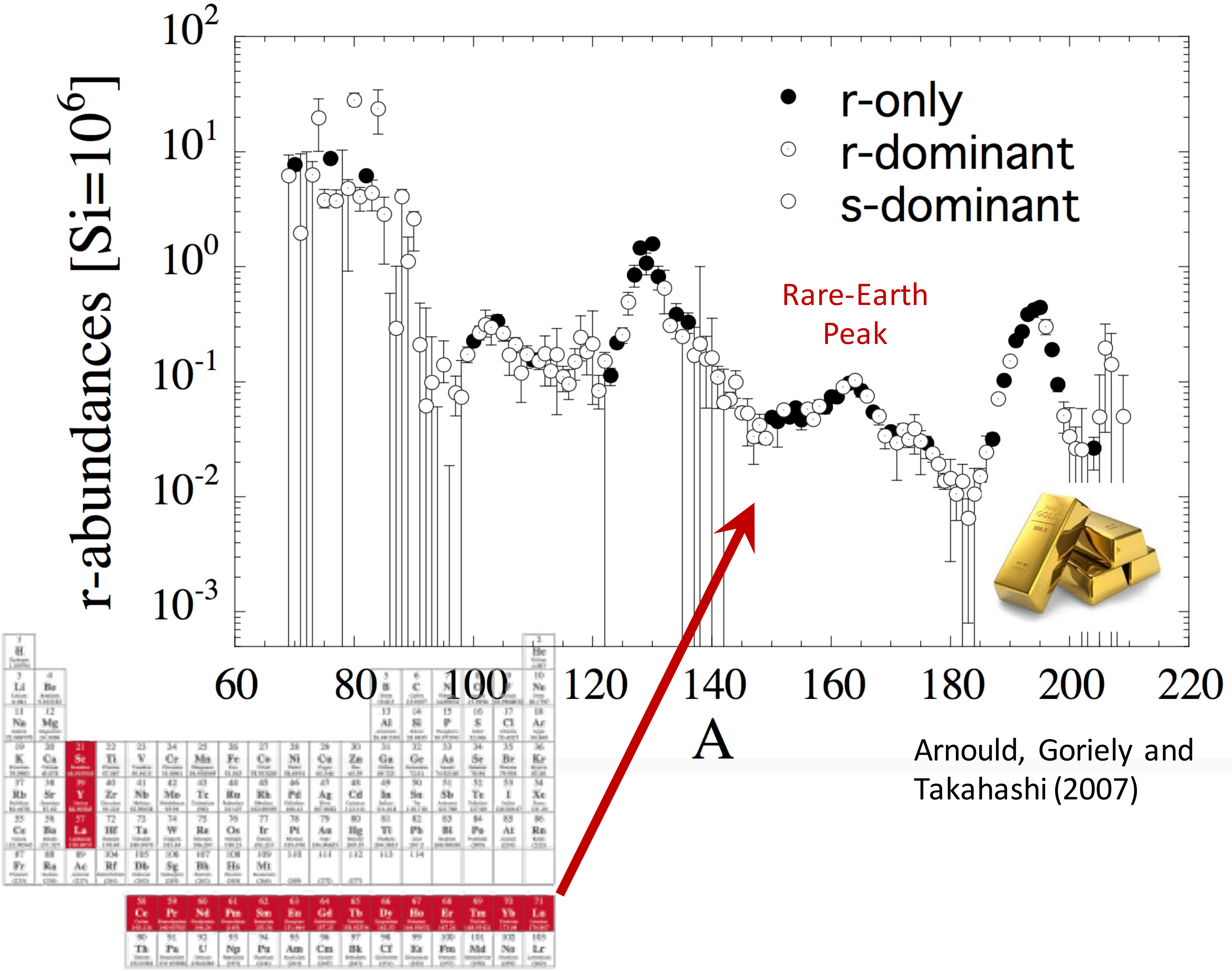


Owen and Blondin

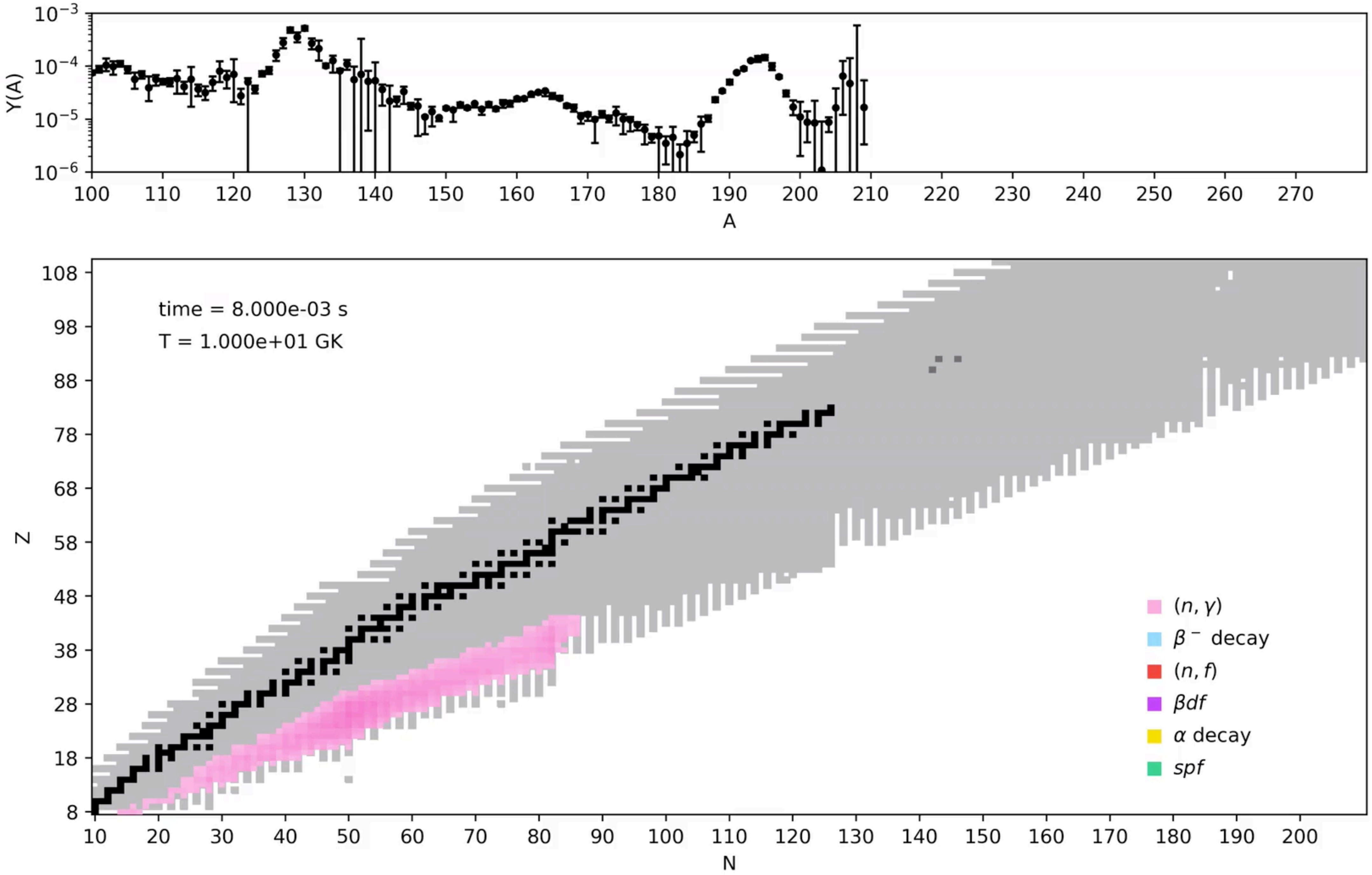
# Observed Solar *r*-process Residuals

Depending on the conditions, the *r*-process can produce:

- Poor metals (Sn,…)
- Lanthanides (Nd, Eu,…)
- Transition metals (Ag, Pt, Au,…)
- Actinides (U,Th,…)



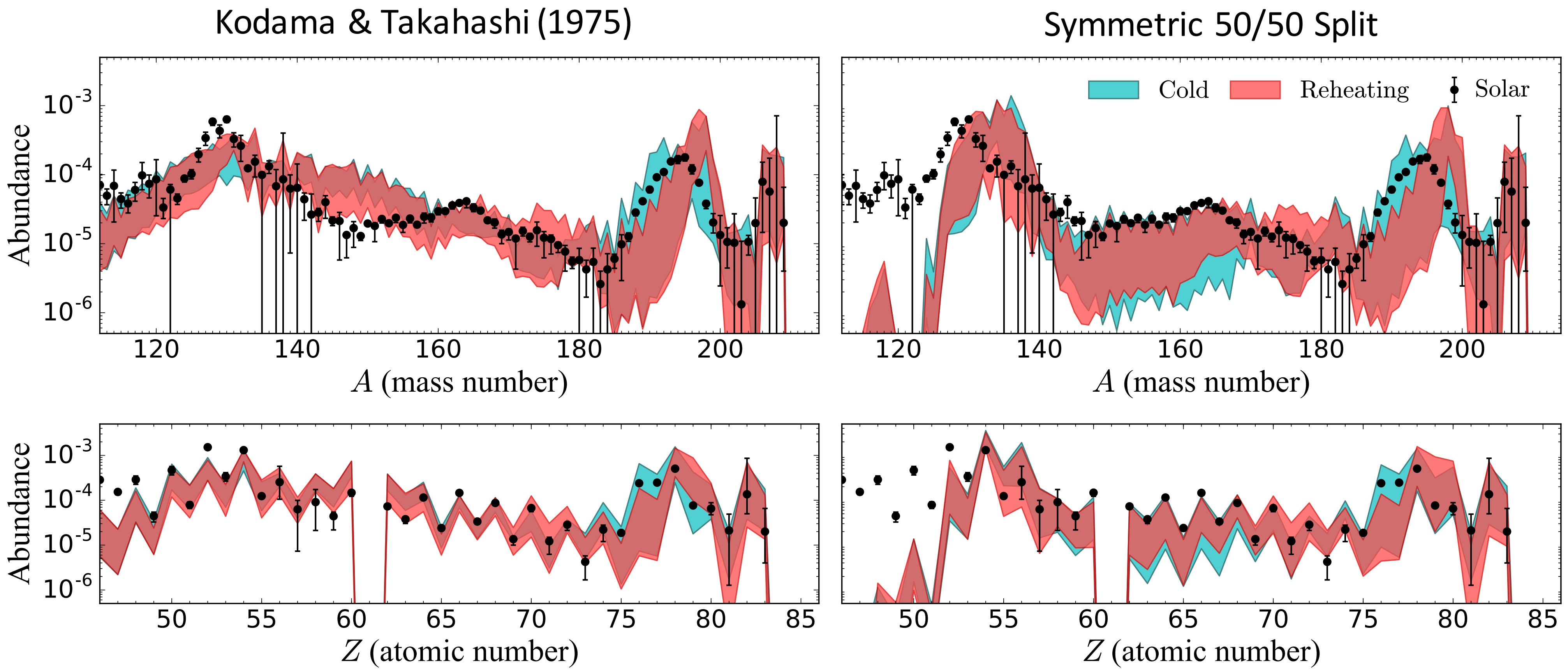

Arnould, Goriely and Takahashi (2007)



Y(A)
A
time = 8.000e-03 s
T = 1.000e+01 GK
Z
N
(n, γ)
β⁻ decay
(n, f)
βdf
α decay
spf

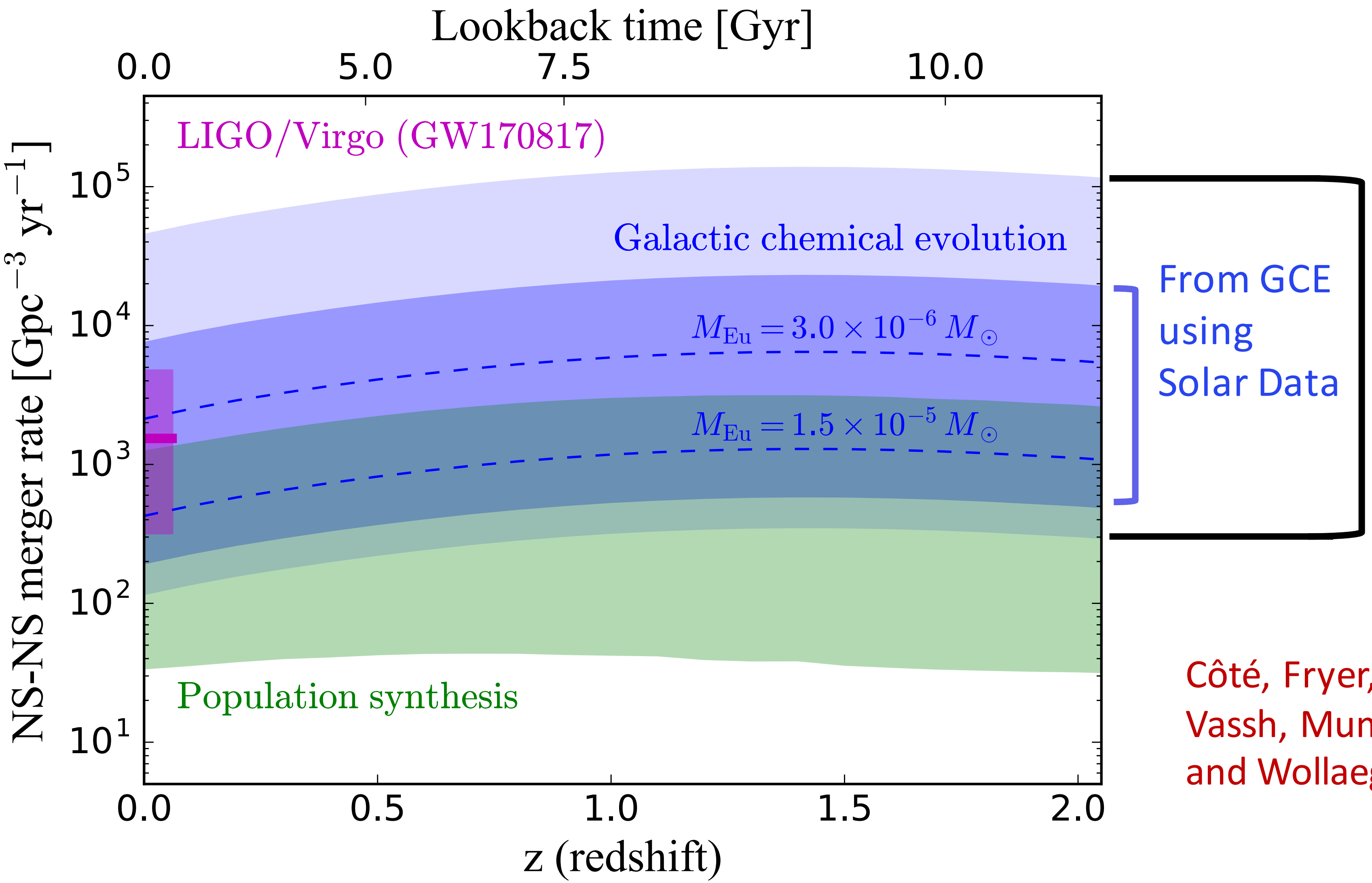
# *r*-process Sensitivity to Mass Model and Fission Yields

- 10 mass models: DZ33, FRDM95, FRDM12, WS3, KTUY, HFB17, HFB21, HFB24, SLY4, UNEDF0
- N-rich dynamical ejecta conditions: **Cold** (Just 2015), **Reheating** (Mendoza-Temis 2015)




Côté et al (2018)

# GW170817 and *r*-process uncertainties from nuclear physics




When nuclear physics uncertainties are considered

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

(ApJ 855, 2, 2018)

# GW170817 and NSM production of *r*-process nuclei

Much like supernova light curves are powered by the decay chain of $^{56}Ni$, kilonovae are also powered by radioactive decays

The kilonova observed following GW170817 suggested the production *r*-process material (lanthanides)

There was no clear signature of the presence of the heaviest, fissioning nuclei (actinides)

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PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

**Californium-254 and Supernovae***

G. R. BURBIDGE AND F. HOYLE,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

AND

E. M. BURBIDGE, R. F. CHRISTY, AND W. A. FOWLER, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

It is suggested that the spontaneous fission of $Cf^{254}$ with a half-life of 55 days is responsible for the form of the decay light-curves of supernovae of Type I which have an exponential form with a half-life of 55 nights. The way in which $Cf^{254}$ may be synthesized in a supernova outburst, and reasons why the energy released by its decay may dominate all others are discussed. The presence of Tc in red giant stars and of Cf in Type I supernovae appears to be observational evidence that neutron capture processes on both a slow and a fast time-scale have been necessary to synthesize the heavy elements in their observed cosmic abundances.

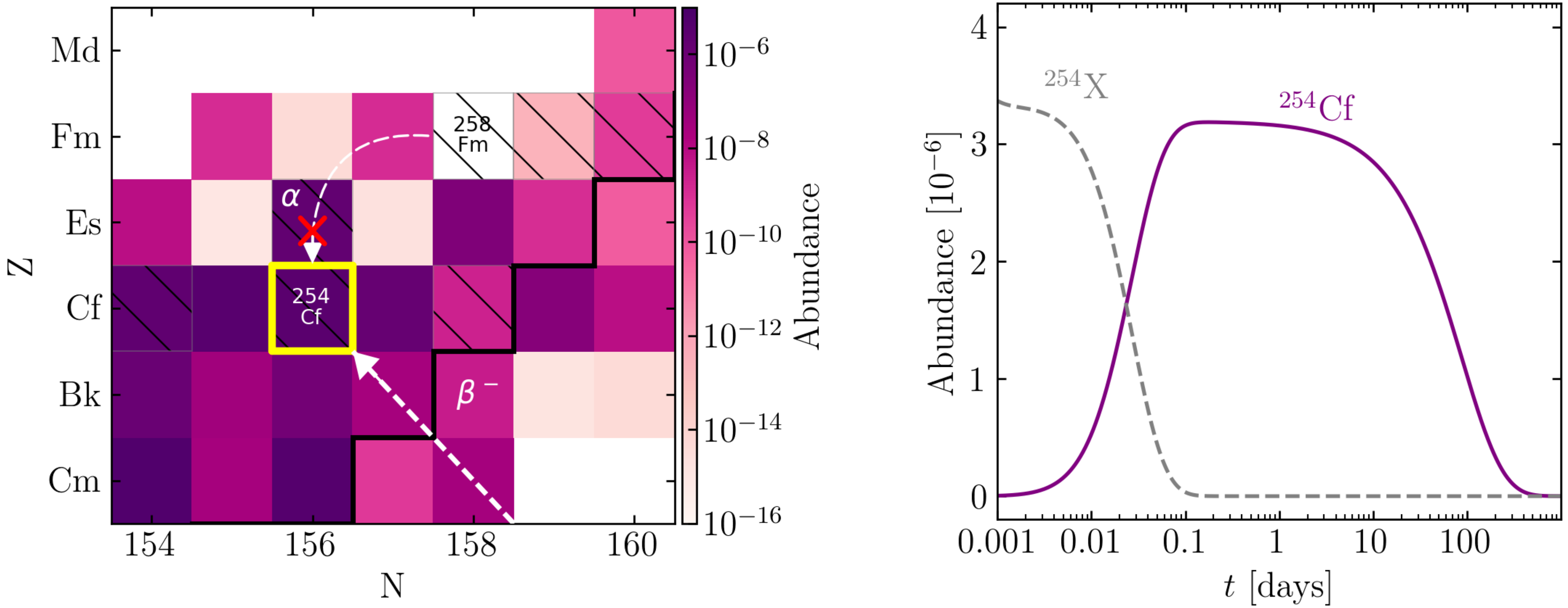
**OBSERVATIONAL DATA**

A CHARACTERISTIC feature of supernovae of Type I is that after an initial period of 50–100 days the light curve develops an exponential tail corresponding to about 0.0137 magnitudes daily, or a half-life of 55±1 days. Baade has analyzed the records of the supernovae *B* Cassiopeiae and *SN* Ophiuchi,[1] and has shown that their exponential decline is very closely similar to his own observations of the supernova in *IC*

sufficient energy to explain the curve. He suggested that it was built by the endothermic reaction $He^4(\alpha,n)Be^7$, occurring at high temperatures. However, recent work[5–7] suggests that this is most unlikely, since $He^4$ would be destroyed by the exothermic Salpeter reaction in which $C^{12}$ is produced. An alternative method of production is through spallation reactions of protons (with $E_p \gtrsim 100$ Mev) on C, N, and O, which are known to give large yields of Li, Be, and B.

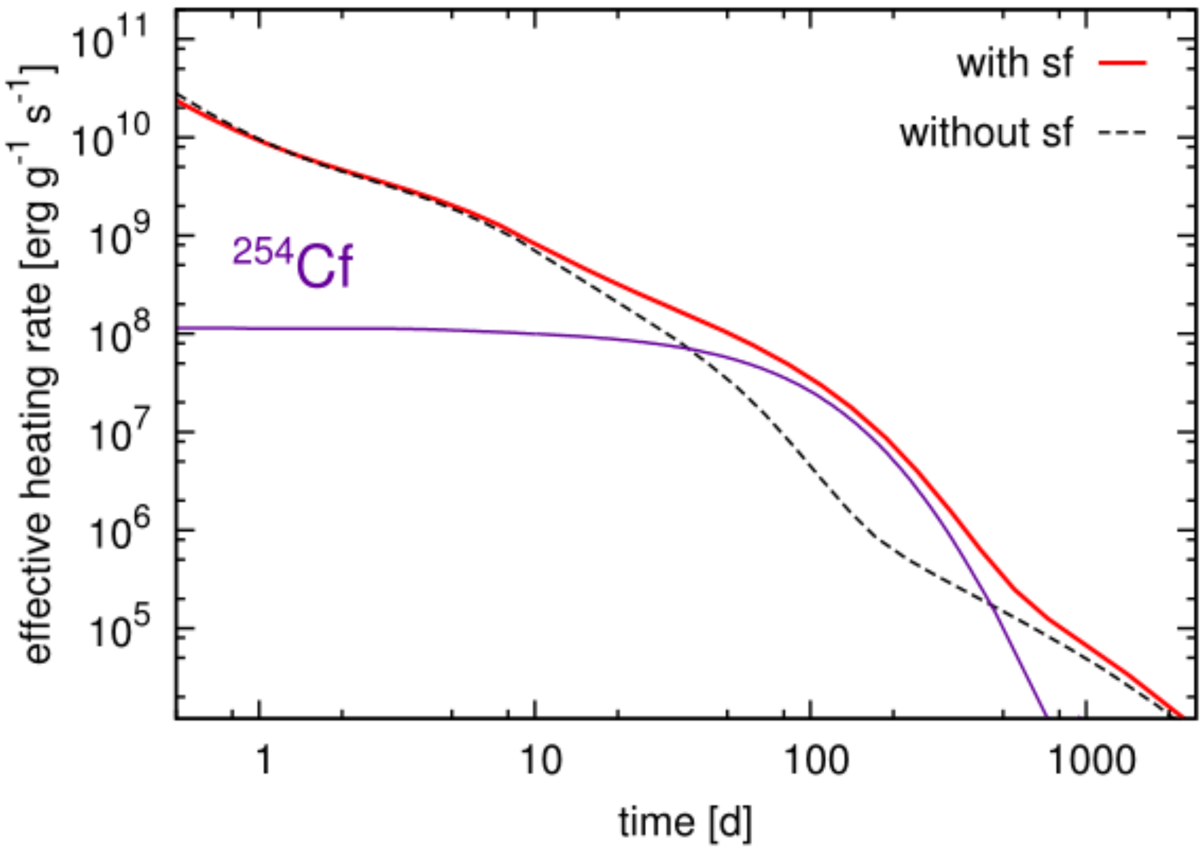
(See also: Baade *et al.* 1956; Huizenga *et al.* 1957; Anders *et al.* 1958…)

# $^{254}$Cf feeding in NSM environments




Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Kawano, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes (accepted to ApJL, **arXiv:1806.09724**)

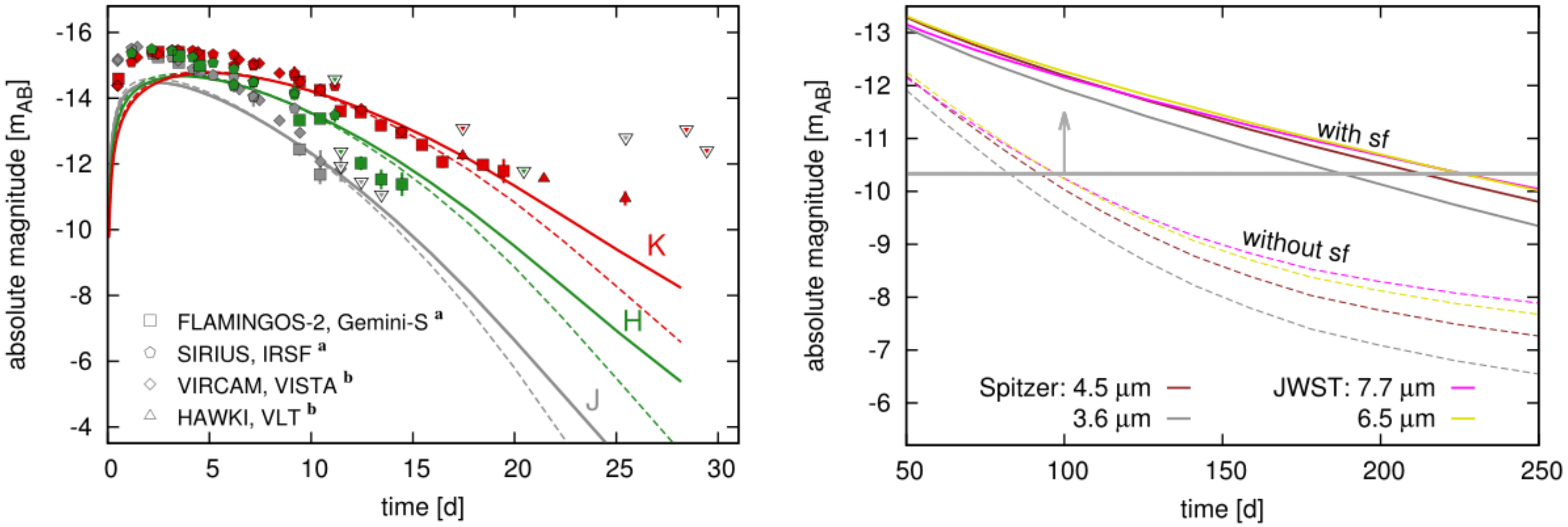
# $^{254}$Cf and effective heating




The spontaneous fission of $^{254}$Cf is a primary contributor to nuclear heating at late epochs
(See also: Wanajo *et al.* 2014)

Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Kawano, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes (accepted to ApJL, **arXiv:1806.09724**)

# Observational impact

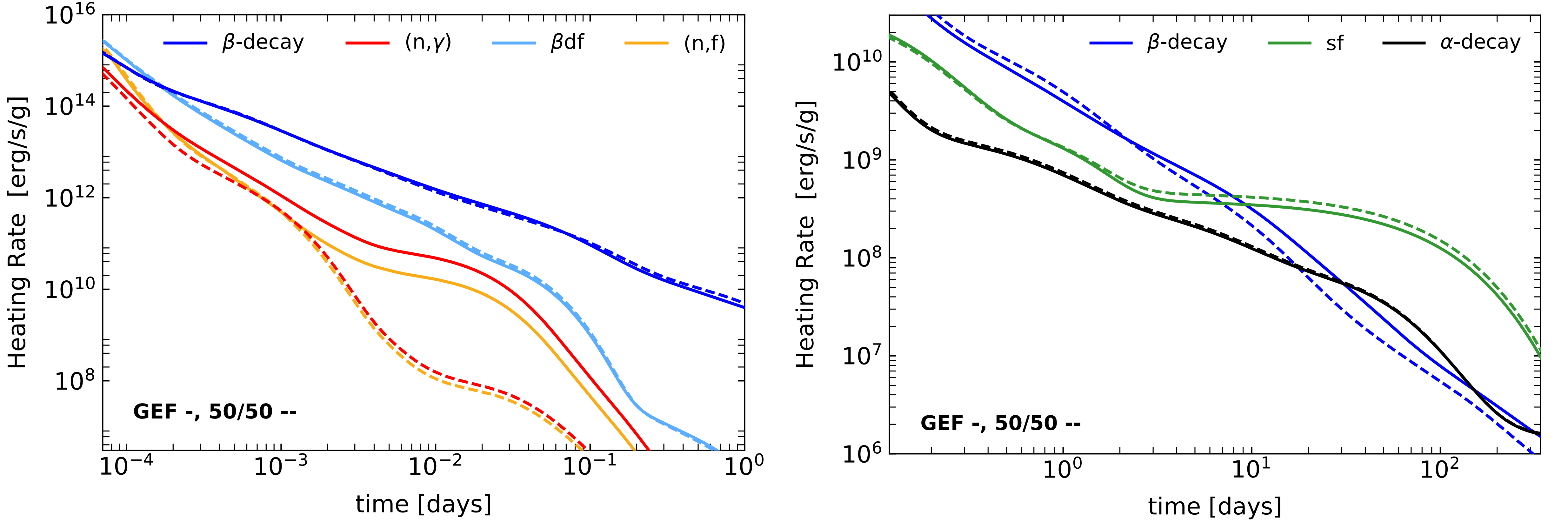



Both near- and middle- IR are impacted by the fission of $^{254}Cf$

JWST may be able to detect future kilonovae out to 250 days if actinides are produced in the event

Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Kawano, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes, submitted 2018 (**arXiv:1806.09724**)

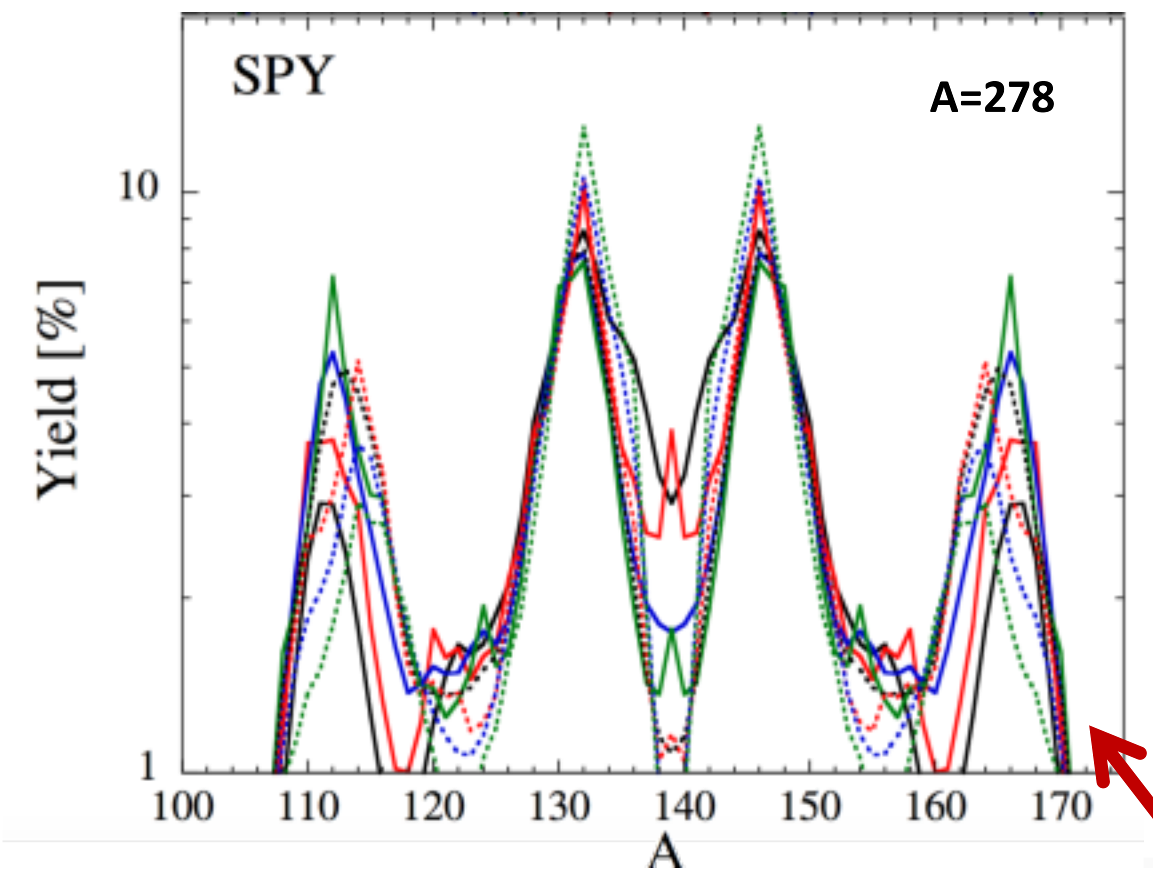
# Dependence of Nuclear Heating on Fission Yields



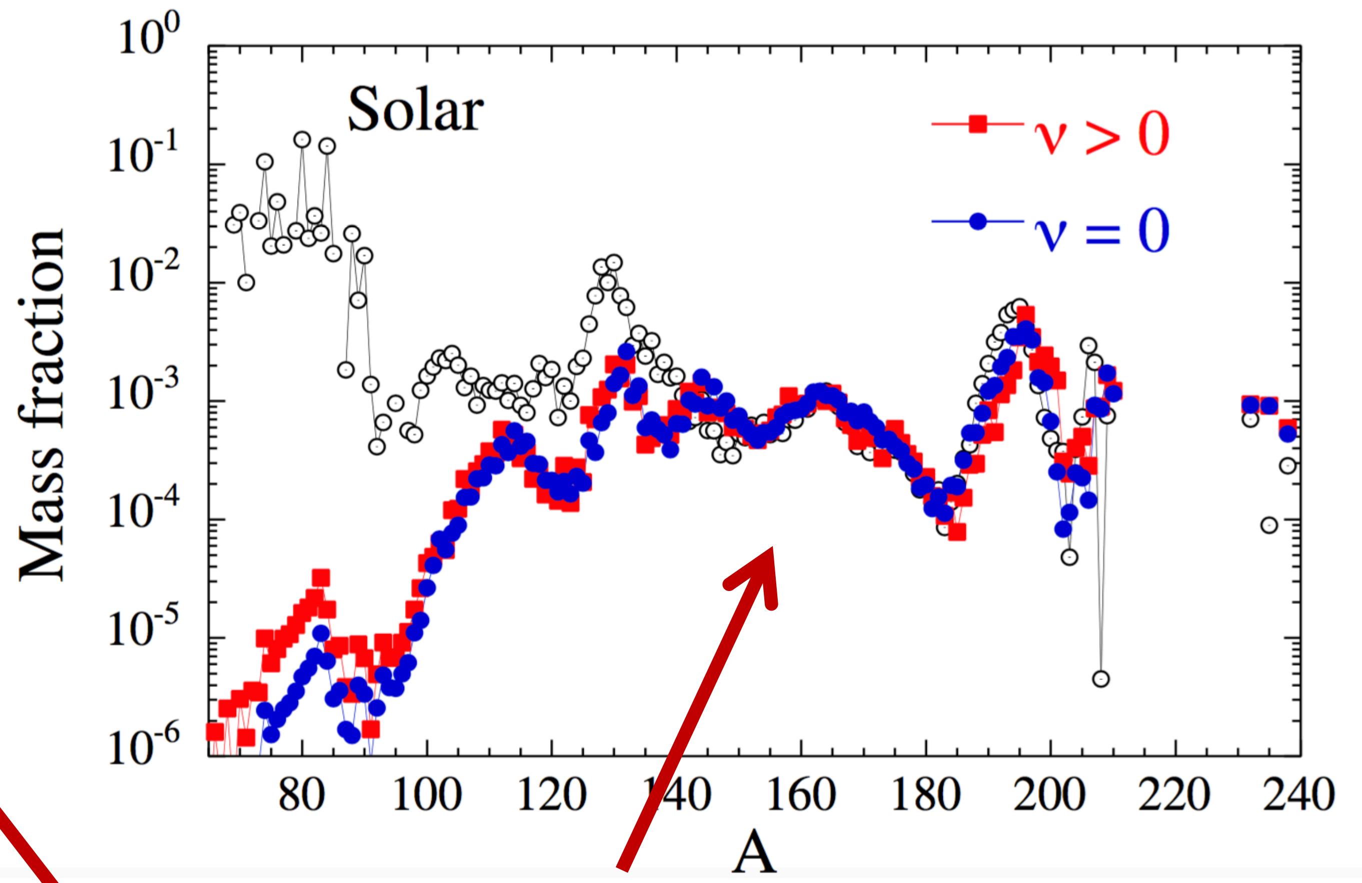

**Cold, very neutron-rich tidal tail ejecta conditions from a neutron star merger simulation**

Vassh et al (in preparation)

# Fission and the Rare-Earth Peak



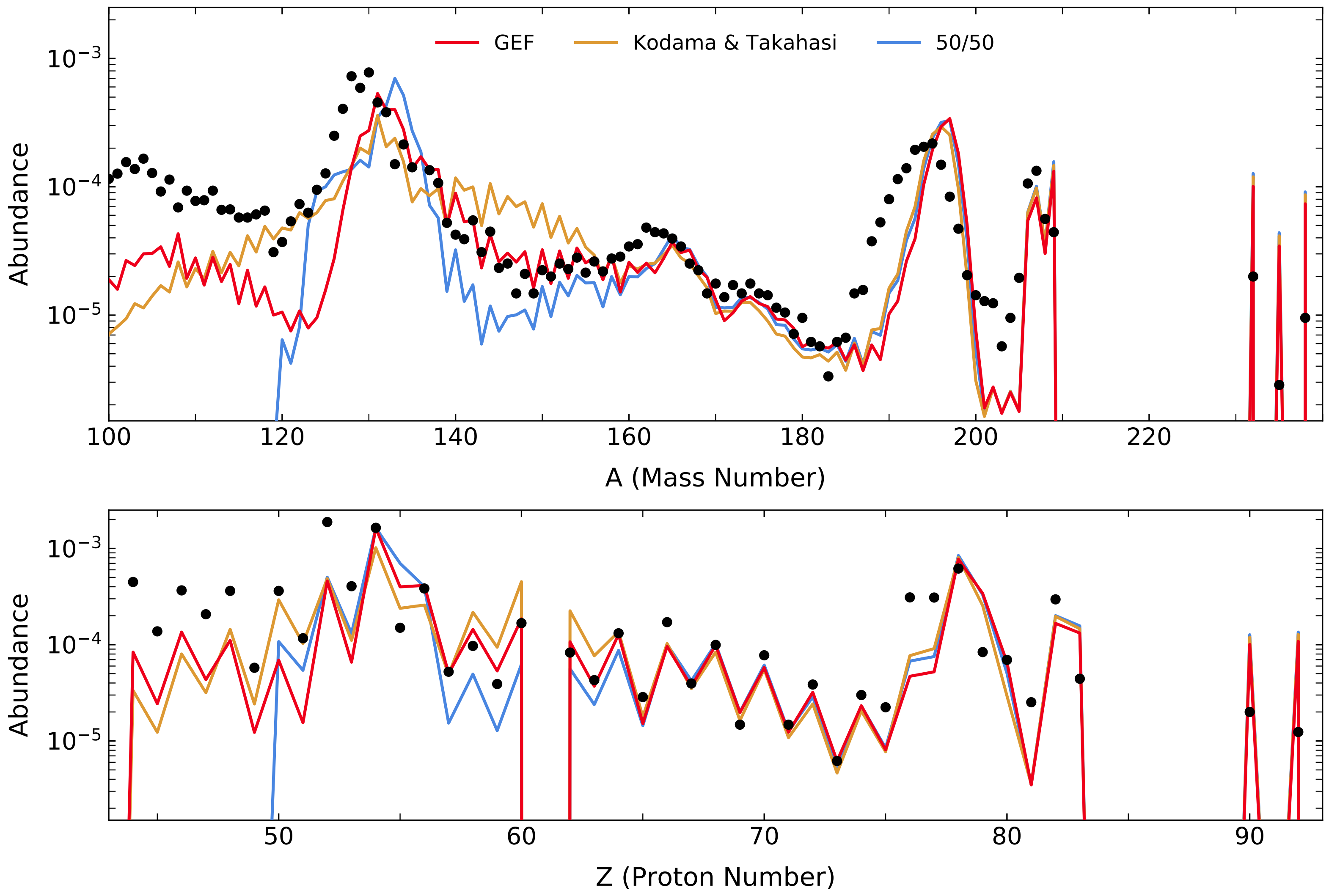

Z=95, Z=96 , Z=97, Z=98, Z=99, Z=100, Z=101, Z=102 (dotted lines – larger Z)




**Rare-earth peak can be populated by fission daughter products of n-rich nuclei**

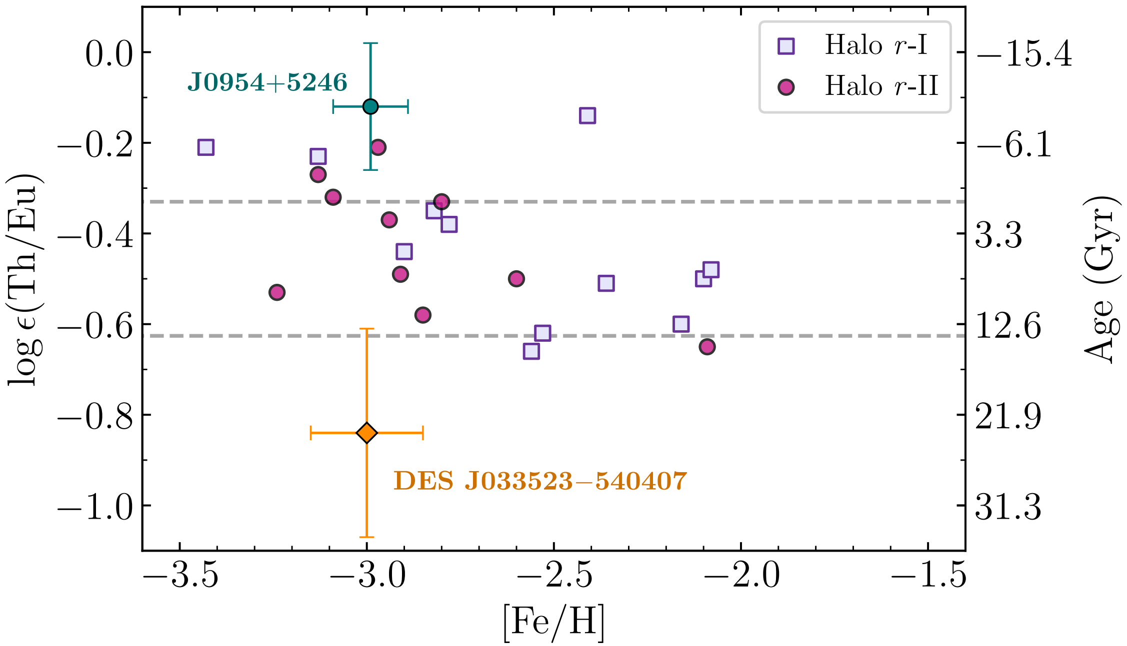
Goriely (2015)

# Dependence of Lanthanide Abundances on Fission Yields



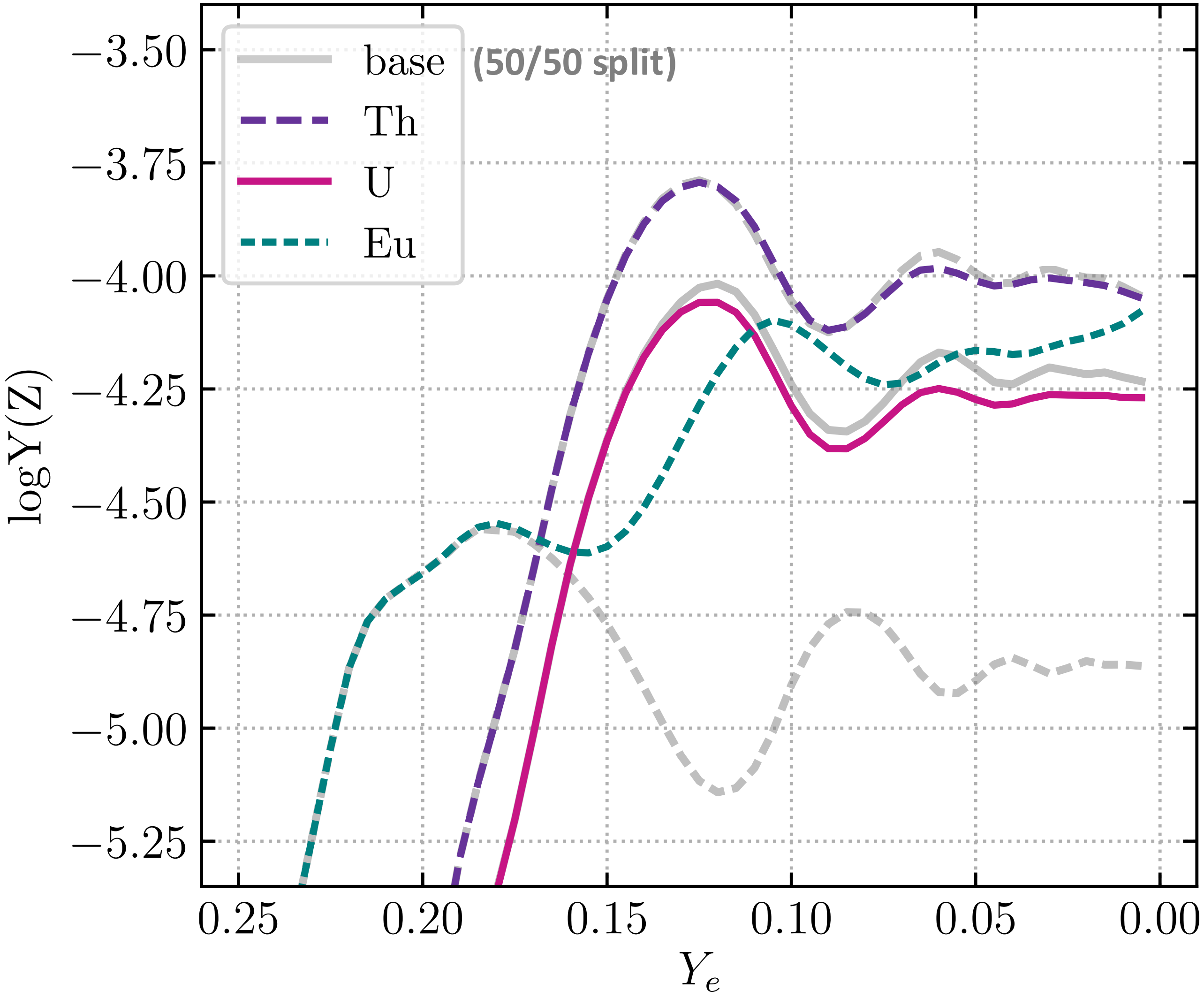

Vassh et al (in preparation)

# Fission Yields and Lanthanide/Actinide Production Ratios




**Thorium/Europium ratio used to estimate ages of old stars, but predictions for Eu vary greatly!**

Holmbeck et al (including Beers and Frebel) (ApJL 859, L24)




Holmbeck, Surman, Sprouse, Mumpower, Vassh, Beers and Kawano (submitted 2018, **arXiv:1807.06662**)

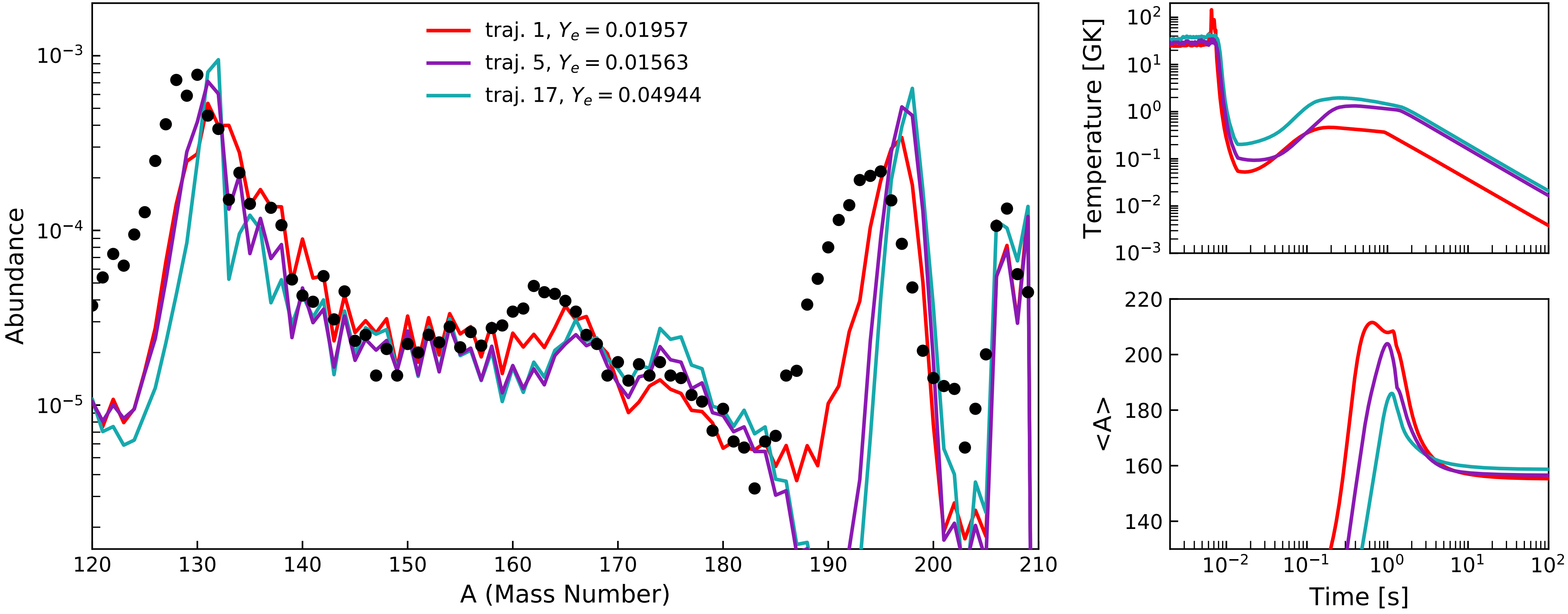
# Dependence on Astrophysical conditions

**Three exemplary dynamical ejecta trajectories from a 1.2/1.4 $M_\odot$ neutron star merger simulation** (Stephan Rosswog):

Traj. 1 – cold with very low $Y_e$ and high fission flow

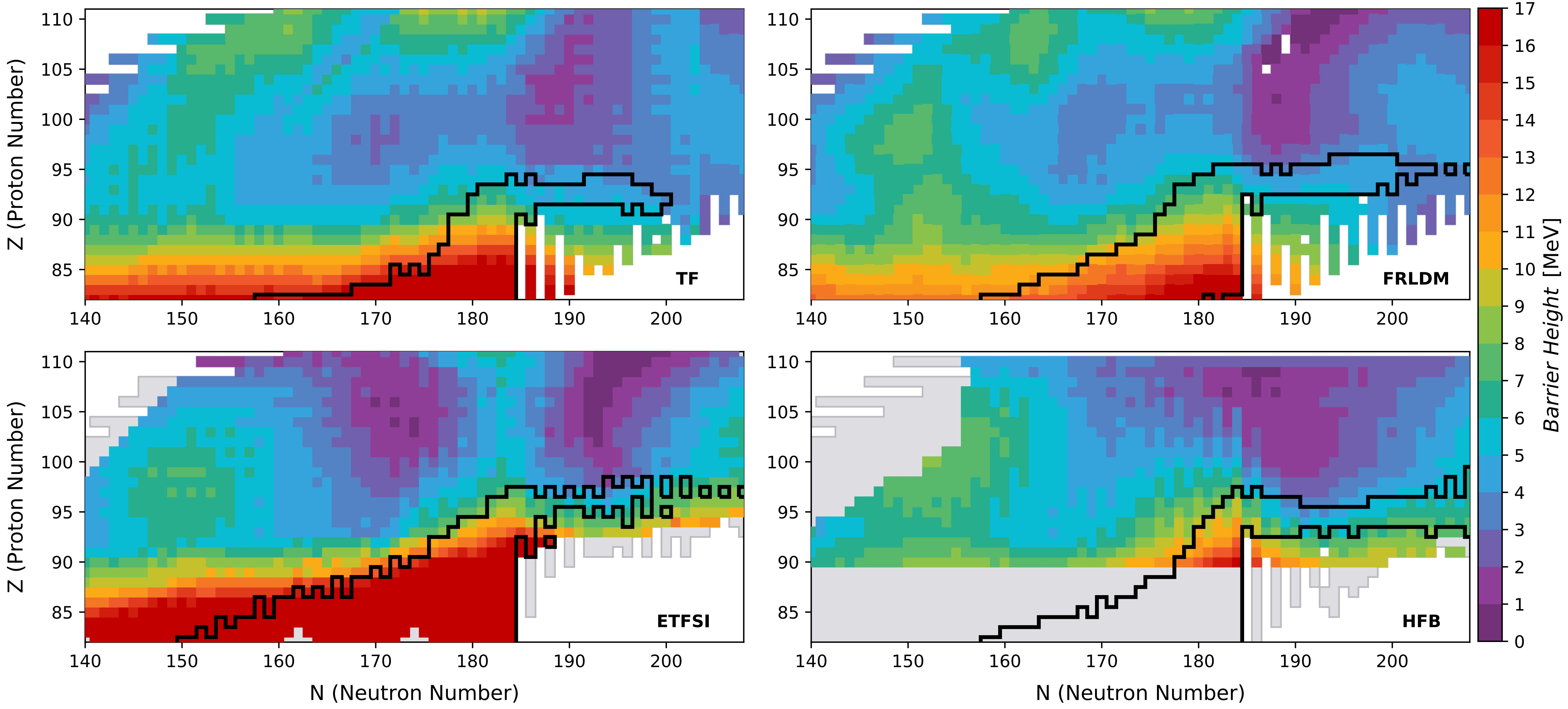
Traj. 5 – hot with very low $Y_e$ and high fission flow

Traj. 17 – hot with low $Y_e$ and low fission flow




Vassh et al (in preparation)

# Fission barriers and the *r*-process path

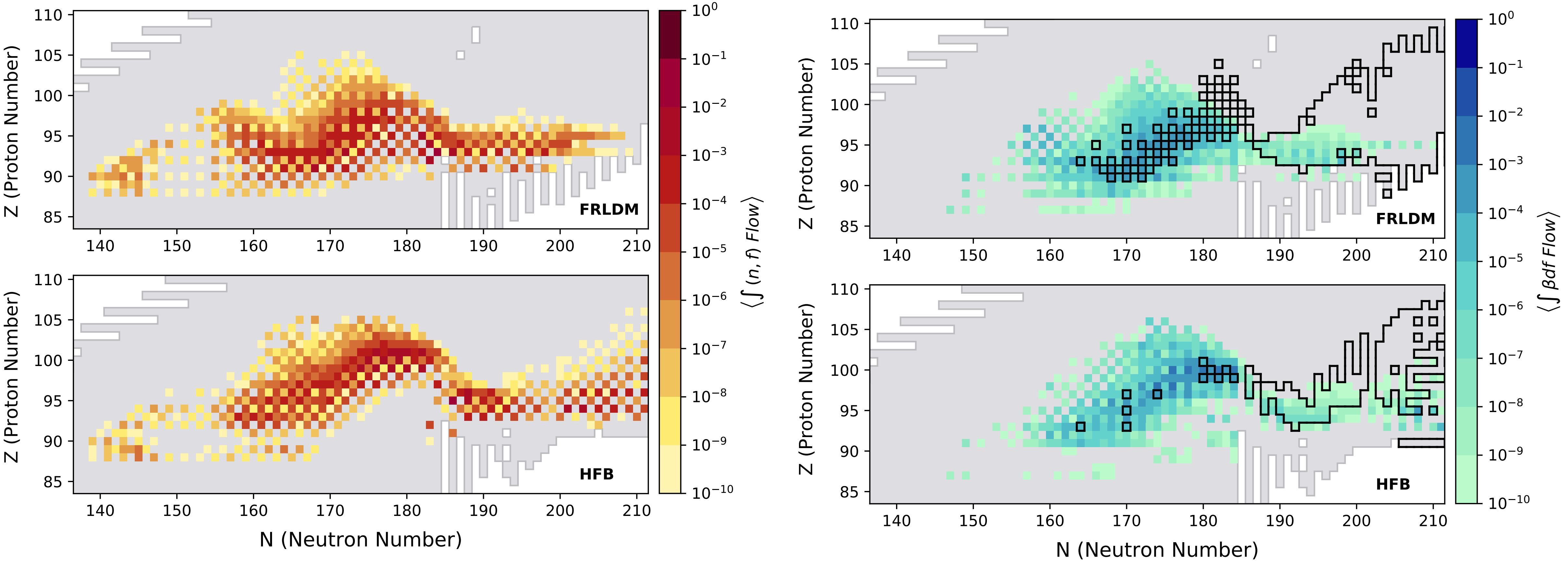



**Cold, very neutron-rich tidal tail ejecta conditions from a neutron star merger simulation**

Vassh et al (in preparation)

# Fission barrier impact on neutron-induced / β-delayed fission

**Average over 30 dynamical ejecta trajectories from a 1.2/1.4 M$_\odot$ neutron star merger simulation**
(Stephan Rosswog)

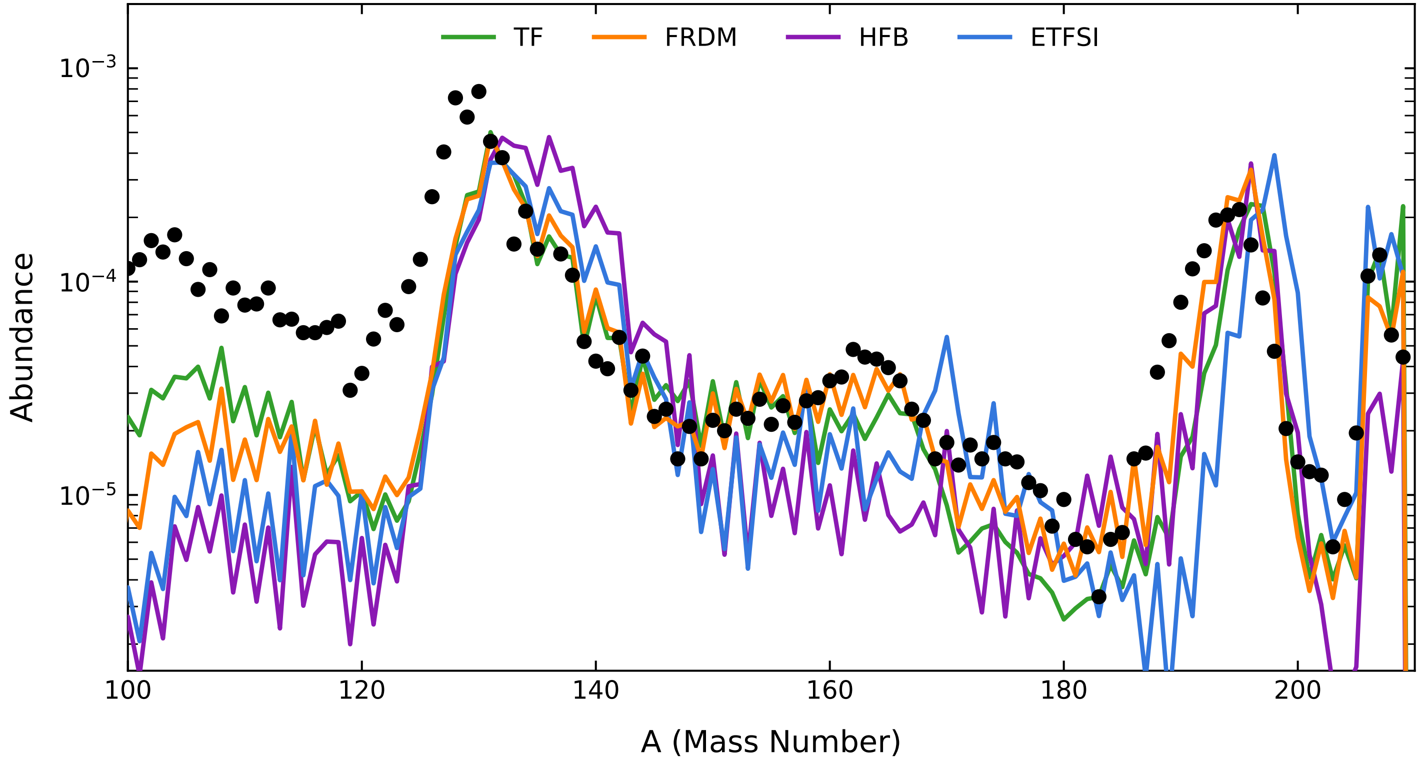


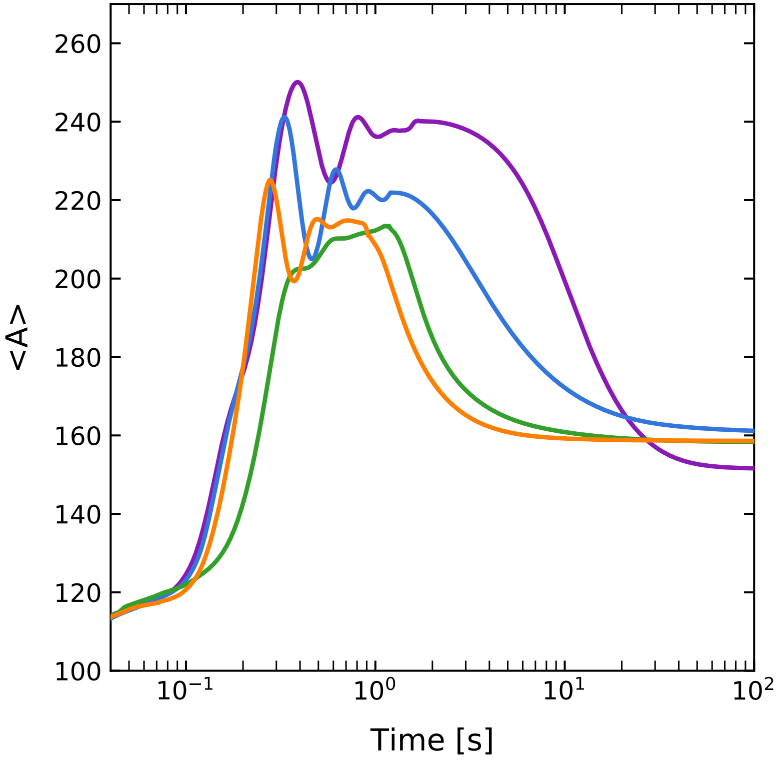

**Flow** = rate x abundance

**Right Panel Black outline** – probability of mc-$\beta$df > 10%

Vassh et al (in preparation)

# Shaping the *r*-process second peak: fission products




**Cold, very neutron-rich tidal tail ejecta conditions from a neutron star merger simulation**

Vassh et al (in preparation)

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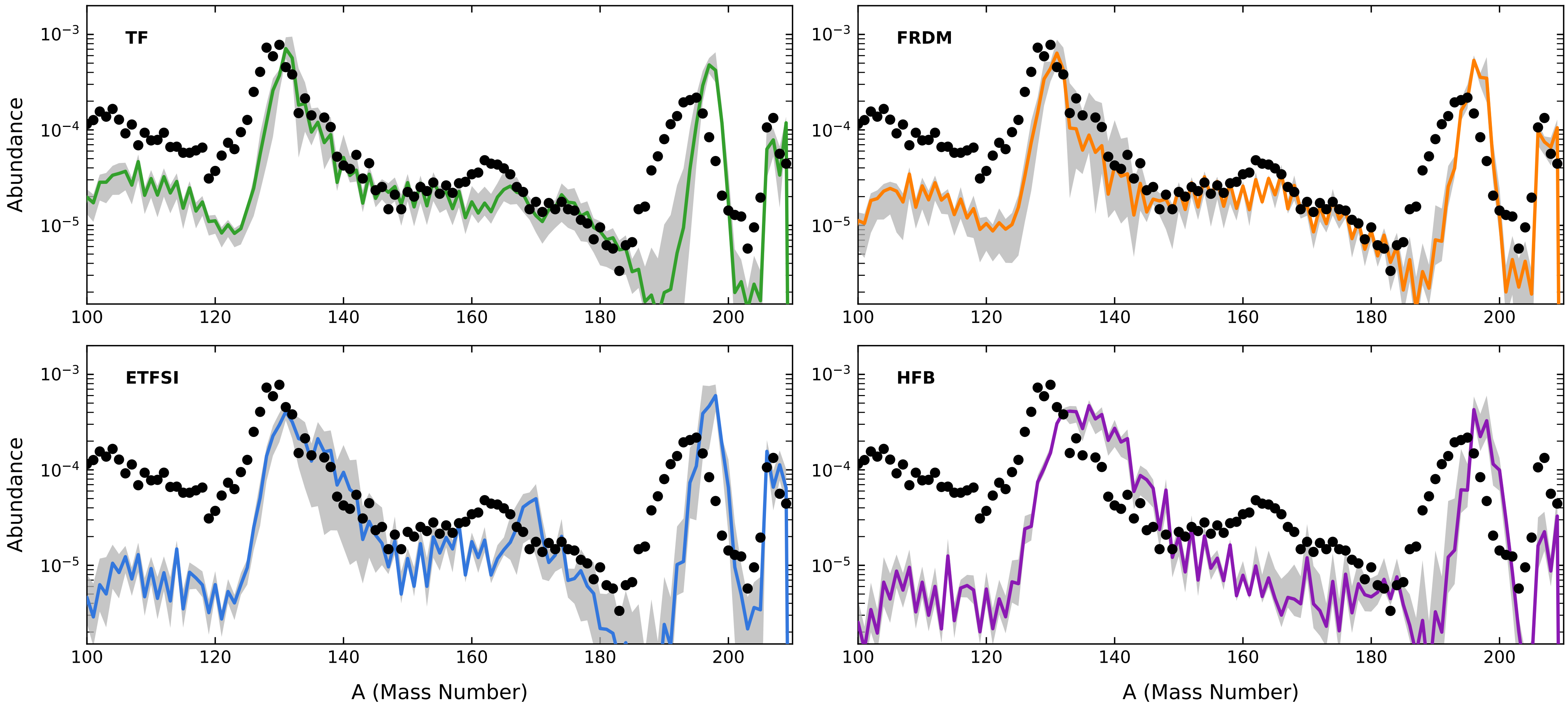
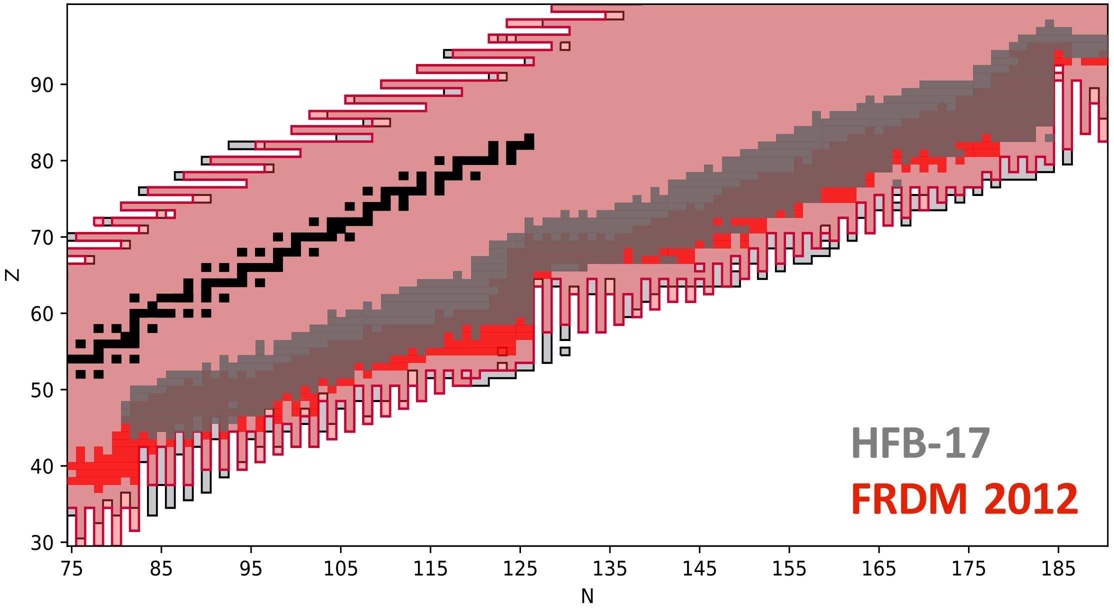



**Averaged over thirty dynamical ejecta trajectories from a 1.2/1.4 $M_{\odot}$ neutron star merger simulation** (Stephan Rosswog)

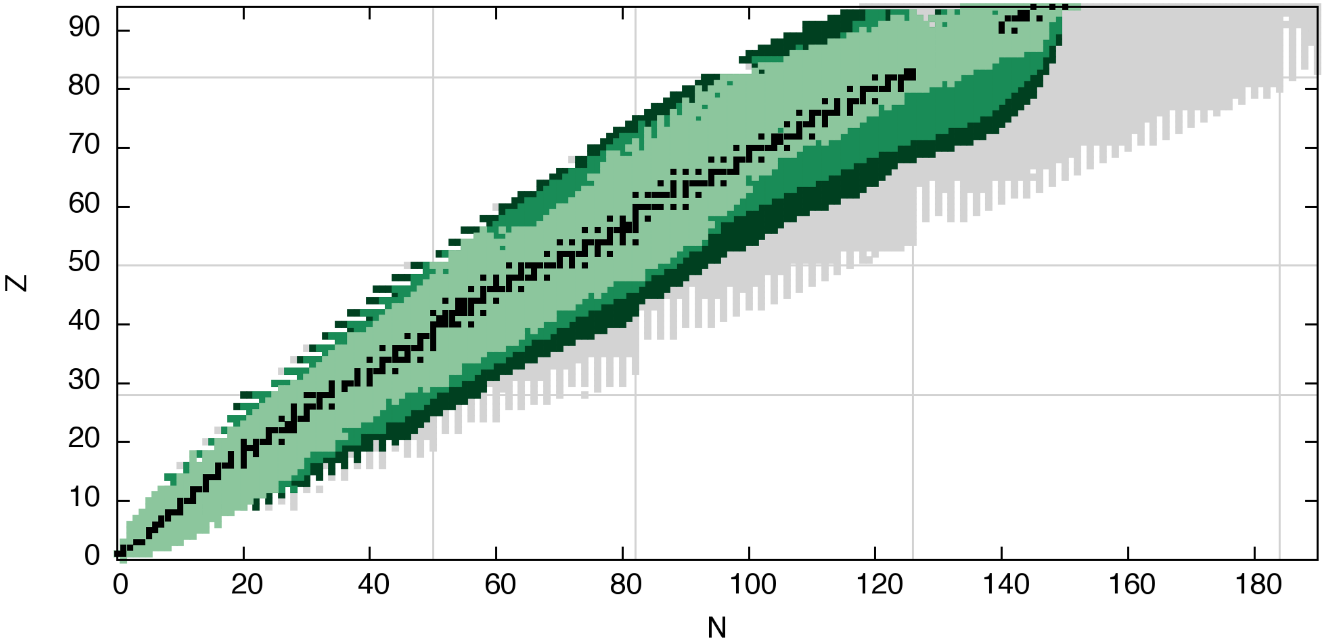
Vassh et al (in preparation)

# Shaping the *r*-process second peak: shell closures




Comparison of the neutron dripline for different mass models and the effect on the abundances near N=82

Vassh et al (in preparation)




Surman and Mumpower

**Experimental** Mass Measurements:

**AME 2016**

**FRIB** - Day 1

**FRIB** - Designed Beam Intensity

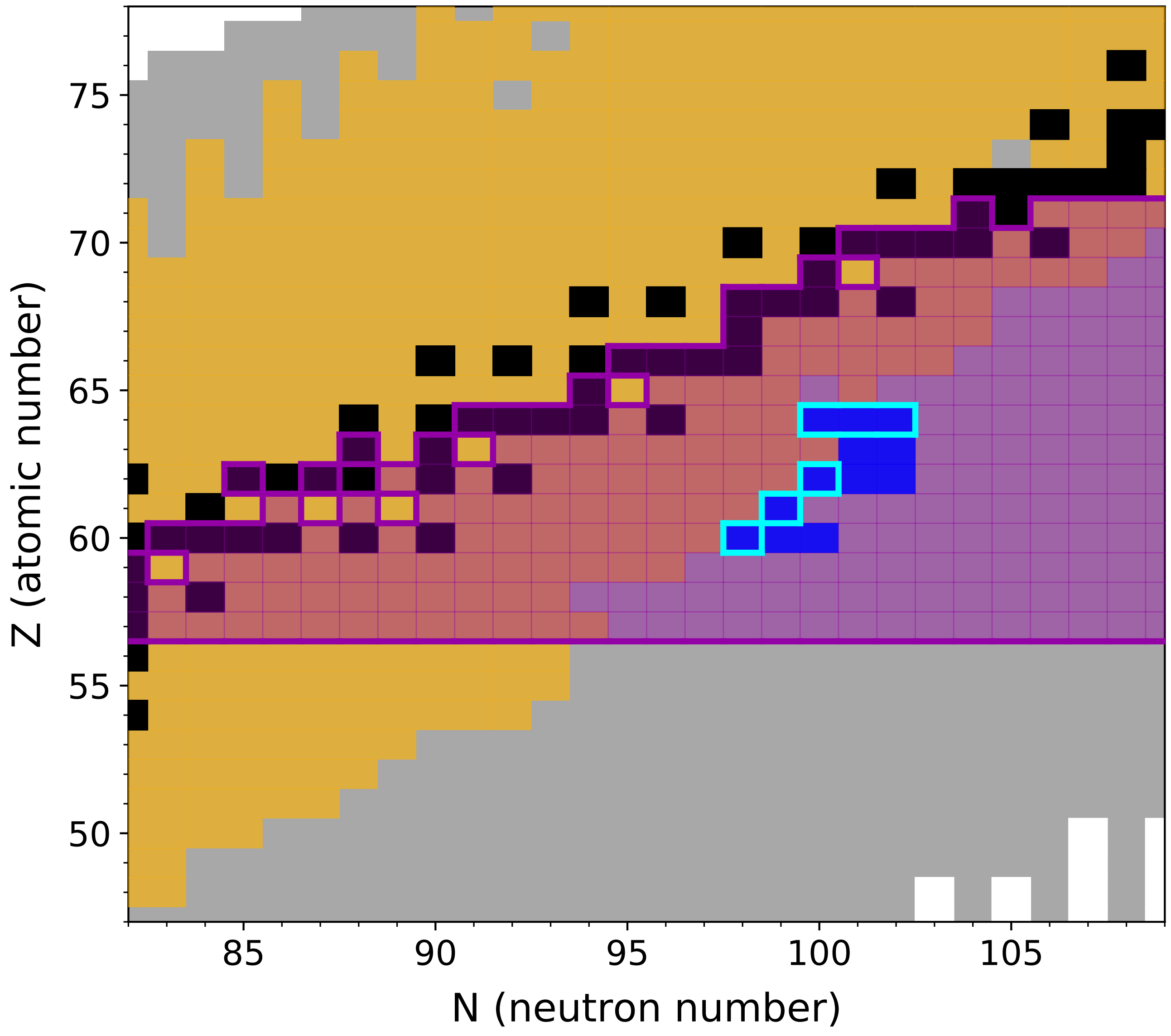
# Studying Rare-Earth Nuclei to Understand *r*-process Lanthanide Production

**Experimental** Mass Measurements:

AME 2016

Jyväskylä

CPT at CARIBU



# Studying Rare-Earth Nuclei to Understand *r*-process Lanthanide Production

**Experimental** Mass Measurements:

AME 2016

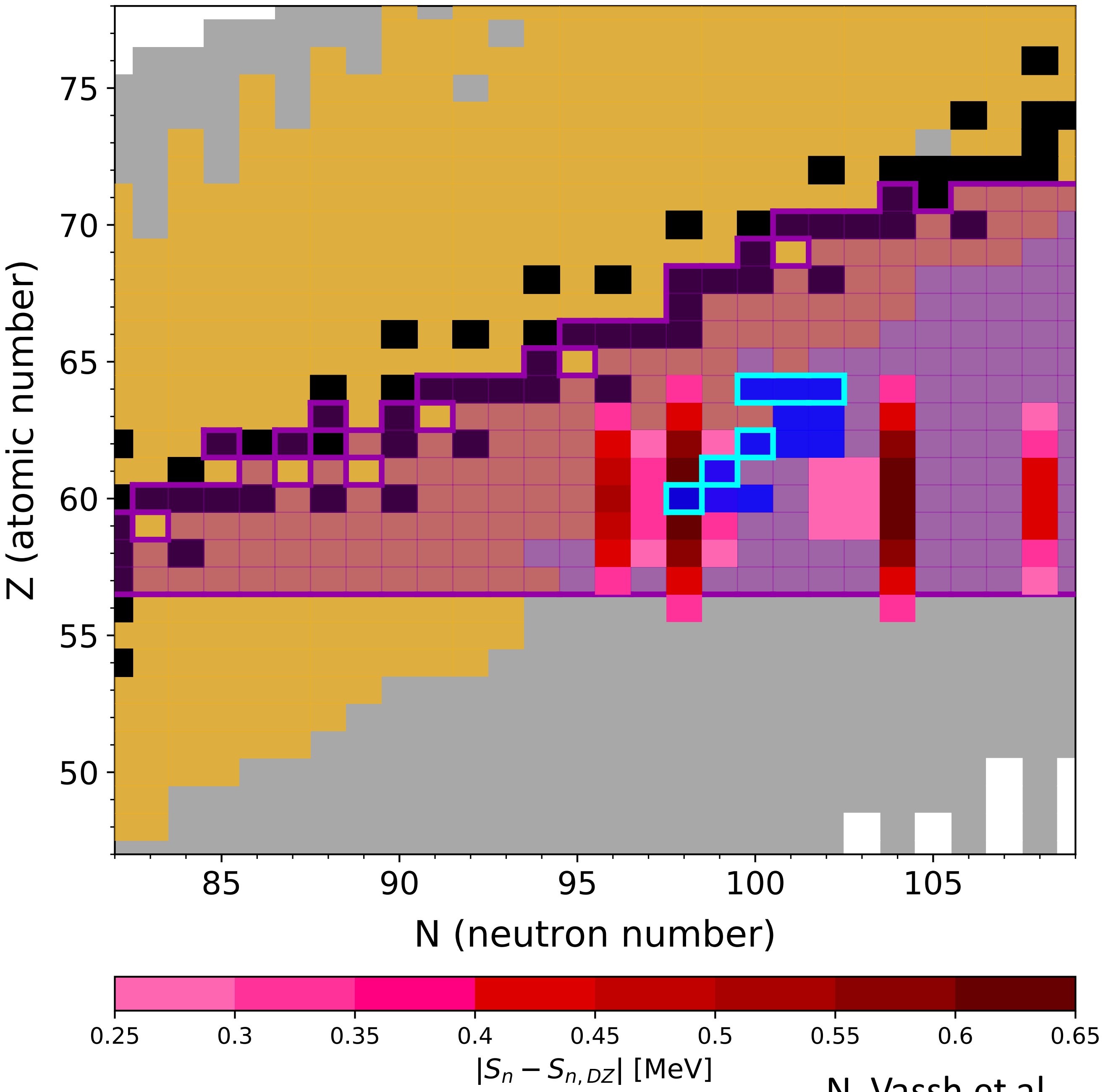
Jyväskylä

CPT at CARIBU

**Theory** (ND, NCSU, LANL):

Markov Chain Monte Carlo Mass Corrections to the Duflo-Zuker Model which **reproduce the observed rare-earth abundance peak**

(**right**: result with s/k=30, tau=70 ms, $Y_e$=0.2)




N. Vassh et al (in preparation)

# Standard *r*-process calculation

Astrophysical conditions

Fission Yields

Rates (n capture, $\beta$-decay, fission....)

Nuclear masses

→

Nucleosynthesis code

(PRISM)

↓

**Abundance prediction**

# Reverse Engineering *r*-process calculation

Astrophysical conditions

Fission Yields

Rates (n capture, $\beta$-decay, fission....)

→ Nucleosynthesis code (PRISM)

↓ Abundance prediction

↙ Markov Chain Monte Carlo (MCMC) Likelihood function

↖ **Nuclear masses**

↑ (back to Astrophysical conditions, Fission Yields, Rates)

# MCMC procedure

- Monte Carlo mass corrections

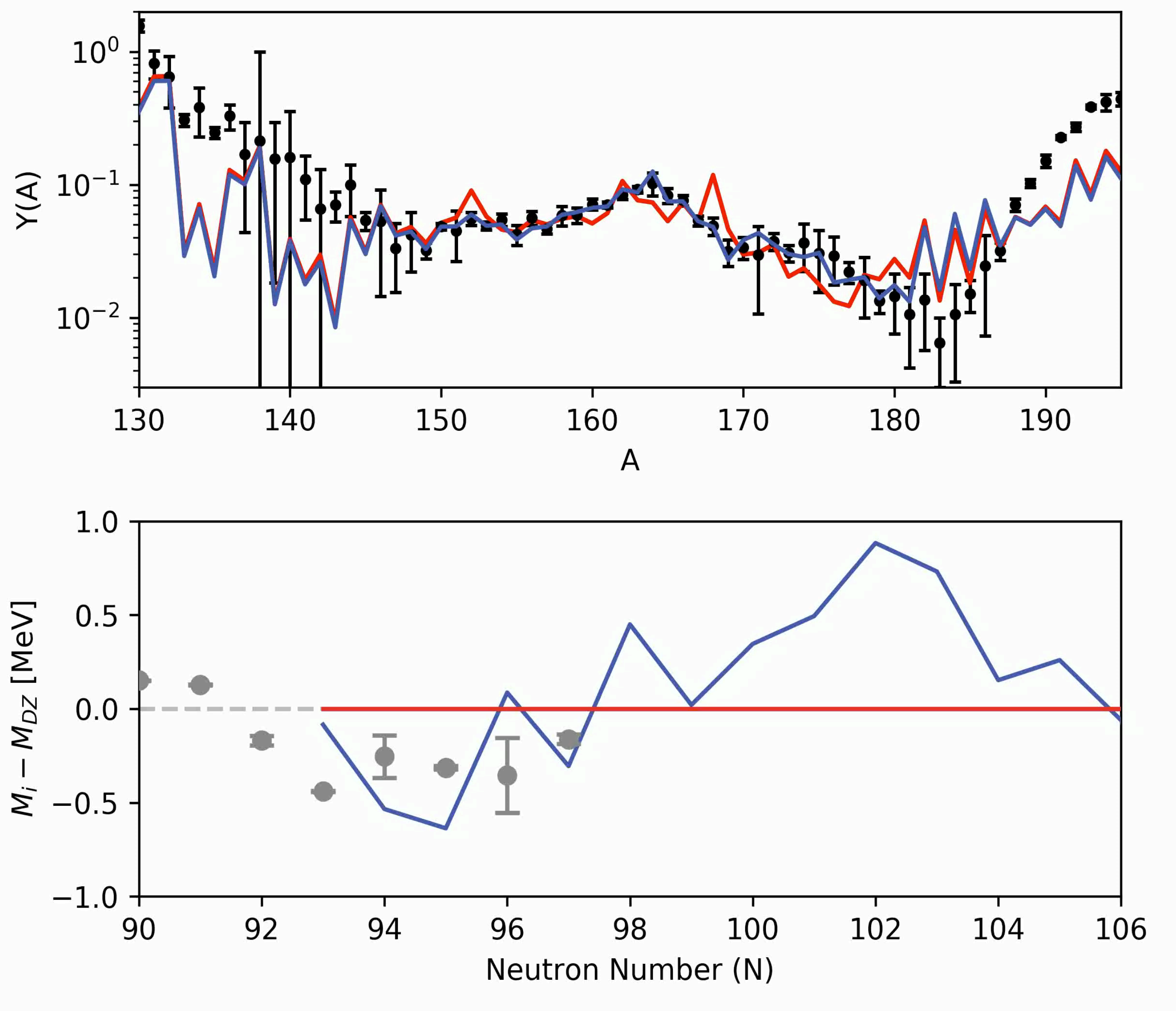
$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

- Check: $\sigma^2_{\rm rms}(M_{\rm AME12}, M) \leq \sigma^2_{\rm rms}(M_{\rm AME12}, M_{DZ})$
- Check:

$$D_n(Z,A) = (-1)^{A-Z+1}\left(S_n(Z,A+1) - S_n(Z,A)\right) > 0$$

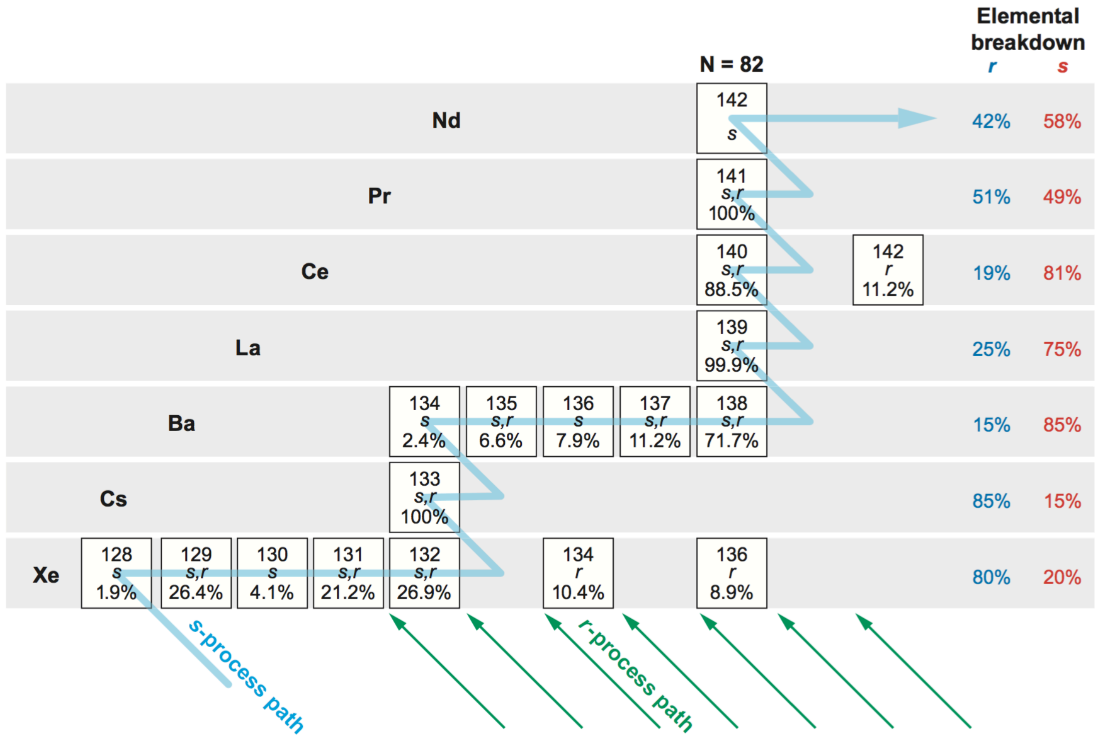
- Update nuclear quantities and rates
- Perform nucleosynthesis calculation
- Calculate $\chi^2 = \sum_{A=150}^{180} \frac{\left(Y_{\odot,r}(A) - Y(A)\right)^2}{\Delta Y(A)^2}$
- Update parameters OR revert to last success

$$\mathcal{L}(\mathrm{m}) = \exp\left(-\frac{\chi^2(\mathrm{m})}{2}\right) \longrightarrow \alpha(\mathrm{m}) = \frac{\mathcal{L}(\mathrm{m})}{\mathcal{L}(\mathrm{m-1})}$$

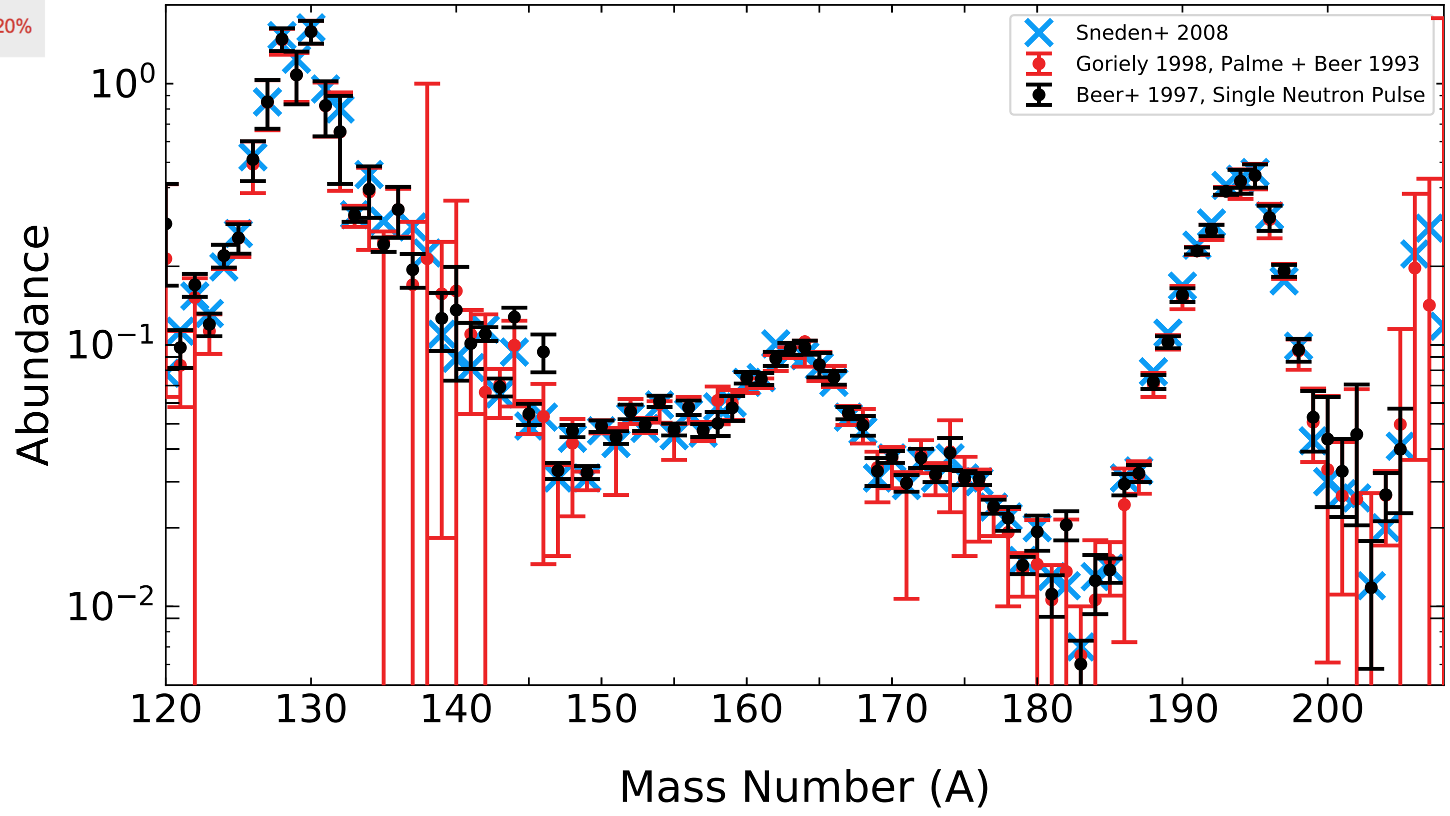



**Black** – solar abundance data
**Grey** – AME 2012 data
**Red** – values at current step
**Blue** – best step of entire run

# Sensitivity to Solar Data: uncertainty from the s-process subtraction



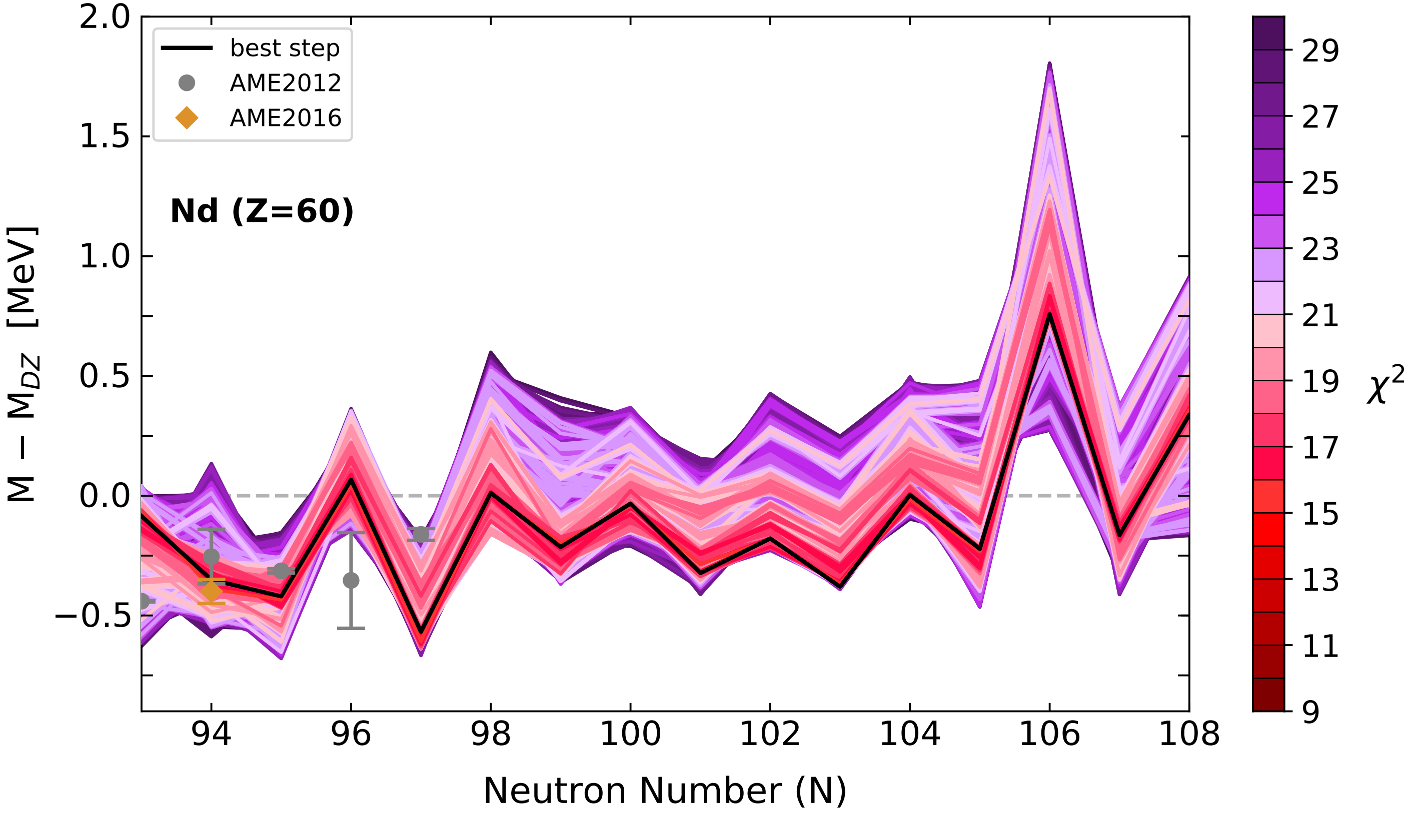

Sneden, Cowan, and Gallino (2008)

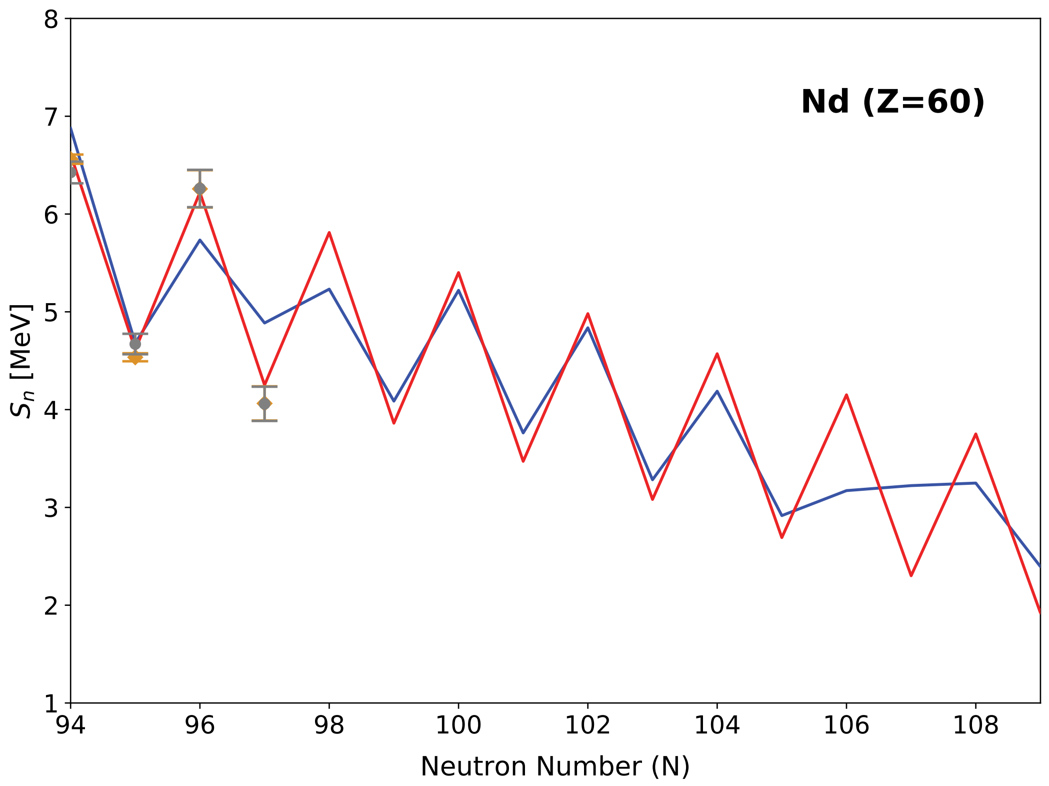


# Parallel Chains Method of MCMC

- Highly correlated parameters → long convergence time for a single run
- Multiple independent runs allow for a thorough search of parameter space
- Well-defined statistics when combine results from independent runs


# Example of a discarded, unphysical MCMC solution




Vassh et al (in preparation)

# Dynamic Mechanism of Rare-Earth Peak Formation

Detailed balance implies

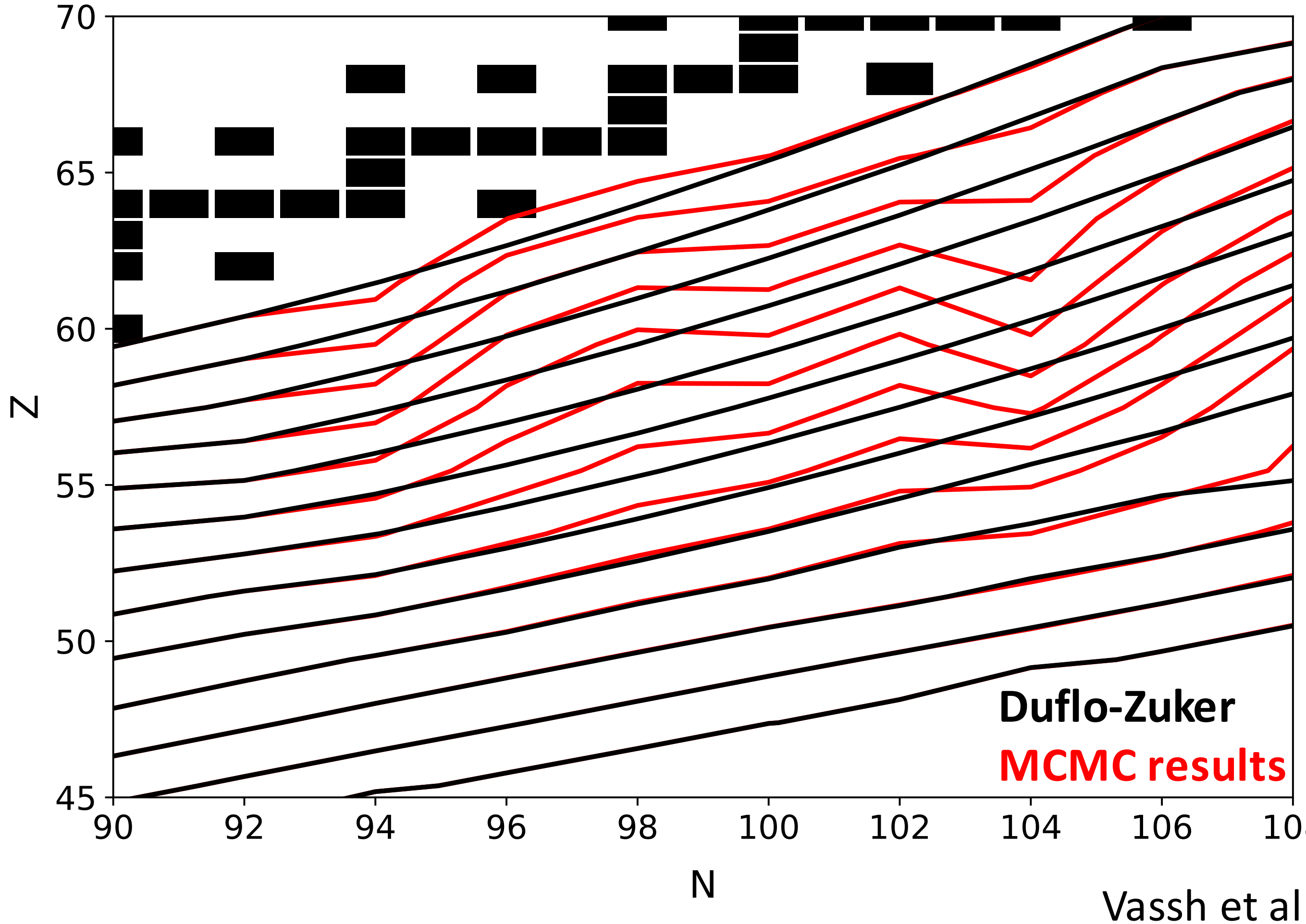
$$(\gamma, \mathrm{n}) \propto e^{-S_\mathrm{n}/kT}$$

↓

*r*-process path tends to lie along contours of constant separation energy

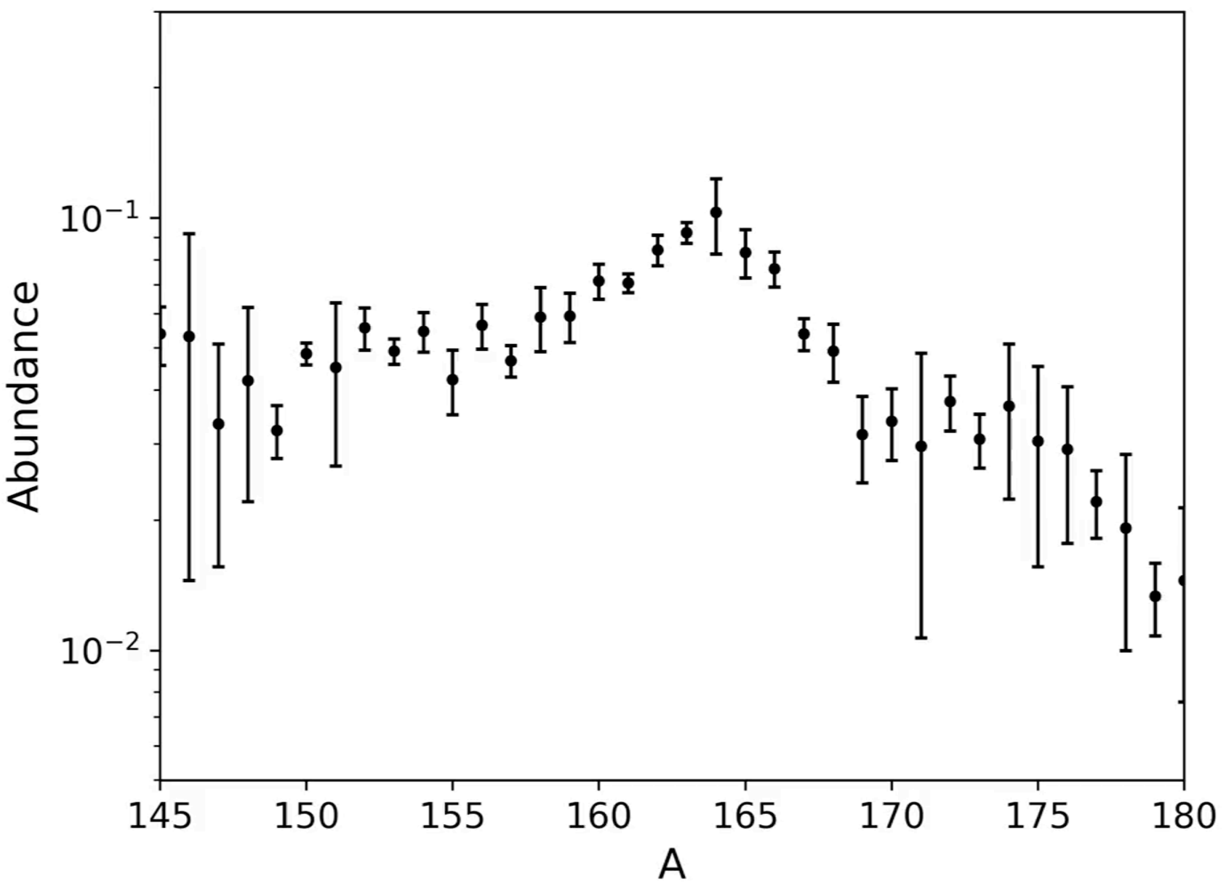
↓

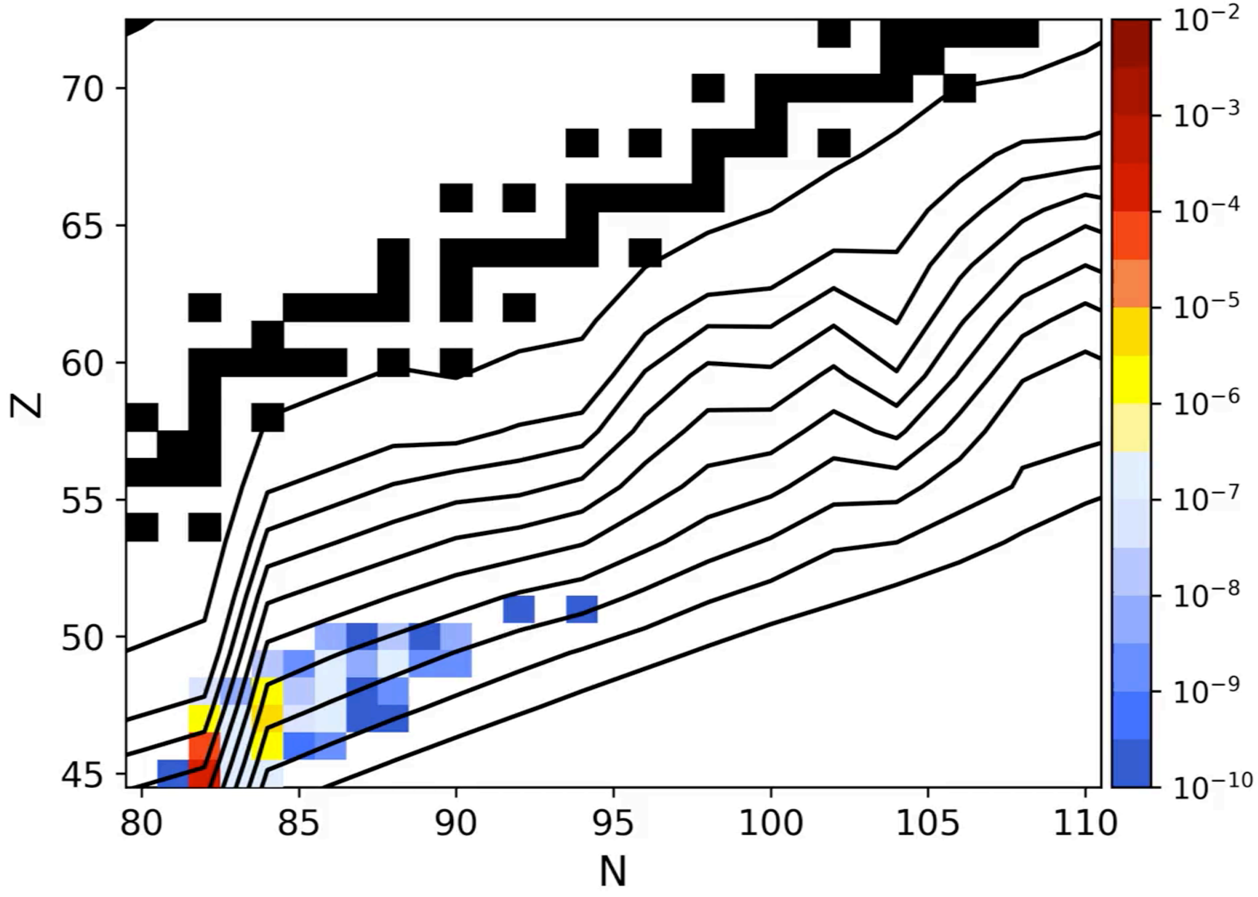
Pile-up of material at kinks




Vassh et al
(in preparation)

# Peak Formation with an MCMC Mass Solution



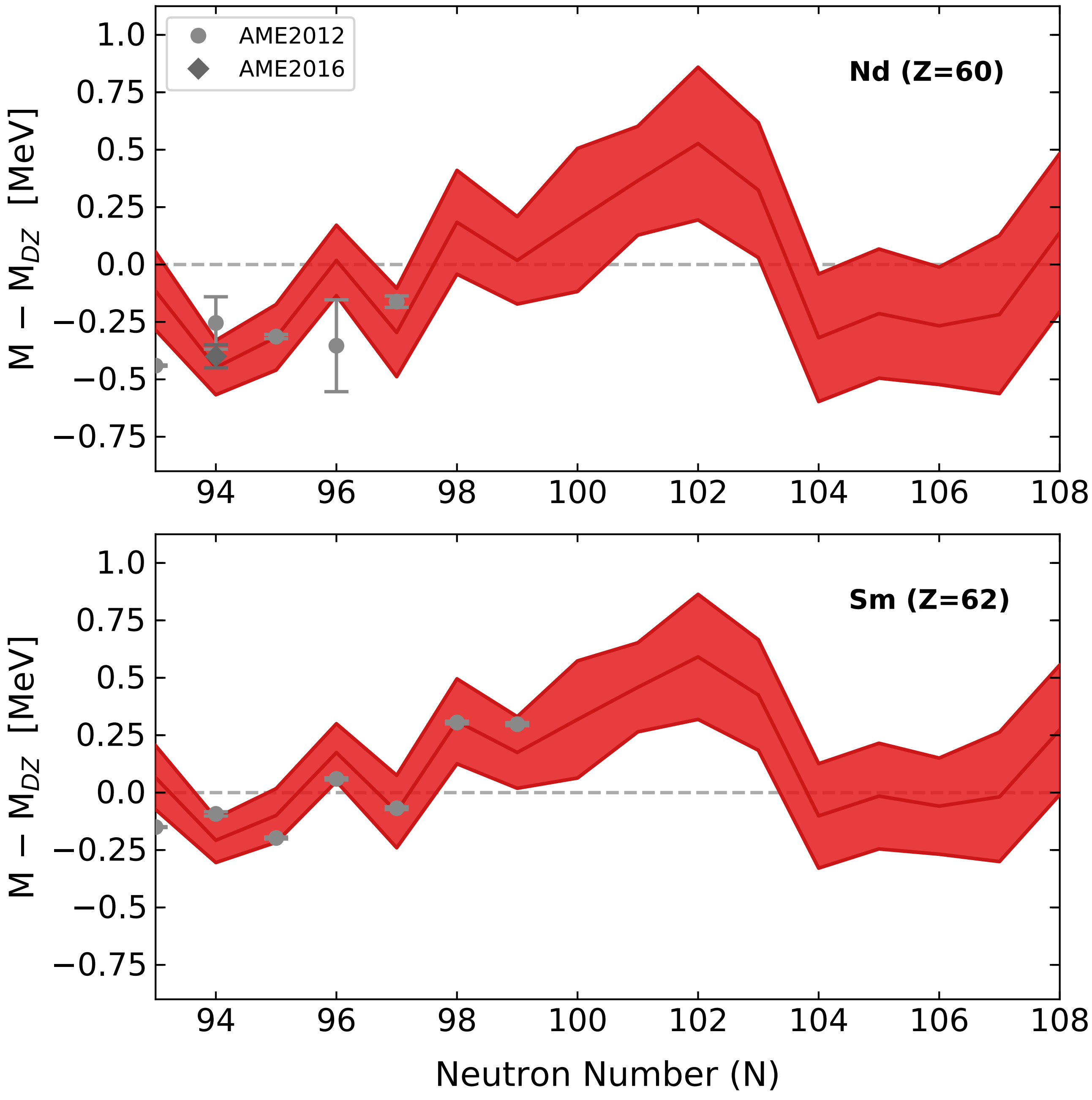



# Results

- Astrophysical trajectory:
  hot, low entropy **wind** as from a NSM accretion disk
  (s/k=30, $\tau$=70 ms, $Y_e$=0.2)

- 50 parallel, independent MCMC runs;
  Average run $\chi^2$~23

Orford, Vassh, Clark, McLaughlin, Mumpower, Savard, Surman, Aprahamian, Buchinger, Burkey, Gorelov, Hirsh, Klimes, Morgan, Nystrom, and Sharma
(Phys. Rev. Lett. **120**, 262702 (2018))



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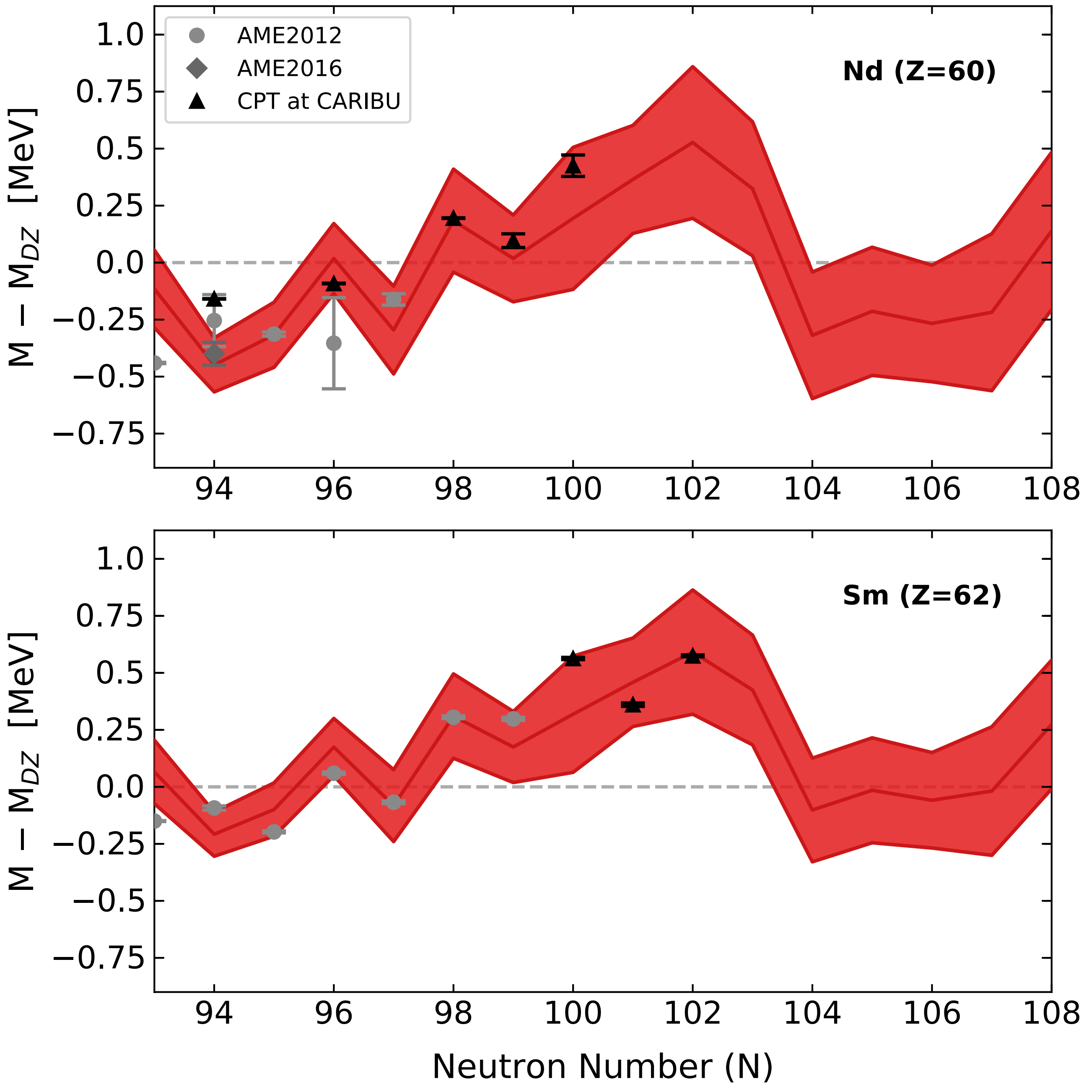


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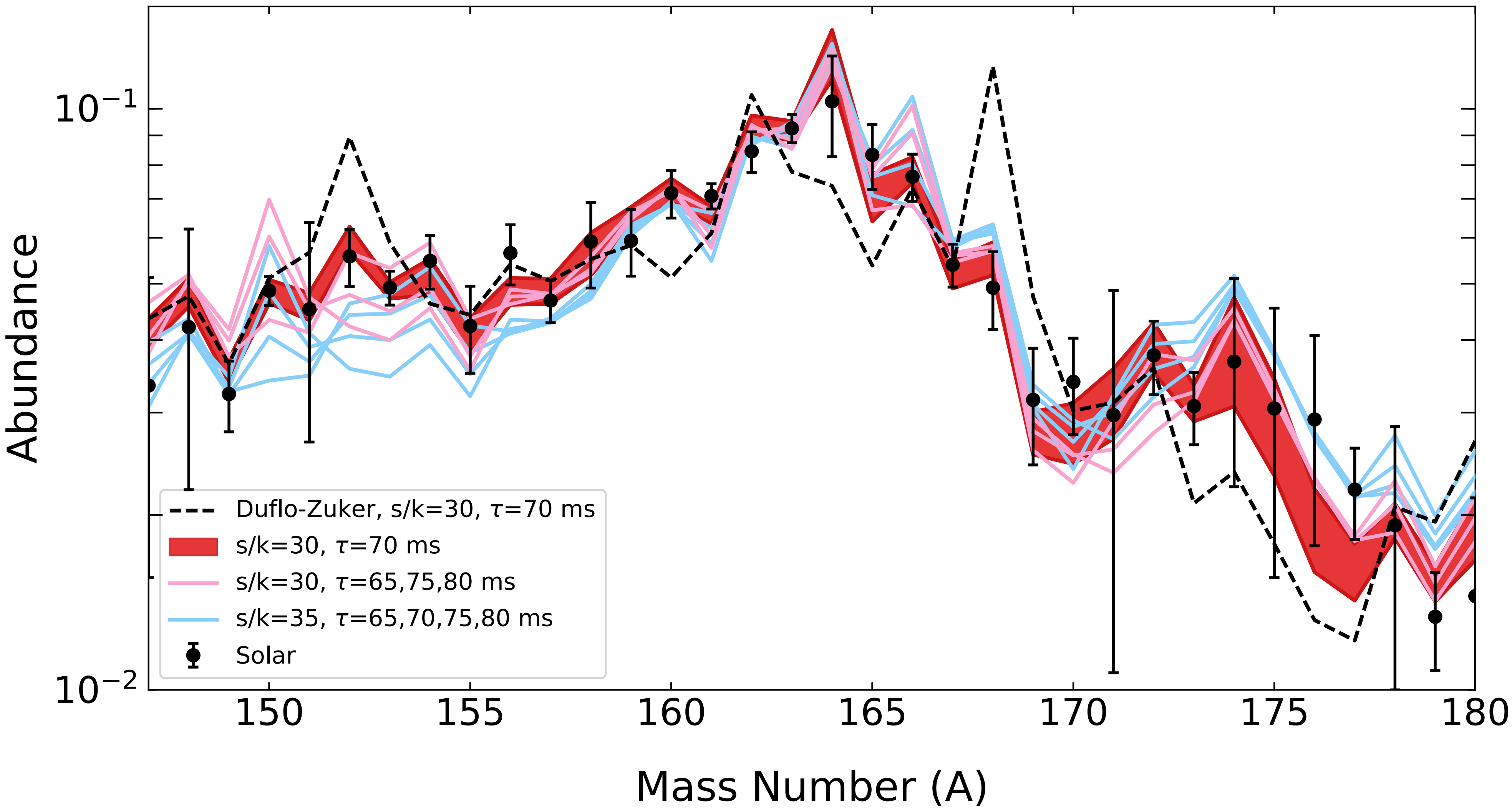
# Rare-Earth Peak with MCMC solutions




Orford, Vassh, et al (Phys. Rev. Lett. **120**, 262702 (2018))

# Nucleosynthesis in Neutron Star Mergers: Many Open Questions

- Can mergers account for most of the *r*-process material observed in the galaxy?
- Are precious metals such as gold produced in sufficient amounts?
- Are actinides produced?
- Under what conditions does nucleosynthesis occur within the merger environment?
- Does fission of the heaviest nuclei shape the observed second *r*-process peak?
- How does the rare-earth peak form?

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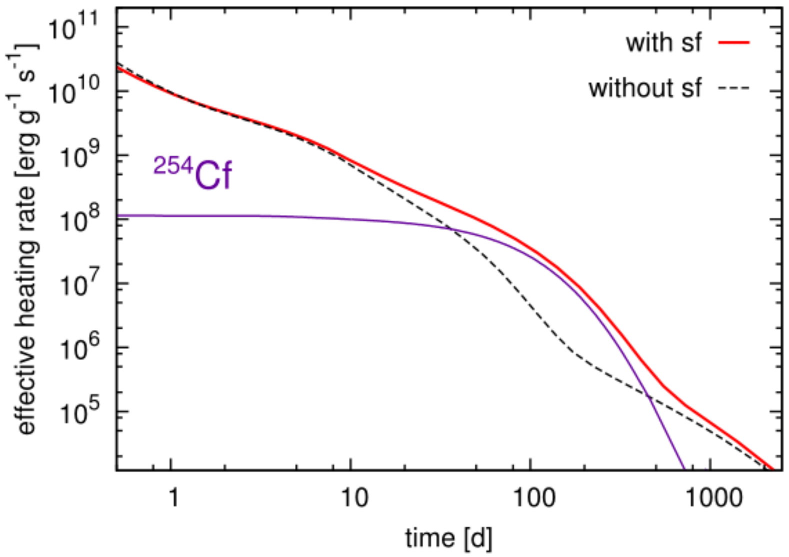
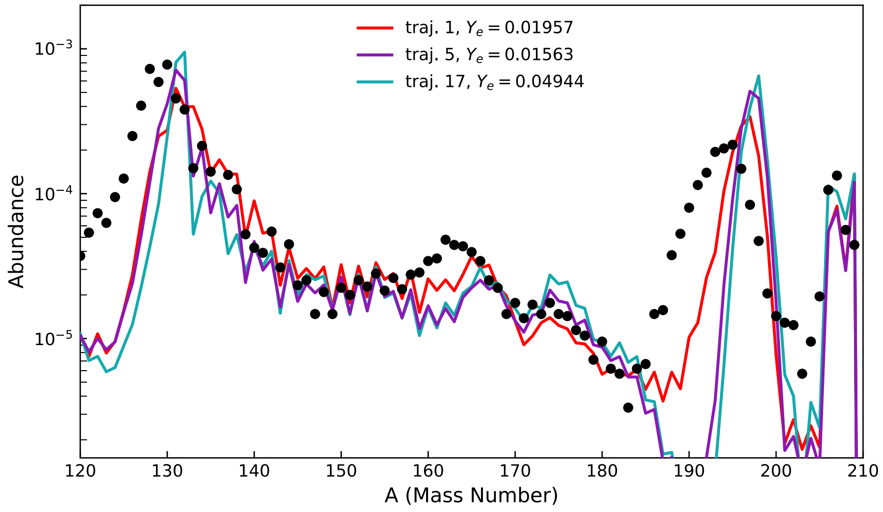
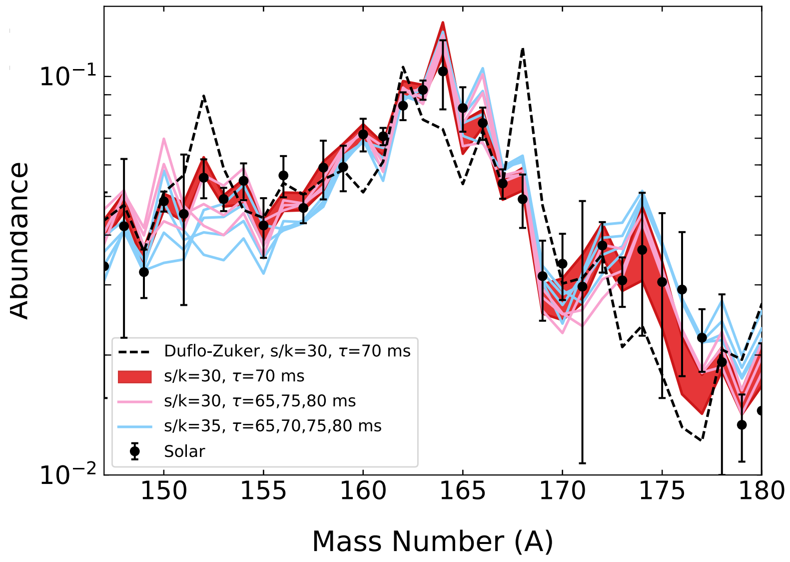



Zhu et al
(accepted to ApJL, **arXiv:1806.09724**)




Vassh et al (in preparation)

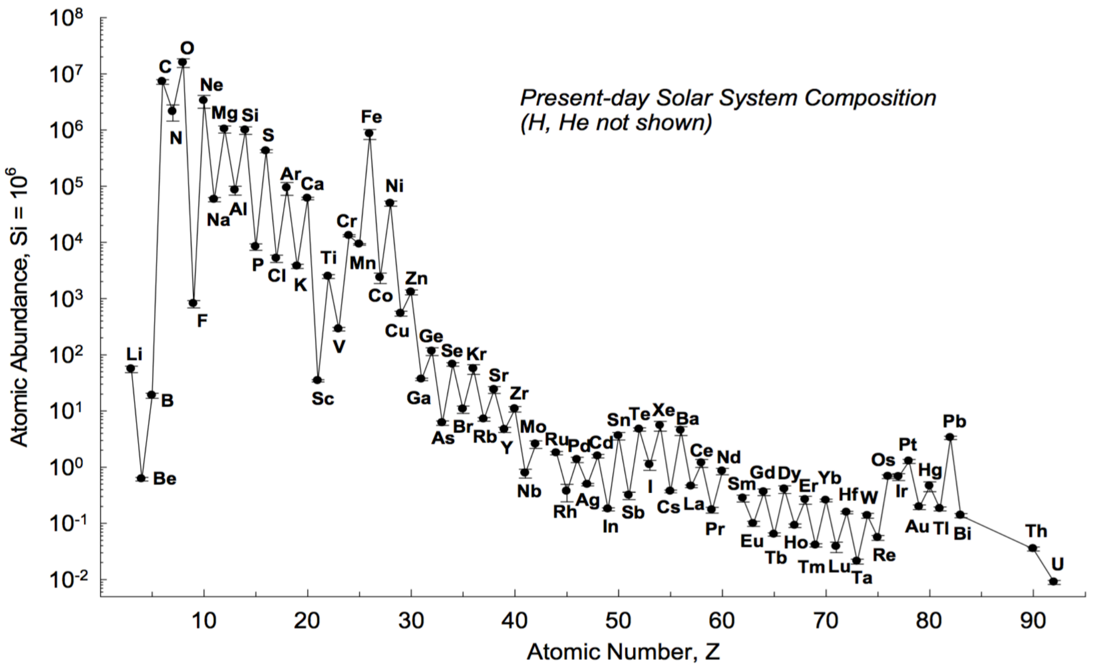



Orford, Vassh, et al
(Phys. Rev. Lett. **120**, 262702 (2018))

# Back-up Slides

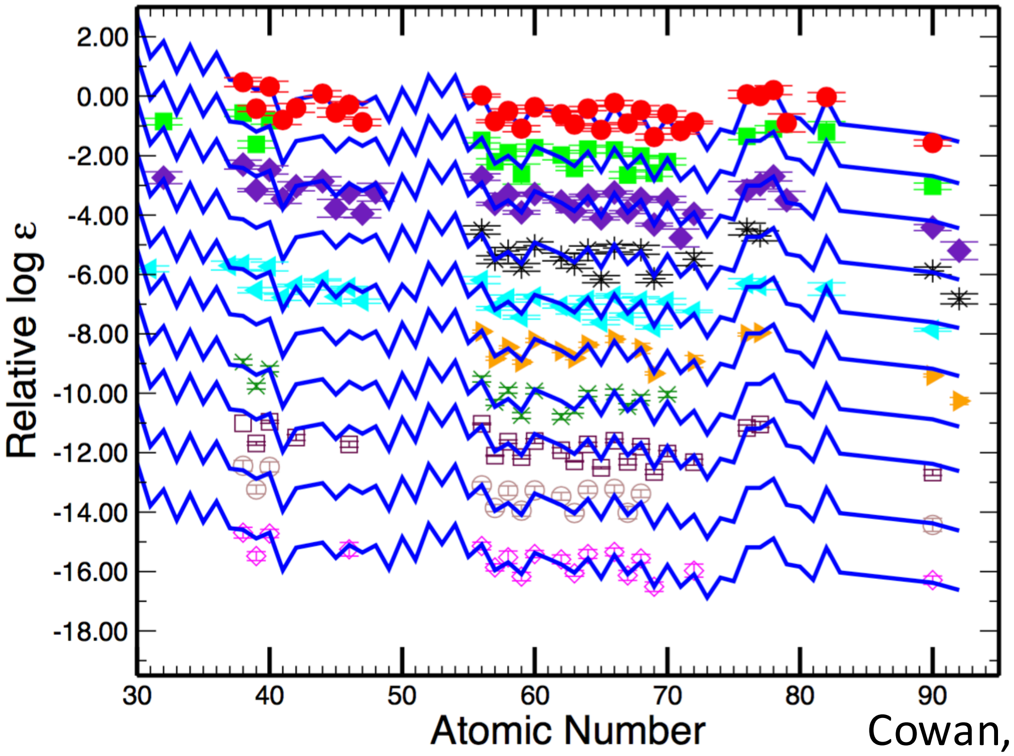
# Observed Elemental Abundances

## Solar System



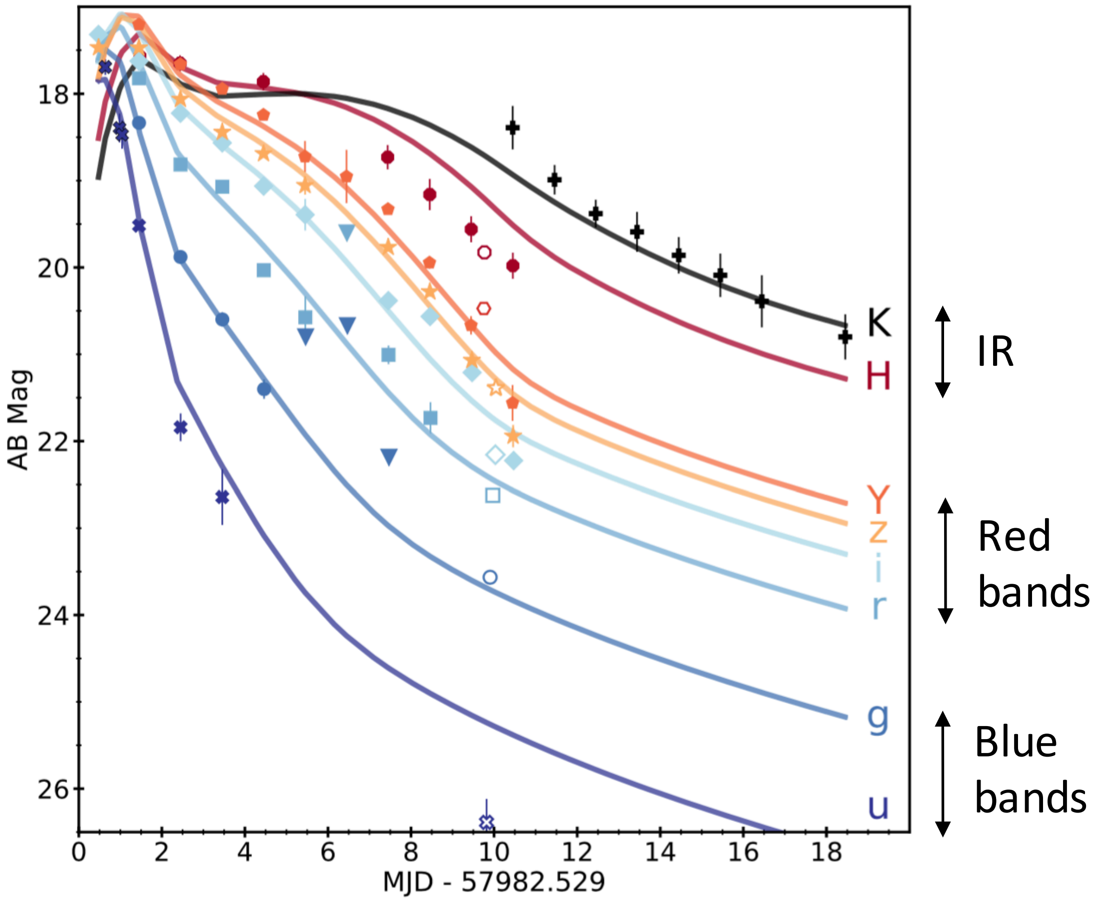

Lodders (2010)

## 10 *r*-process rich halo stars



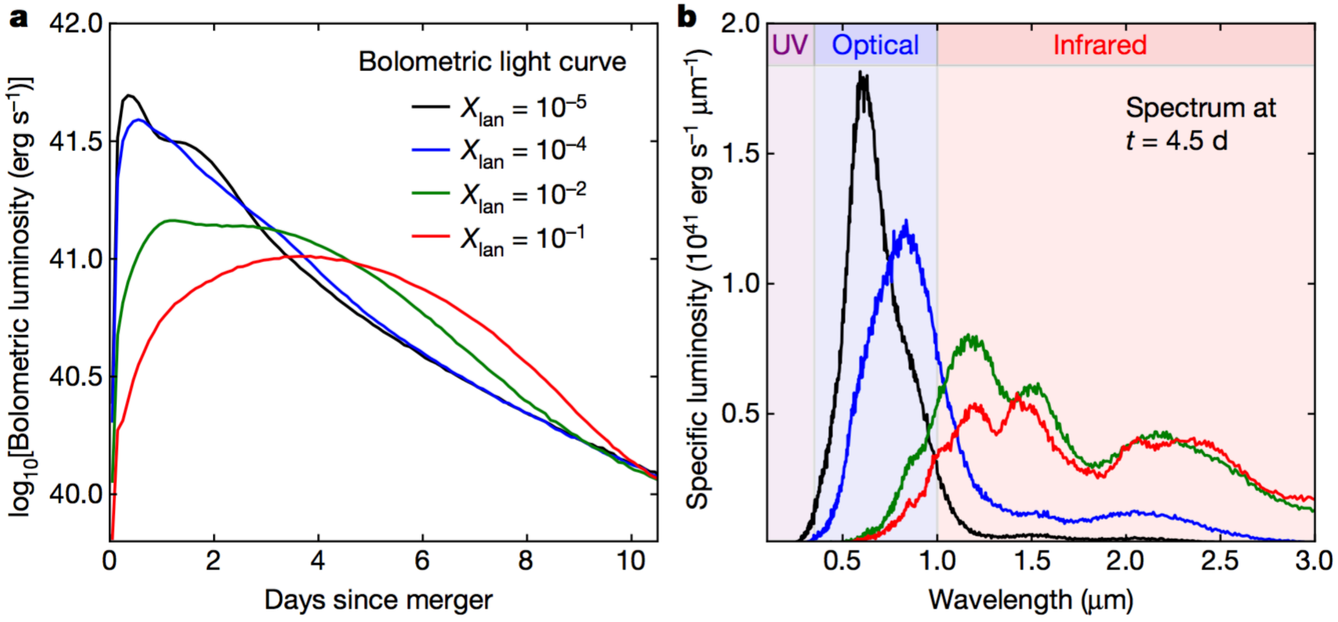

Cowan, Roederer, Sneden and Lawler (2011)

# Lanthanide production in GW170817: "red" kilonova



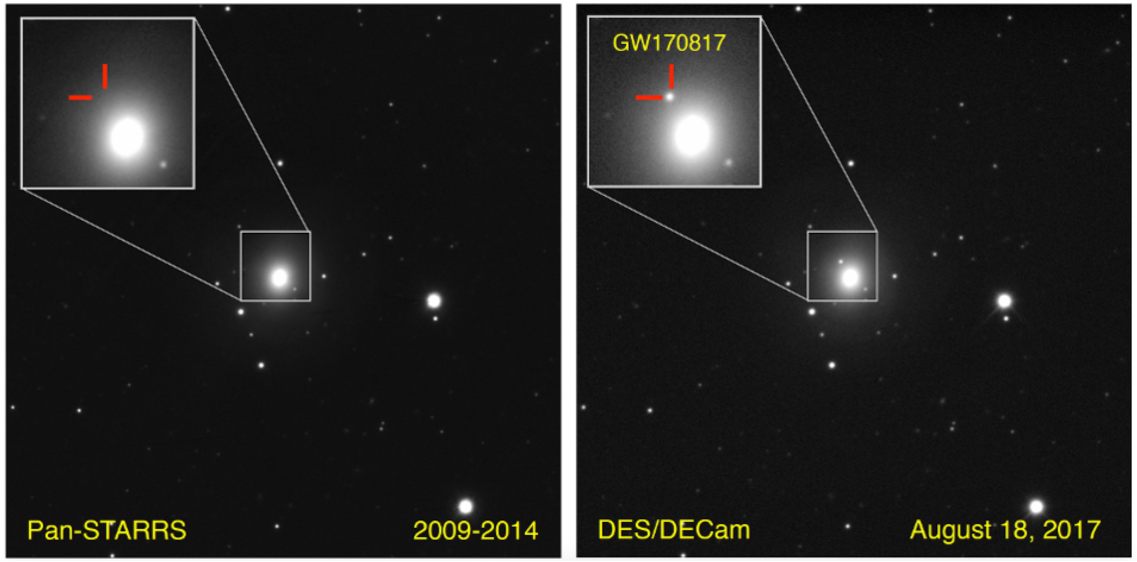

Cowperthwaite et al (ApJL 2017)

Lanthanide mass fraction ↑ , opacity ↑, longer duration light curve shifted toward infrared




Kasen et al (*Nature* 2017)

# GW170817 and *r*-process uncertainties from nuclear physics




| 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 |
| Kasen et al. (2017) | 0.04 | 0.025 |
| Kasliwal et al. (2017b) | $> 0.02$ | $> 0.03$ |
| Nicholl et al. (2017) | 0.03 | – |
| Perego et al. (2017) | 0.005 – 0.01 | $10^{-5}$ – 0.024 |
| Rosswog et al. (2017) | 0.01 | 0.03 |
| Smartt et al. (2017) | 0.03 – 0.05 | 0.018 |
| Tanaka et al. (2017a) | 0.01 | 0.03 |
| Tanvir et al. (2017) | 0.002 – 0.01 | 0.015 |
| Troja et al. (2017) | 0.001 – 0.01 | 0.015 – 0.03 |
| Côté et al (2017) | (0.002-0.01) | (0.01-0.03) |

Estimates of ejected mass for GW170817

Mass fraction range for stable Eu isotopes with 10 mass models

| Astrophysical Trajectory | Fission Fragment Distribution | $^{151}$Eu Mass Fraction $[10^{-3}]$ | $^{153}$Eu Mass Fraction $[10^{-3}]$ | Relative Abundance Range |
|---|---|---|---|---|
| Cold outflow (no reheating) | Kodama & Takahashi (1975) | (5.01 – 11.7) | (3.92 – 8.75) | 0.776 |
| (Just et al. 2015) | Symmetric Split | (0.083 – 2.65) | (0.12 – 2.84) | 3.239 |
| "Slow" ejecta with reheating | Kodama & Takahashi (1975) | (2.67 – 13.3) | (1.89 – 9.62) | 1.568 |
| (Mendoza-Temis et al. 2015) | Symmetric Split | (0.19 – 2.09) | (0.24 – 2.23) | 2.755 |

Côté et al (2017)

# Preliminary Results

- Astrophysical trajectory:
  n-rich NSM **dynamical** ejecta with nuclear reheating

- Simple fission prescription:
  -spontaneous fission for all A>250 nuclei
  -57%,43% fission fragment splits

- 50 independent MCMC runs complete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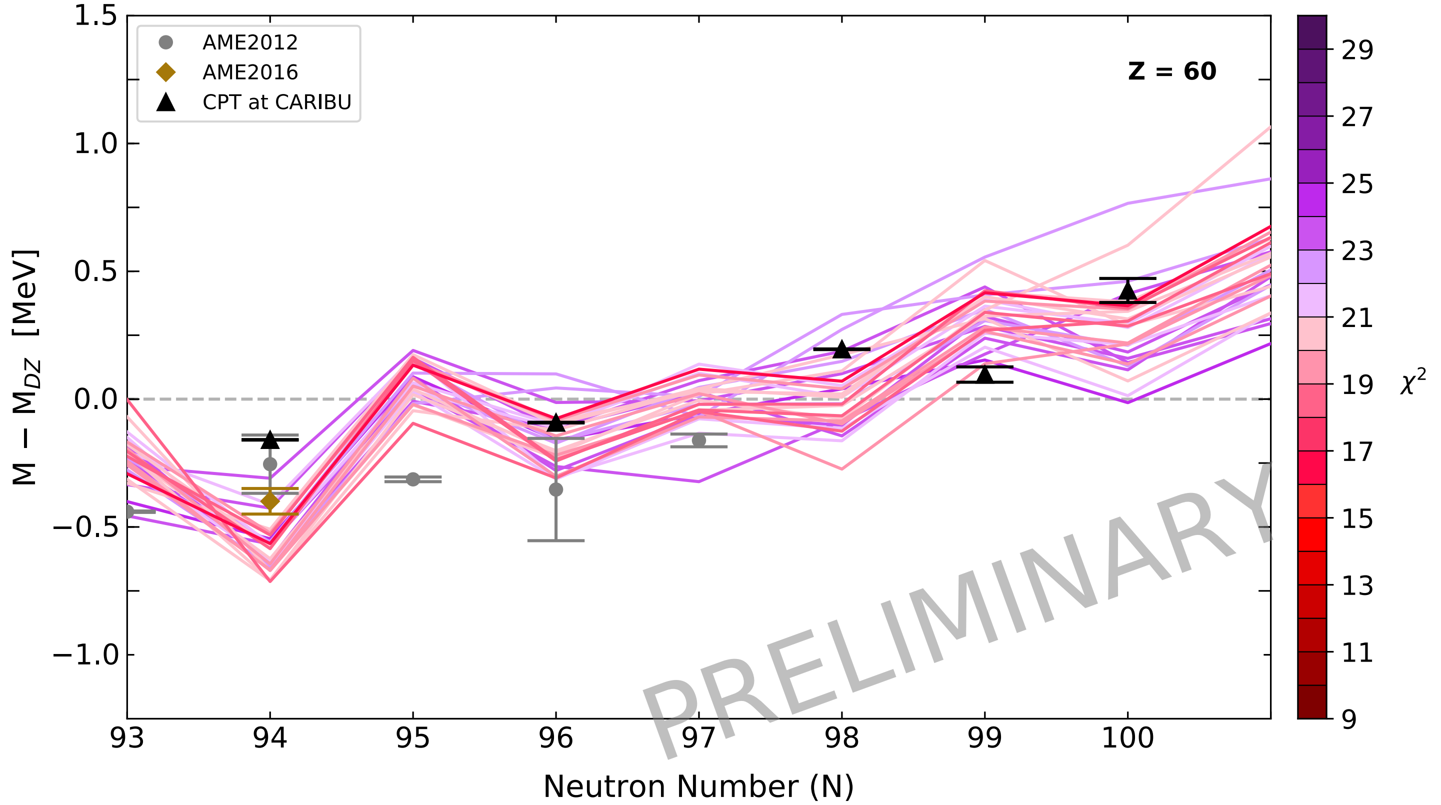
30 Runs (Best Step Colored by $\chi^2$)




Vassh et al
(in preparation)