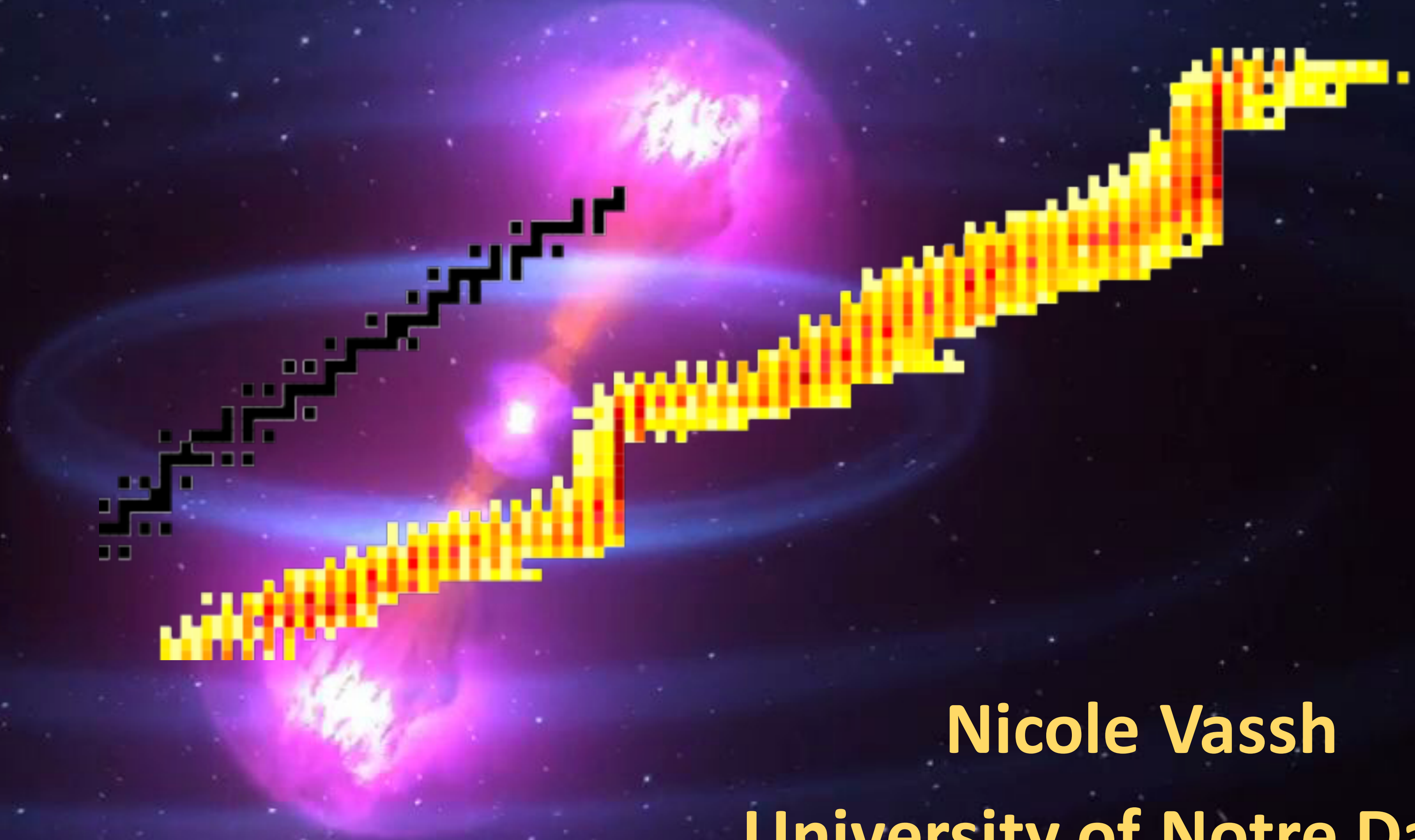
Examining the Origin of the *r*-process Rare-Earth Abundance Peak with Markov Chain Monte Carlo



Nicole Vassh

University of Notre Dame

ISNET-6 Conference, Oct. 9, 2018

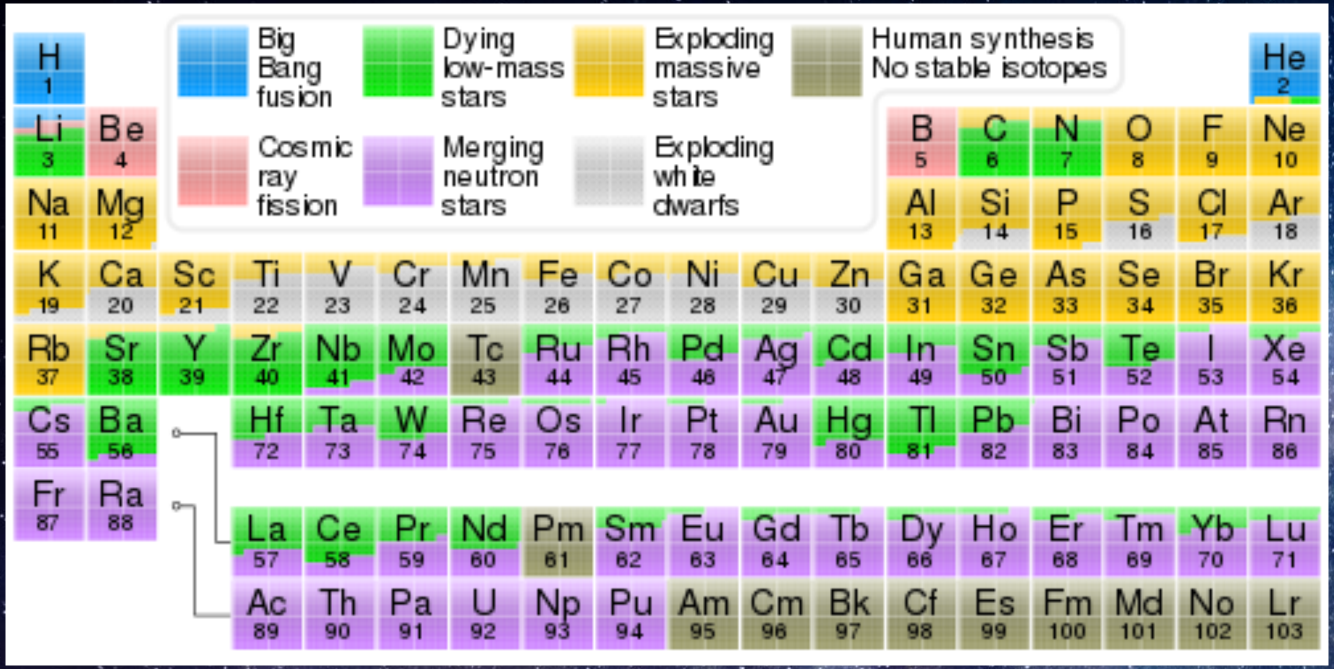
FIRE

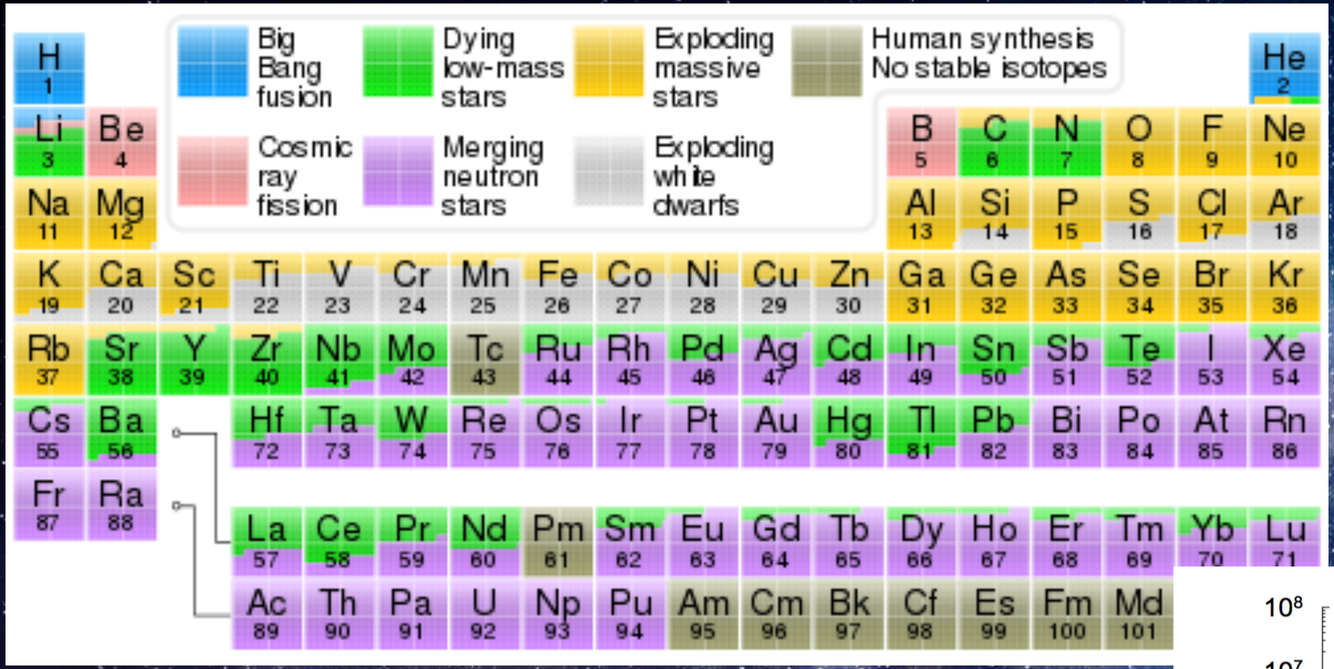
Fission In R-process Elements

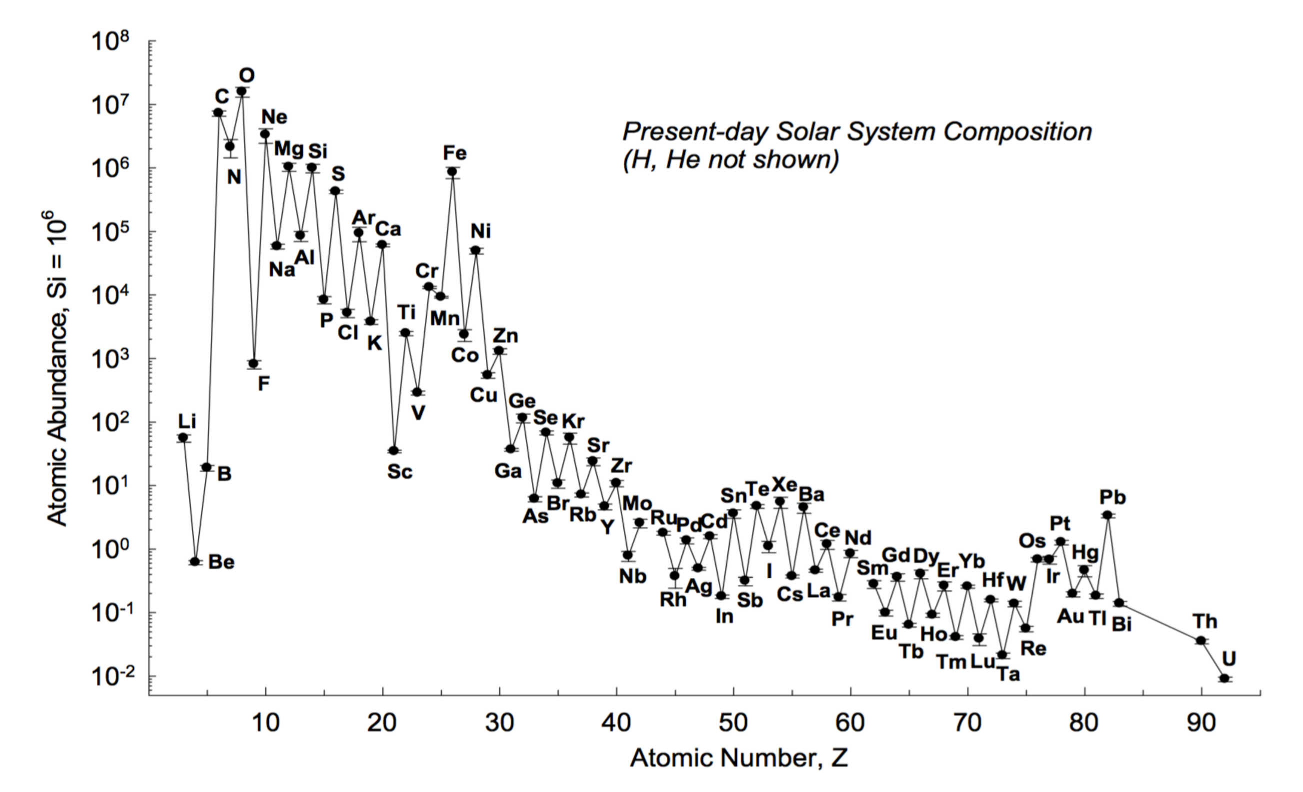
Argonne NATIONAL LABORATORY

The physics problem:

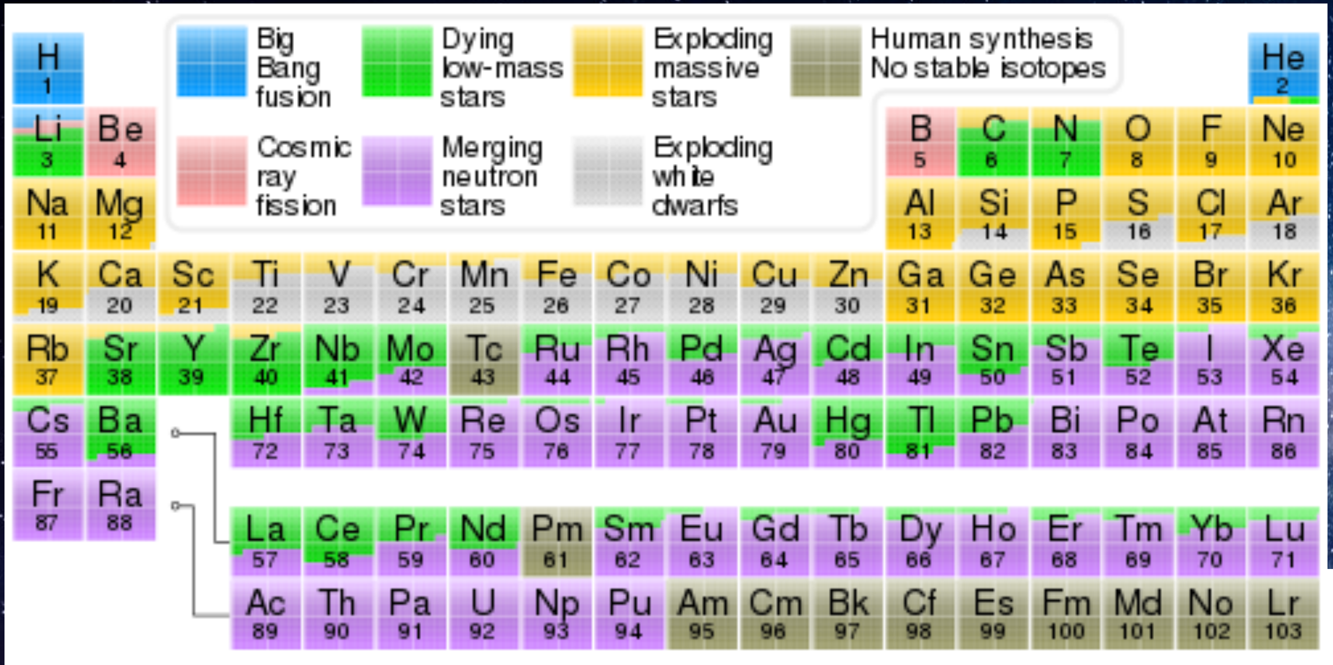
heavy element nucleosynthesis via rapid neutron capture (*r*-process)

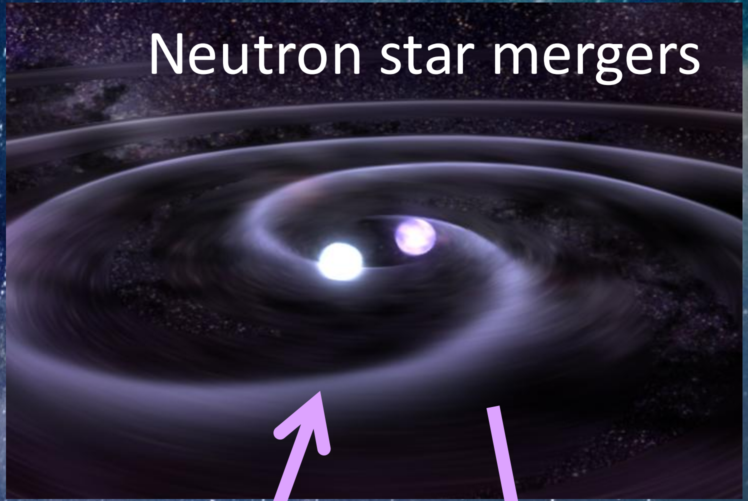

Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

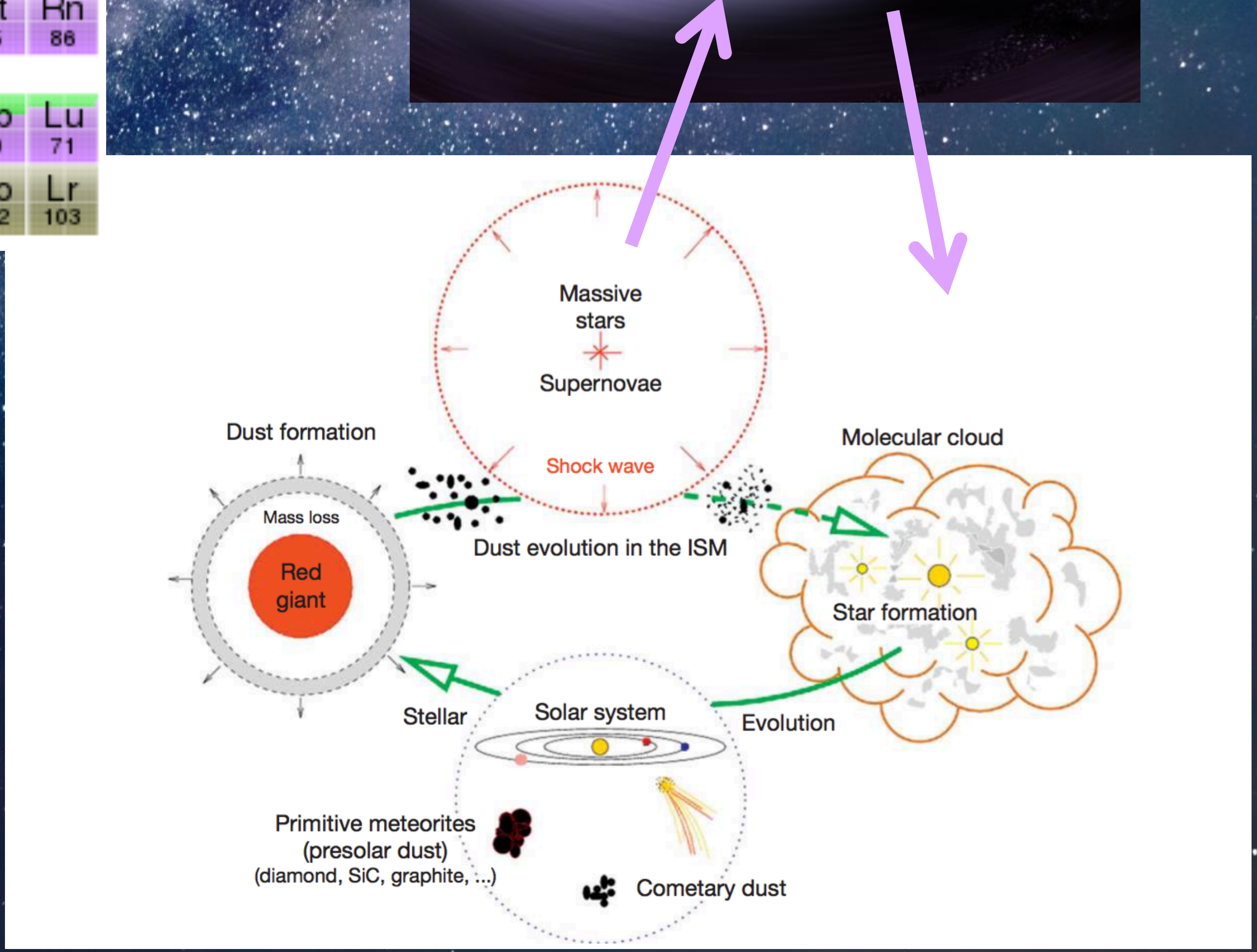




Lodders (2010)



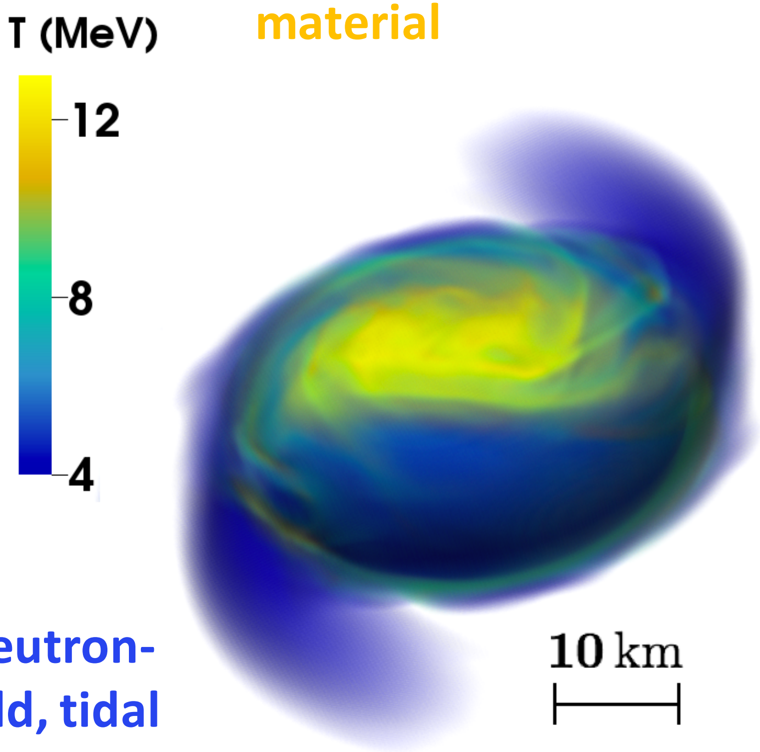




Palm, Lodders, Jones (2014)

Sites of heavy element production in a Neutron Star Merger

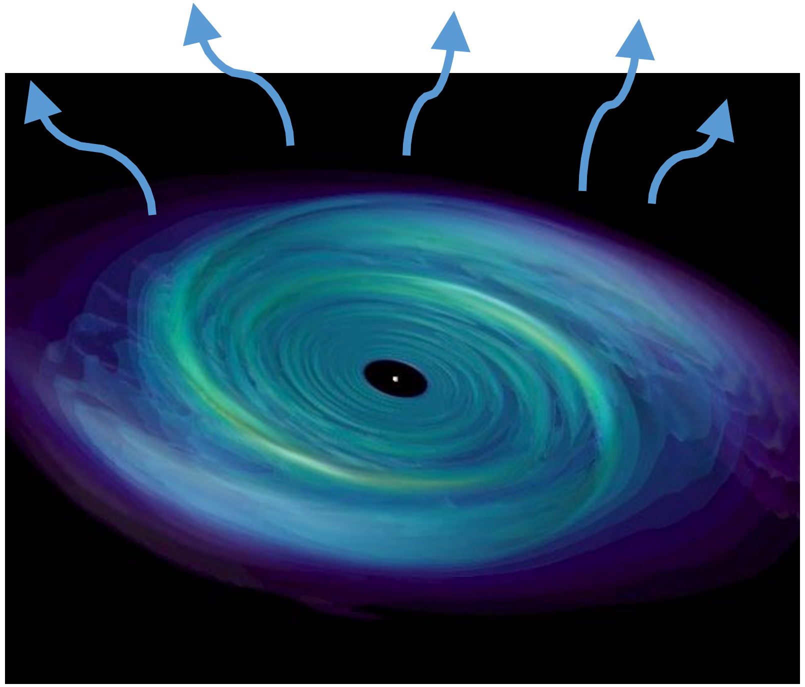
Hot, shocked material



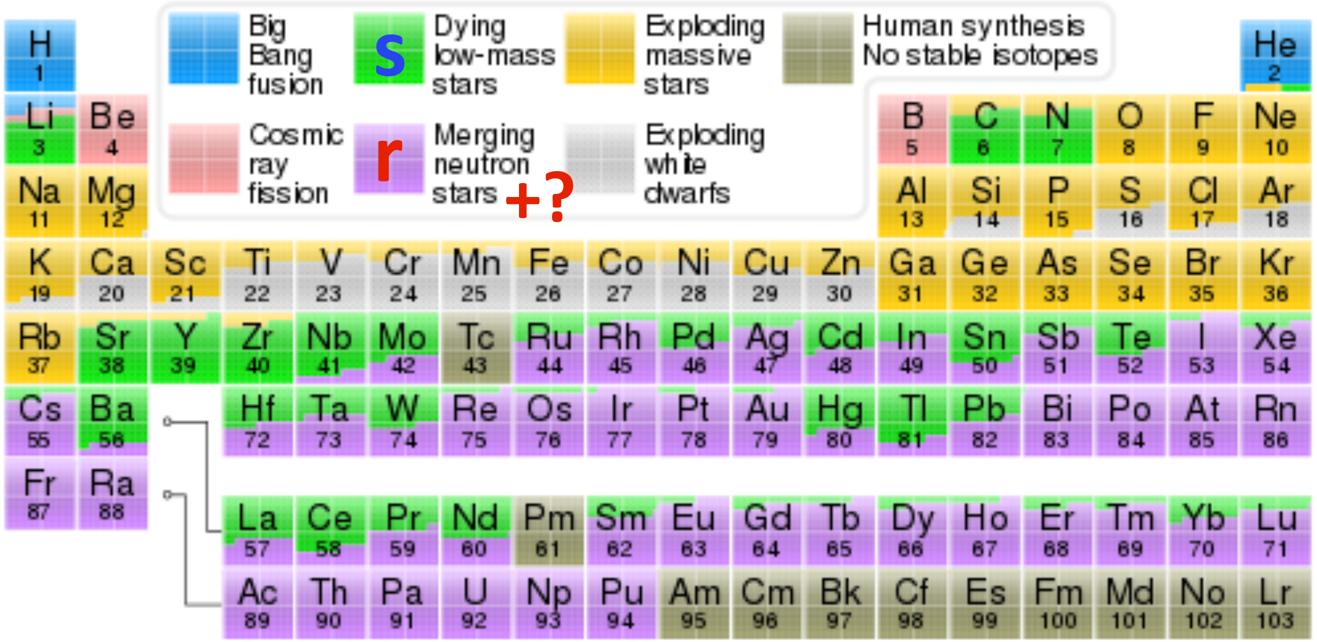
Very neutron-rich cold, tidal outflows

Foucart et al (2016)

Accretion disk winds – exact driving mechanism and neutron richness varies

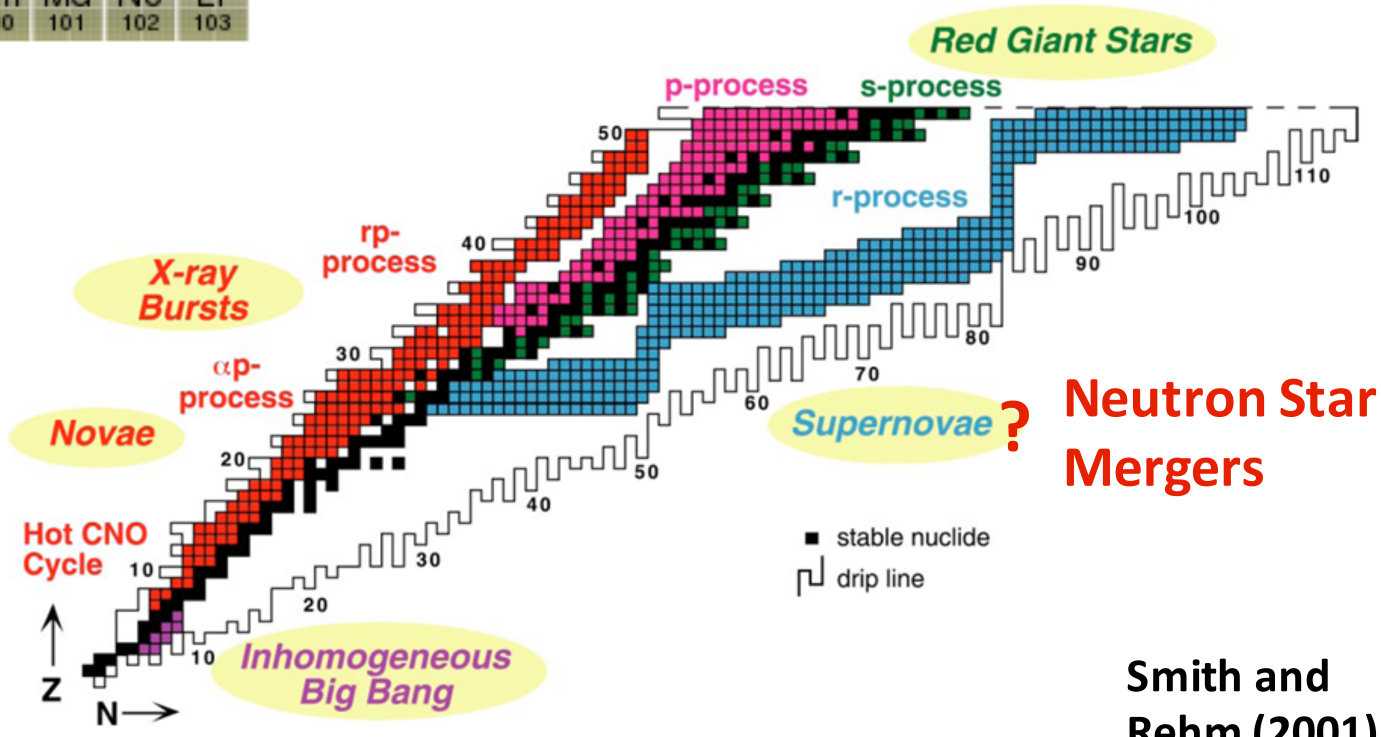


Owen and Blondin



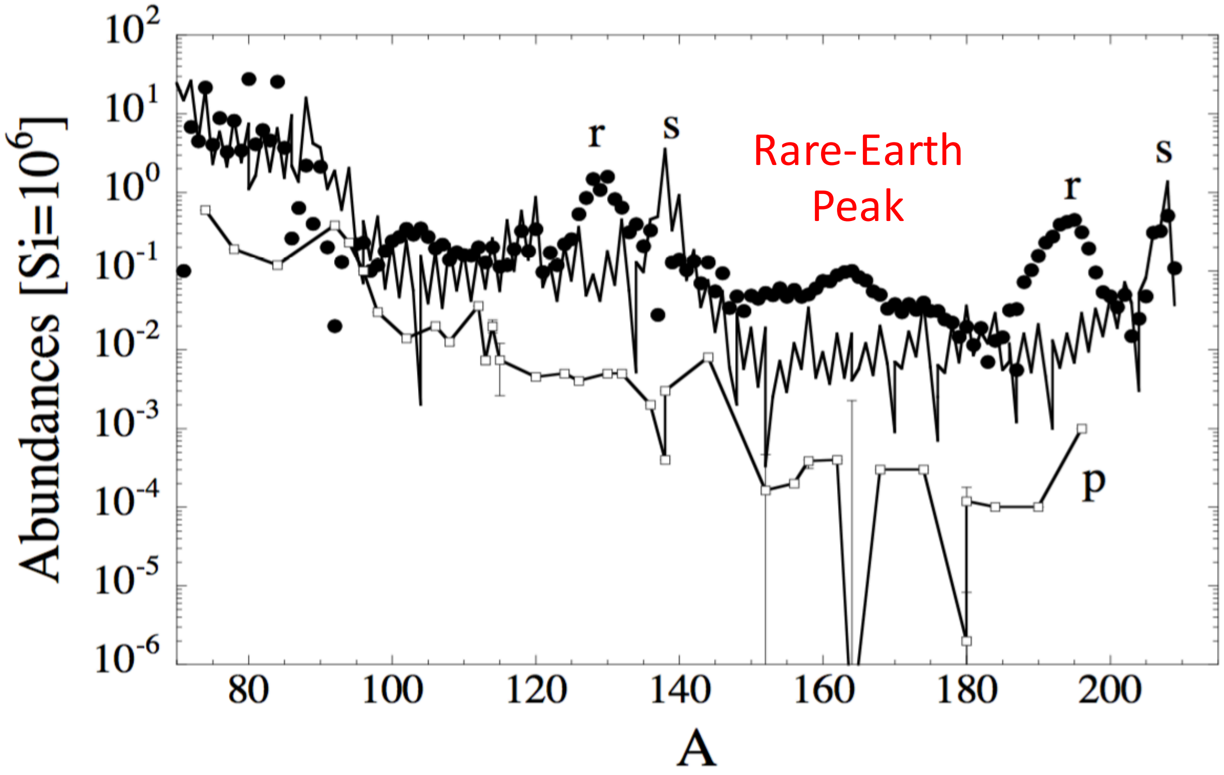
r-process - rapid neutron capture

s-process – slow neutron capture

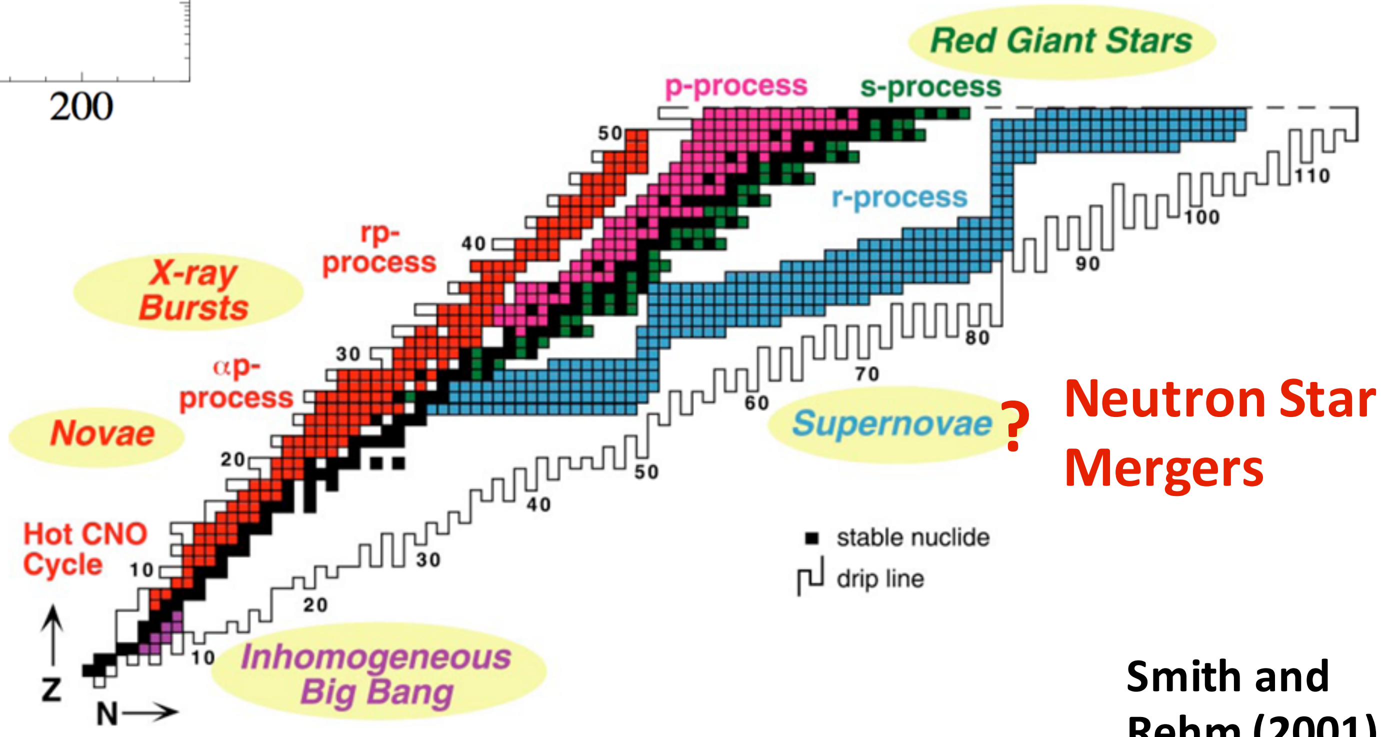


Neutron Star Mergers

Smith and Rehm (2001)



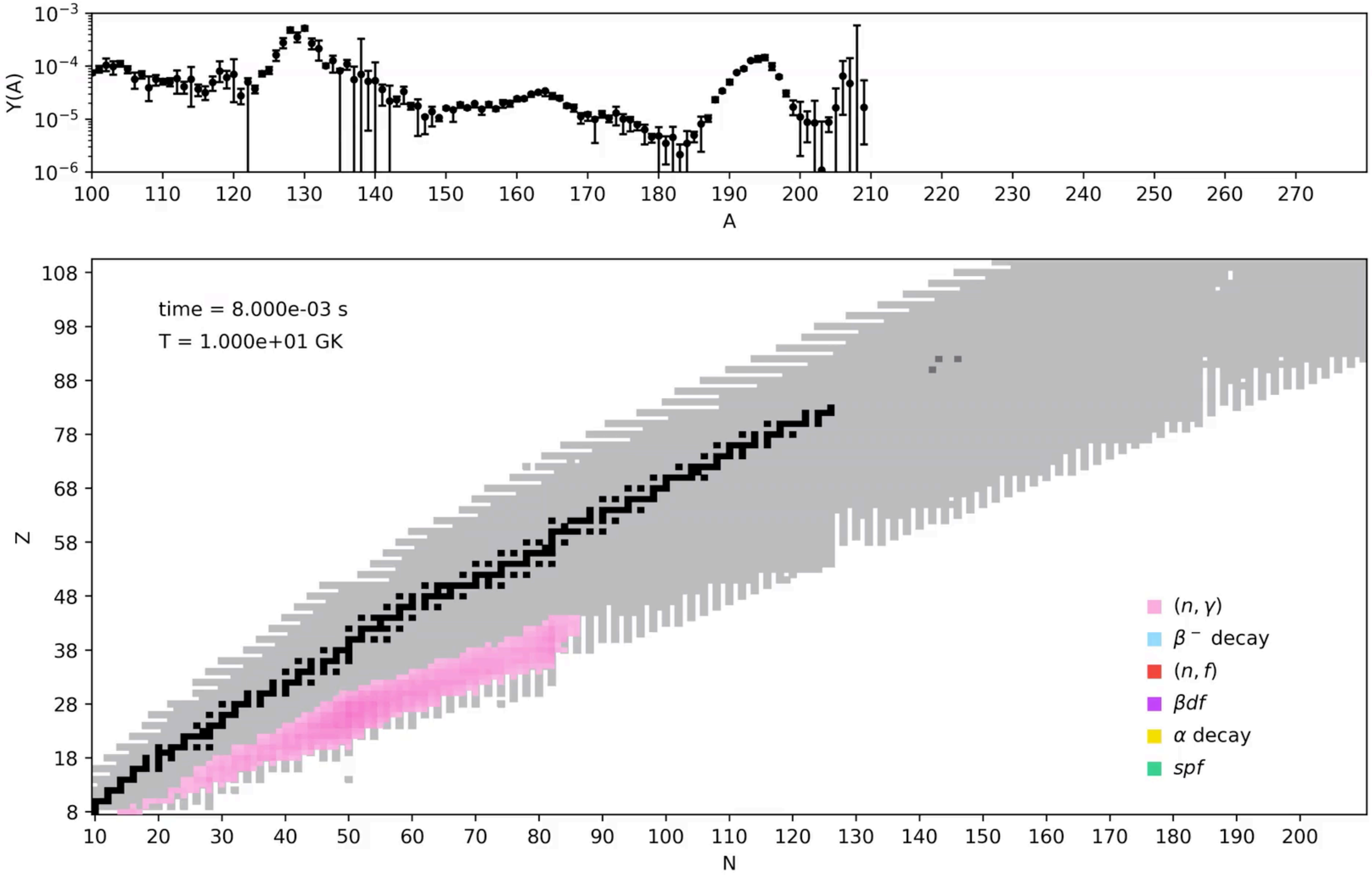
Arnould, Goriely and Takahashi (2007)



?

Neutron Star Mergers

Smith and Rehm (2001)



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

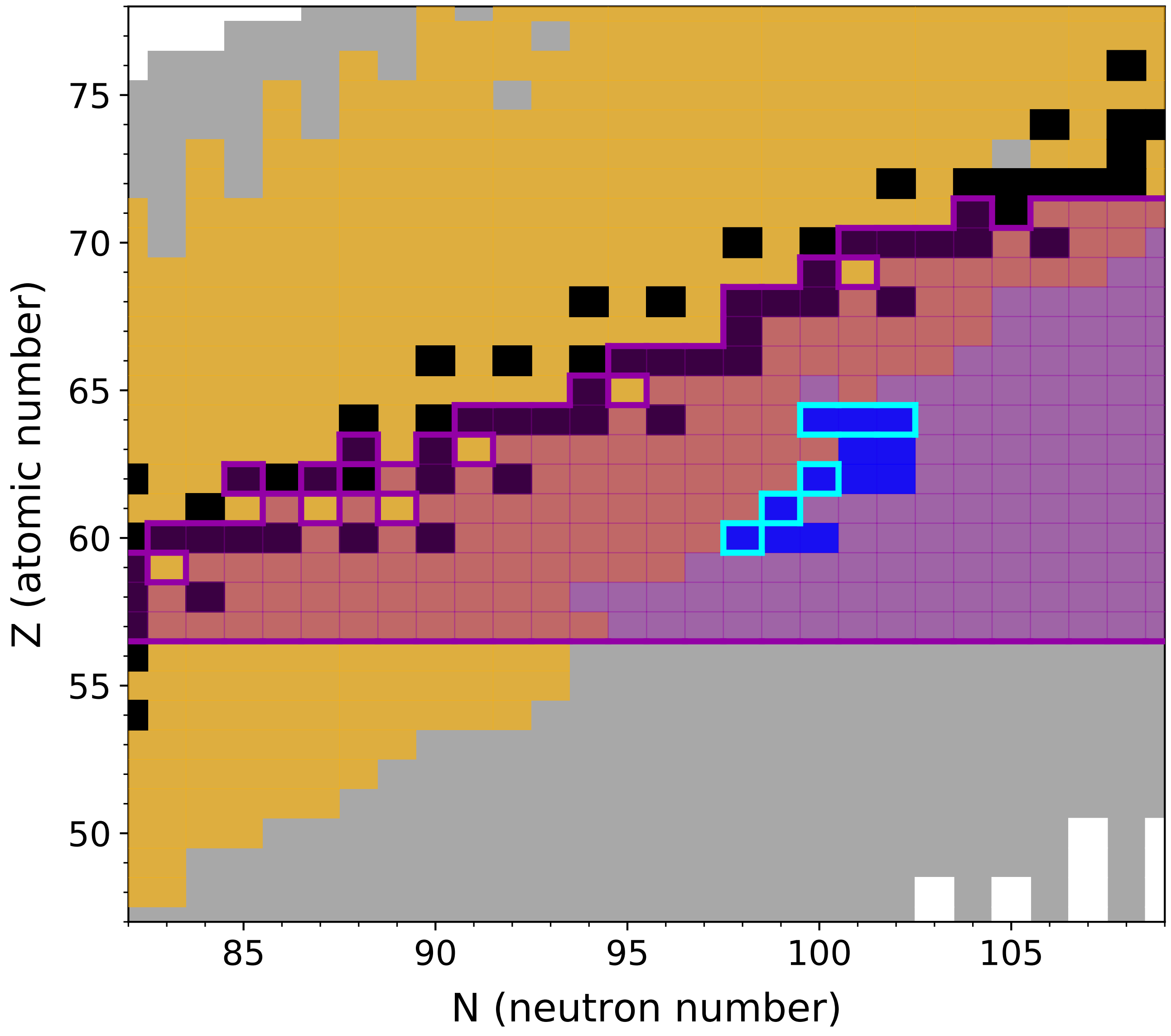
Studying Rare-Earth Nuclei to Understand *r*-process Lanthanide Production

Experimental Mass Measurements:

AME 2016

Jyväskylä

CPT at CARIBU



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

Experimental Mass Measurements:

AME 2016

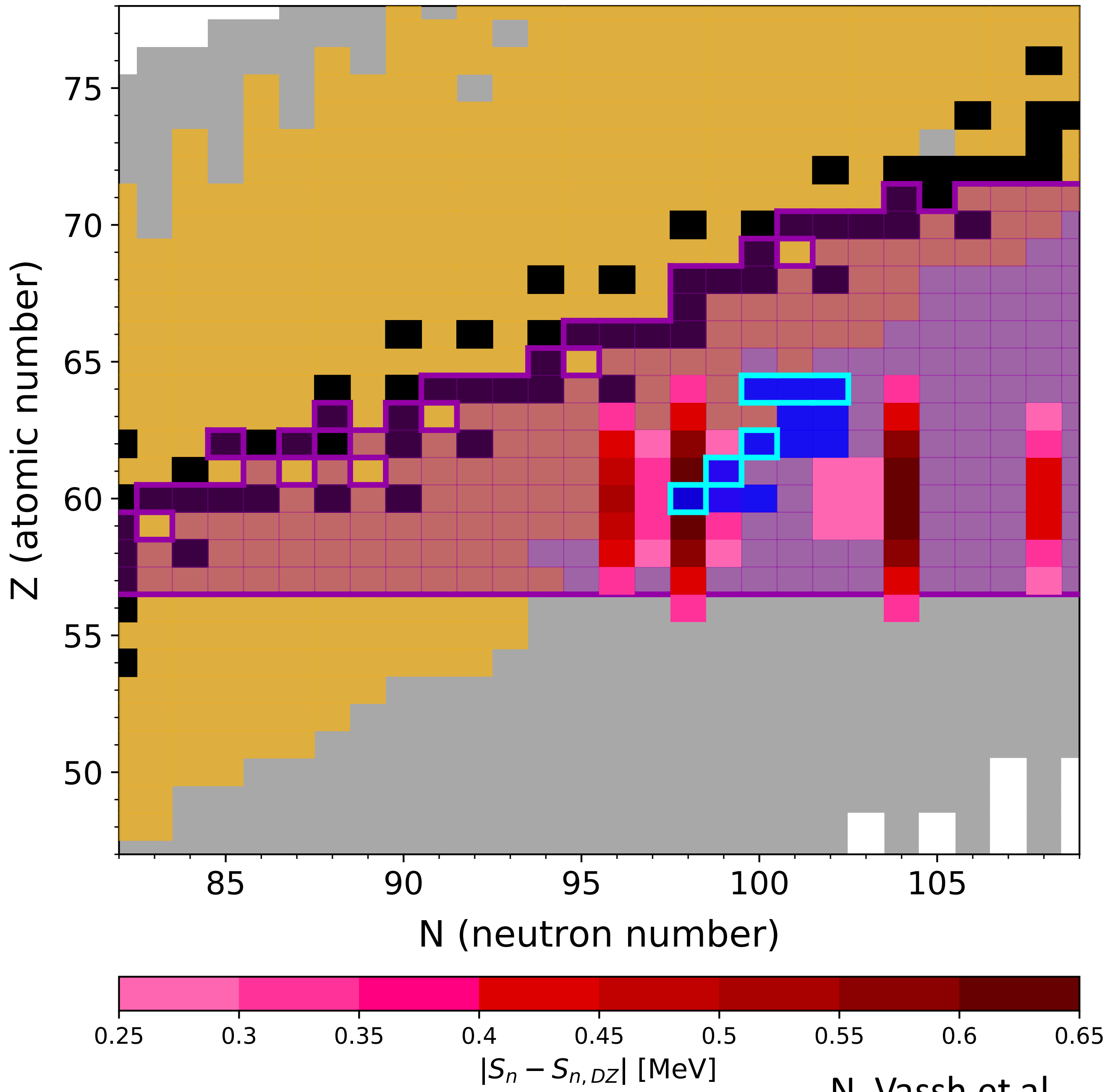
Jyväskylä

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)

The statistical method:
Markov Chain Monte Carlo + nucleosynthesis calculations

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

↑ (to Astrophysical conditions / Fission Yields / Rates)

MCMC procedure

- Monte Carlo mass corrections

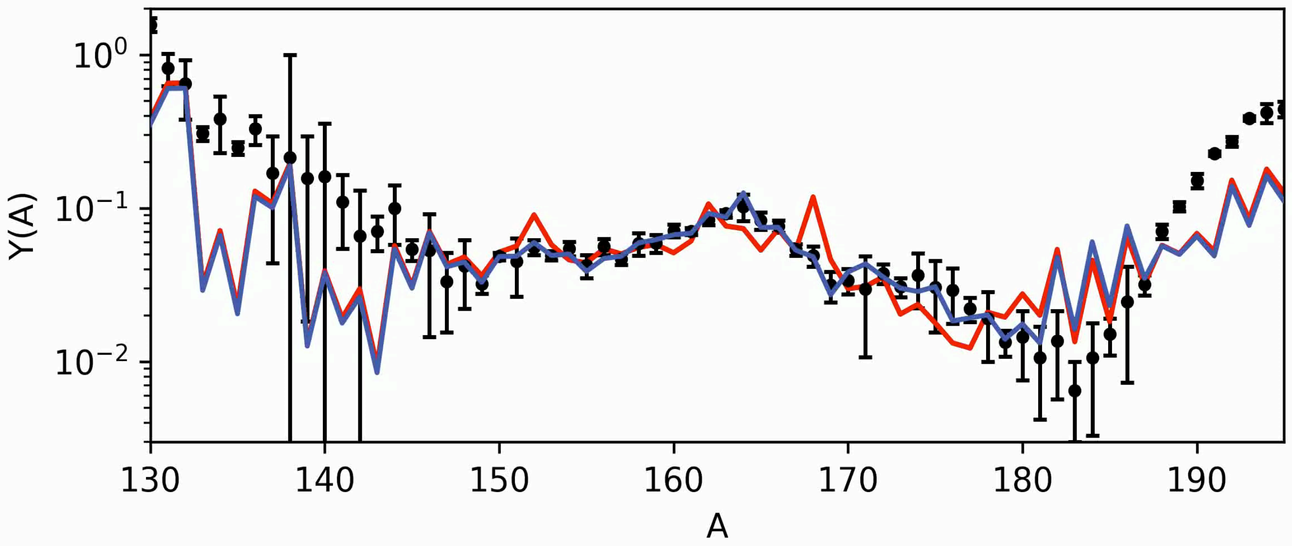
$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

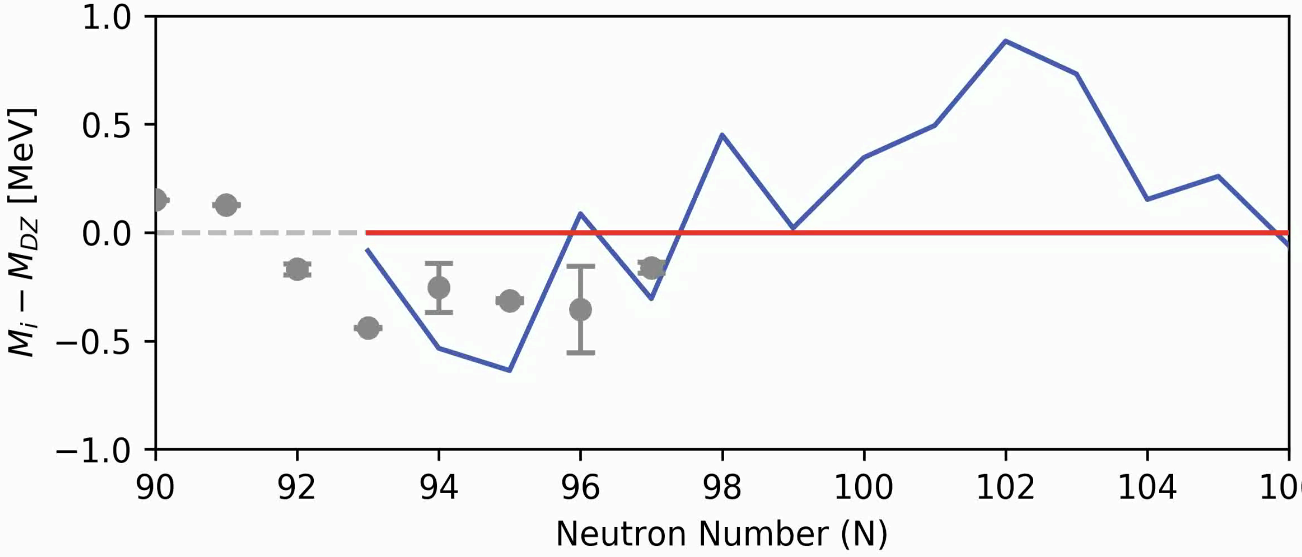
- Check: $\sigma^2_{\mathrm{rms}}(M_{\mathrm{AME12}}, M) \le \sigma^2_{\mathrm{rms}}(M_{\mathrm{AME12}}, M_{DZ})$
- Check:

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

- 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

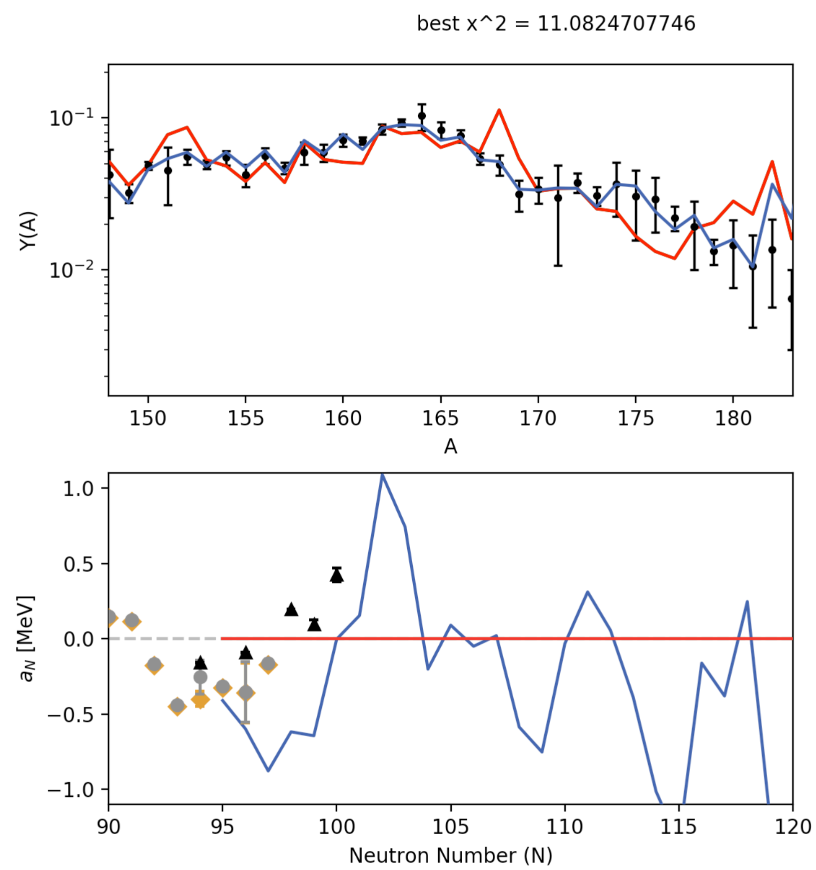
$$\mathcal{L}(\mathrm{m}) = \exp\left(-\frac{\chi^2(\mathrm{m})}{2}\right) \longrightarrow \alpha(\mathrm{m}) = \frac{\mathcal{L}(\mathrm{m})}{\mathcal{L}(\mathrm{m}-1)}$$

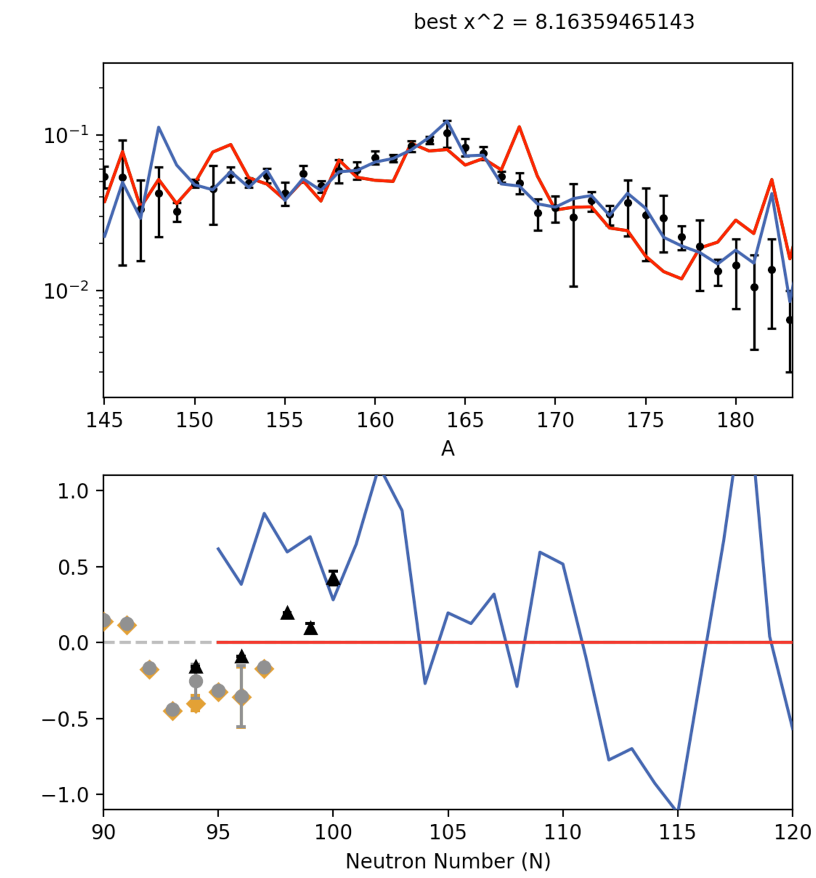


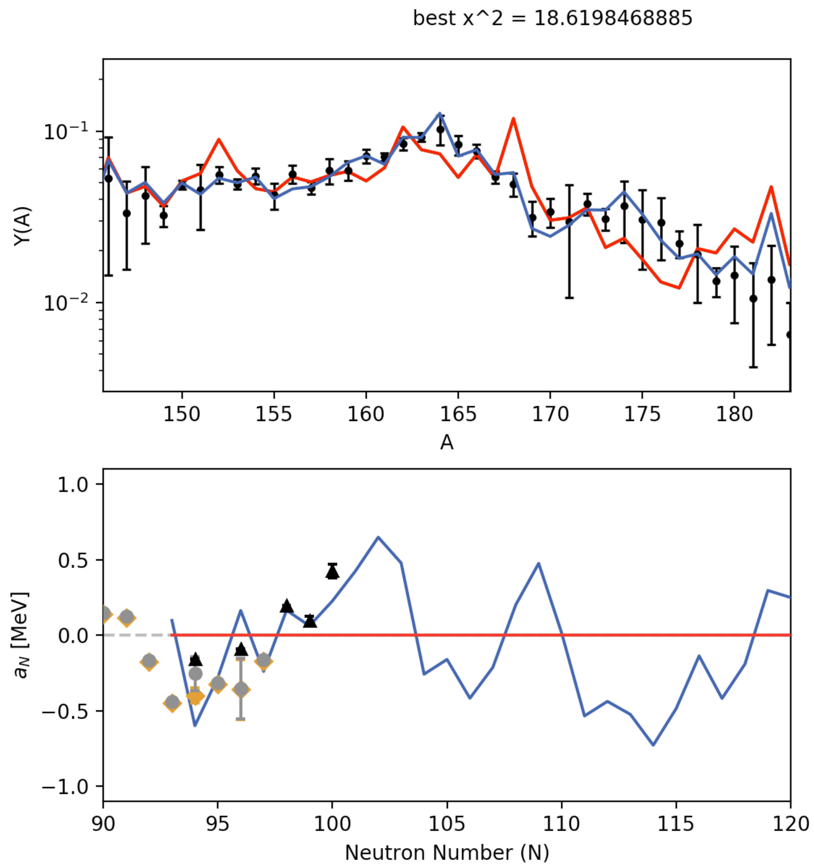


Black – solar abundance data
Grey – AME 2012 data
Red – values at current step
Blue – best step of entire run

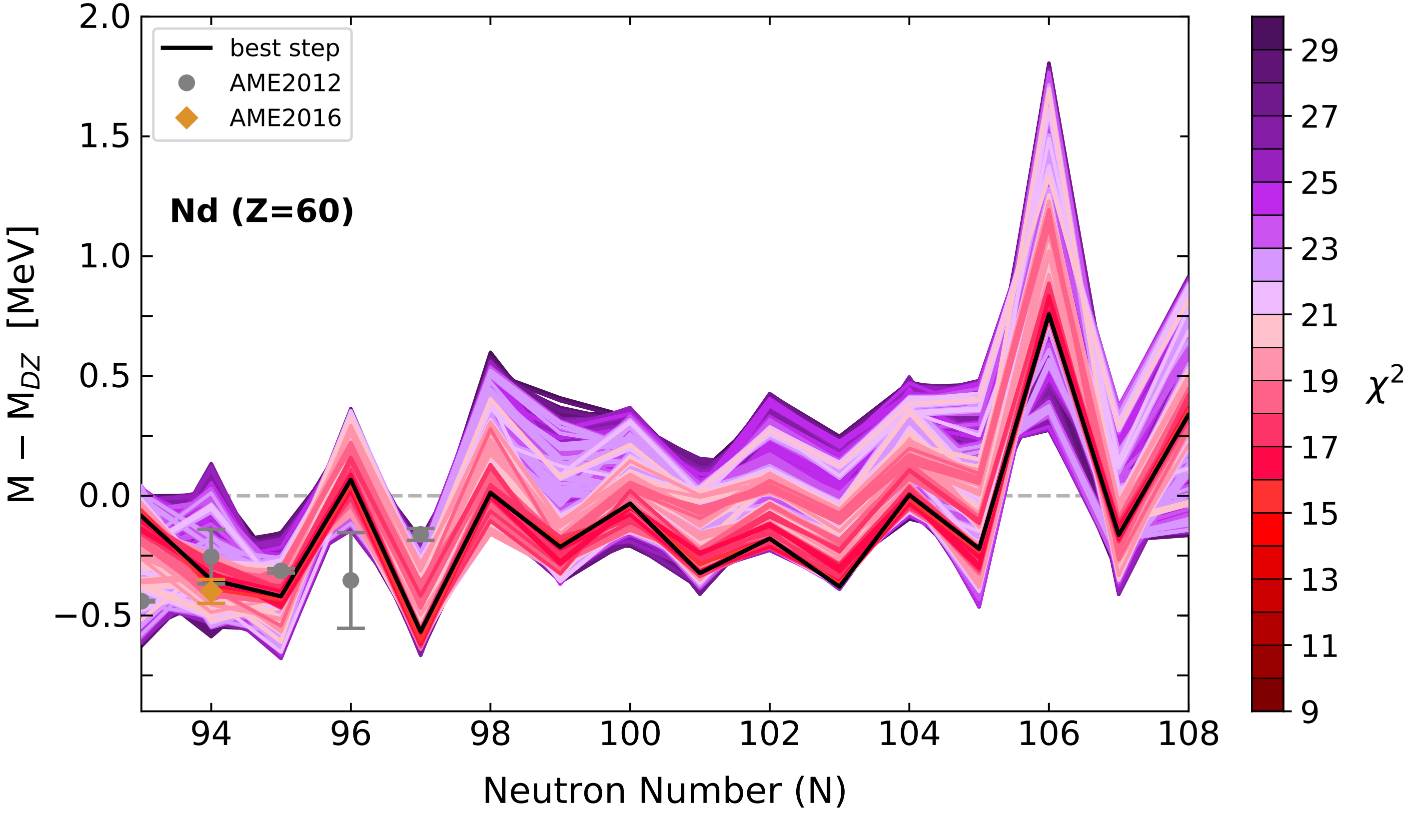
Examples: **before** σ_{rms} check after

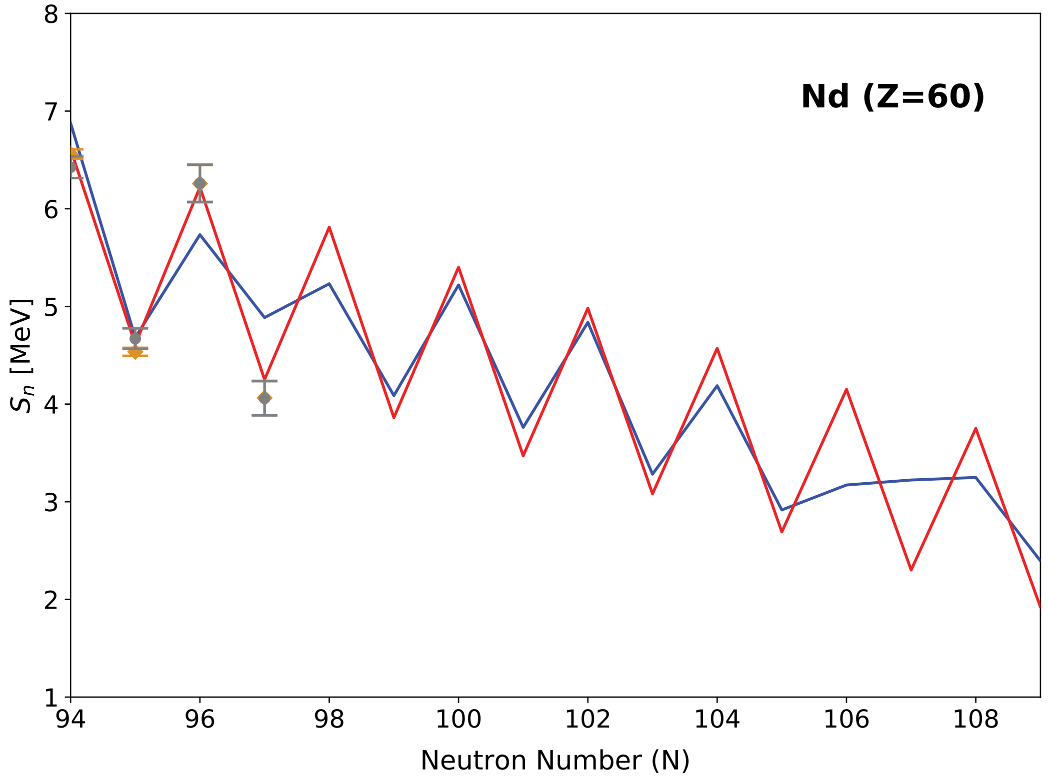






Example of an unphysical solution: before D_N check

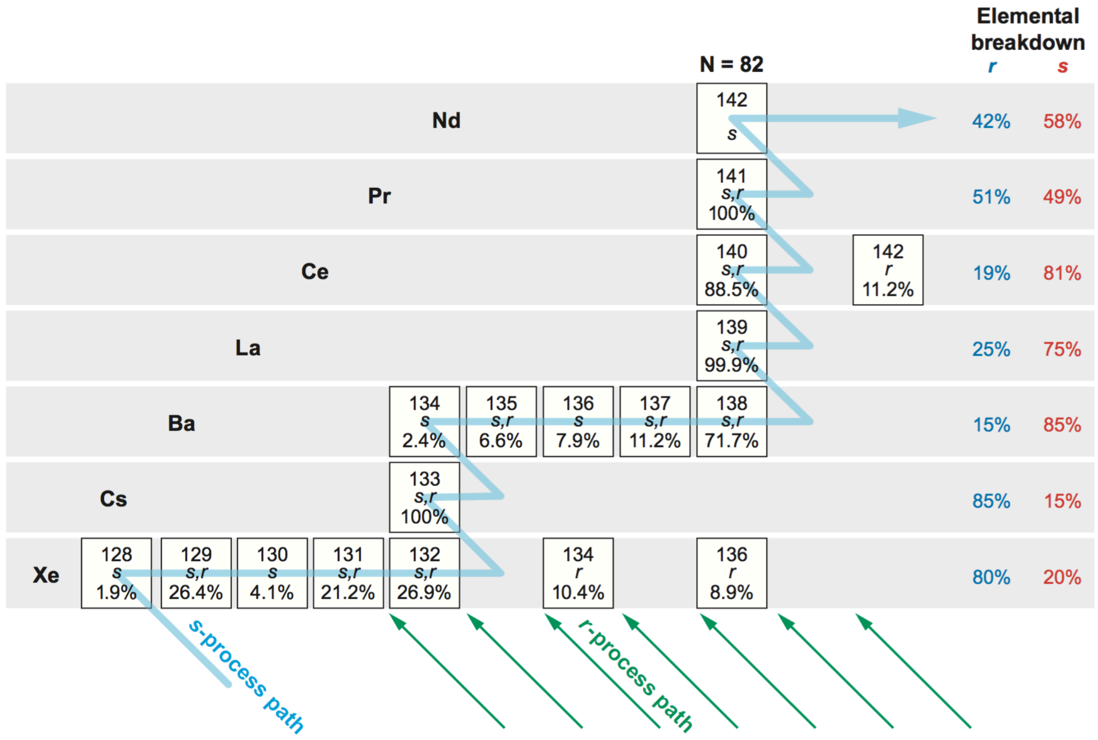




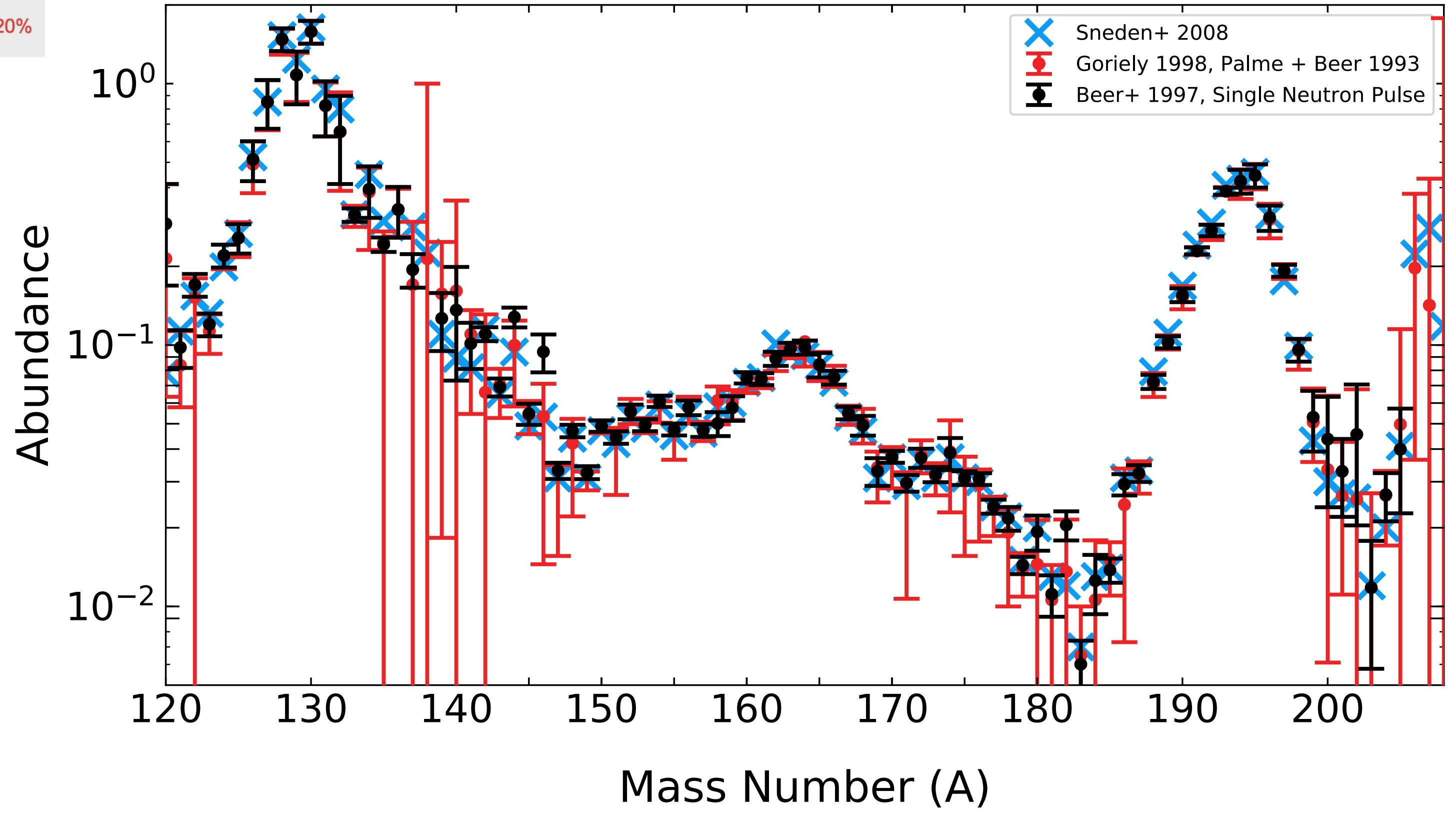
Mass values for **all steps** of an example run

Vassh et al (in preparation)

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

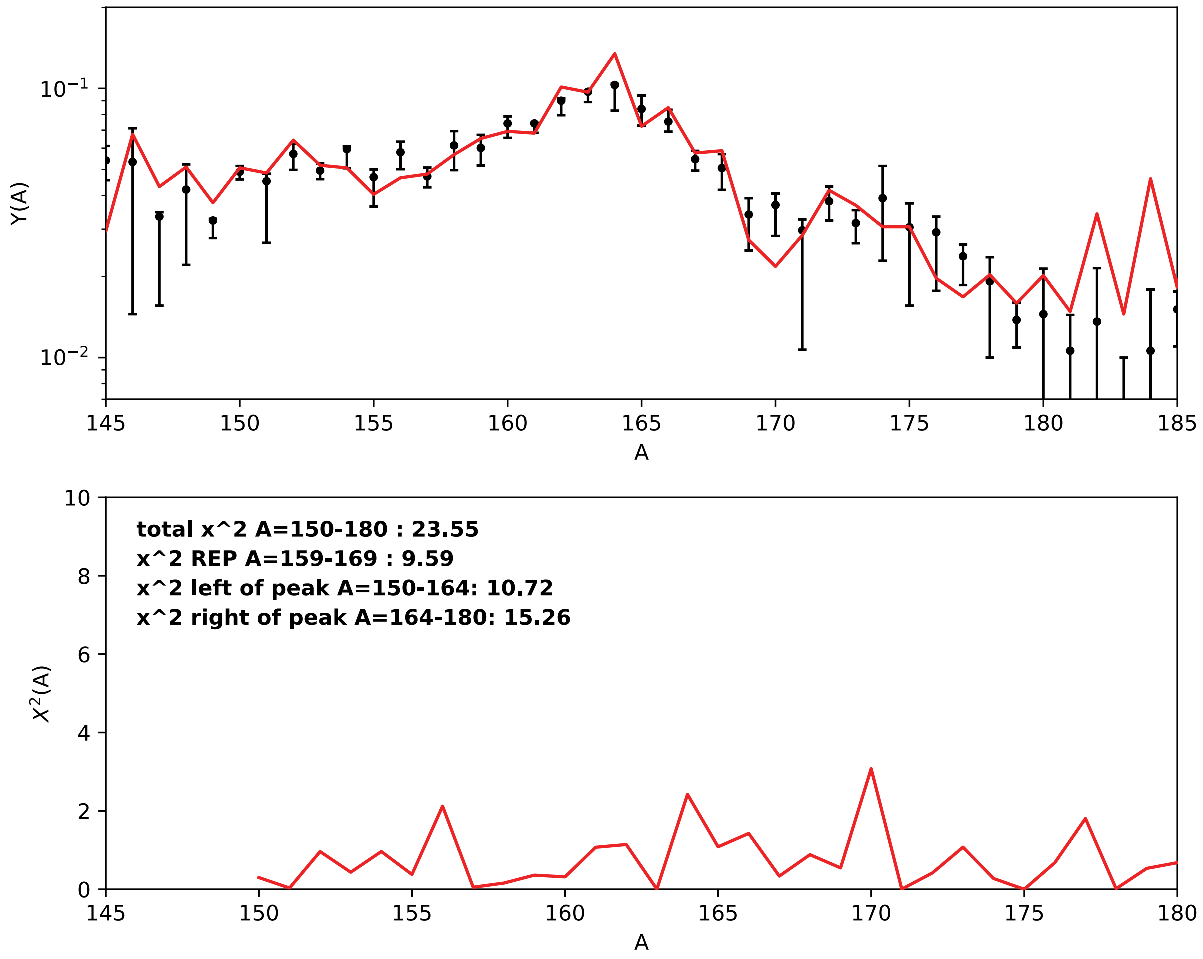


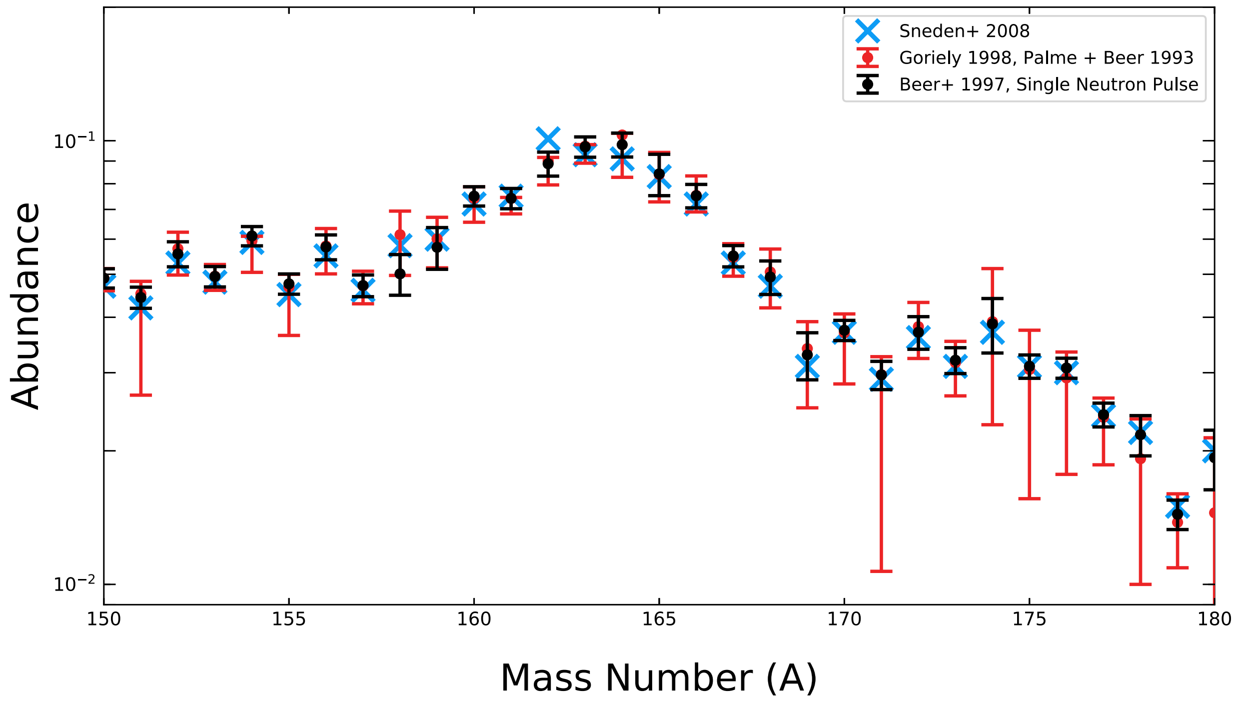
Sneden, Cowan, and Gallino (2008)



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

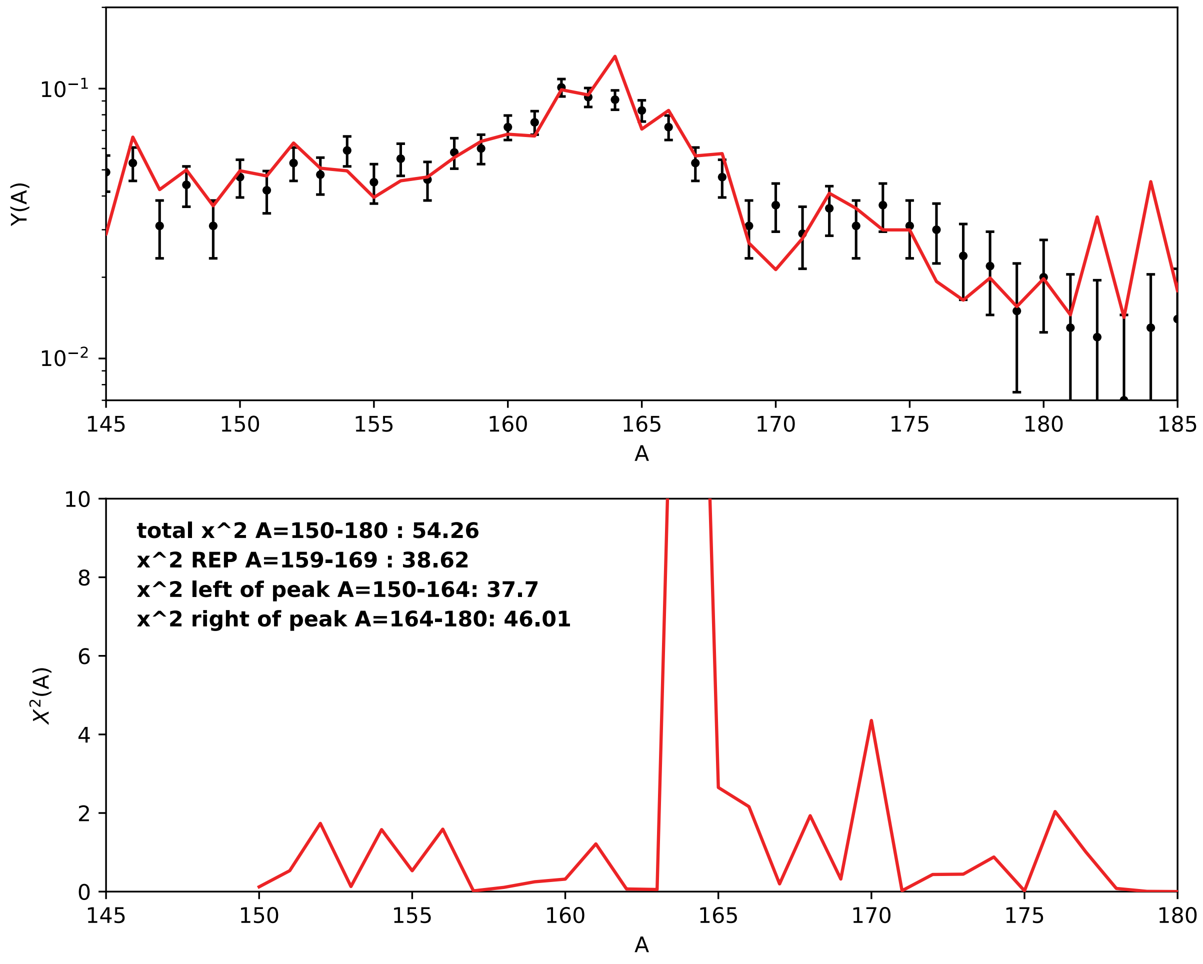
Goriely 1998 Solar Data (black), MCMC Solution (red)

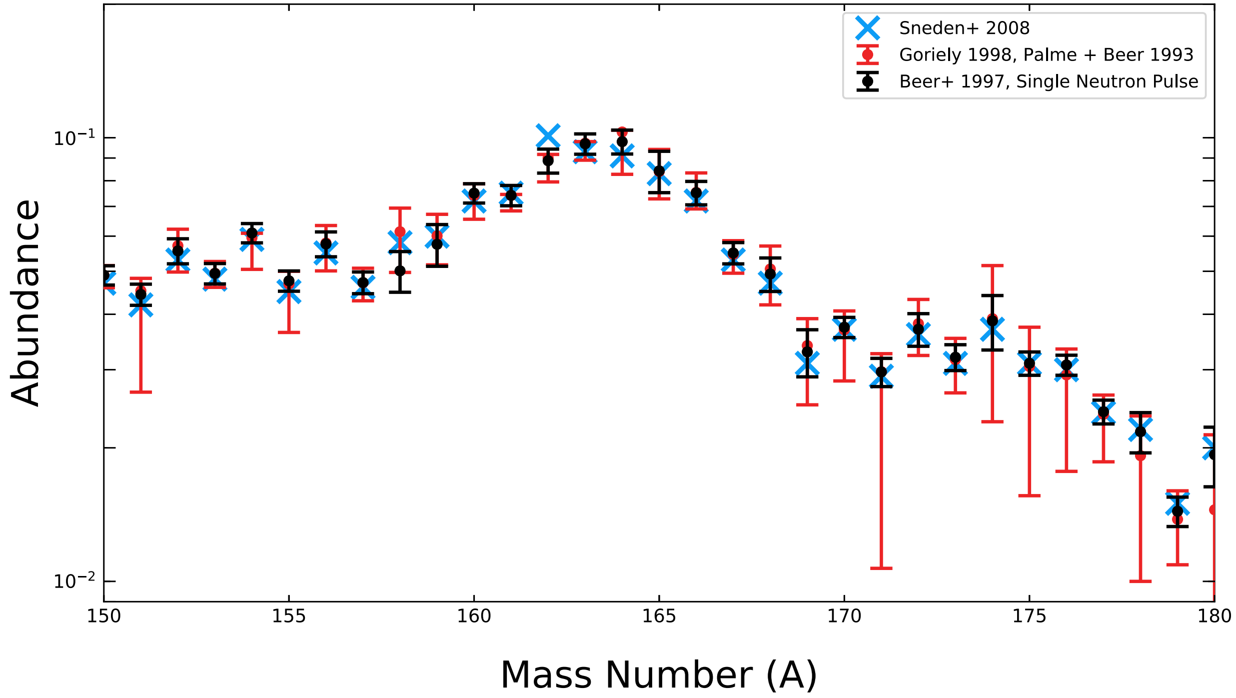




Sensitivity to Solar Data: uncertainty from the s-process subtraction

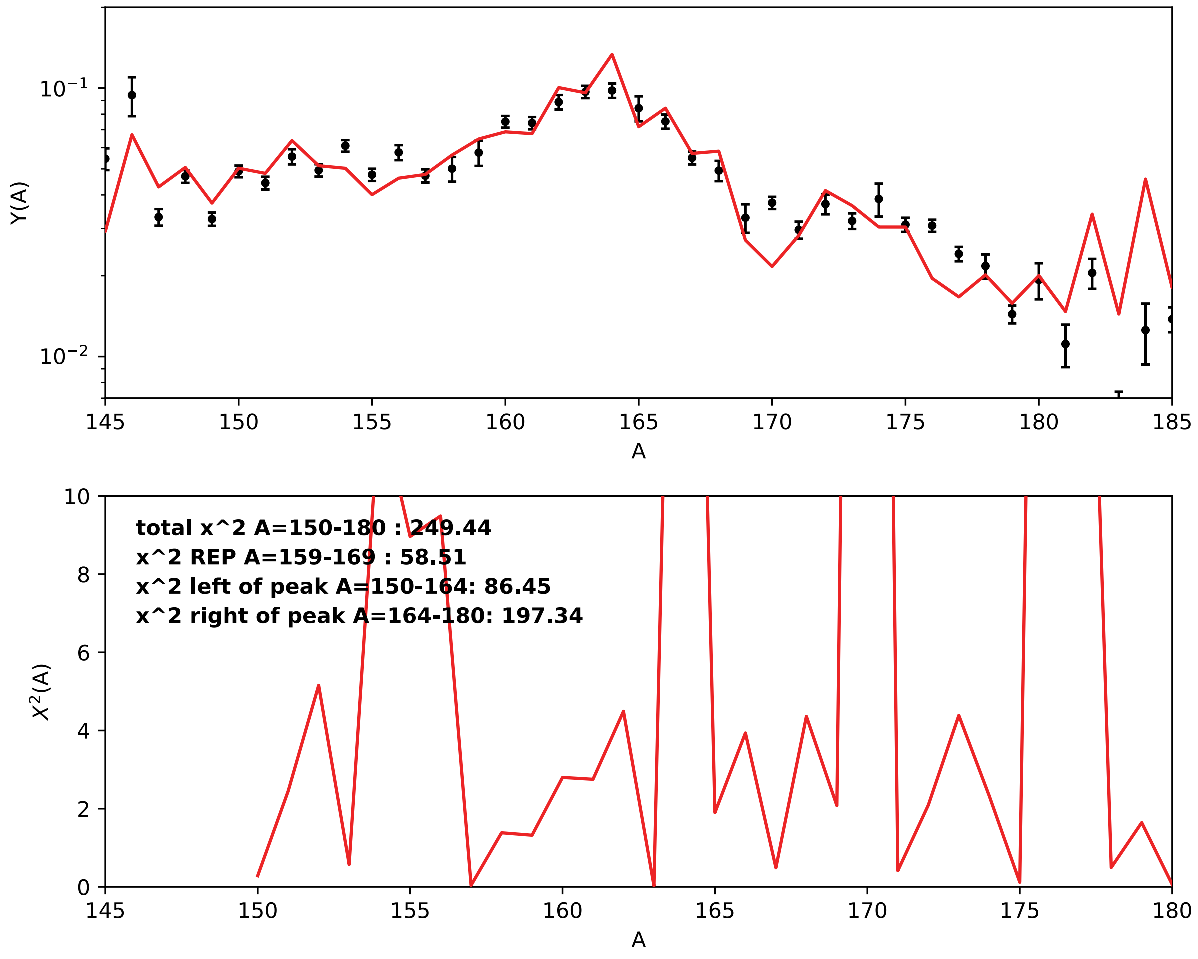
Sneden+ 2008 Solar Data (black), MCMC Solution (red)

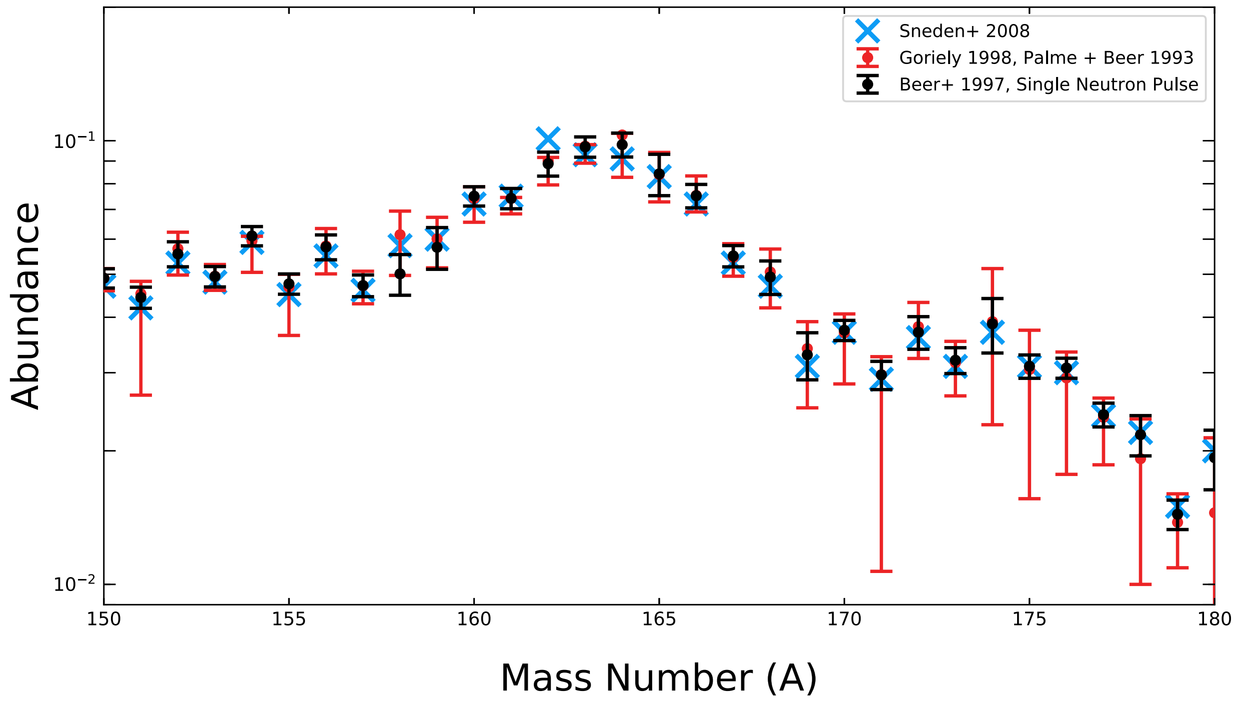




Sensitivity to Solar Data: uncertainty from the s-process subtraction

Beer+ 1997 Solar Data (black), MCMC Solution (red)

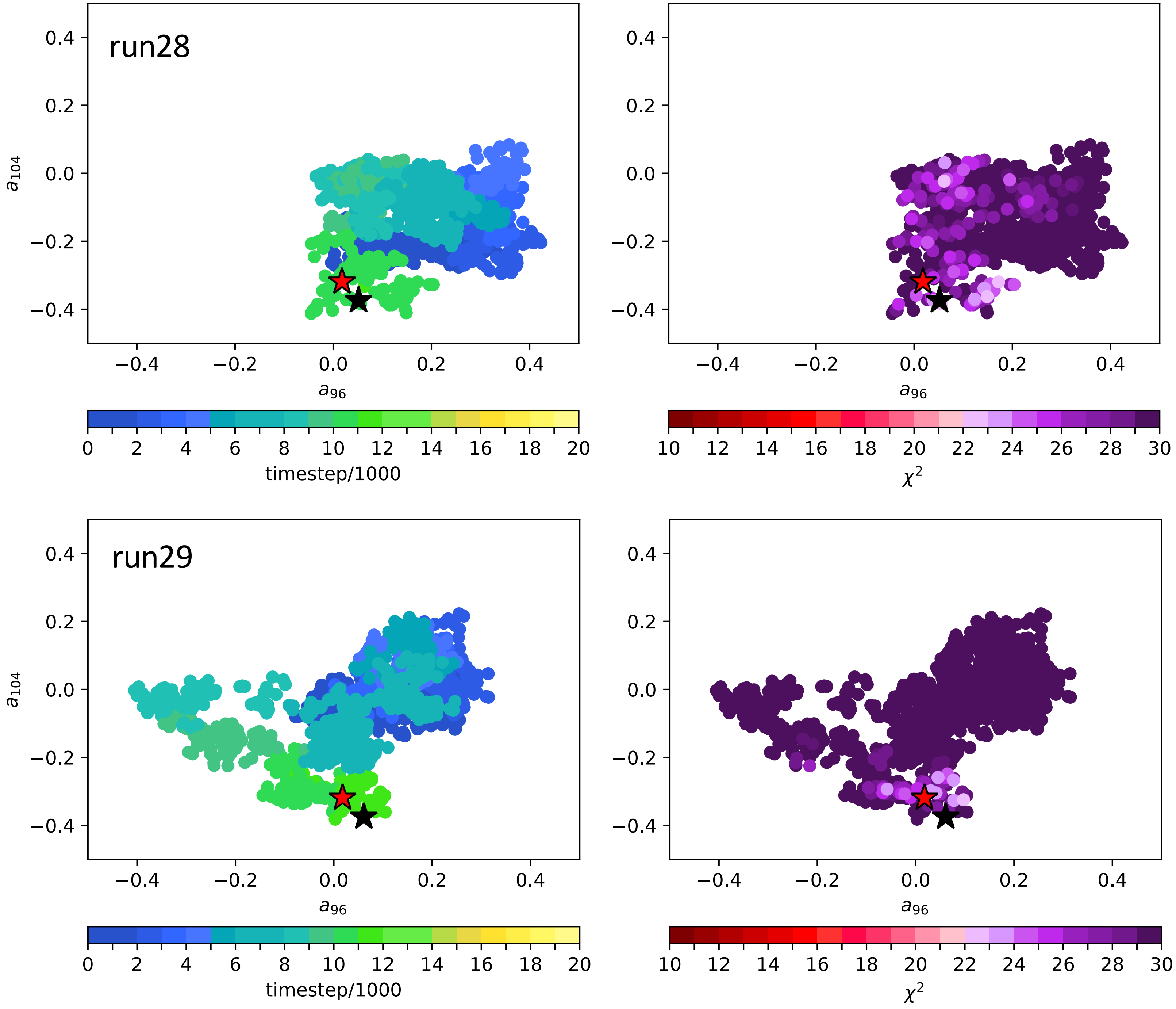




Parallel Chains Method of MCMC

- 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

Parallel Chains Method: searching parameter space

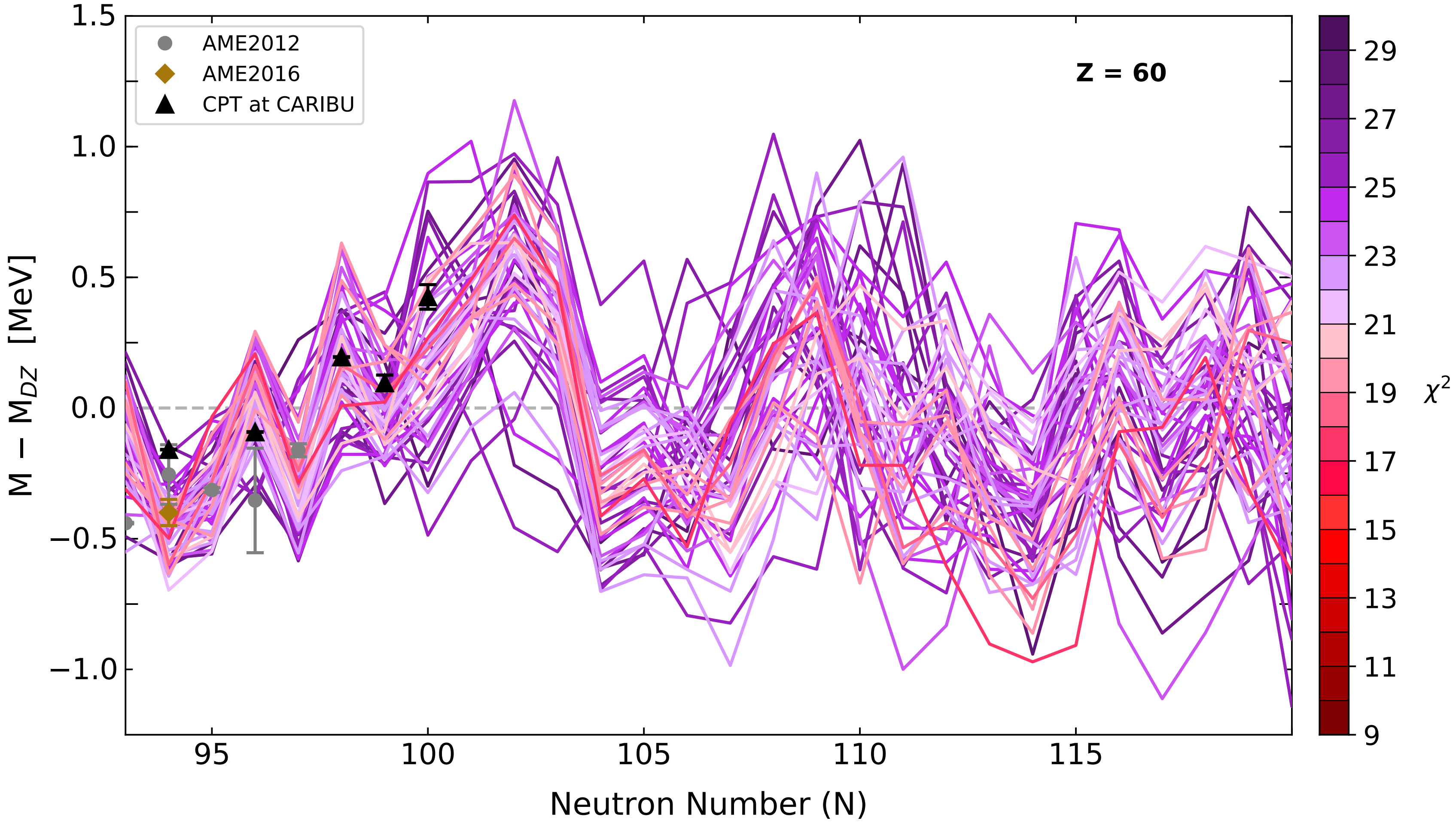


Black star – best step value for the run shown

Red star – average best values of 50 runs

Vassh et al (in preparation)

Parallel Chains Method: error bars



Mass values for **50 MCMC runs** given the same astro conditions

Results:

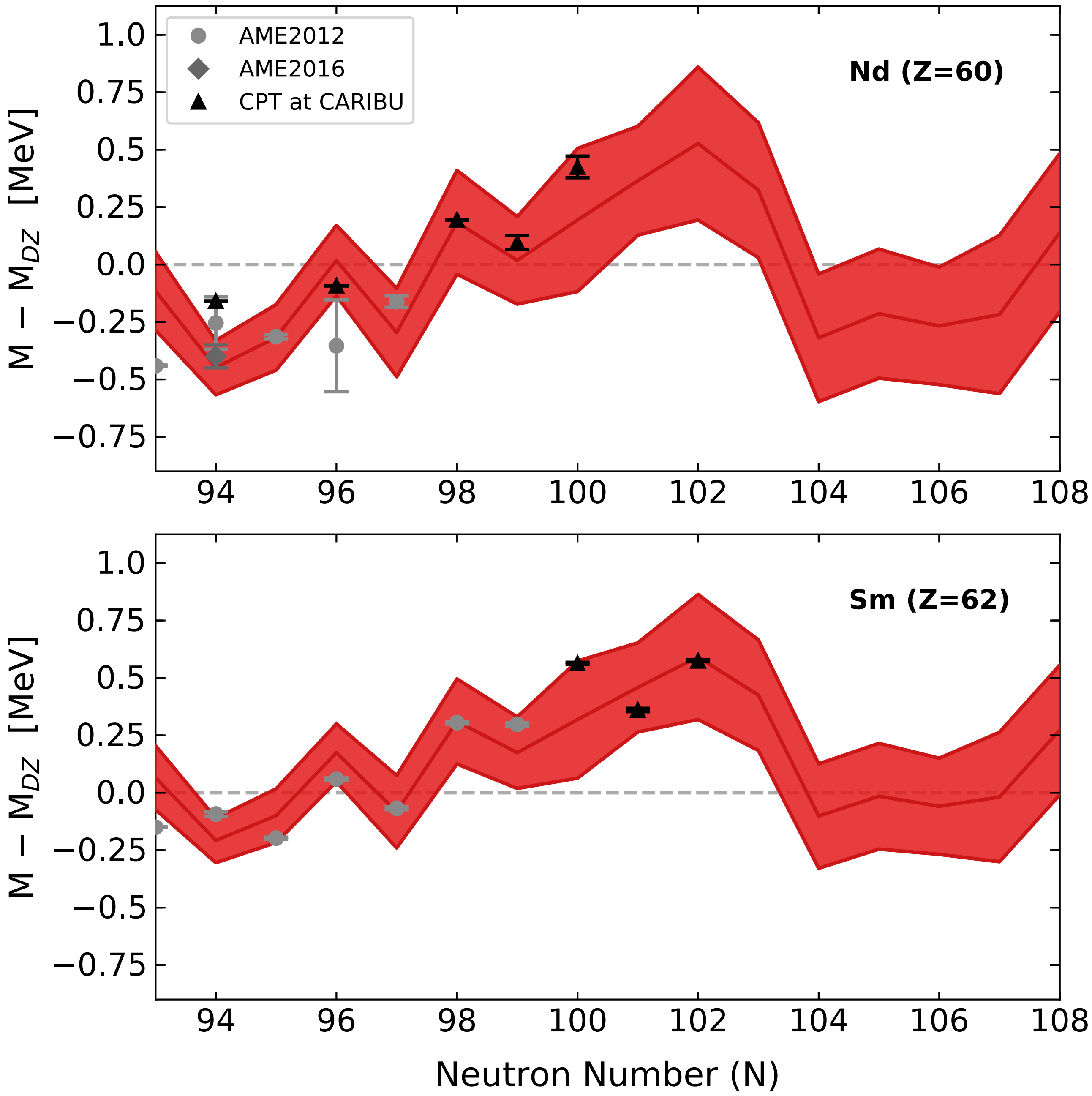
Neutron-rich nuclear masses found capable of peak formation

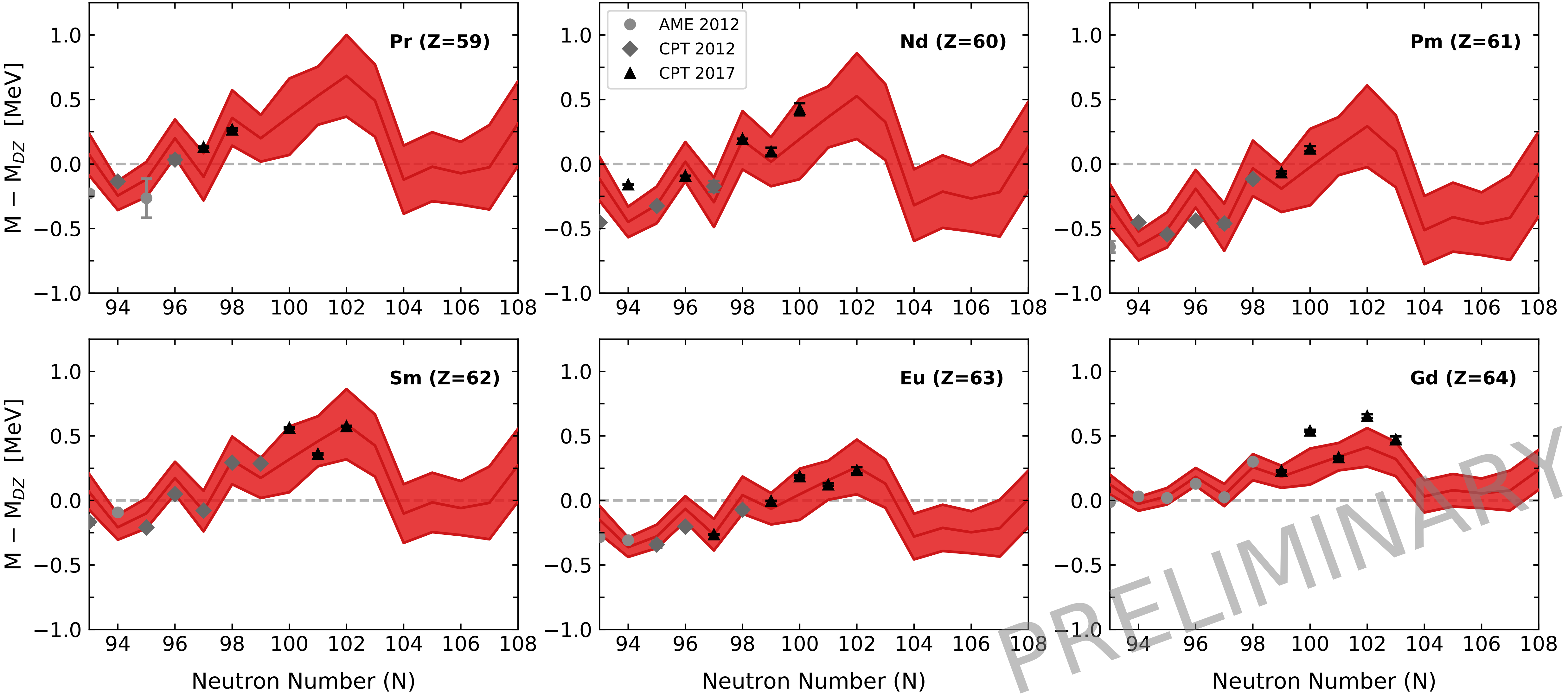
Results

- 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
(Phys. Rev. Lett. **120**, 262702 (2018))





Pr (Z=59)
Nd (Z=60)
Pm (Z=61)
Sm (Z=62)
Eu (Z=63)
Gd (Z=64)
AME 2012
CPT 2012
CPT 2017
M − M_DZ [MeV]
Neutron Number (N)
PRELIMINARY

Dynamic Mechanism Of Rare-Earth Peak Formation

Detailed balance implies

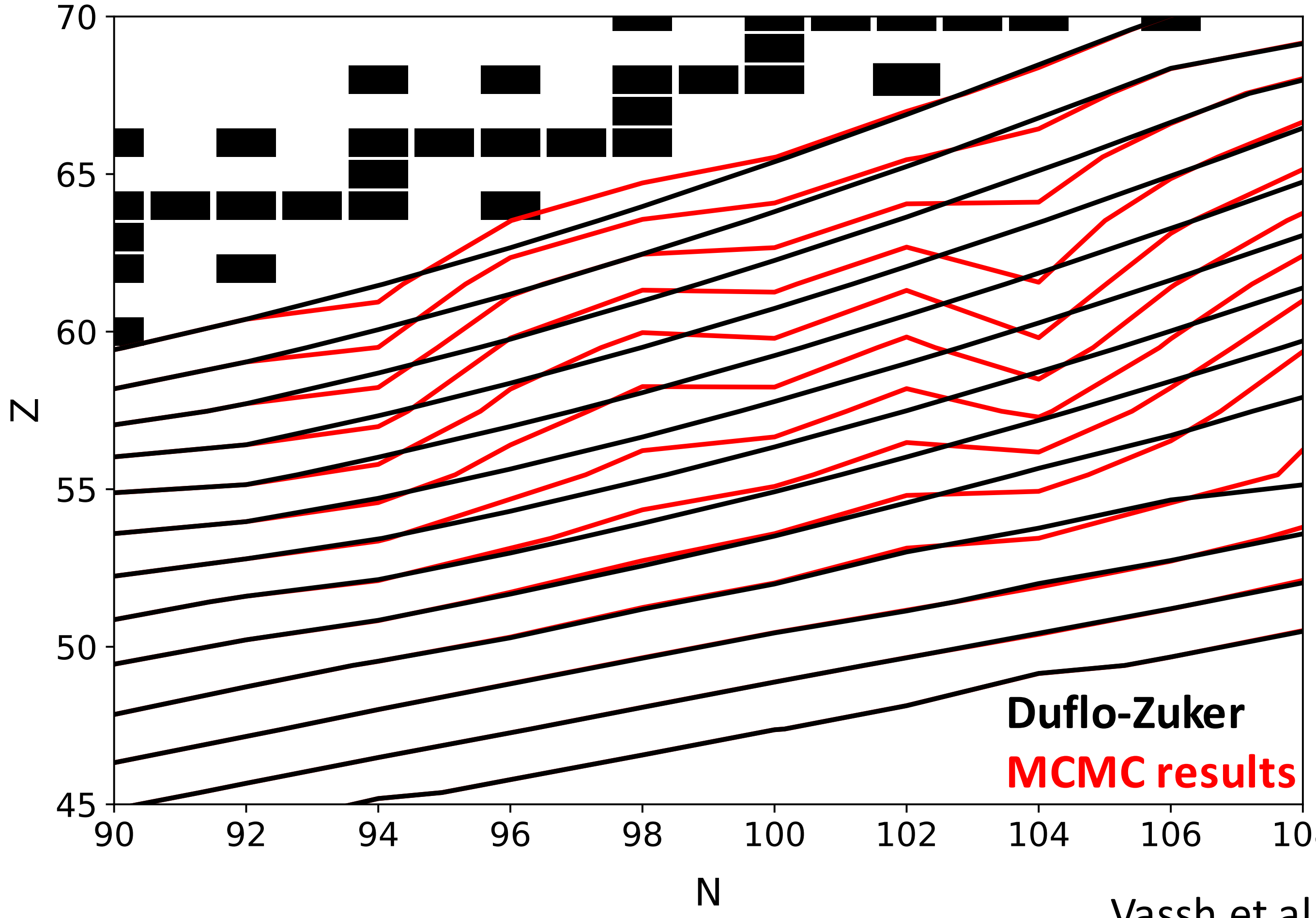
$$(\gamma, \mathrm{n}) \propto e^{-S_\mathrm{n}/kT}$$

↓

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

↓

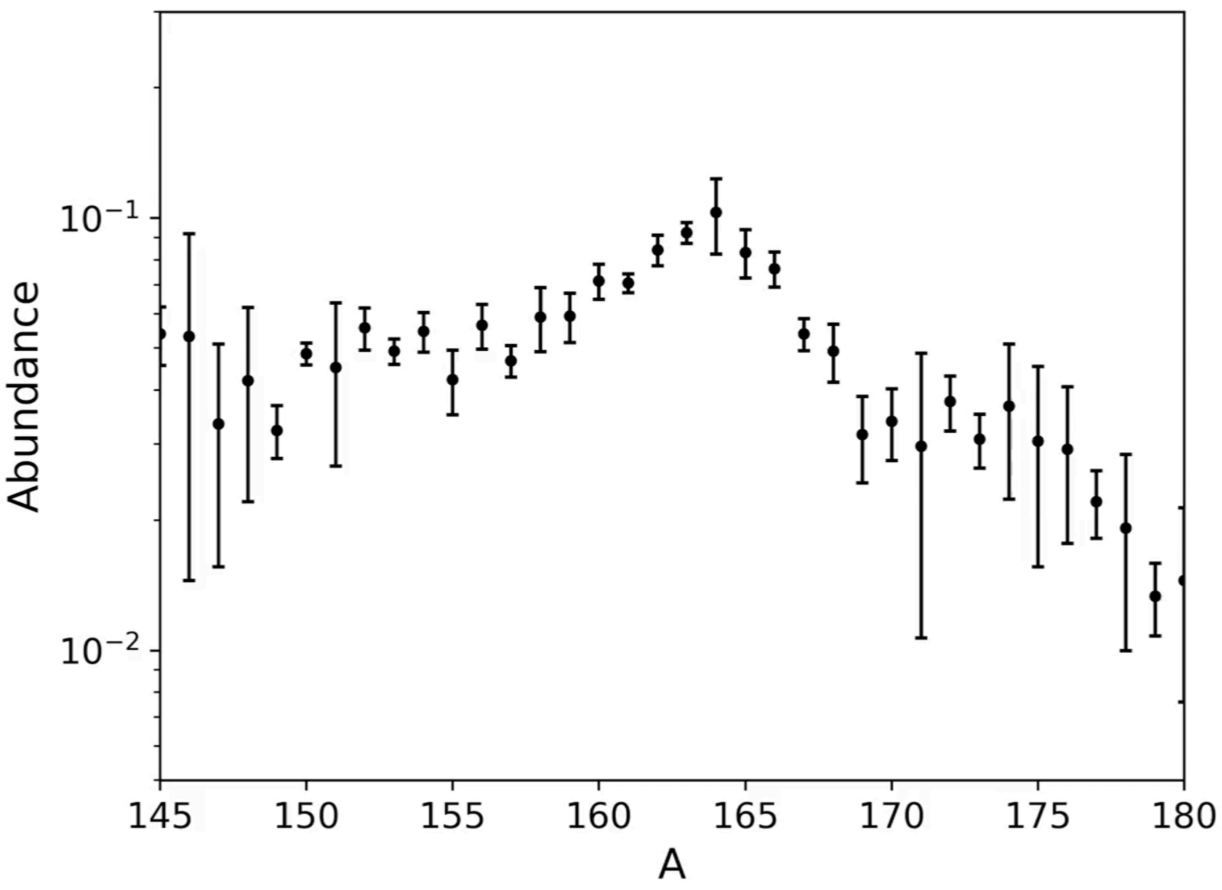
Pile-up of material at kinks

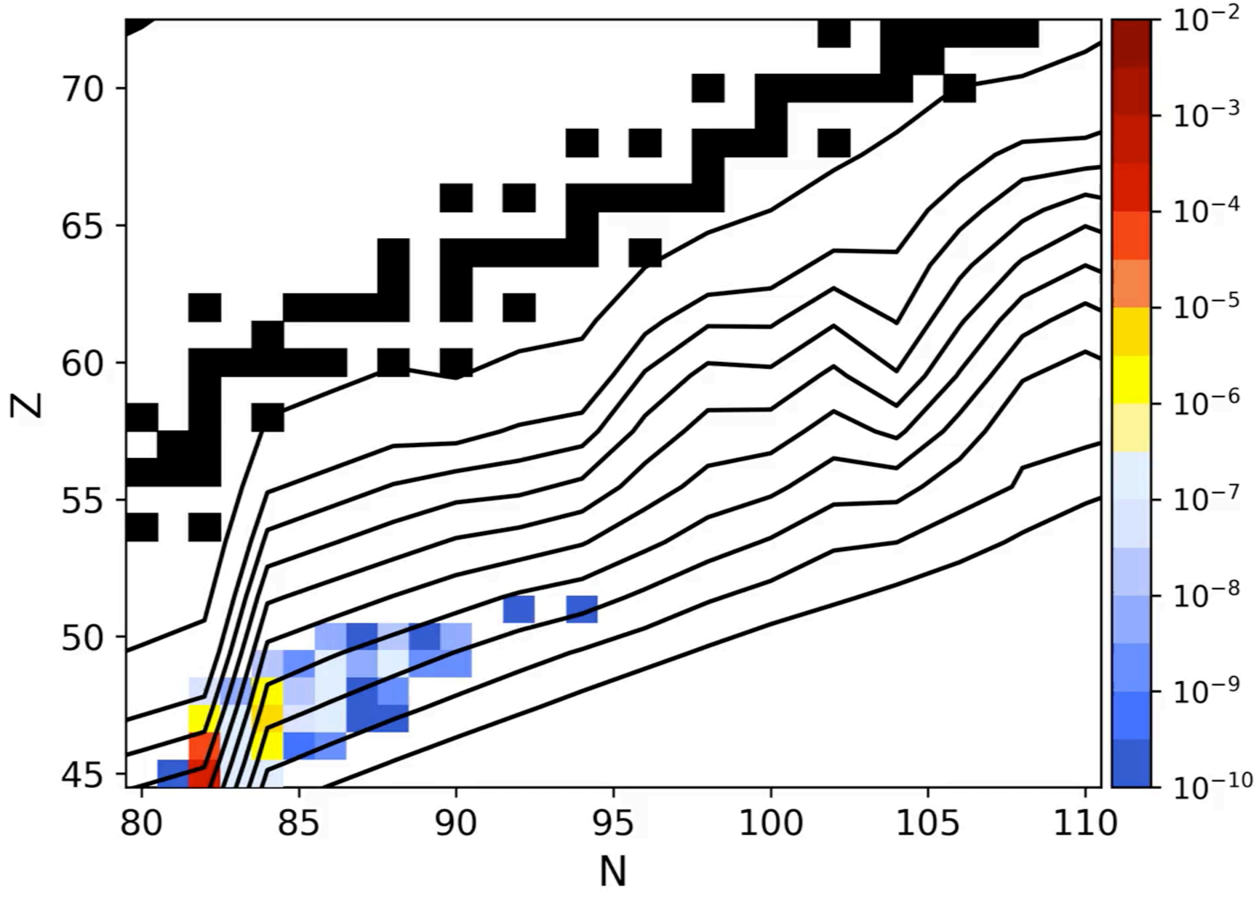


Vassh et al
(in preparation)

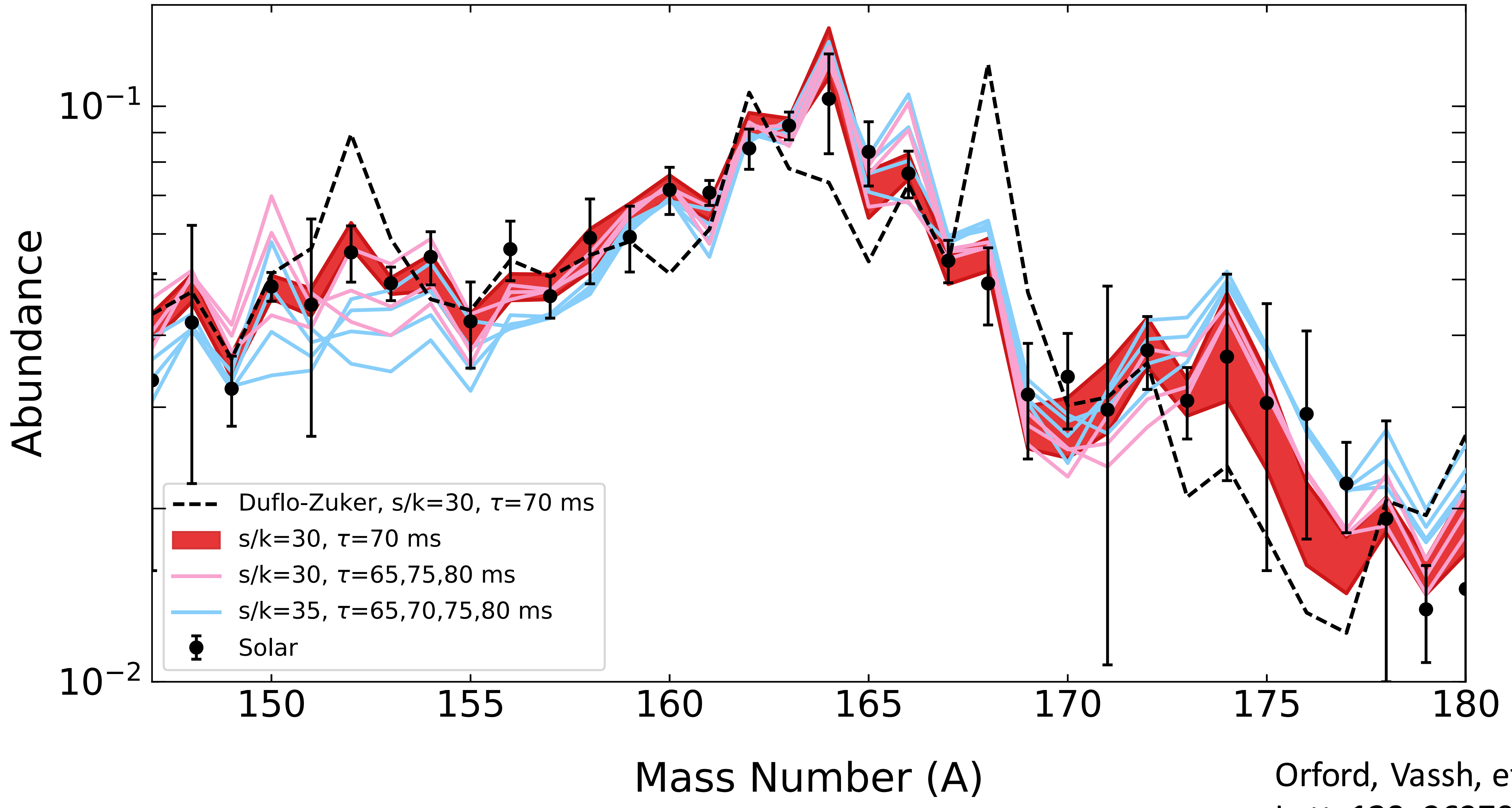
NOTE: FISSION is the other possible means of REP formation

Peak Formation with an MCMC Mass Solution



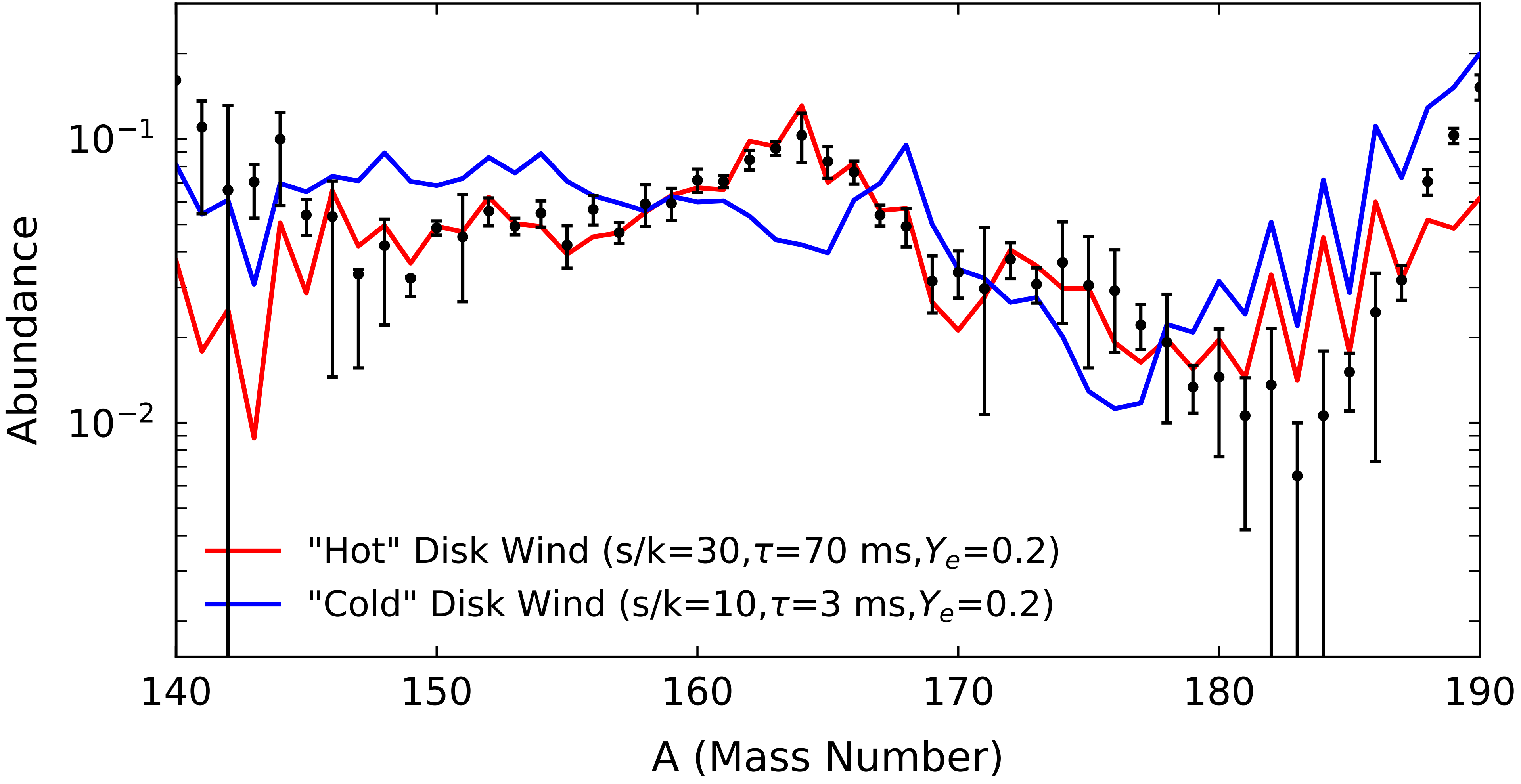


Rare-Earth Peak with MCMC solution + similar astro conditions



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

Rare-Earth Peak with MCMC solution + distinct astro conditions



Vassh et al (in prep.)

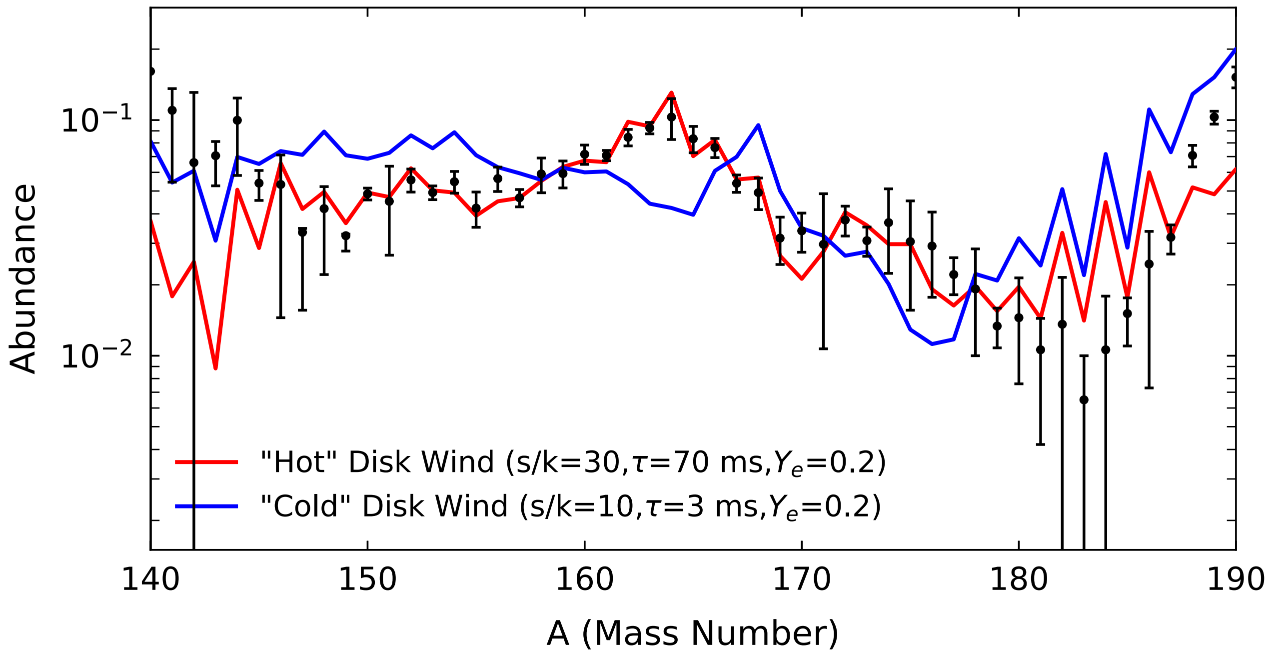
Nucleosynthesis in Neutron Star Mergers: Many Open Questions

- 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?

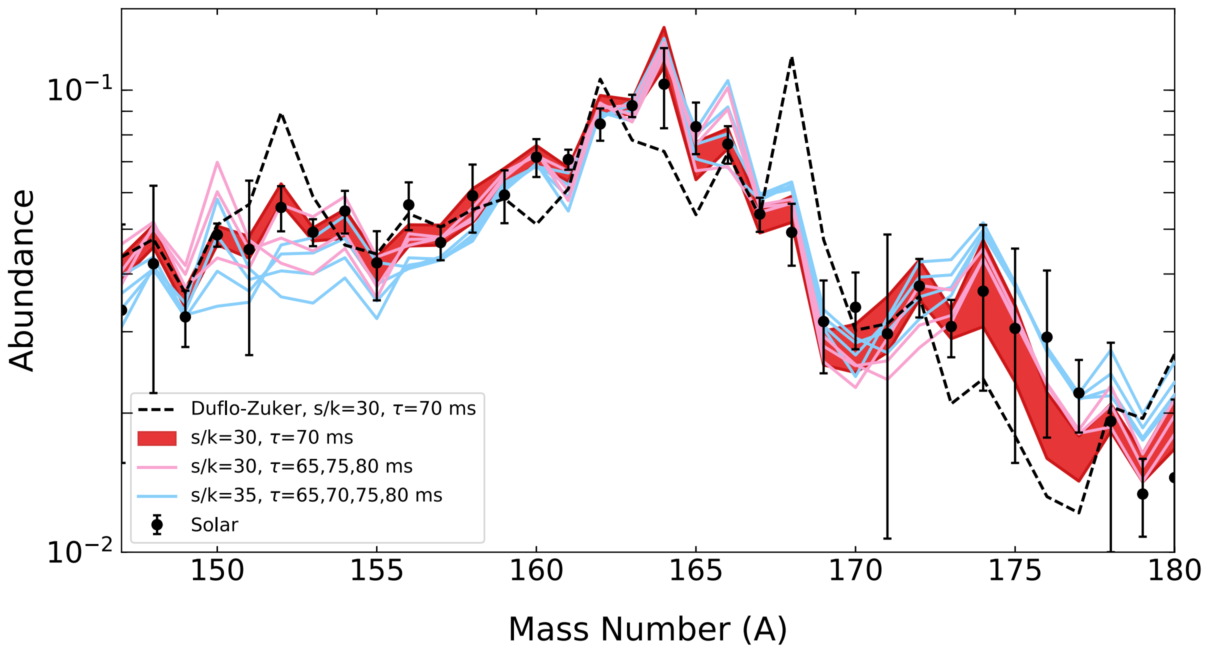
Nucleosynthesis in Neutron Star Mergers: Many Open Questions

- 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?

Monte Carlo methods



Vassh et al (in preparation)

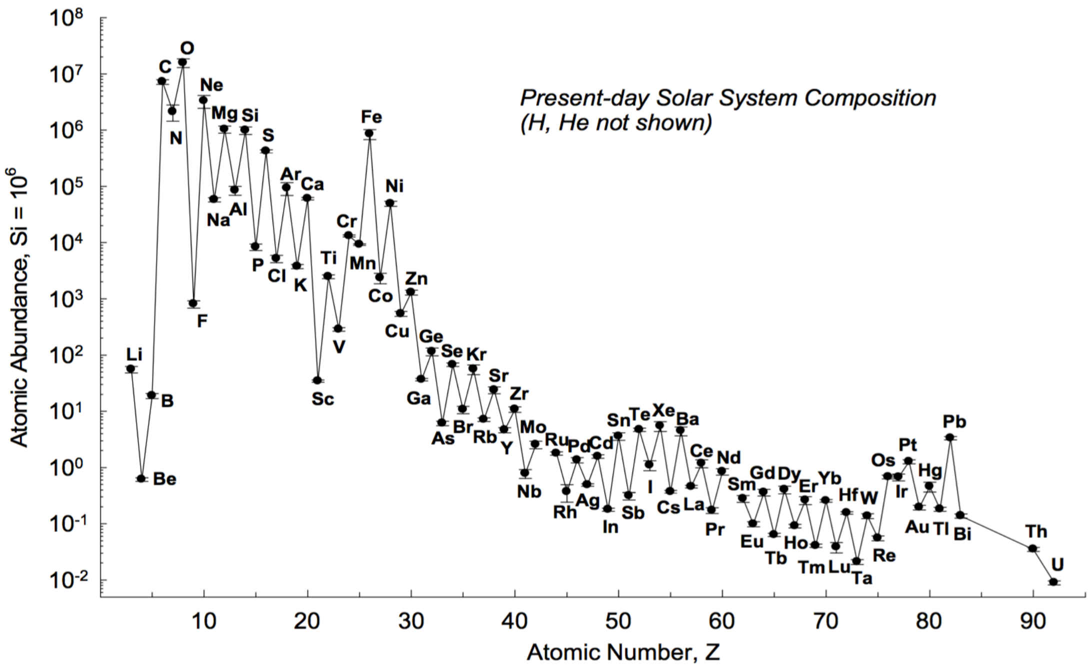


Orford, Vassh, et al (Phys. Rev. Lett. **120**, 262702 (2018))

Back-up Slides

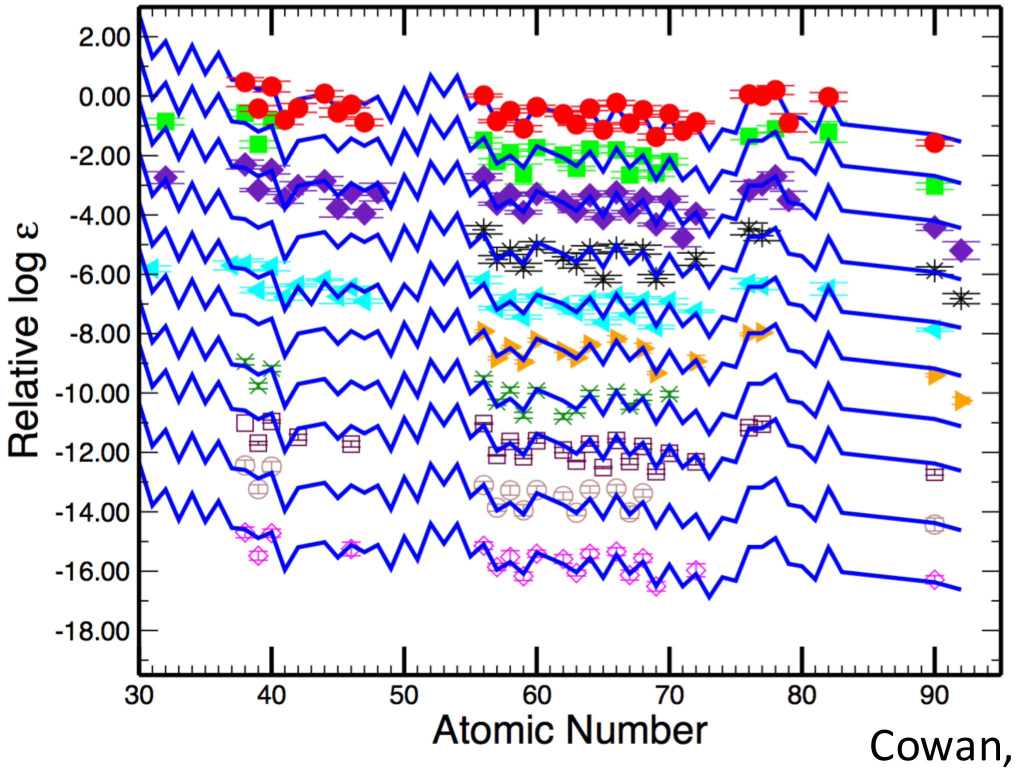
Observed Elemental Abundances

Solar System



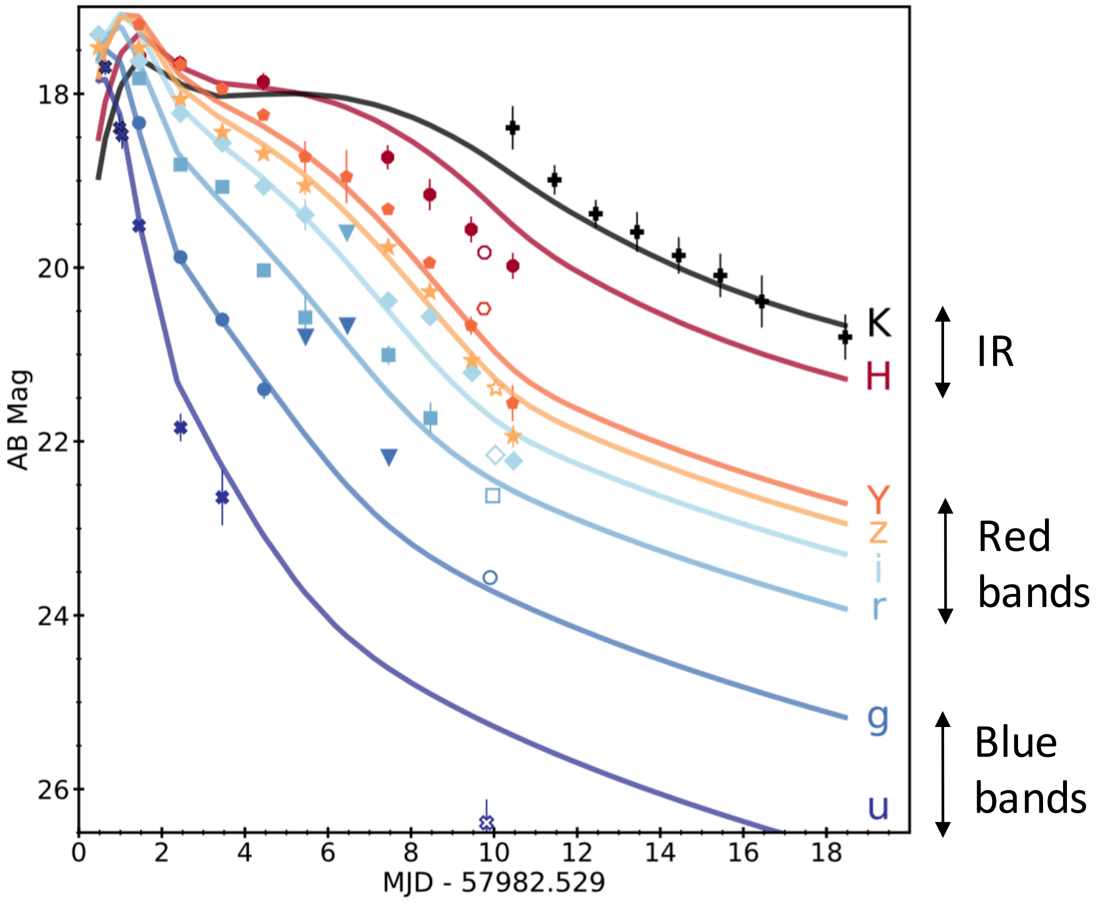
Lodders (2010)

10 *r*-process rich halo stars



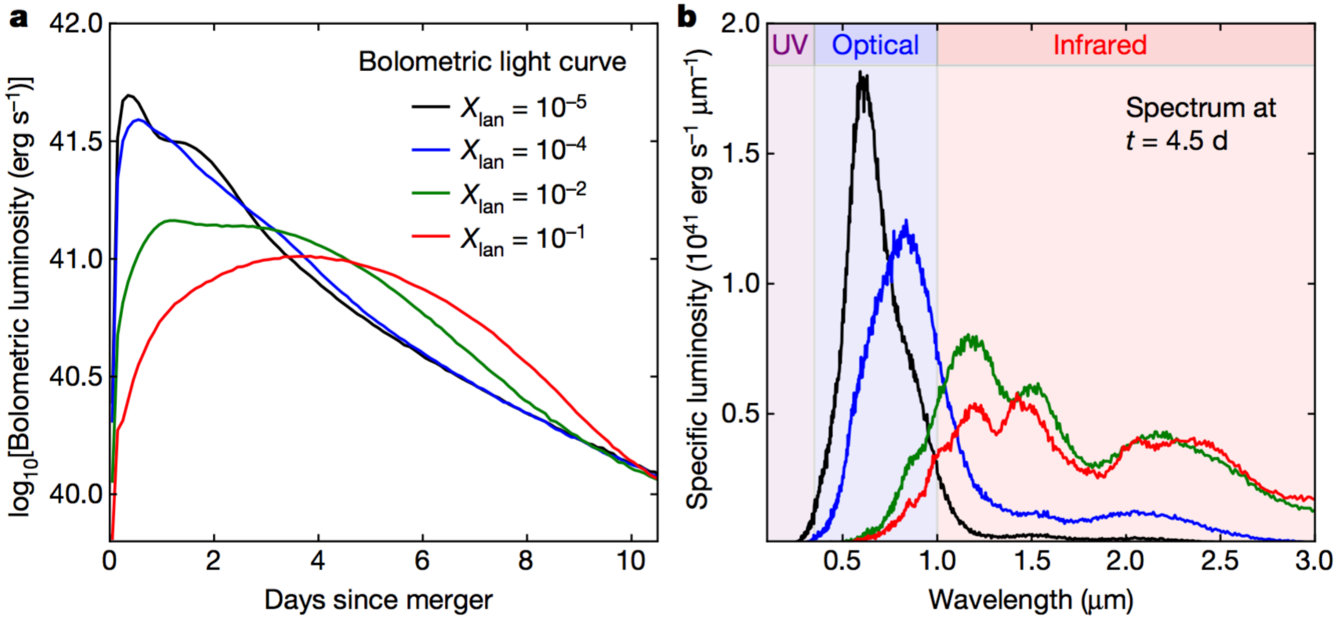
Cowan, Roederer, Sneden and Lawler (2011)

Lanthanide production in GW170817: "red" kilonova



Cowperthwaite et al (ApJL 2017)

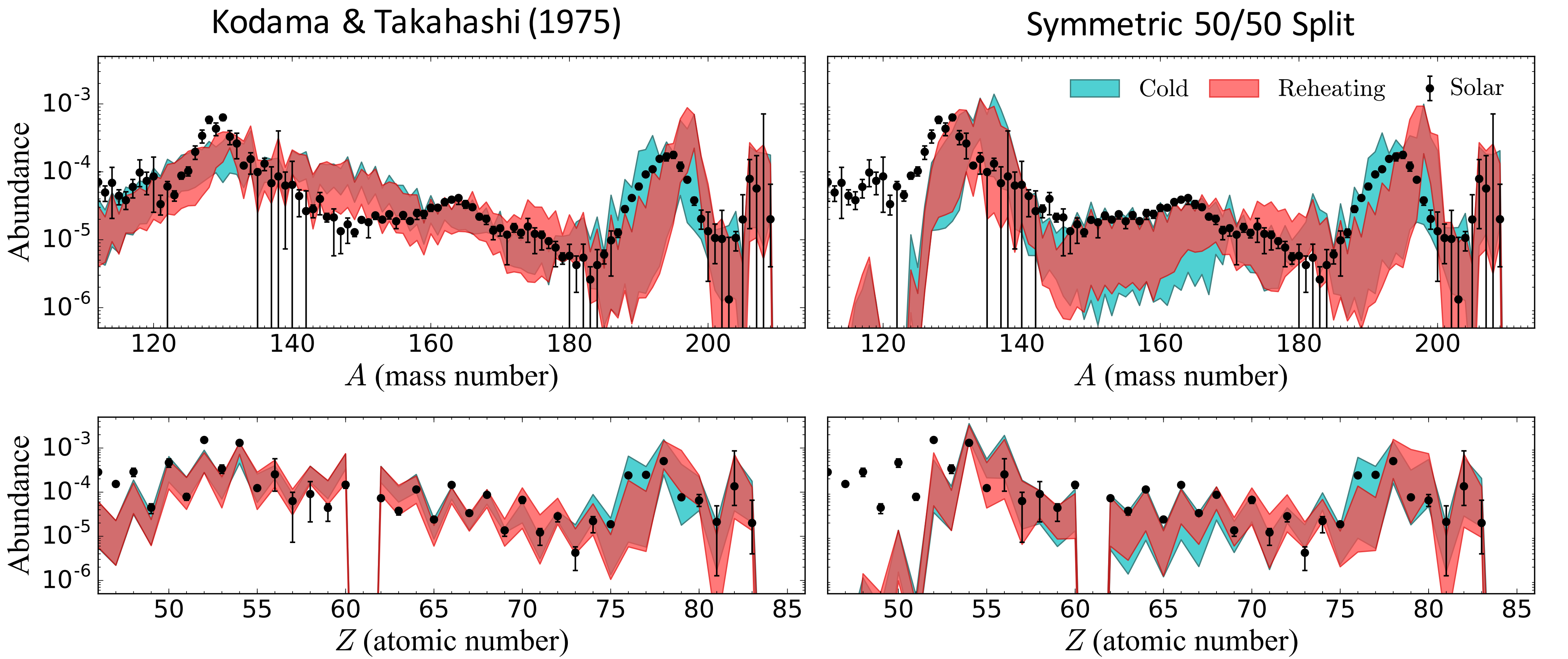
Lanthanide mass fraction ↑ , opacity ↑, longer duration light curve shifted toward infrared



Kasen et al (*Nature* 2017)

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)

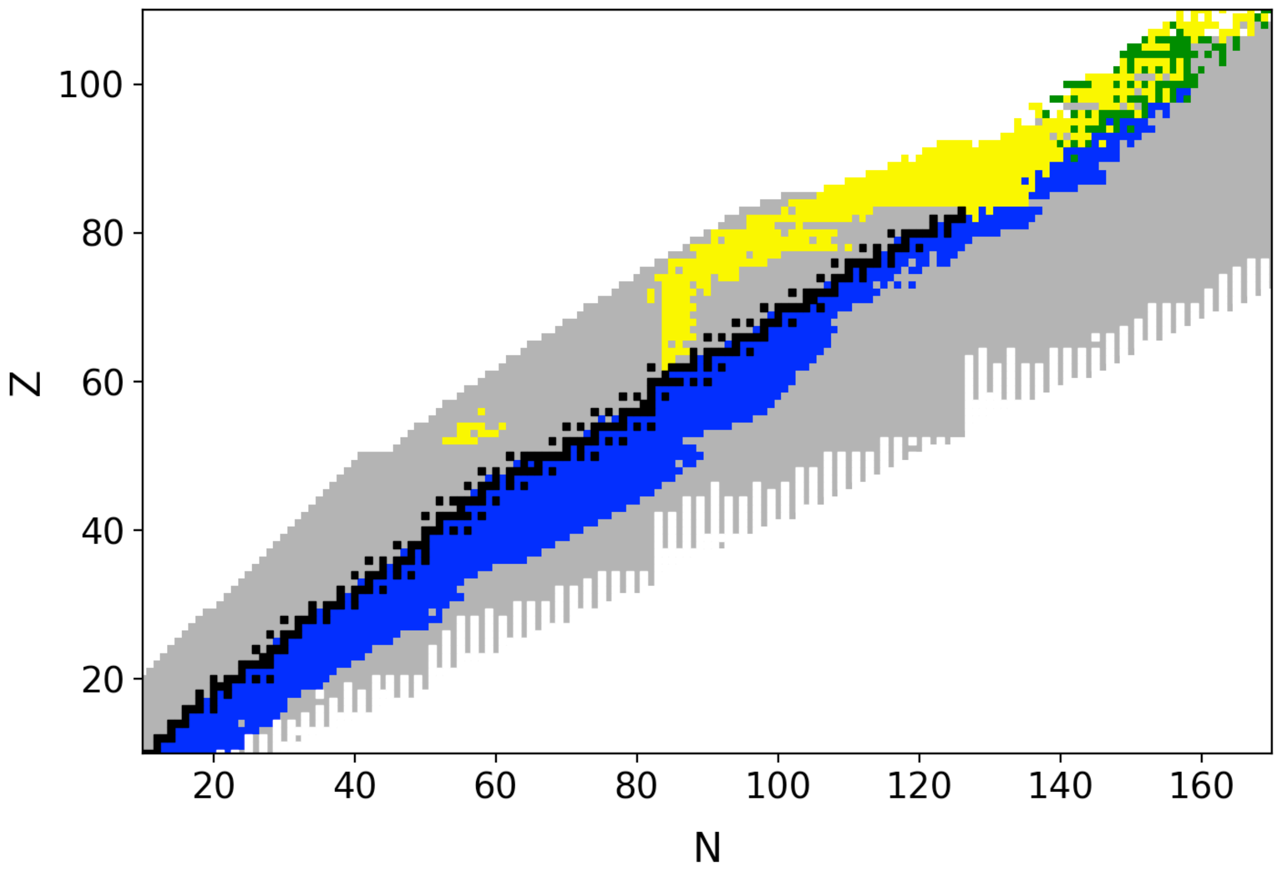


Côté et al (2017)

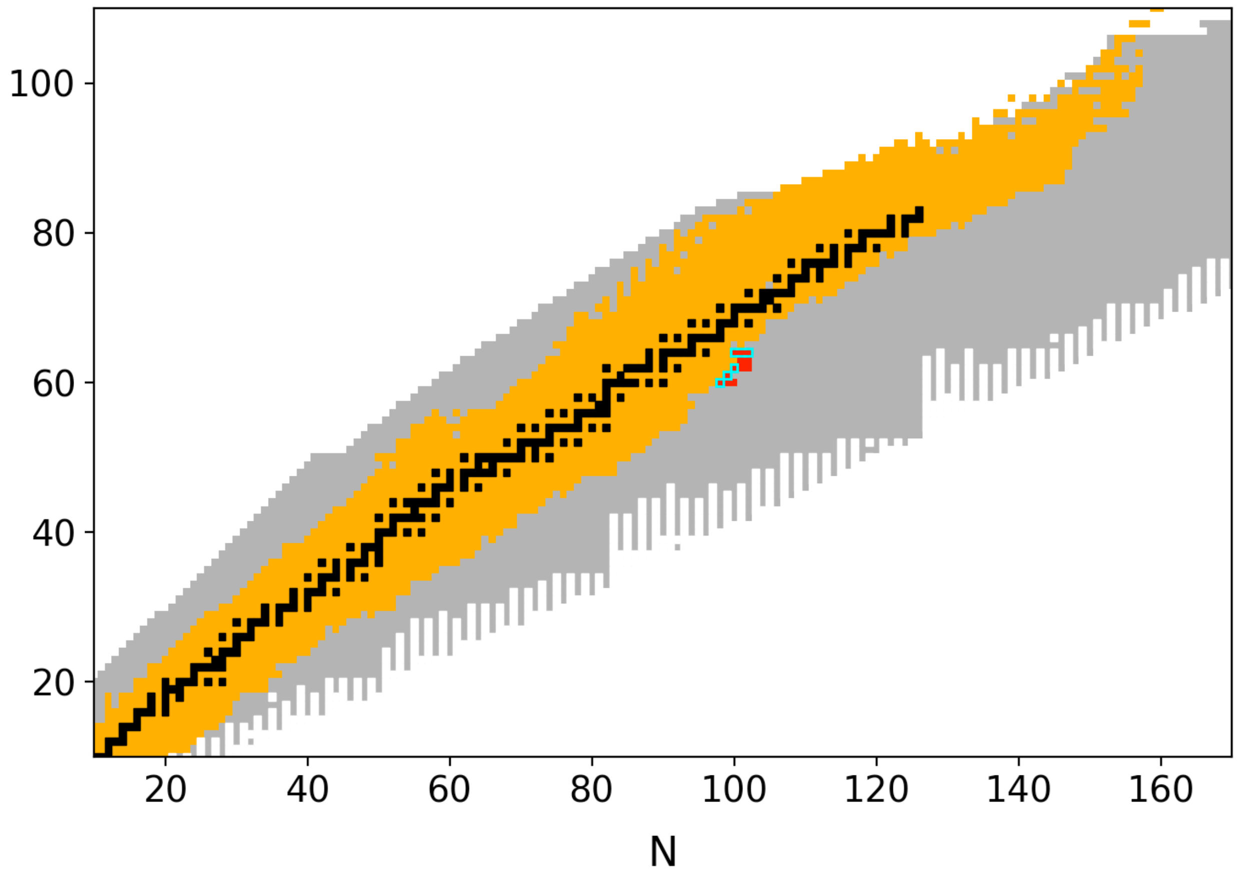
Measured Decay Rates and Masses

NUBASE 2016

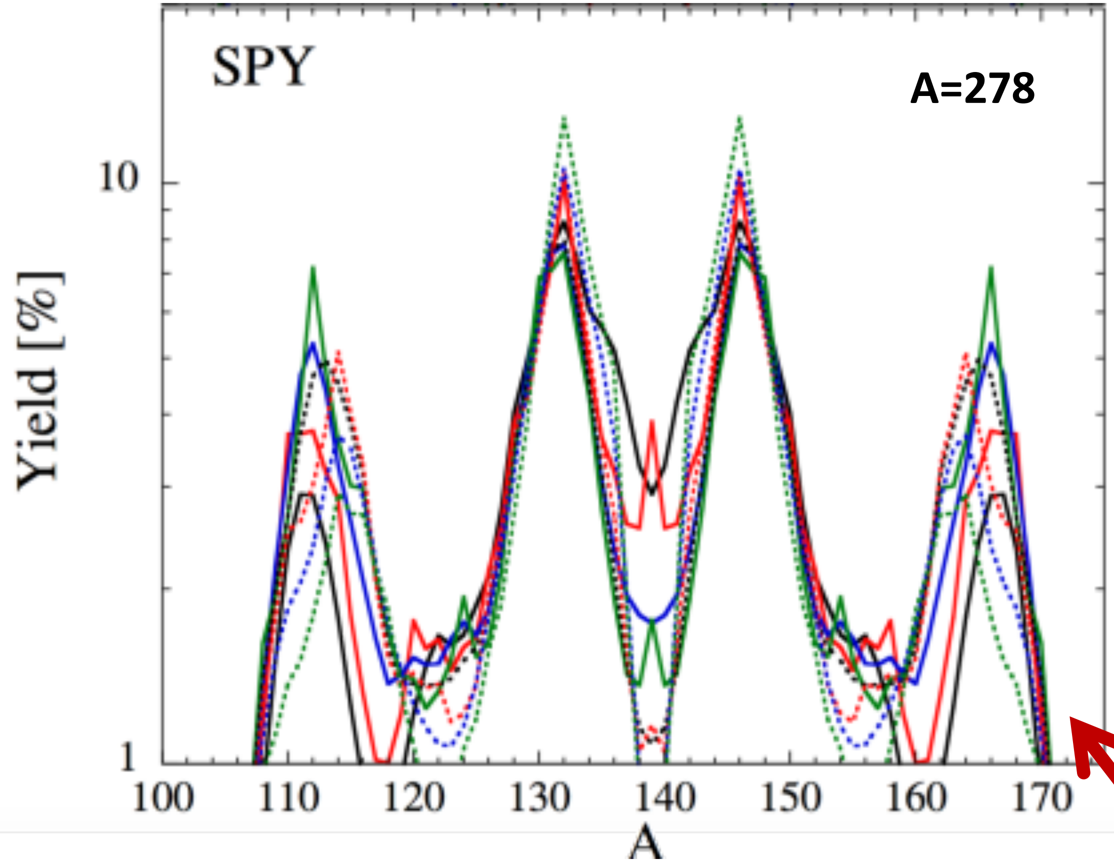
β-decay, α-decay, and spontaneous fission



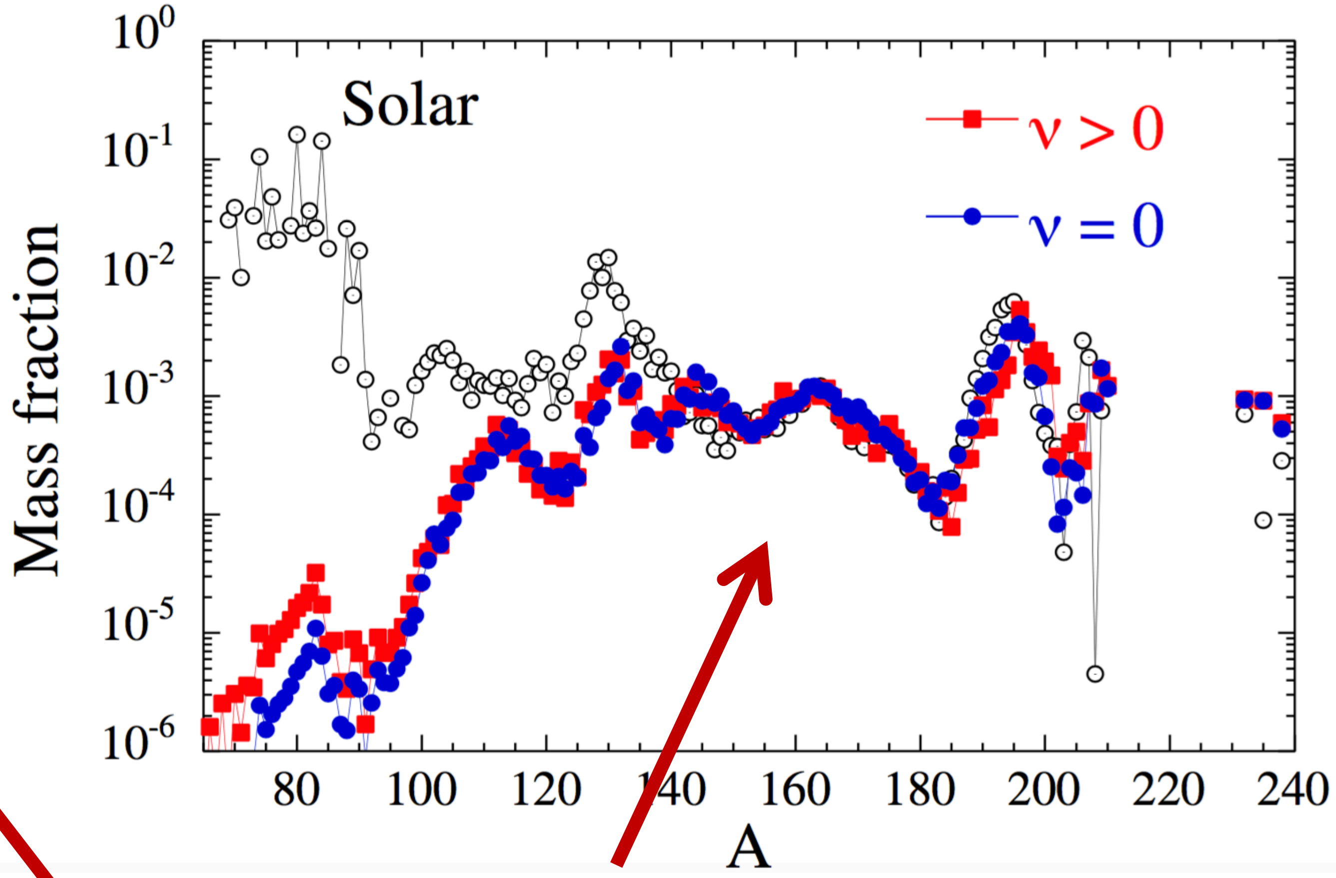
AME 2016 / Jyväskylä / CPT at CARIBU



Dependence on the Fission Fragment Distribution



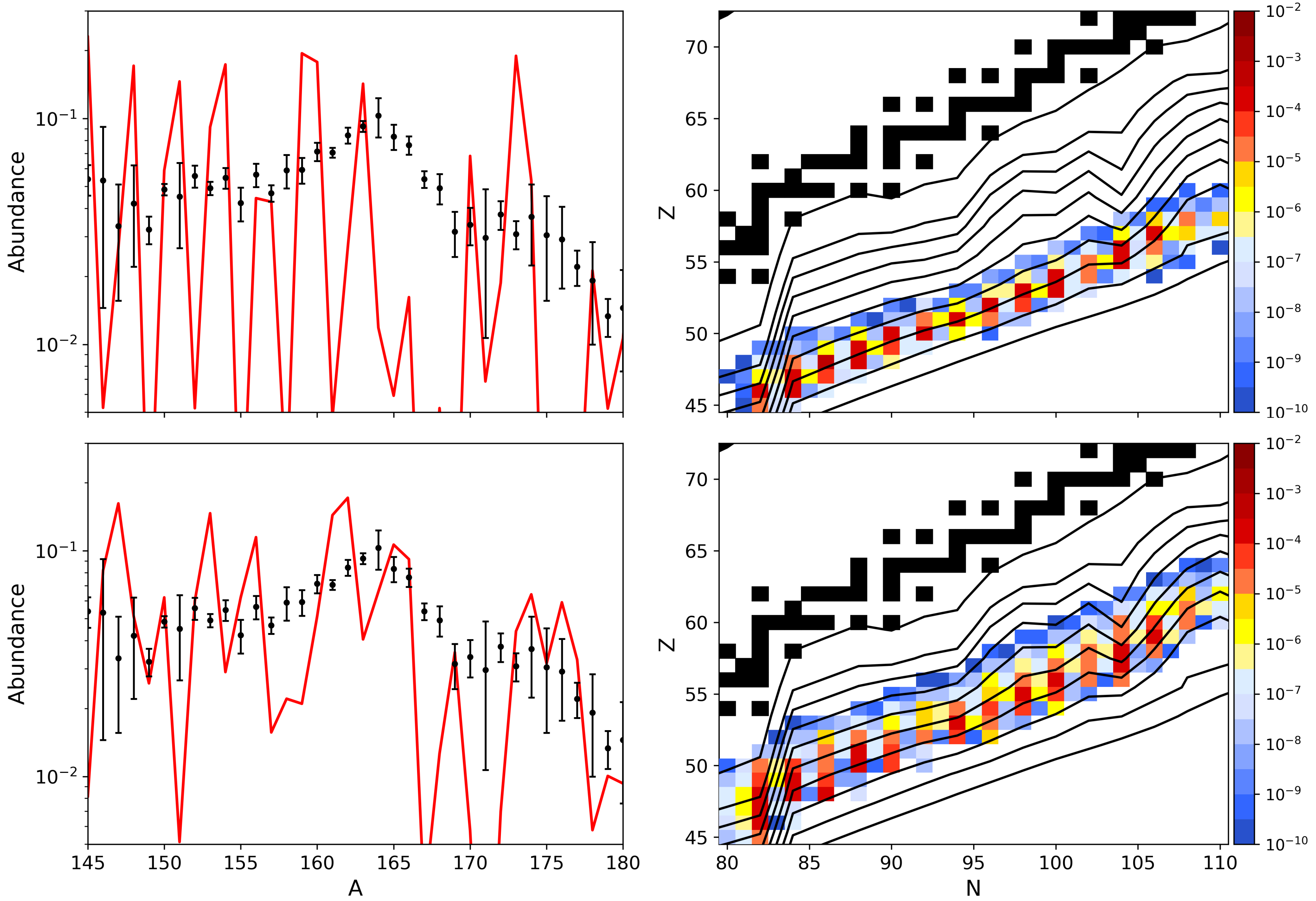
Z=95, Z=96 , Z=97, Z=98, Z=99, Z=100, Z=101, Z=102 (dotted lines – larger Z)



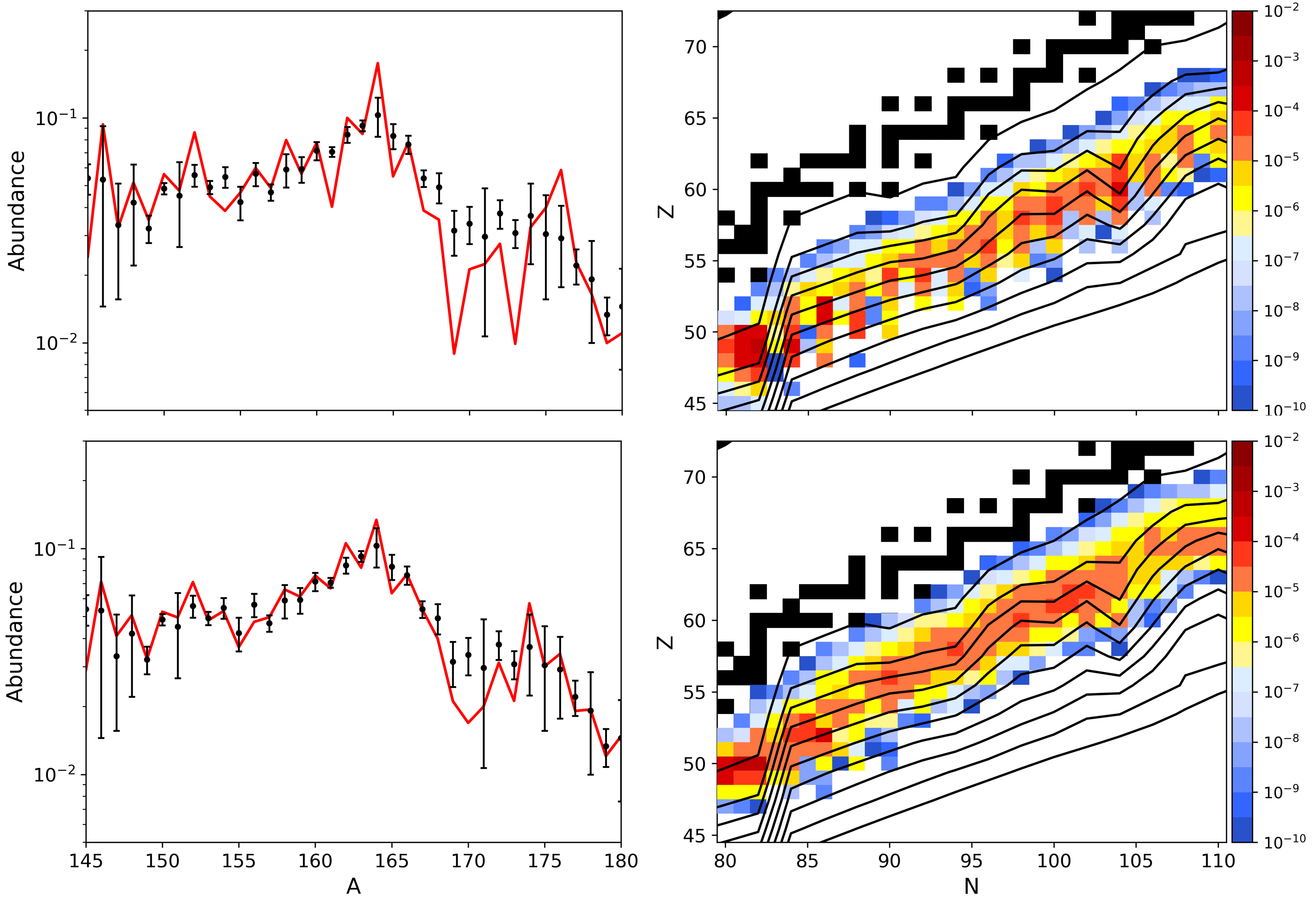
Rare-earth peak can be populated by fission daughter products of n-rich nuclei

Goriely (2015)

Peak Formation with an MCMC Mass Solution



Peak Formation with an MCMC Mass Solution

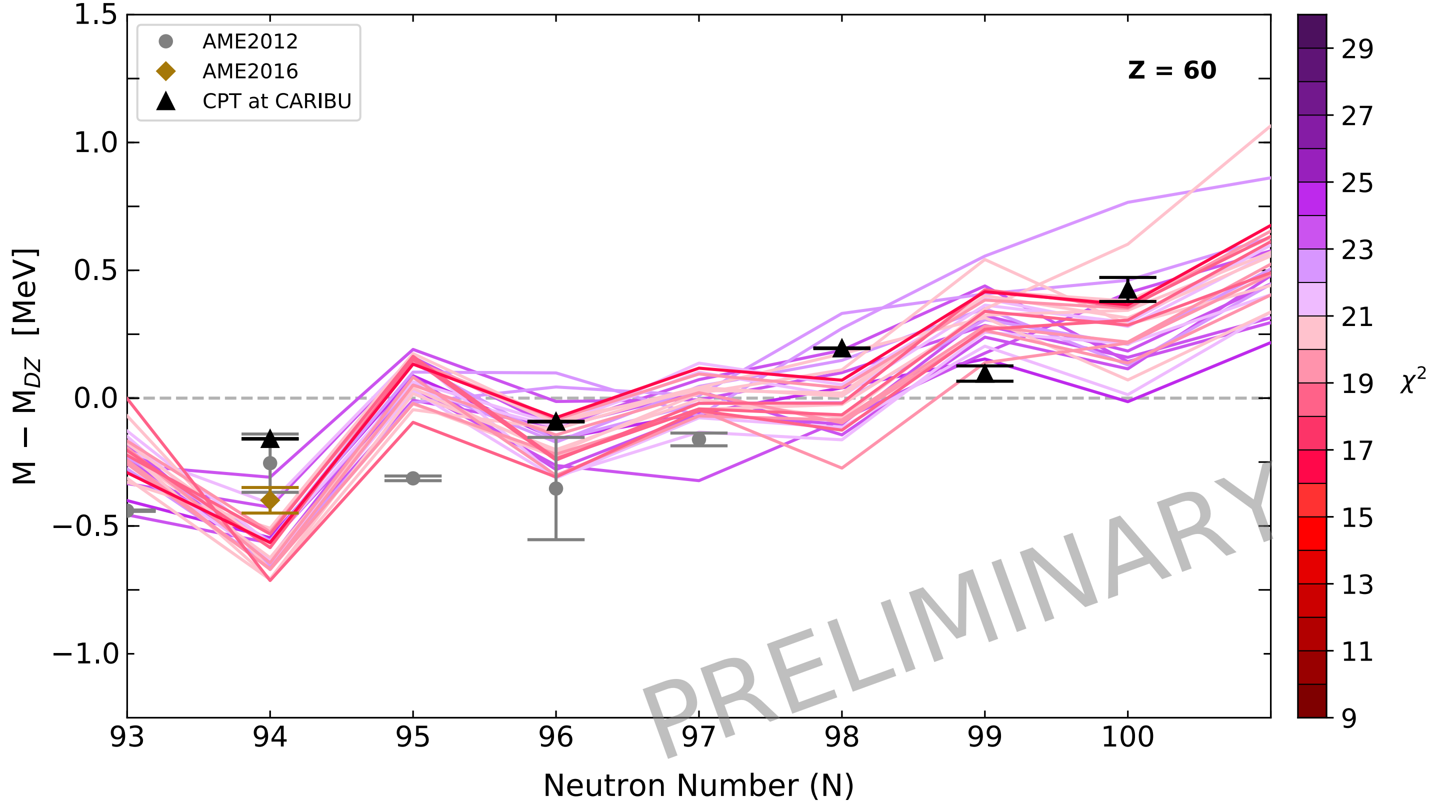


Preliminary Results

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

- 50 independent MCMC runs complete

30 Runs (Best Step Colored by χ^2)



Vassh et al
(in preparation)