Nuclear Mass with Machine Learning and application to the astrophysical r-process

Speaker: Mengke Li (Clemson University)

03/18/2023

Figure: University of Warwick/Mark Garlick

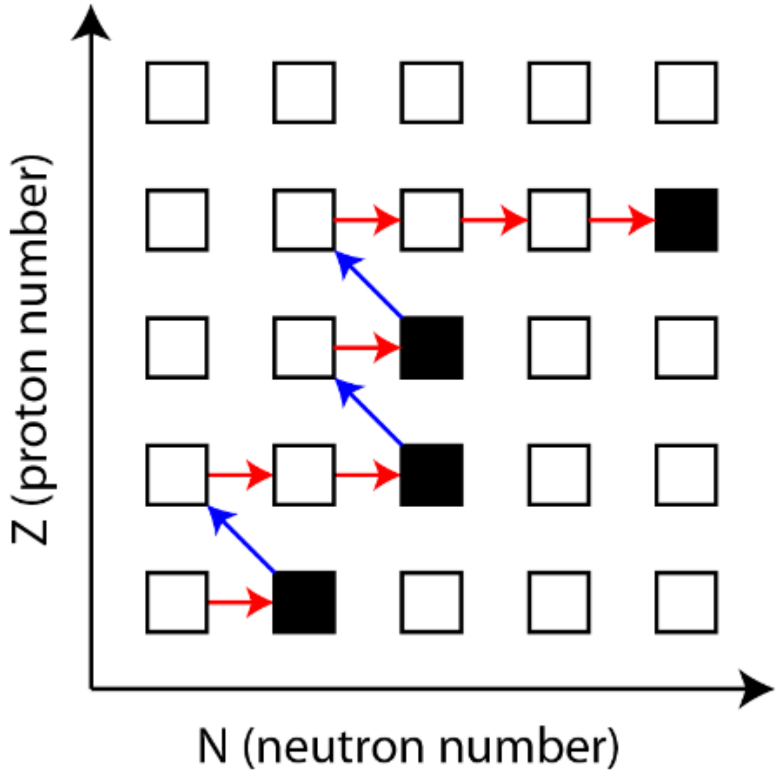
Motivation

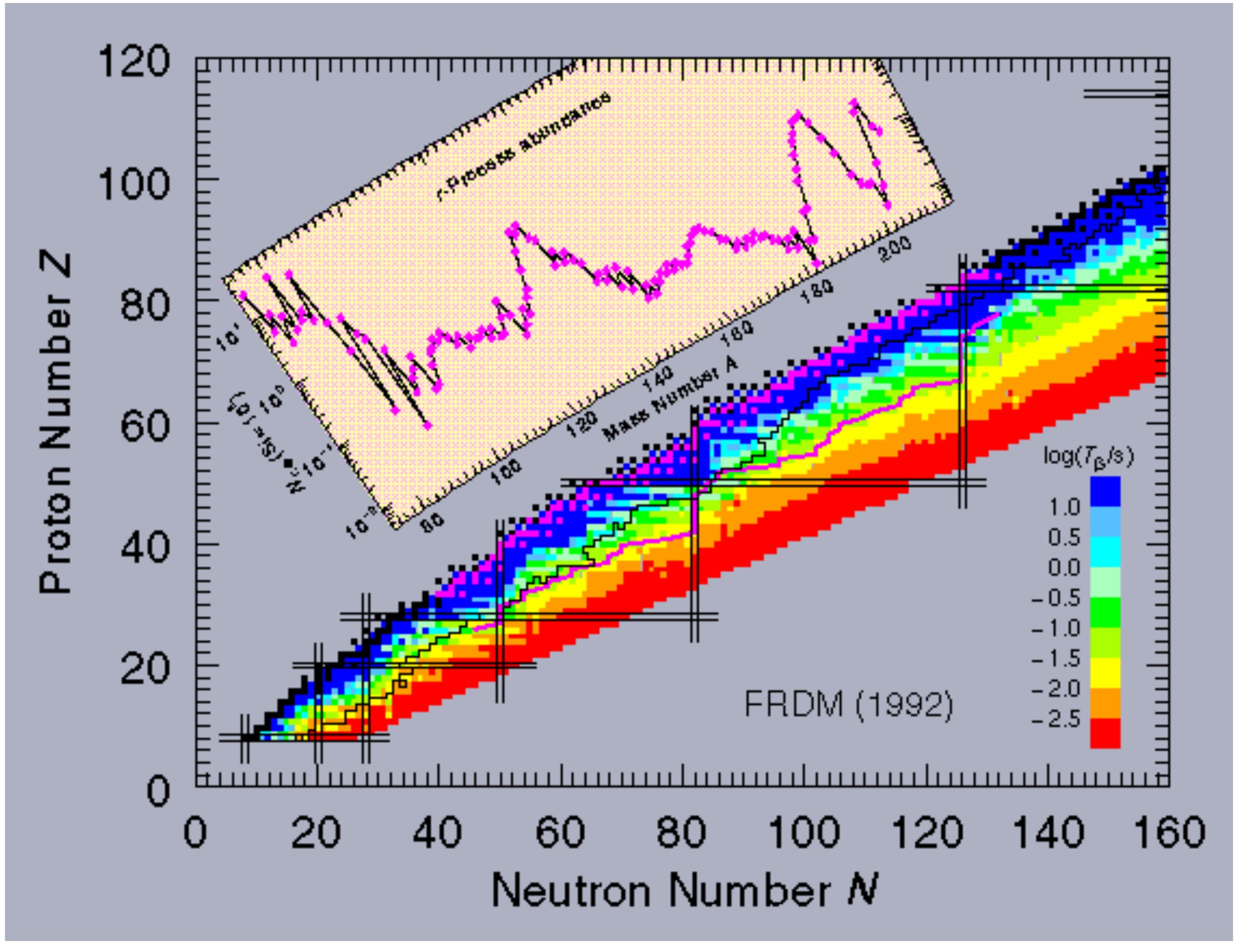
- GW170817
  - First detection of the gravitational wave from binary neutron star merger(NSM).
  - Confirms that NSM can produce heavy nuclei (heavier than Fe)
  - How this event produces heavy nuclei?
  - What's the abundance of those heavy nuclei?

R-Process

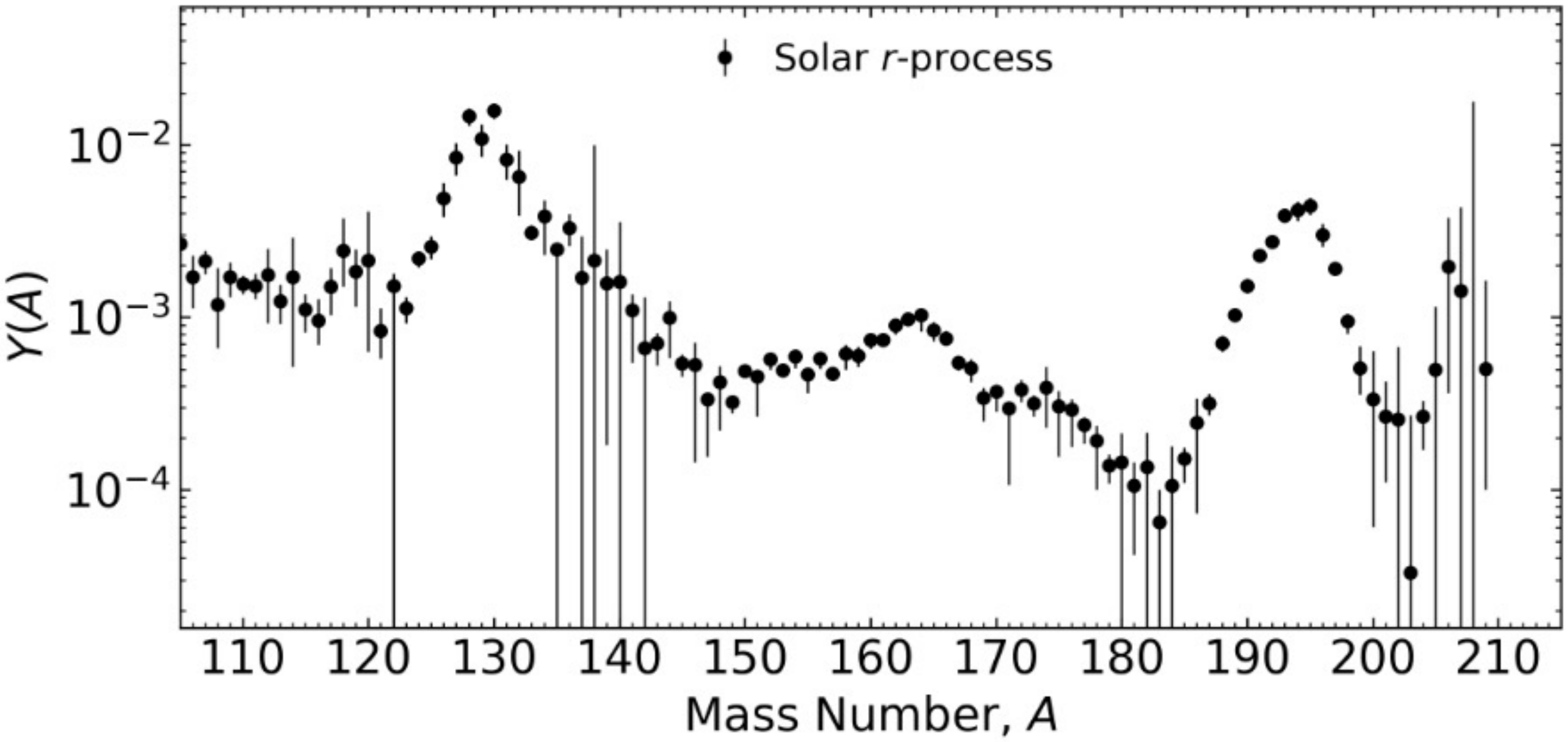
R-process: **Rapid** neutron capture process → **heavy** nuclei

R-process: $\lambda_n \gg \lambda_\beta$
S-process: $\lambda_n \ll \lambda_\beta$





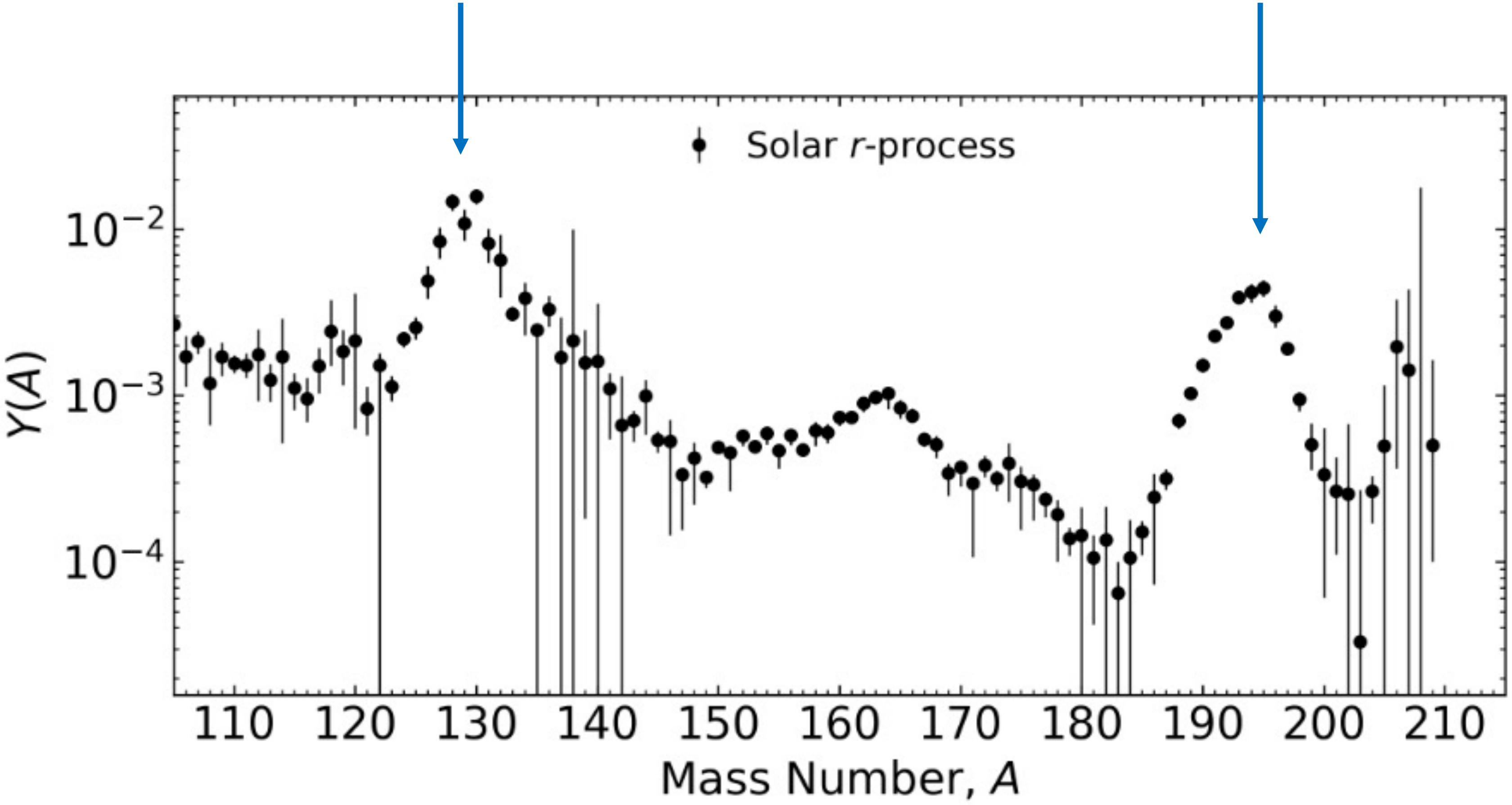
R-Process



Observational information is from meteorites and photospheric observations

R-Process

Second and Third Peaks at A = 130 and 195



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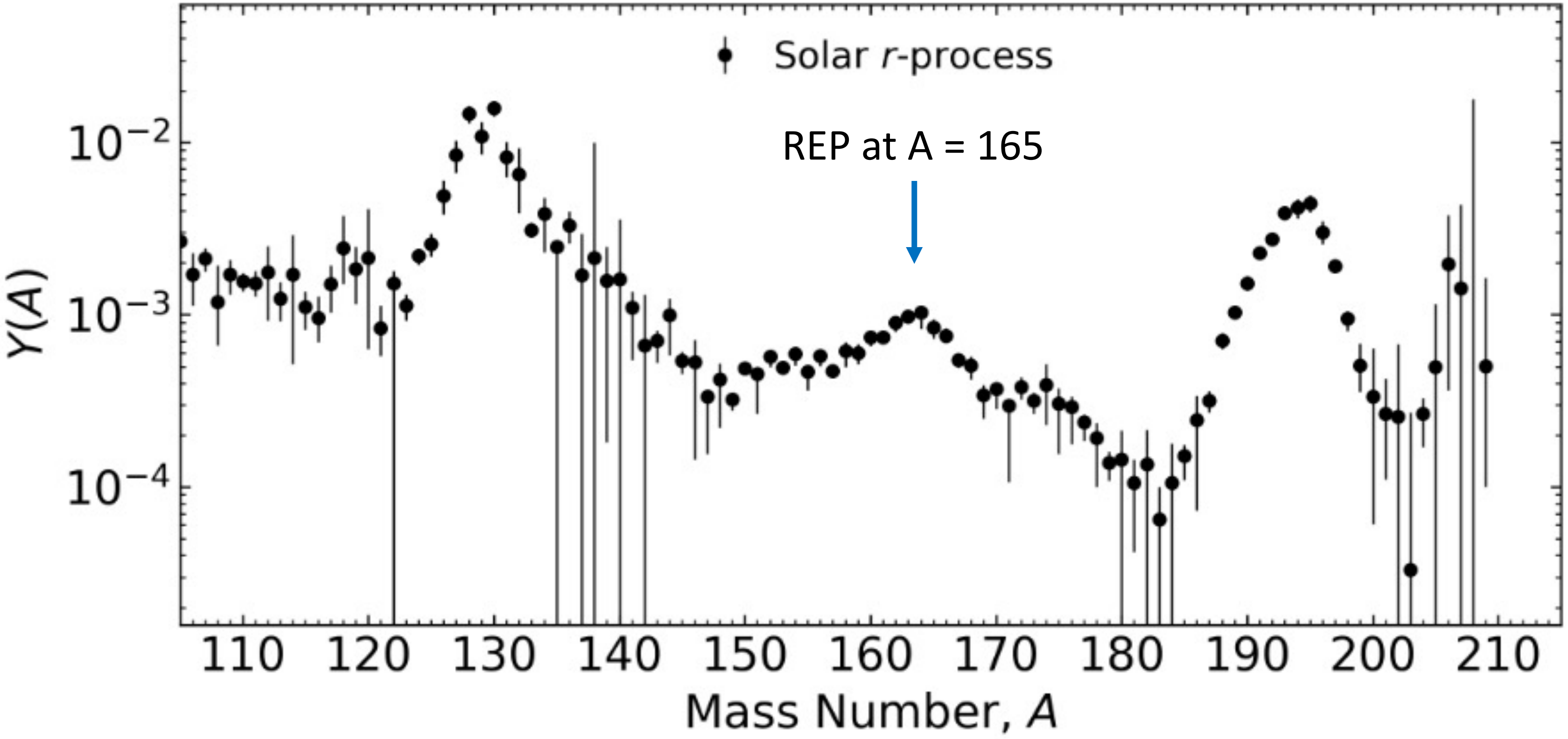
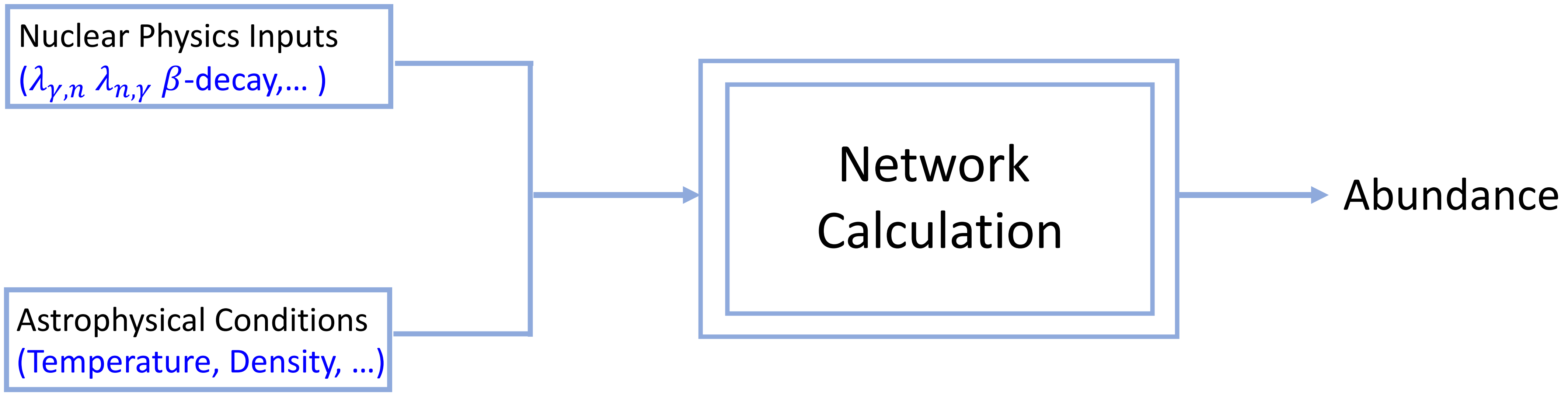
R-Process



Observational information is from meteorites and photospheric observations

R-Process

Combines nuclear physics inputs and astrophysical conditions



R-Process

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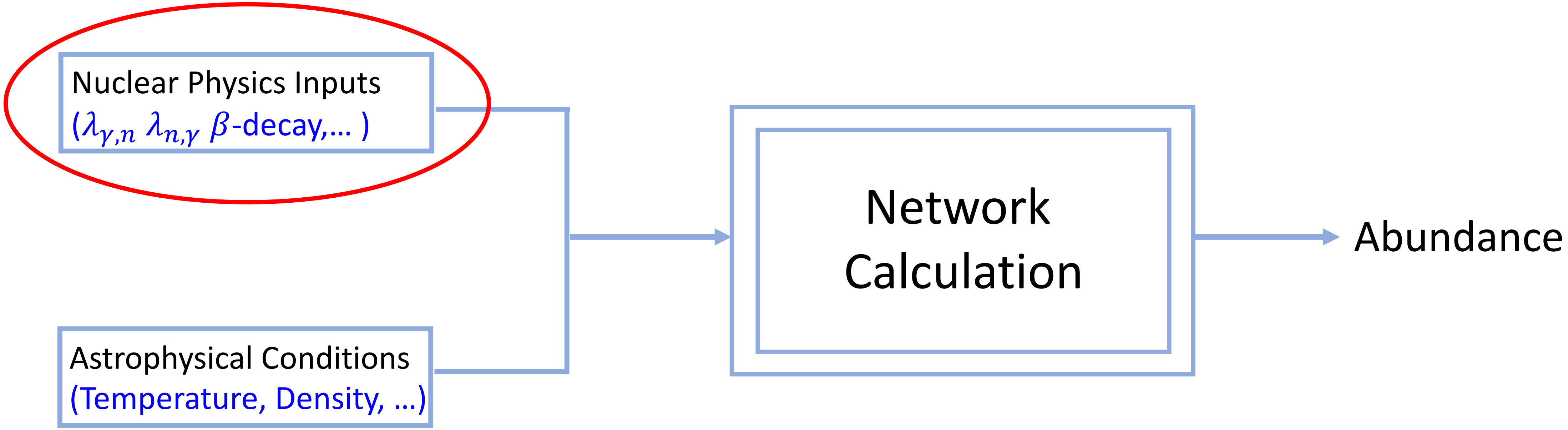

Nuclear Input

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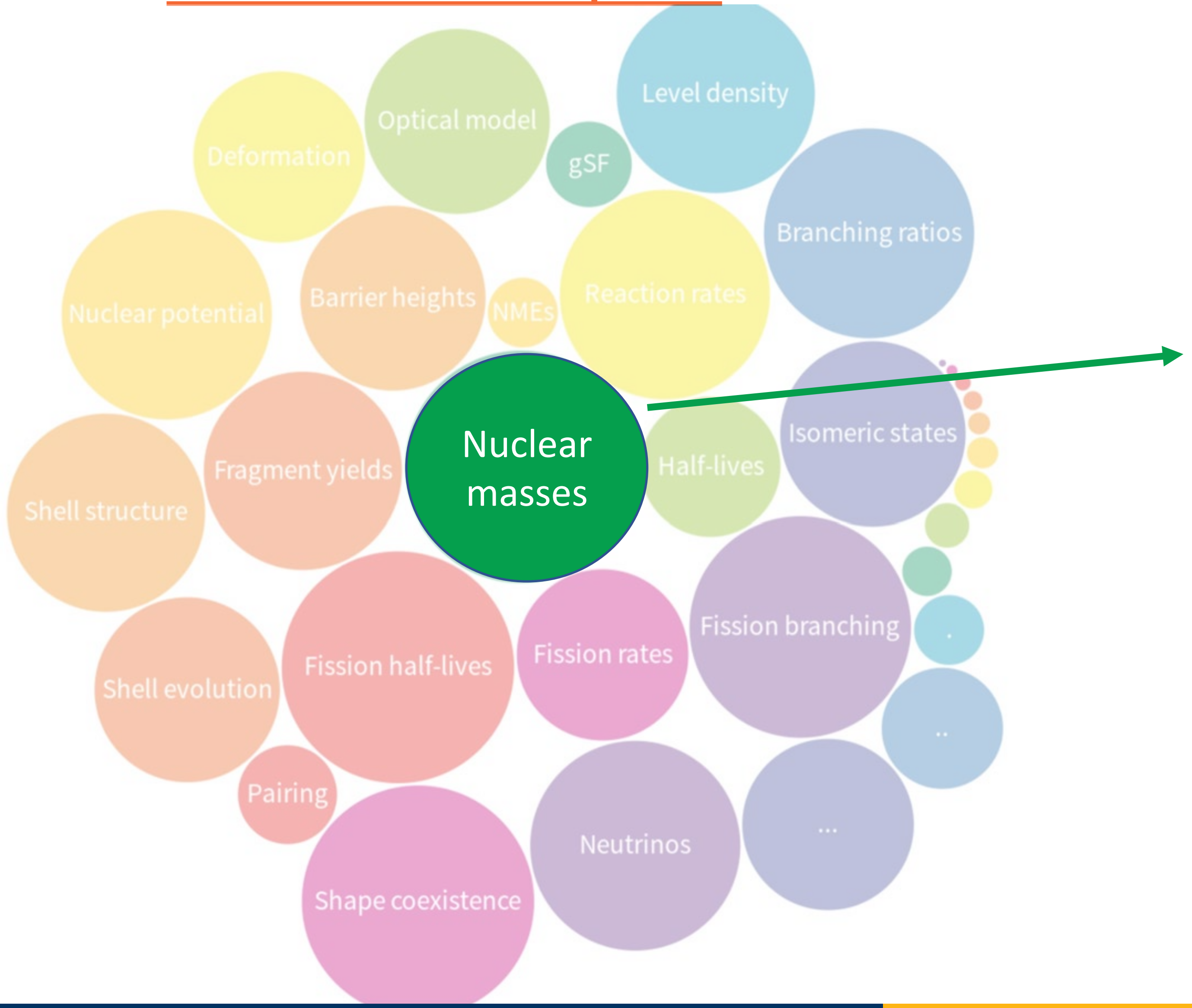
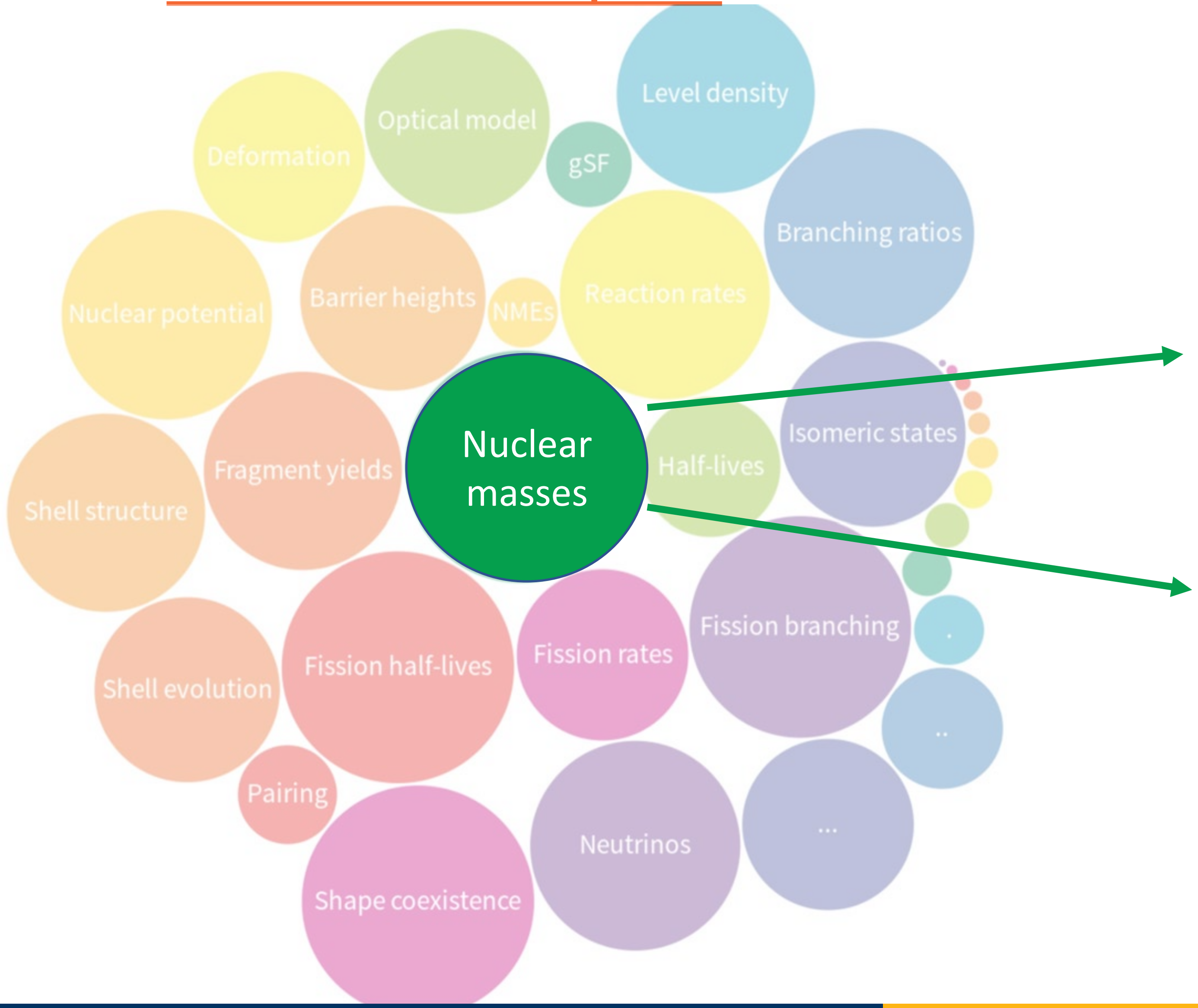


- A critical input for structure and reaction theory calculations

Nuclear Input



- ➢ A critical input for structure and reaction theory calculations
- ➢ Affect nearly all reactions in r-process
  - Photodissociation
  - Neutron capture
  - Fission
  - β-decay
  - … …

Nuclear Input

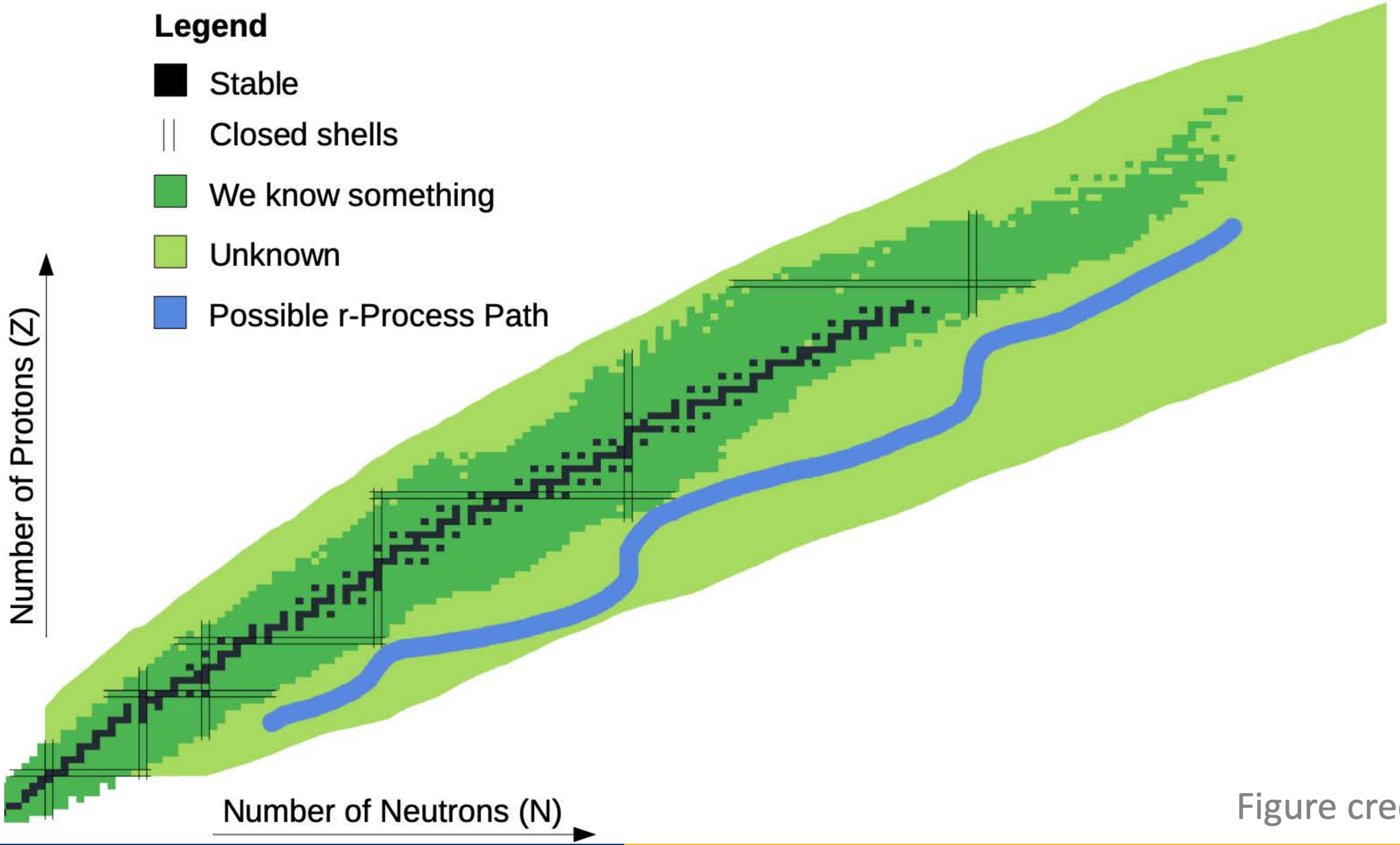
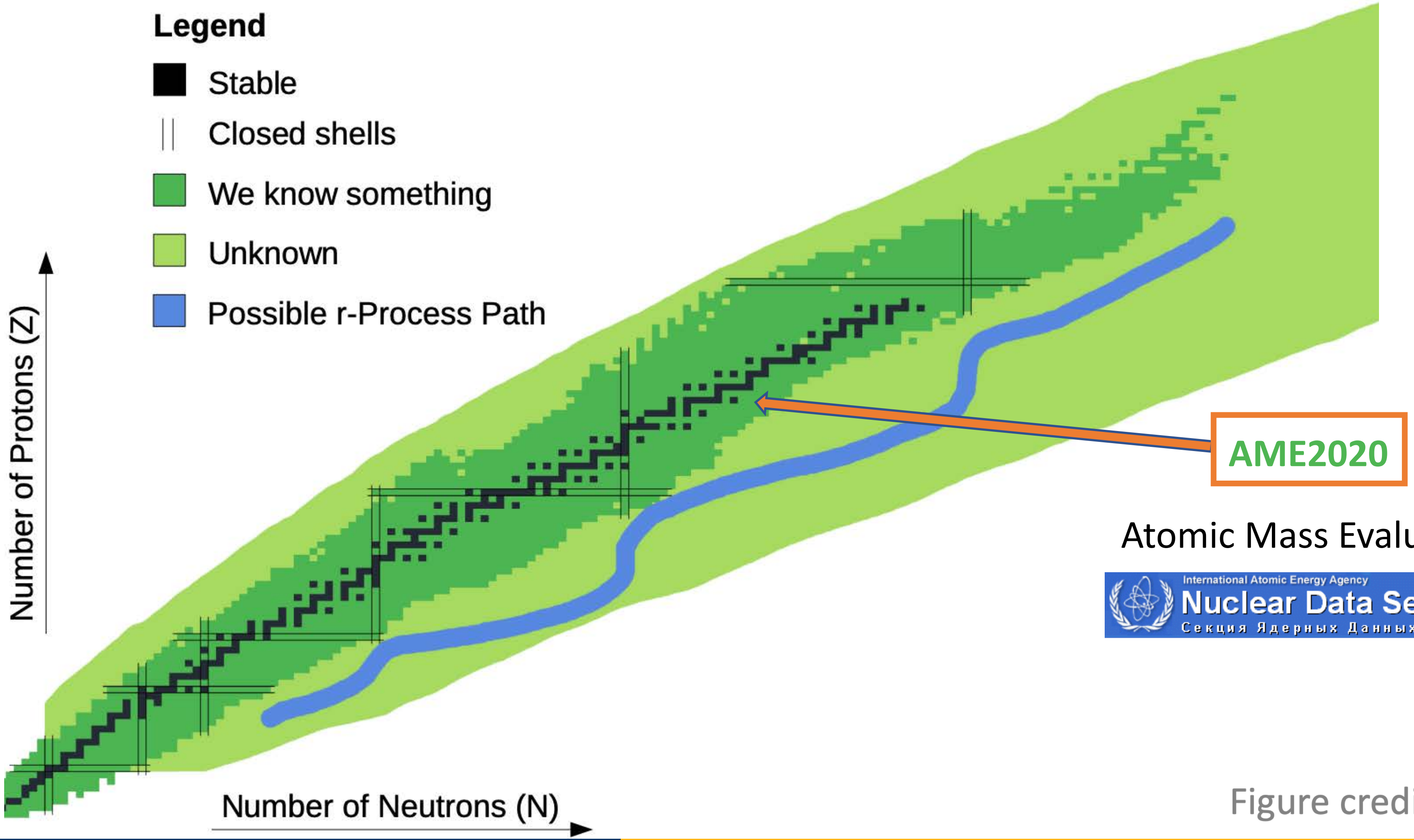


Figure credit: M. Mumpower

Nuclear Input

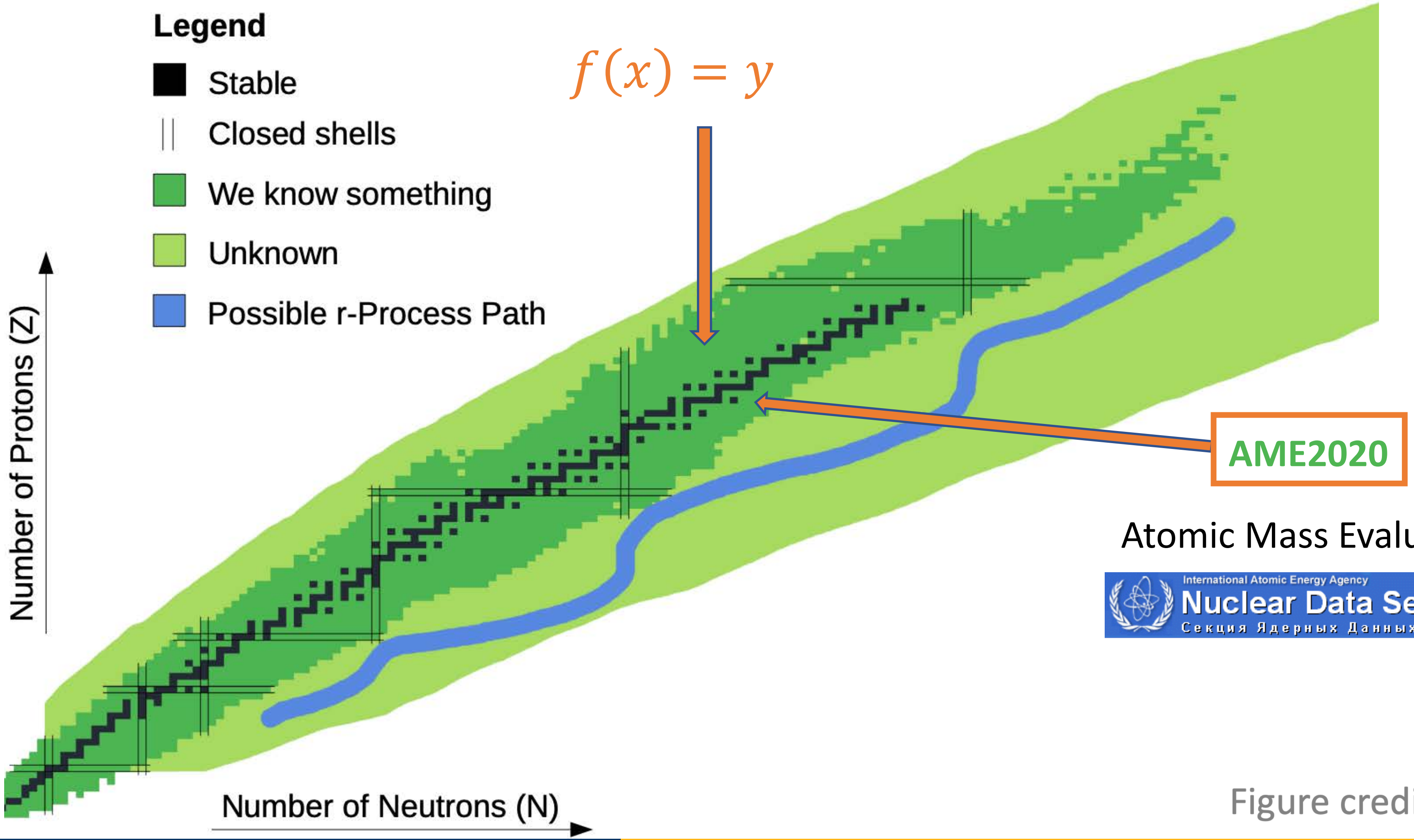


Atomic Mass Evaluation

International Atomic Energy Agency
Nuclear Data Services
Секция Ядерных Данных МАГАТЭ

Figure credit: M. Mumpower

Nuclear Input



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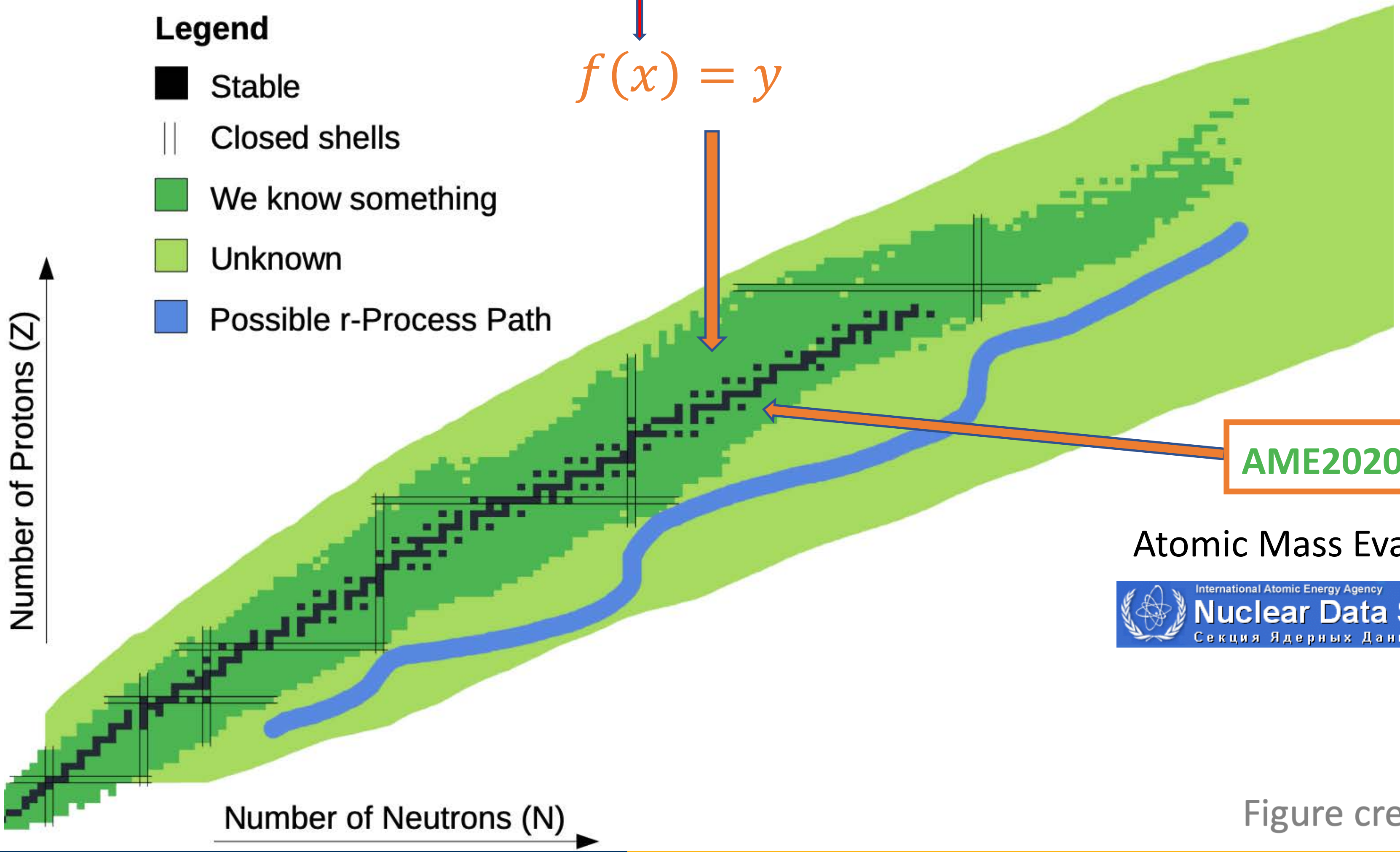
Nuclear Input

(Z, N, A …)

$$f(x) = y$$



AME2020

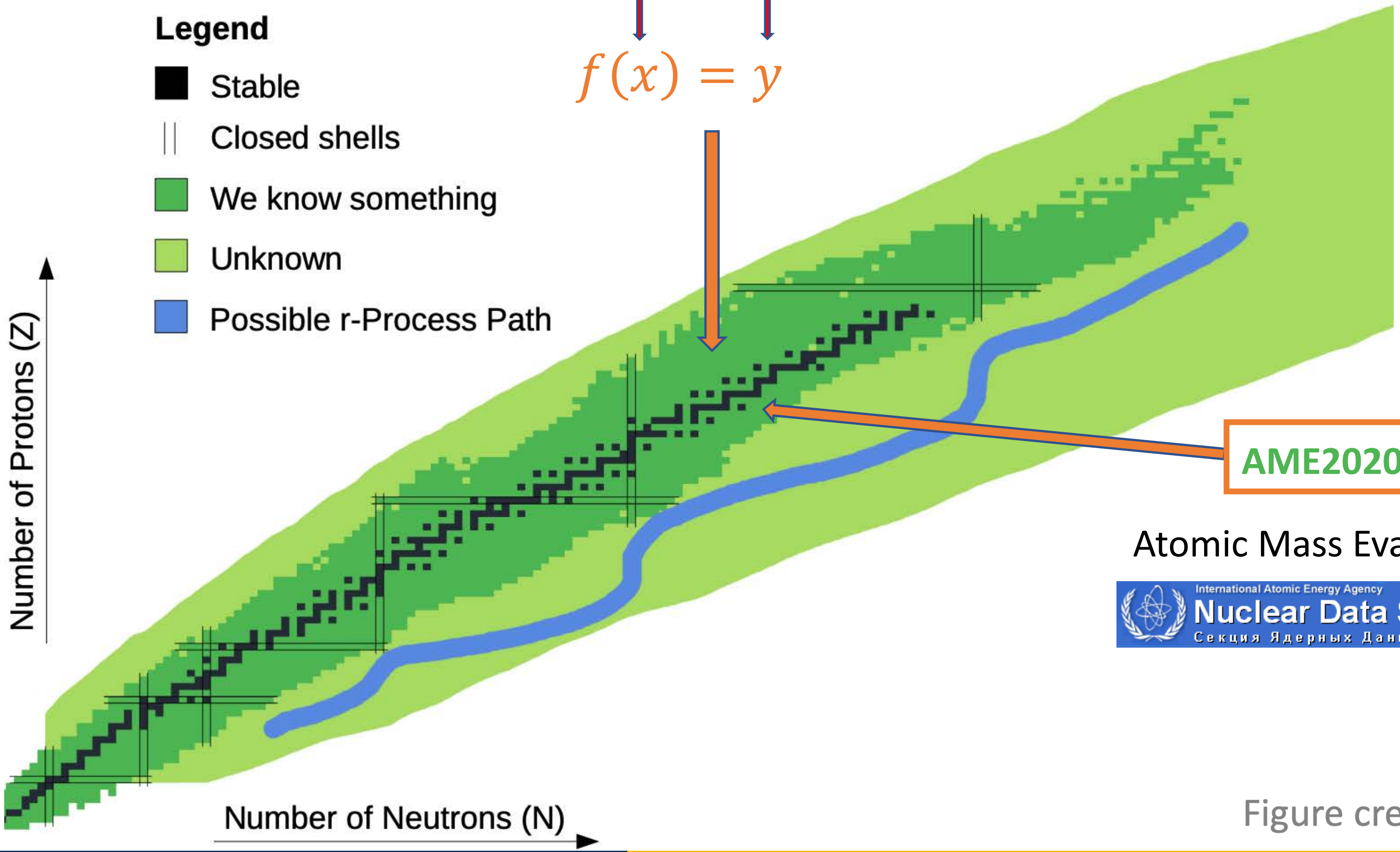
Atomic Mass Evaluation

Figure credit: M. Mumpower

Nuclear Input

(Z, N, A …)   Mass of the nucleus

$$f(x) = y$$



AME2020

Atomic Mass Evaluation

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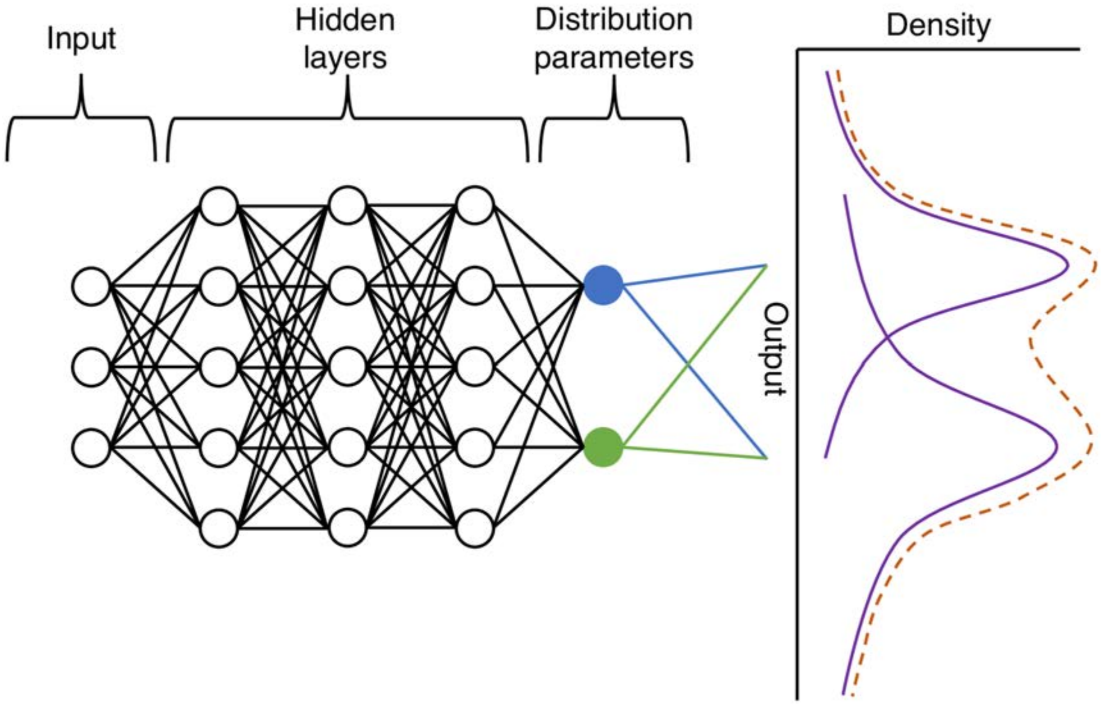
Mass Model

Mixture Density Network (MDN)



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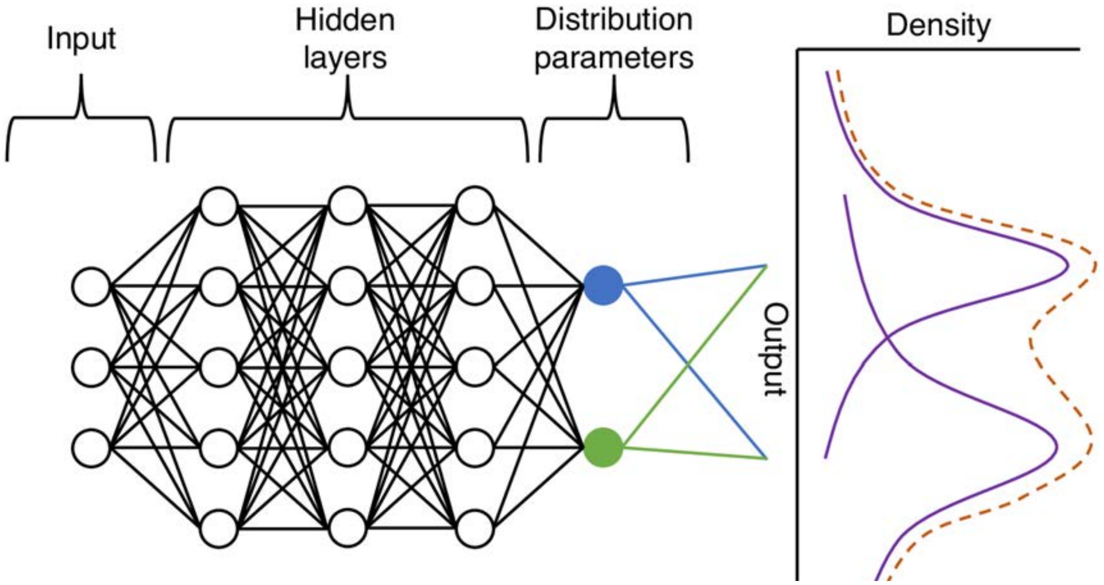
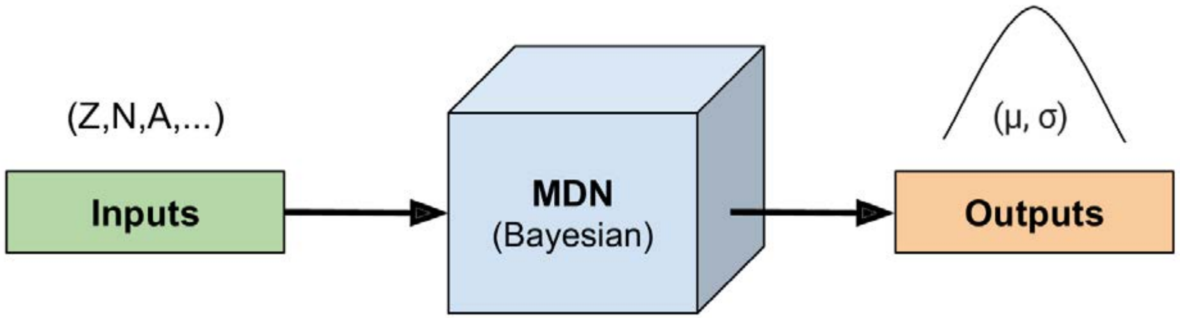
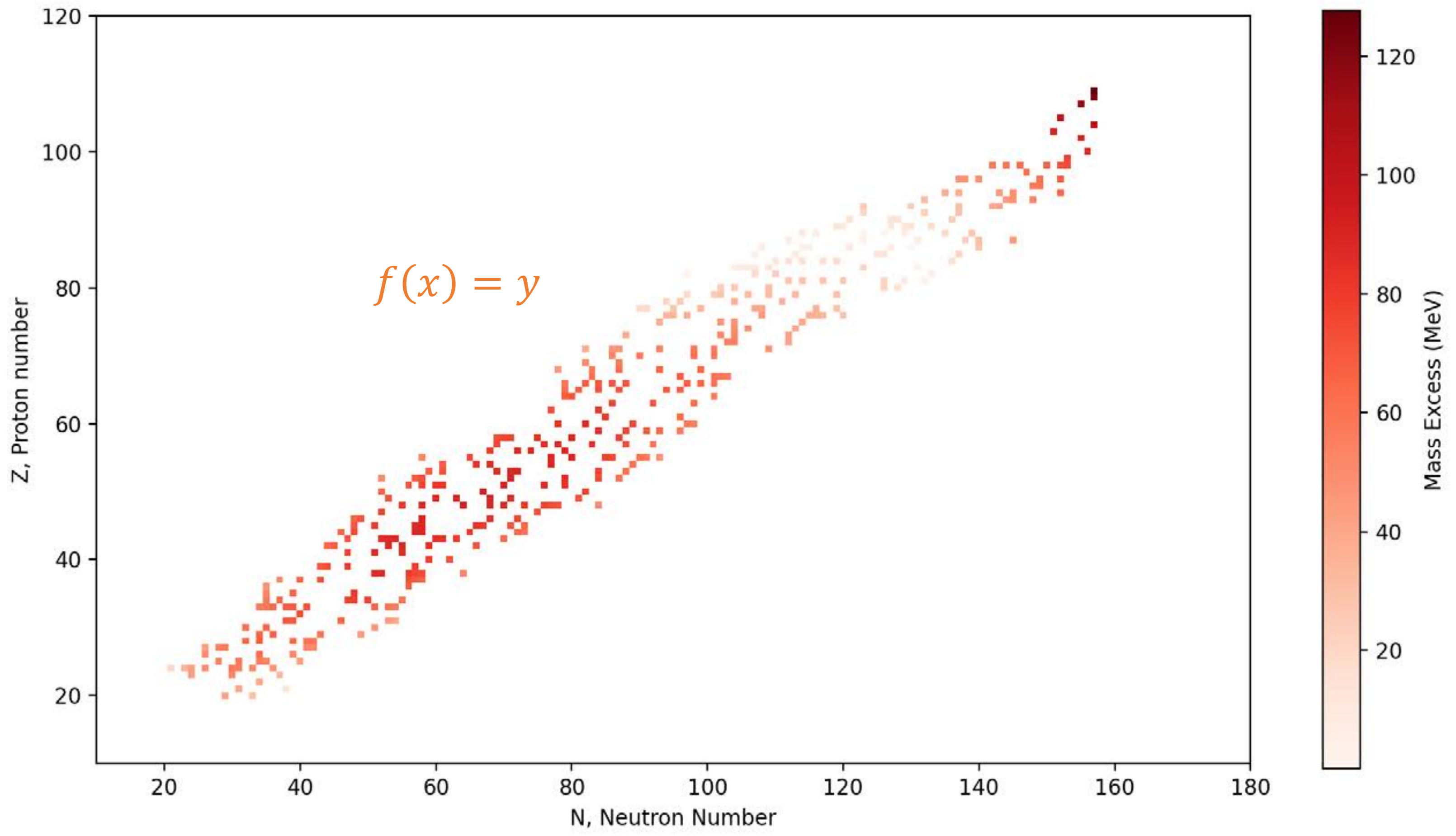




Mass Model

Our Model: Training (20 % data)

Testing (80 % data)



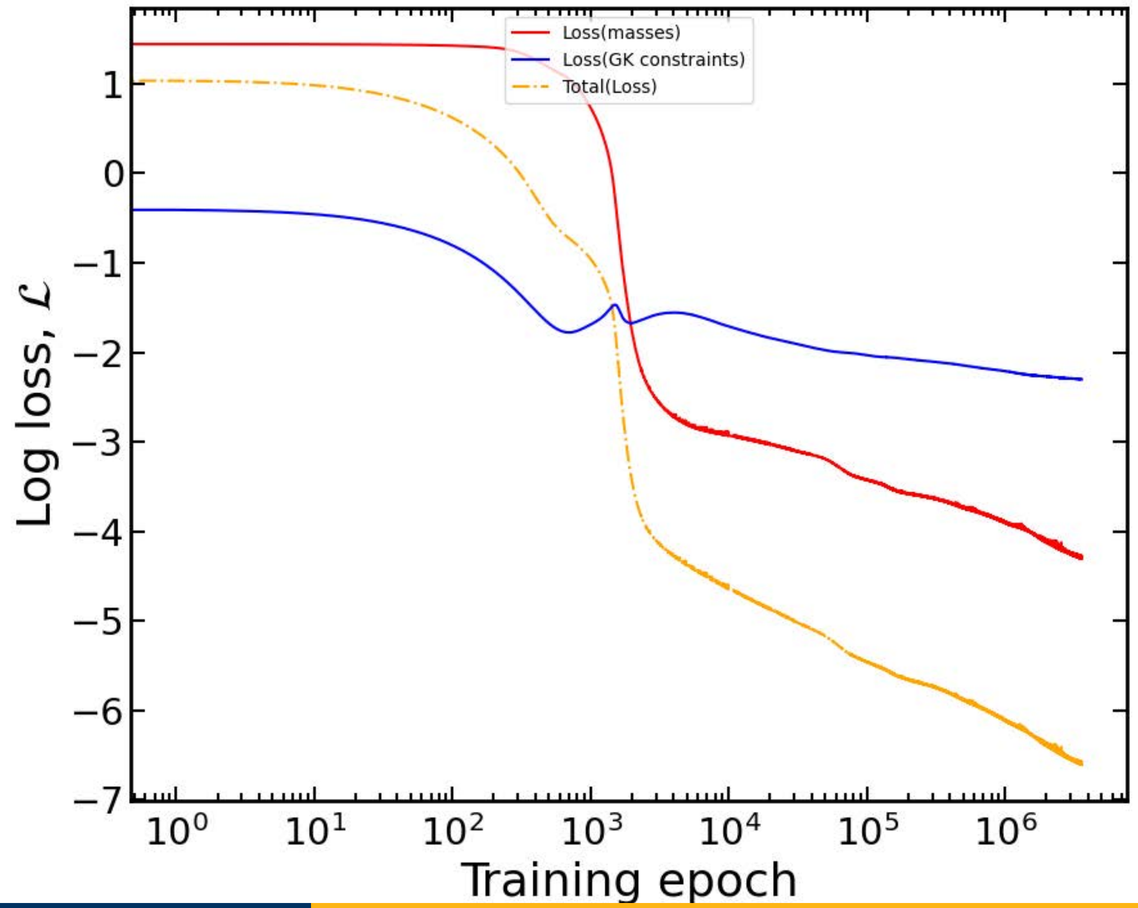
Mass Model

Minimize: $\mathcal{L} = -\ln\left[\sum_{i=1}^{m}\frac{\alpha_i(\mathbf{x})}{(2\pi)^{m/2}\sigma_i(\mathbf{x})}\exp\left\{-\frac{||\mathbf{t}-\mu_i(\mathbf{x})||^2}{2\sigma_i(\mathbf{x})^2}\right\}\right]$

$$\mathcal{L}_2 = \sum_i GK(Z_i, N_i)$$

$GK(Z,N)$: Garvey-Kelson Mass relation:
(Mass relation of its 6 neighbors)

$$\begin{aligned} &M(N+2,Z-2)-M(N,Z)\\ &+M(N,Z-1)-M(N+1,Z-2)\\ &+M(N+1,Z)-M(N+2,Z-1)=0 \end{aligned}$$



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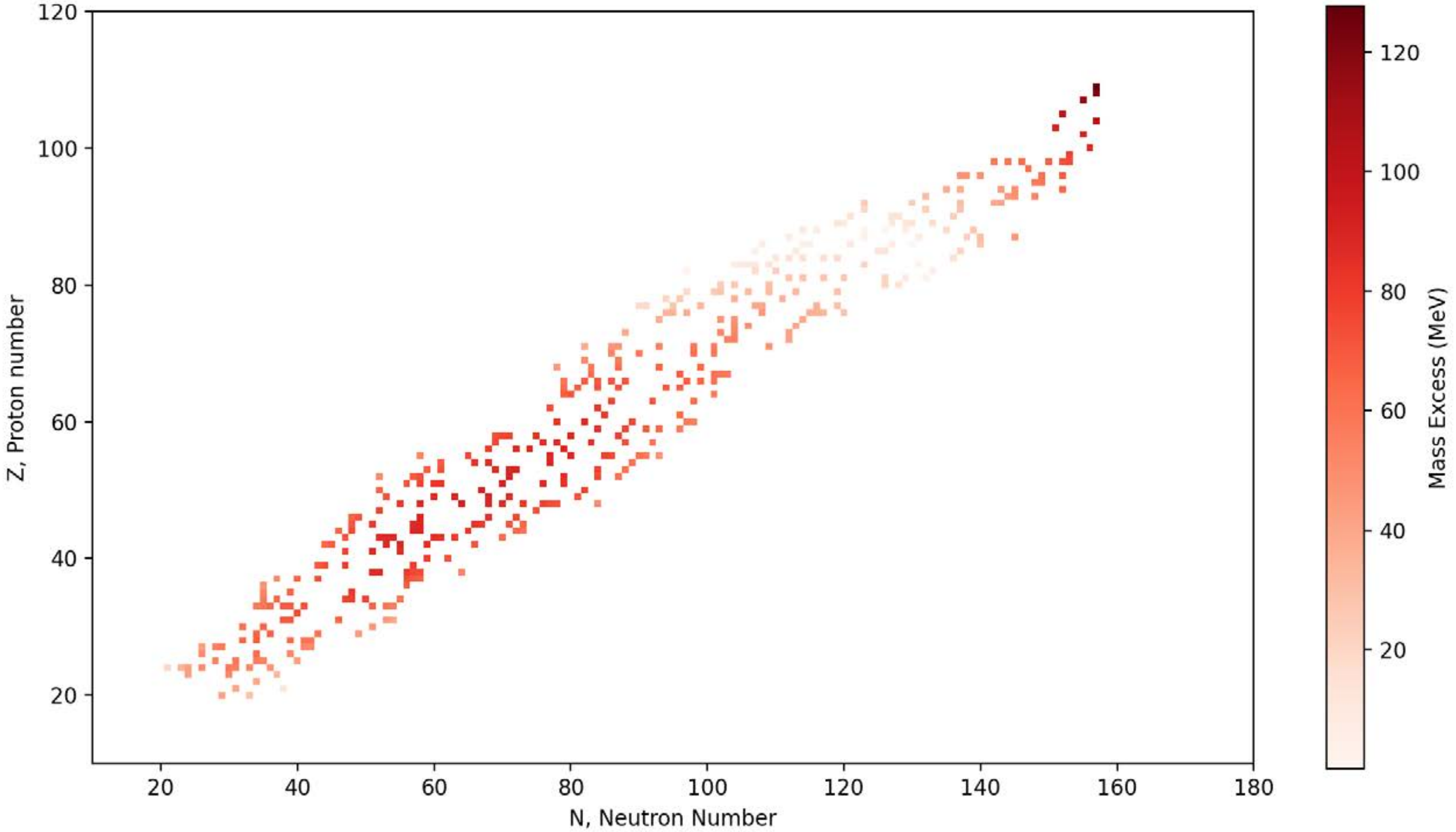

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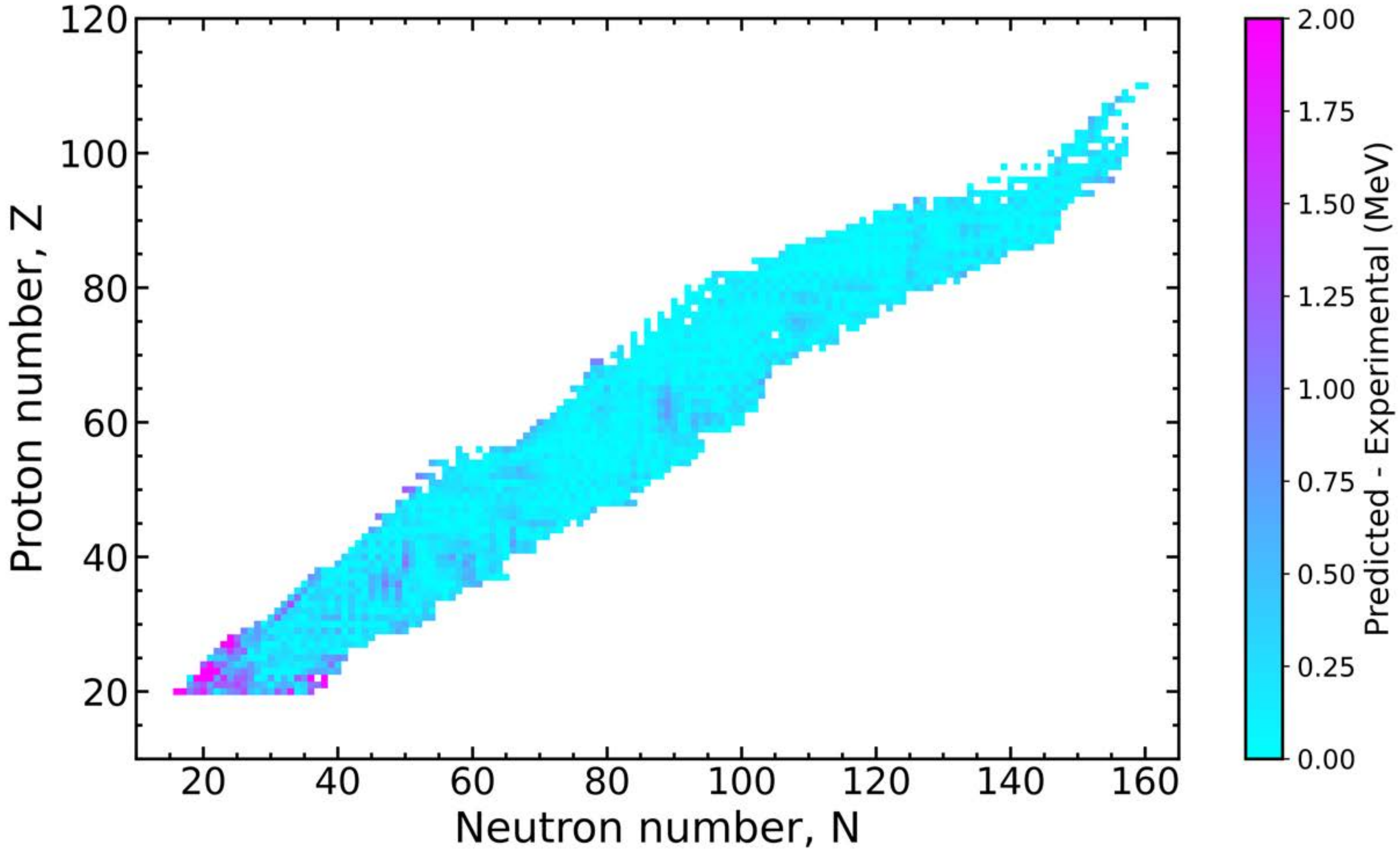
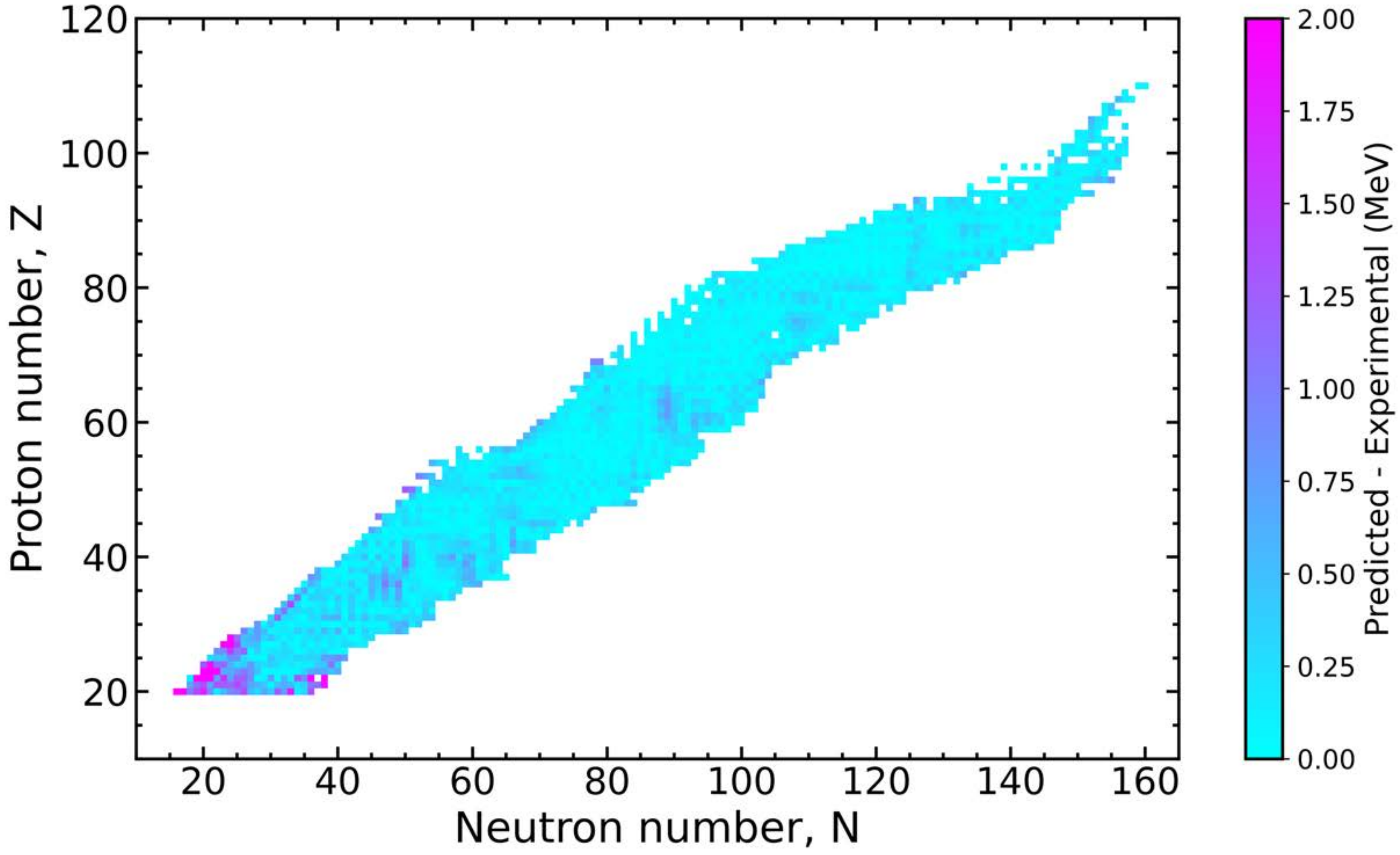


Mass Model

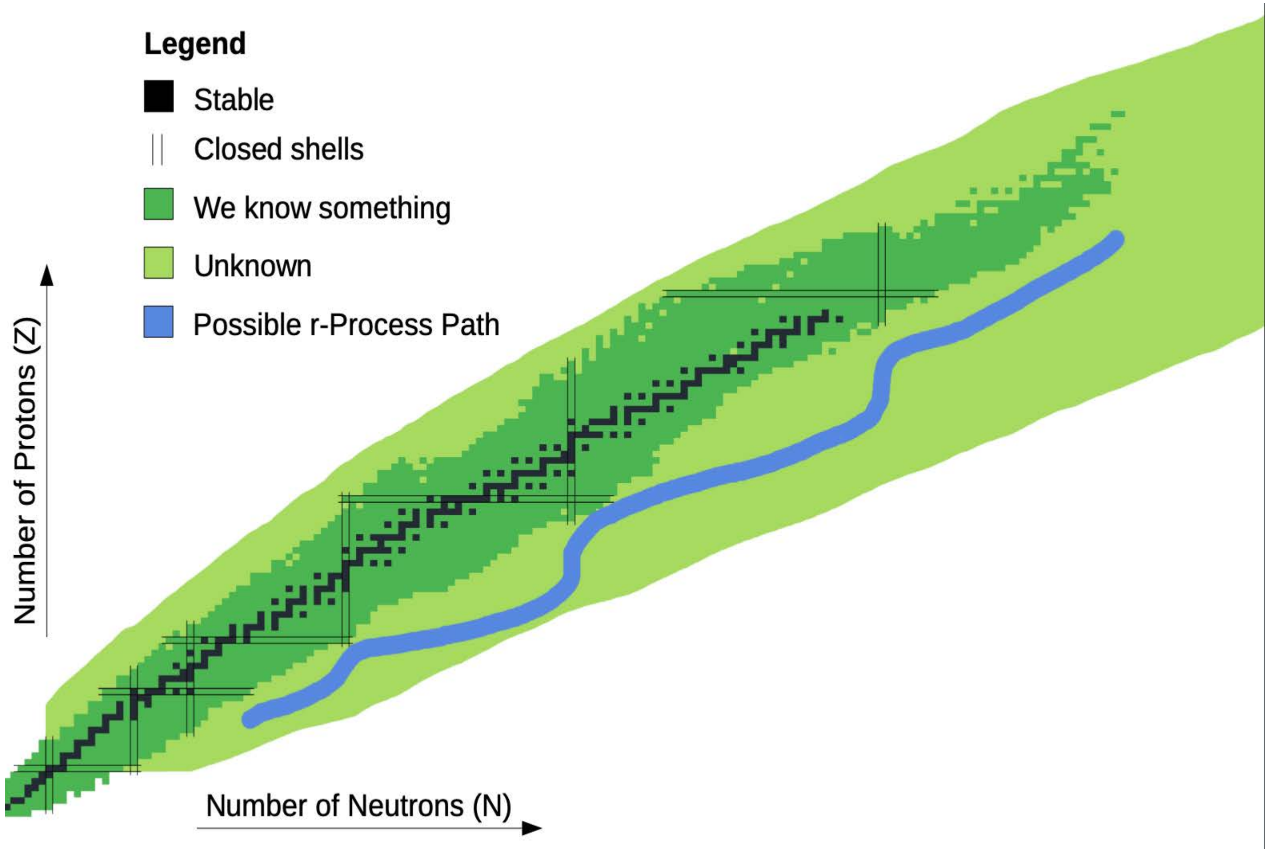
Our Model: Training (20 % data) RMS: 138 keV; Testing (80 % data) RMS: 246keV



FRDM: RMS 537 keV
DZ33 : RMS 405 keV
Hfb32: RMS 560 keV

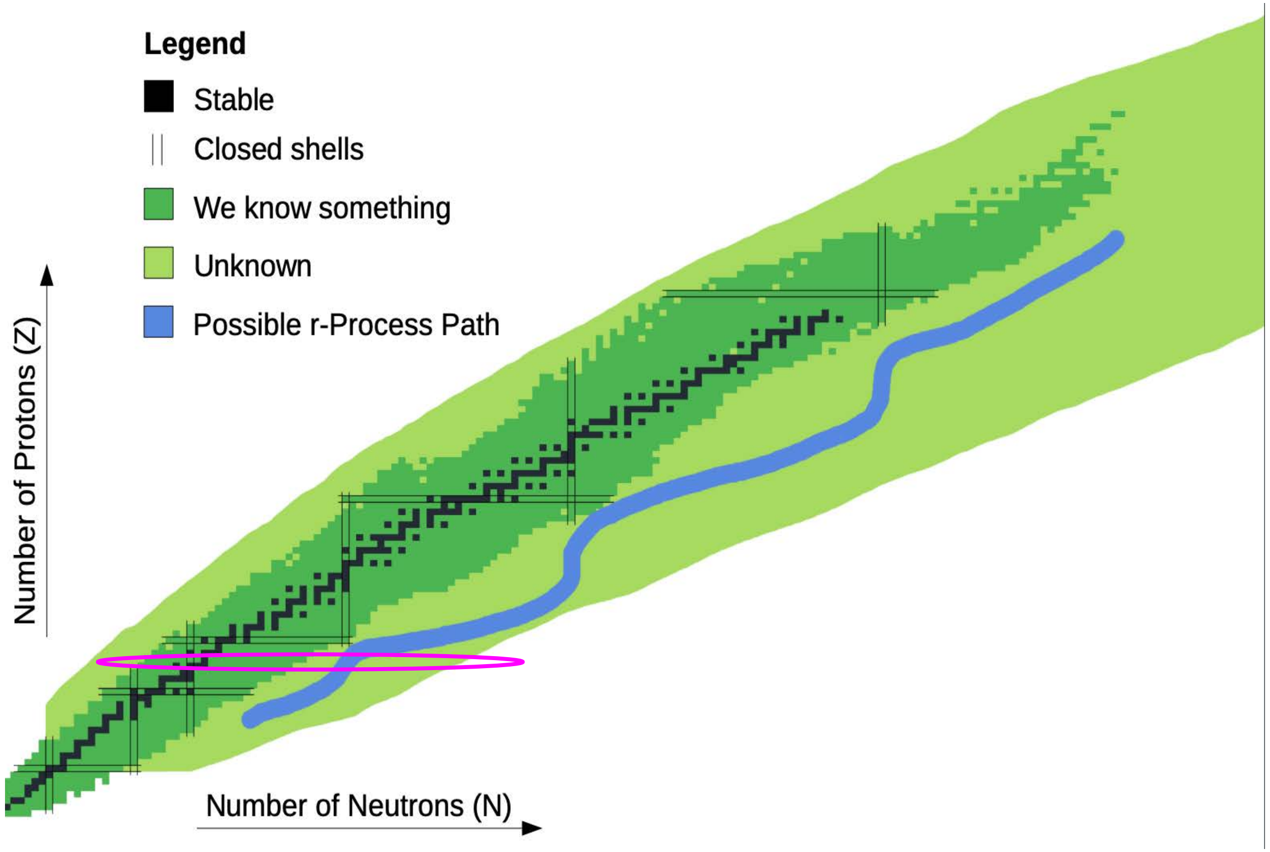
$$\text{RMS} = \sqrt{\sum_{i}^{n} \frac{(Predicted_i - Actual_i)^2}{n}}$$

Mass Model



Li, Sprouse, Lovell, Meyer, Mohan & Mumpower in preparation

Mass Model



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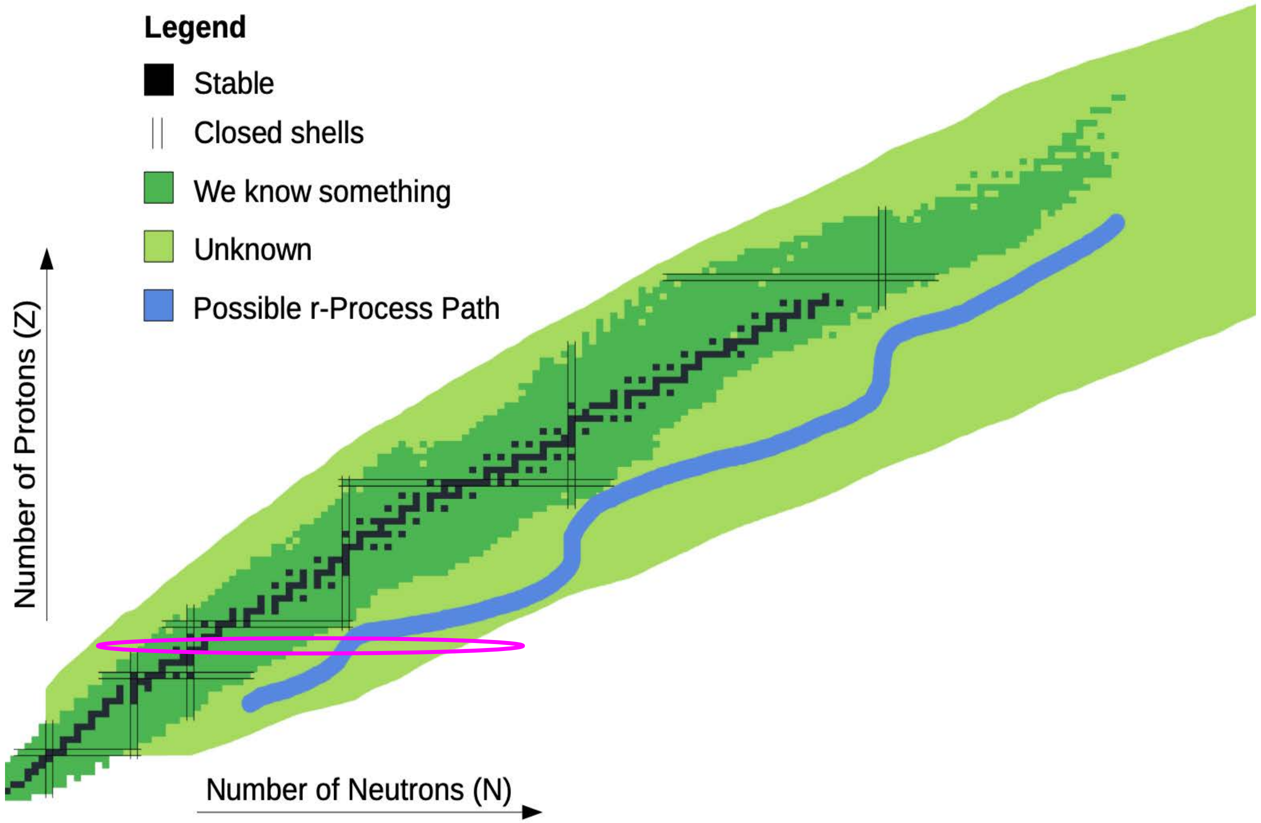

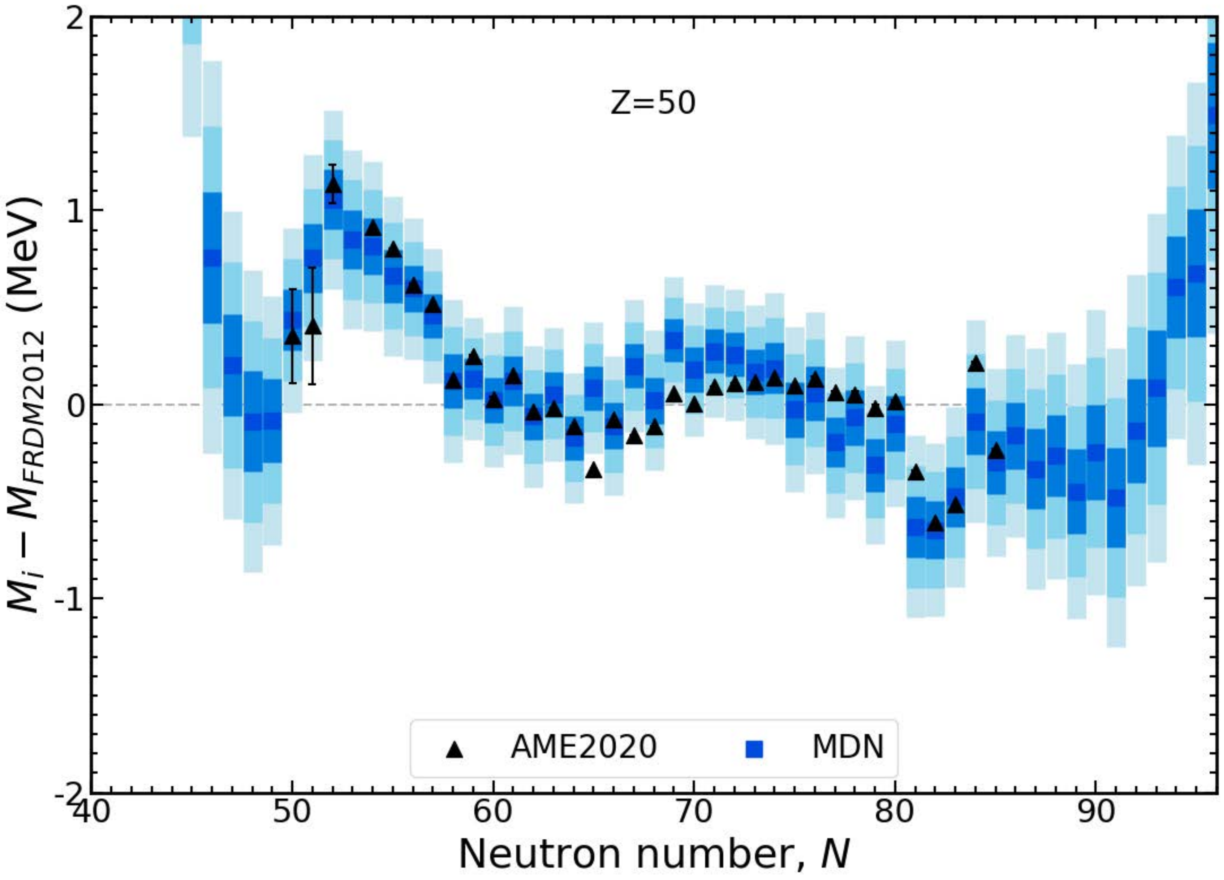

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Application to the r-process

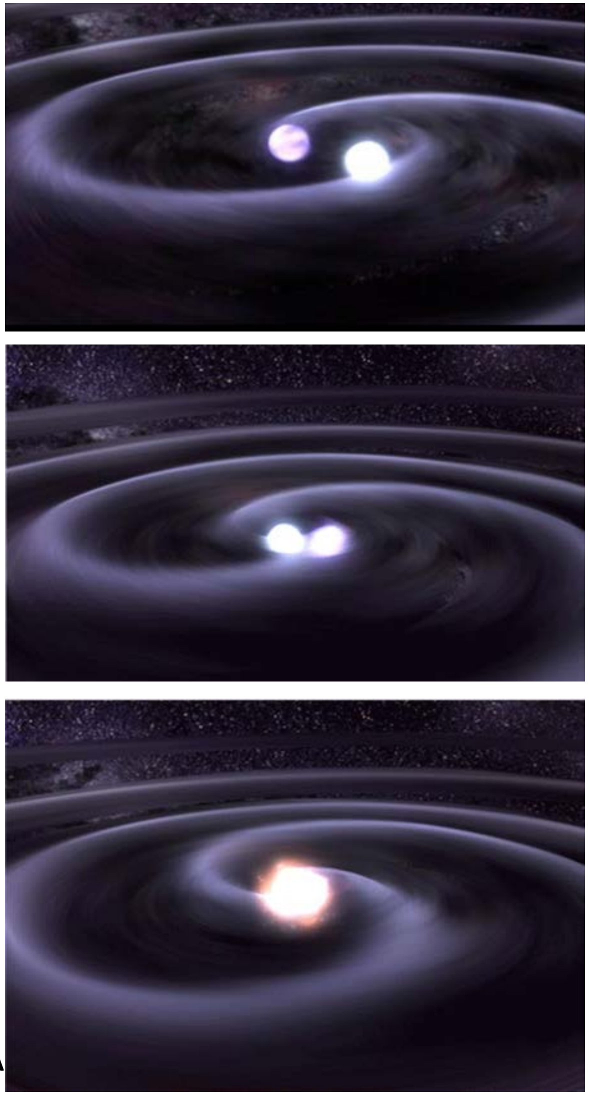
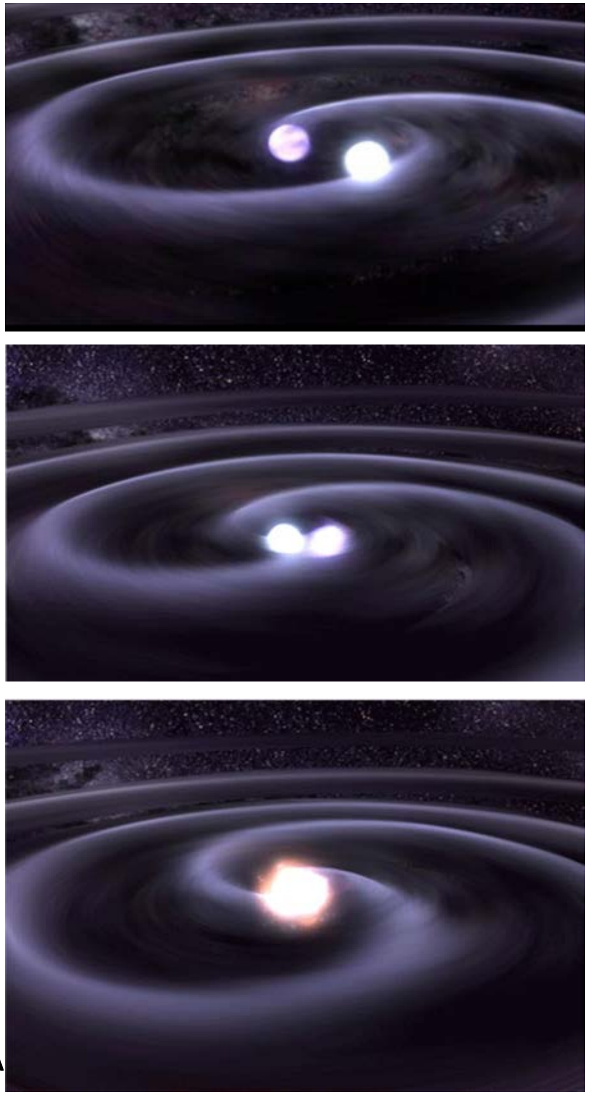


Figure: NASA

- Super high temperature (10^9 K)
- Super neutron rich environment (10^{24} cm^{-3})
- Rapid neutron capture process or r-process happens

  (n-capture faster than β^- decay)
- Astrophysical site for production of heavy nuclei

Application to the r-process



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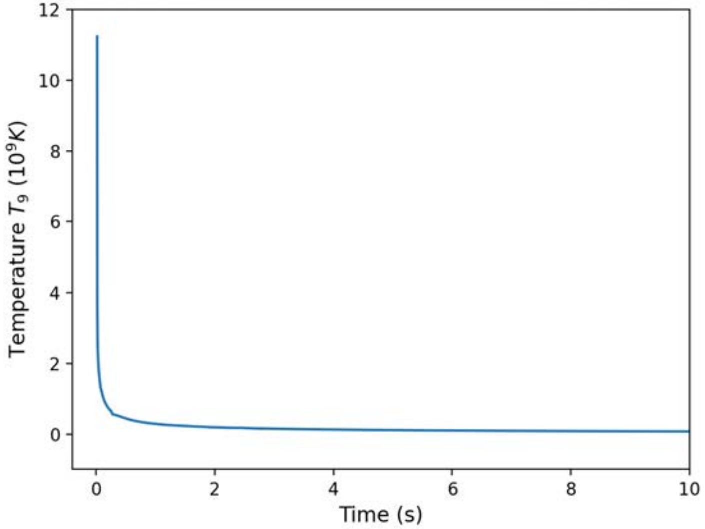
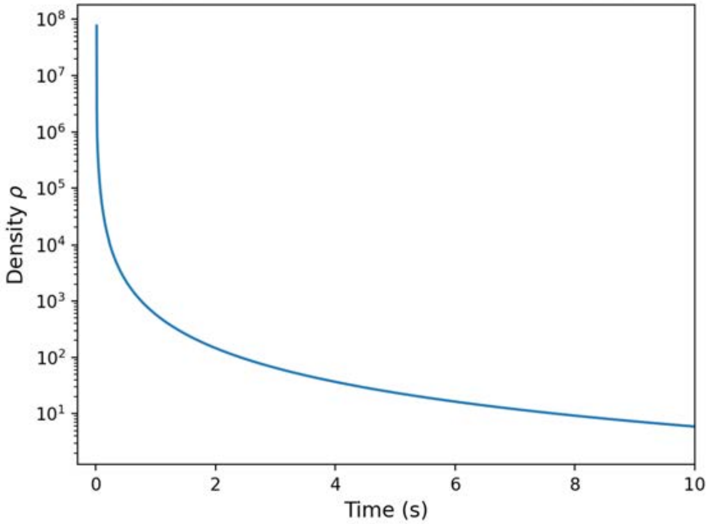
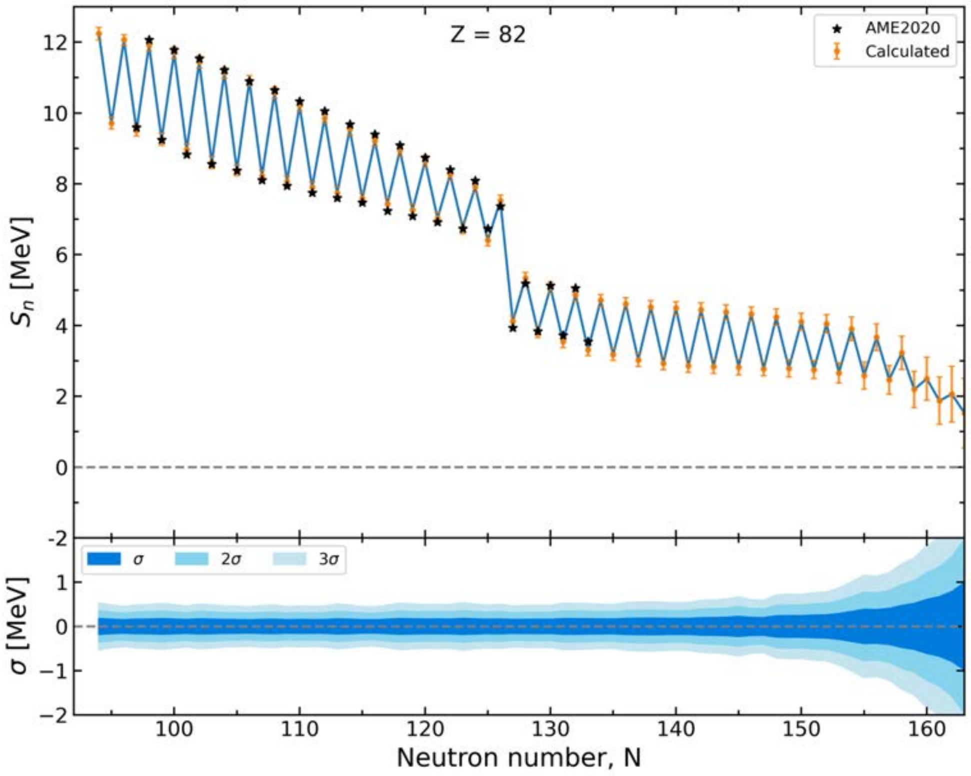




Application to the r-process

Neutron Separation Energy: $S_n(Z, A) = M(Z, N-1) + M_n - M(Z, A)$



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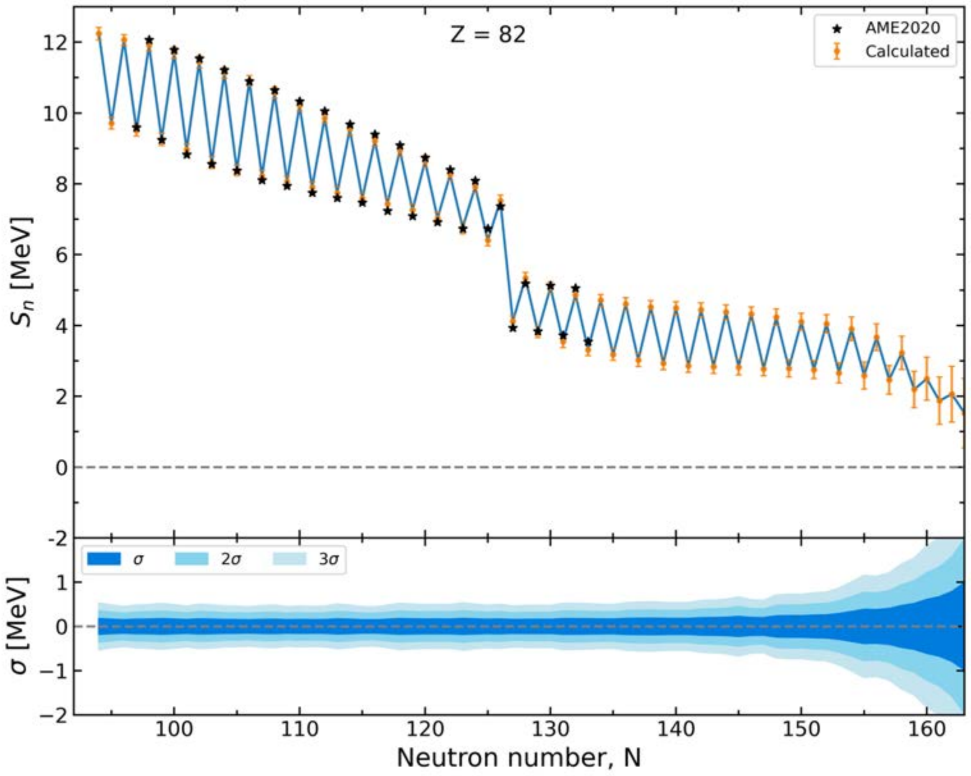

$\lambda_{\gamma n} \propto e^{-\frac{S_n}{kT}}$

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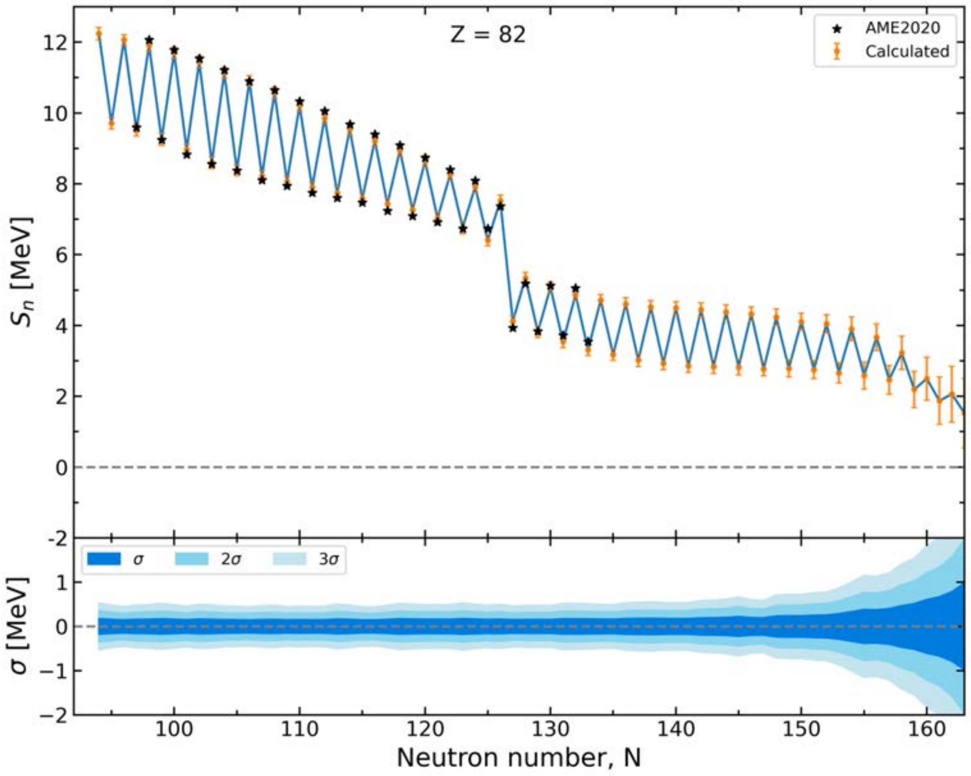

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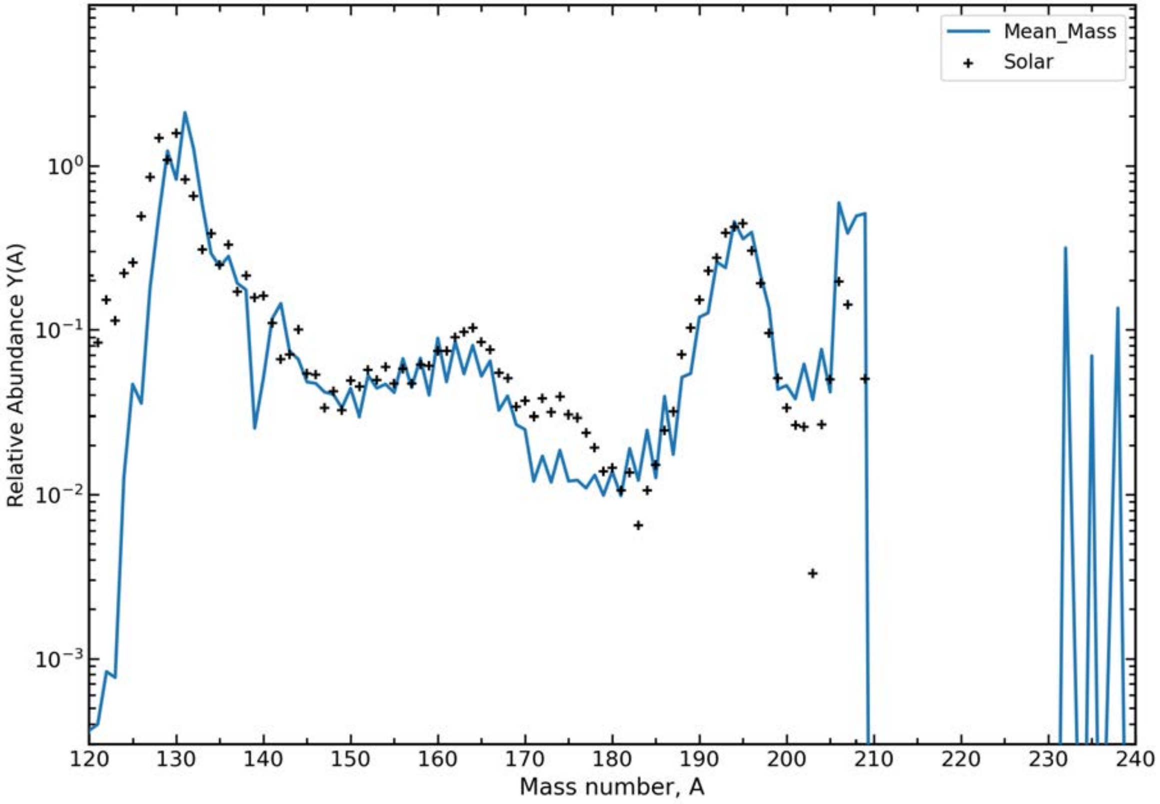

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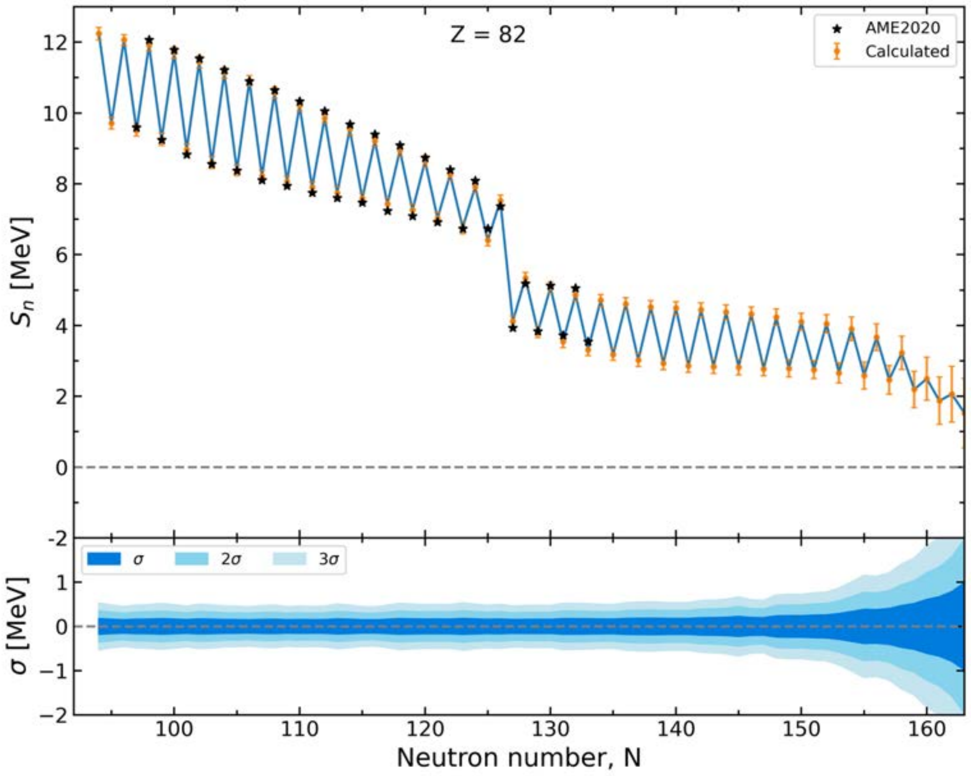

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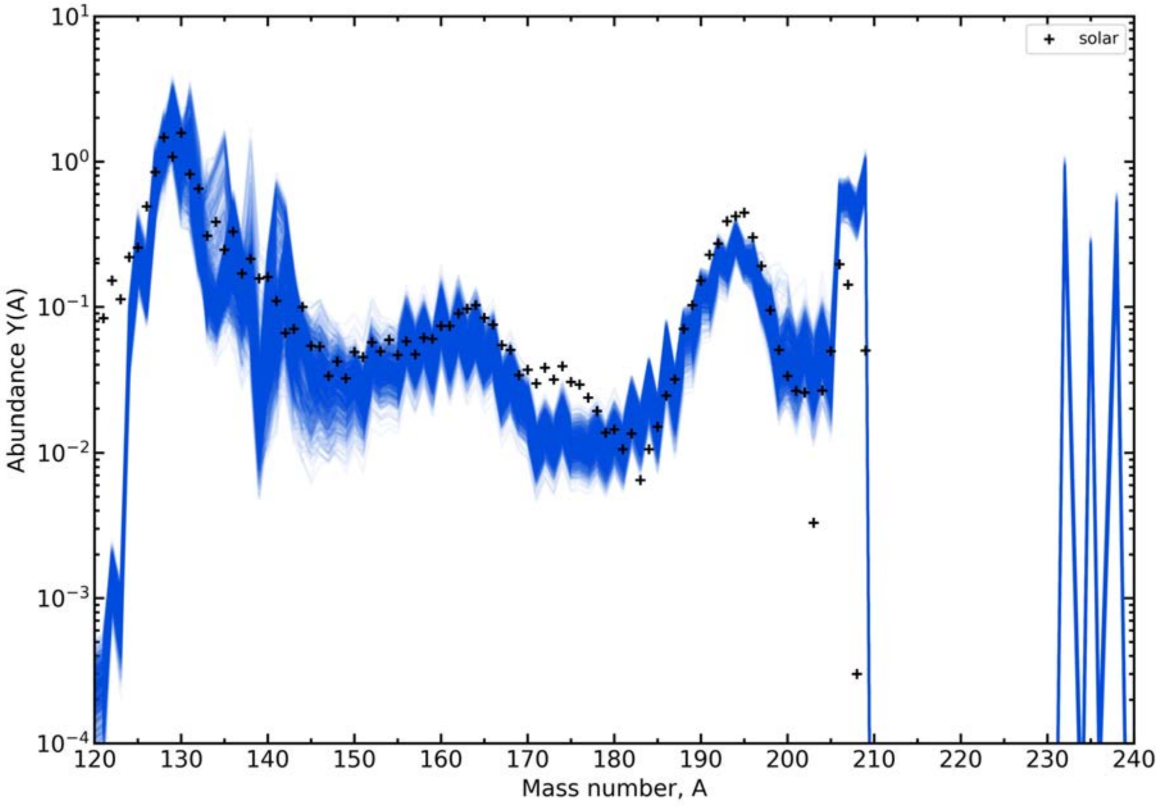

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Summary and Future work

- Summary
  - Studied the nuclear mass model using machine learning technique
  - Applied this mass model to r-process simulation which gives a reasonable abundance pattern
- Future work
  - Improve this mass model by optimizing input features
  - Understand the deviation between observed and simulated r-process abundance pattern

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Acknowledgements

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Arvind Mohan

Thank you for your attention!

Input Feature Space