Studying lanthanide production in *r*-process nucleosynthesis

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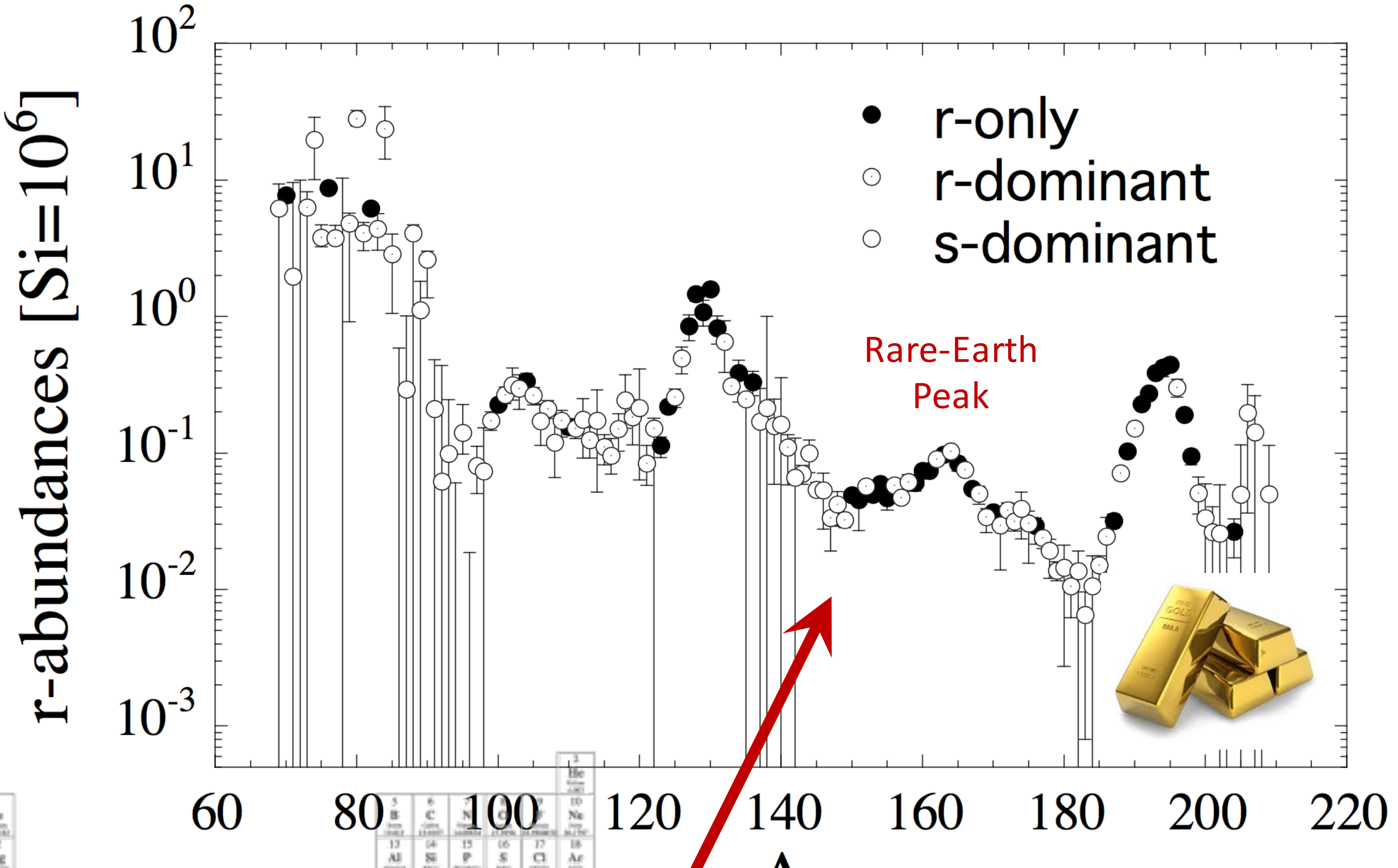
CIPANP 6/1/18

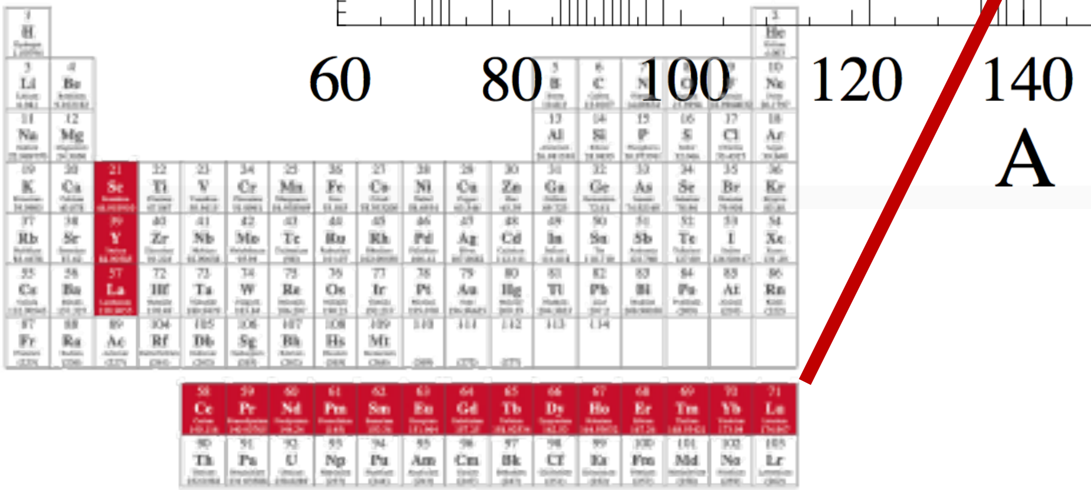
Fission In R-process Elements

Observed Solar *r*-process Residuals

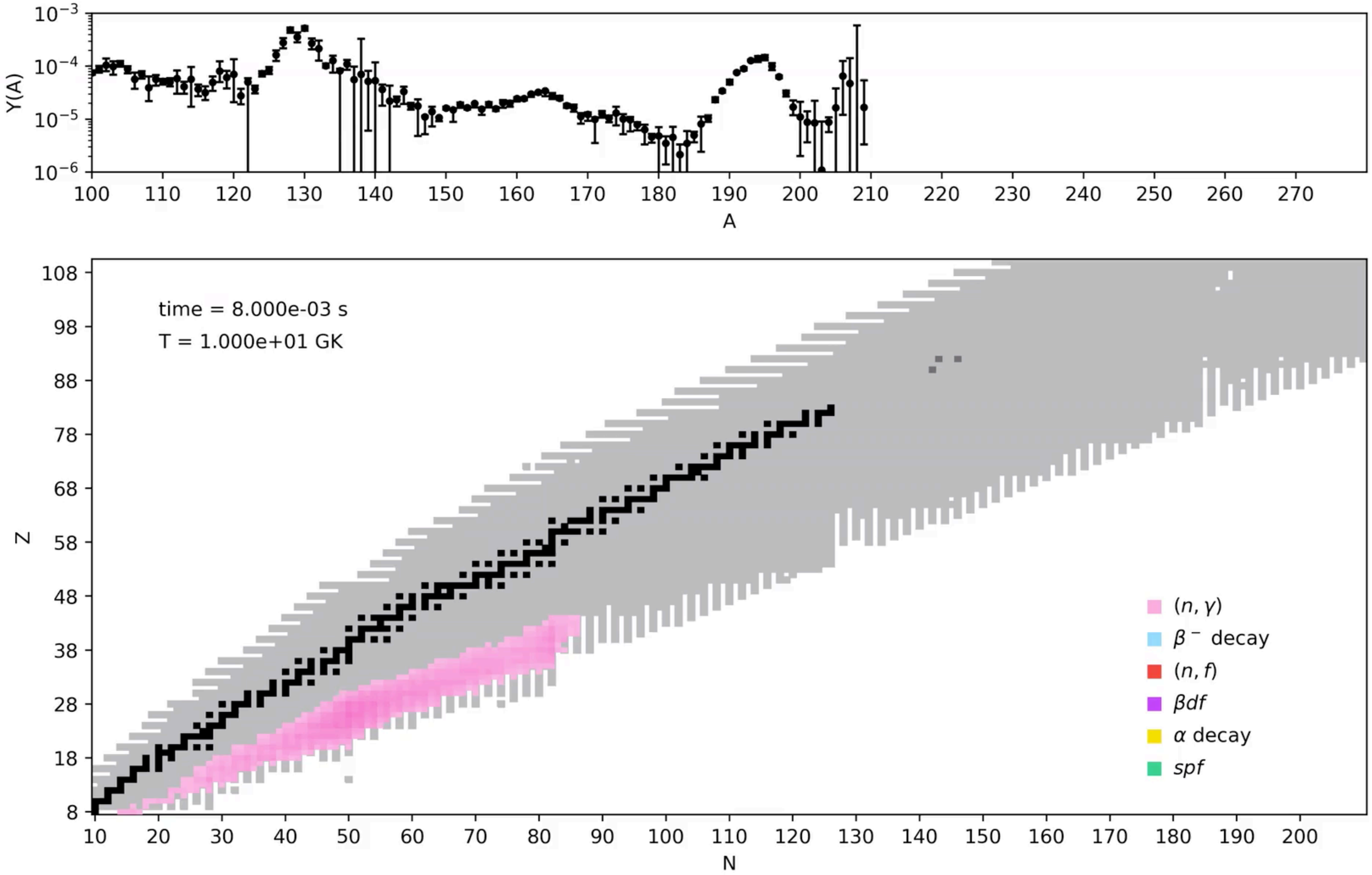
Depending on the conditions, the *r*-process can produce:

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



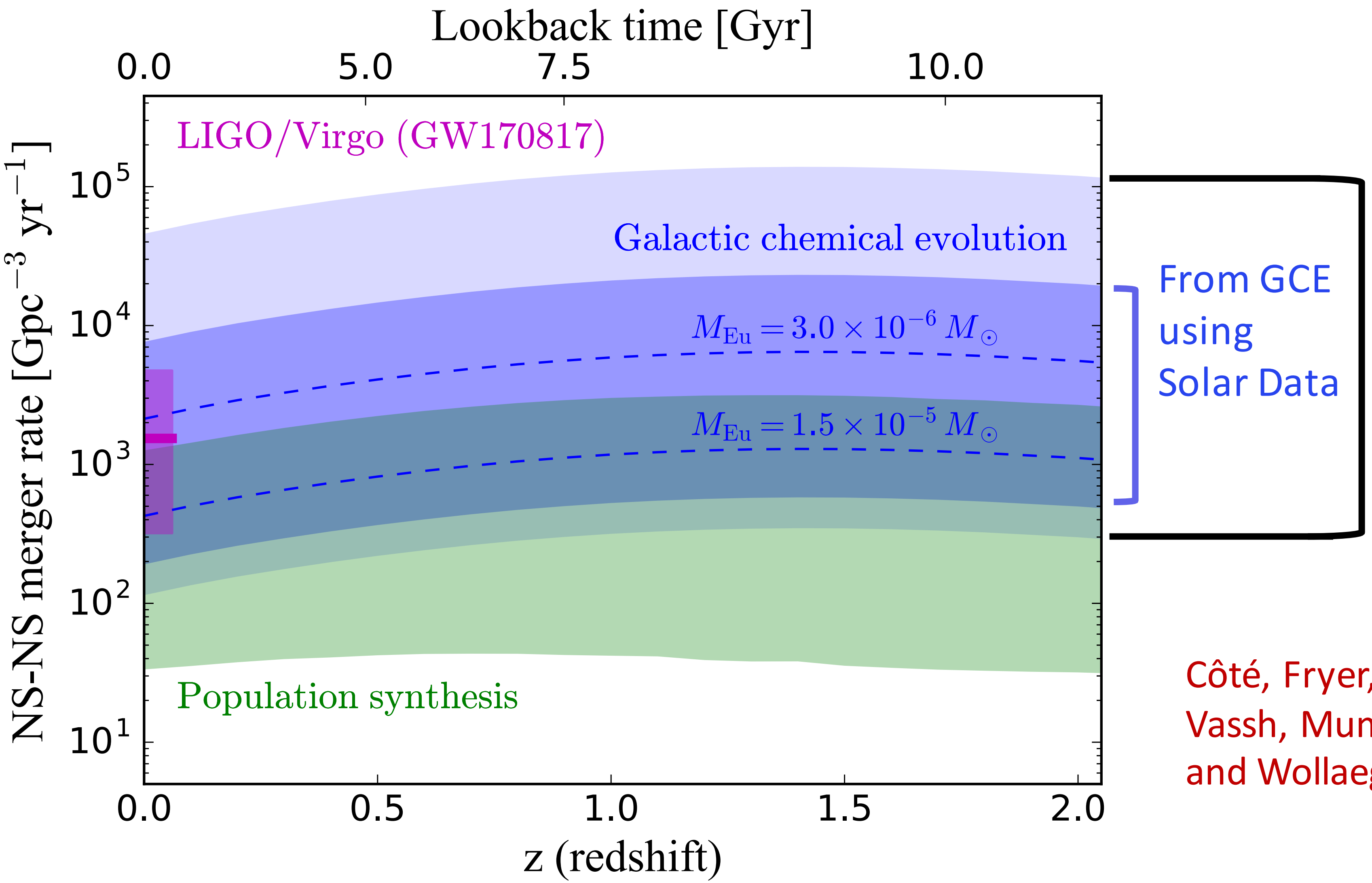


Arnould, Goriely and Takahashi (2007)



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

GW170817 and *r*-process uncertainties from nuclear physics

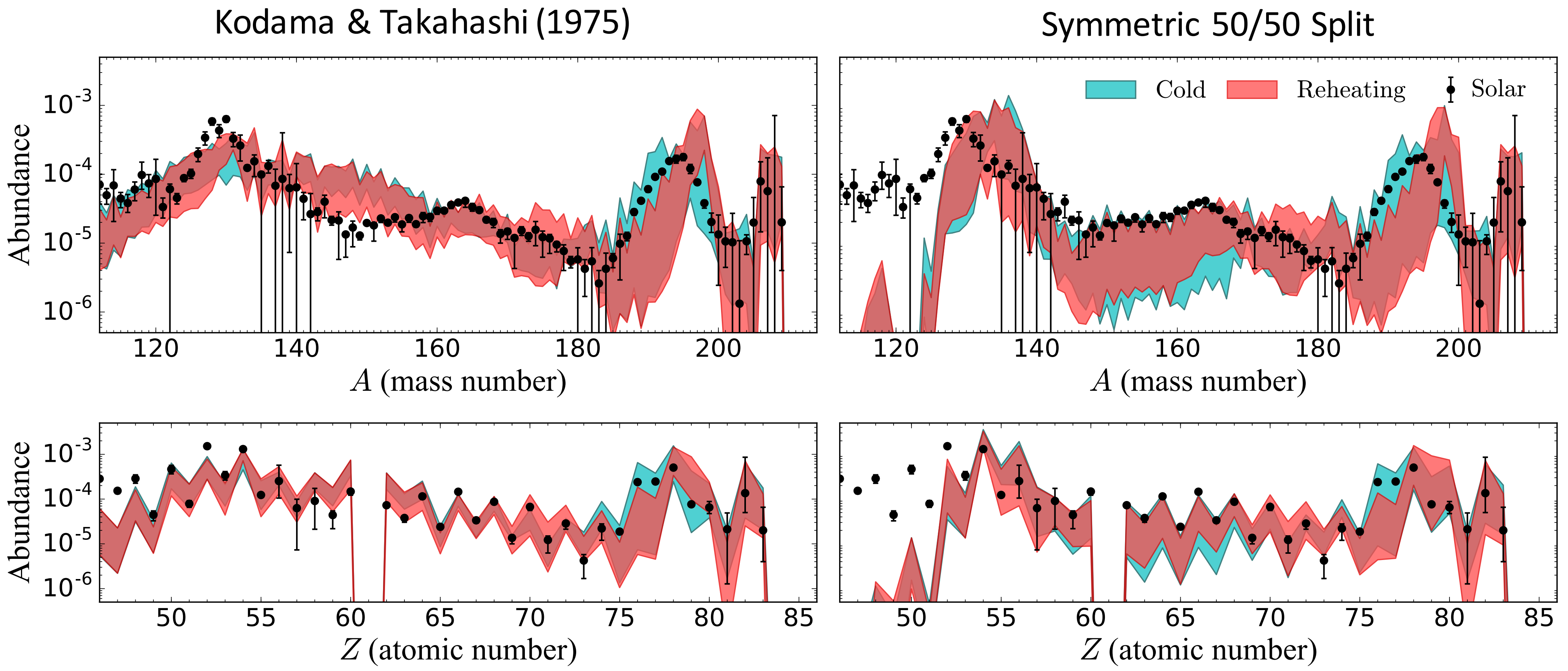


Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman and Wollaeger

(ApJ 855, 2, 2018)

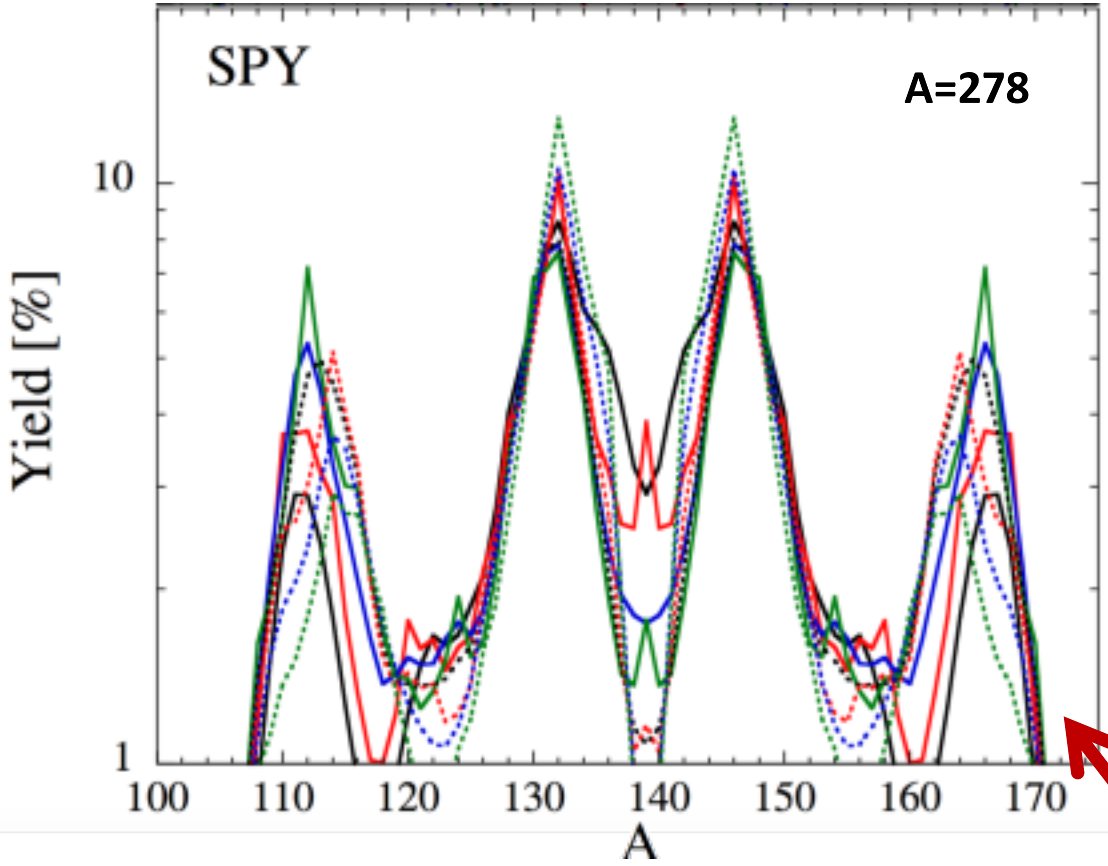
r-process Sensitivity to Mass Model and Fission Yields

- 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)

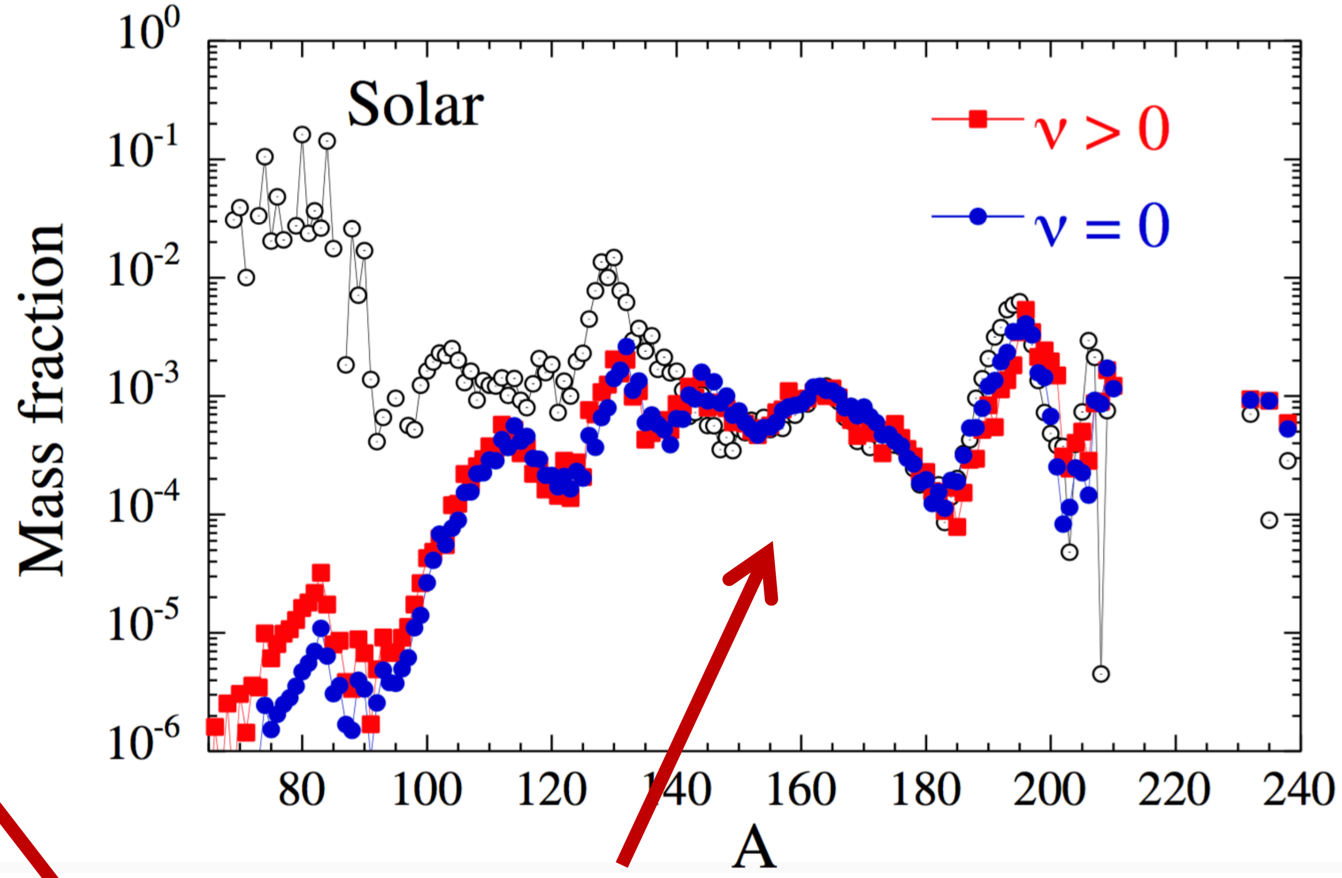


Côté et al (2018)

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)

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

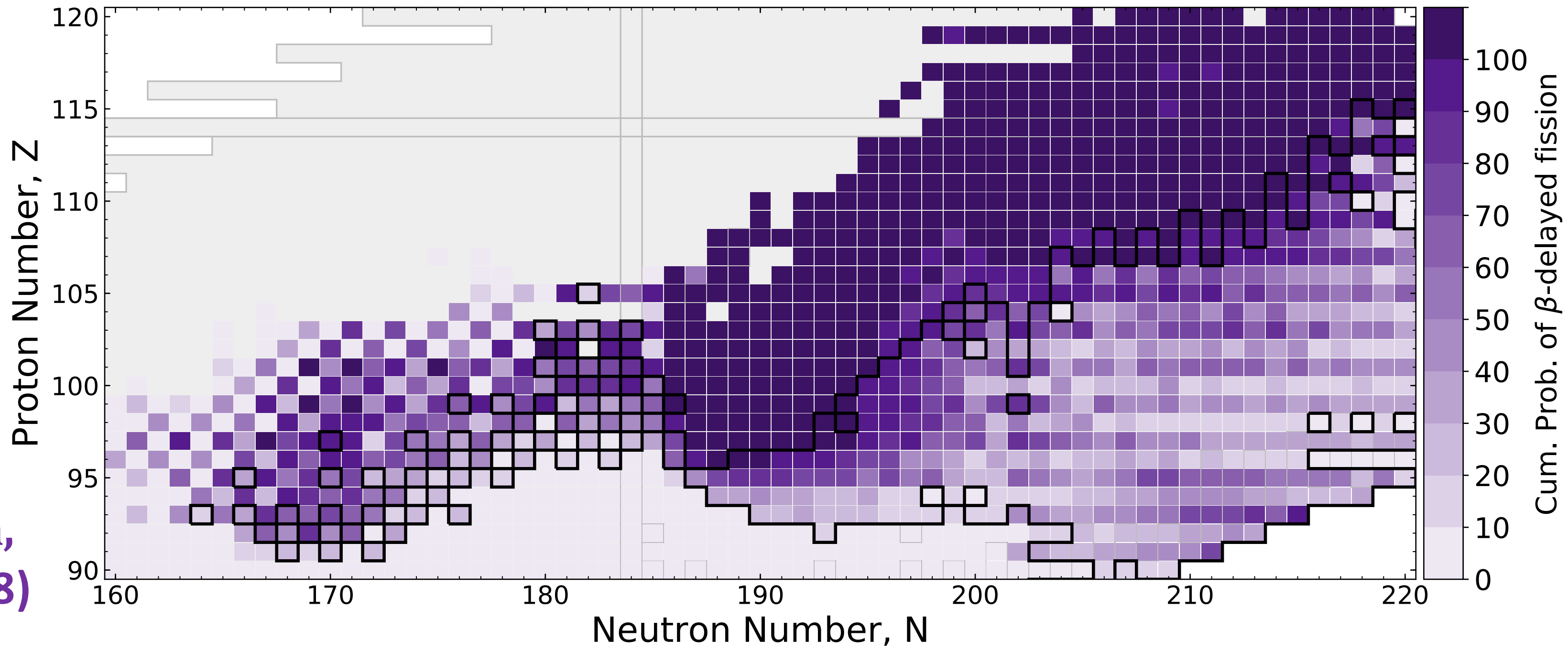
Los Alamos NATIONAL LABORATORY EST. 1943

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

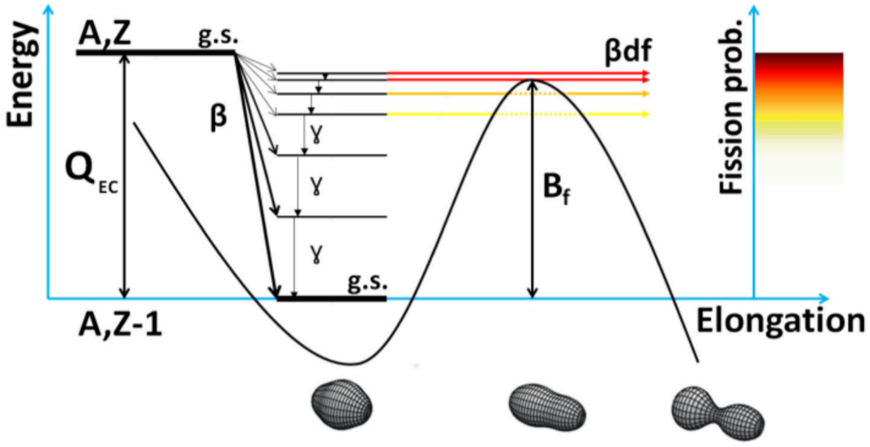
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

β-delayed fission in *r*-process nucleosynthesis

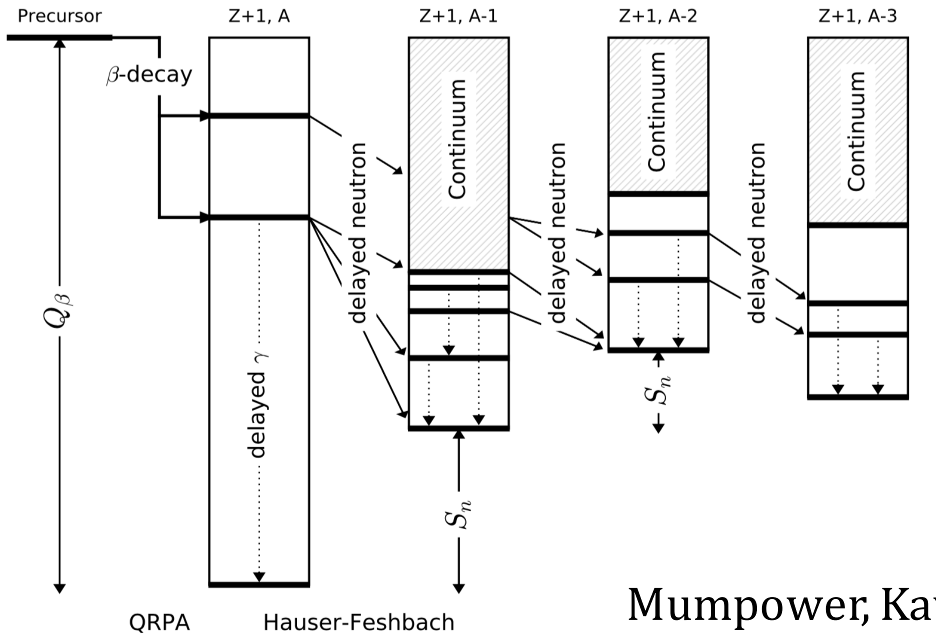
Mumpower, Kawano, Sprouse, Vassh, Holmbeck, Surman, and Möller (2018) arXiv:1802.04398



Black outline – probability of multi-chance βdf > 10%



Andreyev, Nishio, and Schmidt (2018)

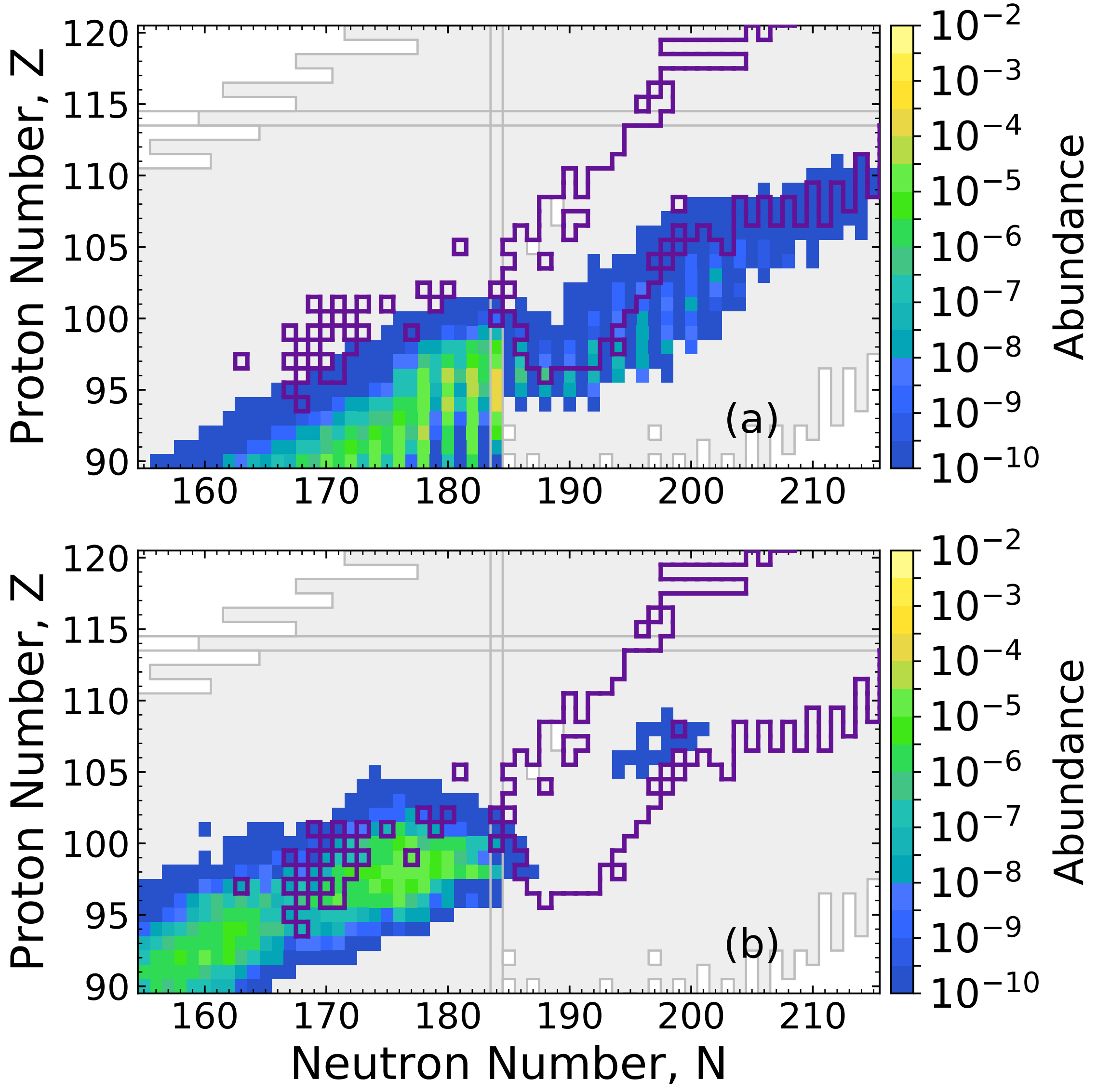


. . .

Mumpower, Kawano, and Möller (2016)

Superheavy island blocked by β-delayed fission

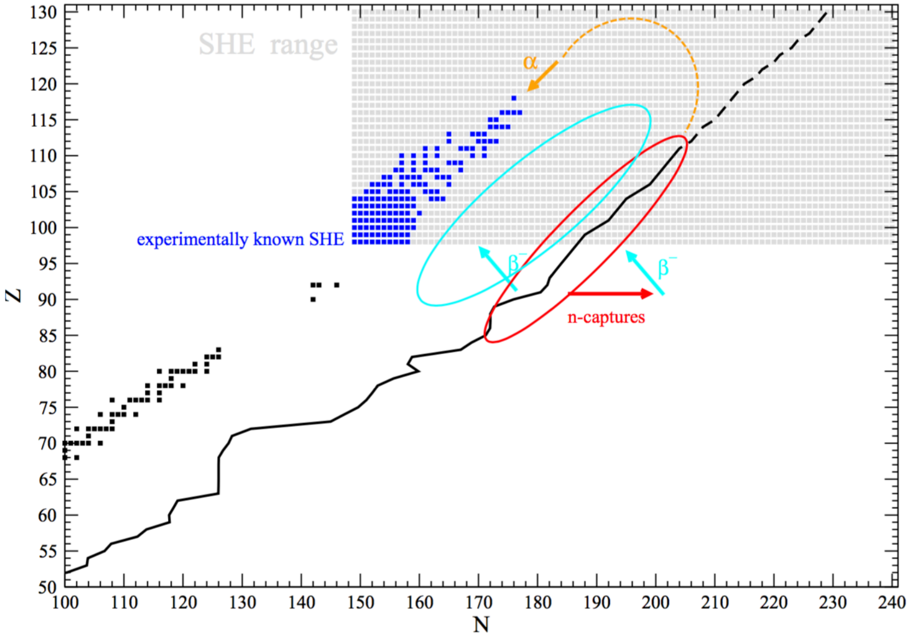
Right: Example - βdf alone can prevent the population of the superheavy island of stability
(purple outline – probability of βdf > 90%)



Mumpower et al (submitted 2018)

Below: previous calculations with Z<100 identified possibility to circumvent region with βdf probability ~100%

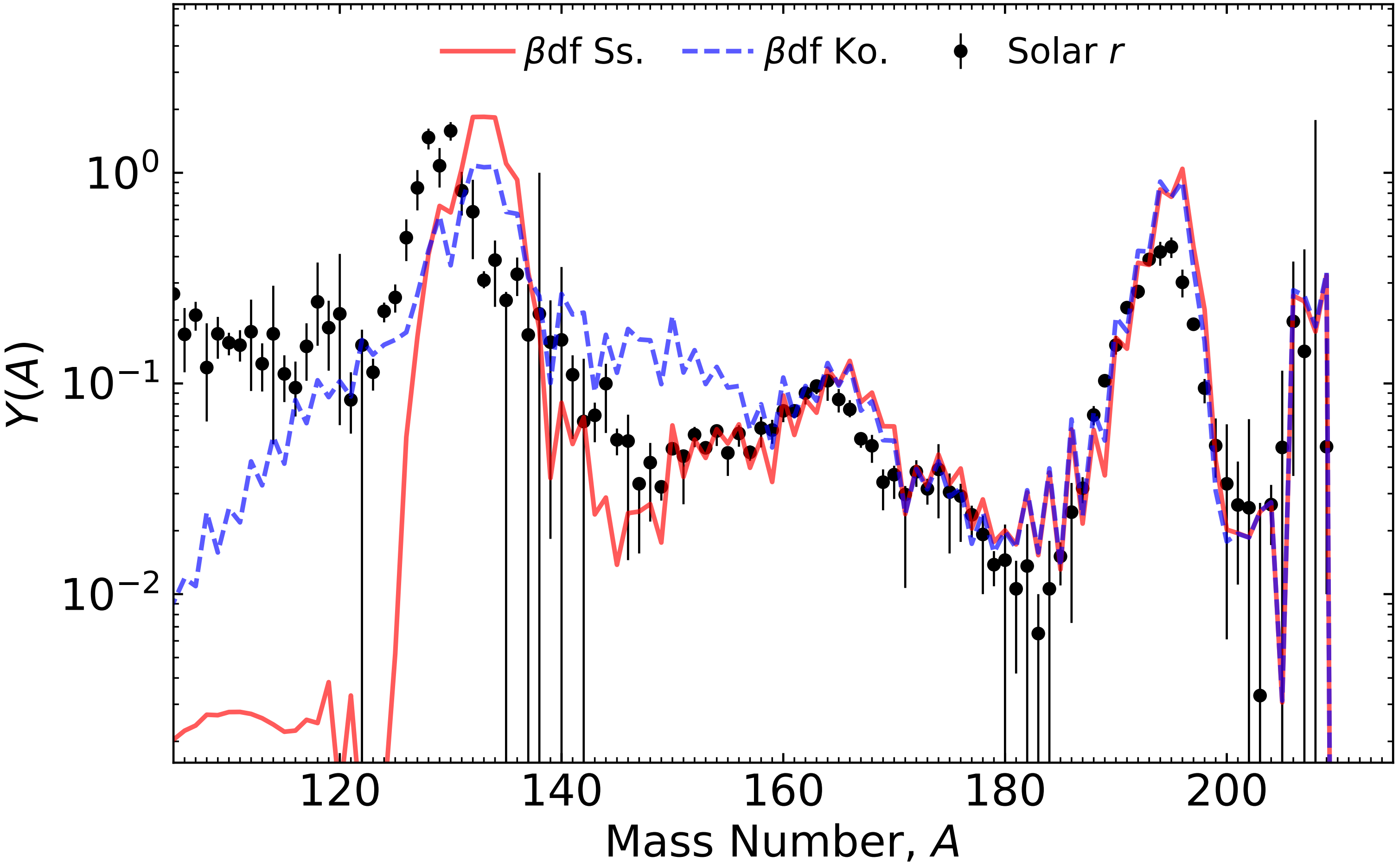
Petermann, Langanke, Martínez-Pinedo, Panov, Reinhard, and Thielemann (2012)



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

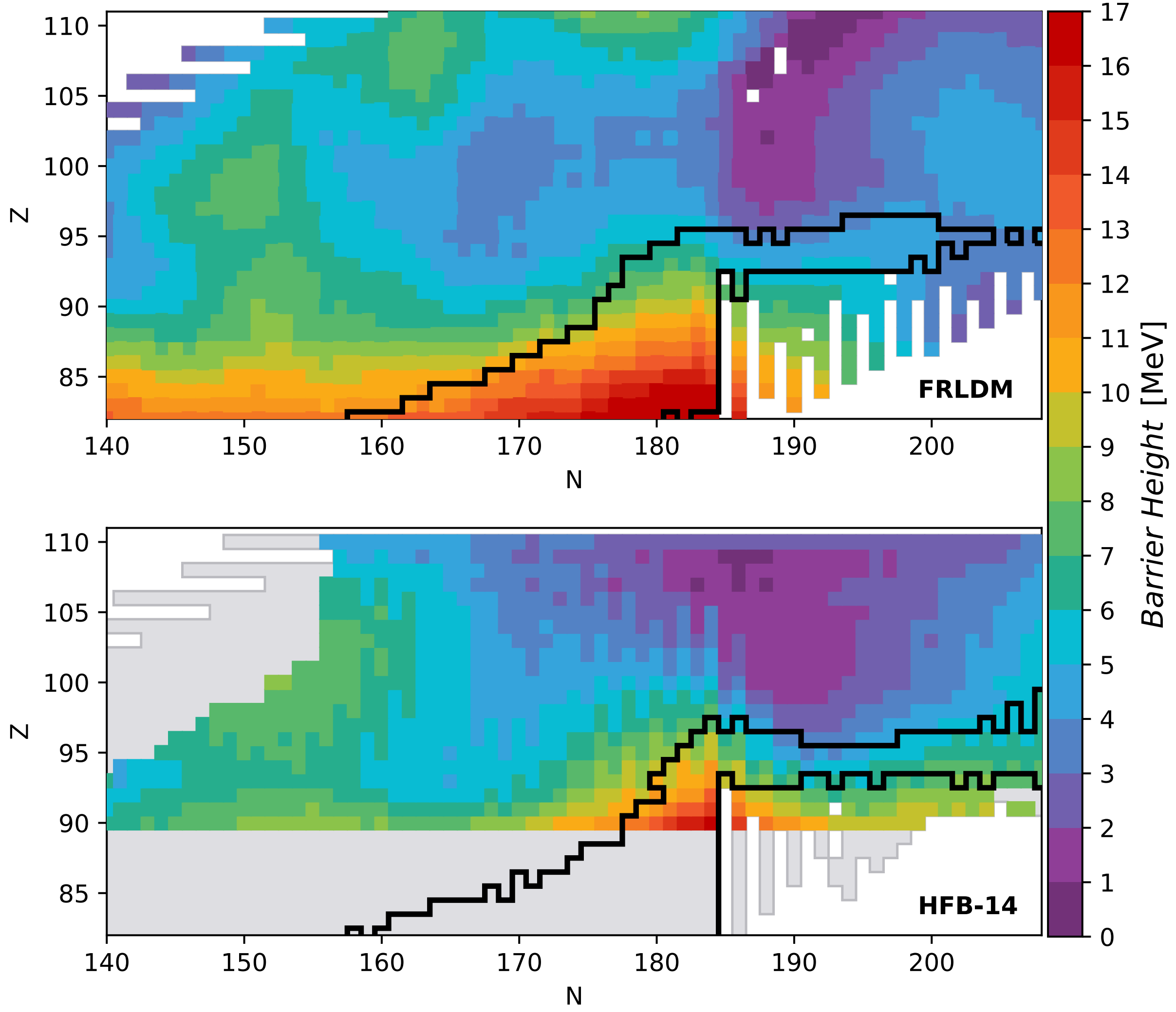
β-delayed fission yields in *r*-process nucleosynthesis

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



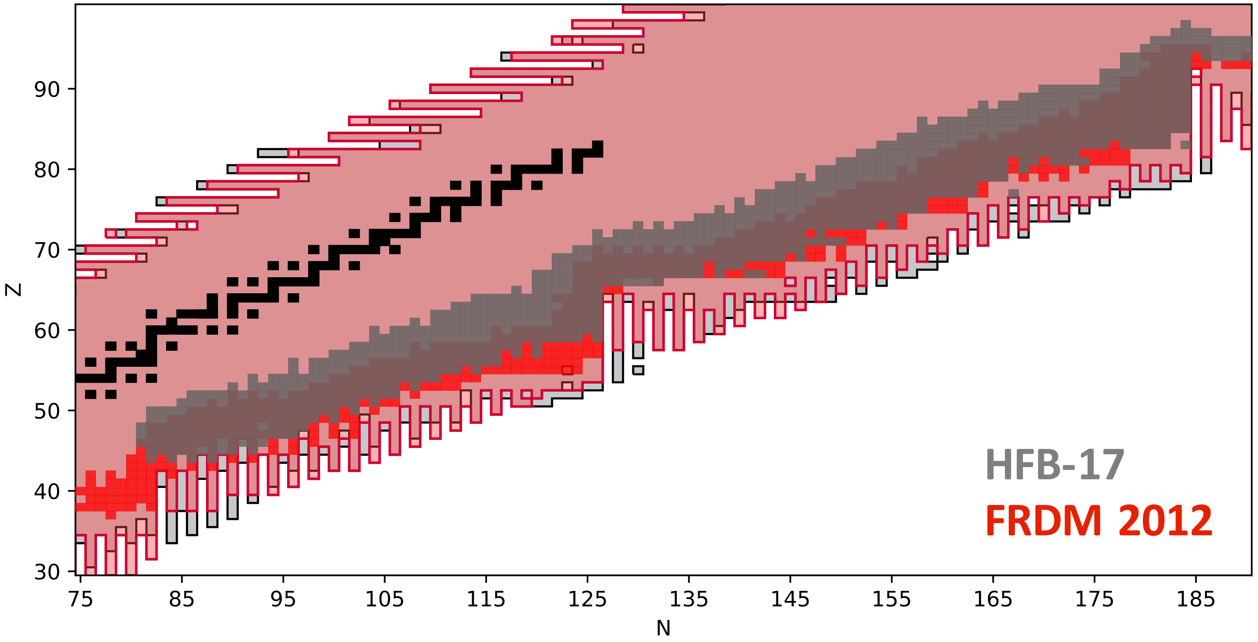
Mumpower et al (submitted 2018)

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



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

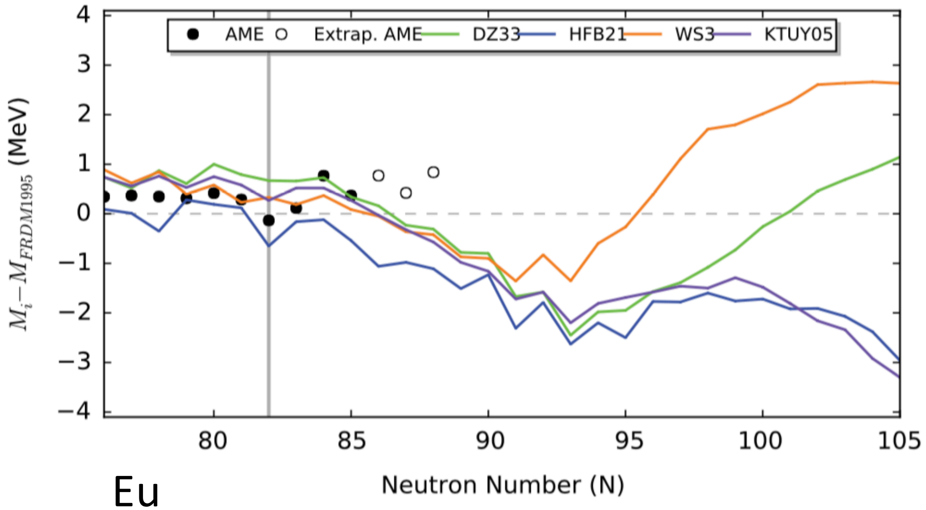
Below: dripline mass model comparison and effect on the abundances near N=82 (A~130 peak)



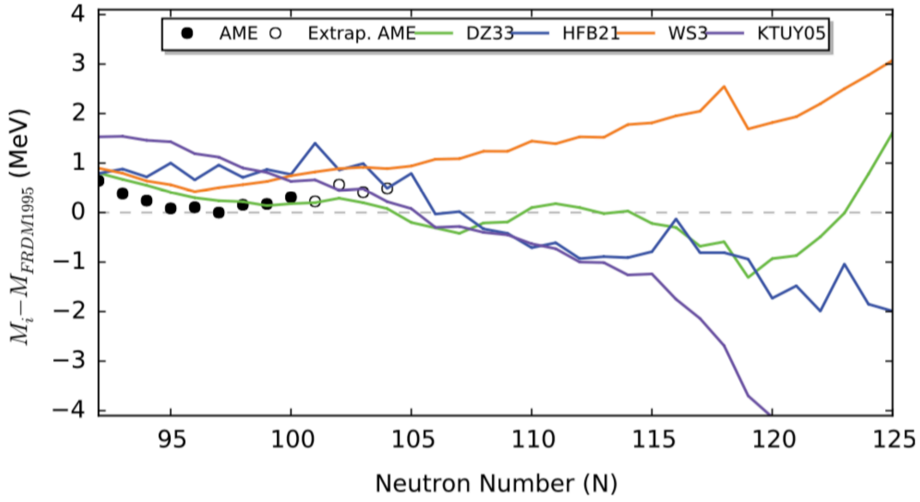
Vassh et al (in preparation)

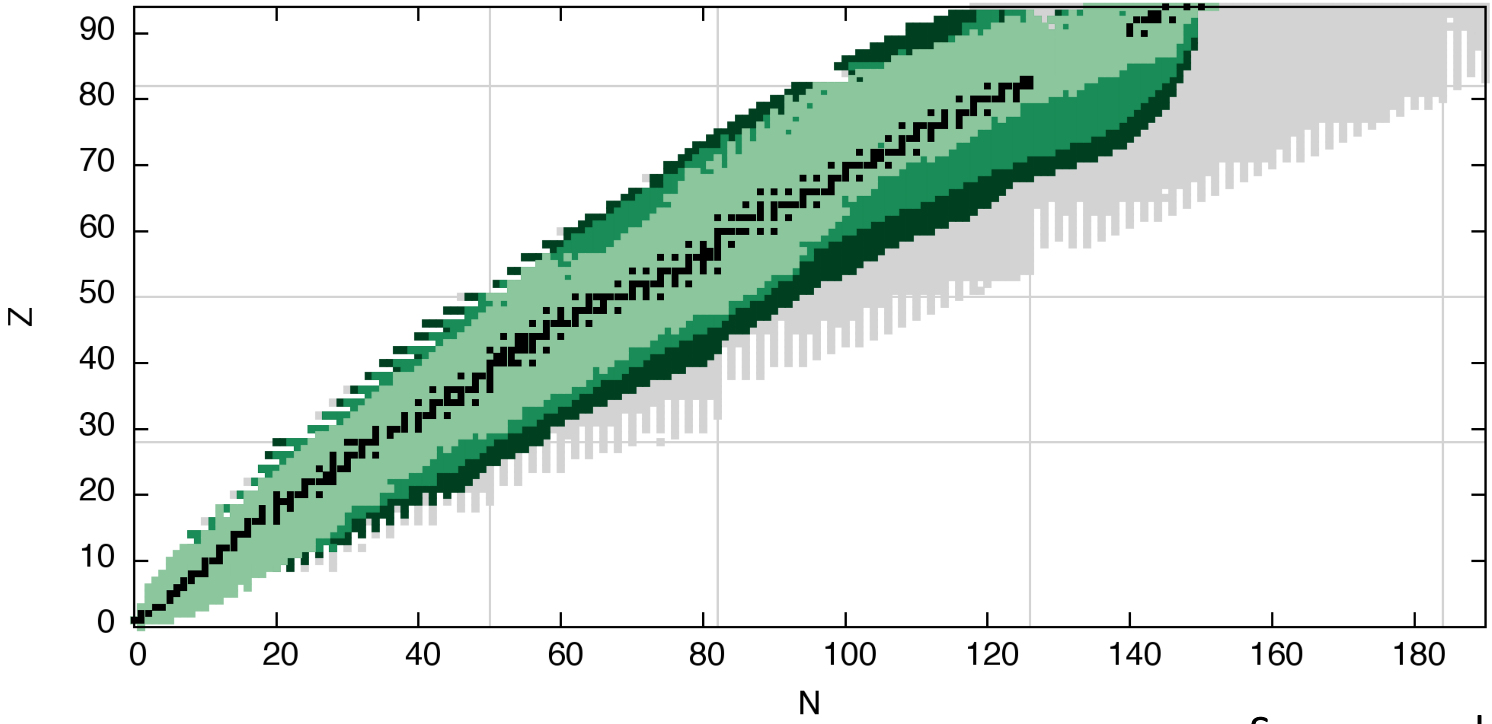
Masses: Model Divergence and FRIB Reach

Sn



Eu





Surman and Mumpower

Experimental Mass Measurements:

AME 2016

FRIB - Day 1

FRIB - Designed Beam Intensity

Mumpower, Surman, McLaughlin, and Aprahamian (2016)

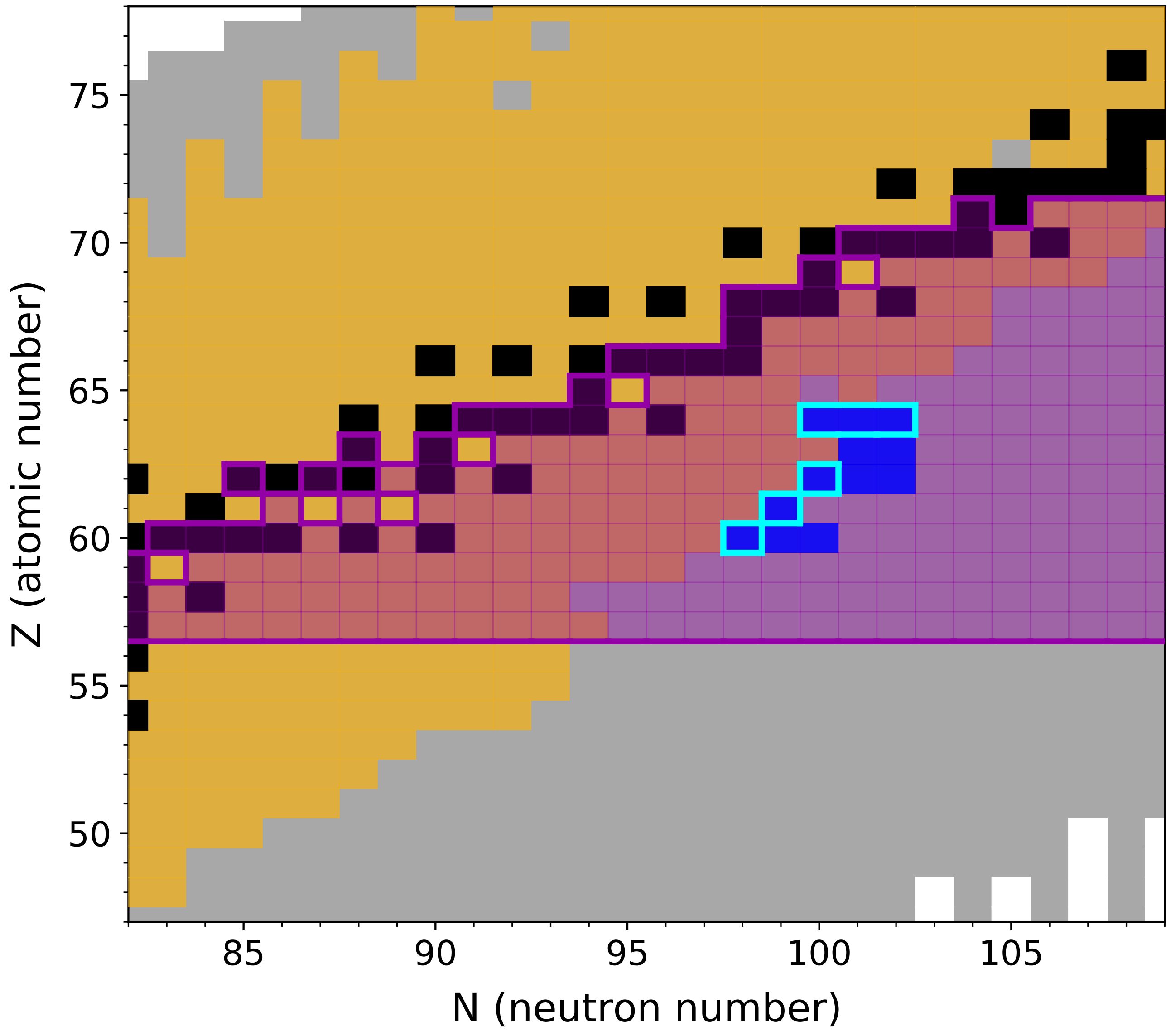
Studying Rare-Earth Nuclei to Understand *r*-process Lanthanide Production

Experimental Mass Measurements:

AME 2016

Jyväskylä

CPT at CARIBU



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

Experimental Mass Measurements:

AME 2016

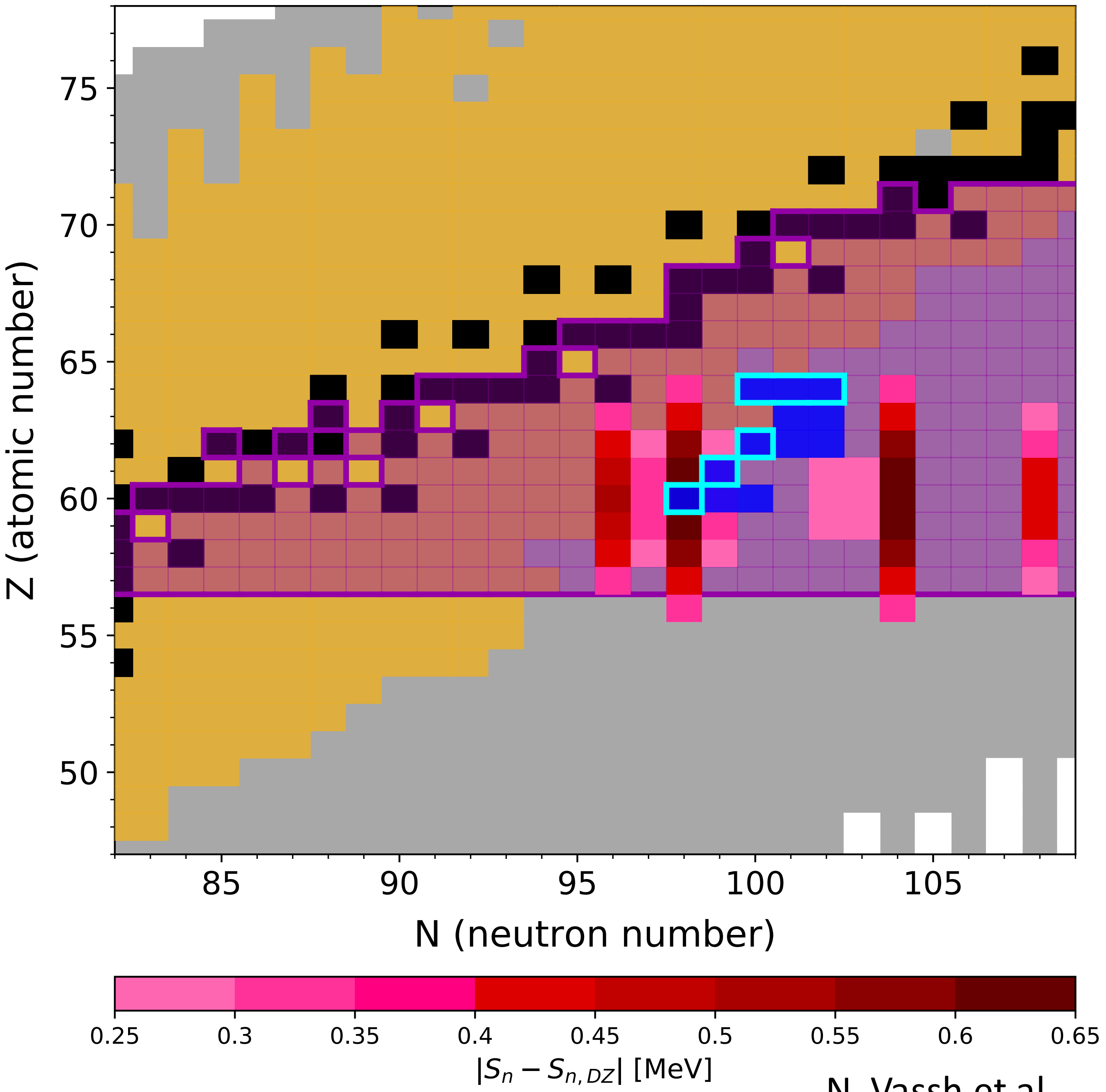
Jyväskylä

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, τ=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

↙

Markov Chain Monte Carlo (MCMC)
Likelihood function

↖

Nuclear masses

↑

MCMC procedure

- Monte Carlo mass corrections

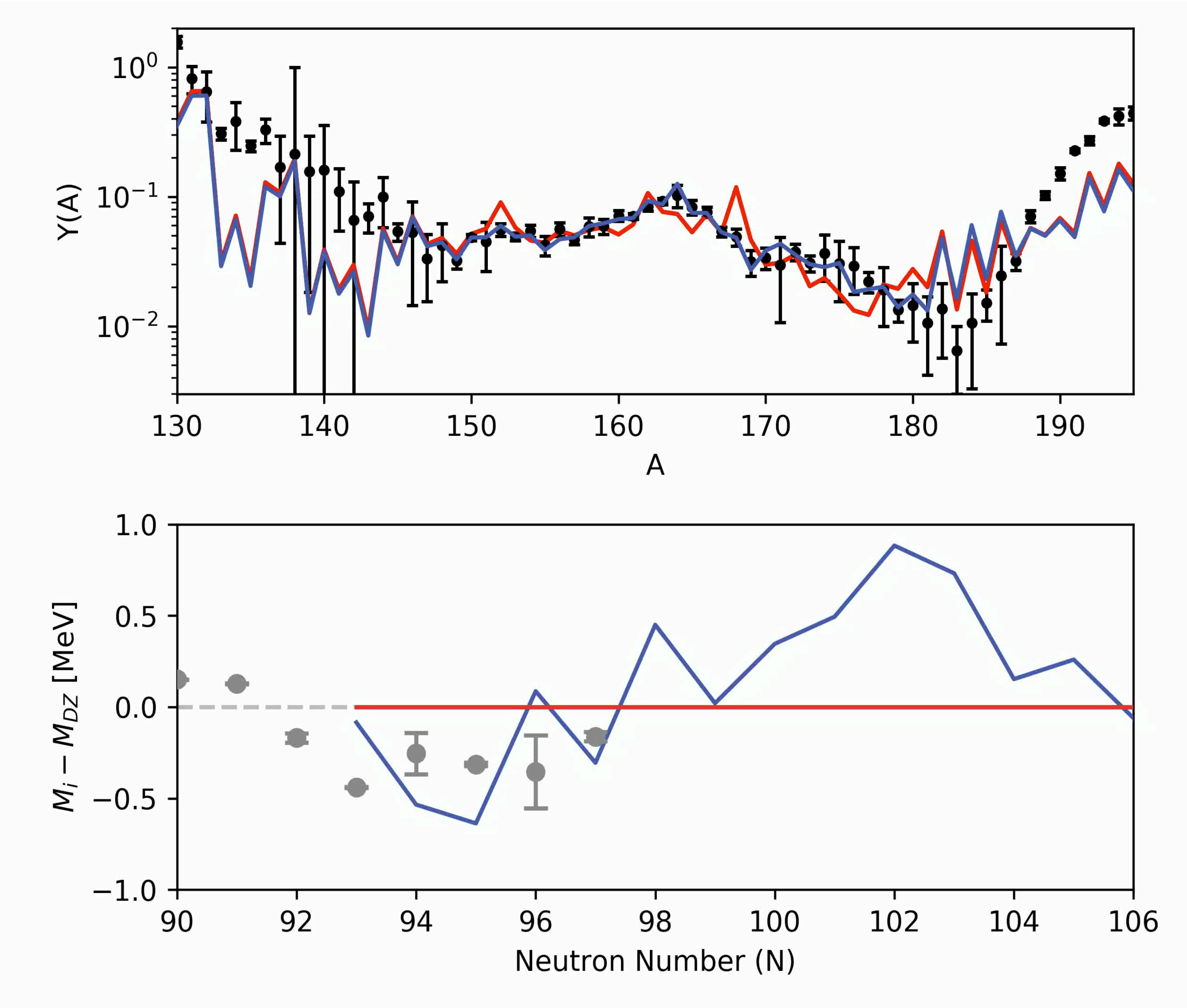
$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

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

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



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

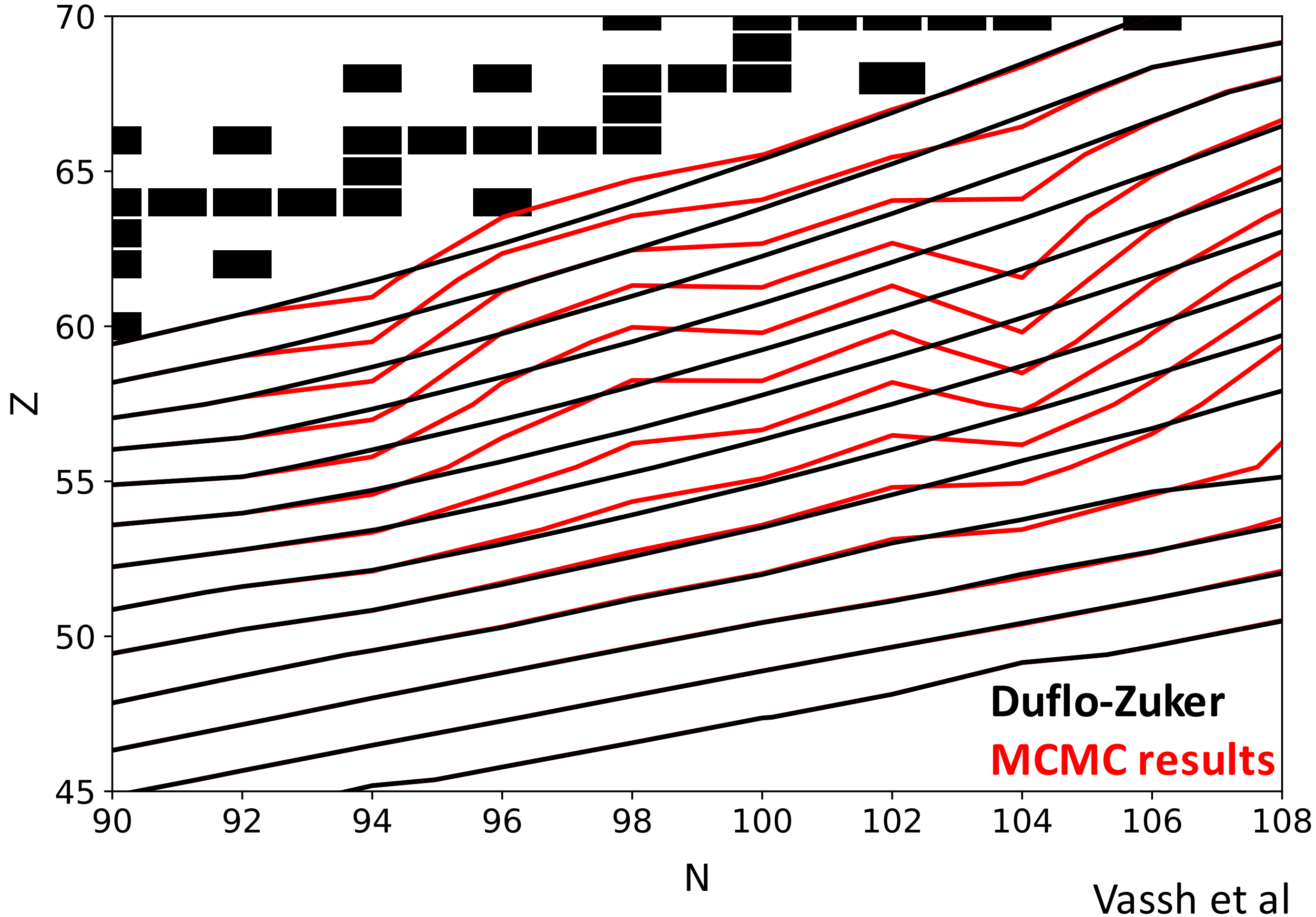
$$(\gamma, \mathrm{n}) \quad \propto \quad e^{-S_\mathrm{n}/kT}$$

↓

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

↓

Pile-up of material at kinks



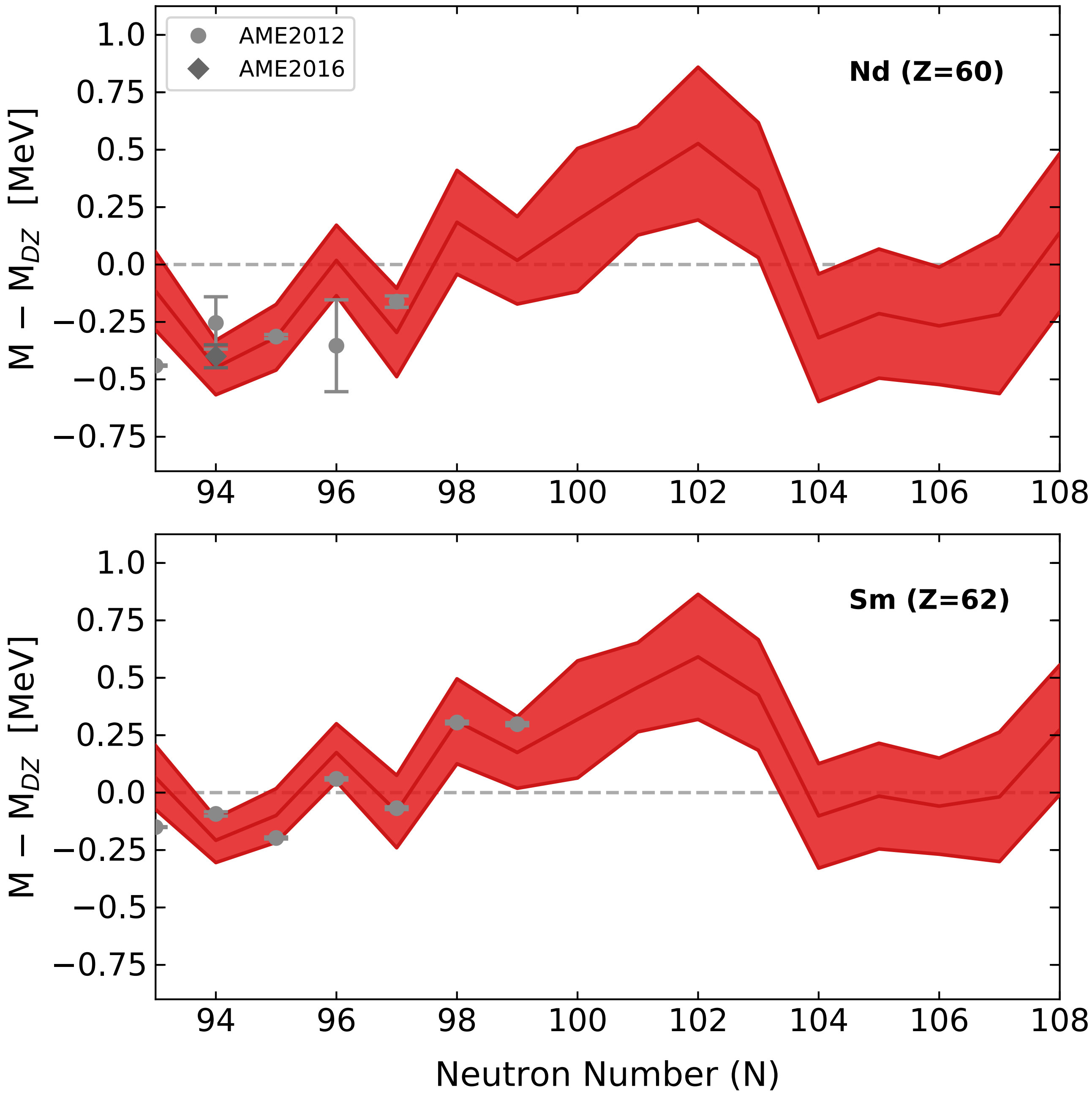
Vassh et al
(in preparation)

Results

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

- 50 parallel, independent MCMC runs;
  Average run χ^2~23

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



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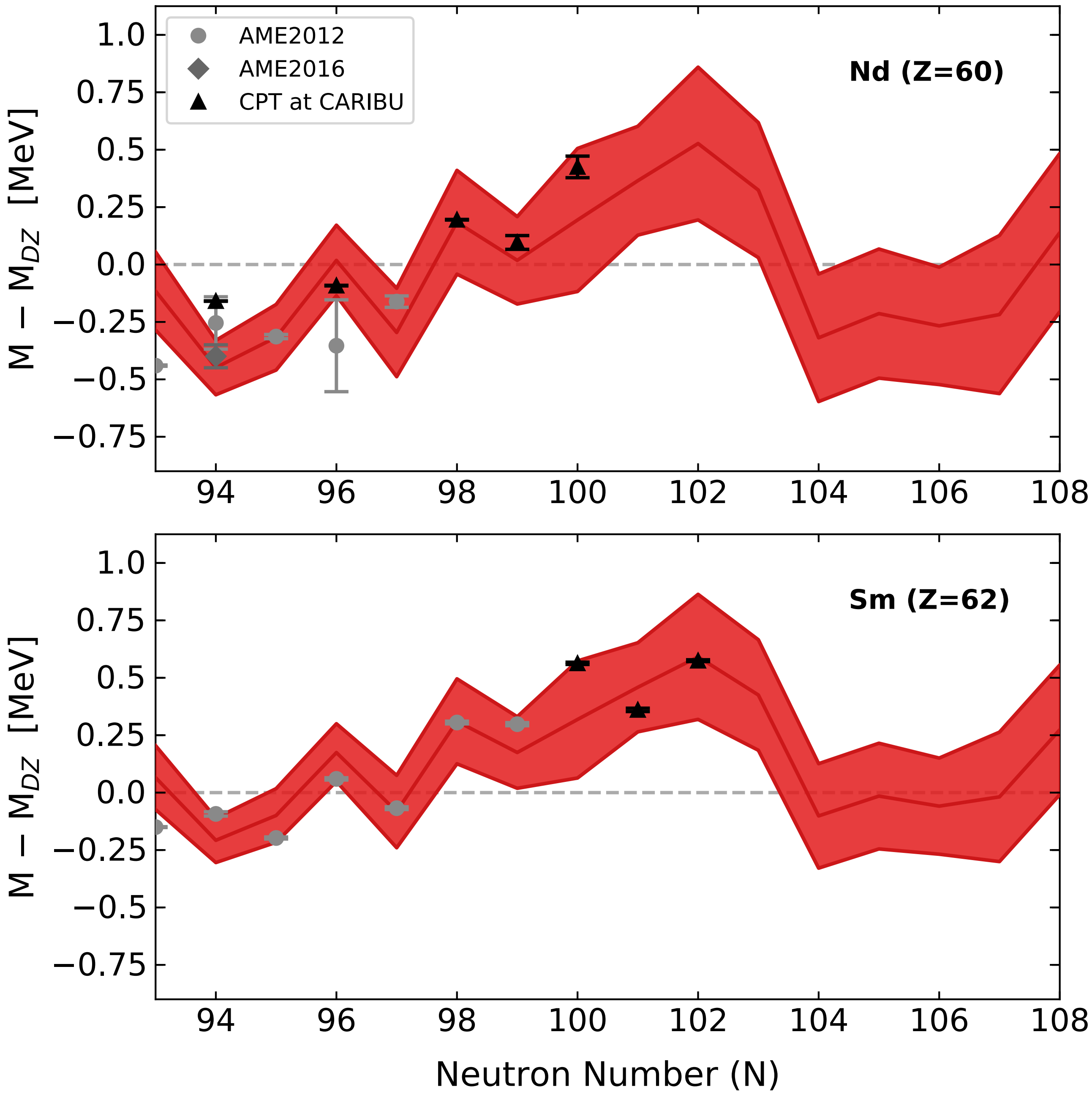
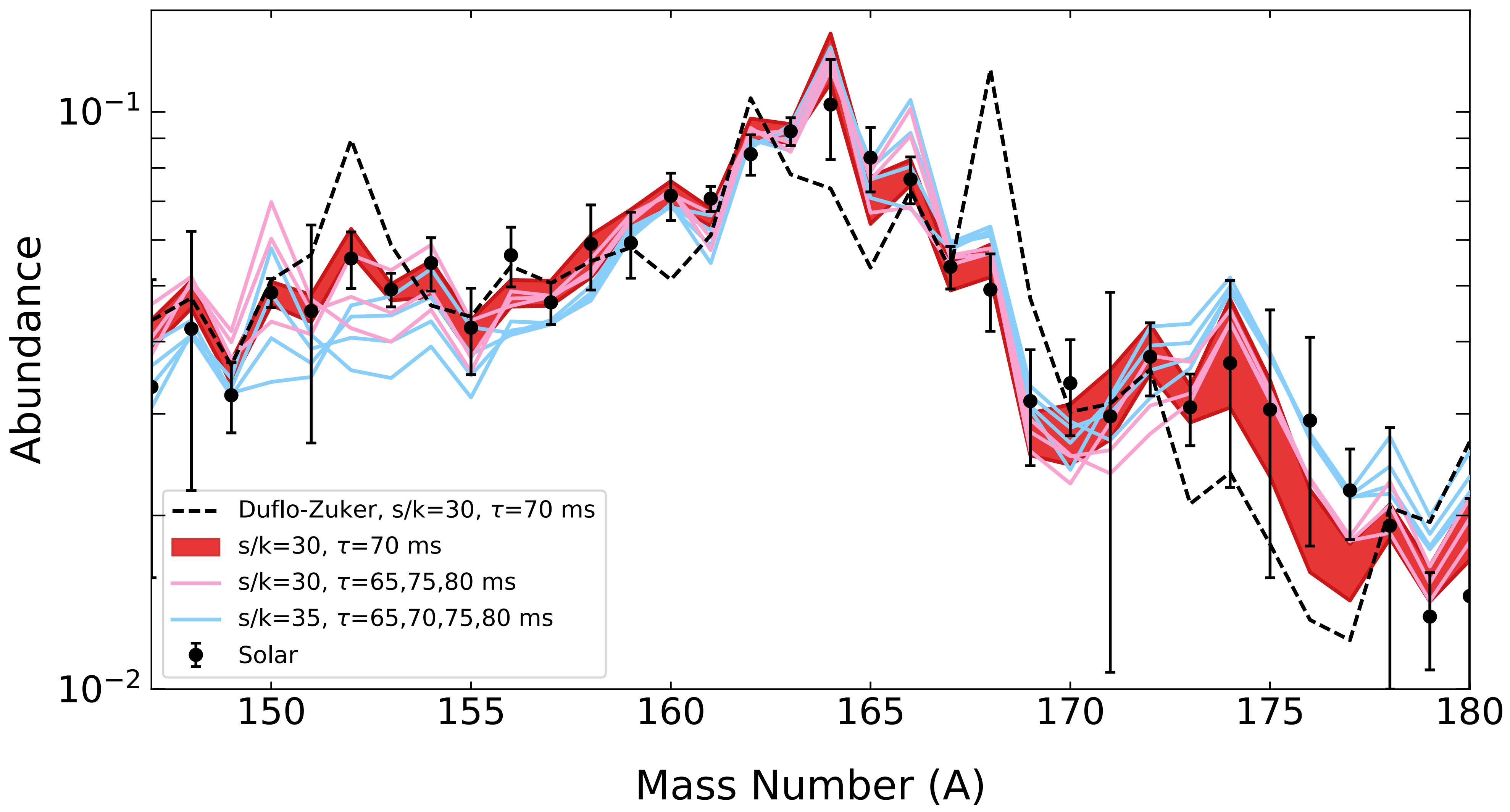


Rare-Earth Peak with MCMC solutions



Orford, Vassh, et al (accepted to PRL)

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?

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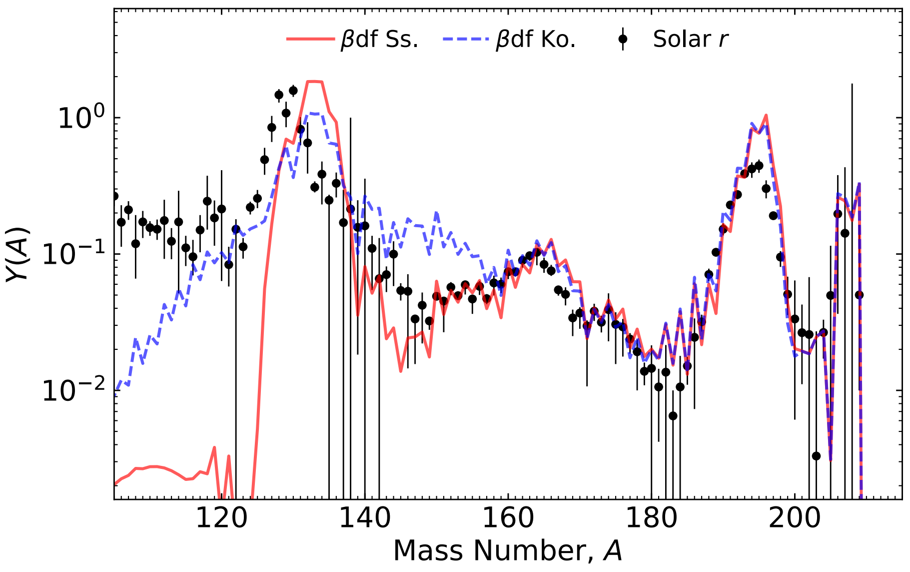
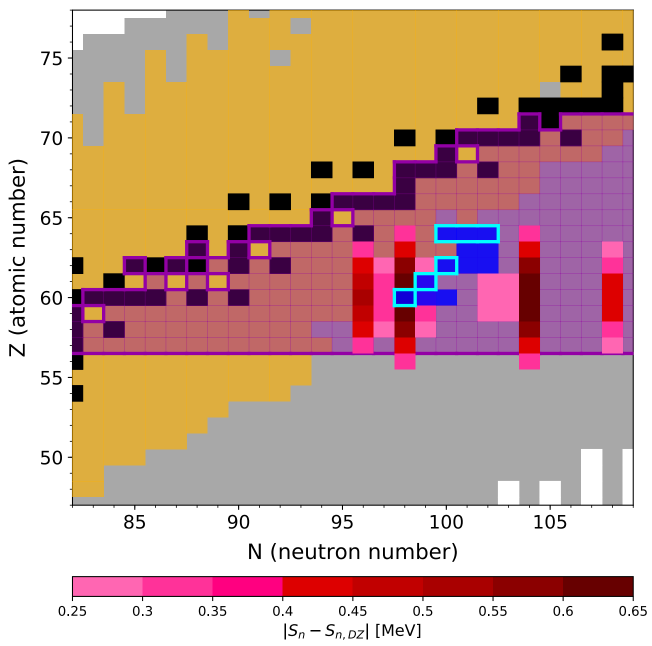
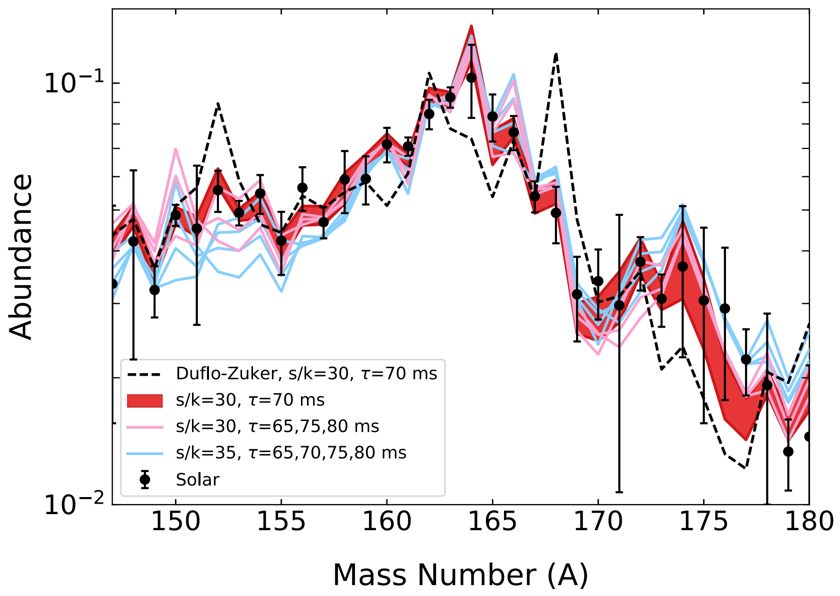


Mumpower et al (**arXiv:1802.04398**)



Vassh et al (in preparation)

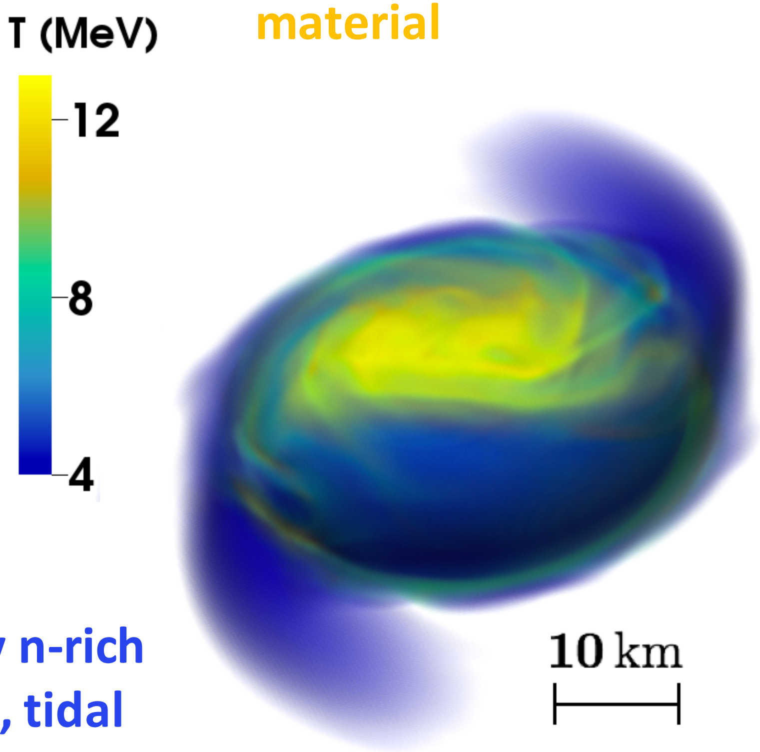


Orford, Vassh, et al (accepted to PRL)

Back-up Slides

r-process sites within a Neutron Star Merger

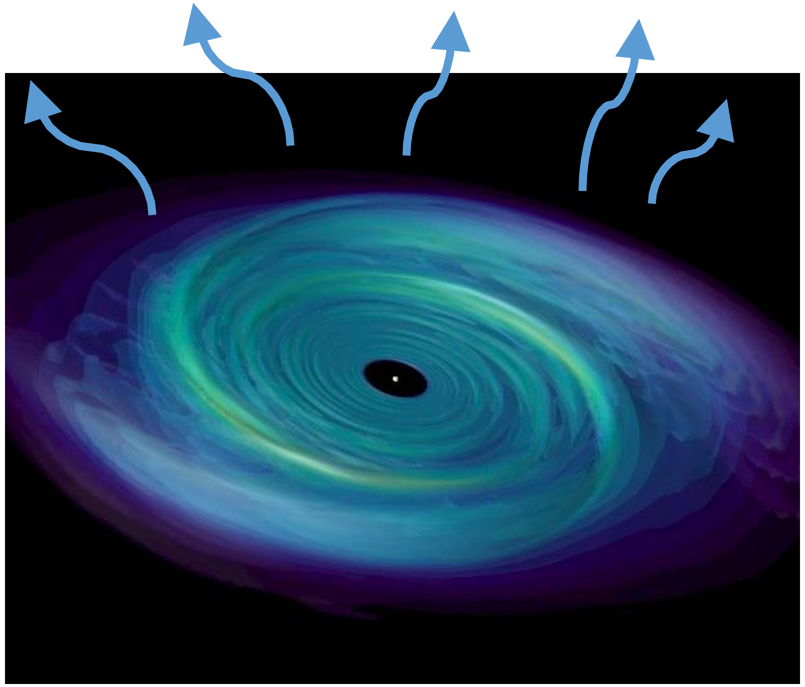
Hot, shocked material



Very n-rich cold, tidal outflows

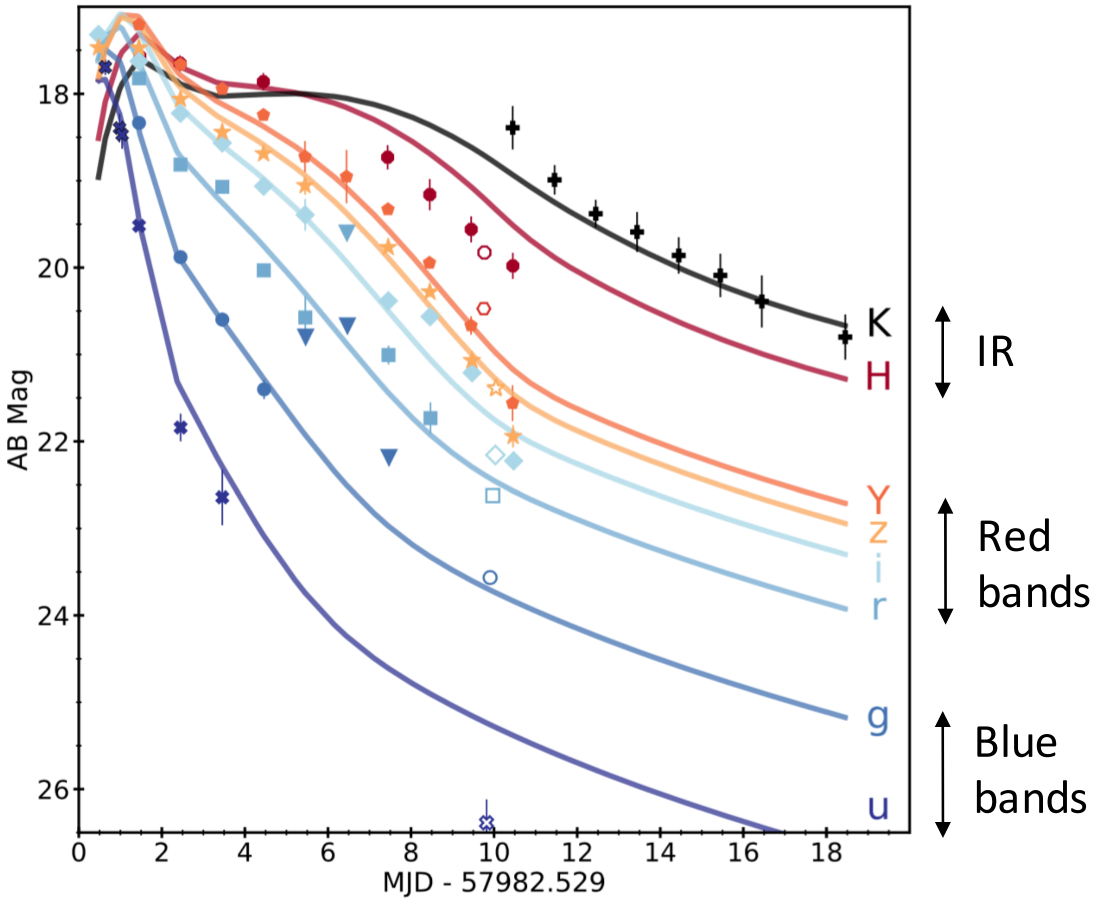
Foucart et al (2016)

Accretion disk winds – **exact driving mechanism and neutron richness varies**



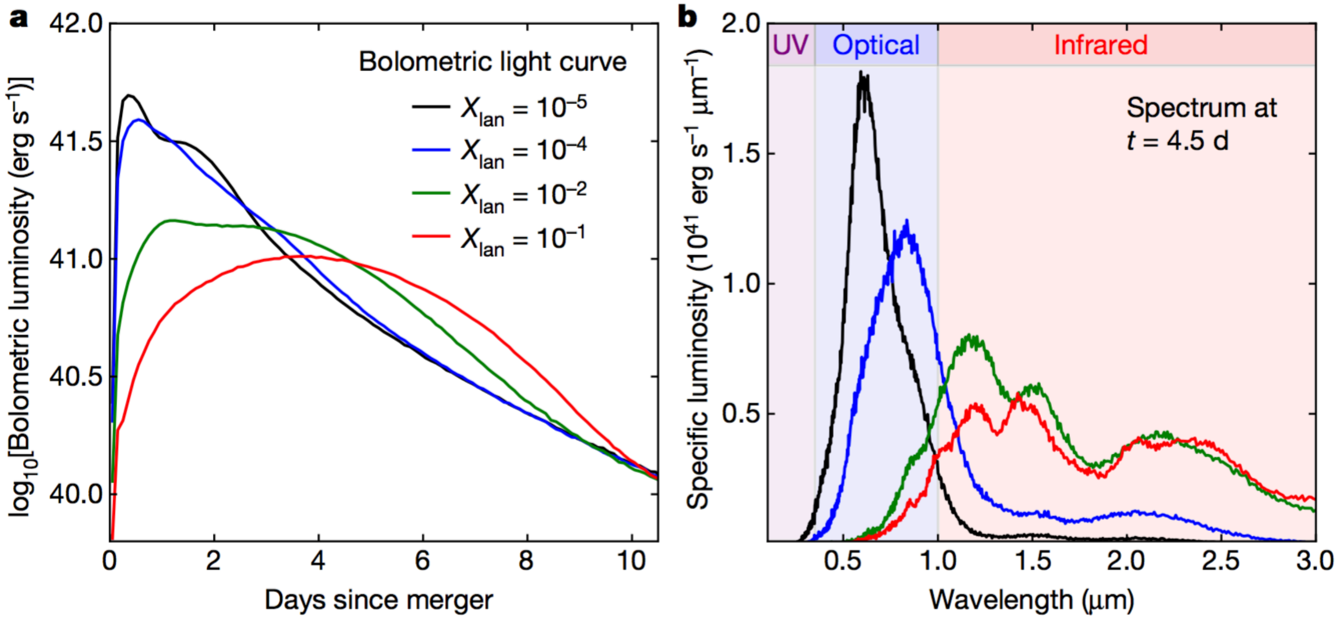
Owen and Blondin

Lanthanide production in GW170817: "red" kilonova



Cowperthwaite et al (ApJL 2017)

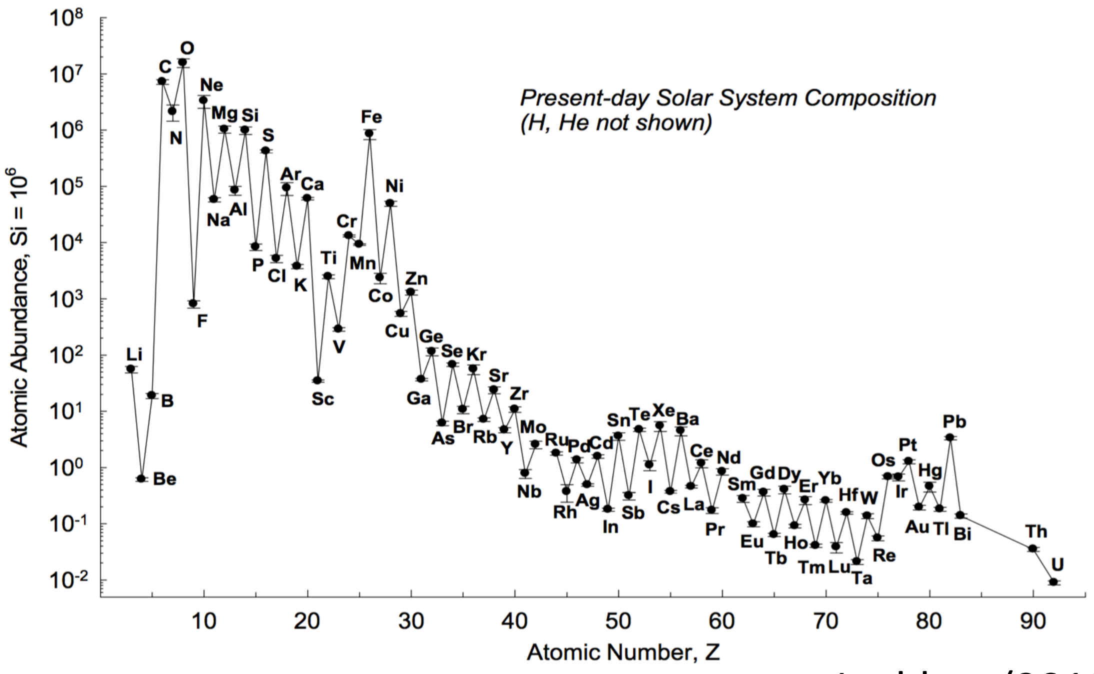
Lanthanide mass fraction ↑ , opacity ↑, longer duration light curve shifted toward infrared



Kasen et al (*Nature* 2017)

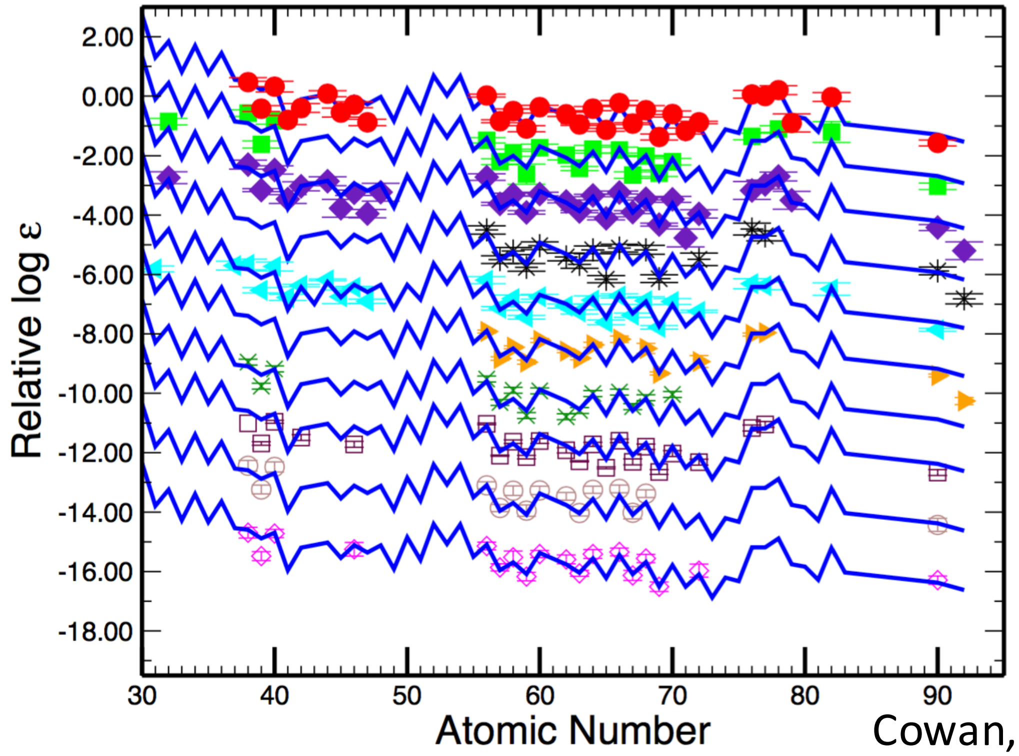
Observed Elemental Abundances

Solar System



Lodders (2010)

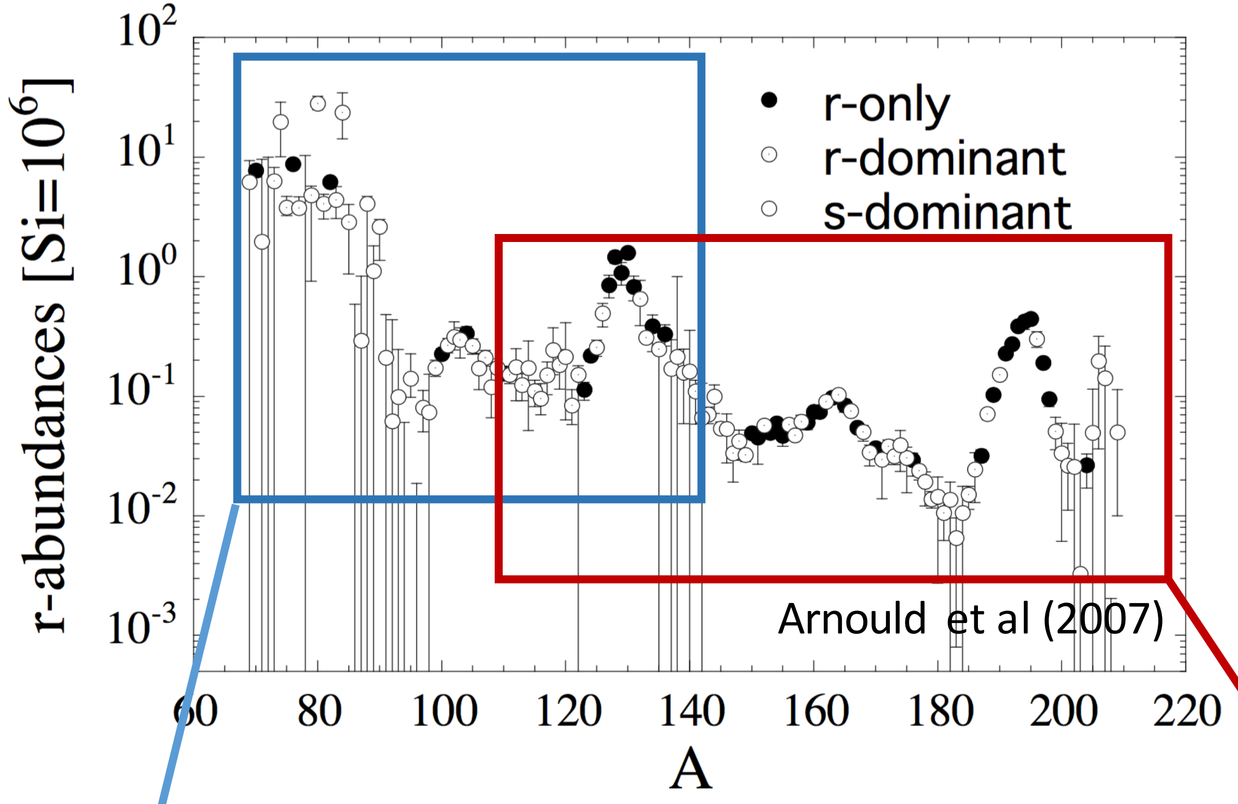
10 *r*-process rich halo stars



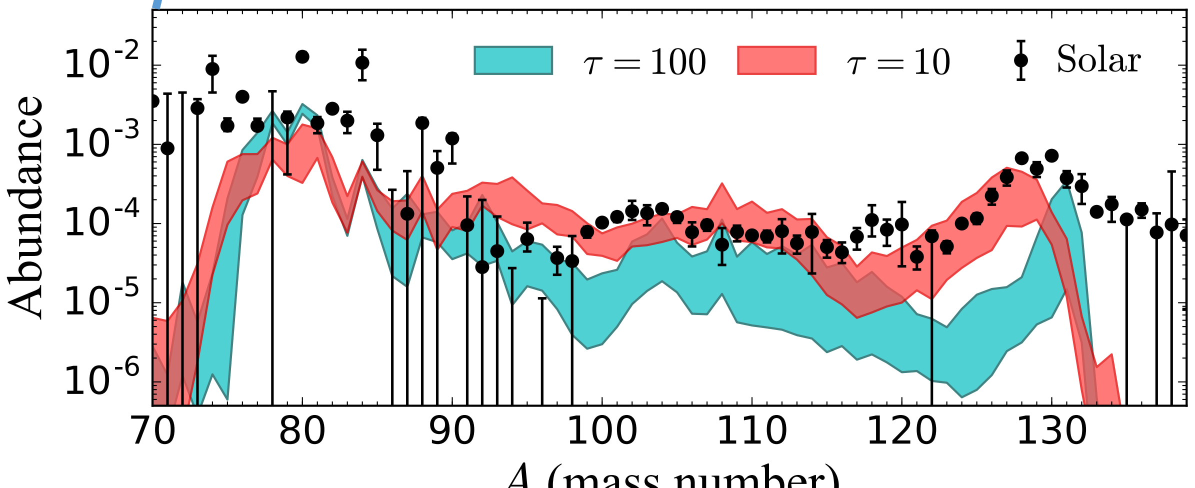
Cowan, Roederer, Sneden and Lawler (2011)

r-process Calculations for NSM Ejecta

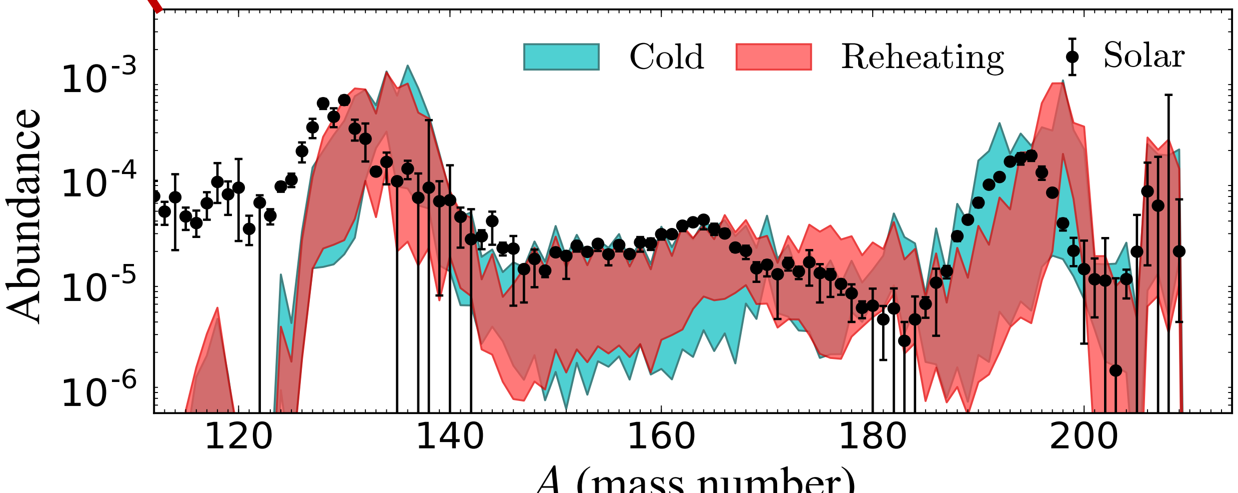
Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman and Wollaeger (2017)



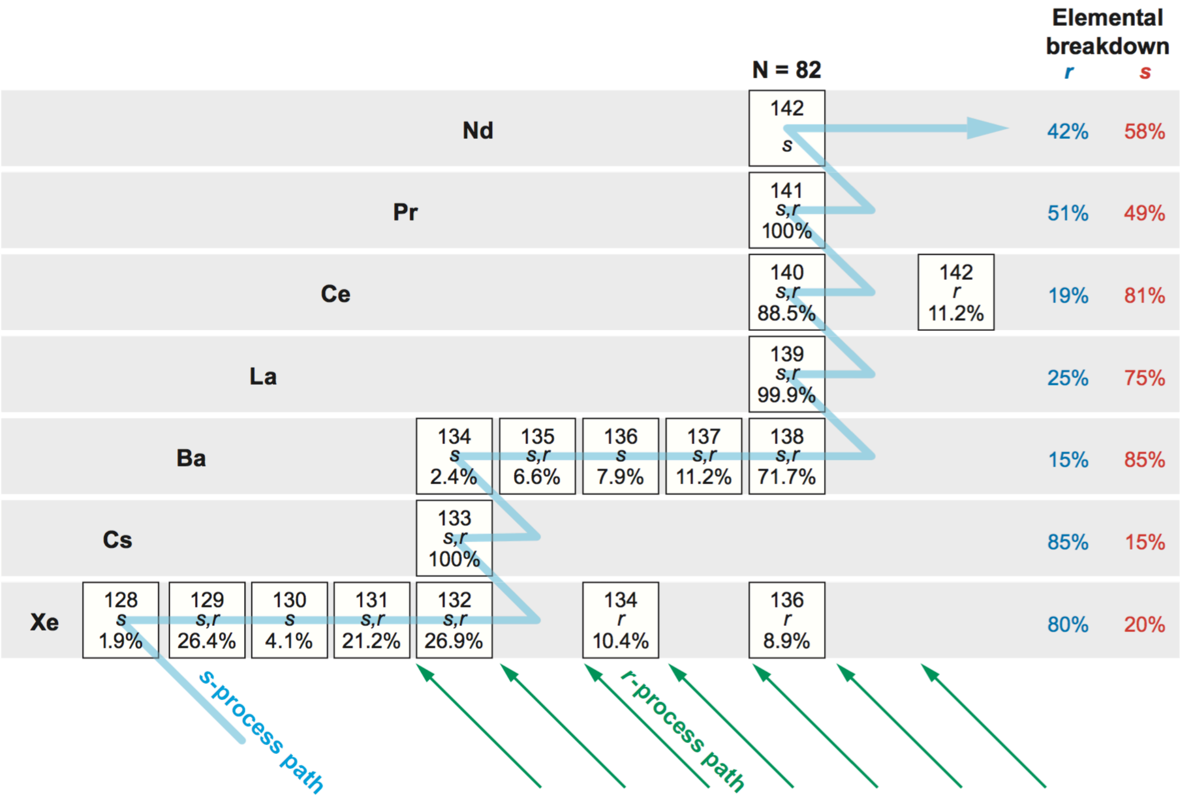
Wind ejecta (s/k=10, Y_e=0.27)



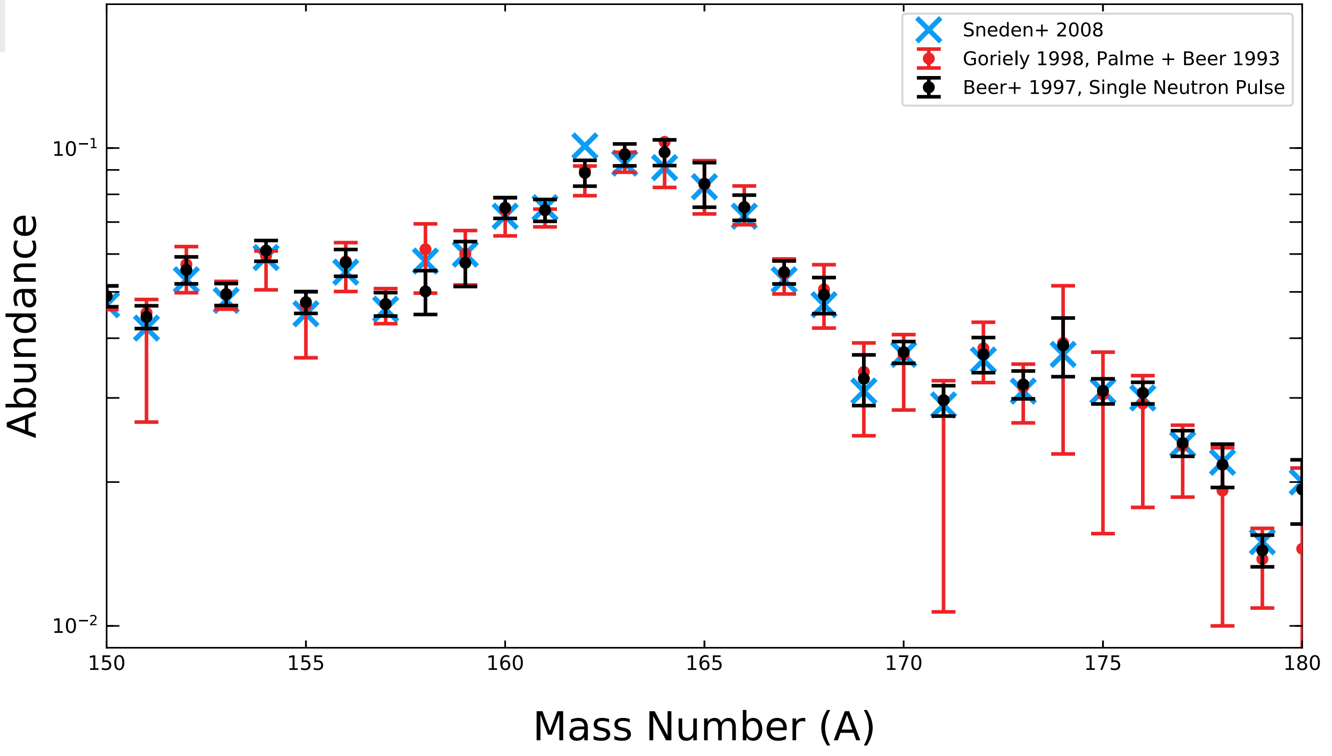
Very n-rich **dynamical** ejecta



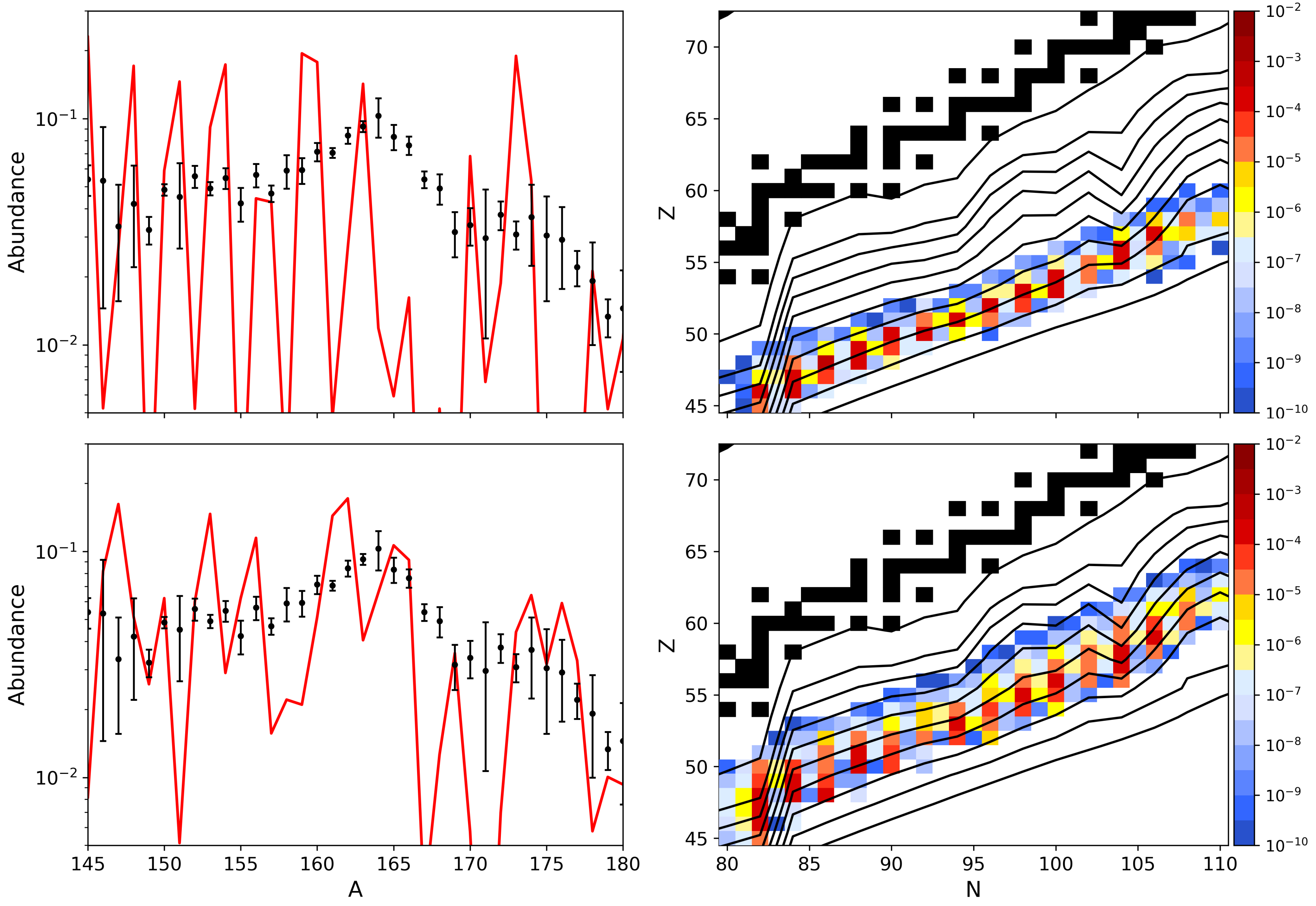
Sensitivity to Solar Data: uncertainty from the s-process subtraction



Sneden, Cowan, and Gallino (2008)



Peak Formation with an MCMC Mass Solution



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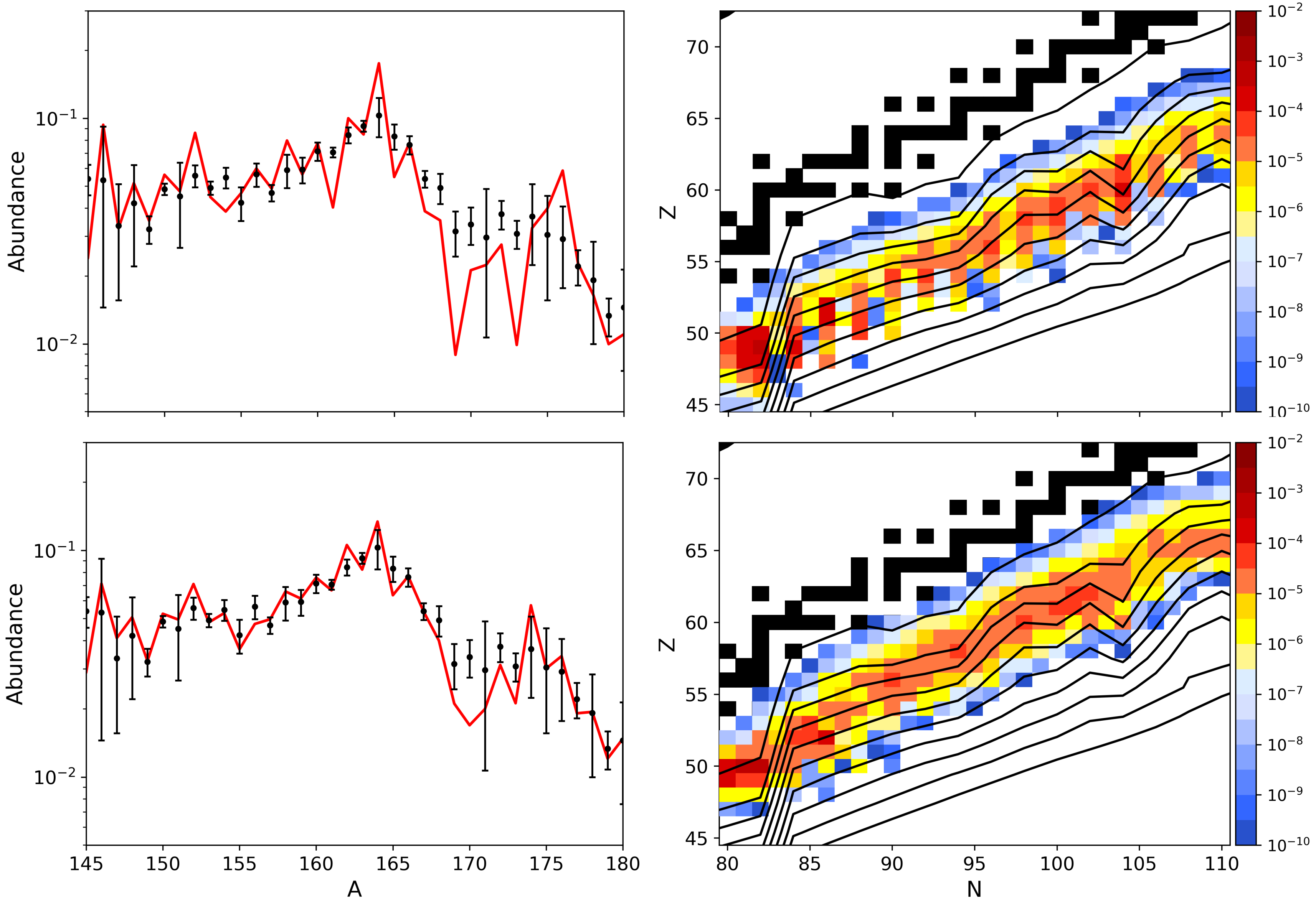
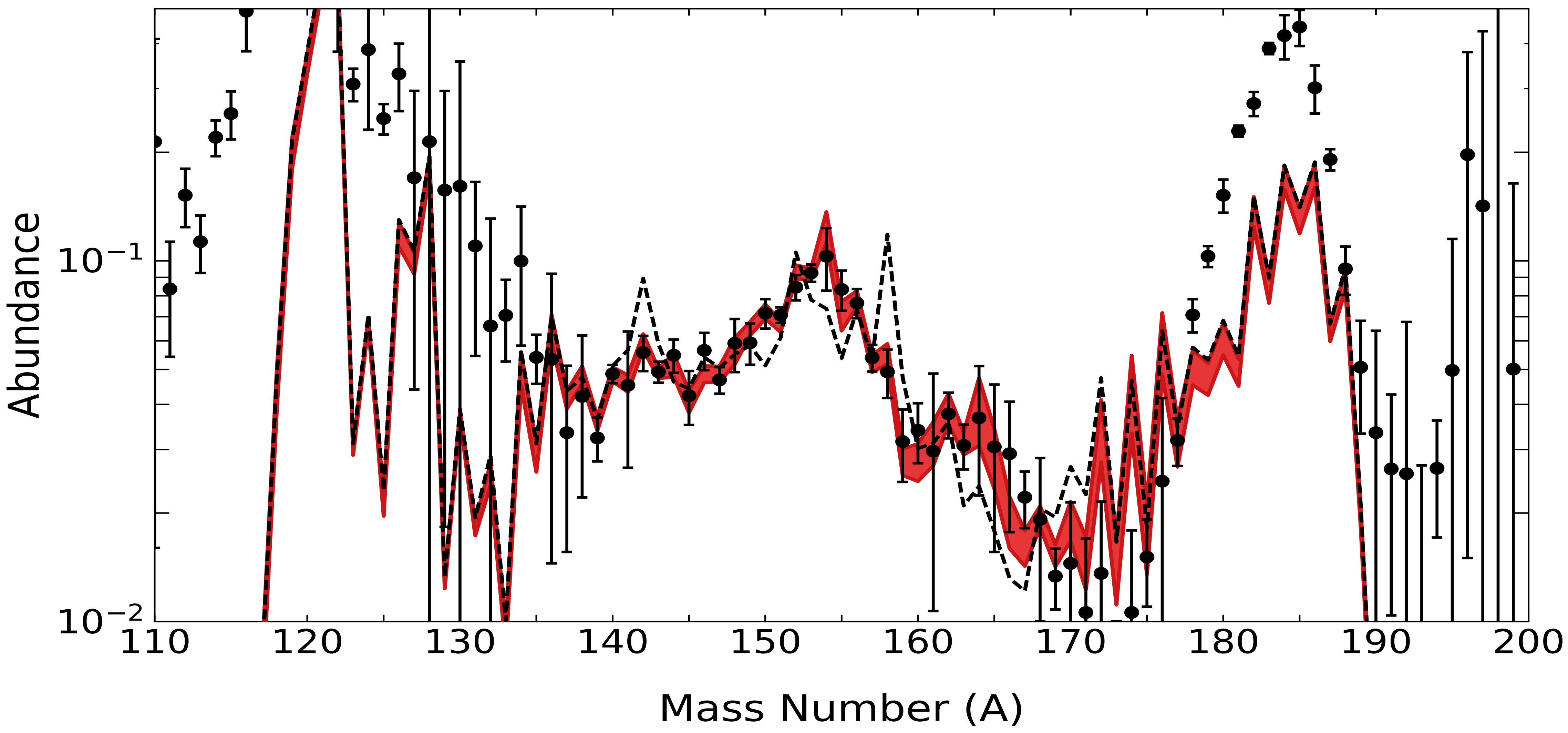




(Abundance pattern range using the mass values found by our MCMC given disk wind conditions s/k=30, τ=70 ms, Y_e=0.2)

Vassh et al (in preparation)

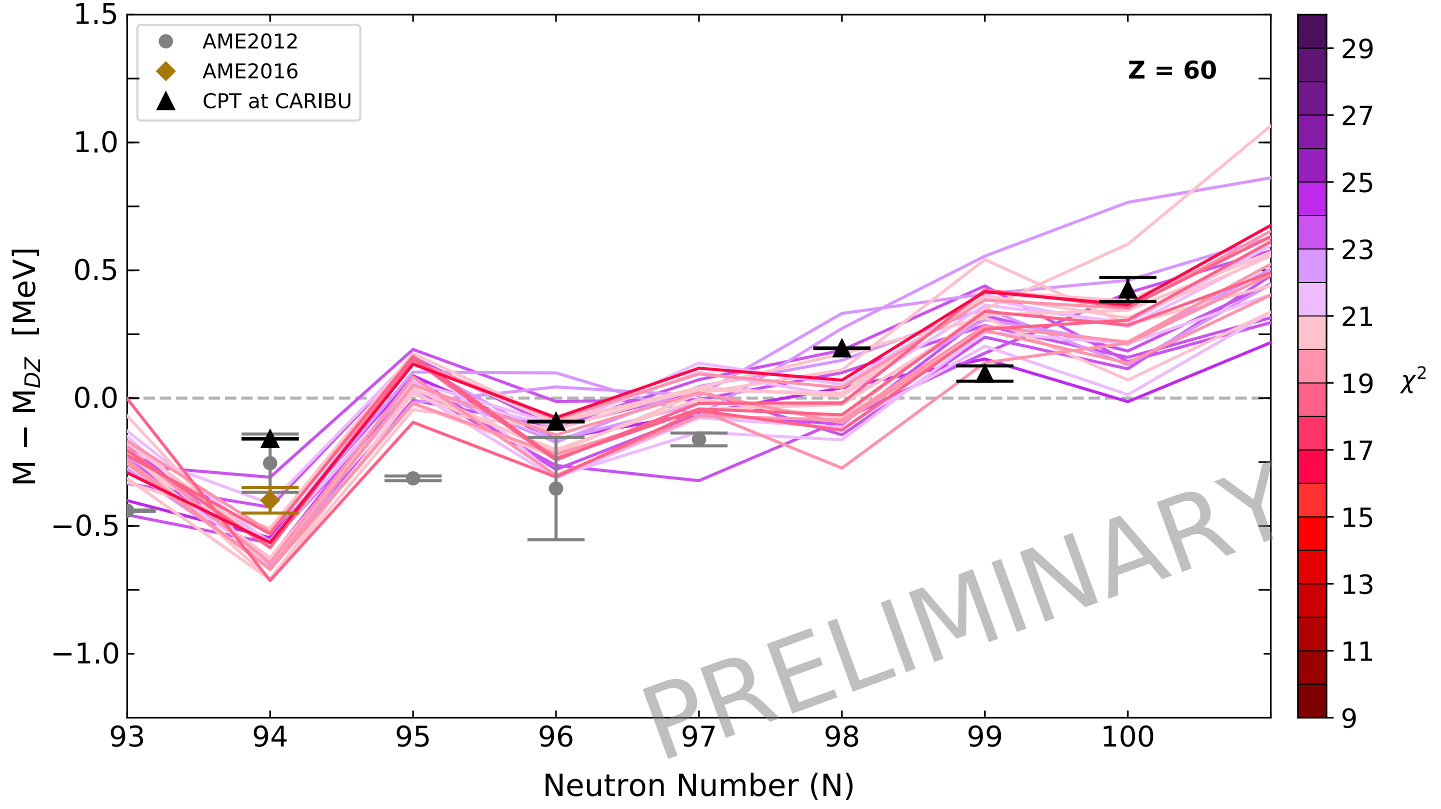
Preliminary Results

- 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)



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