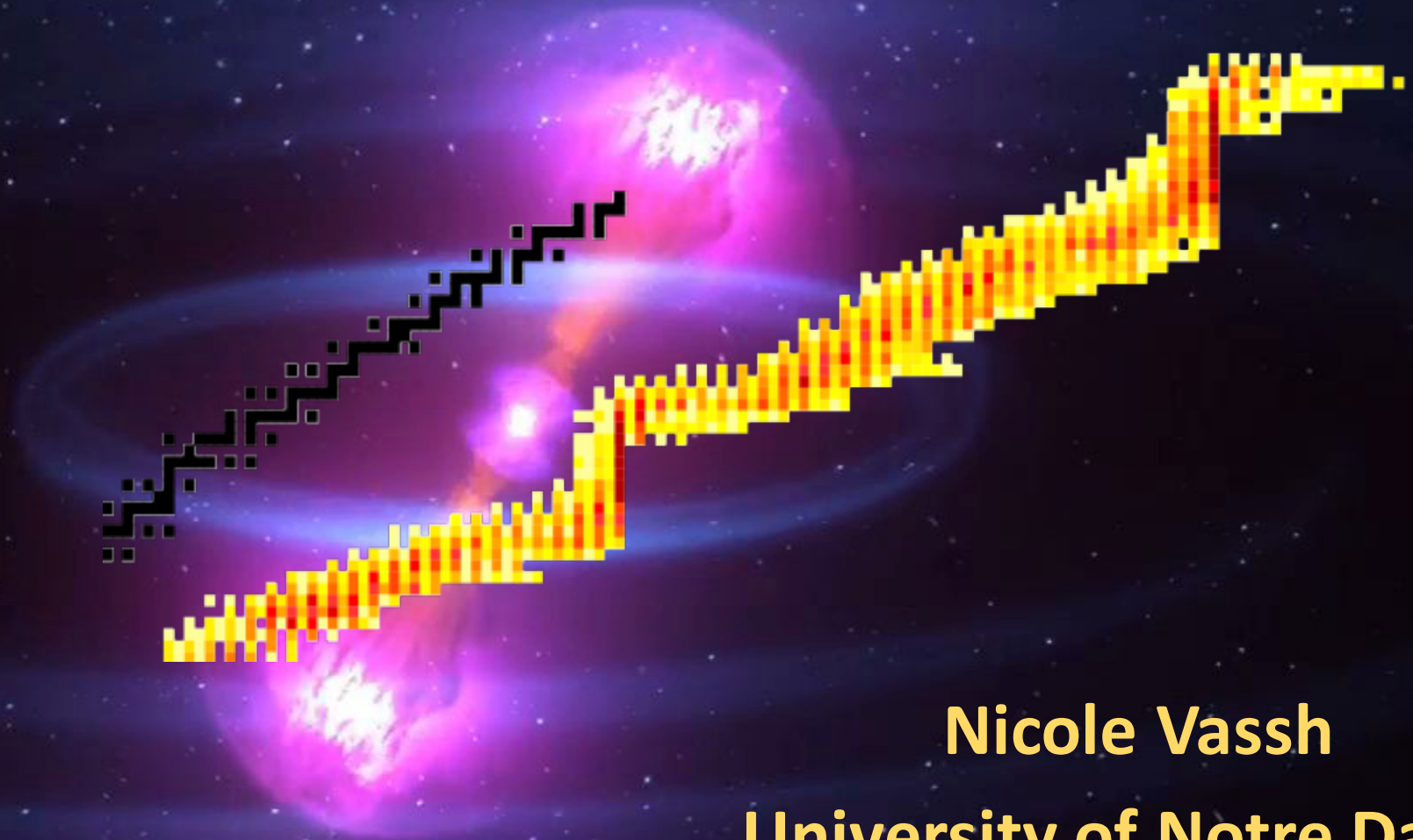


Studying lanthanide production in r -process nucleosynthesis



Nicole Vassh

University of Notre Dame

CIPANP 6/1/18



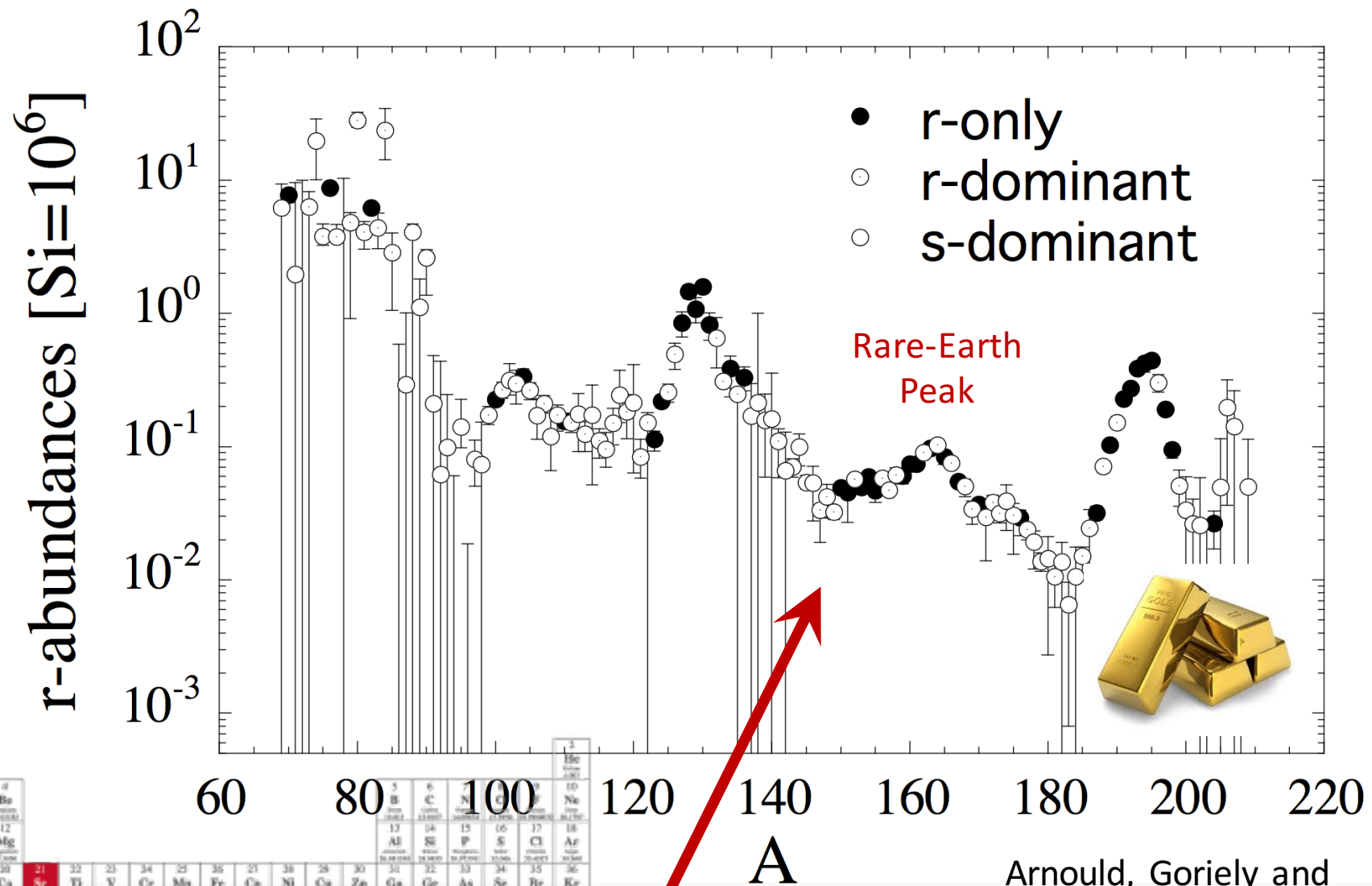
Fission In R-process
Elements



Observed Solar *r*-process Residuals

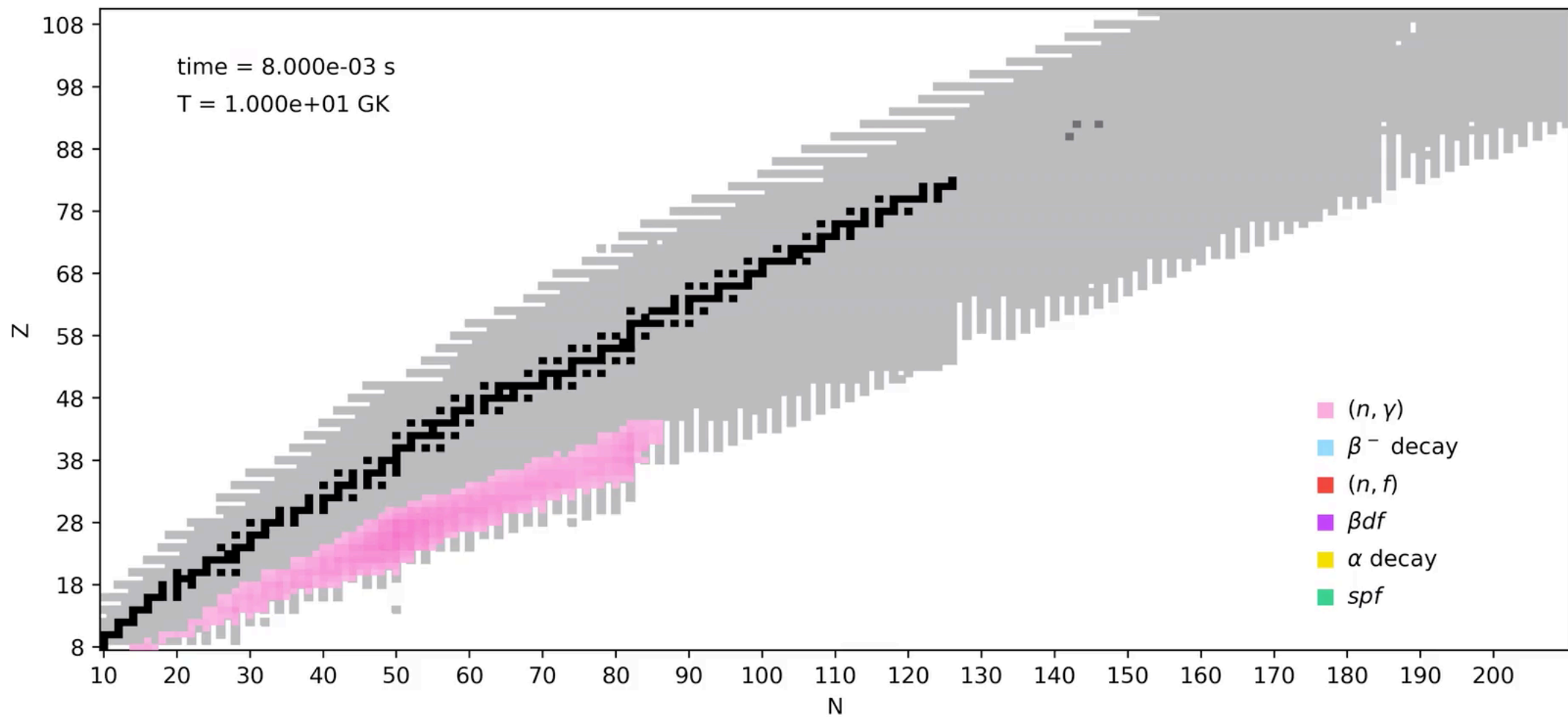
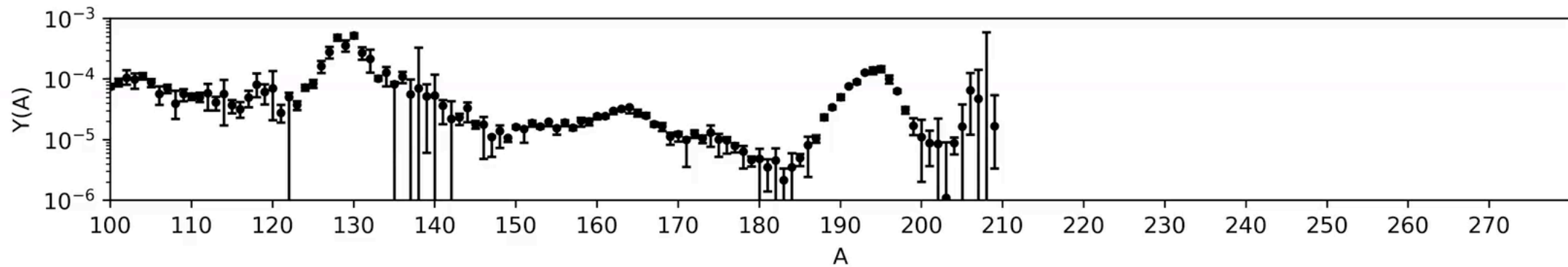
Depending on the conditions, the *r*-process can produce:

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

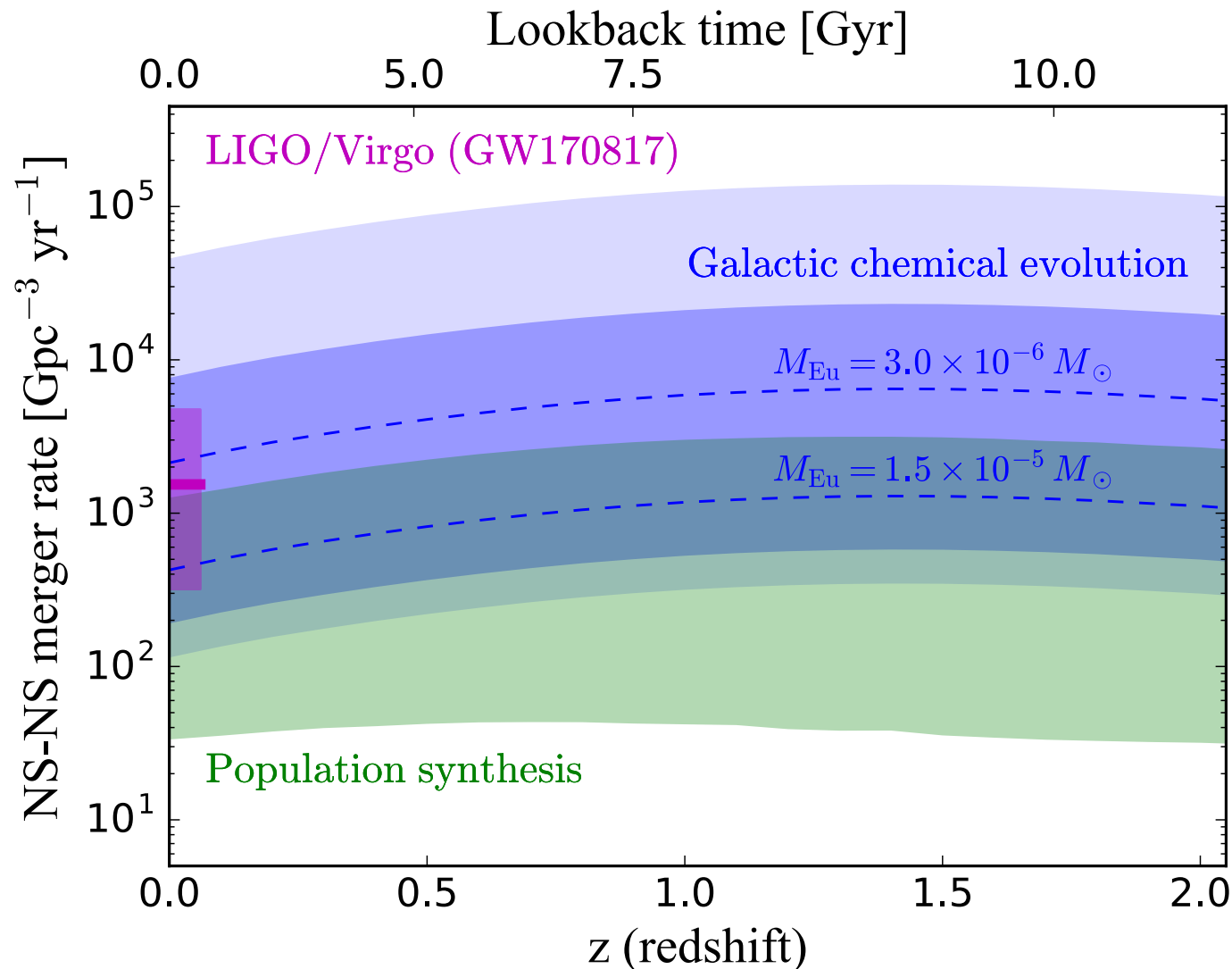


Arnould, Goriely and Takahashi (2007)

1 H Hydrogen 1.00794	2 He Helium 4.002602																	10 Ne Neon 19.992646	11 Na Sodium 22.98976928															
3 Li Lithium 6.941	4 Be Beryllium 9.012182	5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.006434	8 O Oxygen 15.999	9 F Fluorine 18.9984032	12 Mg Magnesium 24.304	13 Al Aluminum 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.9216	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80			
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9062	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.36	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.603	53 I Iodine 126.905	54 Xe Xenon 131.29	55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium 144.91288	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.50015	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93032	70 Yb Ytterbium 173.05448	71 Lu Lutetium 174.96706
87 Fr Francium 223	88 Ra Radium 226	89 Ac Actinium 227	90 Th Thorium 232	91 Pa Protactinium 231	92 U Uranium 238	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 260																		



GW170817 and r -process uncertainties from nuclear physics



From GCE
using
Solar Data

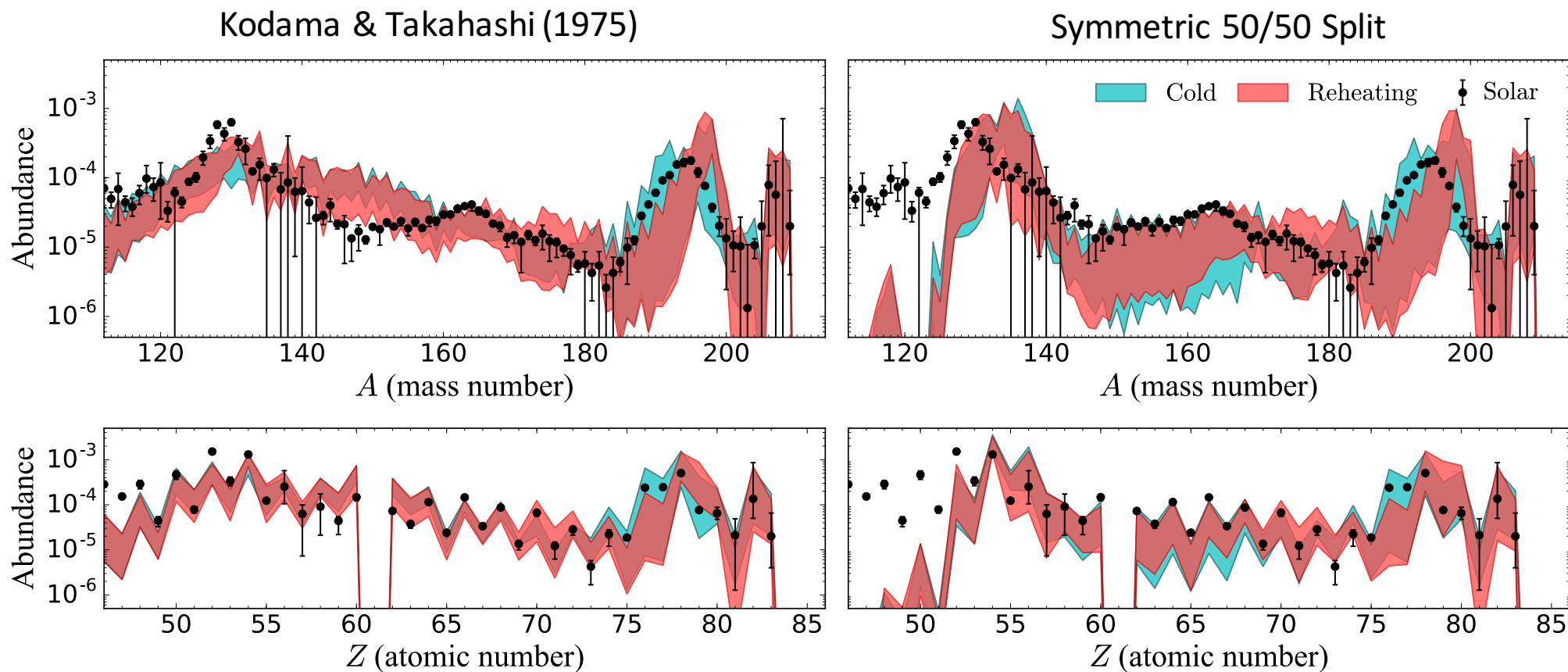
When nuclear physics
uncertainties are
considered

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

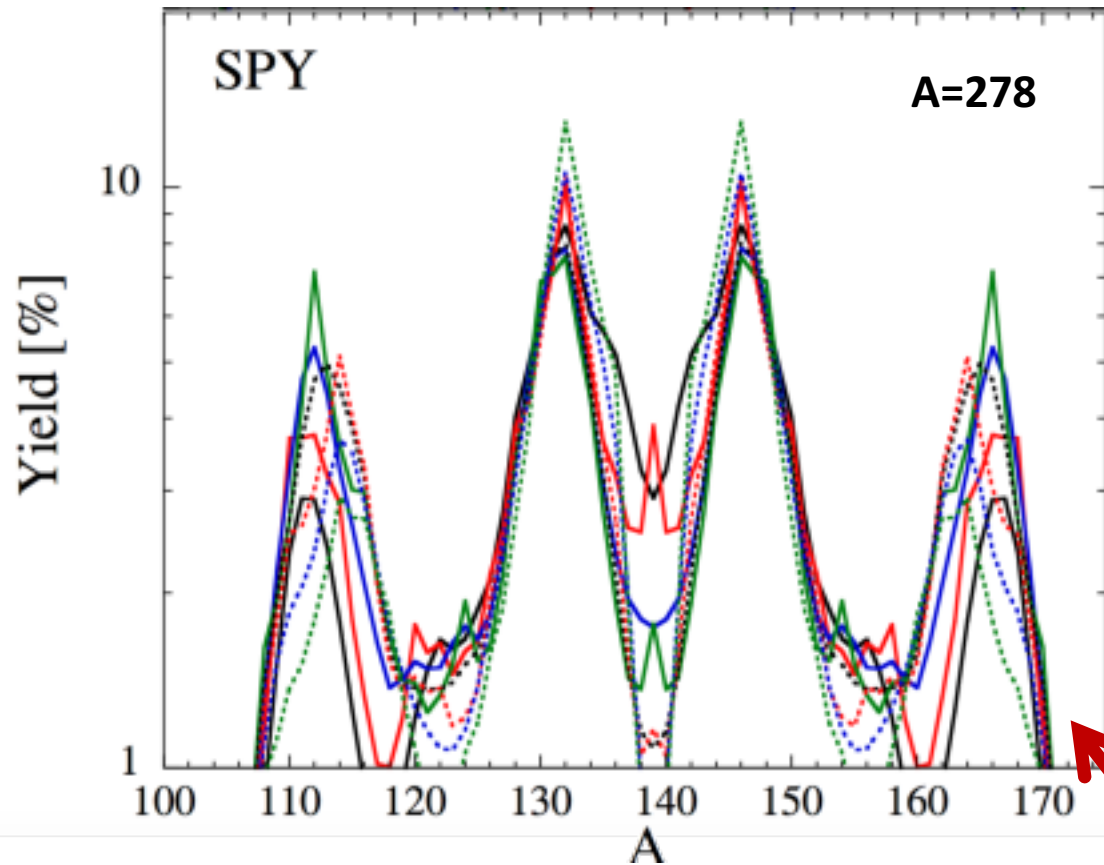
(ApJ 855, 2, 2018)

r -process Sensitivity to Mass Model and Fission Yields

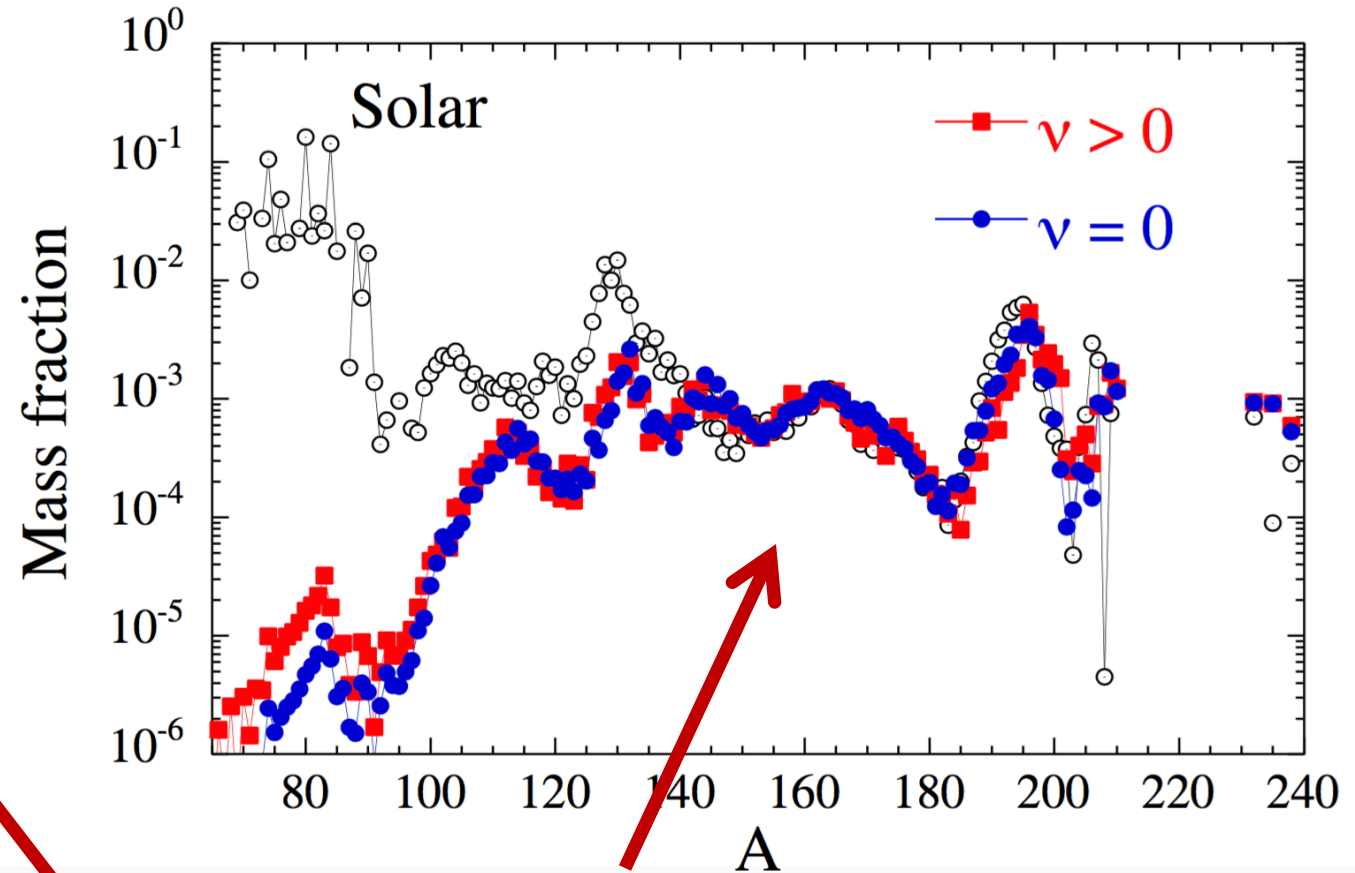
- 10 mass models: DZ33, FRDM95, FRDM12, WS3, KTUY, HFB17, HFB21, HFB24, SLY4, UNEDF0
- N-rich dynamical ejecta conditions: **Cold** (Just 2015), **Reheating** (Mendoza-Temis 2015)



Dependence on the Fission Fragment Distribution



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



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

Goriely (2015)



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



UNIVERSITY OF
NOTRE DAME

Vassh and Surman



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

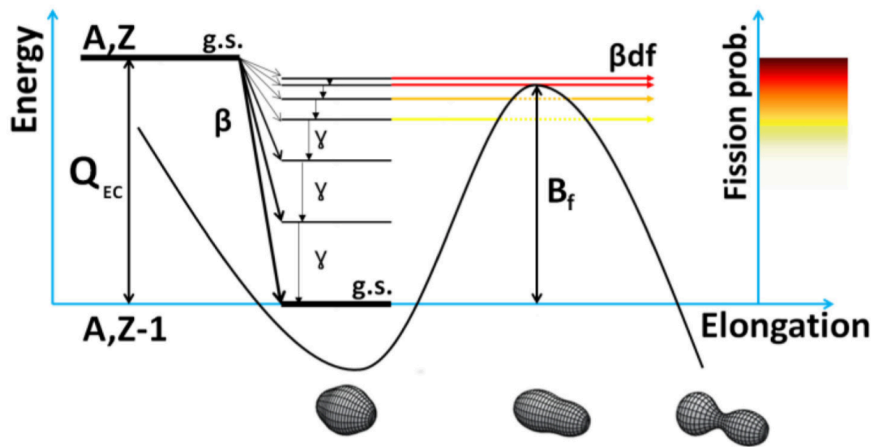


McLaughlin and Zhu

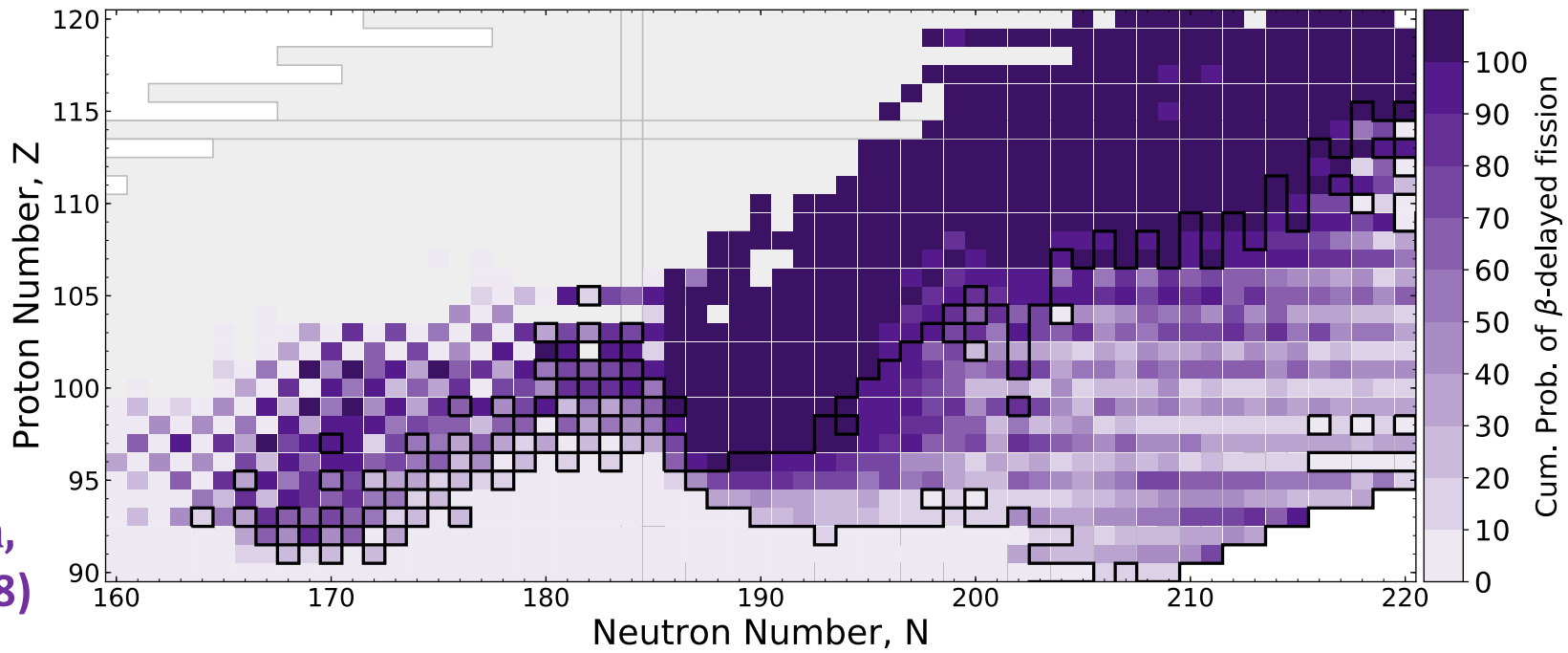


β -delayed fission in r -process nucleosynthesis

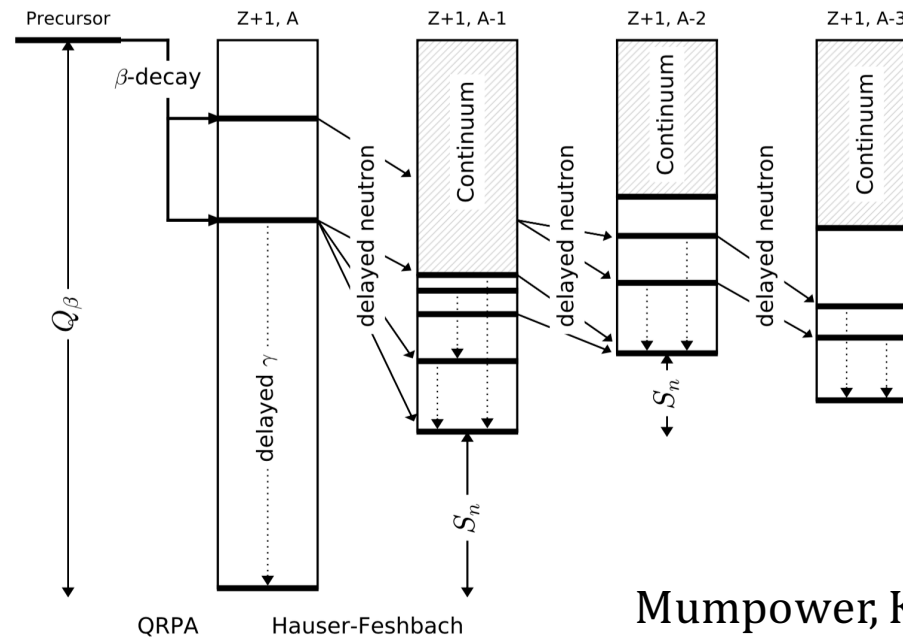
Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, and Möller (2018)
arXiv:1802.04398



Andreyev, Nishio, and Schmidt (2018)



Black outline – probability of multi-chance β df > 10%

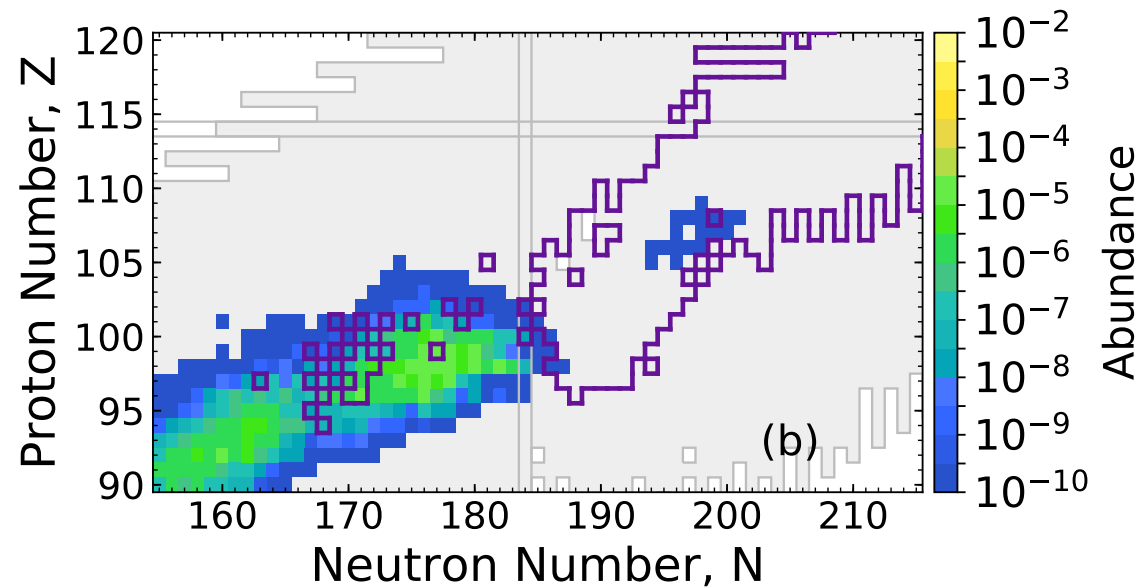
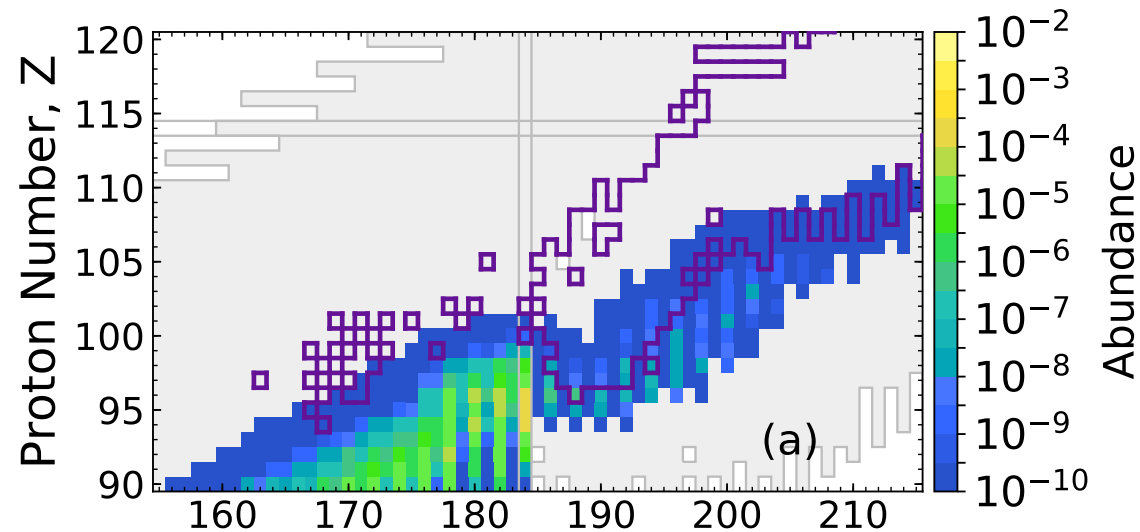


Mumpower, Kawano, and Möller (2016)

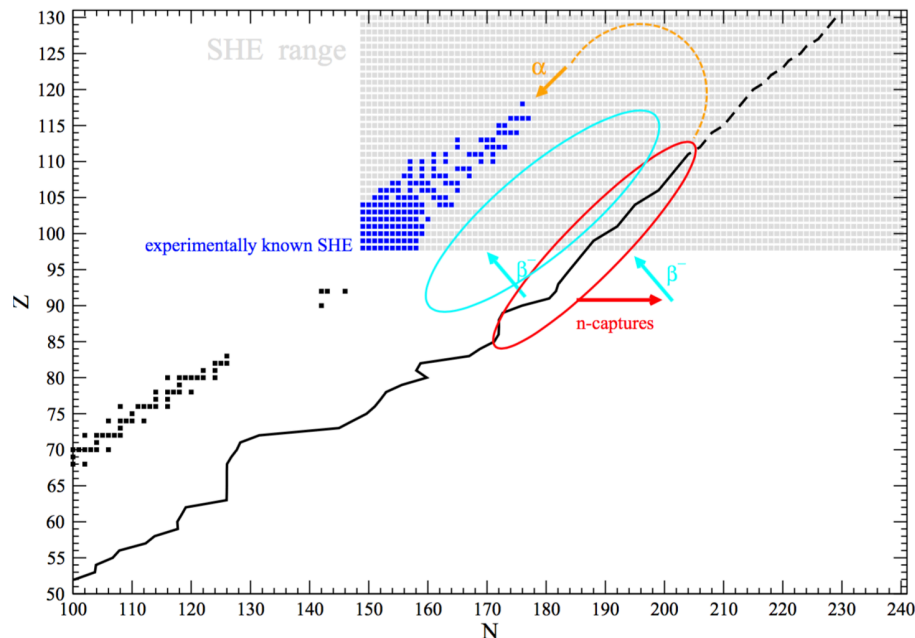
Superheavy island blocked by β -delayed fission

Right: Example - β df alone can prevent the population of the superheavy island of stability
 (purple outline – probability of β df > 90%)

Below: previous calculations with $Z < 100$ identified possibility to circumvent region with β df probability $\sim 100\%$



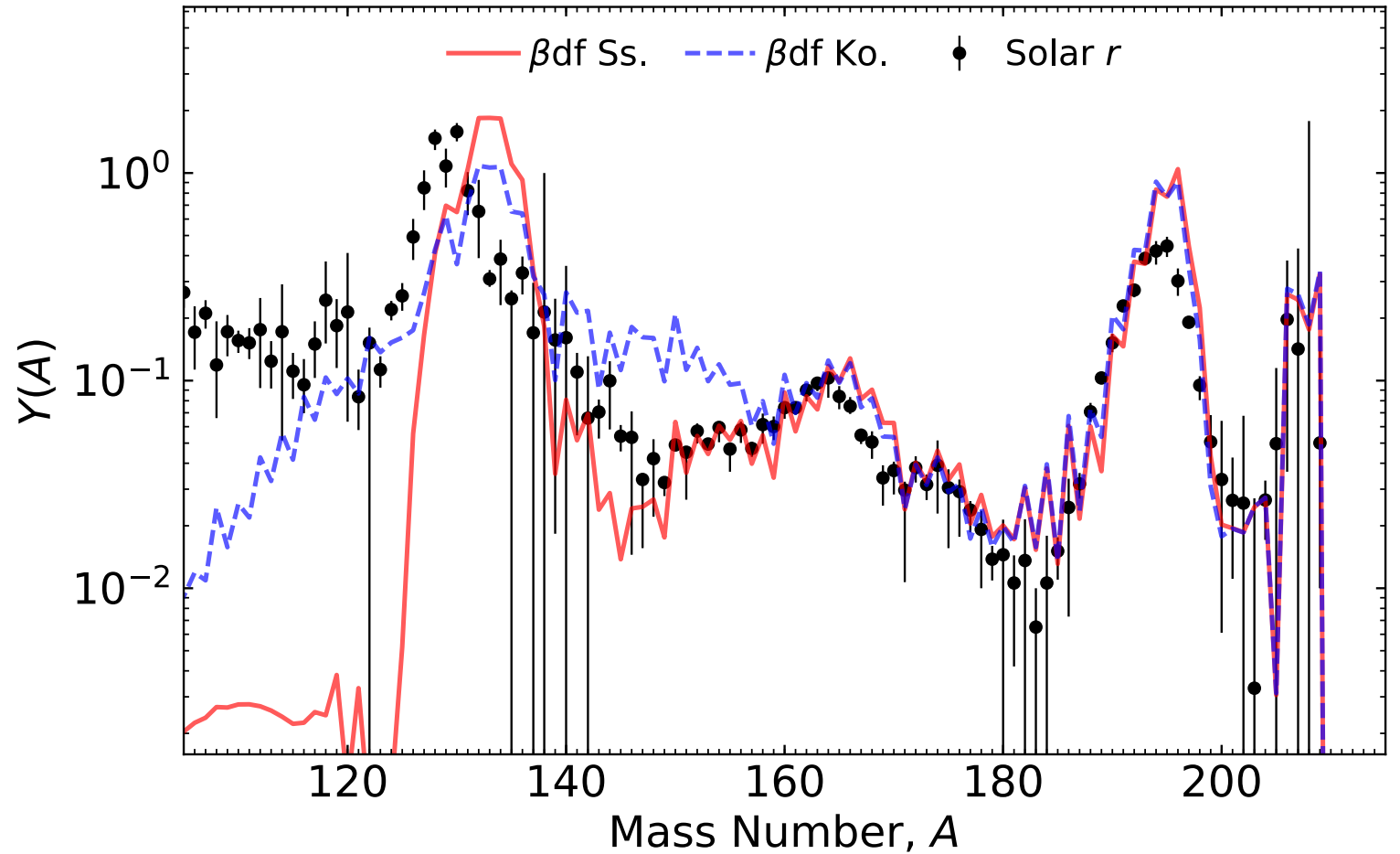
Petermann,
 Langanke,
 Martínez-Pinedo,
 Panov, Reinhard,
 and Thielemann
 (2012)



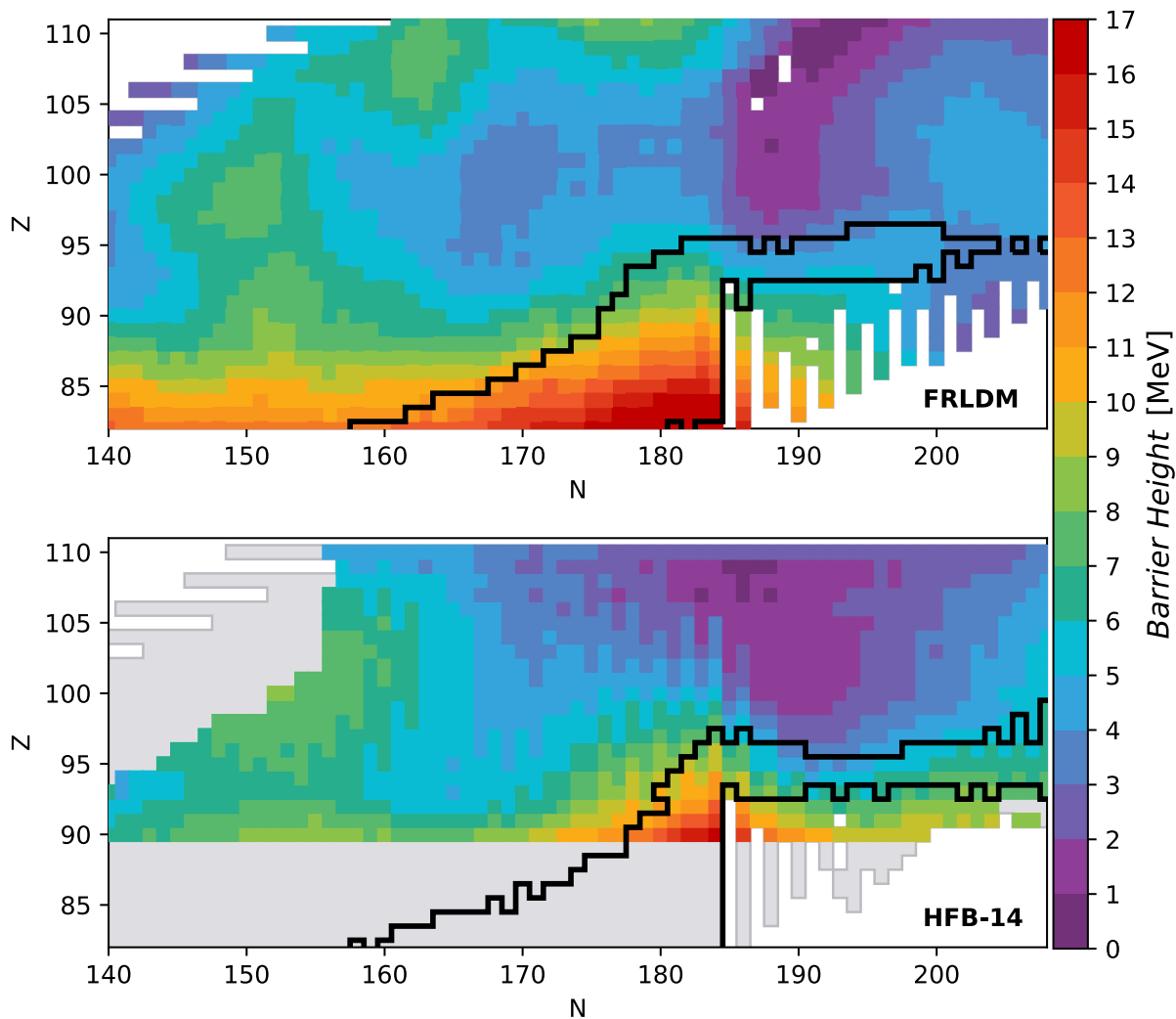
See also:
 Thielemann,
 Metzinger, and
 Klapdor (1983)

β -delayed fission yields in r -process nucleosynthesis

Right: keeping a symmetric (50/50) split for neutron-induced fission yields while exchanging β df yields from Kodama et al to a symmetric split

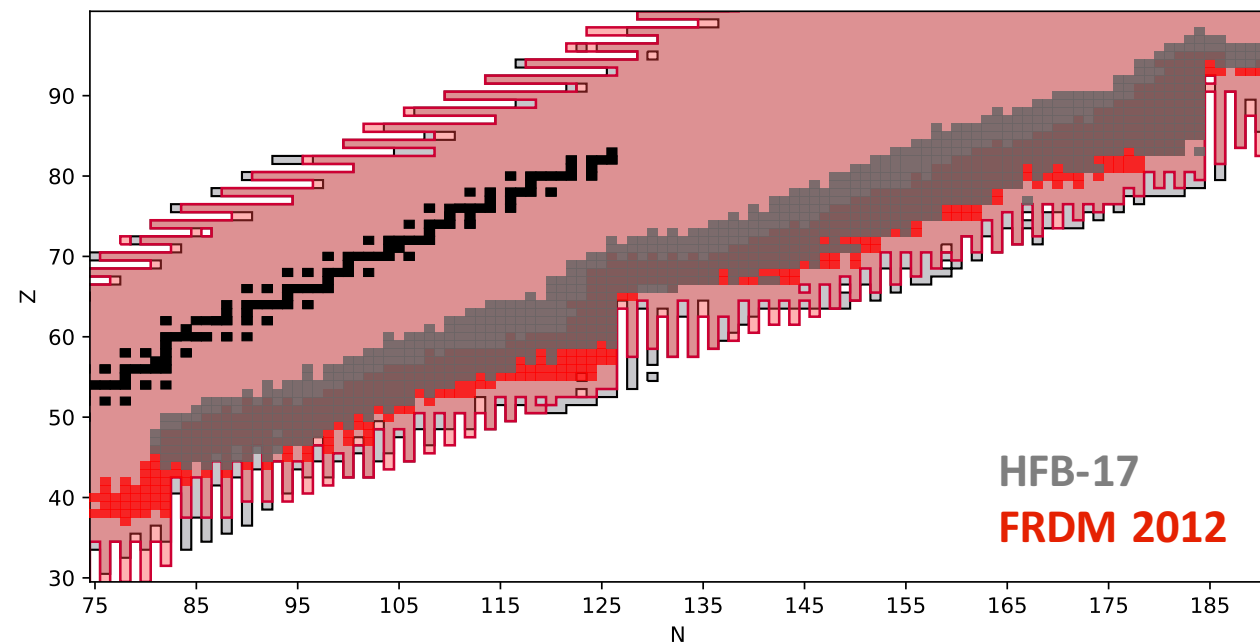


Shaping the r -process second peak: fission barriers and shell closures

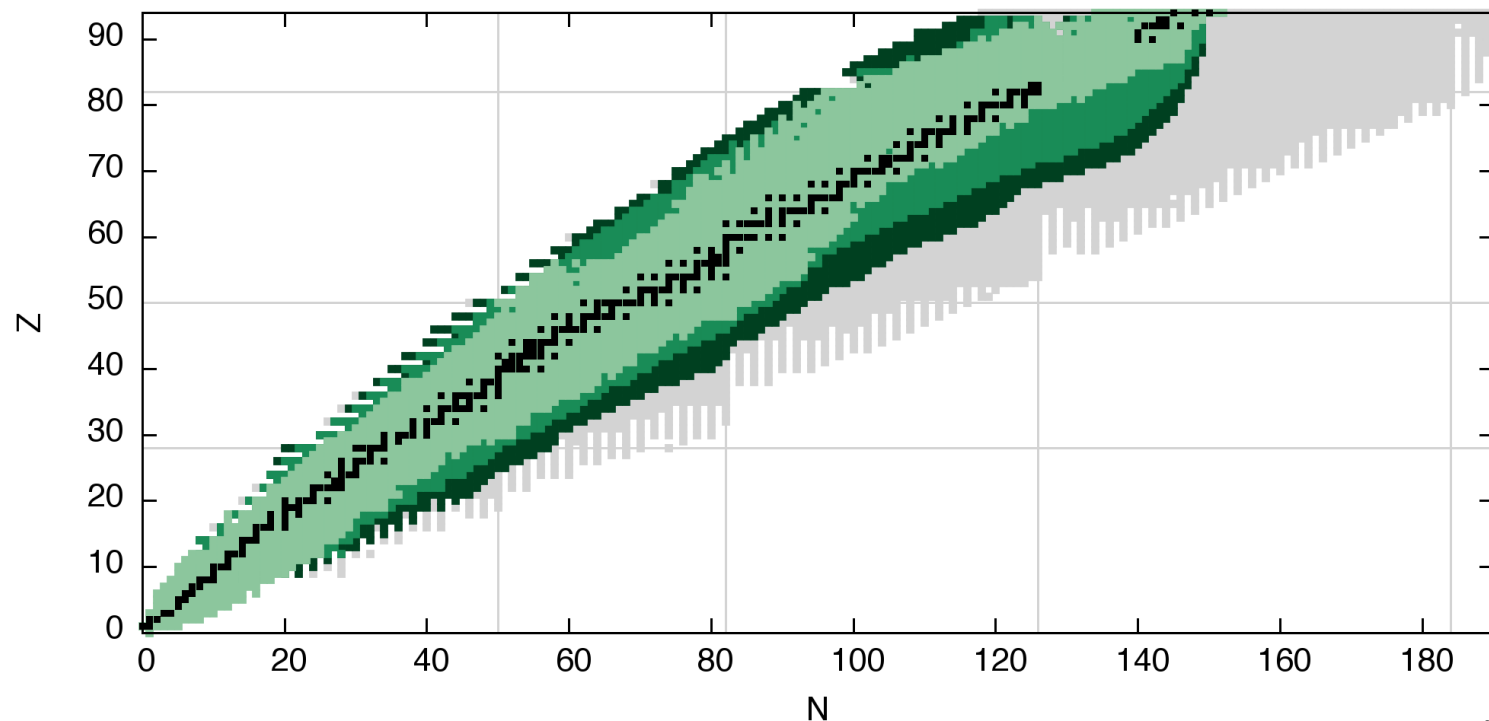
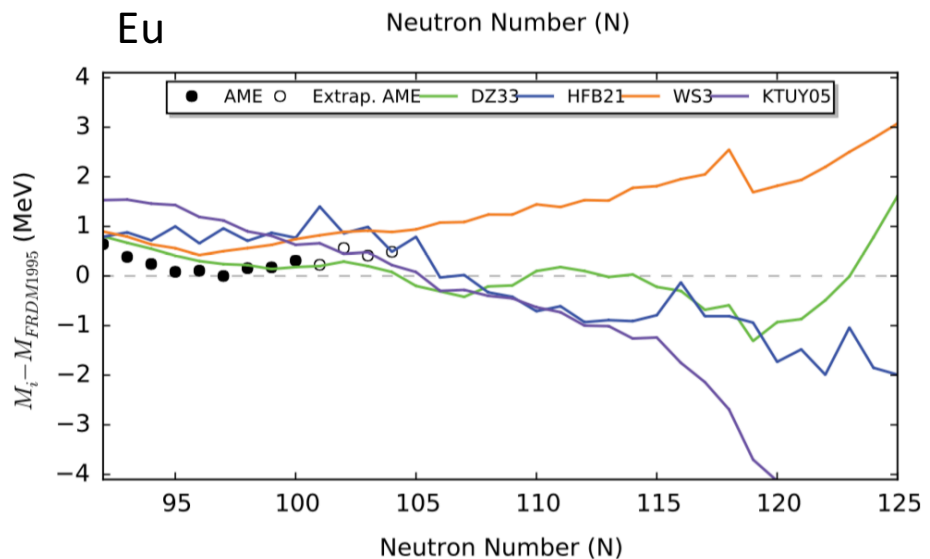
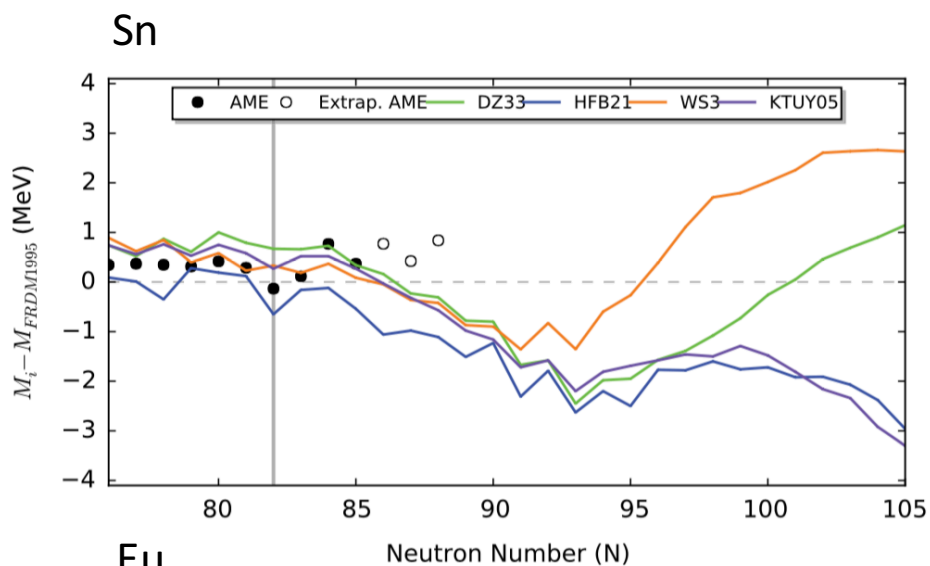


Left: impact of fission barrier heights on the r -process path

Below: dripline mass model comparison and effect on the abundances near N=82 ($A \sim 130$ peak)



Masses: Model Divergence and FRIB Reach



Experimental Mass Measurements:

AME 2016

FRIB - Day 1

FRIB - Designed Beam Intensity

Surman and
Mumpower

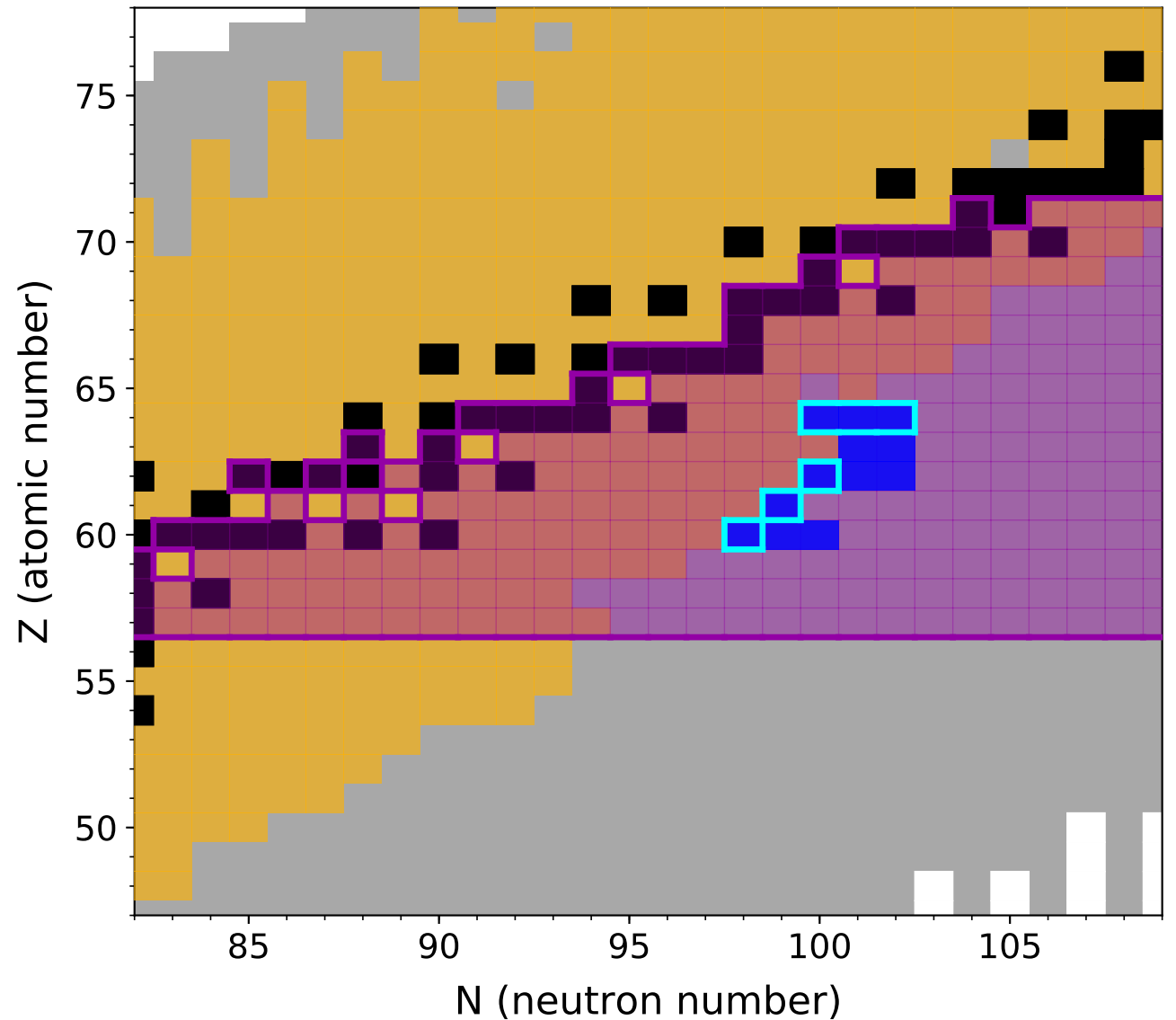
Studying Rare-Earth Nuclei to Understand *r*-process Lanthanide Production

Experimental Mass Measurements:

AME 2016

Jyväskylä

CPT at CARIBU



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

Experimental Mass Measurements:

AME 2016

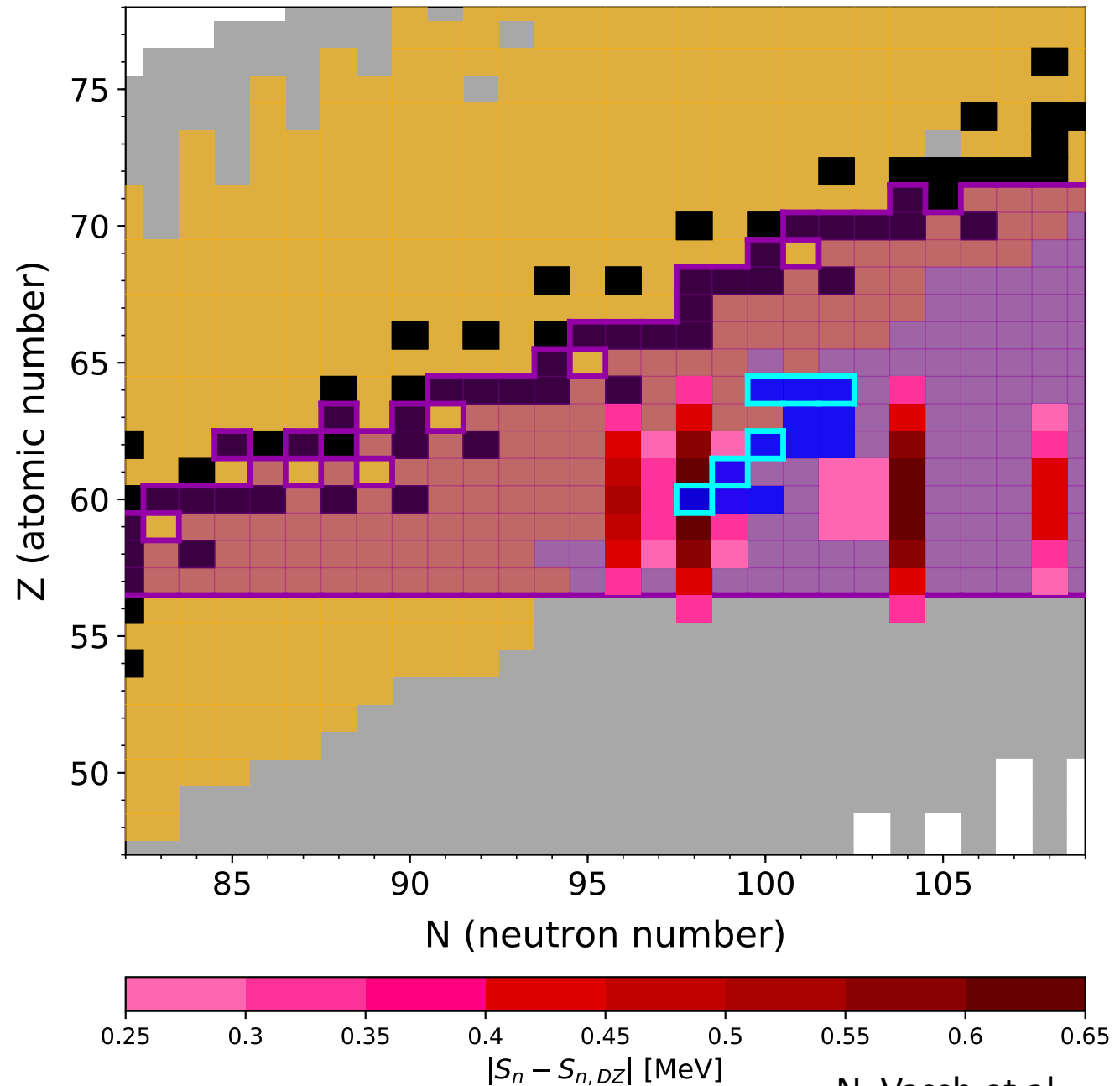
Jyväskylä

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, β -decay, fission....)

Nuclear masses



Nucleosynthesis code
(PRISM)



**Abundance
prediction**

Reverse Engineering r -process calculation

Astrophysical conditions

Fission Yields

Rates (n capture, β -decay, fission....)



Nucleosynthesis code
(PRISM)



Abundance
prediction

Nuclear masses



Markov Chain Monte
Carlo (MCMC)
Likelihood function



MCMC procedure

- Monte Carlo mass corrections

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

- Check: $\sigma_{\text{rms}}^2(M_{\text{AME12}}, M) \leq \sigma_{\text{rms}}^2(M_{\text{AME12}}, M_{DZ})$

- Check:

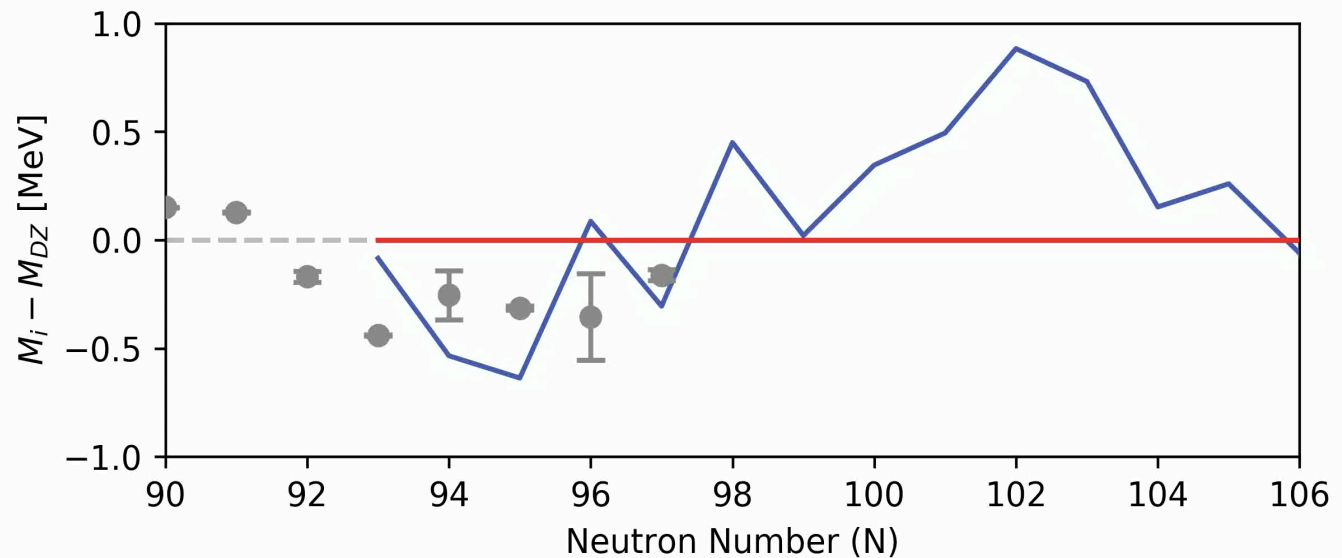
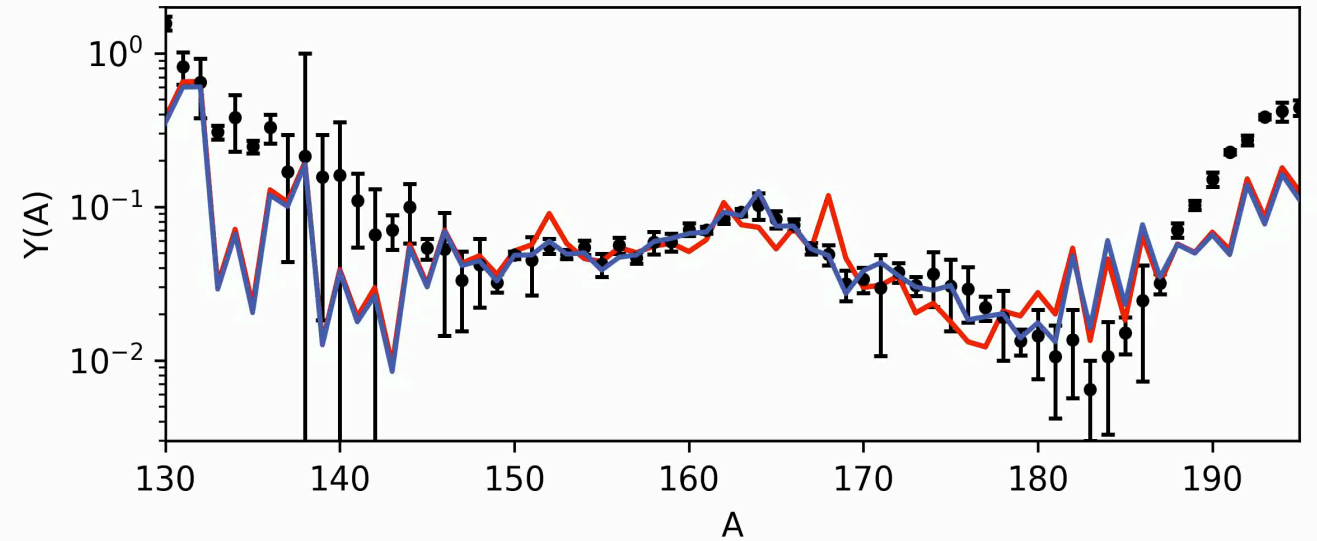
$$D_n(Z, A) = (-1)^{A-Z+1} (S_n(Z, A+1) - S_n(Z, A)) > 0$$

- Update nuclear quantities and rates
- Perform nucleosynthesis calculation

- Calculate $\chi^2 = \sum_{A=150}^{180} \frac{(Y_{\odot,r}(A) - Y(A))^2}{\Delta Y(A)^2}$

- Update parameters OR revert to last success

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



Black – solar abundance data

Grey – AME 2012 data

Red – values at current step

Blue – best step of entire run

Dynamic Mechanism of Rare-Earth Peak Formation

Detailed balance implies

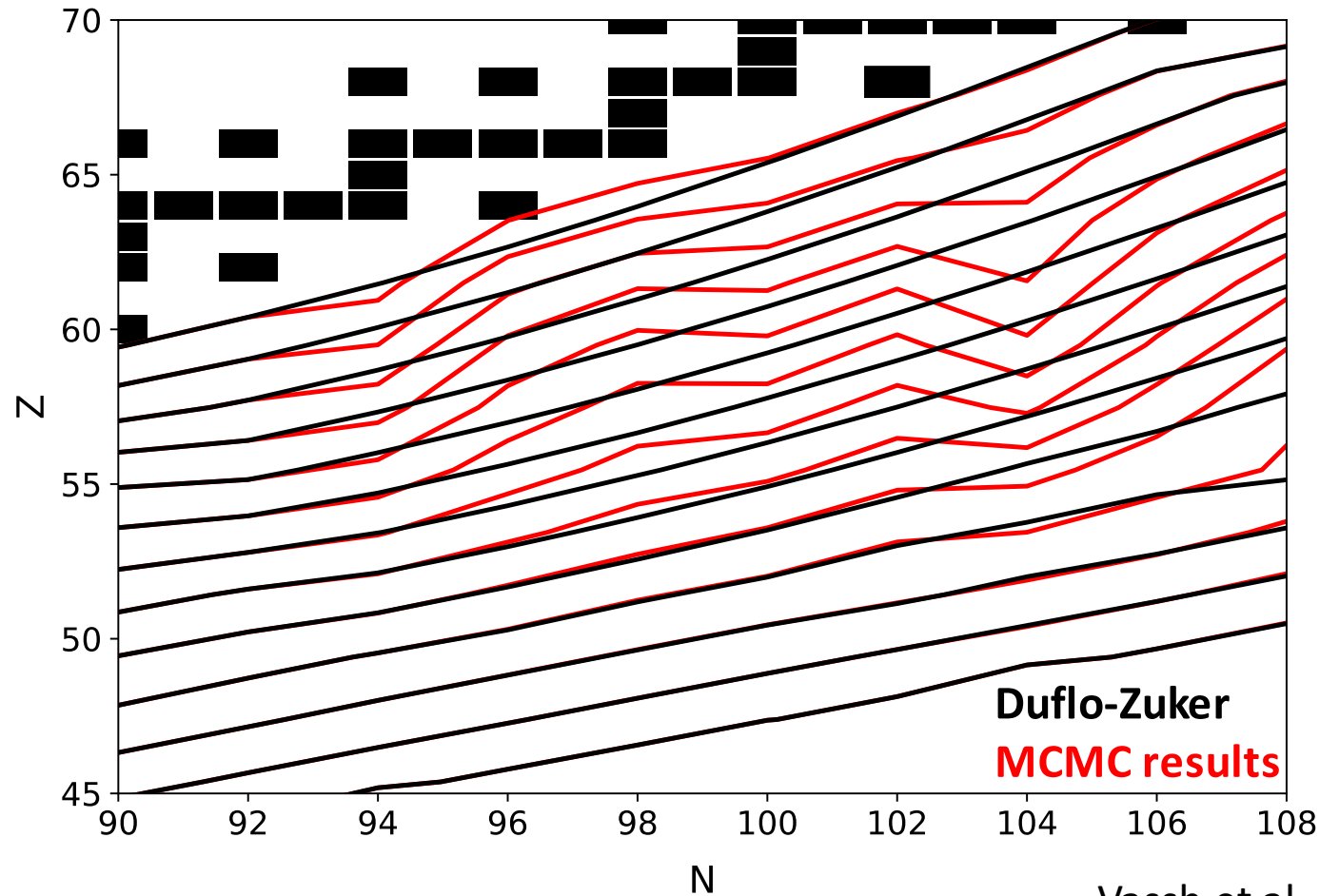
$$(\gamma, n) \propto e^{-S_n/kT}$$



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



Pile-up of material at kinks

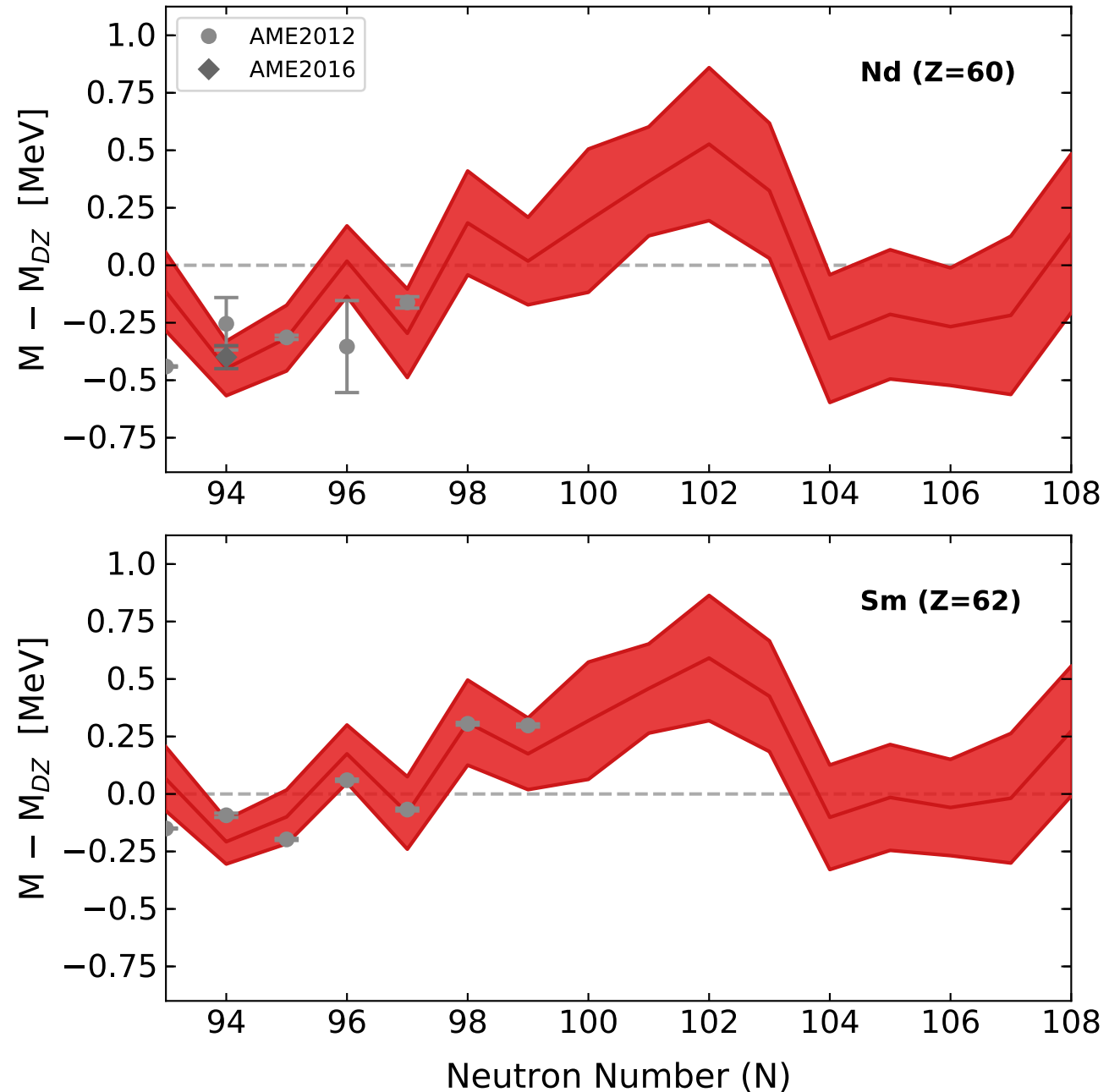


Vassh et al
(in preparation)

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 $\chi^2 \sim 23$

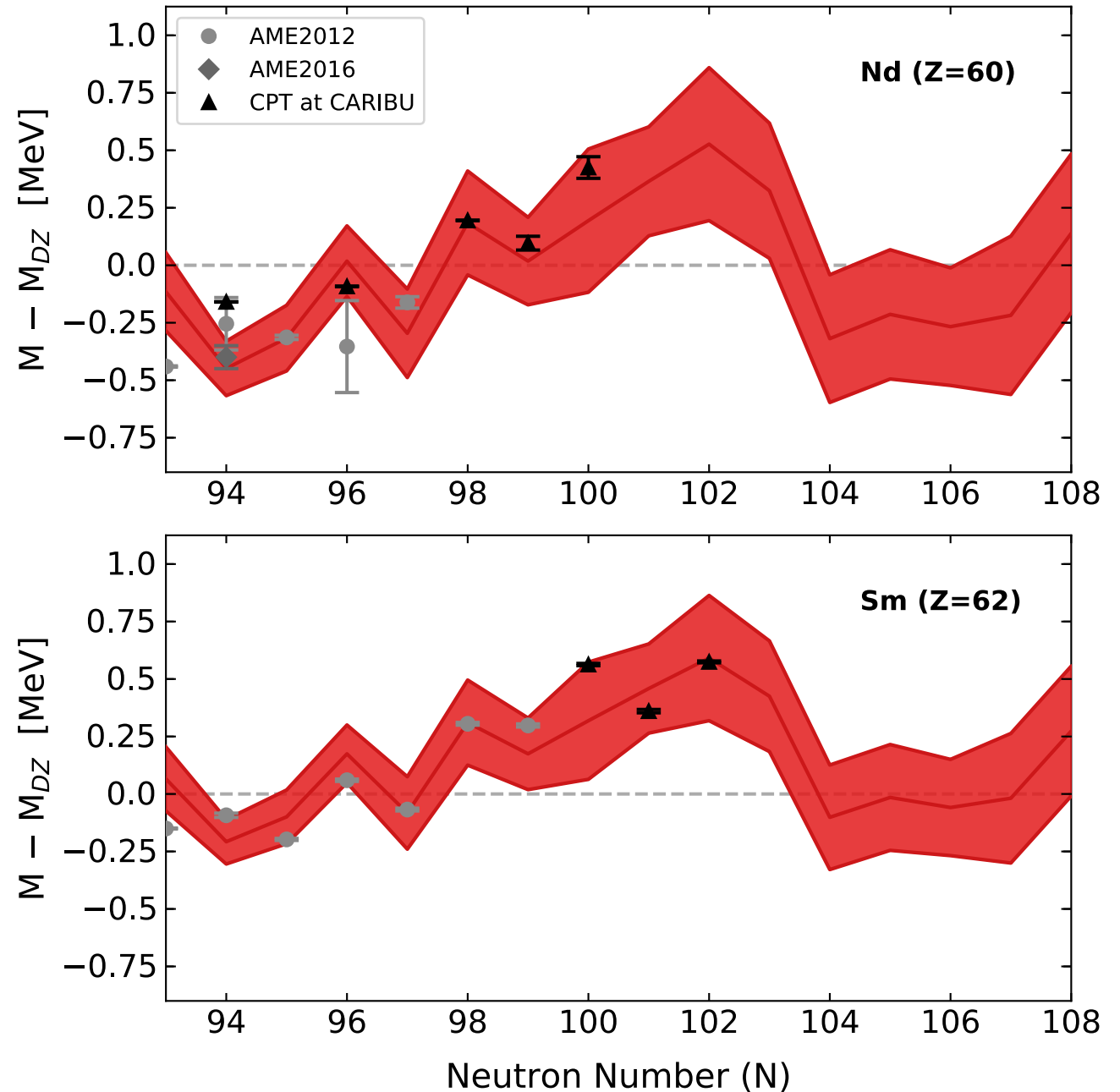
Orford, Vassh, Clark, McLaughlin, Mumpower,
Savard, Surman, Aprahamian, Buchinger,
Burkey, Gorelov, Hirsh, Klimes, Morgan,
Nystrom, and Sharma
(accepted to PRL)



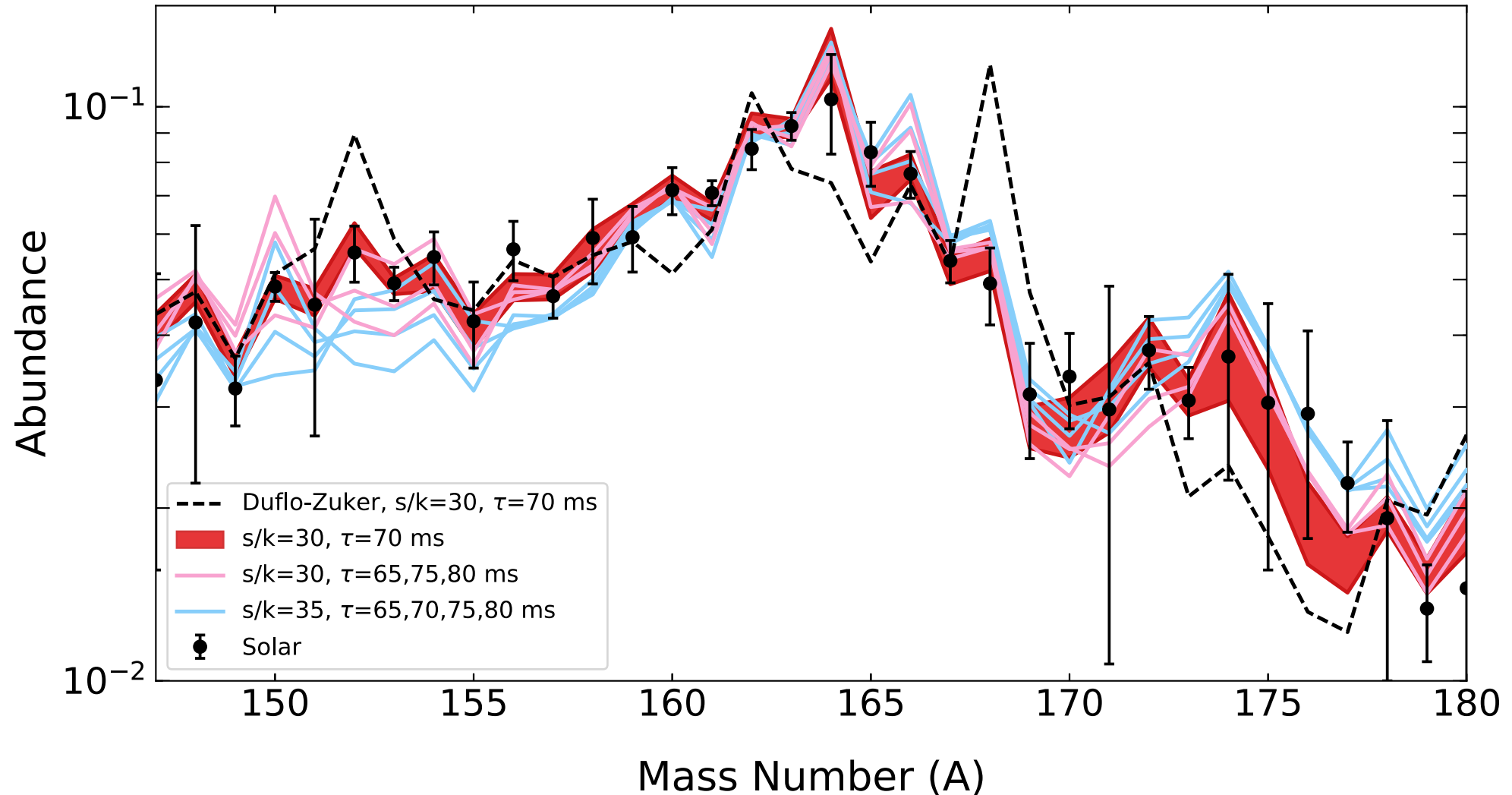
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Nystrom, and Sharma
(accepted to PRL)



Rare-Earth Peak with MCMC solutions

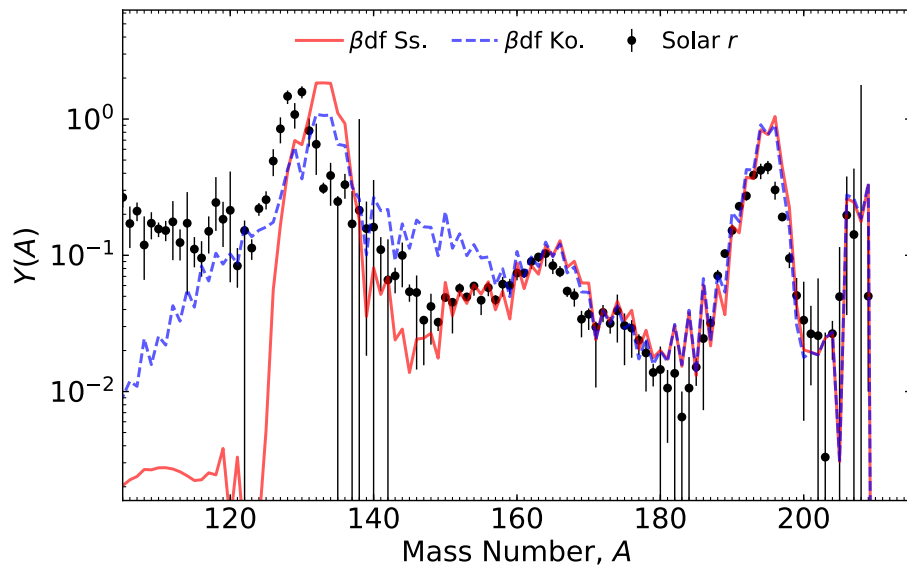


Nucleosynthesis in Neutron Star Mergers: Many Open Questions

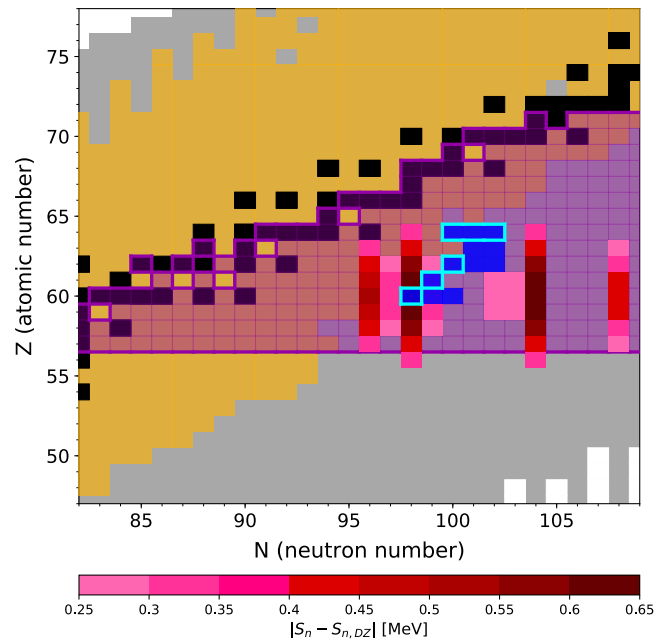
- Can mergers account for most of the r -process material observed in the galaxy?
- Are precious metals such as gold produced in sufficient amounts? Are actinides produced?
- Where within the merger environment does nucleosynthesis occur and under what specific conditions?
- Does fission of the heaviest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

Nucleosynthesis in Neutron Star Mergers: Many Open Questions

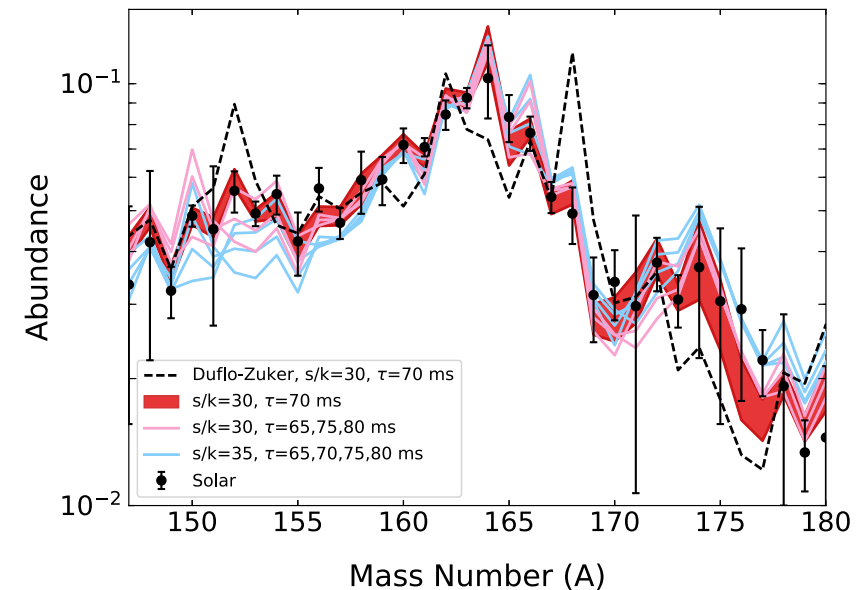
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Mumpower et al (arXiv:1802.04398)



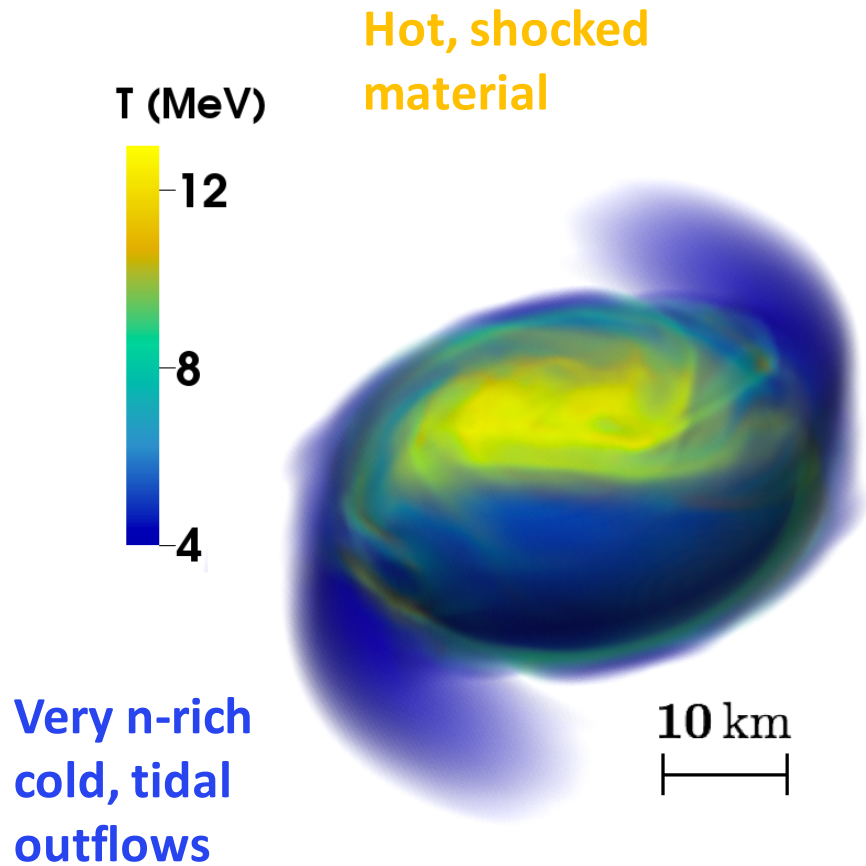
Vassh et al (in preparation)



Orford, Vassh, et al (accepted to PRL)

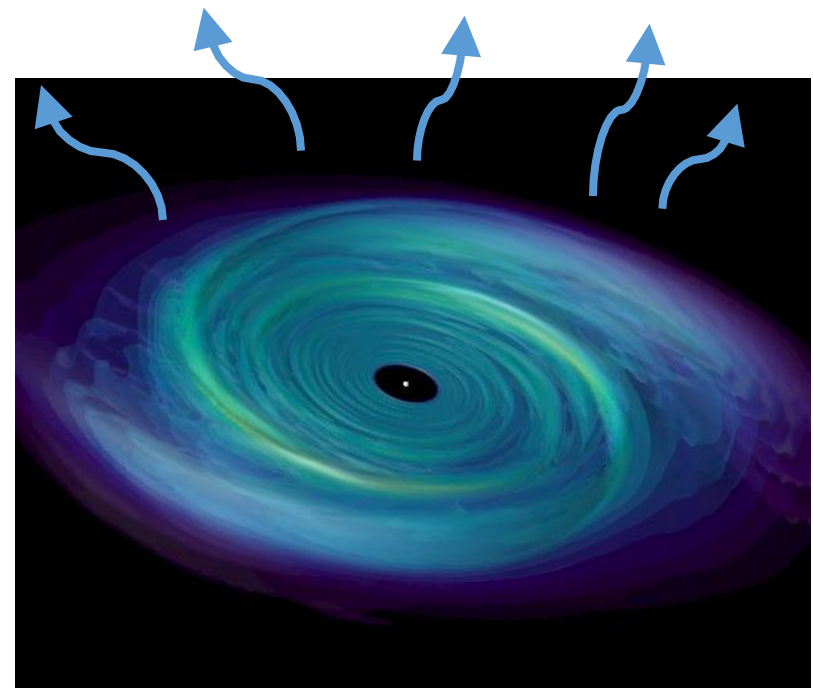
Back-up Slides

r-process sites within a Neutron Star Merger



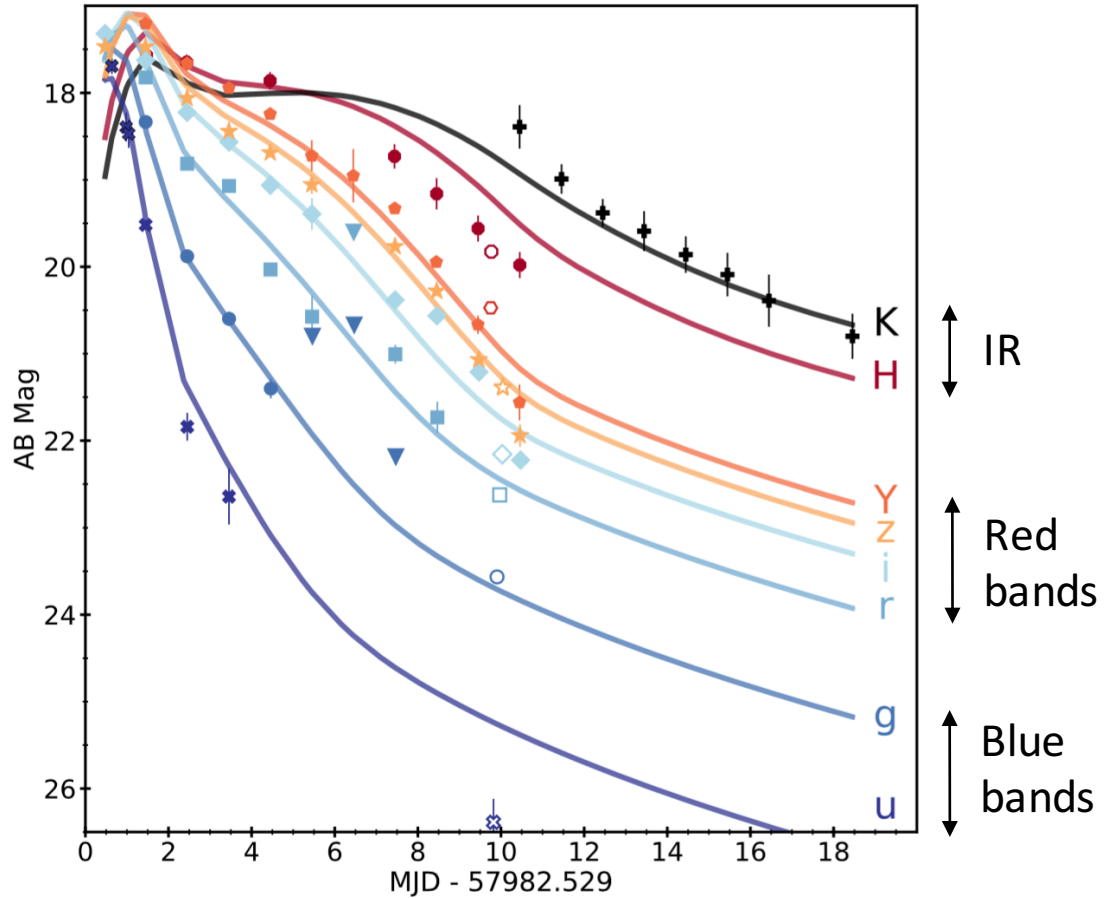
Foucart et al (2016)

Accretion disk winds – exact driving mechanism and neutron richness varies



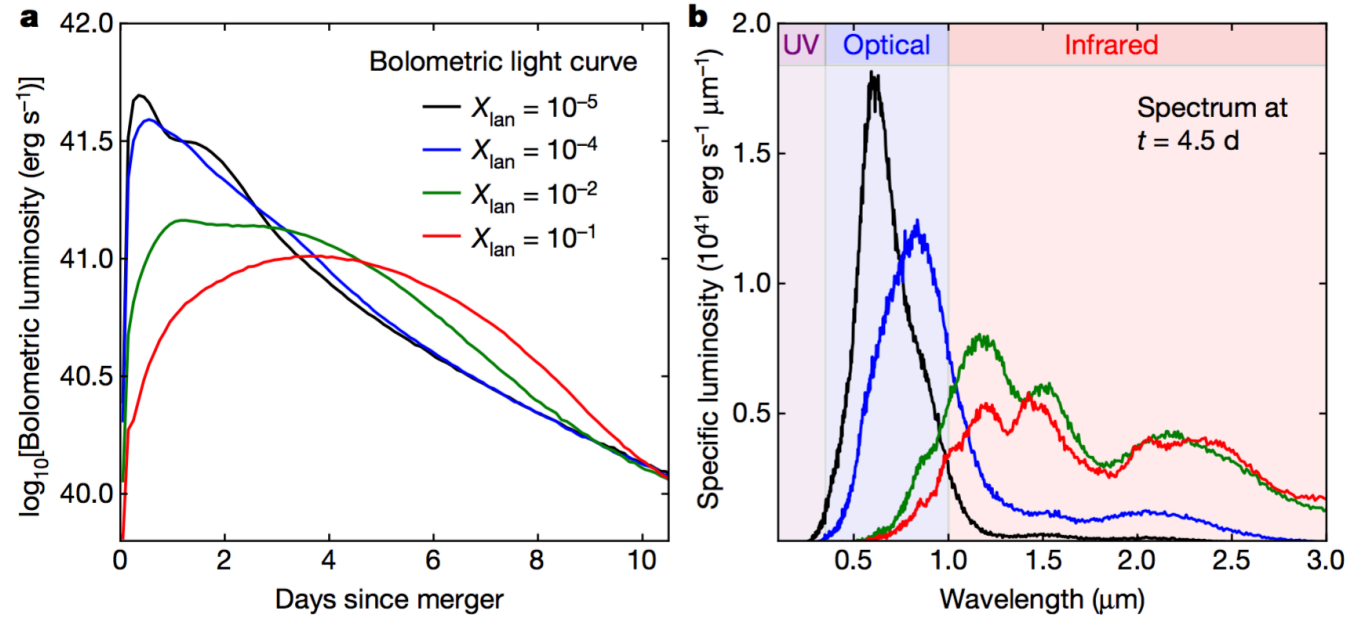
Owen and Blondin

Lanthanide production in GW170817: “red” kilonova



Cowperthwaite et al (ApJL 2017)

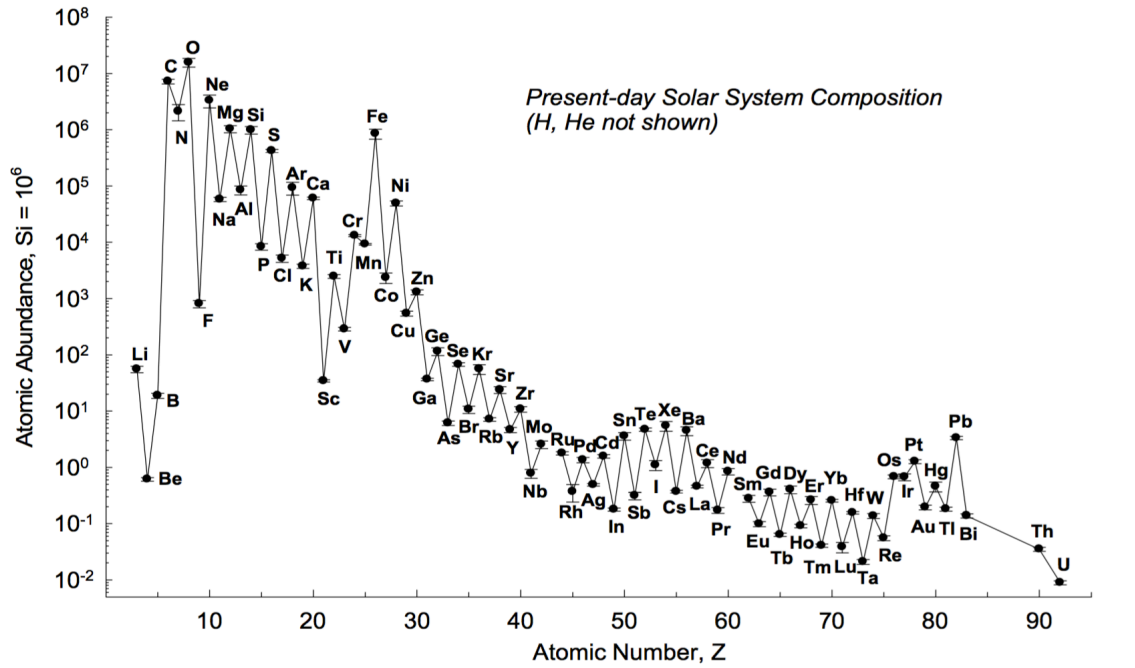
Lanthanide mass fraction \uparrow , opacity \uparrow , longer duration light curve shifted toward infrared



Kasen et al (*Nature* 2017)

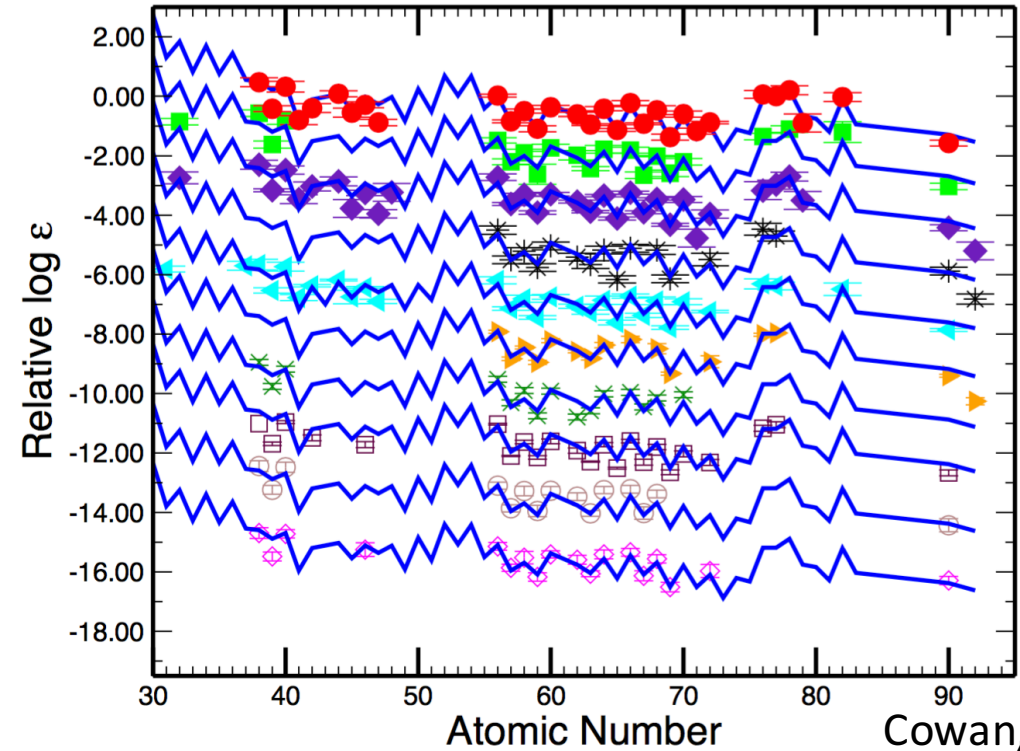
Observed Elemental Abundances

Solar System



Lodders (2010)

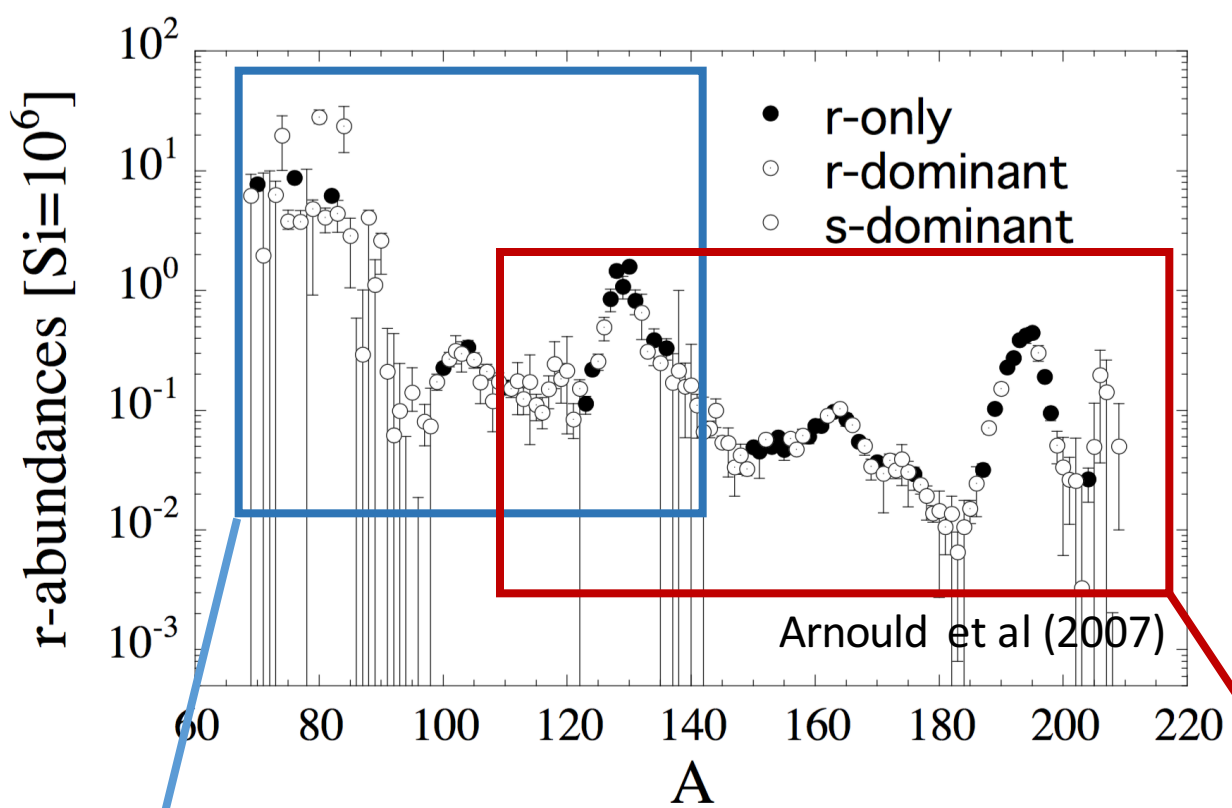
10 *r*-process rich halo stars



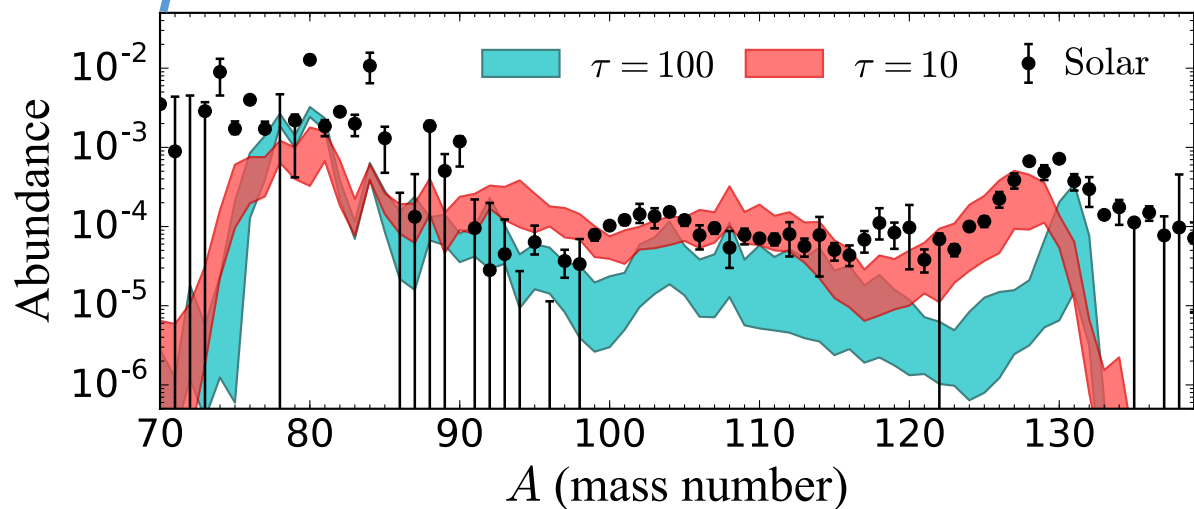
Cowan, Roederer,
Snedden and Lawler
(2011)

r-process Calculations for NSM Ejecta

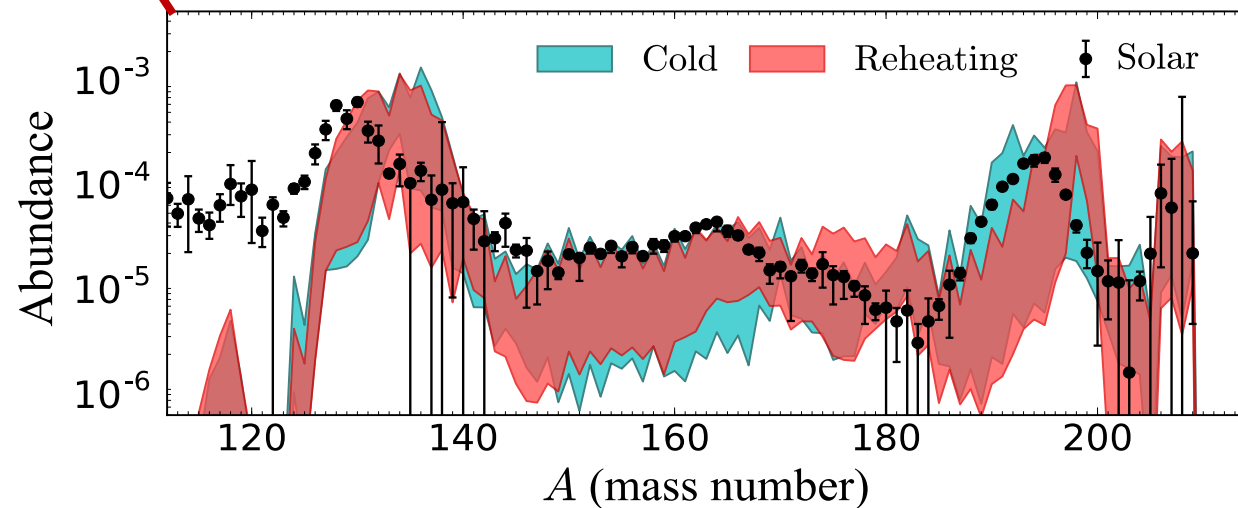
Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman and Wollaeger (2017)

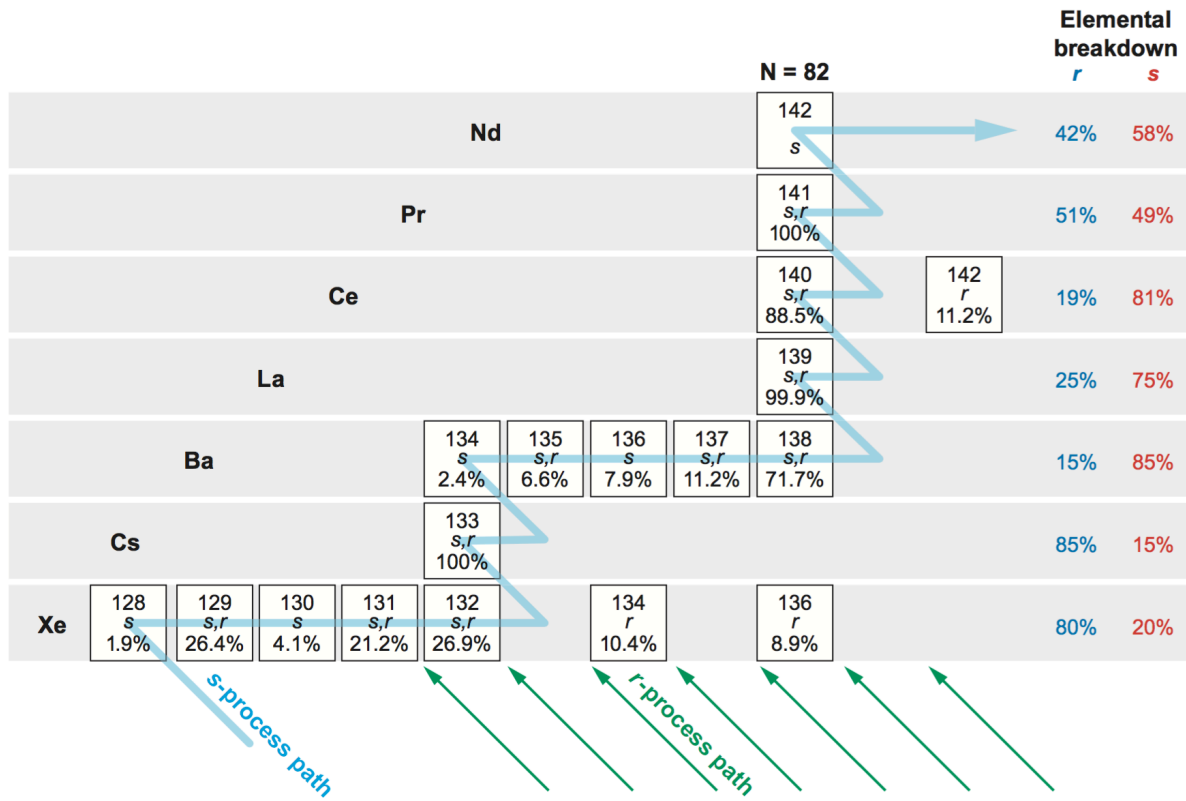


Wind ejecta ($s/k=10, Y_e=0.27$)



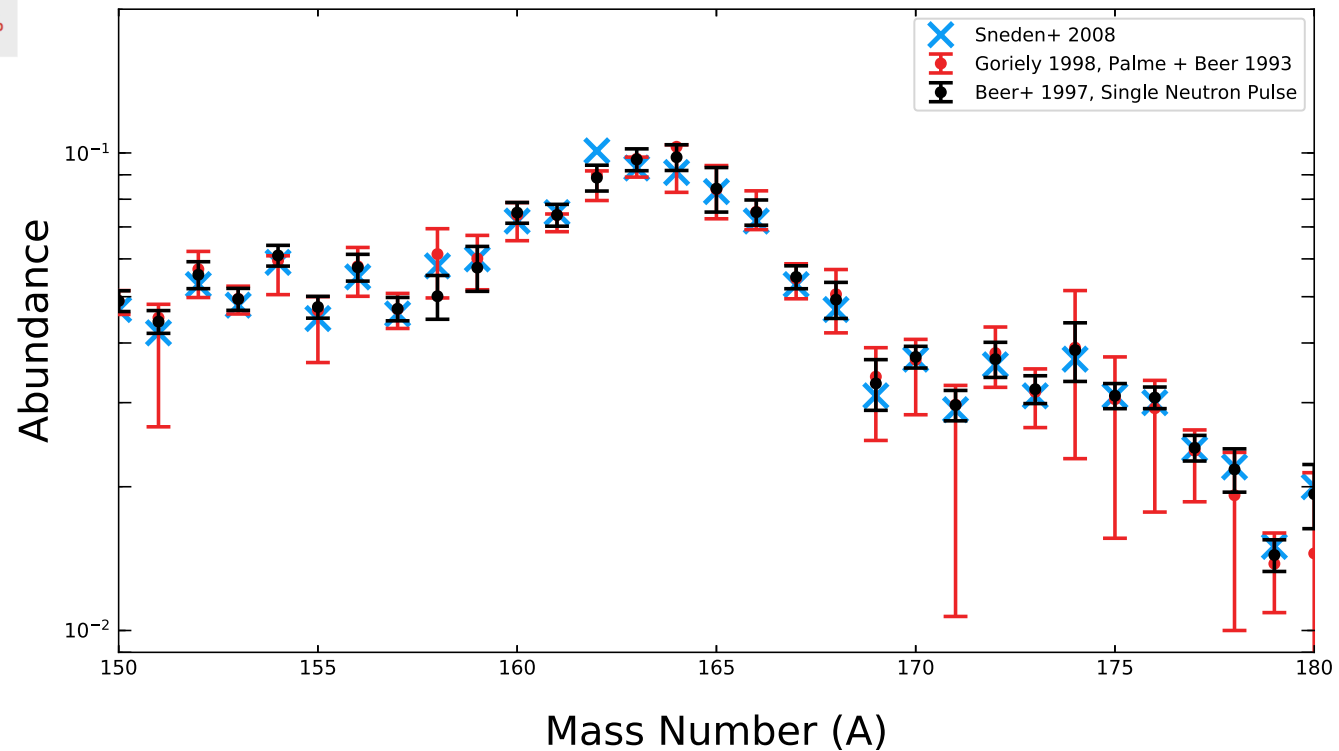
Very n-rich dynamical ejecta



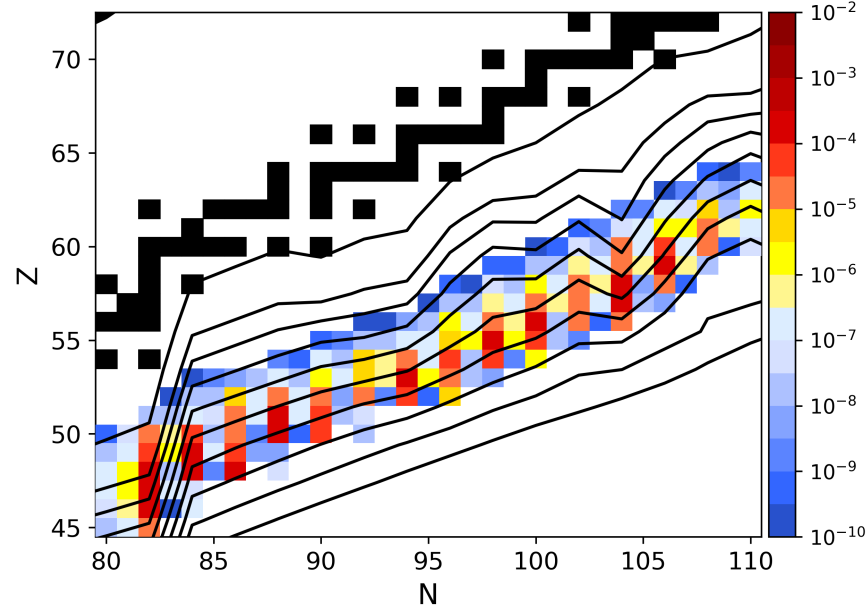
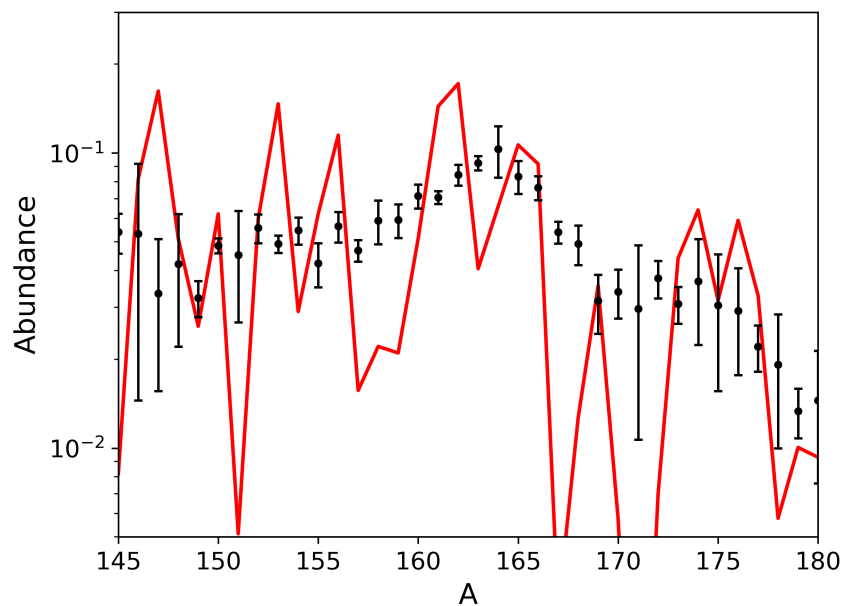
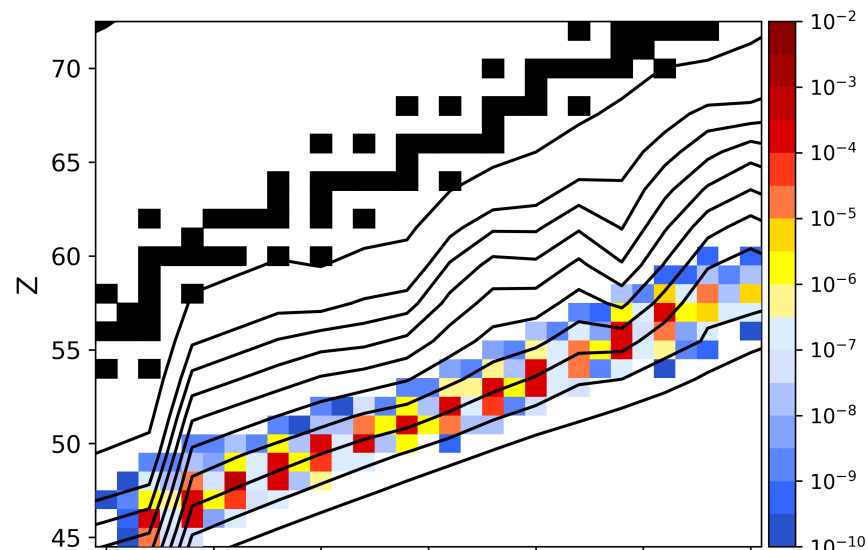
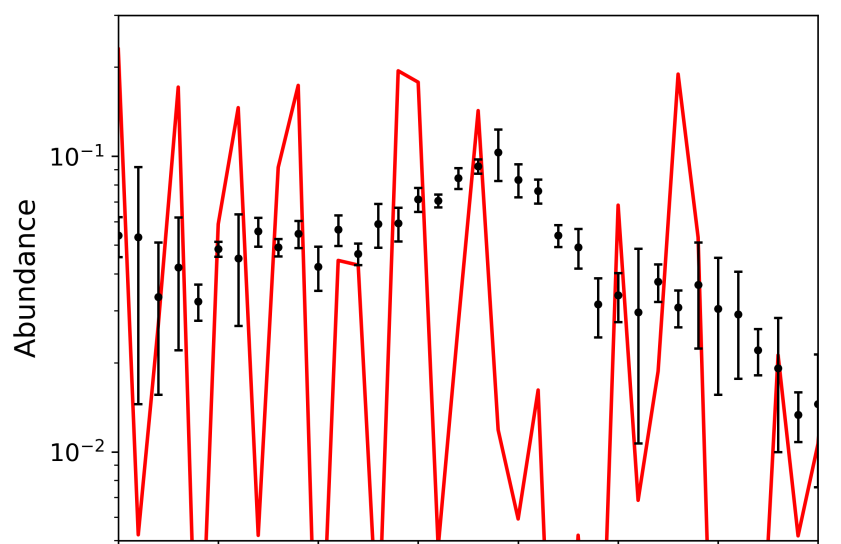


Sneden, Cowan, and Gallino (2008)

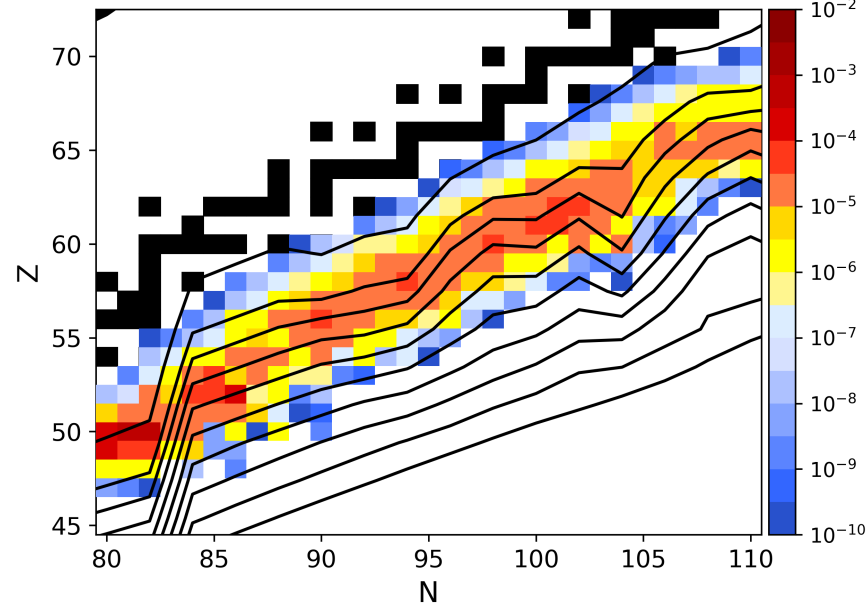
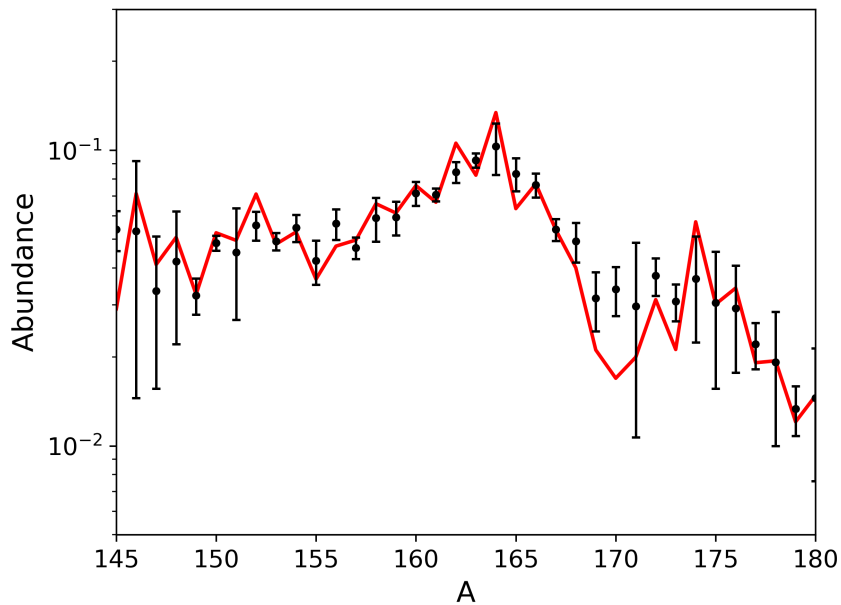
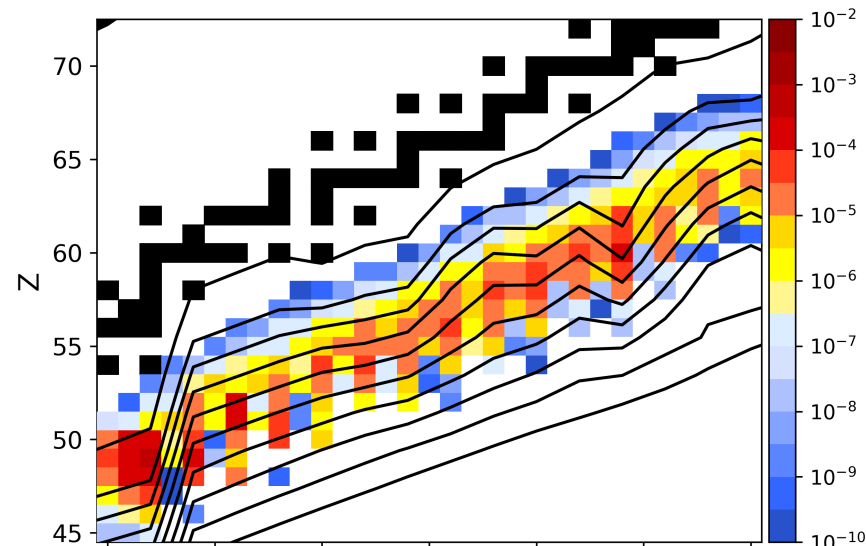
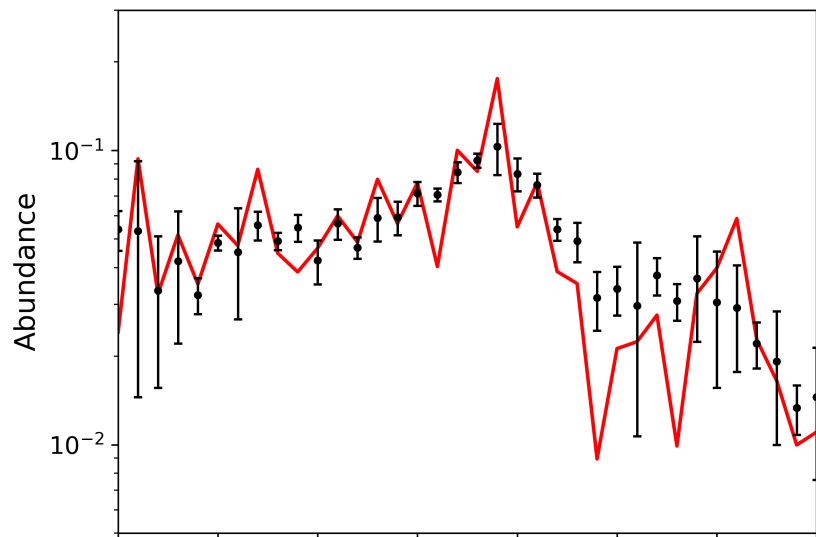
Sensitivity to Solar Data: uncertainty from the s-process subtraction

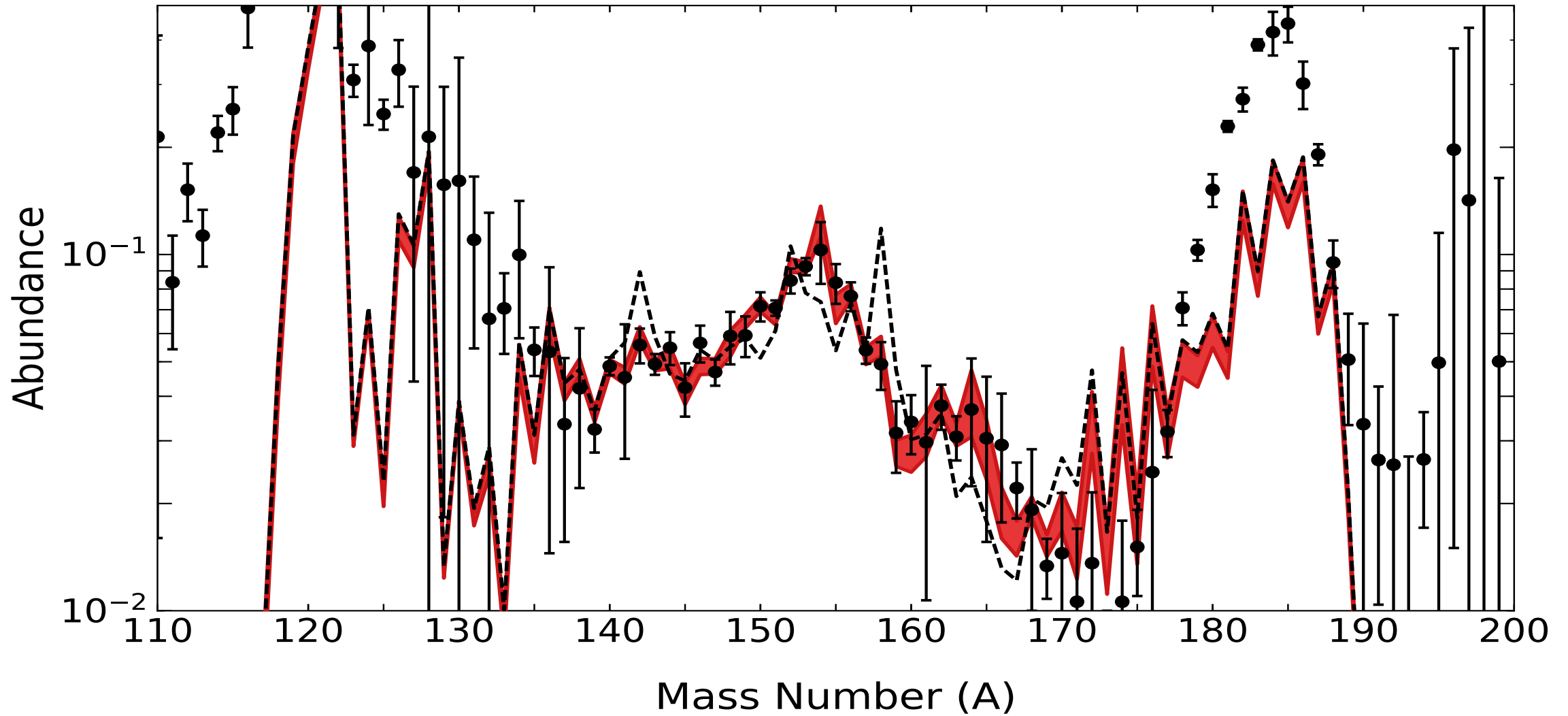


Peak Formation with an MCMC Mass Solution



Peak Formation with an MCMC Mass Solution





(Abundance pattern range using the mass values found by our MCMC given disk wind conditions $s/k=30$, $\tau=70$ ms, $Y_e=0.2$)

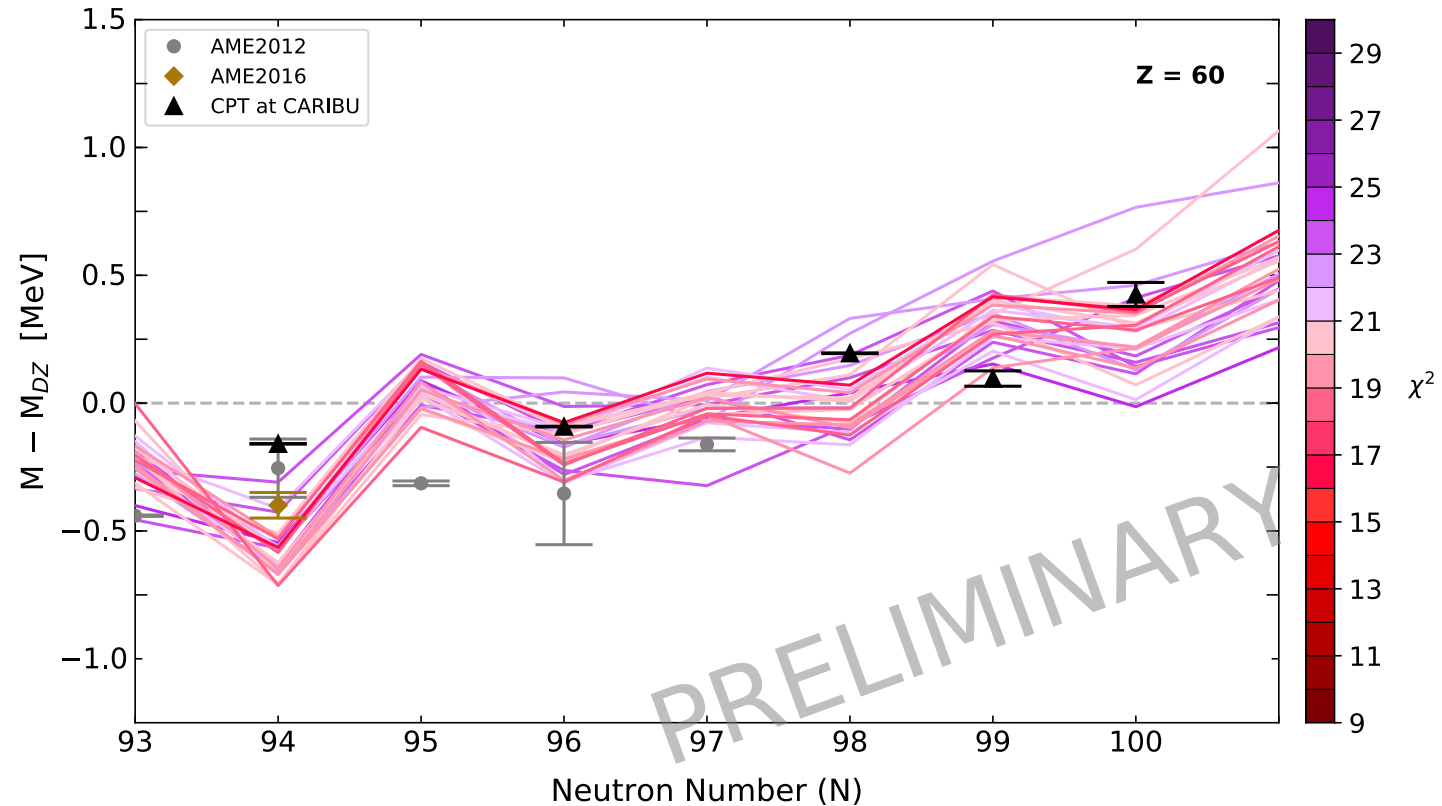
Vassh et al (in preparation)

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



30 Runs (Best Step Colored by χ^2)



Vassh et al
(in preparation)