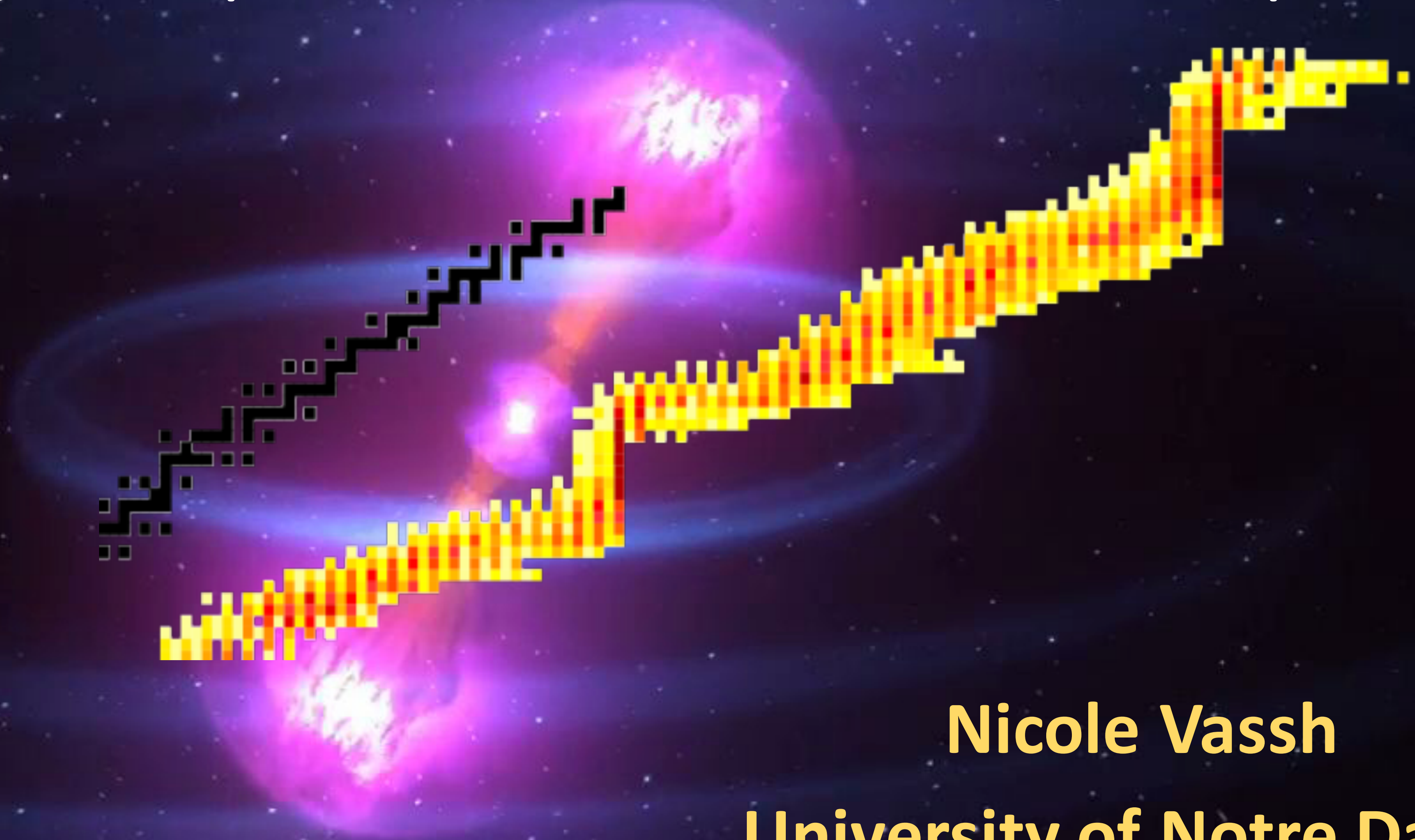
# Reverse engineering properties of neutron-rich lanthanides by examining the *r*-process rare-earth abundance peak




**Nicole Vassh**

**University of Notre Dame**

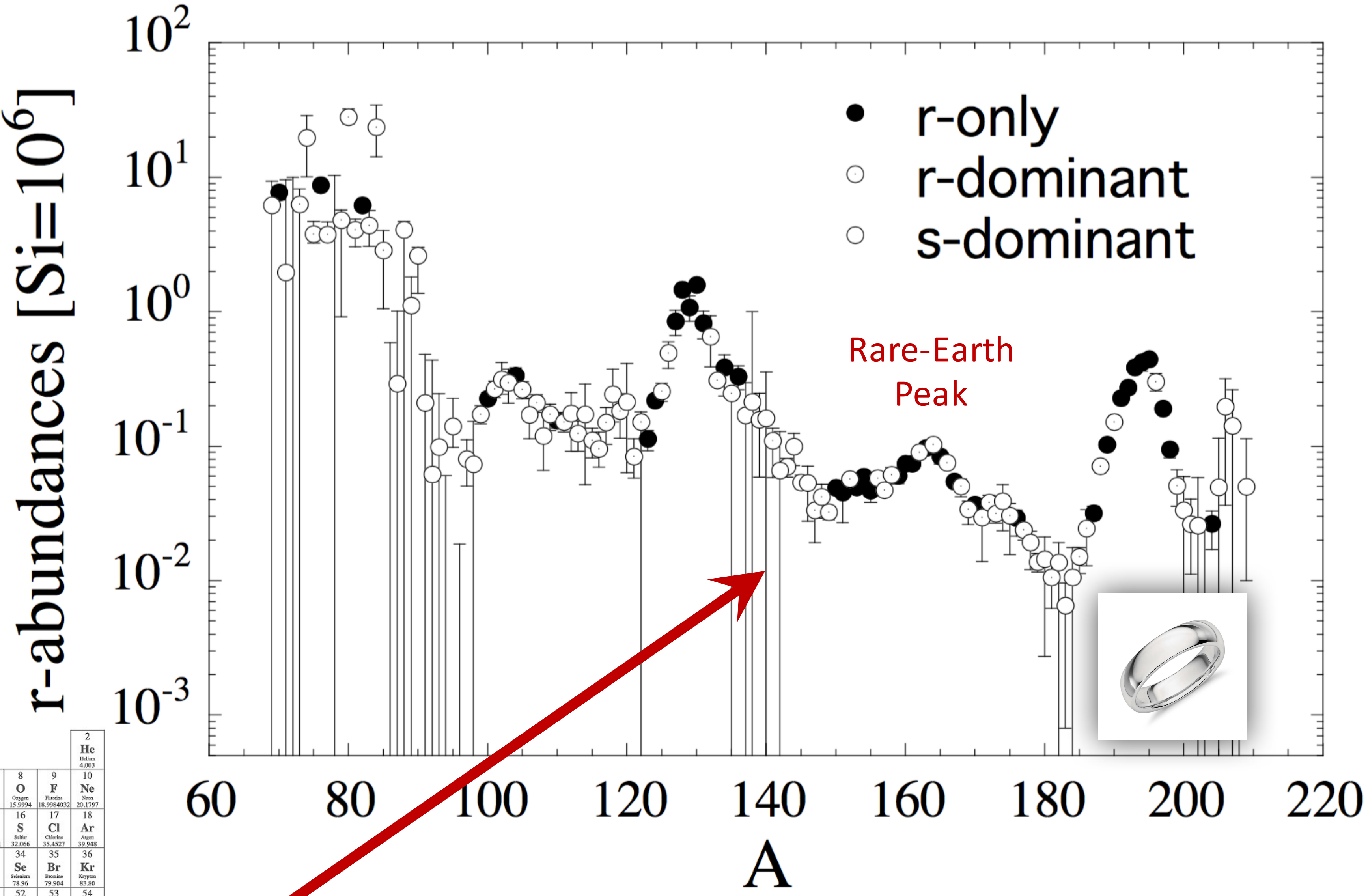


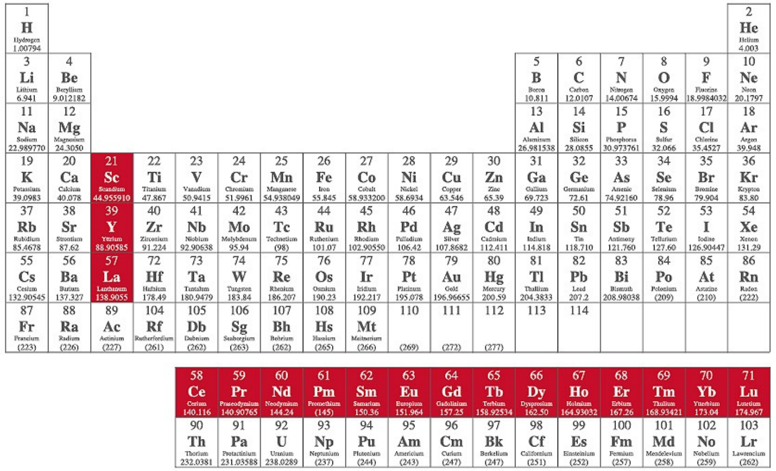
INT-JINA Symposium 3/14/18


Fission In R-process Elements

Argonne NATIONAL LABORATORY

# Observed Solar *r*-process Residuals

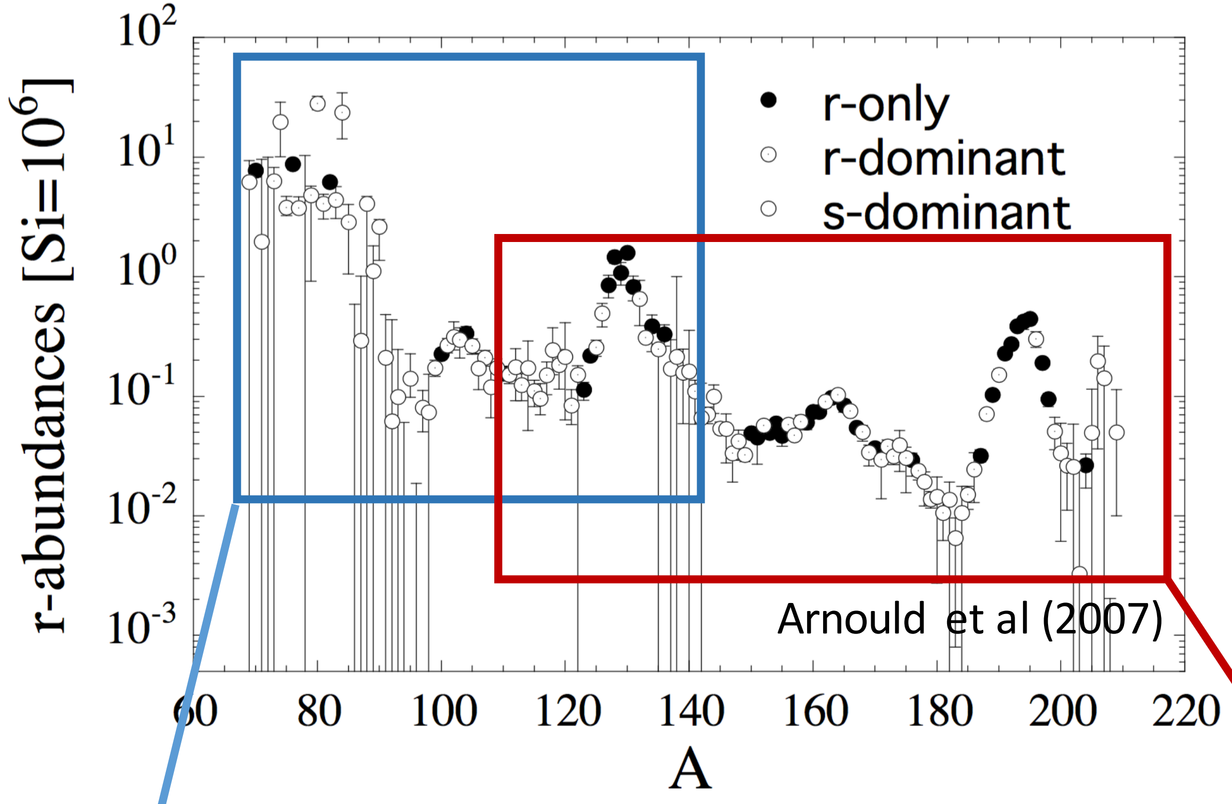


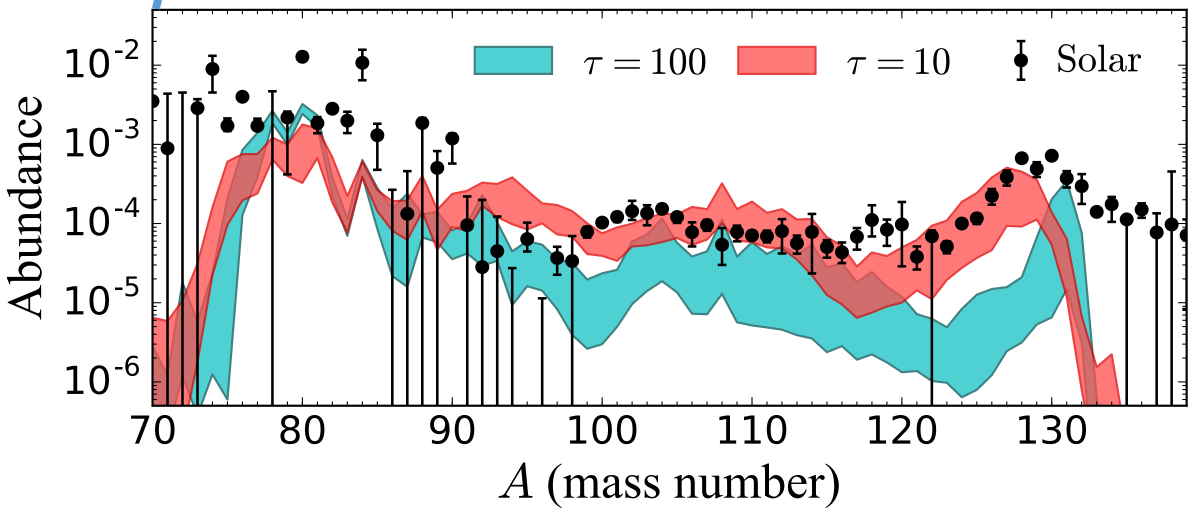
Arnould, Goriely and Takahashi (2007)

# *r*-process Calculations for NSM Ejecta

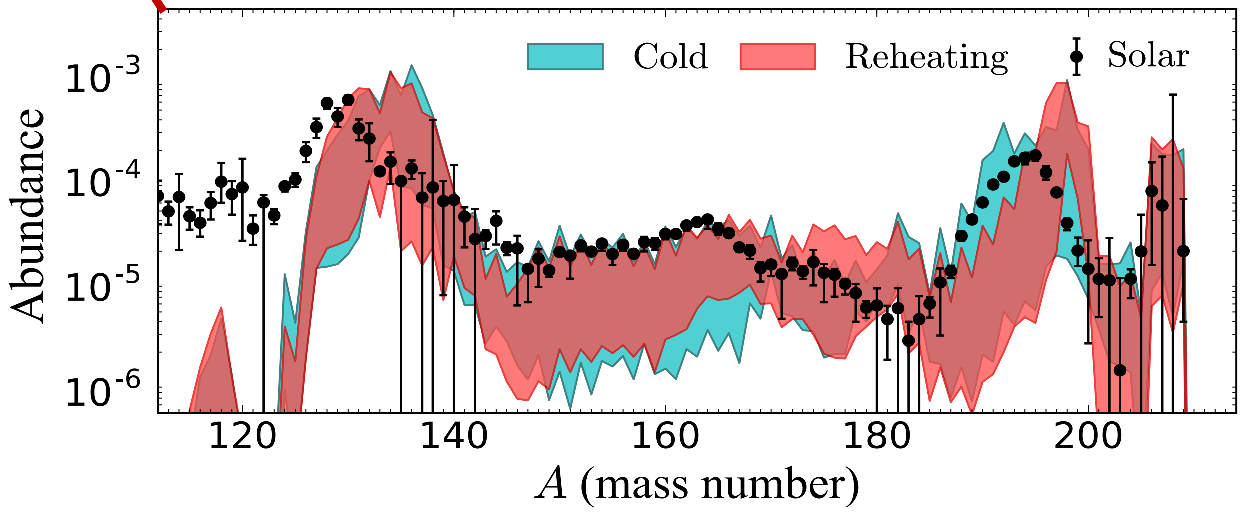
Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman and Wollaeger (2017)




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

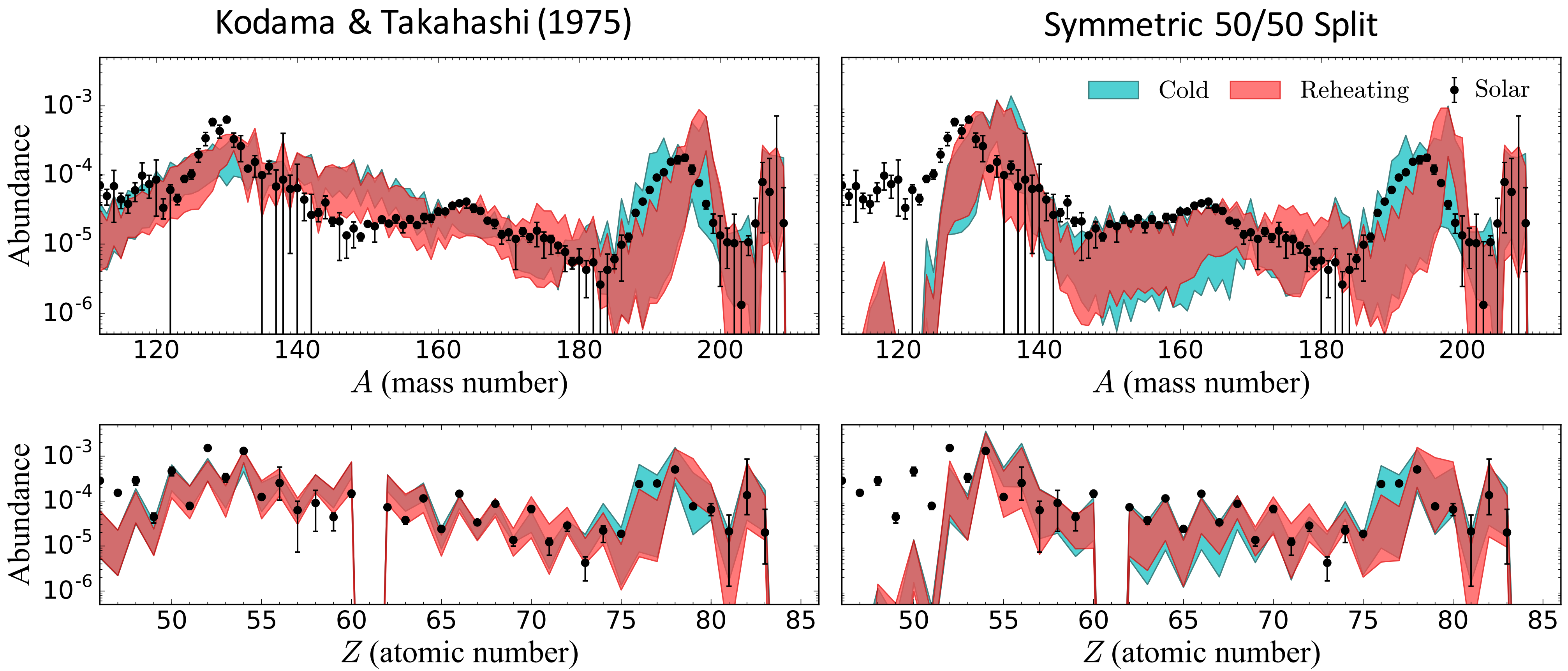



Very n-rich **dynamical** ejecta



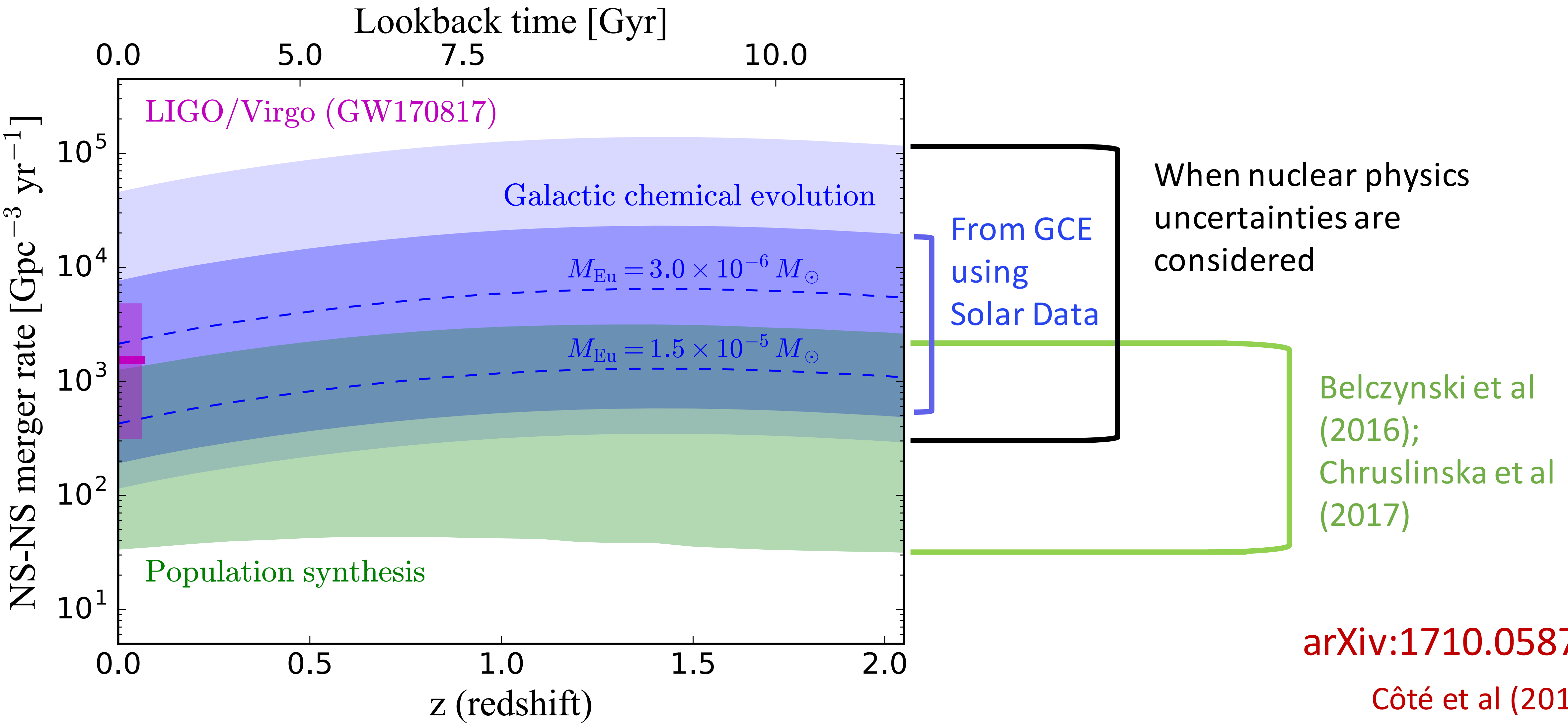
# *r*-process Sensitivity to Mass Model and Fission Yields

- 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 (2017)

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




arXiv:1710.05875

Côté et al (2017)

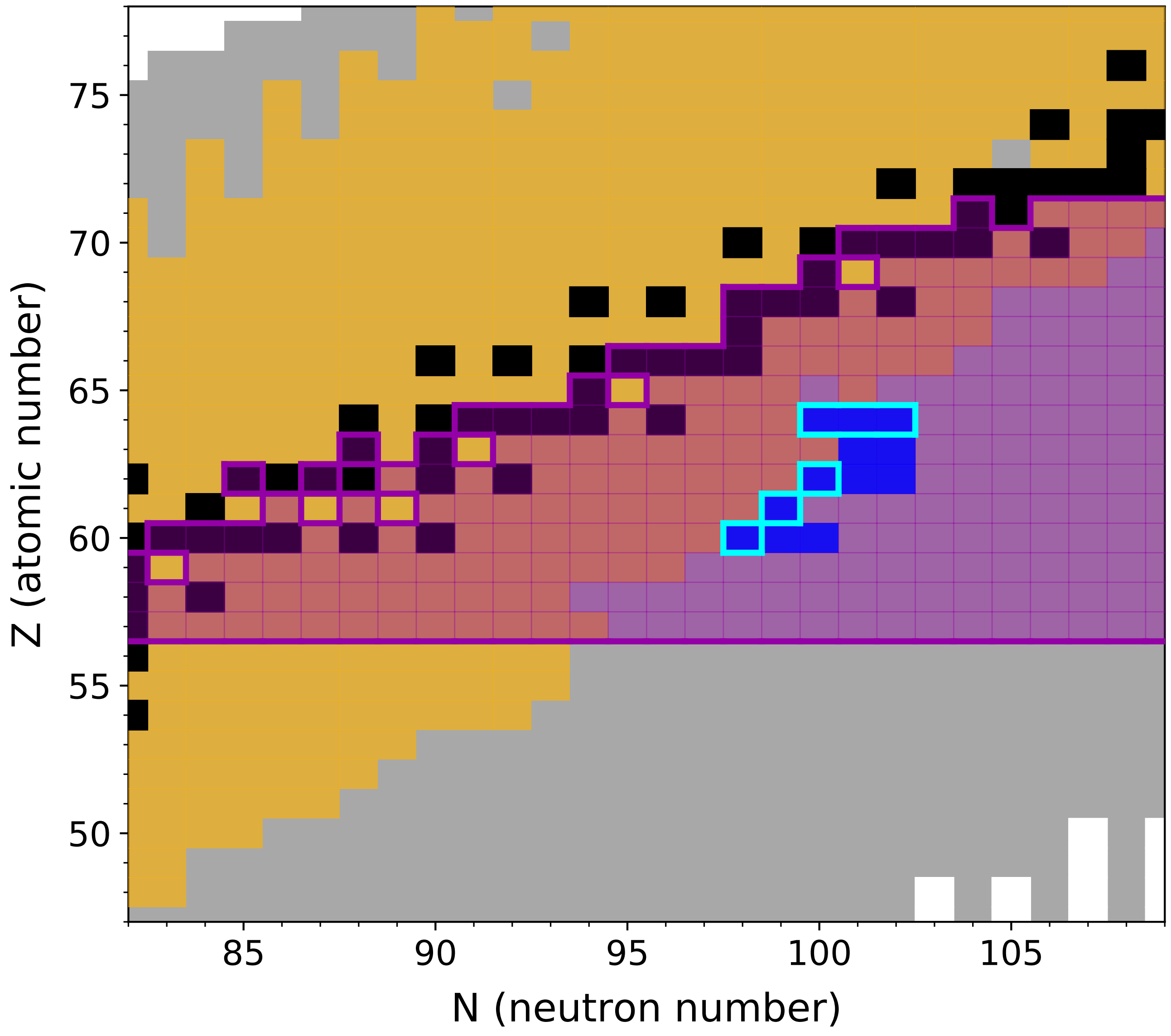
# Studying Rare-Earth Nuclei to Understand *r*-process Lanthanide Production

**Experimental** Mass Measurements:

AME 2016

Jyväskylä

CPT at CARIBU



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

**Experimental** Mass Measurements:

AME 2016

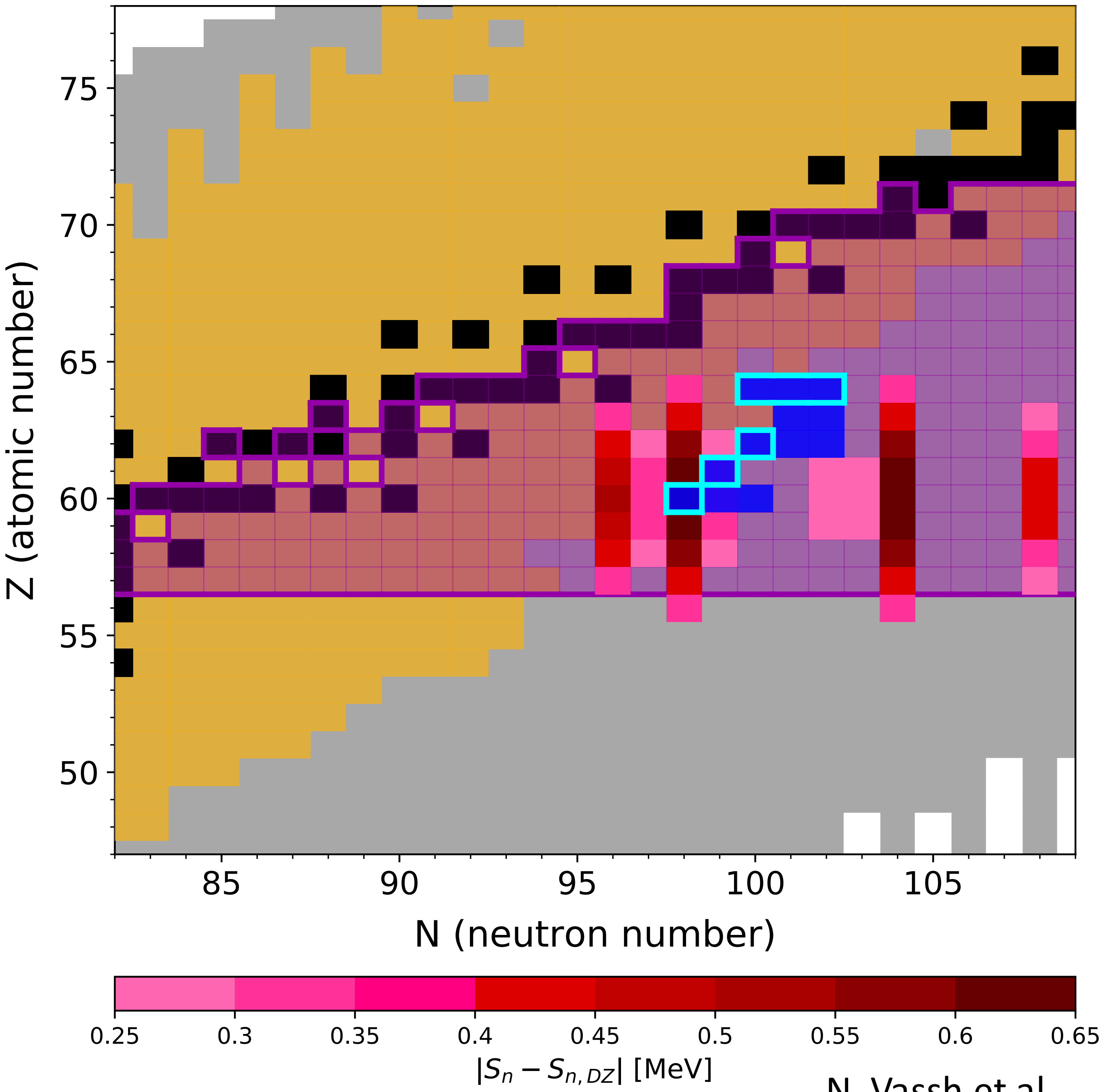
Jyväskylä

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, $\beta$-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**

↑ (to Astrophysical conditions / Fission Yields / Rates)

# MCMC procedure

- Monte Carlo mass corrections

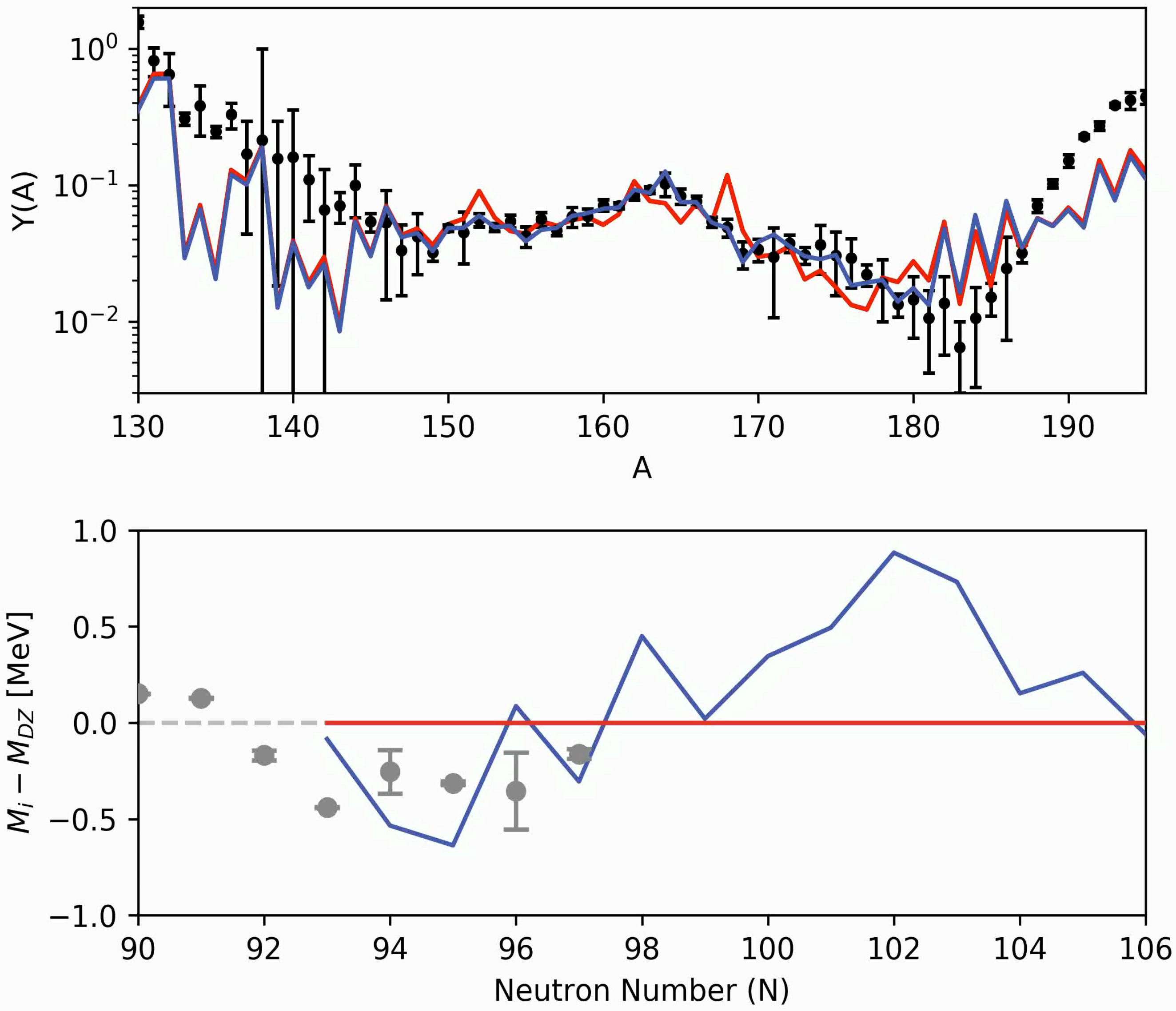
$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

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

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

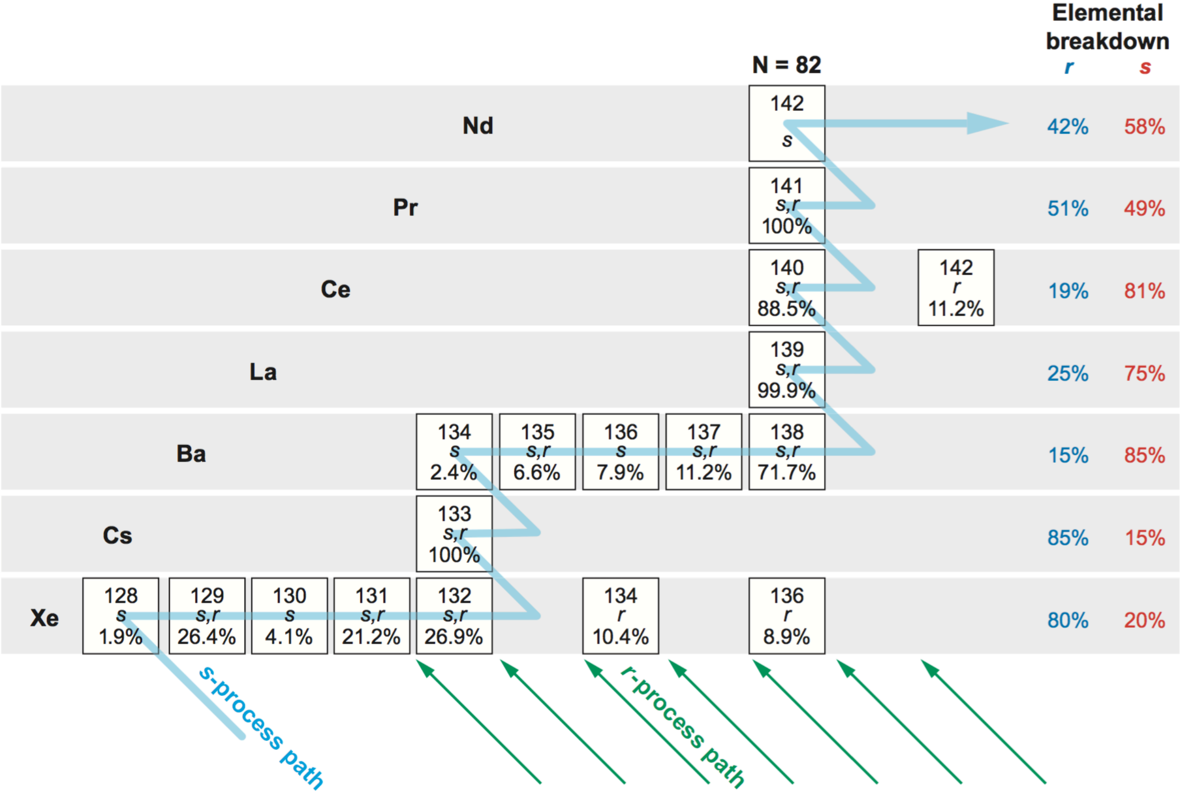
- Update nuclear quantities and rates
- Perform nucleosynthesis calculation
- Calculate $\chi^2 = \sum_{A=150}^{180} \frac{\left(Y_{\odot,r}(A) - Y(A)\right)^2}{\Delta Y(A)^2}$
- Update parameters OR revert to last success

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

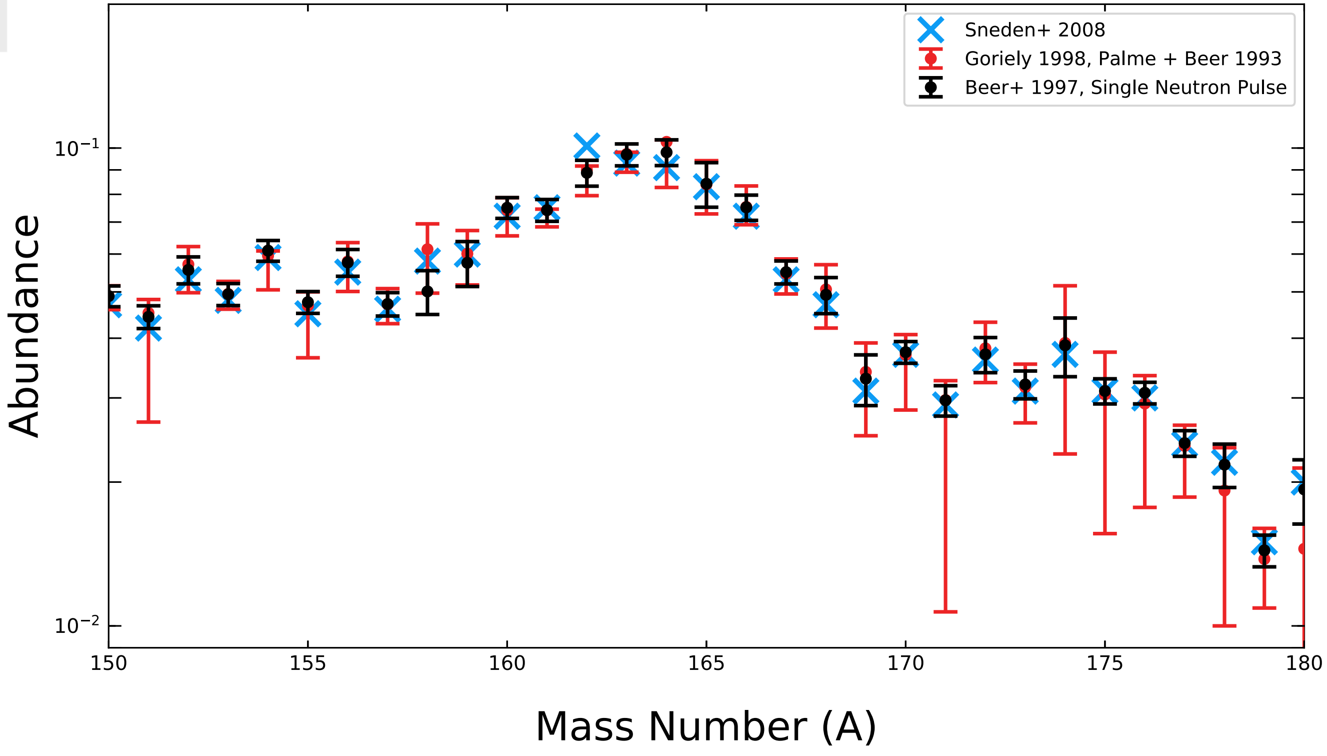



**Black** – solar abundance data
**Grey** – AME 2012 data
**Red** – values at current step
**Blue** – best step of entire run

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



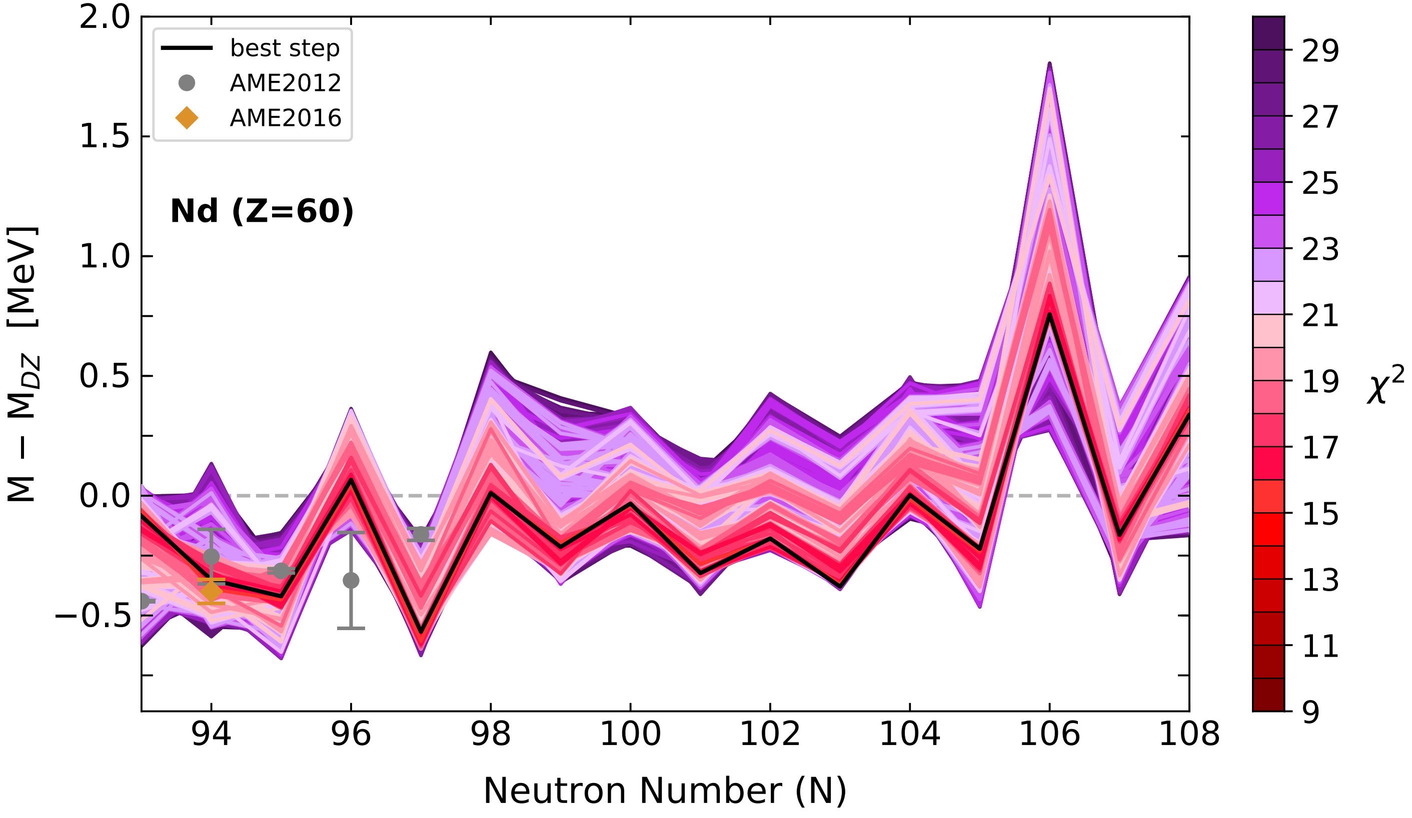

Sneden, Cowan, and Gallino (2008)

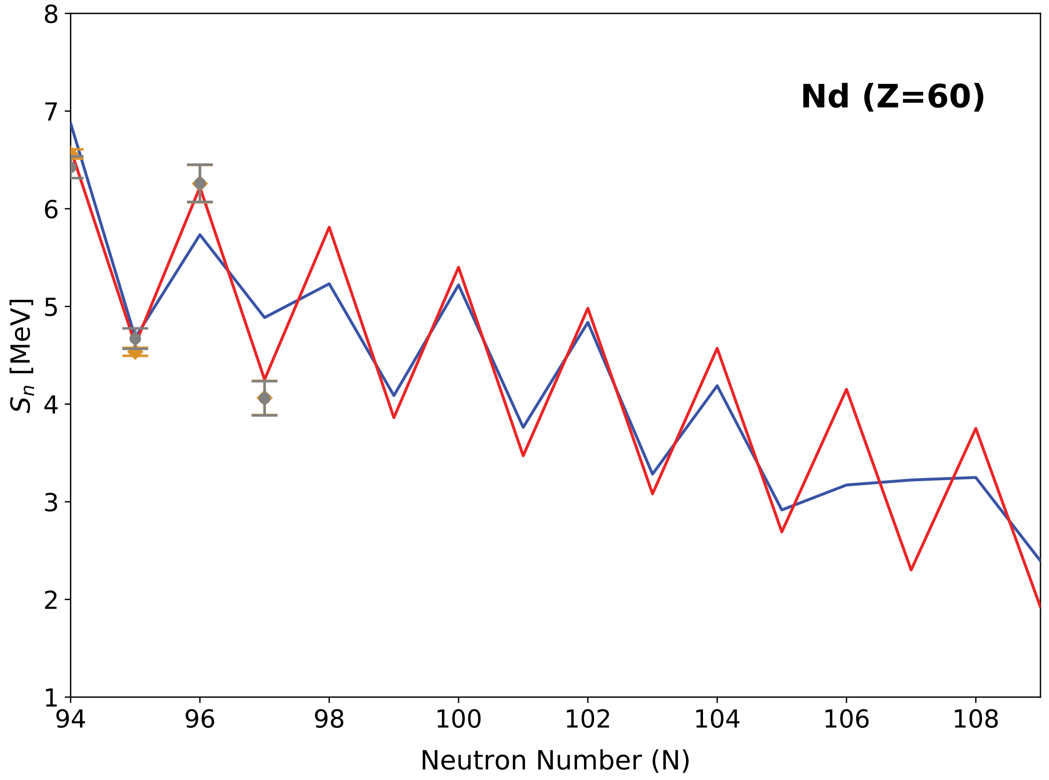


# Parallel Chains Method of MCMC

- 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

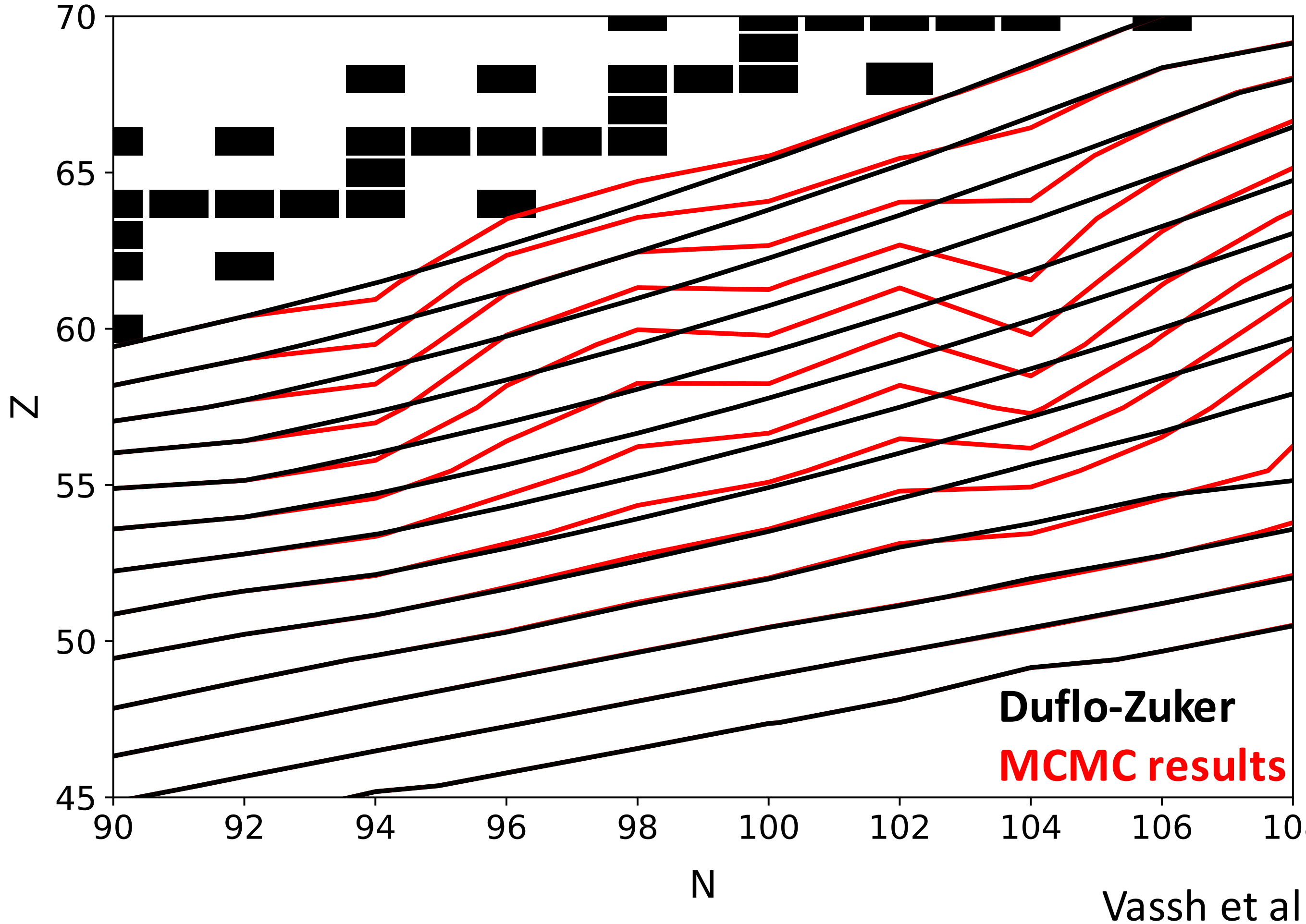
$$(\gamma, \mathrm{n}) \propto e^{-S_\mathrm{n}/kT}$$

↓

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

↓

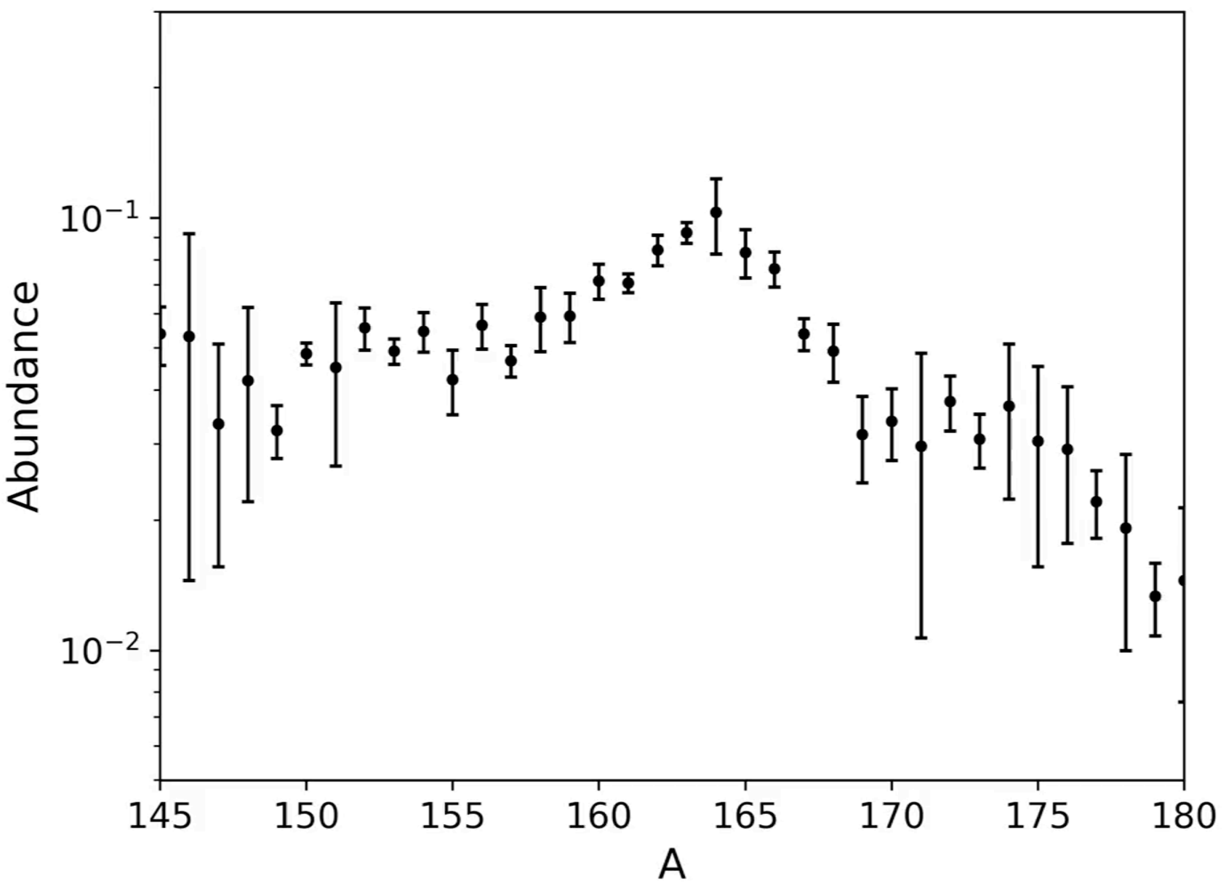
Pile-up of material at kinks

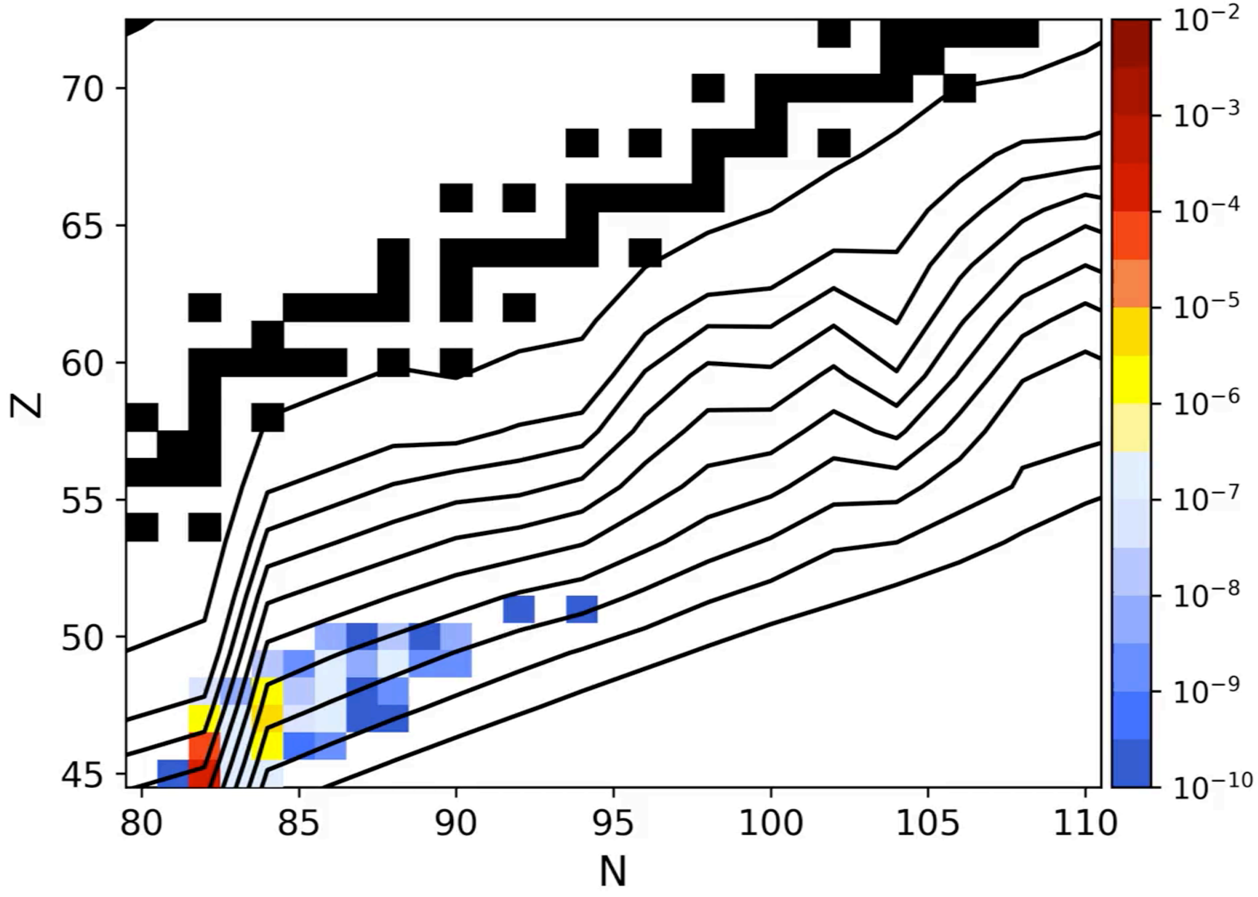



Vassh et al
(in preparation)

NOTE: FISSION is the other possible means of REP formation

# Peak Formation with an MCMC Mass Solution

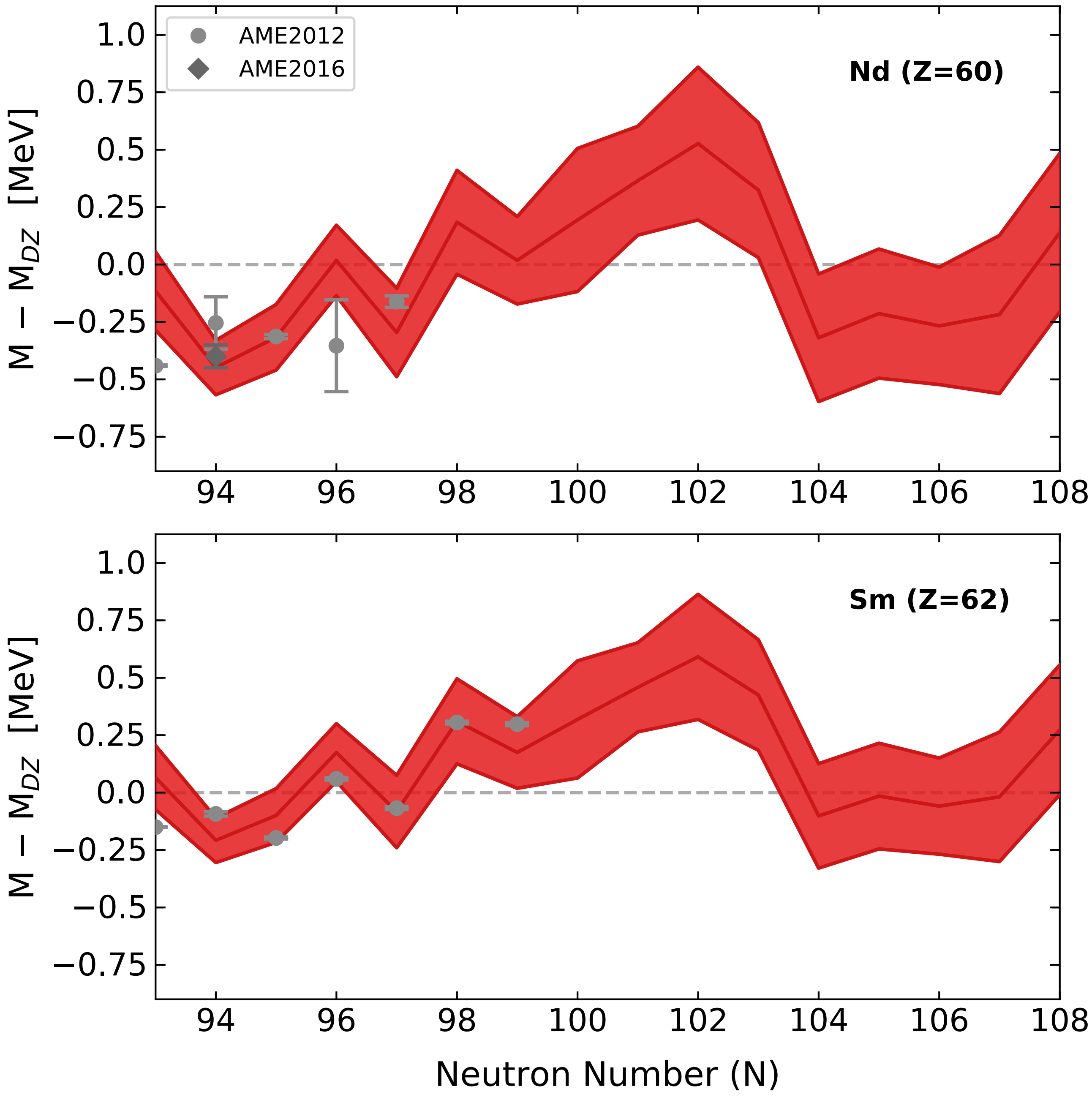


# Results

- 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 $\chi^2 \sim 23$




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

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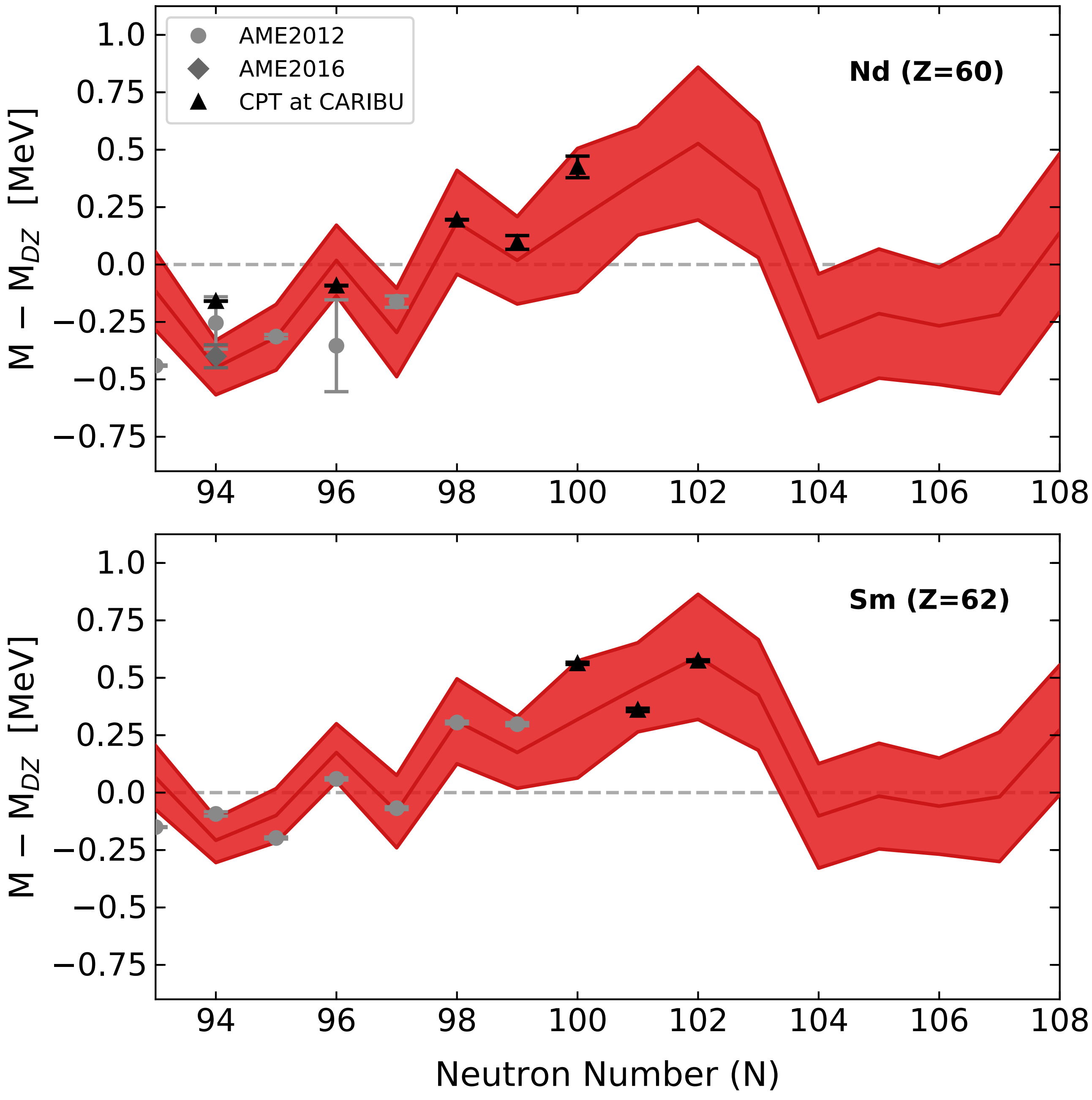


Orford, Vassh, Clark, McLaughlin, Mumpower, Savard, Surman, Aprahamian, Buchinger, Burkey, Gorelov, Hirsh, Klimes, Morgan, Nystrom, and Sharma
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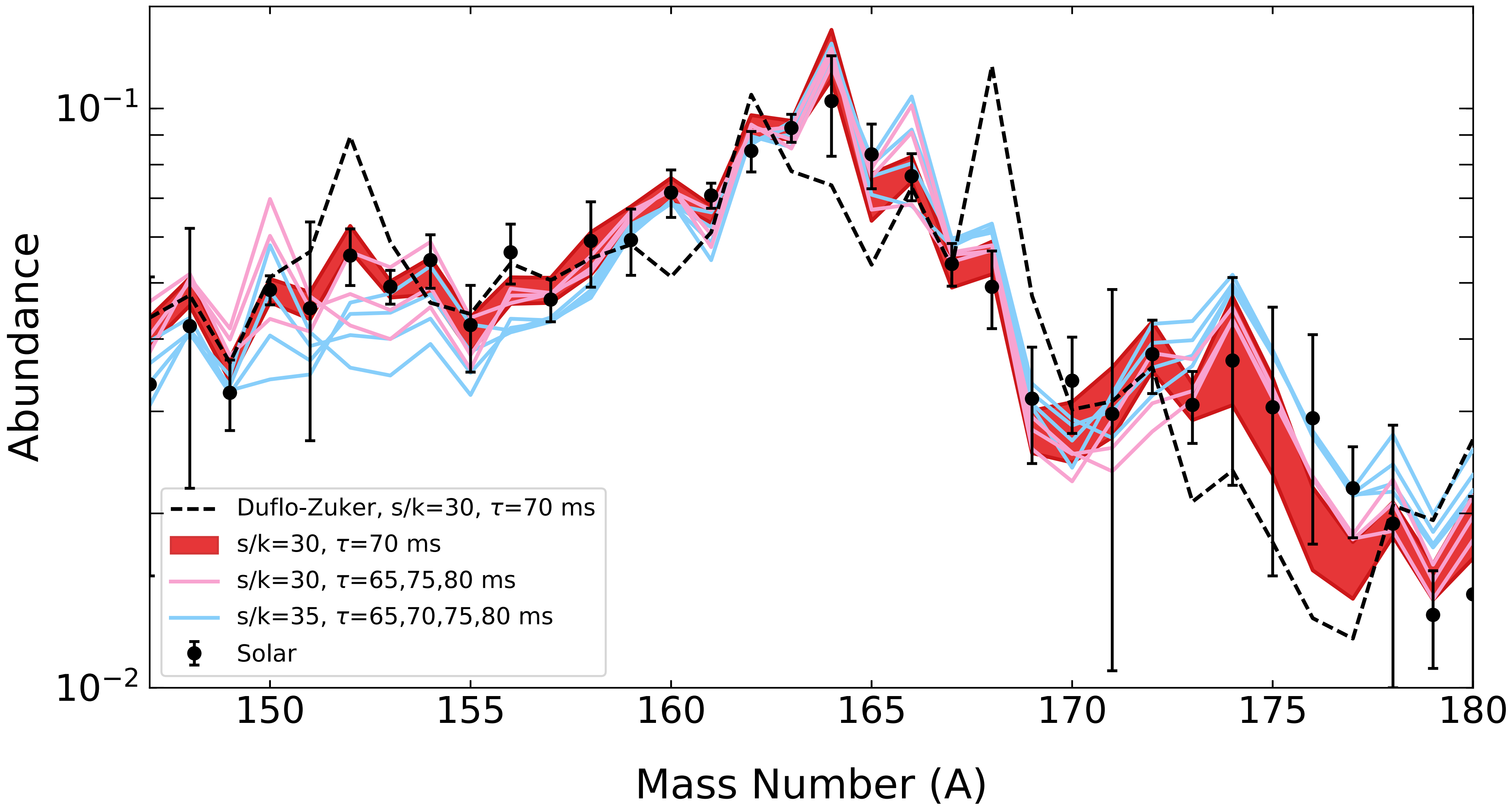
# Rare-Earth Peak with MCMC solutions

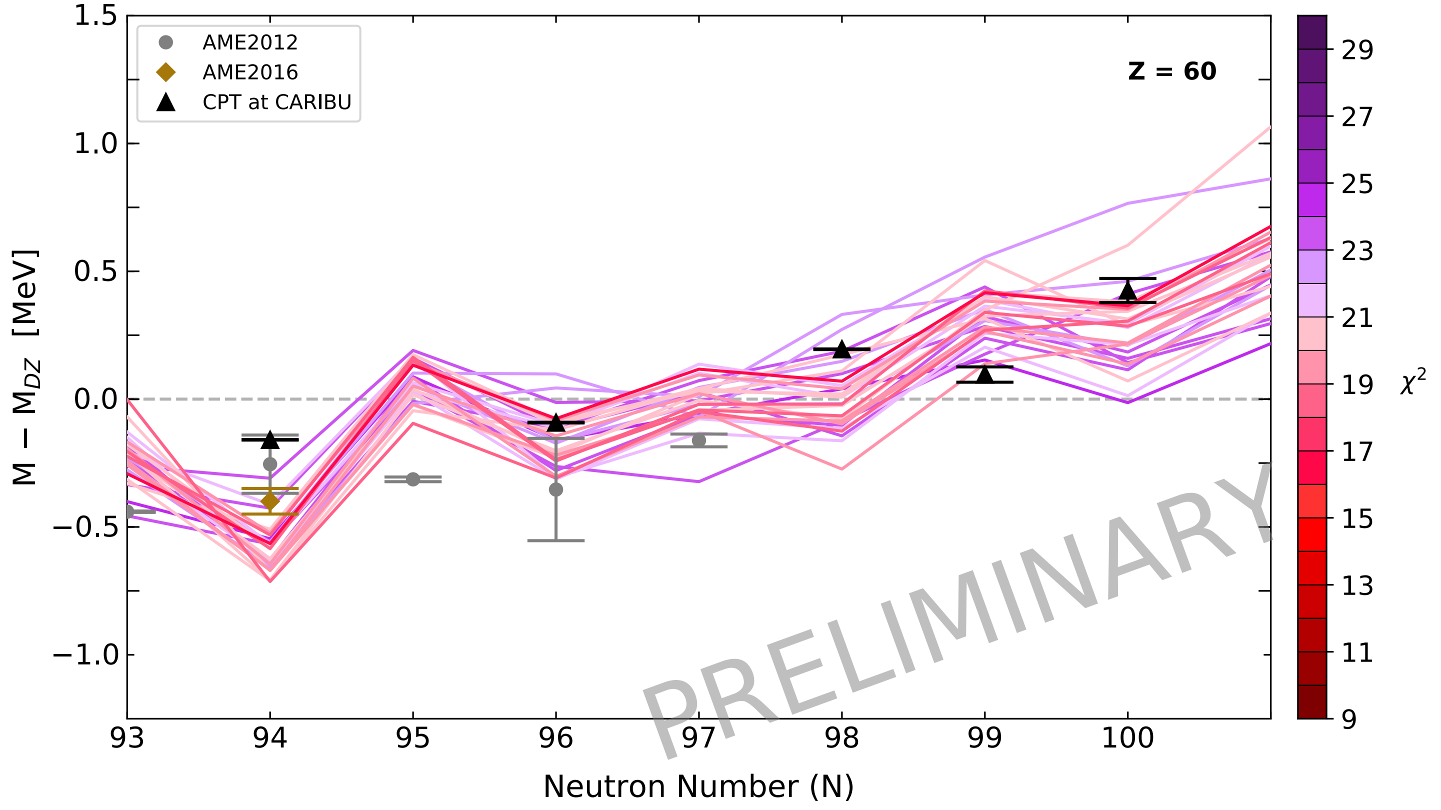



Orford, Vassh, et al (submitted to PRL)

# Preliminary Results

- Astrophysical trajectory: n-rich NSM **dynamical** ejecta with nuclear reheating
- 50 independent MCMC runs complete

30 Runs (Best Step Colored by $\chi^2$)





Vassh et al
(in preparation)

# Nucleosynthesis in Neutron Star Mergers: Many Open Questions

- Can mergers account for all 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?
- How does the rare-earth peak form?

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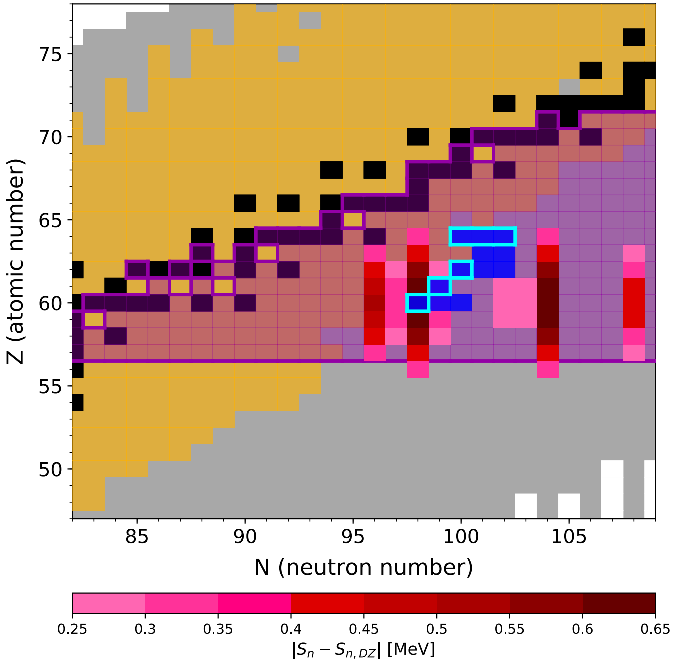
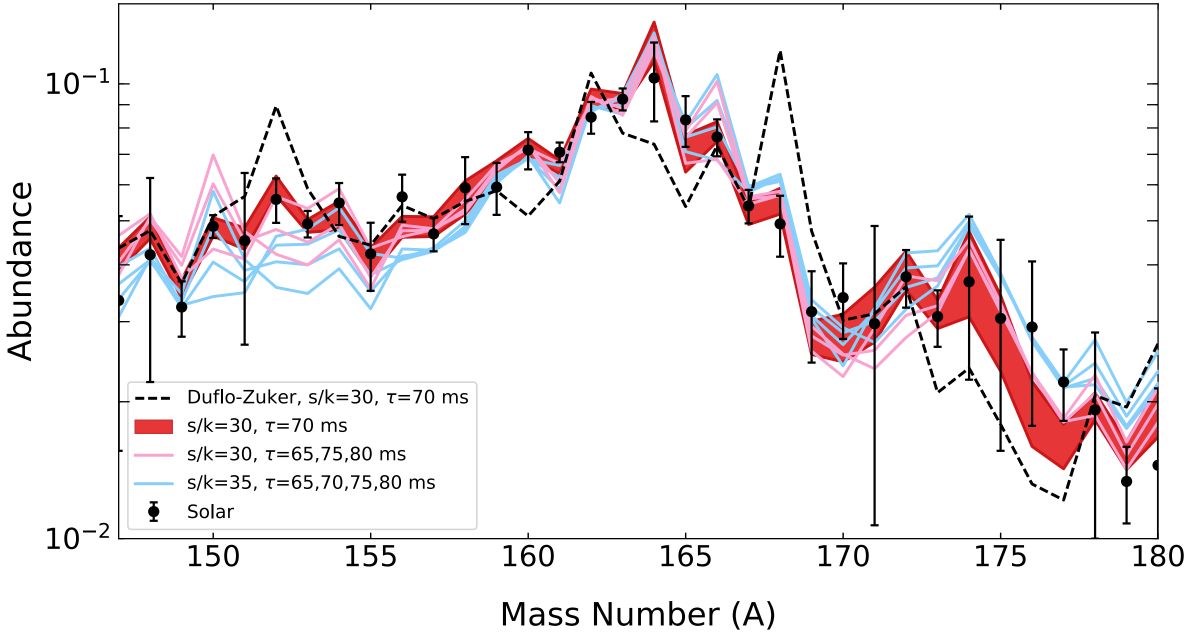



Vassh et al (in preparation)




Orford, Vassh, et al (submitted to PRL)

# Back-up Slides

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

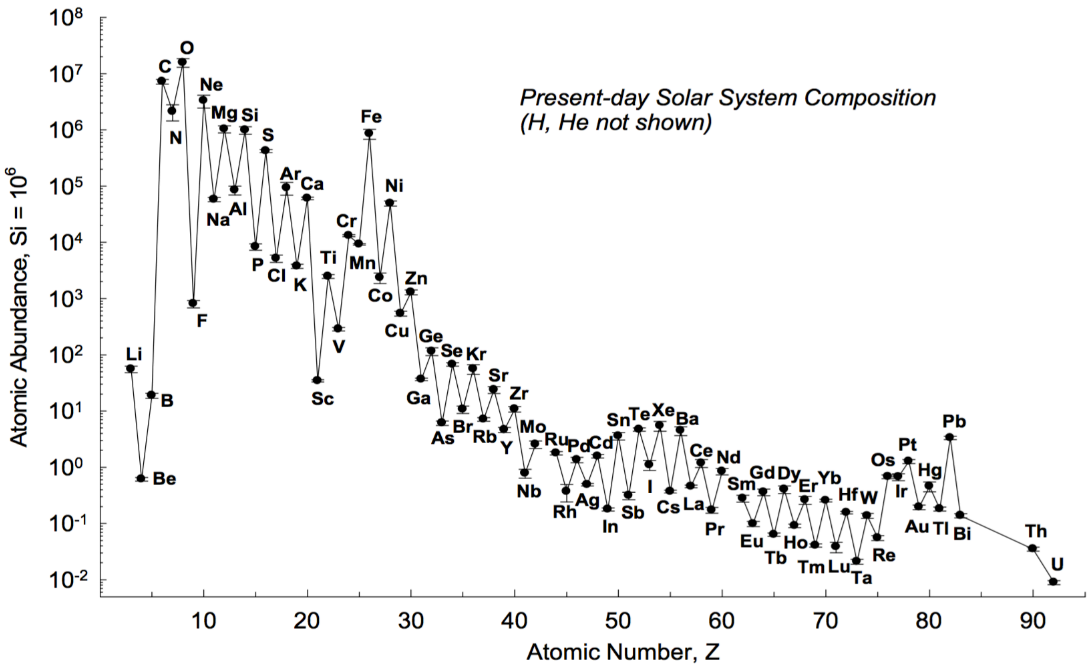
Los Alamos NATIONAL LABORATORY EST. 1943

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

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

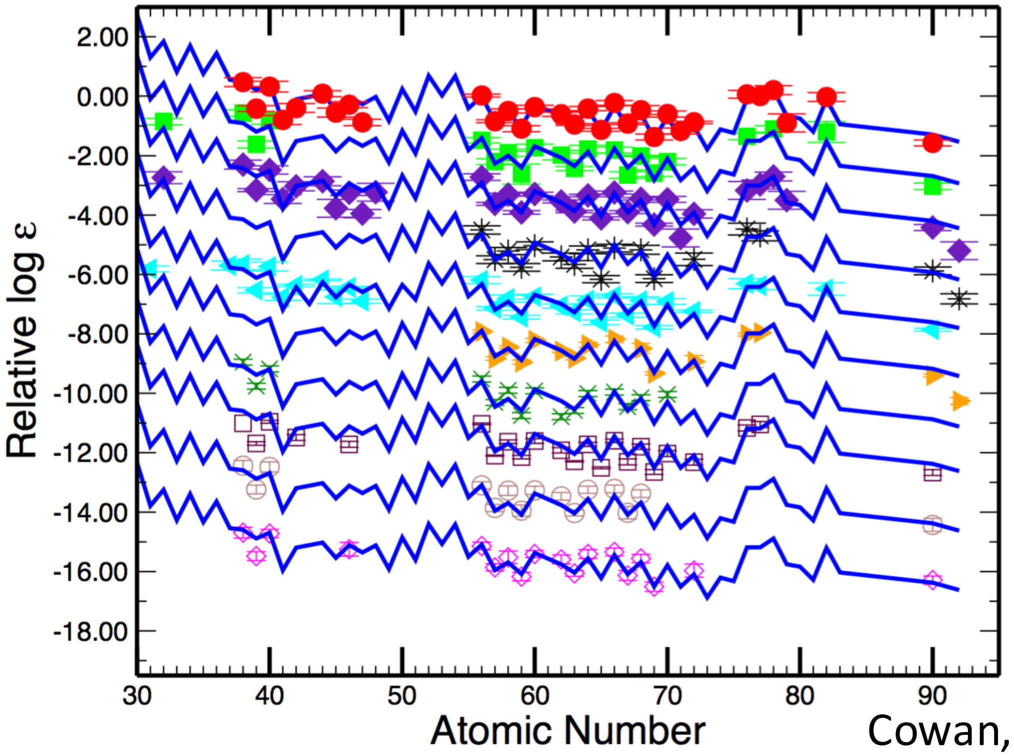
# Observed Elemental Abundances

**Solar System**



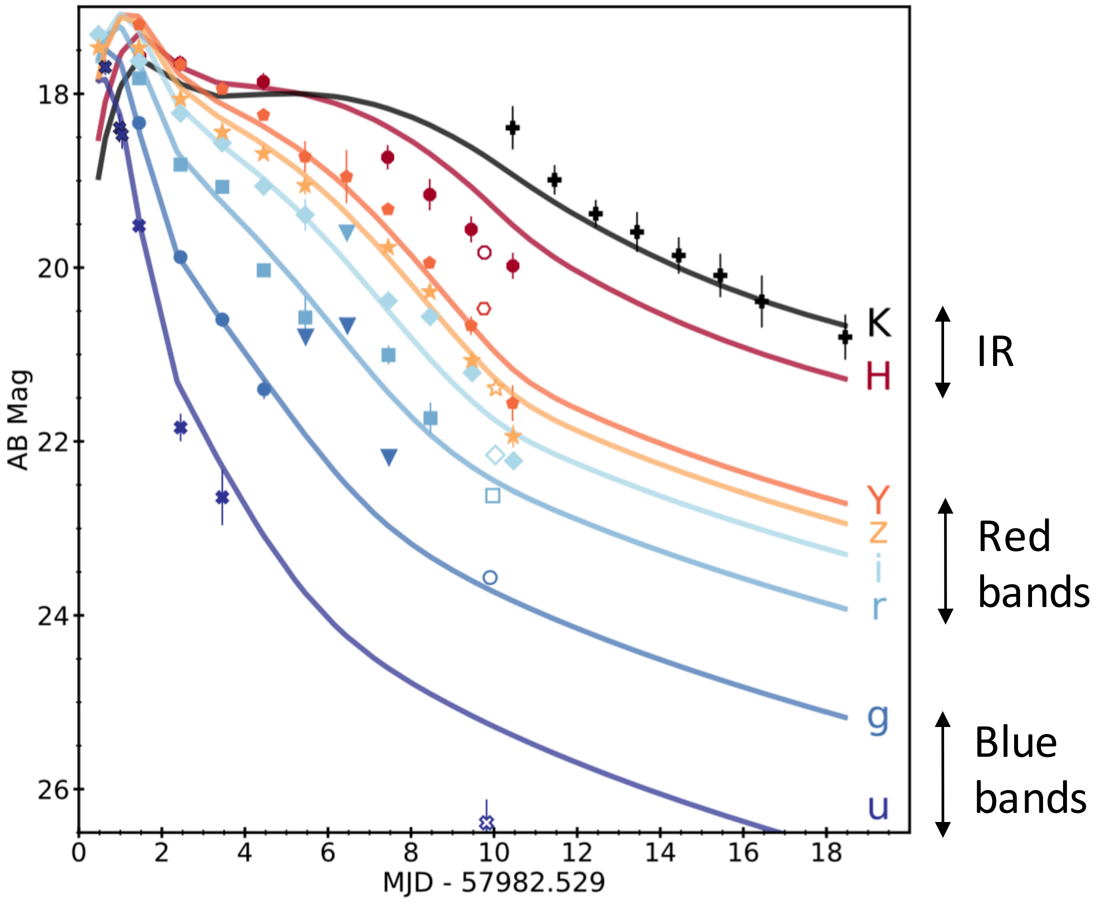

Lodders (2010)

**10 *r*-process rich halo stars**



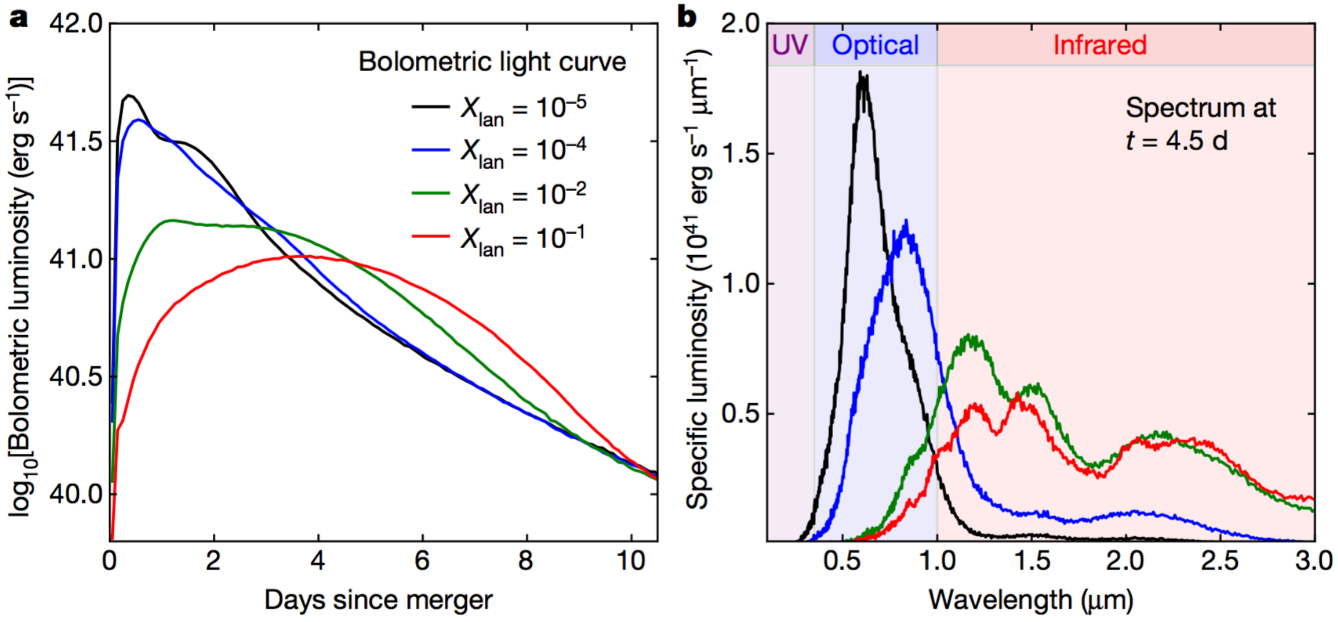

Cowan, Roederer, Sneden and Lawler (2011)

# Lanthanide production in GW170817: "red" kilonova




Cowperthwaite et al (ApJL 2017)

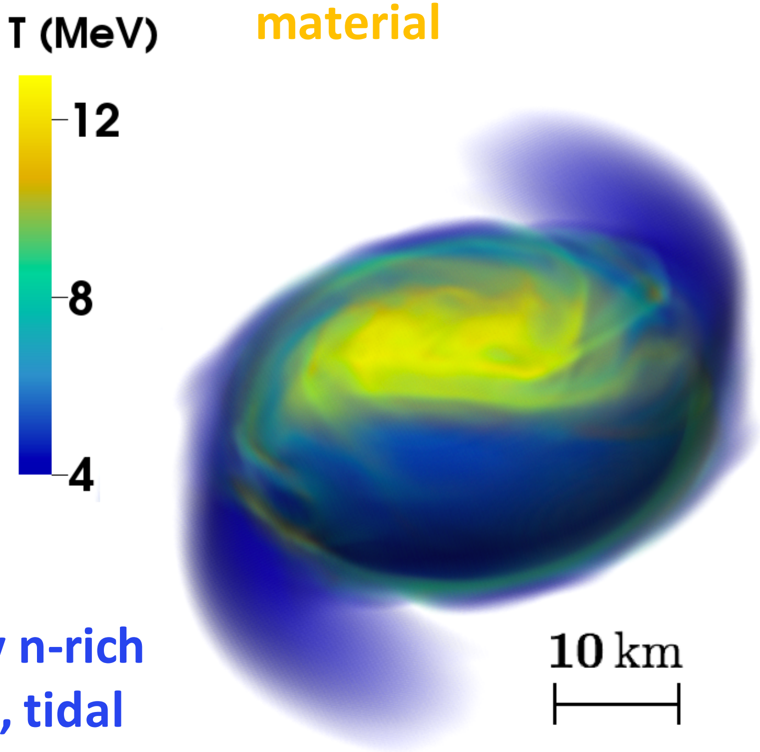
Lanthanide mass fraction ↑ , opacity ↑, longer duration light curve shifted toward infrared




Kasen et al (*Nature* 2017)

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

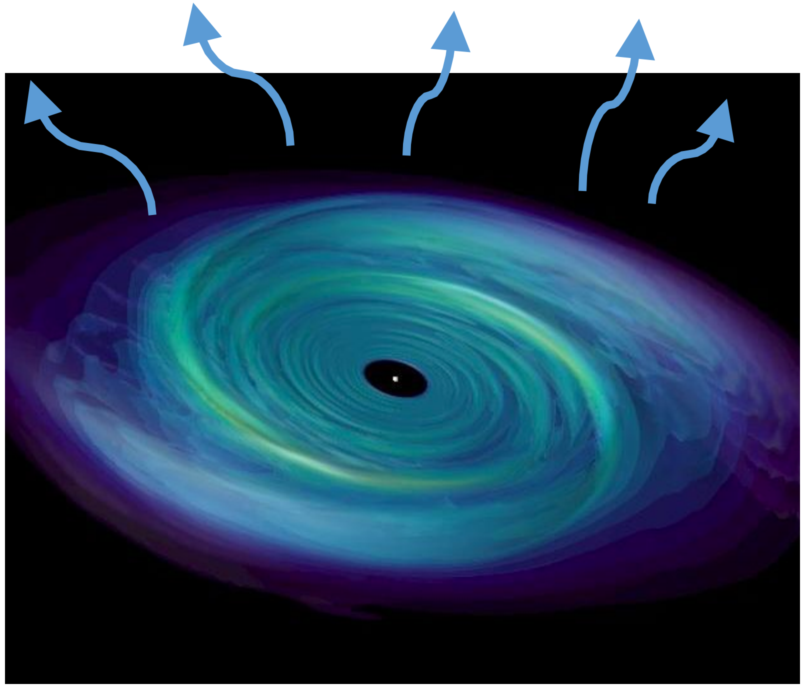
Hot, shocked material




Very n-rich cold, tidal outflows

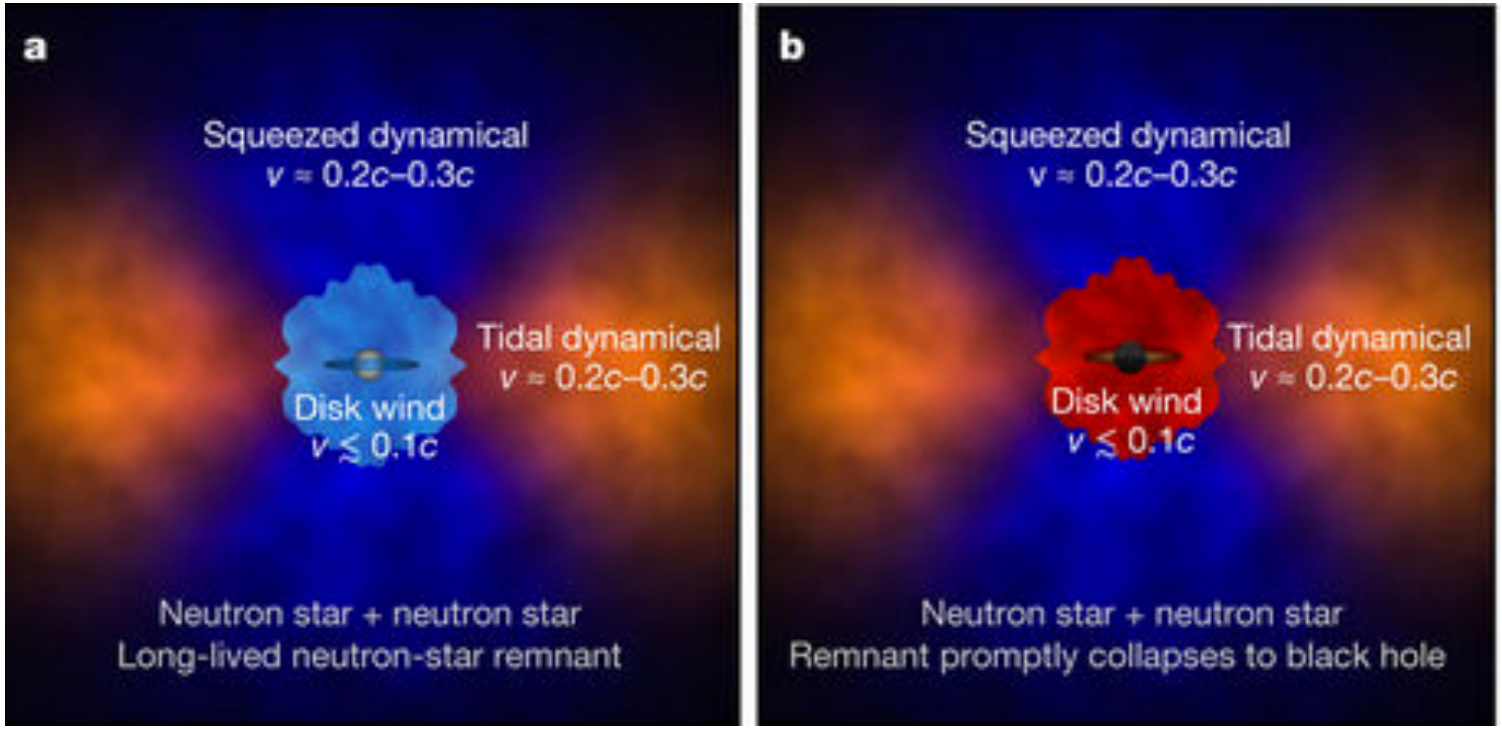
Foucart et al (2016)

Accretion disk winds – exact driving mechanism and neutron richness varies



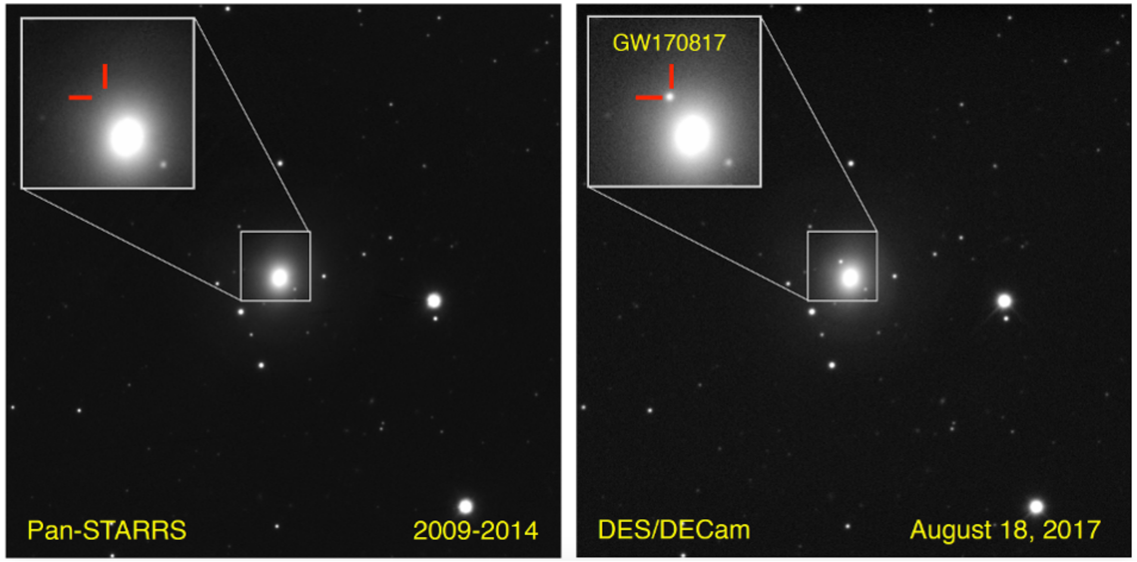
Owen and Blondin

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




Kasen, Metzger, Barnes, Quataert, and Ramirez-Ruiz (*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) |

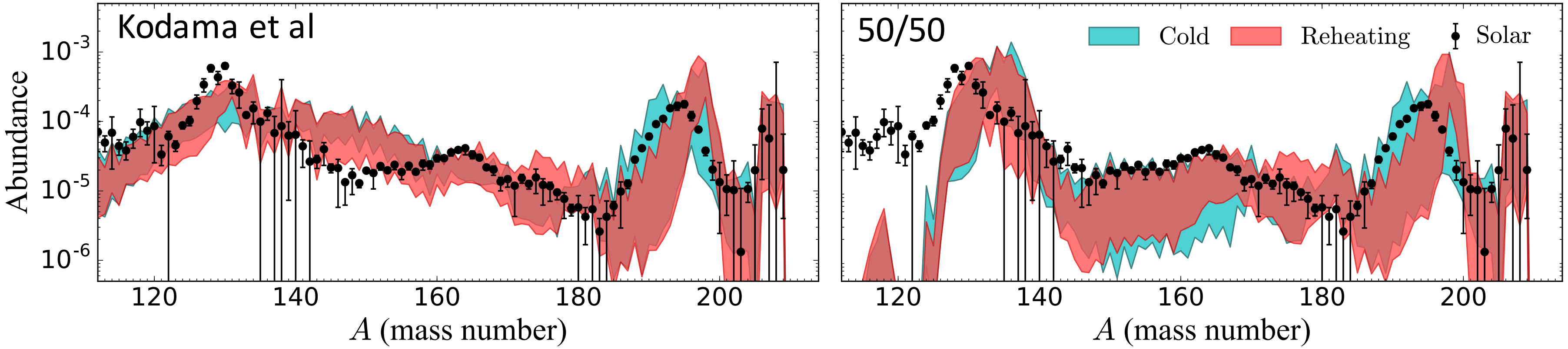
Estimates of ejected mass for GW170817

Mass fraction range for stable Eu isotopes with 10 mass models

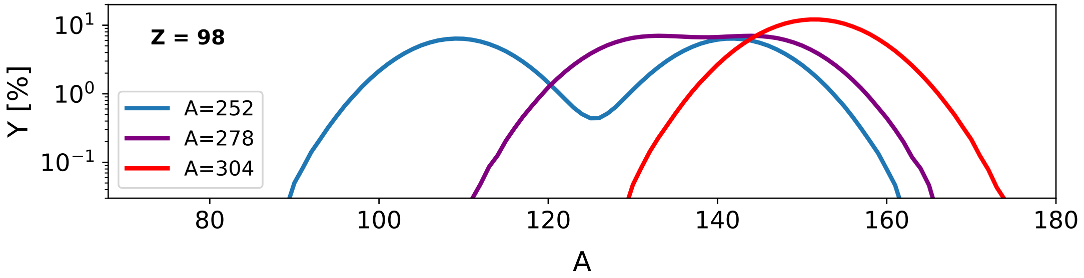
| Astrophysical Trajectory | Fission Fragment Distribution | $^{151}$Eu Mass Fraction $[10^{-3}]$ | $^{153}$Eu Mass Fraction $[10^{-3}]$ | Relative Abundance Range |
|---|---|---|---|---|
| Cold outflow (no reheating) | Kodama & Takahashi (1975) | (5.01 – 11.7) | (3.92 – 8.75) | 0.776 |
| (Just et al. 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)

# Dependence on the Fission Fragment Distribution

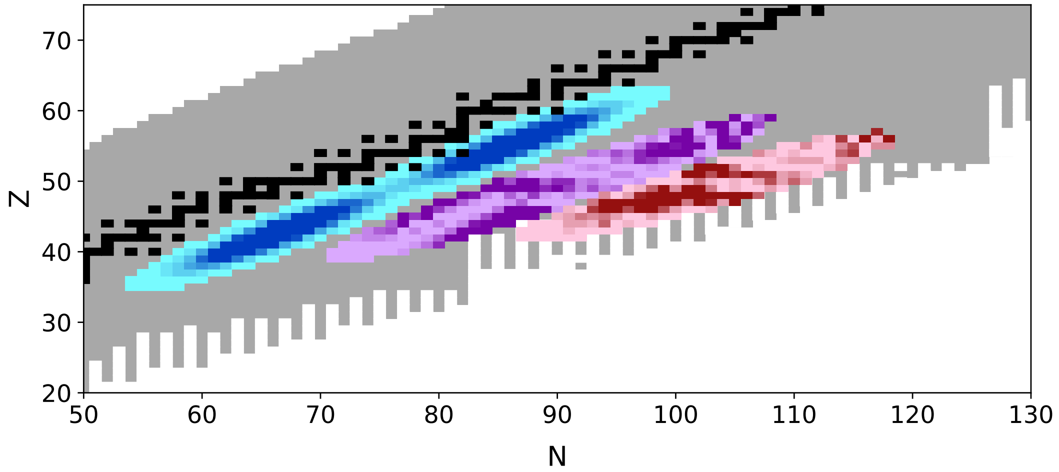



Côté et al (2017)



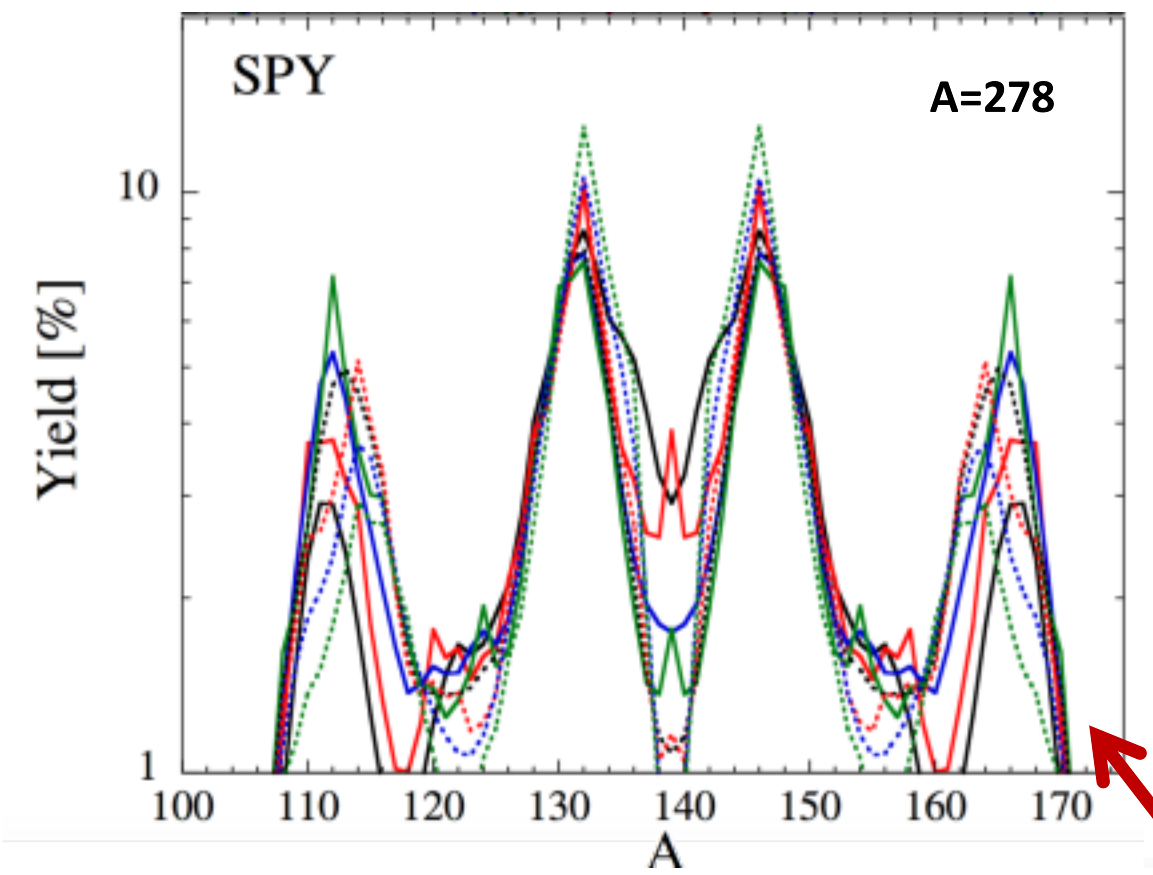

Kodama & Takahashi (1975)

$$Y_{A_f,Z_f}(Z,A)$$
$$\propto \exp\{-(Z-Z_A)^2/c_Z\}$$
$$\times[\exp\{-(A-A_L)^2/c_A\}+\exp\{-(A-A_H)^2/c_A\}]$$

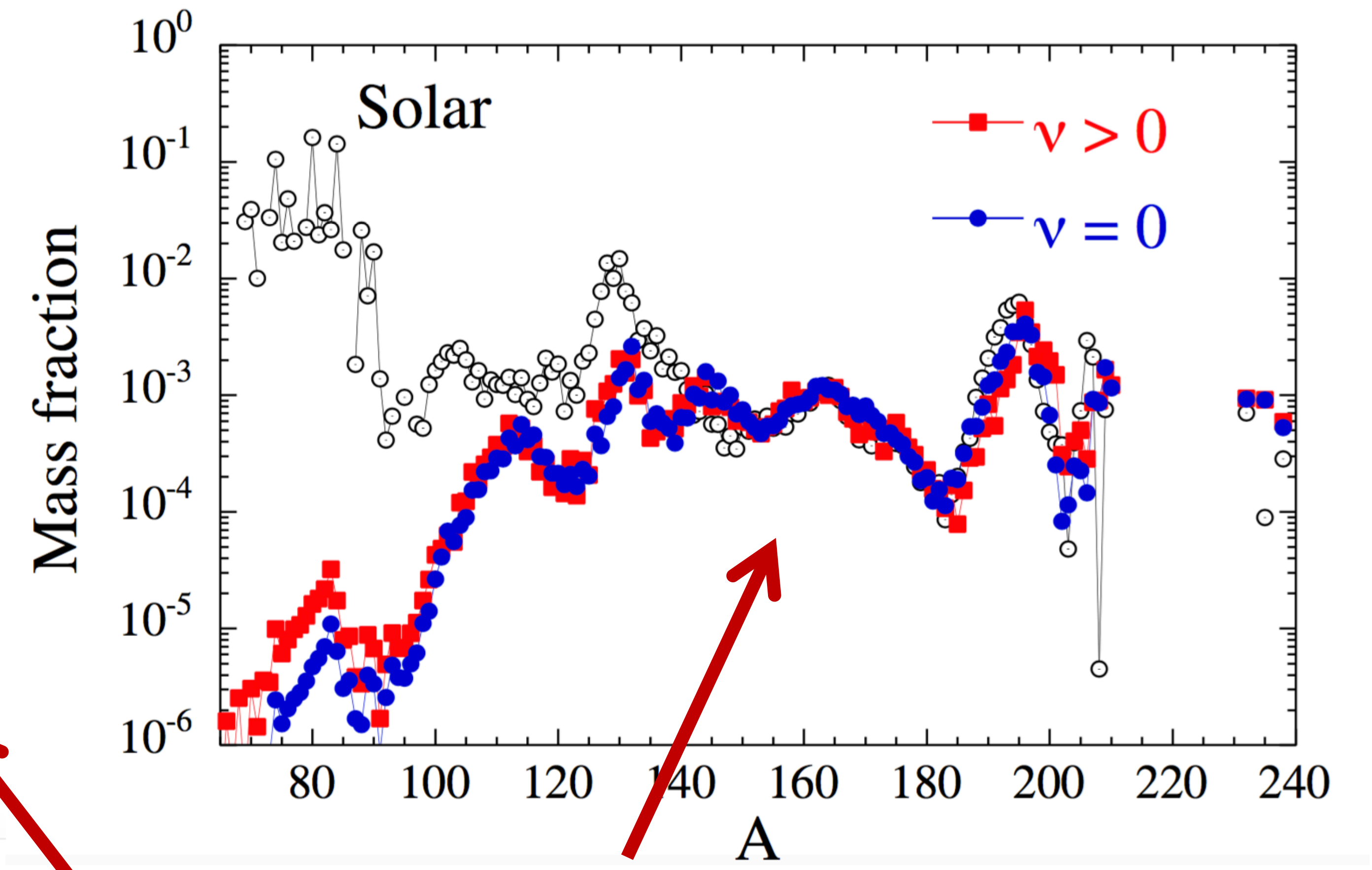



Vassh et al
(in preparation)

# Dependence on the Fission Fragment Distribution



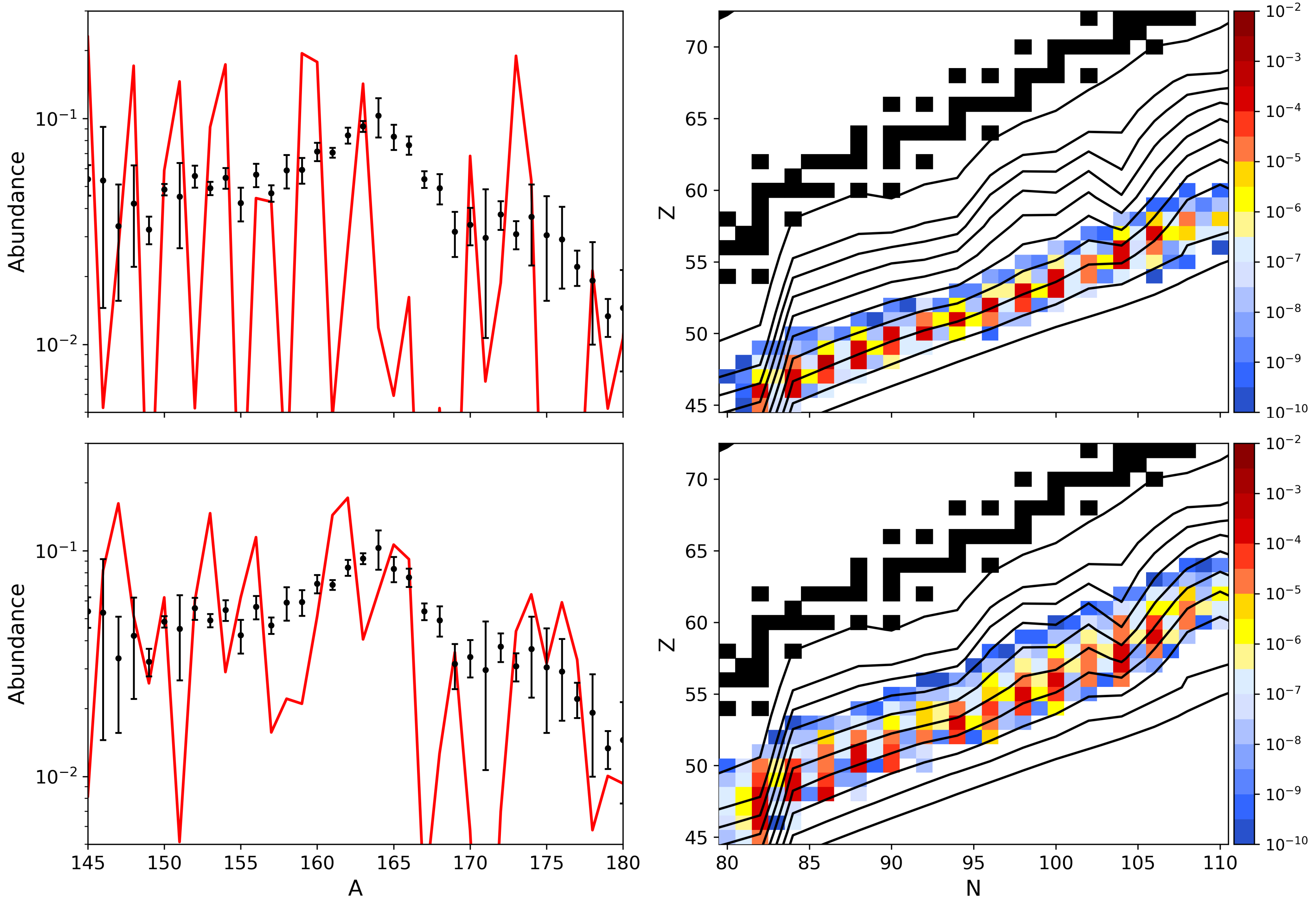

Z=95, Z=96 , Z=97, Z=98, Z=99, Z=100, Z=101, Z=102 (dotted lines – larger Z)




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

Goriely (2015)

# Peak Formation with an MCMC Mass Solution



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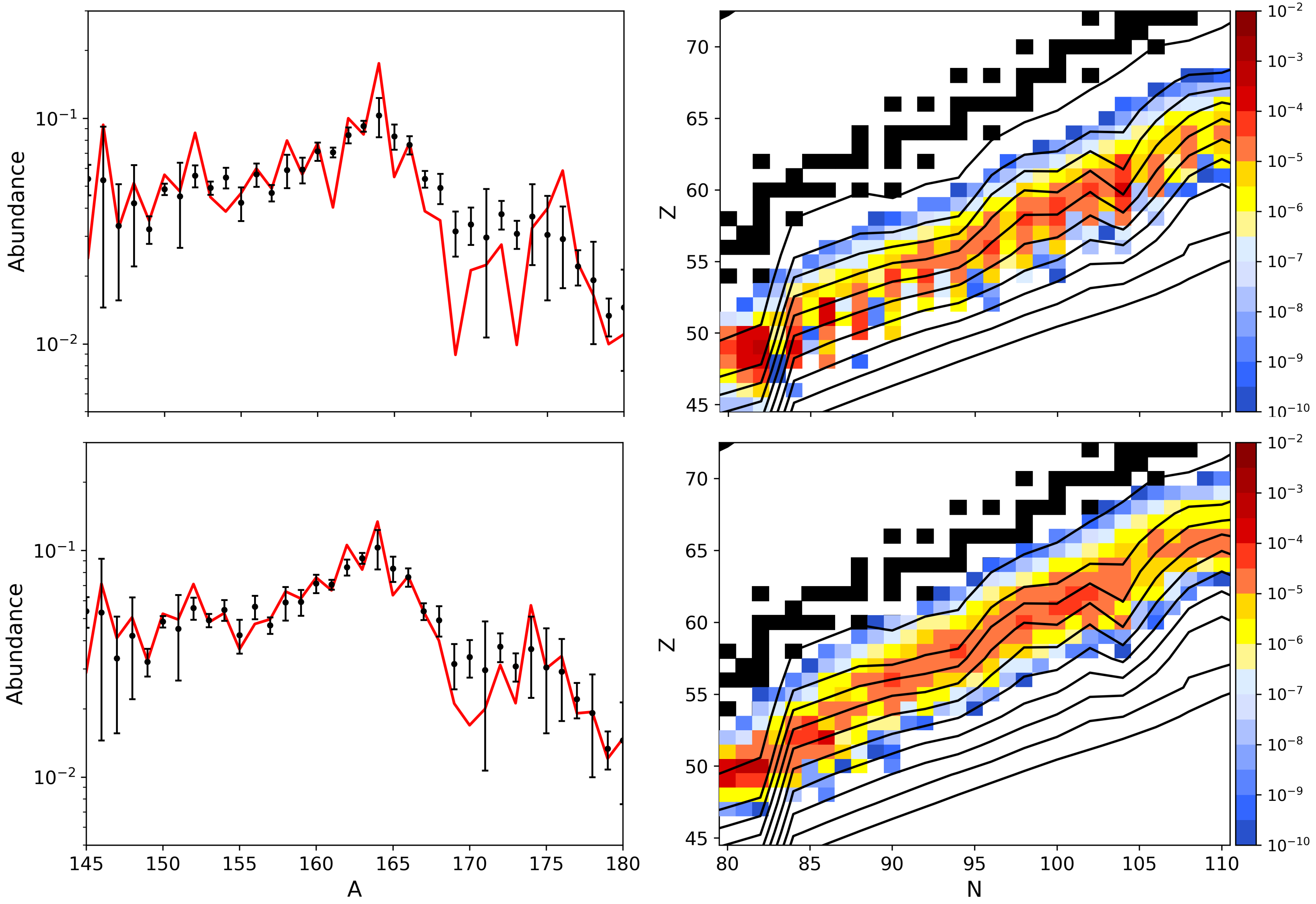
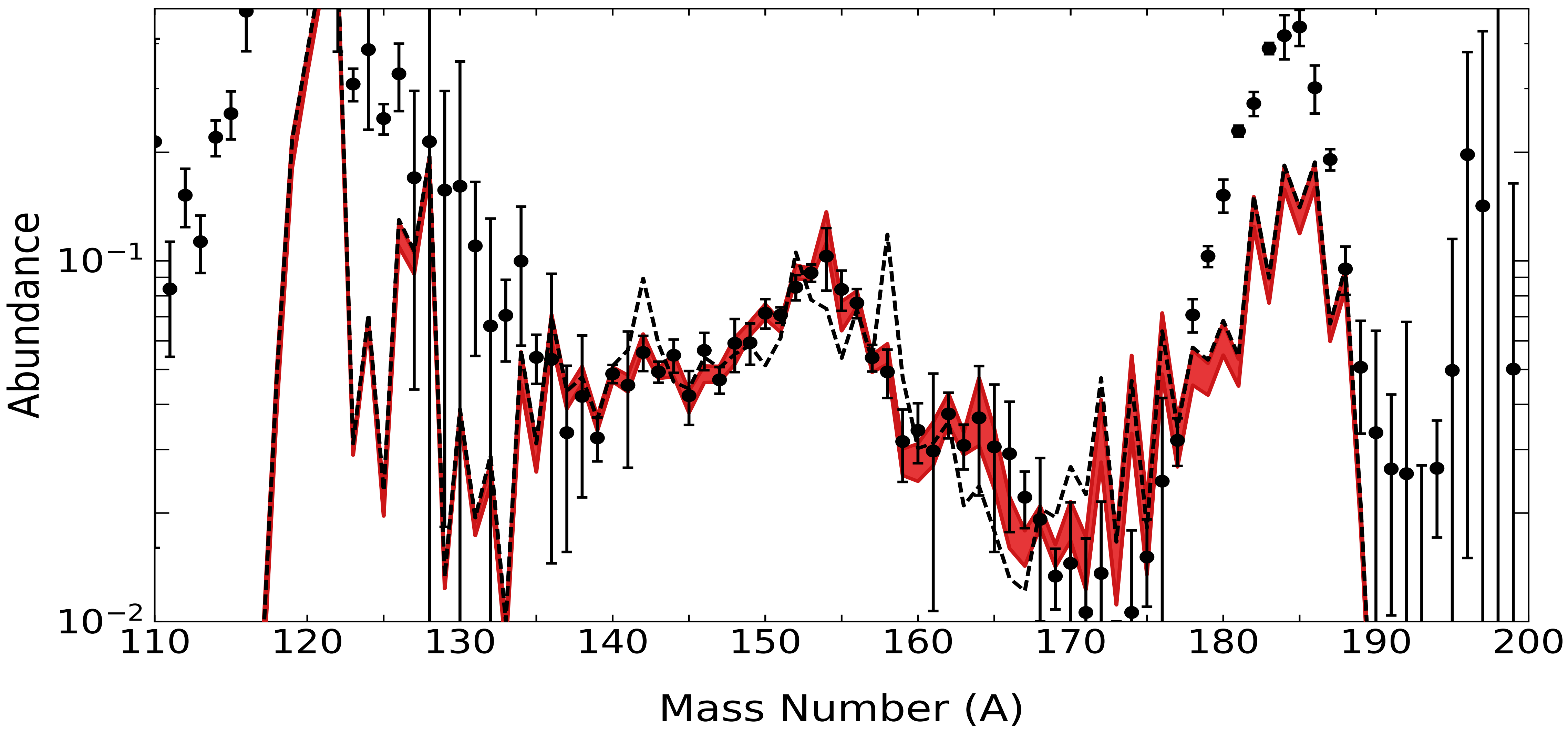




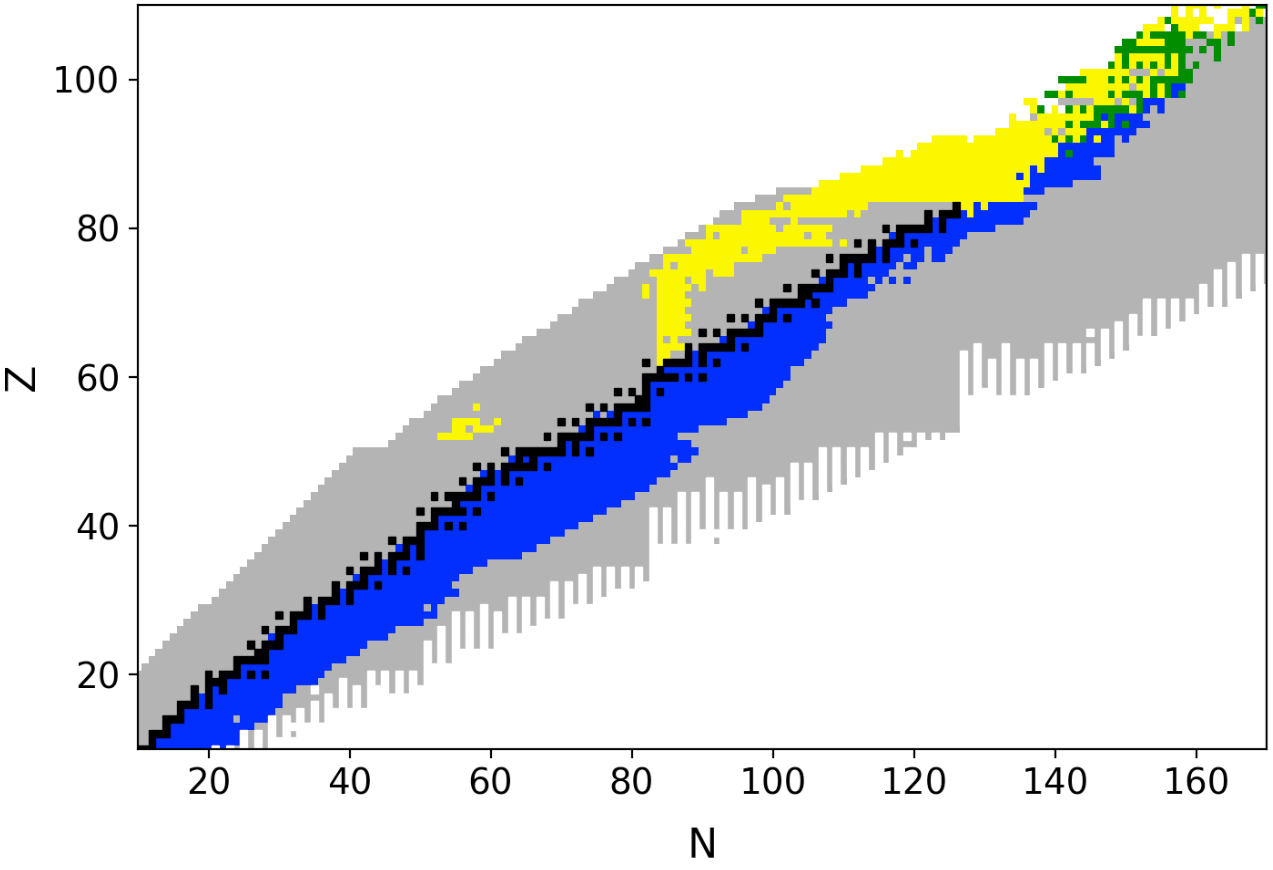

(Abundance pattern range using the mass values found by our MCMC given disk wind conditions s/k=30, $\tau$=70 ms, $Y_e$=0.2)

Vassh et al (in preparation)

# Measured Decay Rates and Masses

NUBASE 2016

$\beta$-decay, $\alpha$-decay, and spontaneous fission




AME 2016 / Jyväskylä / CPT at CARIBU